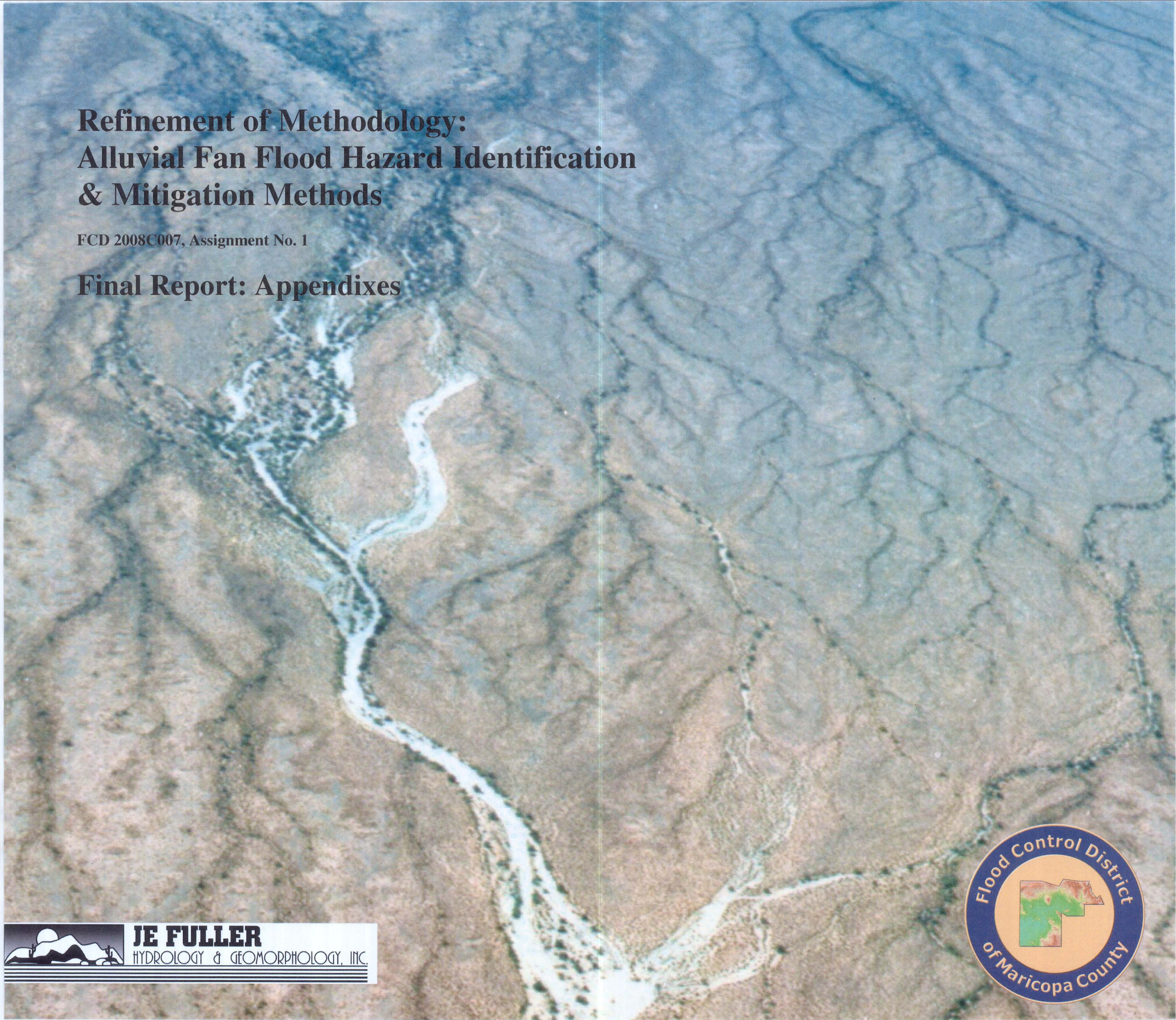
Refinement of Methodology: Alluvial Fan Flood Hazard Identification & Mitigation Methods

FCD 2008C007, Assignment No. 1

Final Report: Appendixes



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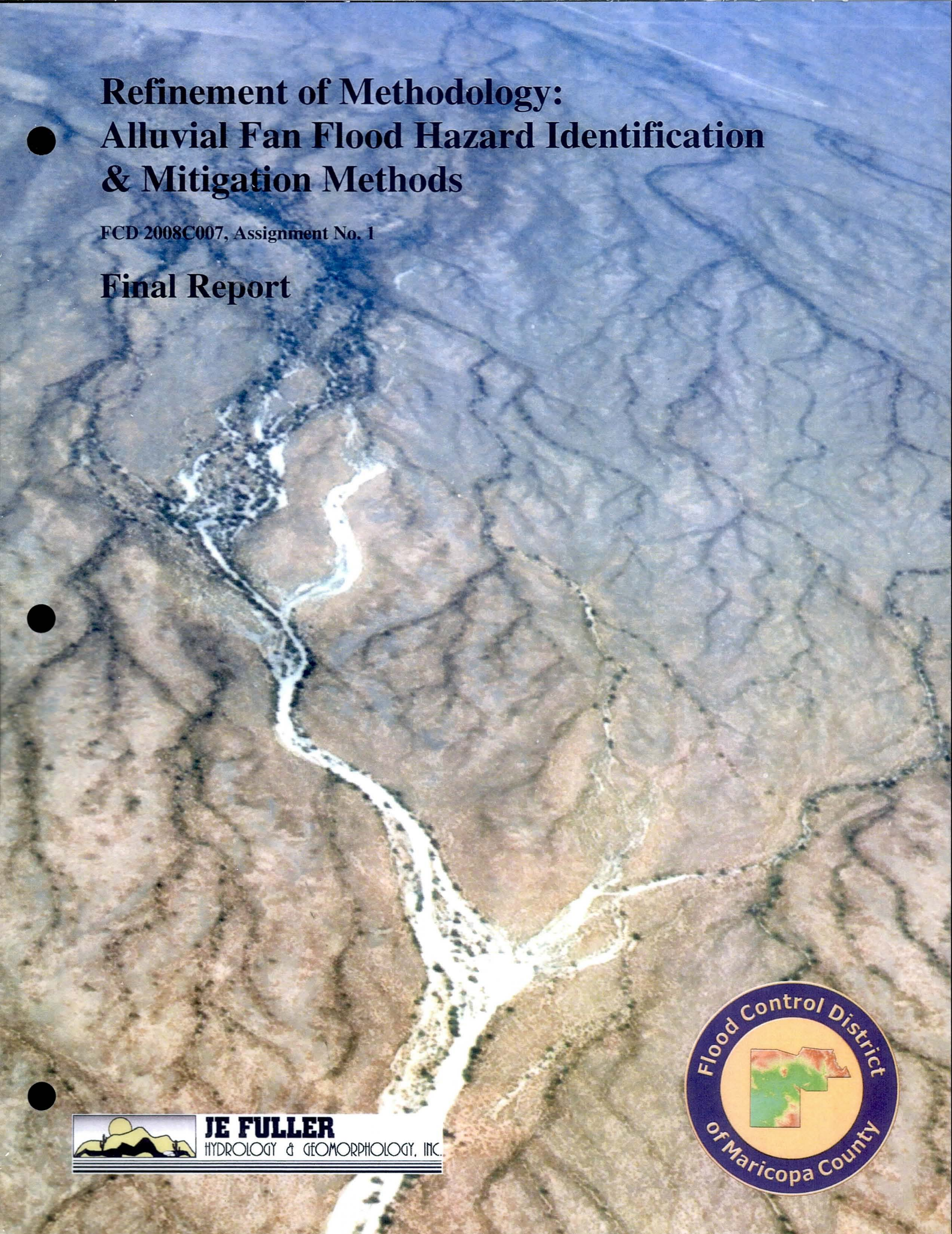

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Executive Summary

The "Refinement of Methodology: Alluvial Fan Hazard Identification & Mitigation Methods Study" (PFHAM Study) was initiated to develop guidelines and recommendations for regulations that will be used to identify, classify and address flood hazards on alluvial fan landforms in Maricopa County, Arizona. The scope of work for this study called for professional engineering services needed to update and refine the Flood Control District of Maricopa County's (District) current Piedmont Flood Hazard Assessment Manual (PFHAM) methodology, to identify engineering procedures to quantify flood hazards on alluvial fan landforms, to recommend hazard mitigation measures, and to refine landform definitions used in the PFHAM. The methodologies proposed in this report are intended for application to alluvial fans in Maricopa County, Arizona. While the proposed analytical methodologies may be applicable to other types of alluvial fans and uncertain flow path flood hazard areas, such applications are beyond the scope and intent of this report.

The types of alluvial fan flood hazards found in Maricopa County are representative of piedmont surfaces in tectonically inert portions of the semi-arid southwestern United States. Alluvial fan landforms in Maricopa County tend to have relatively low slopes (< 3%) and are dominated by low volume, flash floods. Active alluvial fans make up a small percentage of the alluvial fan landform surfaces in Maricopa County. The active fan areas tend to be located away from mountain fronts, are of limited areal extent, and to be dominated by shallow sheet flooding, except in the zones closest to the hydrographic apexes. Debris flows are not a significant risk for most active alluvial fans in Maricopa County. Avulsions have been documented on several active alluvial fans in Maricopa County, but are thought to occur with relatively low frequency, primarily during large water floods.

To develop the recommended Integrated Alluvial Fan Hazard Assessment Methodology in Maricopa County, the following tasks were completed:

- **Literature Search**. Relevant publications and guidance documents on alluvial fan flooding were researched to identify potential assessment, management and modeling procedures. It was documented that alluvial fans in Maricopa County tend to lie at the low end of the hazard spectrum of fans described in the literature.
- **Historical Analysis**. A review of four active alluvial fans in Maricopa County that had been urbanized over the past 40 years indicated minor sedimentation and maintenance problems, but no flooded homes or failures of structural flood control measures. However, none of the sites has yet experienced a design flood.
- **Surficial Dating Techniques**. A review of geologic dating methods determined that numerical methods are available that would be applicable in Maricopa County, but that a regional dating chronology study would be required to fully implement significantly higher resolution surficial dating.
- **Debris Flow Hazards**. A study of debris flow risk concluded that debris flows are unlikely to affect alluvial fan flooding in Maricopa County. A composite methodology for quantifying debris flow risk was developed for use on local fans.
- **Alluvial Fan Site Analyses**. Four alluvial fan sites, representing a range of typical alluvial fan conditions found in Maricopa County, were selected for more

detailed hydrologic, hydraulic, sediment, and geomorphic analyses. The site analyses were used to formulate the recommended Integrated Alluvial Fan Hazard Assessment Methodology.

- **Hydrologic Modeling**. The following conclusions were derived from the hydrologic modeling analyses:
    - FLO-2D is preferred over HEC-1 for modeling fans and alluvial plains.
    - Significant flood peak attenuation occurs below the hydrographic apex.
    - Use of the apex discharge is overly conservative in the distal fan areas.
- **Hydraulic Modeling**. The following conclusions were derived from the hydraulic modeling analyses:
    - FLO-2D modeling is preferred for modeling fans and alluvial plains.
    - Most fans in Maricopa County are dominated by shallow sheet flooding.
    - High depth and velocity zones are limited in extent on most fans.
    - Unregulated development on alluvial fans will adversely impact downstream areas.
- **Sedimentation Modeling**. The following conclusions were derived from the sediment modeling analyses:
    - No sediment model was identified that adequately depicts alluvial fan sedimentation processes.
    - Single event sedimentation is very low relative to the total active fan area.
    - Long-term sedimentation may impact alluvial fan flooding processes.
    - There is a lack of sediment data needed for development, calibration and verification of alluvial fan sediment models.
- **Avulsion**. The following conclusions were derived from the avulsion analysis:
    - Avulsions are known to occur on fans in Maricopa County.
    - Avulsions occur rarely, but the expected frequency is as yet unknown.
    - A methodology was developed to predict potential avulsion hazards.
    - A methodology, called the virtual levee scenario method, was developed using FLO-2D modeling to simulate the potential impact of avulsions on alluvial fan flood hazards.
- **Flood Hazard Classification**. A methodology was developed to quantify flood hazards on alluvial fans into ultrahazardous, high, moderate and low categories. The method is based on FLO-2D modeling results, assessments of debris flow and avulsion risk, and the 100-year discharge. Portions of active alluvial fan floodplains subject to ultrahazardous "active alluvial fan flooding" would be subject to special FEMA criteria. The remainder of the 100-year flooding on active alluvial fans may be subject to high, moderate, or low hazard are subject to lower, less restrictive development criteria.

Based on the results of the analyses described above, a recommended Integrated Alluvial Fan Hazard Assessment Methodology was developed. The methodology, illustrated in Figure E-1, is a composite of engineering and geomorphic modeling techniques, meets FEMA criteria for evaluation of alluvial fan flood hazards, and consists of the following three steps:

- **Stage 1: Landform Identification**. In Stage 1, it is determined whether a study area lies on an alluvial fan landform, as opposed to a riverine floodplain or alluvial plain landform. Alluvial fan landforms are advanced for Stage 2 analysis.

- **Stage 2: Definition of Active and Inactive Areas**. In Stage 2, the active portions of alluvial fan landforms are distinguished from inactive portions. The active portions of alluvial fan landforms are advanced forward for analysis in Stage 3. Inactive alluvial fan areas can be evaluated using more traditional techniques.
- **Stage 3: Delineation of Regulatory Floodplain**. In Stage 3, the portions of an active alluvial fan that are subject to inundation during a 100-year flood are delineated. The result of the Stage 3 analysis is a regulatory floodplain delineation map and quantified flood hazard information. The floodplain delineation distinguishes ultrahazardous "active alluvial fan flooding" areas subject to the most severe FEMA restrictions, from other less hazardous types of flooding on active alluvial fans and piedmont areas with uncertain flow paths. The less hazardous flood zones include classifications from which appropriate floodplain management strategies can be formulated.

The recommended Integrated Alluvial Fan Hazard Assessment Methodology in Maricopa County was reviewed and endorsed by a "Blue Ribbon Panel" of alluvial fan experts from across the United States and who represented a wide variety of technical, scientific, and regulatory disciplines. The Blue Ribbon Panel recommended that the integrated methodology be applied to a representative alluvial fan in Maricopa County, and submitted to FEMA together with the PFHAM Study documentation as a test case.

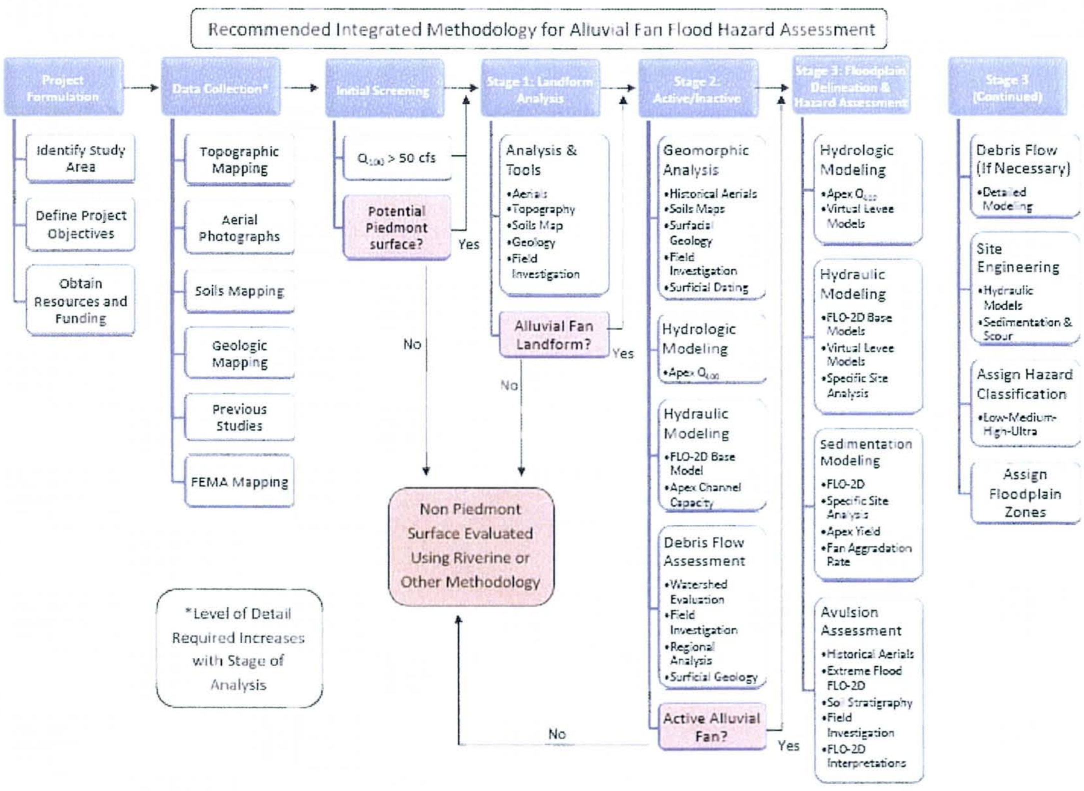

Figure E-1. Decision tree matrix showing the recommended integrated methodology.

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(Note: 2009 aerial base used in all Figures unless otherwise noted.)

1. Introduction

1.1. Objectives

This study is officially entitled "Refinement of Methodology: Alluvial Fan Hazard Identification & Mitigation Methods." In this report, it is referred to as the "PFHAM Study." The PFHAM study was initiated to develop guidelines and recommendations for regulations that will be used to identify, classify and address flood hazards on alluvial fan landforms in Maricopa County, Arizona.

1.2. Scope

The scope of work for this study called for professional engineering services needed to update and refine the Flood Control District of Maricopa County's current Piedmont Flood Hazard Assessment Manual (PFHAM) methodology, to identify engineering procedures to quantify flood hazards on alluvial fan landforms, to recommend hazard mitigation measures, and to refine landform definitions used in the PFHAM. Specific study tasks are listed in the project scope of services included in Appendix L.

1.3. Applicability

The methodologies proposed in this report are intended for application to alluvial fans in Maricopa County, Arizona. The types of alluvial fan flood hazards found in Maricopa County are representative of piedmont surfaces in tectonically inert portions of the semi-arid southwestern United States. While the proposed analytical methodologies may be applicable to other types of alluvial fans and uncertain flow path flood hazard areas, such applications are beyond the scope and intent of this report.

1.4. Authority

This study was performed under contract FCD 2008C007, Work Assignment #1 by JE Fuller/Hydrology & Geomorphology, Inc. (JEF) on behalf of the Flood Control District of Maricopa County (District).

1.5. Study Participants

The PFHAM study was conducted as a cooperative effort between the consultant team and a special Alluvial Fan Task Force composed of staff from the District's Engineering, Planning, and Regulatory Divisions. State and local agencies with special interest in alluvial fan floodplain hazards also participated in the study. Finally, the results and recommendations of the PFHAM study were peer-reviewed by a "Blue Ribbon Panel" of technical experts from academia, regulatory agencies, and consulting engineering firms.

A complete listing of the study team members is provided in Appendix M.

1.6. Terminology

One of the key findings of the PFHAM study is the importance of precise terminology when discussing alluvial fan flood hazards. This is especially true for the term "alluvial fan." Much of the confusion and controversy about alluvial fan flood hazards stems from miscommunication over what is meant by this term. In this report, unless stated otherwise, the term "alluvial fan" refers to an alluvial fan landform. Alluvial fan landforms are geologic features composed of alluvial deposits that usually have a fan shape. In Maricopa County, alluvial fan landforms are part of a set of landforms developed in the low gradient portion of the fluvially dominated margins of low relief basins and mountain ranges. Use of the phrase "alluvial fan landform" has implications that relate to its formative processes operating over long periods of geologic time, but has no definitive implications regarding flood processes that occur within engineering time scales.

The flood hazard assessment methodologies described in this report apply to "active" alluvial fans, which comprise a minority of the alluvial fan landform surfaces in Maricopa County. The phrase "active alluvial fan" implies a set of processes that have occurred in recent geologic time and which may or may not be operating within relatively short engineering time scales. These "active" fan processes can be inferred from the physical characteristics of the alluvial fan landform. Adding confusion to the phrase "active alluvial fan" is that FEMA has tied specific regulatory requirements, conditions, and inferred flood processes to a vary similar term, "active alluvial fan flooding." In this report, the phrase "active alluvial fan" is used in a geologic sense, and relates to the Stage 2 delineation in the FEMA guidelines. "Active alluvial fan flooding," the phrase which is tied to the most restrictive FEMA regulations, is only applied in Stage 3 of the recommended methodology described in this report.

Finally, an active alluvial fan "floodplain," which is the primary focus of this report, represents only the portion of an active alluvial fan that is at risk of inundation by the one-percent chance flood. A portion of an active alluvial fan floodplain may be subject to "active alluvial fan flooding," as that term is current defined and regulated by FEMA, and is limited to the "ultrahazardous" portions of the 100-year floodplain on an active alluvial fan. The remainder of the 100-year flooding on active alluvial fans may be subject to varying degrees of flood hazards (classified as high-moderate-low in this report), but those flood hazards do not rise to the level of "ultrahazardous." To avoid at least some of the confusion relating to this similar-sounding, but fundamentally different terminology, alternative terminology utilizing terms such as "active piedmont flooding" is proposed as part of the recommended methodology described in Section 3 of this report.

More detailed discussion of terminology and recommended definitions for key terms is provided in Section 3.1 of this report.

2. Summary of Findings

A variety of technical, regulatory, administrative and bibliographic tasks were performed for the PFHAM study, including the following:

- Literature Review
- Evaluation of Historical Development on Alluvial Fan Landforms
- Alluvial Fan Site Evaluations
- Sedimentation Evaluation
- Holocene Dating Techniques
- Debris Flow Potential Assessment
- Avulsion Potential Evaluation

A summary of the findings of each of these tasks is provided in the following paragraphs.

2.1. Literature Review

2.1.1. Alluvial Fan Literature Search

In 2008, JEF performed a specialized literature review for the District under contract FCD2007C051, Work Assignment #1. This literature review focused on the following specific research topics relating to alluvial fans:

- Existing Alluvial Fan Floodplain Delineation Methodologies
- FEMA CLOMR/LOMR[1] Methodologies
- NRC Alluvial Fan Committee Interviews
- Debris Flow Hazard and Risk Assessment
- Frequency of Alluvial Fan Channel Avulsions
- Alluvial Fan Flood Mitigation Measures
- Alluvial Fan Flood Hazard Quantification Methods

For each research topic, separate memoranda were provided to the District and were revised in response to District comments. The literature collected and the memoranda summarizing the findings are included on the DVD attached to Appendix A.

<u>Existing Alluvial Fan Floodplain Delineation Methodologies</u>. The literature research revealed that Maricopa County is one of the few communities to have developed comprehensive alluvial fan floodplain delineation techniques. Existing alluvial fan floodplain delineation methods used in Maricopa County comply with FEMA procedures, as outlined in *Guidelines and Specifications for Flood Hazard Mapping Partners, Appendix G: Guidance for Alluvial Fan Flooding Analyses and Mapping* (hereafter, the FEMA Guidelines; FEMA, 2003). The FEMA Guidelines essentially follow the procedure recommended in the National Research Council (NRC, 1996) report

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[1] CLOMR: Conditional Letter of Map Revision; LOMR: Letter of Map Revision.

Alluvial Fan Flooding. The FEMA Guidelines allow a number of delineation methodologies that include geomorphic methods, one- and two-dimensional fixed bed hydraulic modeling, and composite methods that combine engineering and geologic approaches. Since 1998, Maricopa County has primarily applied a floodplain delineation methodology that relies heavily on geomorphic interpretation. None of the other communities and agencies investigated have adopted alluvial fan management or delineation practices which differ significantly from the FEMA Guidelines, would improve on the existing PFHAM methodology, or offer technical guidance for quantifying flood hazards on fluvially-dominated fans (as opposed to debris flow fans).

<u>FEMA CLOMR/LOMR Methodologies</u>. Review of past alluvial fan CLOMR and LOMR submittals reviewed by FEMA indicated that structural measures are the primary approach to mitigating alluvial fan flood hazards. Few new alluvial fan delineations have been performed since publication of the NRC *Alluvial Fan Flooding* report and subsequent revision of FEMA's Appendix G guidelines. All new alluvial fan floodplain delineations are required to use the three-stage methodology developed by the NRC *Alluvial Fan Flooding* Report.

<u>NRC Alluvial Fan Committee Interviews</u>. Follow-up interviews with the original NRC Alluvial Fan Task Force Committee members revealed the that the members have performed no new research on alluvial fan flood hazard assessment work since publication of the NRC *Alluvial Fan Flooding* report and FEMA's adoption of the Committee's recommended approach. All of the NRC committee members continue to regard their report as ground-breaking work, and consider the report to still be relevant for flood hazard assessment on alluvial fans.

<u>Debris Flow Hazard and Risk Assessment</u>. The debris flow hazard and risk assessment literature search revealed a large body of technical work, primarily from mountainous regions in Europe. Review of the literature indicated that a more focused analysis of debris flow hazards in Maricopa County was warranted. A more locally relevant evaluation of debris flow potential and modeling methodologies was completed as part of the PFHAM study, and is described in Section 2.6 of this report. The PFHAM evaluation concluded that debris flows pose minimal risk to most alluvial fans in Maricopa County.

<u>Frequency of Alluvial Fan Channel Avulsions</u>.[2] Very few studies of alluvial fan avulsion frequency were identified in the literature review. A few examples of historical and recent avulsions on the Tiger Wash alluvial fan, on fans along the western White Tank Mountain piedmont, and on fans in Rainbow Valley are described in reports by the Arizona Geological Survey (AZGS) as well as in related flood study reports previously prepared for the District (e.g., CH2M HILL, 1992; JEF, 1999, 2001). However, no statistical relationships for avulsion frequency on alluvial fans were discovered. Therefore, more detailed evaluation of avulsion frequency, as well as methods of predicting avulsions was authorized as part of the PFHAM study, the results of which are described in Section 2.7 and Appendix I of this report.

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[2] The Blue Ribbon Panel (Section 4.7) also recommended more detailed analysis of avulsion frequency.

Alluvial Fan Flood Mitigation Measures. Descriptions of flood mitigation measures for debris flows and landslides are found in some of the European literature sources. Examples of alluvial fan flood mitigation measures from fans in America are summarized in reports by the US Army Corps of Engineers (HEC, 1993; USACE, 2004), and consist of rather standard engineering designs for channels, basins, and diversion structures. FEMA does not currently have engineering details or specific analysis guidelines for design of flood mitigation measures on alluvial fans. The NFIP Regulations (CFR 44, Chapter 1, Part 65.13) require that structural measures on alluvial fans address flow path uncertainty, sedimentation and erosion, debris flow, local inflow and system operations and maintenance, but provide no specific guidance on engineering methodologies, hazard quantification, or design criteria.

Alluvial Fan Flood Hazard Quantification Methods. The District's current version of the PFHAM is essentially a floodplain delineation methodology, and does not specifically address quantification of alluvial fan flood hazards and engineering design. The literature search identified three basic types of alluvial fan floodplain delineation methods: (1) probabilistic models, such as the FEMA FAN model, a.k.a., the Dawdy Method (Dawdy, 1979), (2) geomorphic methods, of which the District's current PFHAM is one, and (3) composite methods that combine elements of the geomorphic method and hydraulic modeling techniques. Because of FEMA's acceptance of the geomorphic method described in the NRC *Alluvial Fan Flooding* report, most new alluvial fan floodplain delineation studies have relied primarily on geomorphic-type delineation techniques. The literature search did identify several methodologies that may be useful for quantifying some elements of alluvial fan floodplain delineation studies and flood hazard assessments. However, none of these methodologies were developed specifically for floodplain management purposes, and none have been formally adopted by regulatory agencies, including FEMA.

2.1.2. Alluvial Fan Characteristics Data Collection

In 2009, JEF performed a specialized literature review for the District under contract FCD2007C051, Work Assignment #4. An analysis of the alluvial fans described in the literature sources collected and catalogued as described in Section 2.1.1 above was completed to document their physical characteristics and to investigate whether the information obtained in the literature search was relevant to alluvial fan flood hazards in Maricopa County. For this assignment, each collected article was reviewed and the individual alluvial fans discussed in each source were described. Excel and GIS databases of the alluvial fan characteristics, including their location, were created. The following data were obtained for each fan site in the literature list:

- Fan location
- Physiographic descriptors such as apex elevation, maximum watershed elevation, approximate climate type and vegetative cover
- Fan slope (landform and channel)
- Watercourse channel bed slope (above the fan apex)
- Watershed drainage area (above the fan apex)
- Distance from the apex to the mountain front
- Fan area below the apex

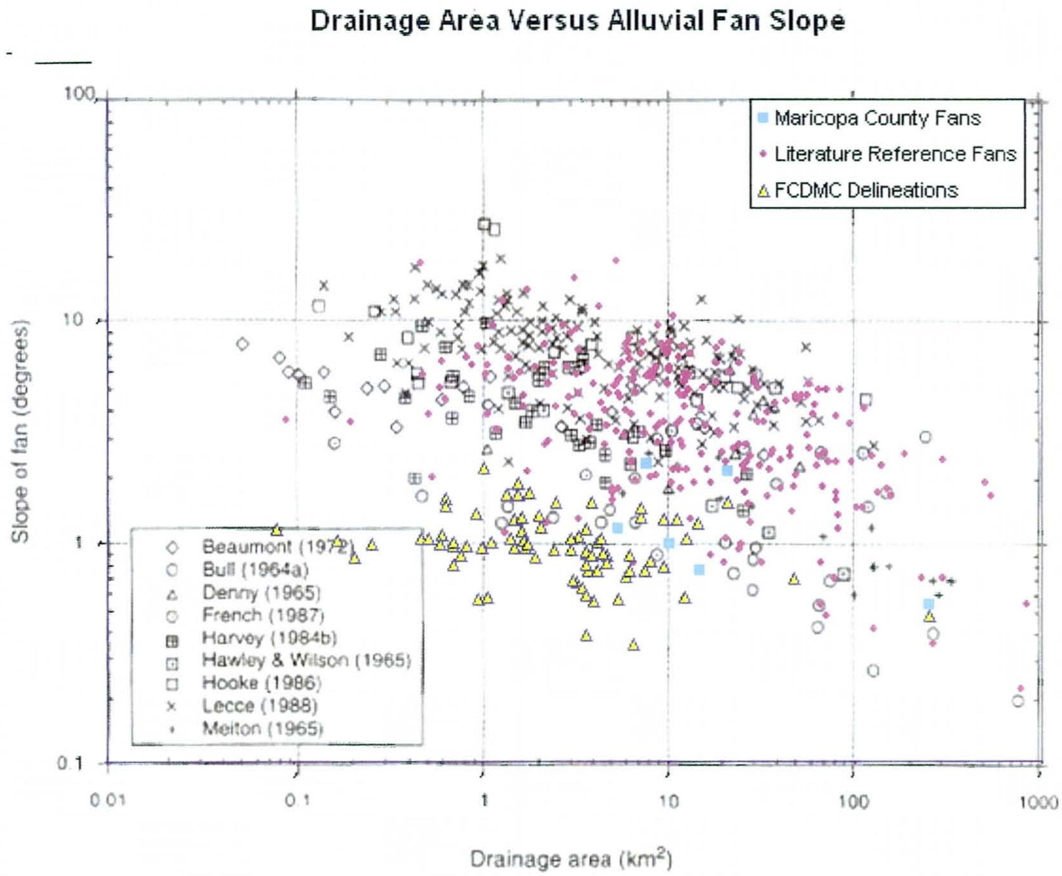

Figure 1. *Plot of fan slope (degrees) vs. drainage area (km2) from Givens (2004) with data from Maricopa County fan sites superimposed (blue squares).*

The following conclusions were drawn from the analysis of the alluvial fans described in the literature:

- Fan slopes ranged from less than one percent to greater than 10 percent. Most of the fans described had slopes greater than 1.7 percent (1 degree).
- Drainage areas ranged from less than one square mile to greater than 75 square miles. Most (67%) of the fan drainage areas described in the literature were less than 10 square miles.
- Fan surface areas ranged from less than 0.5 square miles to greater than 10 square miles. About half (48%) of the fan surface areas were less than one square mile.
- Fan apex elevations ranged from below sea level to above 6,000 feet, with no discernable trend or distribution.
- Most (89%) of the fans are located in arid regions with desert rangeland vegetation, with nearly half of the fans described located in California. Arizona ranked second in the number of fan sites described.
- Approximately 75 percent of the fans have no FEMA floodplain delineation.

Based on this analysis, most alluvial fans in Maricopa County probably lie within, but near the lower end of, the cloud of common values of characteristics for alluvial fans described in the literature, as illustrated in Figure 1. Therefore, the analyses, results, conclusions, and information in the literature sources collected can be assumed to be reasonably relevant to flood hazard assessments on alluvial fans in Maricopa County.

2.1.3. Sheet Flooding Literature Search

There are a range of flow behaviors on alluvial fans, but sheet flooding was found to be of particular importance for piedmont surfaces in Maricopa County. A supplemental literature search task was authorized under contract FCD2007C051, Work Assignment #6, to collect and evaluate sheet flooding literature that might better elucidate alluvial fan flooding issues in Maricopa County. The sheet flooding literature review focused on the following research topics:

- Definition of the term "sheet flooding"
- Defining characteristics of sheet flooding
- Characteristics that distinguish general sheet flooding from alluvial fan sheet flooding
- Flood hazards unique to sheet flooding areas
- Hydrologic and hydraulic modeling tools specifically for sheet flooding areas
- Floodplain regulations or development guidelines for managing sheet flooding areas

One of the key findings of the supplemental literature search was that the term "sheet flow" is used imprecisely in the literature, and that the term "sheet flooding" more accurately describes the natural flood processes that occur on alluvial fans. Therefore, the term "sheet flooding" is used throughout this report and is recommended for use in any future updates of the PFHAM.

Definition(s) of Sheet Flooding. A sheet flood is defined as a broad expanse of unconfined[3] runoff moving downslope (McGee, 1897). Sheet floods have relatively low frequency and high magnitude (Hogg, 1982), while the flow itself is generally shallow and short-lived and has a limited travel distance. Sheet flooding is produced by large discharges, most commonly from high-intensity rainfall, combined with the absence of channelized drainage (Blair & McPherson 1994). The Arizona Department of Water Resources (ADWR) State Standard 4-95 defines types of sheet flooding, which conform to the definition given above. The Maricopa County Floodplain Regulations do not have a definition for sheet flooding (or sheet flow), although the Definitions Section indicates that sheet flooding occurs on portions of alluvial fans.[4] However, it is noted that the defining characteristics listed in the next paragraph may constitute a clearer, more practical definition of sheet flooding than those used above.

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[3] Note that all runoff must be confined in some manner. "Unconfined" is used here to indicate a lack of well-defined flow paths, floodplains, and/or terrains that form obvious lateral boundaries.
[4] See definitions for Alluvial Fan Uncertain Flow Distribution (AFUFD) and Alluvial Fan Zone A (AFZA).

Defining Characteristics of Sheet Flooding. The defining characteristics of sheet flooding include the following:

(1) Flood waters that occur as a broad unconfined sheet
(2) Flat or low slopes, both laterally and longitudinally
(3) Few or no well-defined channels, and a high density of sub-parallel, poorly defined, discontinuous micro-"channels"
(4) Flow conveyed over an unchannelized land surface
(5) Flow depths ranging from several inches (commonly) to several feet (rarely)
(6) Significant loss of flow volume due to infiltration and other abstractions
(7) Ability to transport sediment over large distances on low slopes
(8) Unpredictable flow directions because of low lateral relief, shifting channels, and/or clogging of flow paths by debris or sediment.

Characteristics that Distinguish General Sheet Flooding From Alluvial Fan Sheet Flooding. The literature search did not yield any articles that distinguish general sheet flooding from sheet flooding on an alluvial fan surface. A wide variety of literature sources affirm that sheet flooding does occur on alluvial fans (e.g., NRC, 1995; FEMA, 2003), but none were found that proposed that alluvial fan sheet flooding has characteristics unique to alluvial fans or that are different from sheet flooding on other landforms.

Flood Hazards Unique to Sheet Flooding Areas. No hazards unique to sheet flooding areas were identified in the literature. Sheet flood hazards identified in the literature included: (1) structure inundation (at shallow depths), (2) obscure flow paths that create unconfined flow and uncertain flow distribution, (3) problems resulting from concentration of flow, (4) roadway inundation, (5) under-design of roadway cross drainage structures, (6) erosion and scour, (7) hydrodynamic forces, (8) sediment deposition, and (9) channel avulsion. All of these hazards are also found on other landforms.

Hydrologic and Hydraulic Modeling Tools Specifically for Sheet Flooding Areas. The literature search did not yield any articles about hydrologic or hydraulic modeling tools developed specifically for sheet flooding areas. There are numerous models which can model shallow flooding (e.g., HEC-RAS, FLO-2D, etc.), although none of them were developed specifically to evaluate sheet flooding conditions. The results of the PFHAM study described later in this report indicate that: (1) sheet flooding has a strong two-dimensional component and (2) the rate of hydrograph attenuation is significant in sheet flooding areas. Therefore, the most appropriate hydrologic and hydraulic modeling tools for sheet flooding areas will have the capacity to address two-dimensional flow and hydrograph attenuation.

Existing Sheet Flooding Floodplain Regulations or Development Guidelines. The Maricopa County Floodplain Regulations mention sheet flooding only in the context of alluvial fan flooding, with no specific regulations relating solely to management of sheet flood areas. The Maricopa County Drainage Regulations do not use the terms "sheet flood" or "sheet flow." The Maricopa County Drainage Policies and Standards (2007) reference sheet flooding in Section 3.8.3 (Erosion Hazard Management – Sheet Flow/Unconfined Flow Areas), and recommend minimizing vegetation disturbance and flow concentration, and returning flow to pre-development conditions before exiting a developed property.

Other general guidance for floodplain management in sheet flooding areas was found in ADWR State Standard 4-95 and several local flood control agencies in the southwestern United States. The guidance in the State Standard and from other agencies included recommendations to elevate finished floors, provide scour protection around foundations, elevate or gap fences to allow through flow drainage, set back fences from property lines, align construction parallel to flow (minimizing obstructions), lower building densities, avoid impacts to adjacent properties due to flow concentration, and restrict septic tank placement, as well as general site grading practices.

2.2. Historical Development on Alluvial Fan Landforms

An analysis of historical development on alluvial fan landforms in Maricopa County was performed to assess the successes, failures, and/or drainage problems associated with such development. The historical analysis was intended to gauge the degree of flood hazard severity on alluvial fans in Maricopa County. Four individual site locations (Ahwatukee, Pima Canyon, Reata Wash, and Lost Dog – See Figure 2) were chosen and approved by the District project team. The study site locations were identified using historical and recent aerial photographs, NRCS soils mapping and readily available topographic mapping. The four study sites include areas of dense urbanization (Ahwatukee, Pima Canyon, Reata Pass, Lost Dog), single lot development (Reata Pass), and developments with major structural drainage measures (Ahwatukee, Pima Canyon, Lost Dog). Key site characteristics for the four historical sites are listed in Table 1.

Table 1. Site Characteristics for Historical Alluvial Fan Sites.

Characteristic	Historical Alluvial Fan Sites			
	Ahwatukee	Pima Canyon	Reata Pass	Lost Dog
Watershed area (apex)	1.7 mi2	1.5 mi2	8.1 mi2	2.8 mi2
Watershed slope	8.1 %	7.7 %	12.1 %	4.2 %
Channel Slope				
Upstream of apex	3.8 %	1.6 %	3.4 %	2.5 %
Downstream of apex	1.8 %	1.5 %	3.3 %	2.5 %
Q100 at apex	2778 cfs	2525 cfs	11,900 cfs	5,000 cfs
Fan Profile Shape	Concave up	Concave up	Concave up	Concave up
Max Elevation in Watershed	2586 ft	2555 ft	3880 ft	3,804 ft
Elevation at apex	1350 ft	1310 ft	2185 ft	1,625 ft
Minimum Elevation in fan	1270 ft	1210 ft.	1520 ft	1,440 ft

2.2.1. Ahwatukee Alluvial Fan

The Ahwatukee Alluvial Fan (Figure 3) contained an active alluvial fan before it was urbanized in the 1980s. Prior to its development, the unnamed Ahwatukee Fan wash lost both capacity and definition at its hydrographic apex and the previously channelized flow transitioned to broad sheet flow over the upper fan area. The overall alluvial fan landform remained undeveloped until the 1980s when rapid and dense suburban single-family-unit development occurred over the entire landform. As part of the development

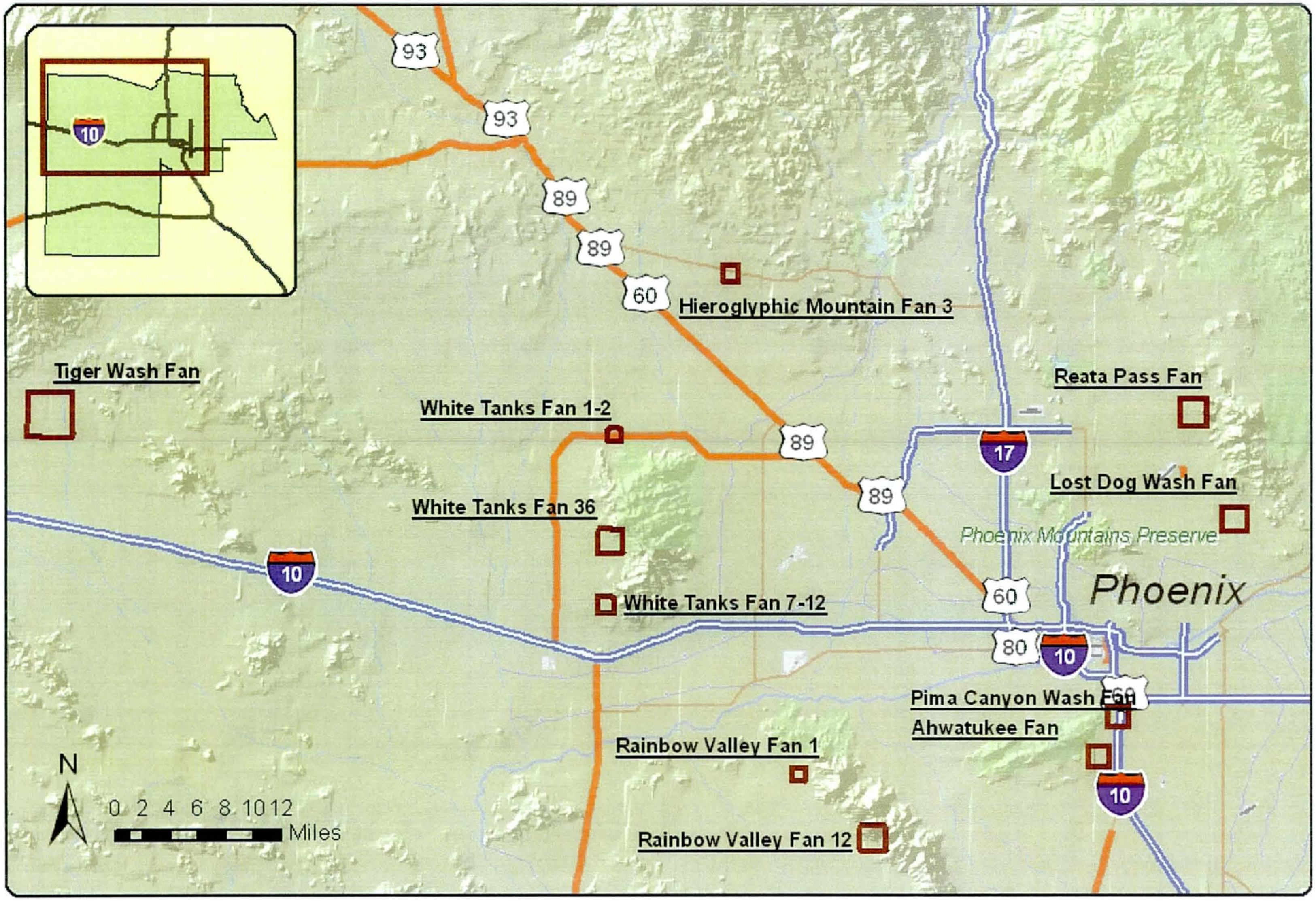

Figure 2. Map showing Maricopa County historical and evaluation fan sites cited in this report.

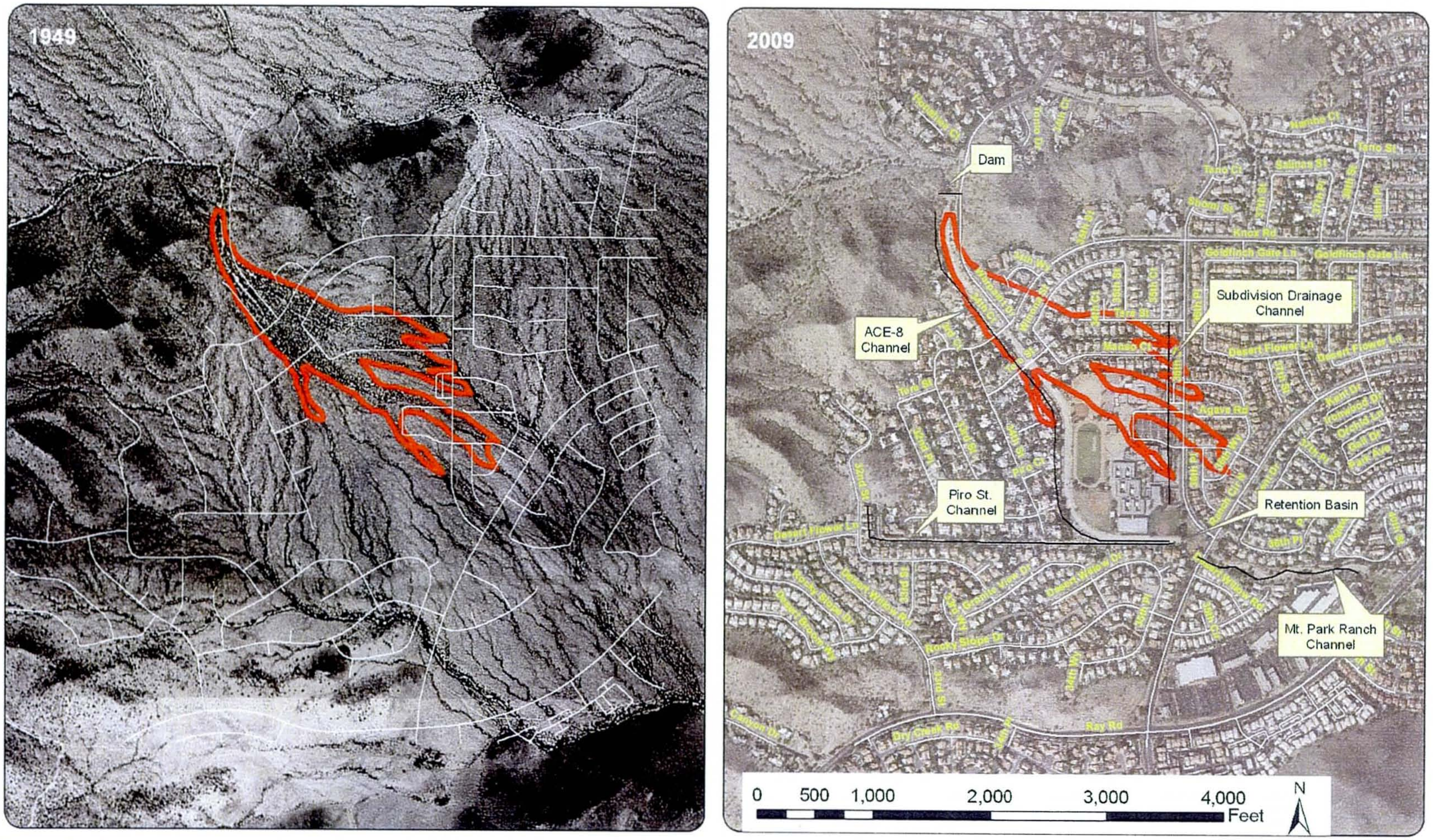

Figure 3. Ahwatukee historical fan site, before (1948) and after development (2009).

*****Note: The aerial base photo for all figures in this report is from 2009 unless otherwise noted in the figure caption.***

drainage plan, flows upstream of the fan apex were detained behind a small, peak-scalping dam. Floodwater exiting the dam was routed to the toe of the alluvial fan via a concrete-lined trapezoidal channel to a small detention basin which drained into a series of rock-lined channels that extended to the toe of the alluvial fan landform.

There is no record that any homes on the Ahwatukee Fan have been damaged by flooding, sedimentation or erosion since construction of the engineered dam-channel flood mitigation system. The concrete-lined channel itself, however, was heavily damaged during a large flood event in 2005, and continues to have on-going issues with damage to the concrete channel lining. Also, some level of sediment deposition occurs in the channel near the dam outlet, as well as in the small detention basin at the downstream end of the concrete channel. Both the sedimentation and the concrete damage have been addressed through routine maintenance by the private homeowners' association which owns the structures. It is likely that these types of sediment and channel maintenance needs will continue indefinitely.

2.2.2. Pima Canyon Alluvial Fan

The Pima Canyon Wash alluvial fan contained an active alluvial fan prior to its urbanization in the late 1980s (Figure 4). The Town of Guadalupe, which is located at the toe of the Pima Canyon alluvial fan, experienced repeated damage to homes and infrastructure from shallow sheet flooding and sediment deposition, dating back to at least the 1930s. Since the 1930s, extensive development has taken place on the fan surface, including the construction of Interstate-10 (1960s) and the Guadalupe Flood Retarding Structure (FRS; 1970s), channelization of Pima Wash (1980s), construction of residential subdivisions and transportation infrastructure (1980s), and development of a golf course (1990s) in the former wash bottom and portions of the active alluvial fan. Since the original construction dates, there has been no record of any flood damage to any home or building on the Pima Canyon alluvial fan, although periodic sediment removal and maintenance is performed by a private homeowners association and golf course maintenance crews.

Development-related flood control improvements on the Pima Canyon alluvial fan have been tested by at least one very large rainfall event in July 2008, which was estimated at about a 350-year rainfall event.[5] The July 2008 storm generated record (though not 100-year) flooding and sedimentation along Pima Canyon Wash and in the Guadalupe FRS. Although record rainfall was recorded on parts of the fan, the actual damage to structures on the fan was minimal. It is likely that flood-related sedimentation and erosion of the main channel of Pima Wash, both in and around the golf course, will continue to occur indefinitely.

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[5] The extreme rainfall in the 2008 event occurred on the fan surface, not the upper watershed. Peak discharges upstream of the fan apex were probably much less than the 100-year peak flow rate. Rainfall intensities in the upper watershed were much less than 100-year levels.

2.2.3. Reata Pass Alluvial Fan

The Reata Pass alluvial fan (Figure 5) is the largest of the four historical sites, and has a large active fan area downstream of its hydrographic apex, as well as a classic fan shape. The earliest urbanization of the fan surface consisted of residential grid style construction on the lower fan landform in the early 1960s. More extensive development of large lot luxury homes has occurred on the upper alluvial fan since the mid-1990s. To date, the largest problem area on the fan has been within the 1960s-style rectangular grid development at the Pima Acres subdivision, where essentially no drainage infrastructure was provided for off-site flows. Elsewhere on the fan, sedimentation has clogged culverts and blanketed dip crossings during small floods, creating a maintenance burden on both the City and the local homeowners' associations. The large lot development on the upper portion of Reata Pass fan preserved much of the natural, distributary drainage patterns of the fan landform, with the natural wash corridors designated and protected by City regulations as environmentally sensitive wildlife habitat.

While no significant flood damages to homes have been reported on the Reata Pass Fan, neither have there been any storm events greater than a 10-year event since development began. Thus, the flood mitigation infrastructure is largely untested. FLO-2D modeling described in Section 2.3.3 and Appendix F of this report indicates that numerous homes on the Reata Pass alluvial fan may be subject to significant flooding during a 100-year event. If large floods occur in the future, they are likely to cause significant damage to flood-prone homes on the most active parts of the upper alluvial fan landform. In addition, it is likely that the existing sediment maintenance problems resulting from small flows will persist indefinitely. Regardless of the future flood potential damage, the short historical record indicates that the current engineering and floodplain management practices have performed adequately, at least with respect to flood damage to homes.

2.2.4. Lost Dog Wash Alluvial Fan

Prior to urbanization between 1997 and 2005, the Lost Dog Wash was located on a small active alluvial fan characterized by unconfined distributary flow downstream (Figure 6) of its hydrographic apex. Lost Dog Wash is now confined to an engineered channel that routes flood water down the western portion of the fan landform, under the 120th Place-Via Linda Road intersection, ending at the Central Arizona Project Canal (CAP). At the CAP, flood water is ponded and routed northwest along the CAP canal. Lost Dog Wash has not had any significant rainfall events since the area was urbanized, and the drainage structures remain substantially untested. However, minimal sedimentation and maintenance concerns are expected in the future, with the possible exception of the ponding and depositional area upstream of the CAP canal, and then only in the event of a large flood.

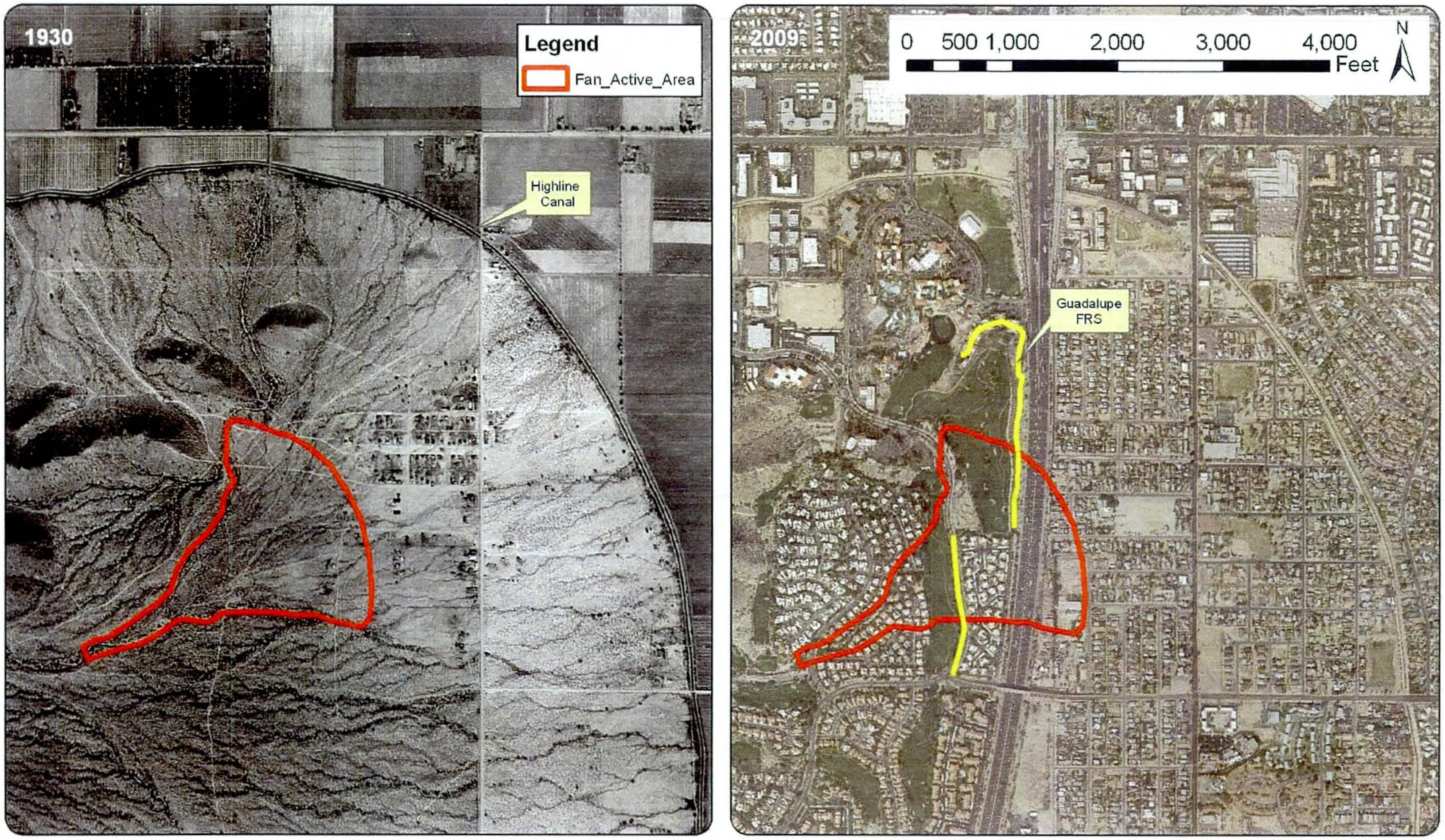

Figure 4 . Pima Canyon historical fan site, before (1930) and after development (2009).

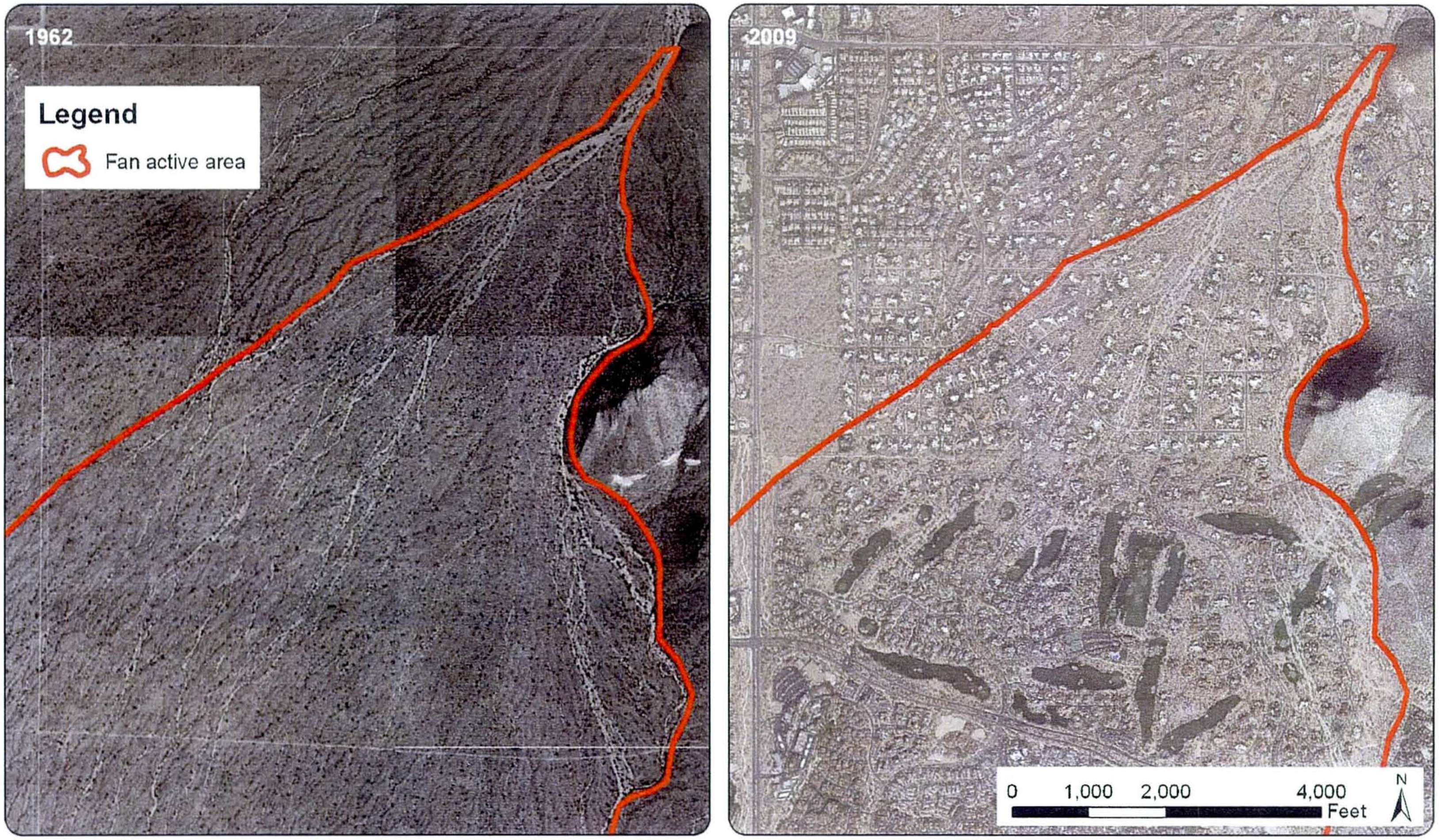

Figure 5. Reata Pass historical fan site, before (1962) and after development (2009).

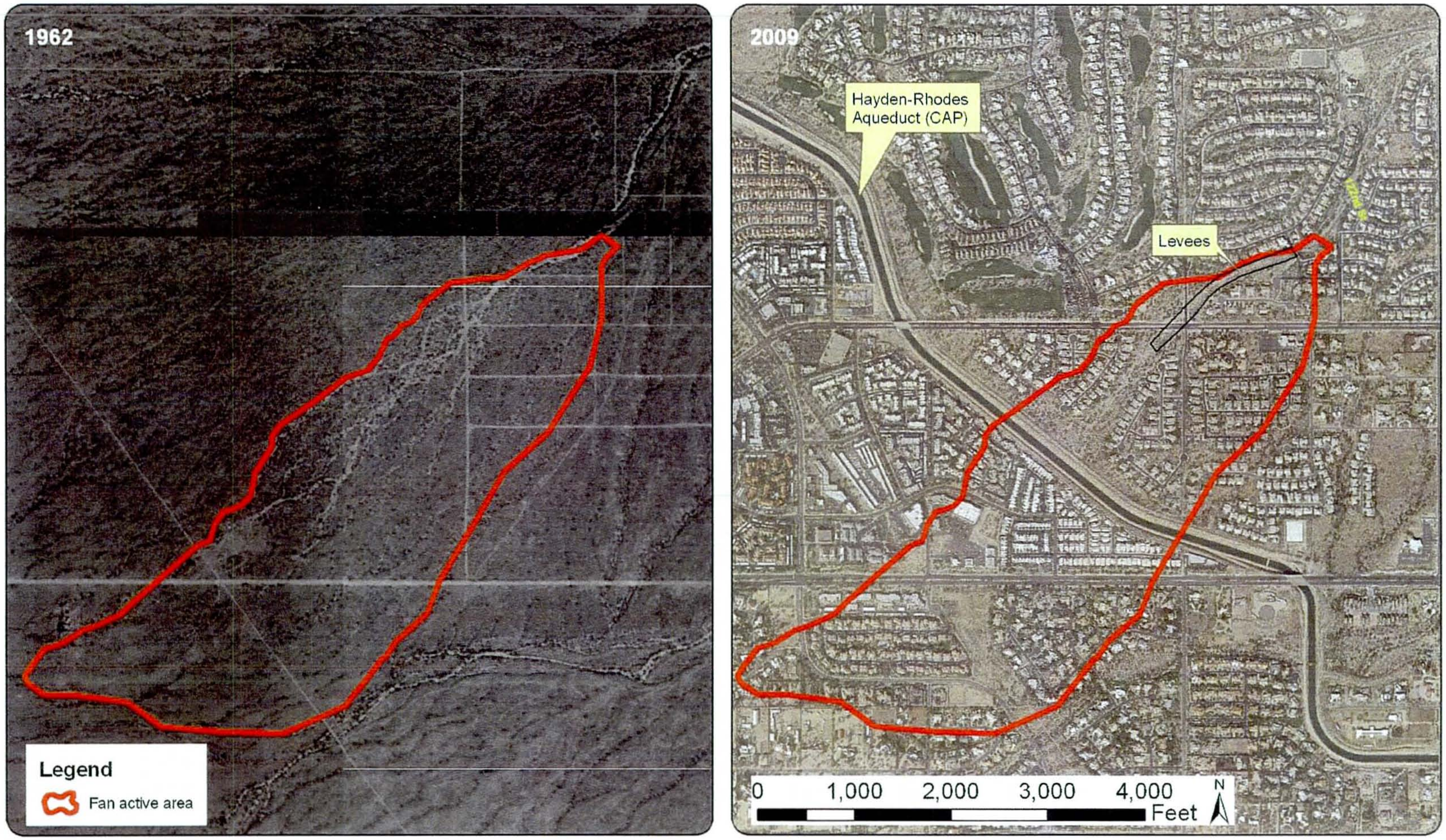

Figure 6. Lost Dog historical fan site, before (1962) and after development (2009).

2.2.5. Summary of Historical Analyses

Based on analysis of the four historical sites, it is concluded that the engineered drainage systems at the four historical alluvial fan study sites have performed adequately during the 20 to 40 year period of record, at least with respect to addressing any flow rate or flow path uncertainty, as well as any sedimentation associated with the now-developed active alluvial fans. Interestingly, there is no record that any of the engineered drainage systems at the four sites explicitly considered alluvial fan flooding as part of the design process. It is likely, however, that drainage engineers were aware of the bifurcating drainage pattern since they took steps to confine flooding to a single channel and/or route it through flood control basins. The range of structural measures used included a peak-scalping detention basin, a concrete-lined channel, an earthen channel with drop structures, mass grading (golf course & development), a regional detention basin (near the fan toe), levees, diversion dikes, culverts, dip crossings, and bridges, as well as some non-structural regulatory measures. Although there has been only one near-regulatory type event on only one of the fans,[6] and the systems remain largely untested, the record indicates the following:

- No homes on the fans have been damaged by alluvial fan flooding in the past 20 to 40 years.
- The structural measures, while they have sustained some damage and required sediment maintenance, have essentially performed their intended function thus far.
- No evidence of adverse impacts from channel avulsions, excessive sedimentation or scour was identified.
- Periodic sediment removal is required, especially near the upper end of the fans, but has not been excessive or beyond the capacity of the HOA's or the local jurisdiction.

Given the episodic and probable low return frequency of fan-altering (avulsive, excessive sedimentation, etc.) flood events, the conclusions listed above should be carefully weighed in light of the short period of record at the four fan sites.

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[6] To date, there is no known systematic evaluation of hydraulic structure performance in Maricopa County from which to determine whether existing design standards result in under or over engineering, either on alluvial fan landforms or on other types of systems subject to flooding. One Blue Ribbon Panel member suggested that such analyses be performed to identify a histogram of the number of features tested by specific recurrence interval events.

2.3. *Alluvial Fan Site Evaluations*

Four alluvial fan sites in Maricopa County (Figure 2) were selected for more detailed analysis and evaluation of methods for quantifying alluvial fan flood hazards. The following four sites were selected:

- White Tanks Fan 36
- Reata Pass Alluvial Fan
- Rainbow Valley Fan 1
- Rainbow Valley Fan 12

The four sites represent a range of alluvial fans found in Maricopa County, as well as a range of landform slopes, watershed sizes, degree of urbanization, and flow types, as shown in Table 2. Each of the selected sites had available topographic mapping and some type of previous hydrologic modeling prepared for the District or another public agency.

Table 2. Characteristics of Alluvial Fan Evaluation Sites

Site Name	Fan & Watershed Slope (ft/ft)	Watershed Size and Discharge	Type of Urbanization	Flow Types
White Tanks Fan 36	0.022 (fan) 0.097 (watershed)	5.7 mi2 (apex) Q100=2800 cfs 9.9 mi2 (fan)	Rough dirt roads One home site Powerline crossings Future development	Channelized Distributary Sheet Flooding Coalescing
Reata Pass Fan	0.034 (fan) 0.121 (watershed)	8.1 mi2 (apex) Q100=11900 cfs 5.2 mi2 (fan)	Dense residential Large lot residential Dense commercial	Channelized Distributary Sheet Flooding Coalescing
Rainbow Valley Fan 1	0.010 (fan) 0.122 (watershed)	7.2 mi2 (apex) Q100=3900 cfs 1.0 mi2 (fan)	Undeveloped fan area Toe urbanized	Channelized Distributary Sheet Flooding
Rainbow Valley Fan 12	0.018 (fan) 0.210 (watershed)	1.1 mi2 (apex) Q100=1000 cfs 7.0 mi2 (fan)	Undeveloped Powerline crossing Minor agricultural (toe)	Channelized Distributary Sheet Flooding Coalescing

2.3.1. Fan Evaluation Site Descriptions

Brief descriptions of the four alluvial fan evaluation sites are provided in the following paragraphs.

2.3.1.1. White Tanks Fan 36

The White Tanks Fan 36 site (WTF36) is located on the western piedmont slopes of the White Tanks Mountains within the Town of Buckeye in west-central Maricopa County (Figure 7; Table 2). The site was first identified as an active alluvial fan by Hjalmarson and Kemna (1991), and was selected as an alluvial fan data collection site by the District in 1992 (CH2M HILL, 1992). The Arizona Geological Survey (AZGS) has also published a number of studies of the site, including flood hazard mapping (Field and Pearthree, 1992), detailed surficial geology mapping (Field and Pearthree, 1991), and trenching of the active fan surface (Field, 2001). WTF 36 was also included as one of the sites considered in Field's (1994) Ph.D. dissertation on alluvial fan flooding in Arizona. WTF 36 was the site of one of the District's first applications of the PFHAM methodology (JEF, 1999), and was evaluated as part of the District's Sun Valley Area Drainage Master Plan (JEF, 2006) which included detailed HEC-1 hydrologic modeling and drainage infrastructure planning tasks.

The hydrographic apex of the WTF 36 site is located significantly downstream of the geologic mountain front of the White Tanks Mountains. At the hydrographic apex, the drainage pattern rapidly transitions from an incised, well-defined channel on the upper piedmont to a highly distributary channel on the active alluvial fan surface. Distributary flow then rapidly transitions to sheet flooding within about one mile of the hydrographic apex. Downstream of that point, shallow sheet flooding conditions persist over most of the rest of the alluvial fan landform. Smaller, secondary hydrographic apexes also occur in the lower and distal parts of the WTF 36 site. In the lower portions of the fan, on-fan runoff apparently becomes more dominant, as indicated by the incipient dendritic drainage pattern on the fan surface.

Flood runoff from the site drains toward the Buckeye Flood Retarding Structure #1 (FRS), which truncates the alluvial fan landform and serves as the downstream limit for this study. There is no gauged record of flooding or rainfall for the WTF 36 site, although the District's Alluvial Fan Data Collection and Monitoring Study (CH2M HILL, 1992) paleoflood analysis indicated that the maximum flow preserved in the geologic record was approximately 2,000 to 4,000 cfs. Analysis of historical aerial photographs indicates that a very large avulsive flood occurred between 1949 and 1953 (JEF, 1999), probably as a result of extreme rainfall in August 1951, as recorded at a nearby station in Buckeye (Figure 8).

At present, the WTF 36 site is mostly undeveloped, with the exception of one rural homestead located approximately one mile downstream of the main hydrographic apex, and an area of rural development located at the extreme southwestern tip of the alluvial landform just upstream of the Buckeye FRS #1. However, prior to the current economic recession, most of the WTF 36 area was slated for residential construction as part of several large master planned communities. It is likely that the WTF 36 will be fully built out within two decades.

The WTF 36 site was selected for this study because there is general consensus from a variety of investigators that it includes an active alluvial fan, it may well be the most well-studied alluvial fan landform in Maricopa County, it has an existing PFHAM delineation that was approved by FEMA, it has experienced a historical avulsive flood event, and because it is likely to be developed in the near future.

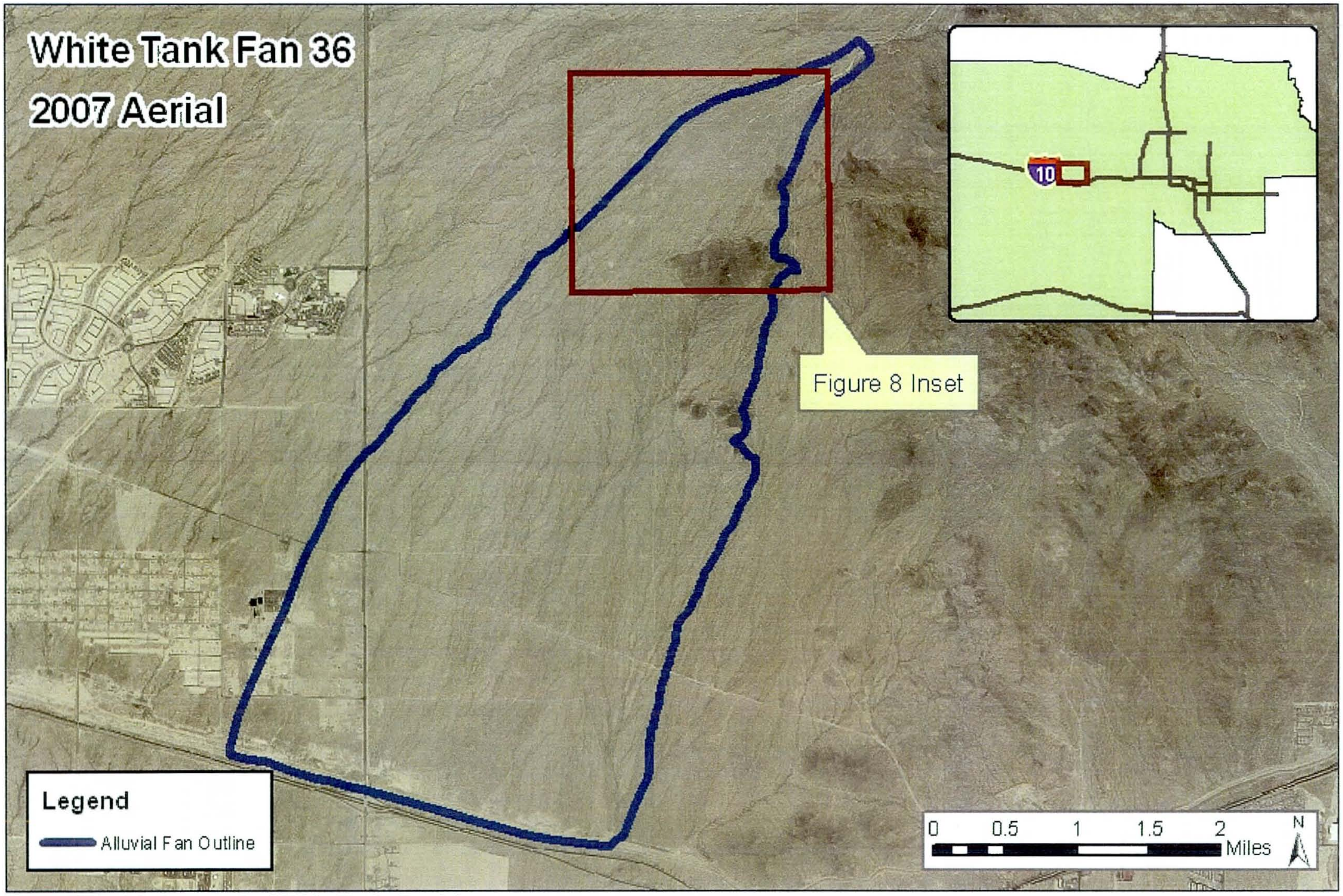

Figure 7. Aerial photograph of White Tanks Fan 36.

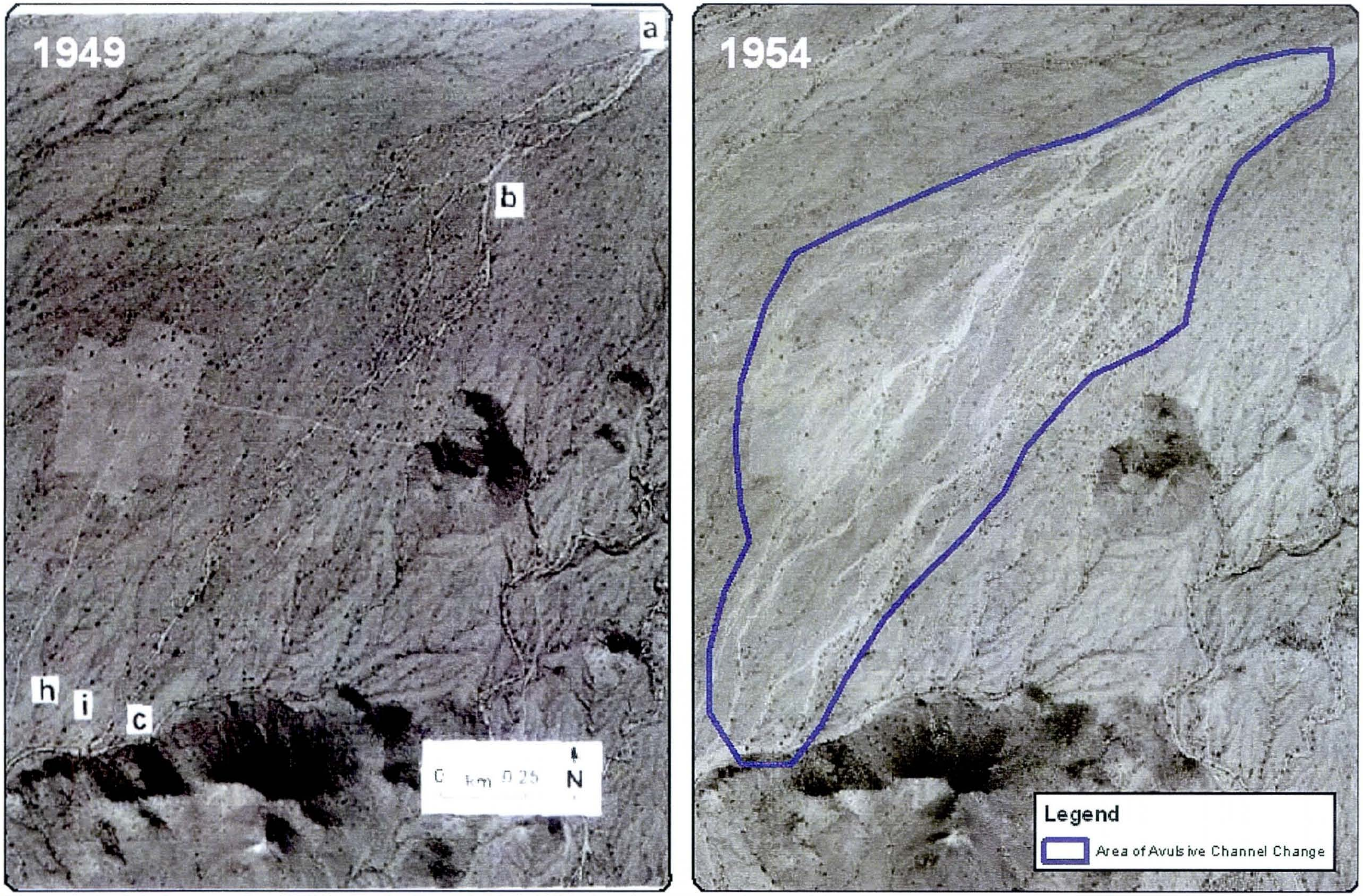

Figure 8. Aerial photographs of White Tanks Fan 36, 1949-1954, showing area of 1951 avulsive channel change outlined in blue.

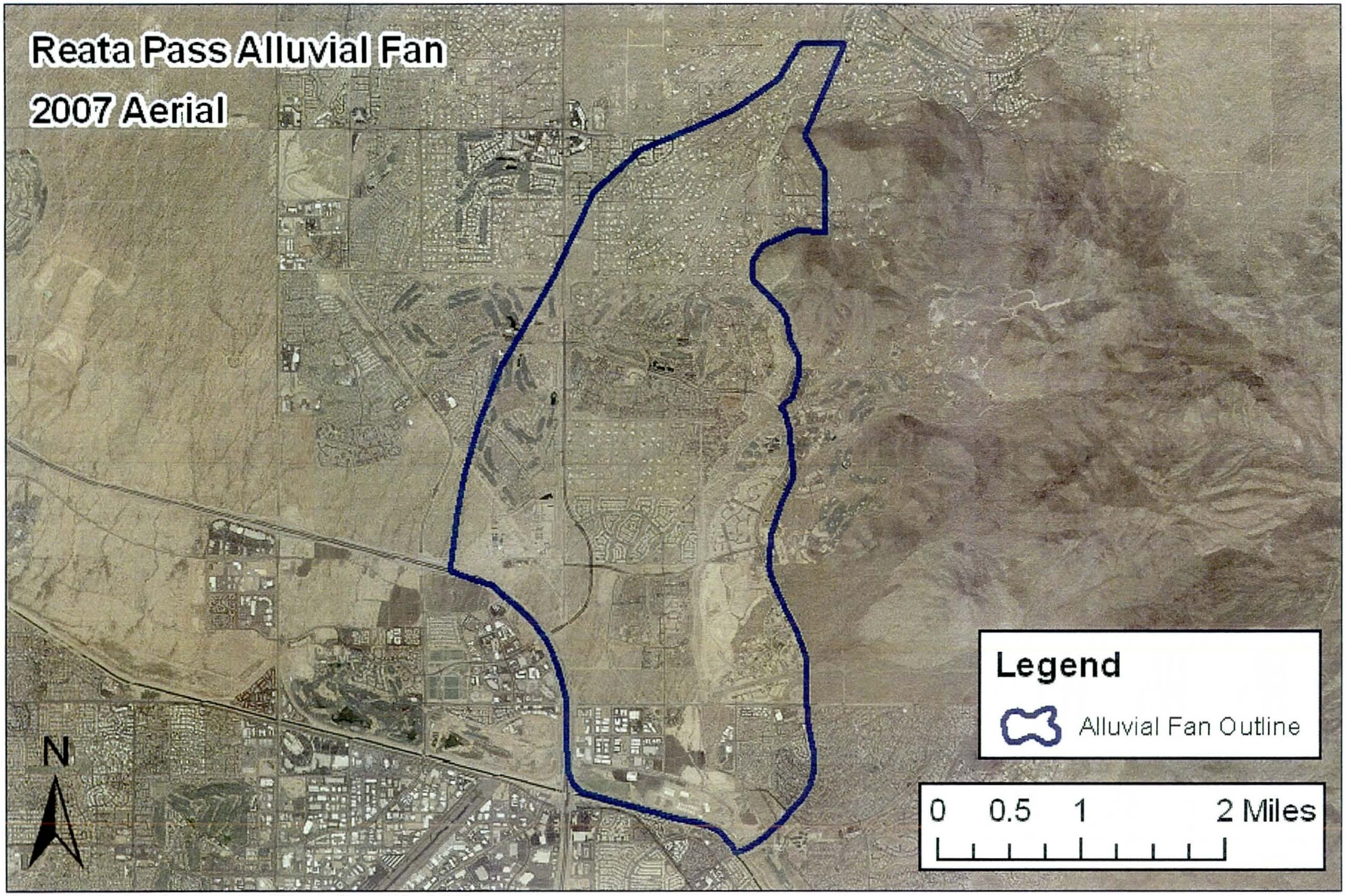

Figure 9. Aerial photograph of Reata Pass Alluvial Fan.

2.3.1.2. Reata Pass Alluvial Fan

The Reata Pass Fan site (RPF) is located on the western piedmont slopes of the McDowell Mountains within the City of Scottsdale in northeastern Maricopa County (Figure 9; Table 2). The site was identified as an alluvial fan as part of a FEMA floodplain delineation in the 1980s, and was delineated using the FEMA FAN model (a.k.a., the Dawdy Method). The City of Scottsdale previously proposed major structural improvements to mitigate alluvial fan flooding hazards on the RPF site as part of their Desert Greenbelt Project, but the project has never been constructed. There have been several HEC-1 hydrologic modeling studies that analyzed the RPF site (See Appendix D). Geologic mapping of the area has been performed (Christensen, 1976), as well as a geomorphic landform classification (Rhoads, 1986) which identified portions of the site as an active alluvial fan. The RPF site was also selected as one of the historical alluvial fan sites described in Section 2.2 of this report.

The hydrographic apex of the RPF site is located quite close to the geologic mountain front of the McDowell Mountains. At the hydrographic apex, the drainage pattern rapidly transitions from an incised, well-defined channel leaving the mountain canyons to a system of distributary channels that cross the upper alluvial fan surface. Near the mid-fan area, the natural distributary flow pattern probably transitioned to sheet flooding, but is now obscured or confined by recent urbanization. Several secondary hydrographic apexes also occur along the eastern margin of the RPF site where significant tributary systems exit the McDowell Mountains and debouche onto the piedmont.

Flood runoff from the RPF site drains south toward the Central Arizona Project (CAP) canal levee, which impounds upstream runoff, truncates the alluvial fan landform, and serves as the downstream limit for this study. Since 2001, the District has maintained a streamflow gauge near the hydrographic apex of the RPF alluvial fan, as well as several other ALERT monitoring stations in the vicinity. No significant floods at the RPF site have been captured by the District's ALERT system, nor is there any evidence of large floods visible in the historical aerial photographs, which date back to 1953.

There are several styles of development on the RPF site. Near the hydrographic apex, development consists of luxury homes on large lots, with paved roads and at-grade crossings. Most of the defined flow paths are not obstructed by development, allowing some level of distributary flow to continue. Near the upper mid-fan area, a large master planned residential golf community has been constructed that includes structural flood control measures such as flow collection systems, diversion structures, detention basins, and bridge/culvert crossings. Further south, there is a mixture of older, large-lot subdivisions that lack adequate drainage infrastructure and newer, dense residential development with traditional flood control measures.

The RPF site was selected for this study because it is one of the larger, steeper alluvial fan landforms in Maricopa County, it has a large 100-year discharge and correspondingly large flood velocities and depths, it has been urbanized by a variety of development styles, it has an existing FAN model delineation that was approved by FEMA, and because of the risk of future flood damage to existing development by alluvial fan flooding.

2.3.1.3. Rainbow Valley Fan 1

The Rainbow Valley Fan 1 site (RVF1) is located on the western piedmont slopes of the Sierra Estrella within the City of Goodyear in western Maricopa County (Figure 10; Table 2). The site was identified as a possible active alluvial fan as part of the Rainbow Valley ADMP (JEF, 2010). The Arizona Geological Survey (AZGS) has also published detailed surficial geology mapping (Pearthree et. al., 2004). There is a current FEMA-approved riverine floodplain delineation for the lower portion of the alluvial fan landform.

The hydrographic apex of the RVF 1 site is located well downstream of the geologic mountain front of the Sierra Estrella. At the hydrographic apex, the main channel drainage pattern becomes slightly more braided, but does not change drastically. The apex consists of potential high-flow overflow onto a potentially active fan surface which appears to be subject shallow sheet flooding. The lower portions of the RVF 1 alluvial fan site consist mostly of older, inactive surfaces into which the more active upstream portions flow.

Flood runoff on the RVF 1 site drains east toward and through the Estrella master-planned community, although any alluvial fan flooding characteristics end upstream of Estrella Parkway. There is no gauged record of flooding or rainfall for the RVF 1 site. Analysis of historical aerial photographs revealed no evidence of avulsive channel change between 1939 and 2010. At present, the RVF 1 site is undeveloped.

The RVF 1 site was selected for this study because is represents one end member of the range of alluvial fan landform types common in Maricopa County, that of a potentially active area that could easily be confused with a riverine floodplain. In fact, the RVF 1 site has elements of both riverine and alluvial fan flooding, depending on the recurrence interval considered and type of sedimentation trends that occur along the existing main channel. The RVF 1 site also an existing FEMA-approved riverine floodplain delineation, and is located upstream of existing dense development that was apparently designed without consideration of potential upstream alluvial fan flood hazards.

2.3.1.4. Rainbow Valley Fan 12

The Rainbow Valley Fan 12 site (RVF 12) is located on the western piedmont slopes of the Sierra Estrella within the Cities of Goodyear and Avondale, as well as unincorporated Maricopa County (Figure 11; Table 2). The site was first identified as an active alluvial fan, and was selected as an alluvial fan data collection site by the District in 1992 (CH2M HILL, 1992). The Arizona Geological Survey (AZGS) has also published detailed surficial geology mapping (Pearthree et. al., 2004) and soil descriptions based on trenching of the active fan surface (CH2M HILL, 1992). The RVF 12 site was evaluated as part of District's Rainbow Valley Area Drainage Master Plan (URS, 2010) which included detailed HEC-1 hydrologic modeling and drainage infrastructure planning tasks.

As evaluated for this study, the RVF 12 site consists of a bajada composed of a number of previously identified hydrographic apexes that coalesce on the alluvial fan landform.

The hydrographic apexes that comprise the RVF 12 site are located immediately downstream of the geologic mountain front of the Sierra Estrella. At the hydrographic apexes, the drainage pattern rapidly transitions from an incised, well-defined channel on the upper piedmont to extensive sheet flooding conditions. This transition occurs via small ephemeral distributary channels. Shallow sheet flooding conditions persist over most of the rest of the alluvial fan landform until it merges with the alluvial plain of Waterman Wash, the axial stream within the Rainbow Valley.

Flood runoff from the site drains toward the geologic floodplain of Waterman Wash, which forms the lower limit of the toe of the alluvial fan landform. The District has operated a system of precipitation, weather, and streamflow gauges at the RVF 12 site since it was identified in their Alluvial Fan Data Collection and Monitoring Study (CH2M HILL, 1992). A paleoflood analysis conducted for that study indicated that the maximum flow preserved in the geologic record was less than 1,000 cfs. Analysis of historical aerial photographs revealed no evidence of avulsive channel change between 1939 and 2010, although soil trench analyses indicate that significant aggradation and minor channel movement has occurred near the hydrographic apex over the past 600 years (Appendix I). At present, the RVF 12 site is undeveloped in the upper fan area, although the toe of the alluvial fan landform has a history of grading associated with irrigated agricultural uses.

The RVF 12 site was selected for this study because of the District's history of flood data collection at the site, its inclusion as an alluvial fan site in previous District studies, the presence of coalescing alluvial fans, the large component of sheet flooding, the proximity of the fan apexes to the mountain front, and the gradual transition from the active fan area to an axial stream.

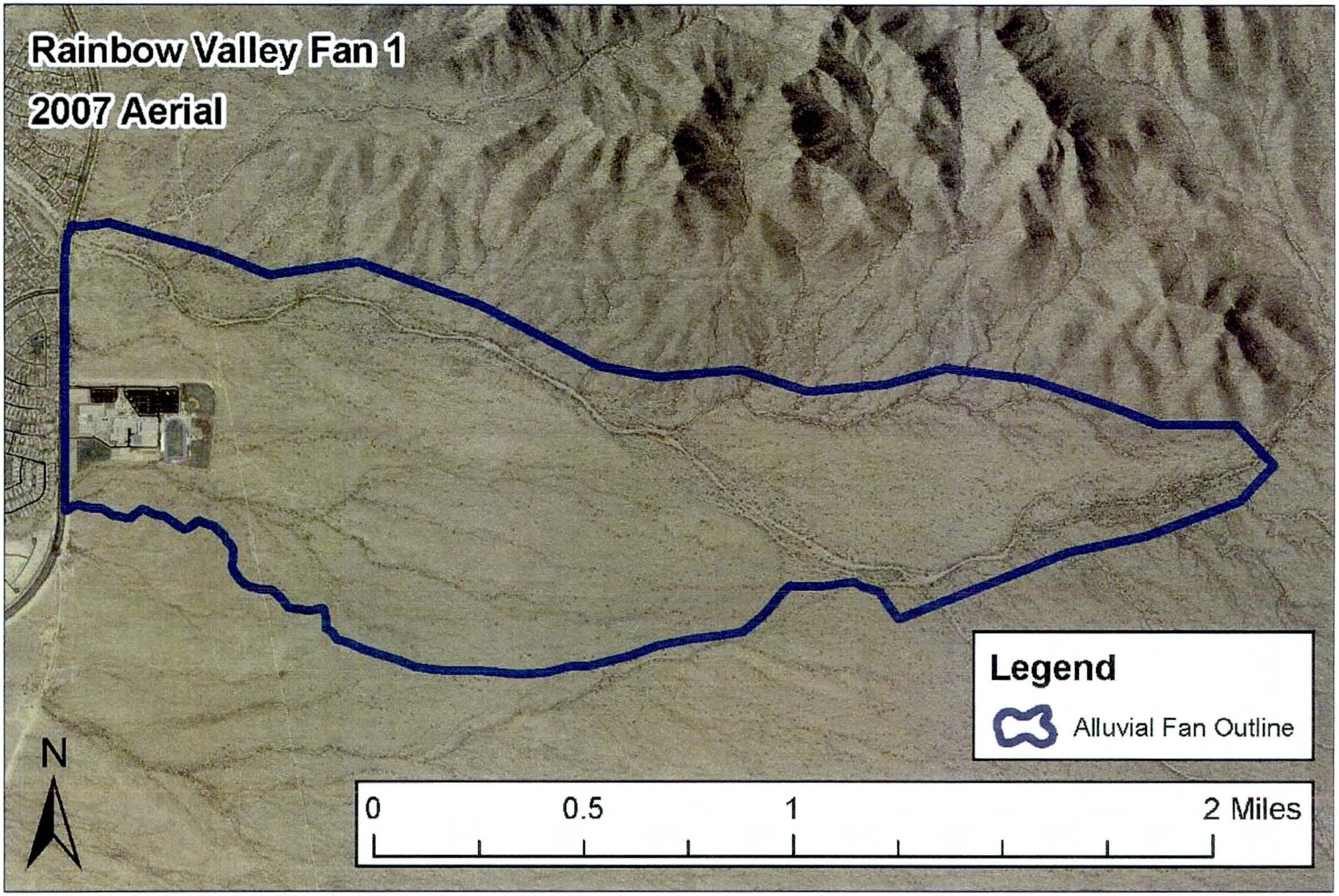

Figure 10. Aerial photograph of Rainbow Valley Fan 1.

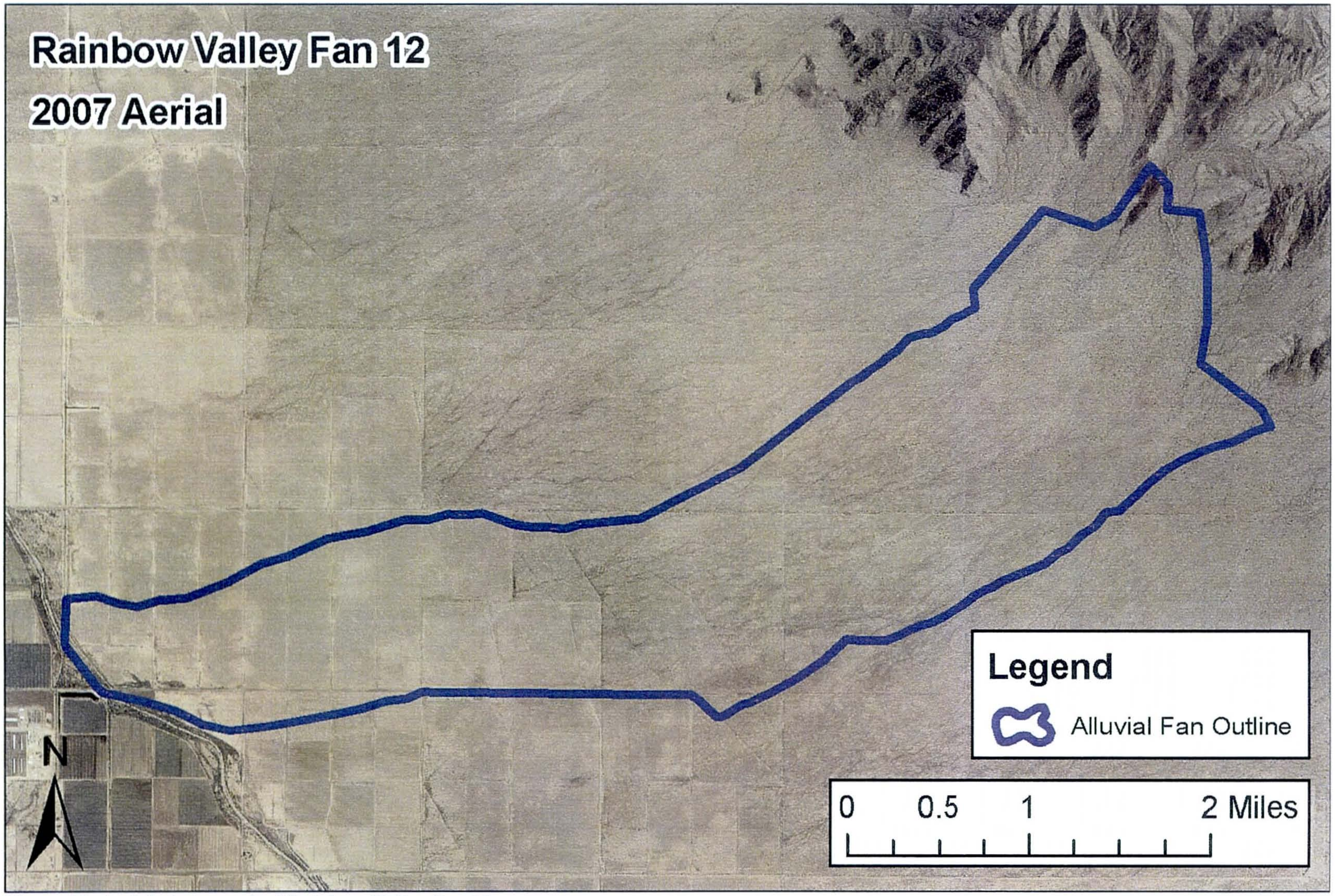

Figure 11. Aerial photograph of Rainbow Valley Fan 12.

2.3.2. Hydrology

The objective of the hydrologic modeling tasks of the PFHAM study was to recommend hydrologic methods for estimating flood hydrographs and peak discharges at concentration points on, or downstream of, an active alluvial fan (hydrographic) apex, in sheet flow areas, and on coalescing fans. Hydrologic modeling tasks performed for the PFHAM study included the following:

- Evaluation of existing hydrologic models provided by the District
- Development of new HEC-1 hydrologic models for each fan site
- FLO-2D modeling of each fan site

2.3.2.1. HEC-1 Modeling

Because of disparities in HEC-1 modeling techniques in the watershed models provided by the District, new HEC-1 models were developed for each of the four fan evaluation sites. The HEC-1 models were coded using current District modeling guidelines, as outlined in the District's *Drainage Design Manual for Maricopa County: Hydrology* and described in Appendix E. For the portions of the watersheds upstream of the hydrographic apexes, the modeling process was no different than any other hydrologic modeling project in Maricopa County. However, there were a number of challenges in applying the HEC-1 model downstream of the hydrographic apexes due to the distributary flow pattern and extensive areas of sheet flooding. Some of the HEC-1 modeling challenges included the following:

- Flow splits. Channel bifurcations must be hard-coded into the HEC-1 model. The percent of flow distributed between channel branches must be determined by a hydraulic rating or engineering judgment. Even if sufficient topographic data are available from which to make a reasonable estimate of the flow division in the channels, uncertainty regarding flow delivered outside the main channel makes such estimates tenuous at best. Furthermore, small changes in bed elevations, vegetative density, channel geometry or roughness may render even the most precise estimates inaccurate in subsequent floods.
- Flow path uncertainty. HEC-1 is not capable of changing the flow distribution to account for channel avulsions, unless multiple models with varying split distributions are used. Traditionally, flow splits on active alluvial fans have been modeled by assuming that the entire apex discharge could flow down any flow path (i.e., all flow paths receive the entire apex discharge). Alternatively, the model could be coded to over-account for flow between branches to provide a less-conservative estimate, by directing a less-than-100% portion of the apex discharge into each routing reach. For example, 70% of the apex flow could be diverted into a binary flow bifurcation, resulting in 140% of the apex discharge in the combined channels. However, no guidance is available from which to establish an appropriate over-accounting value (e.g., 70% vs. 60%). Furthermore, the latter approach does not conserve flow volume, and becomes increasing difficult to apply if multiple splits are encountered as flow traverses the fan surface.
- On-fan subwatersheds. Because active alluvial fans have distributary channel patterns, topographically indistinct drainage divides, and extensive sheet flooding

areas, it is difficult to accurately delineate watershed boundaries below the hydrographic apex. Some of the major data input values for HEC-1 presume that the subbasin area is well defined (basin area, length, time of concentration). In addition, HEC-1 does not allow flow to cross drainage boundaries except at concentration points.

- Concentration points. Discrete concentration points are difficult to identify in distributary and sheet flooding areas. On all of the active alluvial fans evaluated for the PFHAM study, the on-fan areas had either distributary characteristics with numerous flow paths or sheet flooding areas with no obvious concentration point. HEC-1 concentration points were assigned using either engineering judgment or at distinct geographic features such as road alignments.
- Channel routings. Normal depth routing reaches defined using a traditional eight-point cross section inadequately depict the storage that occurs in distributary and sheet flooding areas in which flow zones may be thousands of feet wide with very shallow average depths.
- Influence of manmade features. On developed fans, it is likely that distributary flow and sheet flooding are diverted, stored, or otherwise altered in complex ways by spatially distributed manmade features such as grading for home construction or roads (either perpendicular or sub-parallel to primary flow direction). It is not possible to model such features in detail in a lumped parameter model like HEC-1 without making simplifying assumptions regarding the impact of these features.

2.3.2.2. Two-Dimensional Modeling

Two-dimensional hydrologic modeling was performed using the FLO-2D computer model. FLO-2D is a volume conservation flood routing and physical process model that routes rainfall-runoff and flood hydrographs over unconfined flow surfaces or in channels using the dynamic wave approximation to the momentum equation.[7] It can be used for delineating flood hazards, regulating floodplain zoning or designing flood mitigation. The model will simulate river overbank flows, but it can also be used on unconventional flooding problems such as unconfined flows over complex alluvial fan topography, split channel flows, mud/debris flows and urban flooding. It has a number of components to simulate street flow, buildings and obstructions, sediment transport, spatially variable rainfall and infiltration, floodways and many other flooding details. Predicted flow depth and velocity between the grid elements represent average hydraulic flow conditions computed for a small timestep (on the order of seconds). Typical applications have grid elements that range from 25 ft to 500 ft on a side and the number of grid elements is unlimited. FLO-2D is on FEMA's list of approved hydraulic models for both riverine and unconfined alluvial fan flood studies.

FLO-2D models were prepared for each of the four alluvial fan evaluation sites. FLO-2D modeling techniques are described in more detail in Appendix F and Section 2.3.3 of this

[7] More information on the FLO-2D model is available at www.flo-2d.com. Although the FLO-2D model was used for this study, the District will allow use of any two-dimensional model that meets the criteria and that has the capabilities required to perform the analyses outlined in this report. The rationale for selecting the FLO-2D model is provided in the following discussion, as well as in Sections 2.3.2.3 and 2.3.3.

report. With respect to the hydrologic modeling aspects of FLO-2D, the approach consisted of several elements. First, a computation domain was identified that bracketed the limits of the alluvial fan landform from the hydrographic apex to the toe. Second, an inflow hydrograph computed using HEC-1 was input at a point far enough upstream of the hydrograph apex to assure that flow was adjusted to the ground terrain before it passed the apex. Third, NOAA Atlas 14 point rainfall depths were used for simulating on-fan rainfall. The current FLO-2D code does not areally reduce point rainfall depths with increasing drainage area. Given the relatively small size of the fan watersheds, and the fact that applying the NOAA 14 point rainfall depths directly would be conservative with respect to runoff rate, the lack of aerial reduction was considered insignificant for the purposes of the fan evaluations. Finally, FLO-2D rainfall loss rate methodologies used were identical to those used in the HEC-1 modeling.

2.3.2.3. Comparison of HEC-1 and FLO-2D Hydrologic Modeling

Comparison of the HEC-1 and FLO-2D modeling results revealed a number of key findings, as described in the following paragraphs.

Peak discharges. There are major differences in peak discharges computed using FLO-2D and HEC1, particularly for watersheds located on piedmont surfaces subject to shallow distributary flow and sheet flooding. Differences between HEC-1 and FLO-2D discharges for each of the four alluvial fan evaluation sites are shown in Table 3 to Table 6. The causes of these differences are the subject of on-going studies by the District (Loomis, 2010), but are most likely due to differences in unit hydrograph development (HEC-1 is based on unit hydrograph theory, FLO-2D is not), use of lumped (HEC-1) versus distributed (FLO-2D) modeling parameters, treatment of rainfall losses, computation of infiltration losses, and hydrologic (HEC-1) versus hydraulic (FLO-2D) routing technique.

Table 3. Comparison of HEC-1 and FLO-2D Peak Discharges: White Tanks Fan 36

Cross Section	HEC-1 Discharge (cfs)	FLO-2D Base Discharge (cfs)	Percent Difference	FLO-2D: No Infiltration (cfs)	Percent Difference
10	2842	2802	-1%	3024	6%
1020	767	538	-30%	577	-25%
1050	938	921	-2%	979	4%
10100	1137	1150	1%	1254	10%
20	699	35	-95%	60	-91%
33	740	14	-98%	0	-100%
43	754	12	-98%	0	-100%
50	745	18	-98%	31	-96%
60	709	41	-94%	19	-97%
80	923	58	-94%	122	-87%
100	1010	1615	60%	2107	109%
110	776	101	-87%	237	-69%
140	544	349	-36%	475	-13%
140110	136	90	-34%	137	1%
140150	408	256	-37%	327	-20%
160	1209		-100%	95	-92%

Table 4. Comparison of HEC-1 and FLO-2D Peak Discharges: Reata Pass Fan					
Cross Section	HEC-1 Discharge (cfs)	FLO-2D Base Model Discharge (cfs)	Percent Difference	FLO-2D Model: No Infiltration (cfs)	Percent Difference
60	11913	13119	10%	12884	8%
280	750	4450	493%	4721	529%
240	786	172	-78%	6	-99%
130	1599	417	-74%	397	-75%
120130	1660	2737	65%	2979	79%
110140	1734	2013	16%	2248	30%
150	2372	443	-81%	246	-90%
140150	2431	377	-84%	264	-89%
110120	2601	3129	20%	3041	17%
250	3683	716	-81%	240	-93%
260	3685	230	-94%	6	-100%
90	3693	2090	-43%	1959	-47%
270	3806	369	-90%	149	-96%
60110	4646	4713	1%	4659	0%
60170	4765	5120	7%	4947	4%
170180	5460	2816	-48%	3410	-38%
180	5504	1989	-64%	2884	-48%
330	6485	8050	24%	8237	27%

Table 5. Comparison of HEC-1 and FLO-2D Peak Discharges: Rainbow Valley Fan 1					
Cross Section	HEC-1 Discharge (cfs)	FLO-2D Base Model Discharge (cfs)	Percent Difference	FLO-2D Model: No Infiltration (cfs)	Percent Difference
xs30	3889	3763	-3%	3828	-2%
xs40	4149	3739	-10%	4042	-3%
xs60	661	172	-74%	133	-80%
xs30-60	1	332	33100%	342	34100%

Table 6. Comparison of HEC-1 and FLO-2D Peak Discharges: Rainbow Valley Fan 12					
Cross Section	HEC-1 Discharge (cfs)	FLO-2D Base Model Discharge (cfs)	Percent Difference	FLO-2D Model: No Infiltration (cfs)	Percent Difference
xs60	884	871	-1%	824	-7%
xs90	1070	159	-85%	198	-81%
xs70	1264	73	-94%	126	-90%
xs80	1185	13	-99%	18	-98%
xs120	2281	49	-98%	73	-97%
xs130	2189	16	-99%	51	-98%

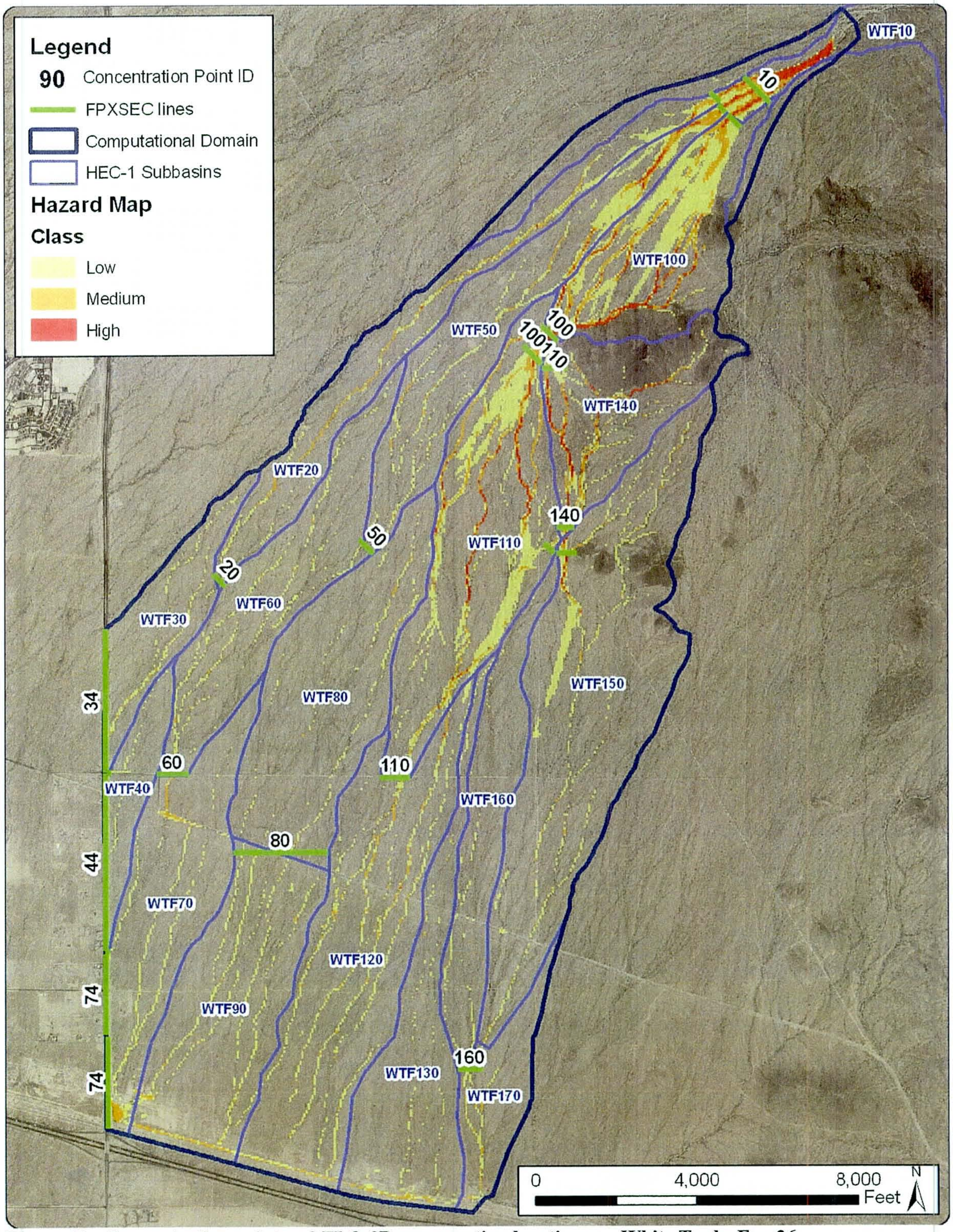

Figure 12. Concentration point and FLO-2D cross section locations on White Tanks Fan 36.

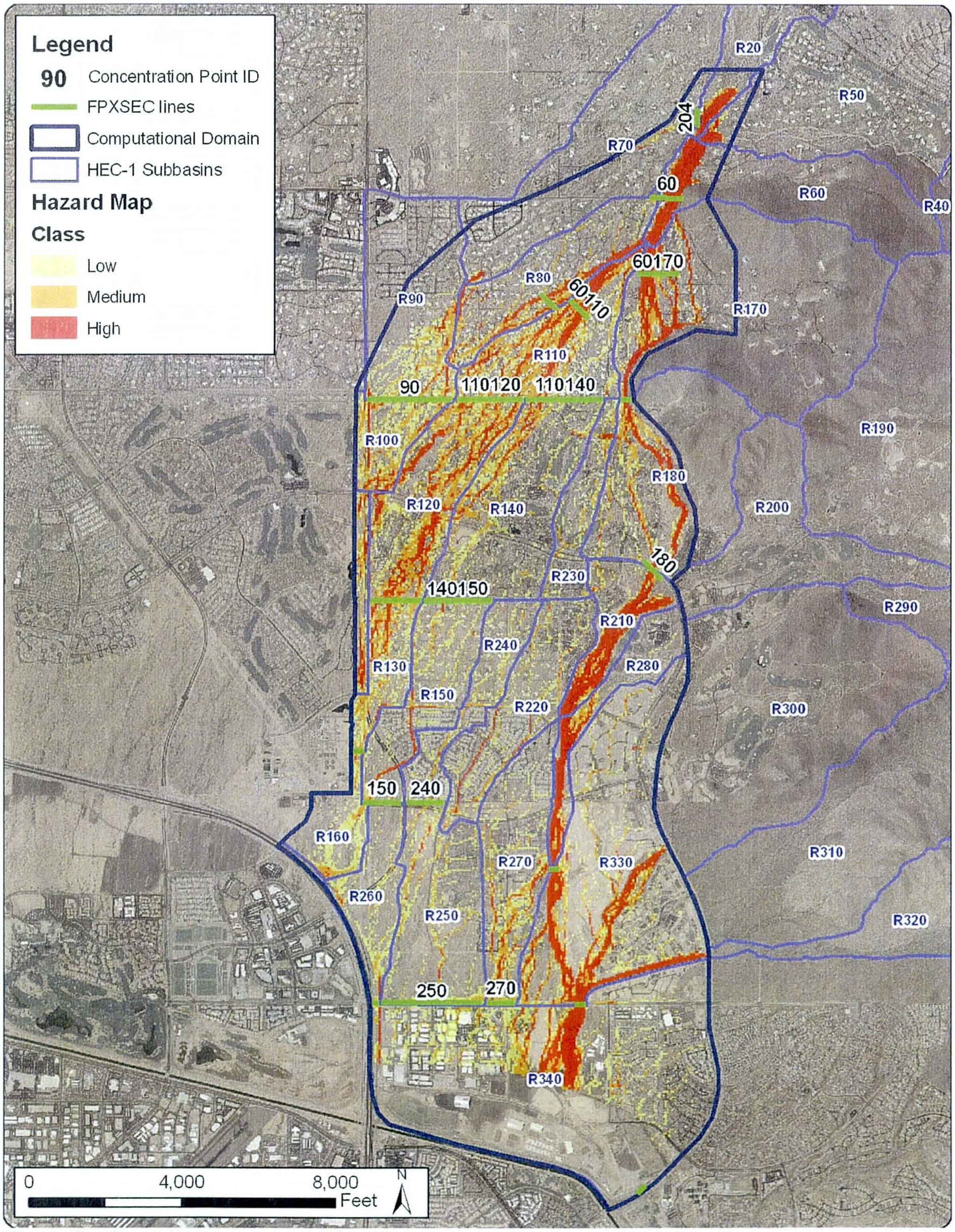

Figure 13. Concentration point and FLO-2D cross section locations on Reata Pass Fan.

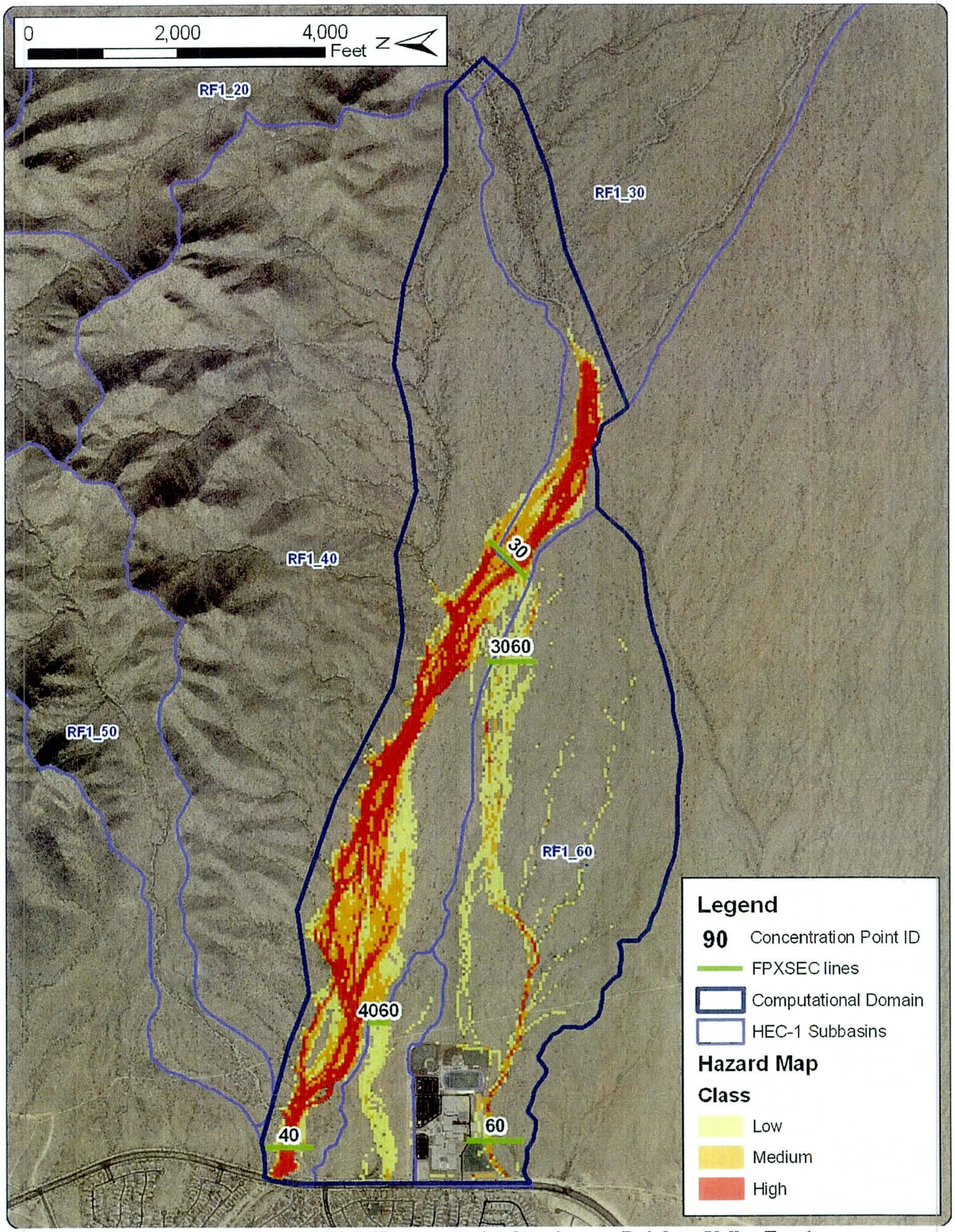

Figure 14. Concentration point and FLO-2D cross section locations on Rainbow Valley Fan 1.

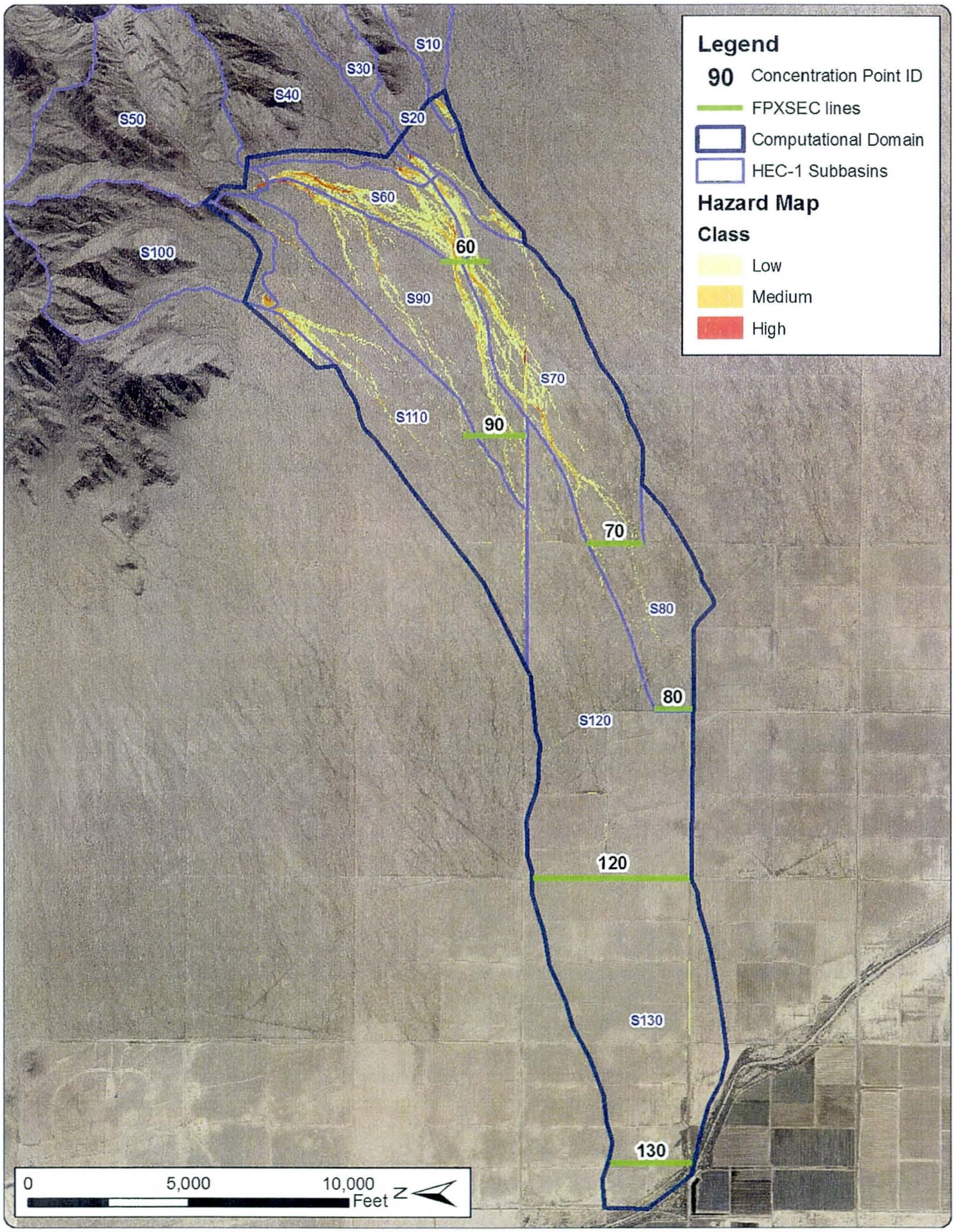

Figure 15. Concentration point and FLO-2D cross section locations on Rainbow Valley Fan 12.

Data requirements. Interestingly, the improved modeling capabilities of FLO-2D compared to HEC-1 do not come at an increased modeling cost or data requirements. The same topographic, rainfall, and soils data are used in both models. FLO-2D may require less data input in that vegetative cover type and density, time of concentration estimates, land use information, sub-watershed delineations, and channel routing parameters may not require explicit data sets. Additionally, FLO-2D offers the capability to include better resolution topographic and geographic data well beyond the lumped-parameter capabilities of HEC-1 that would further improve the FLO-2D model results.

Re-infiltration.[8] HEC-1 applies loss rates only to rainfall, and assumes that all of the "rainfall excess" become runoff at a downstream concentration point. FLO-2D computes rainfall losses similarly to HEC-1, but also continues to compute losses as the "rainfall excess" moves downstream across the land surface, if the ground storage and infiltration capacity has not been met at the time runoff crosses a grid element. This difference alone results in significant differences in the flow volume reaching any concentration point. For the purposes of this report, the continued infiltration of surface runoff as it moves across a land surface has been termed "re-infiltration" to distinguish it from the initial infiltration that occurs as an element of rainfall losses.

Flow peak attenuation. One of the most important findings of the PFHAM study is that significant attenuation of the peak discharge at the hydrographic apex occurs as the flood hydrograph crosses the surface of active alluvial fans in Maricopa County. Use of the peak discharge at the hydrographic apex may over-estimate the peak discharge at any point along the toe of the alluvial fan by up to two orders of magnitude. This finding is based primarily on FLO-2D modeling results, but is consistent with post-flood observations of alluvial fans, in which widespread (i.e., non-channelized) flood inundation floods (Pearthree et. al., 1992; 2004) and large flood peaks that completely dissipated before leaving the fan surface were observed (French and Miller, in press) Significant attenuation is also consistent with the geomorphic character of the drainage system on active alluvial fans in which net channel capacity decreases in the down-fan direction (CH2M HILL, 1992). Additional FLO-2D models coded with no re-infiltration showed similar attenuation across the active fan surface.

Flow attenuation on active fan surfaces is caused by three primary factors. First, on alluvial fans in Maricopa County the acreage of the active alluvial fan area may far exceed the watershed area upstream of the hydrographic apex. These extensive land surfaces are inundated and available for storage of flood water, resulting in high rates of flow attenuation. Second, most of the flooding on active alluvial fans in Maricopa County occurs as shallow sheet floods or distributary flow. The areas subject to high velocities and depths are relatively limited and are located near the hydrographic apex. Outside the limited high hazard zones, shallow flooding moves at relatively slow velocities increasing both the storage time and opportunity for (re)infiltration. Third, active alluvial fans in

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[8] "Re-infiltration" is a form of transmission loss. The term re-infiltration is preferred in this context to distinguish it from losses that occur only along defined flow paths.

Maricopa County typically are composed of permeable sand and/or gravel, which are capable of absorbing large volumes of flood water.

Advantages of FLO-2D modeling. FLO-2D offers a number of advantages over HEC-1 for hydrologic modeling of active alluvial fans. First, there is no need to delineate subwatershed boundaries in poorly-defined distributary and sheet flooding areas. Runoff is accumulated based on site topography and flow hydraulics without regard for pre-conceived basin divides. Furthermore, runoff can flow in different directions at different flow rates and depths, depending on specific site conditions. Second, runoff can leave the model space anywhere along the modeling domain boundary, not just at specific concentration points. Third, the model can generate peak discharges and hydrographs anywhere within the model domain, rather than just at specific concentration points. Fourth, flow does not have to collect at concentration points in FLO-2D but can exit as unconfined sheet flooding, distributary flow along multiple channels or be stored at intermediate ponding areas. Fifth, intermingling of flow along undefined boundaries between coalescing alluvial fans is easily modeled and addressed. Sixth, the flow hydrology and hydraulics are computed concurrently, avoiding any disconnect (and additional labor) between single-focus models. Seventh, routing of a flow hydrograph is inherent in the model code, eliminating the need for estimated hydrologic routing parameters or averaged hydraulic routing cross sections. Eighth, watershed parameters can be entered as distributed characteristics over a relatively small grid size, rather than lumped and averaged over large subbasins, allowing much finer resolution of input data. Ninth, modeling elements can be entered anywhere within the modeling domain, rather than just at pre-determined concentration points and computational nodes. Most importantly, FLO-2D results fit the anecdotal and behavioral expectations of the engineering and geosciences communities better than the HEC-1 results. Therefore, it is the conclusion of the study, that FLO-2D is far superior to HEC-1 for modeling piedmont drainage systems.

Development impacts. As a consequence of the loss of the high rates of flow attenuation that occurs on undeveloped active alluvial fans, unregulated development on active fan surfaces is likely to have major adverse impacts on flow rates at adjacent downstream properties. Development impacts on flooding are likely to include loss of natural flood storage areas, loss of runoff infiltration surfaces, increased runoff volume from constructed or disturbed surfaces, increase runoff frequency from impervious areas, accelerated flow travel times over developed surfaces, concentration of previously unconfined flow, introduction of non-natural runoff sources (over-watering, spillage, etc.), and increased antecedent moisture due to irrigation.

If unregulated development only eliminated the natural flow storage and infiltration areas on an active alluvial fan, a number of adverse consequences would be likely. First, the peak discharge reaching downstream properties is likely to be at or nearer the flow rate at the hydrographic apex. Second, when the increased peak discharges reach distal portions of the fan that lack defined channels, increased overbank flooding and/or erosion of new channels is likely. Third, sediment that was previously stored on the active fan surface will be transported downfan and deposited in areas that previously received little or no sediment deposition. In effect, the fan apex will be translated downstream to a point below the developed portion of the fan. Therefore, it is critical that development on active alluvial fan surfaces be appropriately managed.

Flow path uncertainty. A methodology to account for the impact of flow path uncertainty on peak discharge was developed for use on active alluvial fans in Maricopa County. This methodology, called the "virtual levee scenario" technique, the mechanics of which are described in more detail in Section 2.3.3, as well as in Appendixes F and I of this report. The virtual levee scenario methodology simulates the possible impact of an avulsion on the flood hydrology and hydraulics of an active alluvial fan using an artificial (virtual) levee coded into the FLO-2D model. A series of FLO-2D models (scenarios) such virtual levees that direct flow along potential avulsive flow paths with in the most active portion of an alluvial fan, changing the rate and distribution of flow in the portions of the alluvial fan located downstream of the virtual levees. The maximum computed flow rate and hydraulic characteristics at any given point derived from all of the virtual levee scenarios are then used for floodplain delineation and engineering design. The virtual levee scenario methodology thus accounts for flow path uncertainty within the active parts of the alluvial fan, while not ignoring the important processes of flow attenuation downstream of the hydrographic apex. The virtual levee scenario methodology was developed in conjunction with staff from the District's Engineering Division, and was successfully applied to estimate peak discharges below the fan apex for the White Tanks Fan 1-2 floodplain delineation (JEF, 2009).[9]

The virtual levee methodology offers a number of advantages over other traditional hydrologic modeling techniques on active alluvial fans. First, the method explicitly accounts for flow path uncertainty by considering multiple flow paths that could occur if runoff were redirected along potential avulsive channels in the high hazard portion of an active alluvial fan. Second, the method provides a reasonable technical basis (avulsion) for any over-accounting of the apex hydrograph. Third, the method is based on physical processes identified by geomorphic and hydraulic evaluation of an active alluvial fan (Appendix I). Fourth, the method combines engineering and geomorphic analysis techniques, providing opportunities for verification of quantified results. Fifth, the hydrologic elements allow for flow attenuation both within the channelized portion of the alluvial fan and across the shallow sheet flooding and distributary flow portions of the alluvial fan. In summary, the virtual levee method provides a conservative, but not overly conservative estimate of peak discharge at any point on an active alluvial fan downstream of the hydrographic apex.

2.3.2.4. Hydrologic Modeling Conclusions

Based on the results of the hydrologic modeling evaluation performed for the PFHAM study, the following hydrologic modeling recommendations are proposed:

- Two-dimensional modeling is recommended for all hydrologic modeling below the hydrographic apex of active alluvial fans in Maricopa County.

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[9] The Fan 1-2 study is currently under review by FEMA.

- The District should develop two-dimensional hydrologic modeling guidelines that specifically address:
    - Point rainfall depths
    - Loss rate parameters
    - Limits on re-infiltration volume
    - Pre- and post-processing tools for modeling coalescing alluvial fans
- Hydrologic modeling upstream of the hydrographic apex should be completed as dictated by current District modeling guidelines and standards. Based on the findings of this study, it is recommended that the District develop guidelines for using FLO-2D to model watersheds upstream of the hydrographic apex, particularly for small watersheds or where tributary inflows to the active fan surface occur over broad areas, rather than at discrete concentration points.
- The virtual levee methodology should be used to estimate conservative peak discharges, flood hazard areas, flow depths, and water surface elevations for all areas located downstream of an active alluvial fan apex.

2.3.3. Two-Dimensional Hydraulic Modeling

Two-dimensional hydraulic modeling was performed using the FLO-2D computer model.[10] The objective of FLO-2D modeling of the four alluvial fan sites was to evaluate FLO-2D for use as a tool to quantify flood hazards on active alluvial fans in Maricopa County. To this end, over one hundred separate FLO-2D models were prepared for the four alluvial fan evaluation sites, as well as for several additional alluvial fans in Maricopa County. The following types of FLO-2D models were prepared for the study:

- 100-Year Base Models
- Multiple Frequency Models
- Model Sensitivity Runs
- Encroachment Impact Models
- Flood Hindcast Models
- Avulsion Scenario Models
- Virtual Levee Scenario Models
- Sediment Transport Models

A complete list of the FLO-2D models prepared and evaluated for this study is shown in Table 7. A description of the specific FLO-2D input data and modeling procedures used is provided in Appendix F of this report. Plots of FLO-2D depths, velocities and hazard zones for all of the types of FLO-2D runs are grouped and shown together in Figure 16 to Figure 22. Descriptions of each of the types of FLO-2D runs, as well as some of the key conclusions drawn from them, are provided in the following paragraphs.

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[10] Although the FLO-2D model was used for this study, the District will allow use of any two-dimensional model that meets the criteria and that has the capabilities required to perform the analyses outlined in this report.

Table 7. FLO-2D Models Prepared for the PFHAM Study								
Model Description	**WTF 36**	**RPF**	**RVF 1**	**RVF 12**	**WTF 1-2**	**H3**	**WTF 7-12**	**TW**
Base Model (Q100)								
With re-infiltration	x	x	x	x	x	x	x	x
No on-fan re-infiltration	x	x	x	x			x	
No on-fan rainfall	x	x	x	x				
Detailed topography	x				x			
Finer grid size	x							
Multiple channel option	x							
Multiple Frequency								
Q2	x	x	x	x				
Q10	x	x	x	x				
Q50	x	x	x	x				
Q500	x	x	x	x			x	x
QPMP	x	x	x	x			x	x
Virtual Levee Scenarios	5	3	3	2	7		3	
Fan Area Encroachment	X							
Known Flood Hindcast	1951							1997
Avulsion Scenarios								
Channel obstruction	x							
Extreme flood	x	x	x	x				x
Sediment Transport								
Q100	x	x	x	x	x			
Q500	x	x	x	x				
Q50	x	x	x	x				
Q10	x	x	x	x				
Q2	x	x	x	x				
Q100 – fine D50	x							
Q100 – average D50	x							
Q100 – coarse D50	x							
Q100 – Ackers/White		x						
Q100 – Englund/Hansen		x						
Q100 – Woo		x						
Q100 – Yang		x						
Q100 – Zeller/Fullerton		x			x			
Q100 – clear water inflow		x						

Key:
WTF 36: White Tanks Fan 36 — WTF 1-2: White Tanks Fan 1-2 — WTF7-12: White Tank Fan 7-12
RVF1: Rainbow Valley Fan 1 — RPF: Reata Pass Fan — H3: Hieroglyphic Mtns Fan 3
TW: Tiger Wash Fan — RVF12: Rainbow Valley Fan 12 — *(H3 modeling by PACE)

Table 8. FLO-2D modeling parameters.	
Rainfall	NOAA 14 Point Rainfall Values No rainfall in upstream HEC-1 subbasins overlap areas
Rainfall Losses	Green-Ampt loss rate methodology Initial abstraction, percent vegetative cover, imperviousness based on land use types ARF based on land use type
Topographic Data	Grid elevation from center of grid using Gaussian average tool Elevations built in ArcGIS TIN using 3d Analyst 10-ft topo (White Tanks) from District 2-ft topo (Reata, Rainbow) from District & Scottsdale
FLO-2D Parameters	N-values based on land use Limiting Froude No. = 0.95 per FLO-2D manual guidance for fans Shallow n-value = 0.112 (extrapolates to 0.040 at 3 ft depth) TOL = 0.001 DEPTOL = 0.05 WAVEMAX = -0.25
Modeling	50-ft grid size

2.3.3.1. 100-Year Base Model

The FLO-2D base models simulated the hydrology and hydraulics of the 100-year event on each of the alluvial fan evaluation sites. In addition, 100-year modeling results were considered from the White Tank Mountain Fan 1-2 Floodplain Delineation Study (JEF, 2009), White Tanks Mountain Fan 7-12 Floodplain Delineation Study (JEF, 2010), Hieroglyphic Mountain Fan 3 FLO-2D Modeling Study (PACE, 2010), and the Tiger Wash Alluvial Fan (see Appendix I). The base condition models were used as a standard of comparison to all other FLO-2D models, and were the primary source of 100-year hydraulic data. The following are some of the conclusions drawn from the FLO-2D 100-year base model results shown in Figure 16 to Figure 22:

- Distributary Flow Pattern. The flow pattern below the hydrographic apex makes a rapid transition from a confined, straight-braided single channel pattern to a highly distributary channel pattern. The distributary pattern persists over the entire alluvial fan landform, although in the mid- to distal-fan regions it becomes progressively intermingled with an incipient dendritic or parallel pattern that appears to have developed to convey on-fan runoff.
- Sheet Flooding. Most of the active alluvial fan surfaces are inundated by relatively shallow flow depths broadly distributed over the fan surface. Sheet flooding is probably the dominant type of flooding on any of the active alluvial fan surfaces considered.
- Flow Attenuation. The hydrograph attenuation described in Section 2.3.2 is due in part to the distribution of flow over the fan surface in distributary channels and sheet flooding areas. This distribution of flow allows for extensive flood storage, opportunities for infiltration, and low velocity flow over the fan surface, all of which create opportunities for flow attenuation.

- Low Depth and Velocity. The predicted 100-year flow depths and velocities are relatively low[11] over the vast majority of the fan surface. Areas of low velocity are conducive to sediment deposition and net long-term aggradation, which is not surprising, since it is a defining characteristic of an active alluvial fan.
- Limited High Hazard Zone.[12] As a consequence of predicted low flow depths and velocities, the high hazard zones are spatially limited, generally to small areas immediately below the hydrographic apexes.
- On-Fan Drainage Pattern. FLO-2D modeling predicts that most of the 100-year flooding is conveyed along the existing distributary channel pattern, with only a few minor exceptions noted in Section 2.7 and Appendix I.
- Inundation Limits. In no case did the FLO-2D modeling indicate that the 100-year flood completely inundates the Holocene surface, nor is it likely that a single 100-year flood would inundate the entire active portion of the alluvial fan landform. This finding is consistent with post-flood inundation mapping (Pearthree et. al. 1992, 2004) as well as the findings of other authors cited in the literature search (Pelletier et. al., 2004, French and Miller, in press).
- Anthropomorphic Impacts. The presence of roads and other structures on the fan can alter natural flow paths and create new, artificial channel alignments (e.g., Figure 19).

The FLO-2D base models indicate that flooding at fan evaluation sites is not conveyed via a single channel and that the flow paths locations are relatively predictable if floods occur with minimal sediment transport and relatively unchanging topography.

[11] Note that the reported flow depths and velocities are average values for the FLO-2D grid cell. Maximum depths and velocities may be somewhat higher if more detailed topographic information were used.
[12] Computation of "hazard" shown in Figure 16 to Figure 22 is based on default FLO-2D methodology. The recommended hazard assessment methodology is discussed in more detail in Section 2.3.3.9.

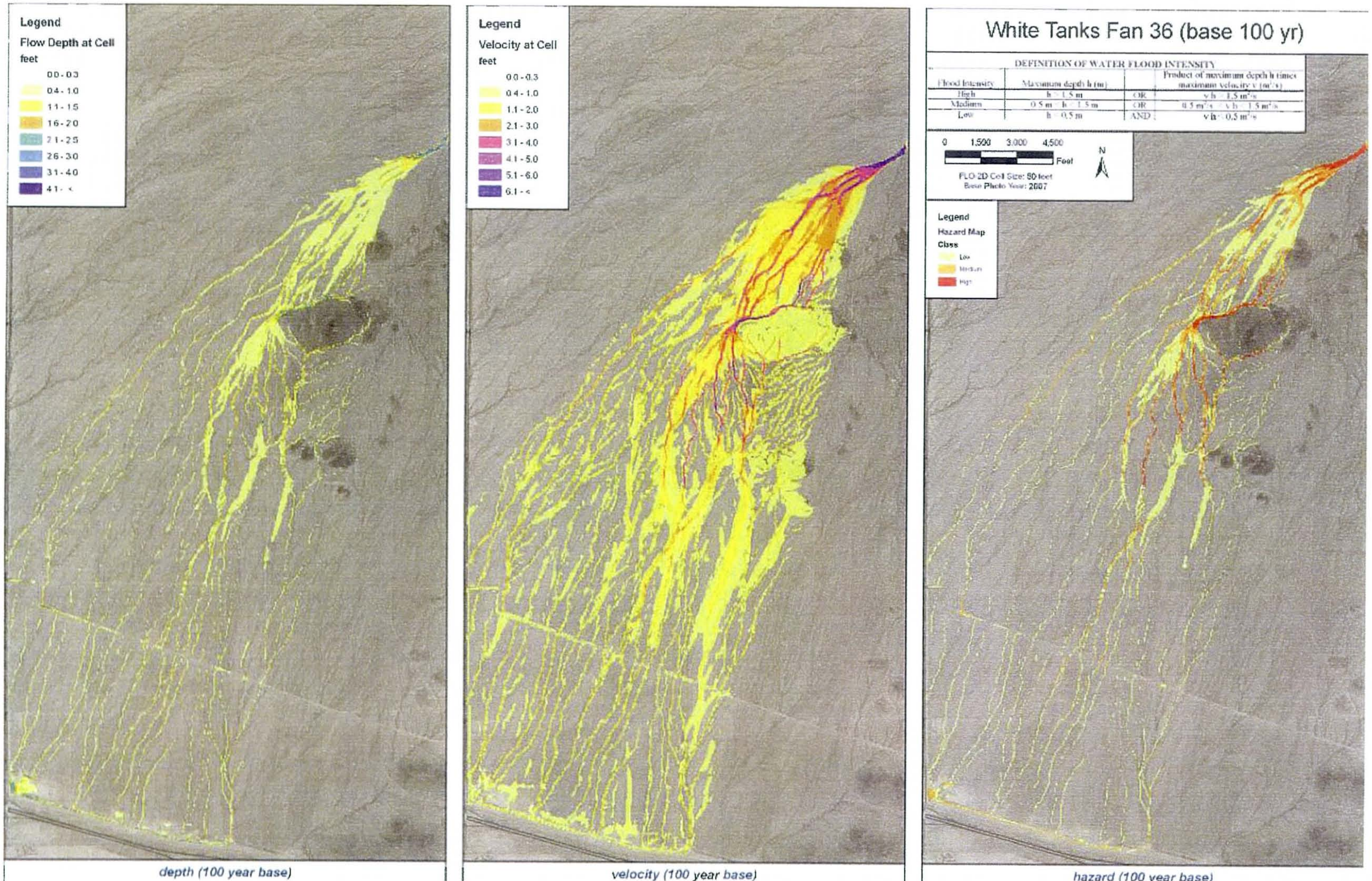

Figure 16. FLO-2D base model for the White Tanks Fan 36 site showing flow depth, velocity, and hazard.

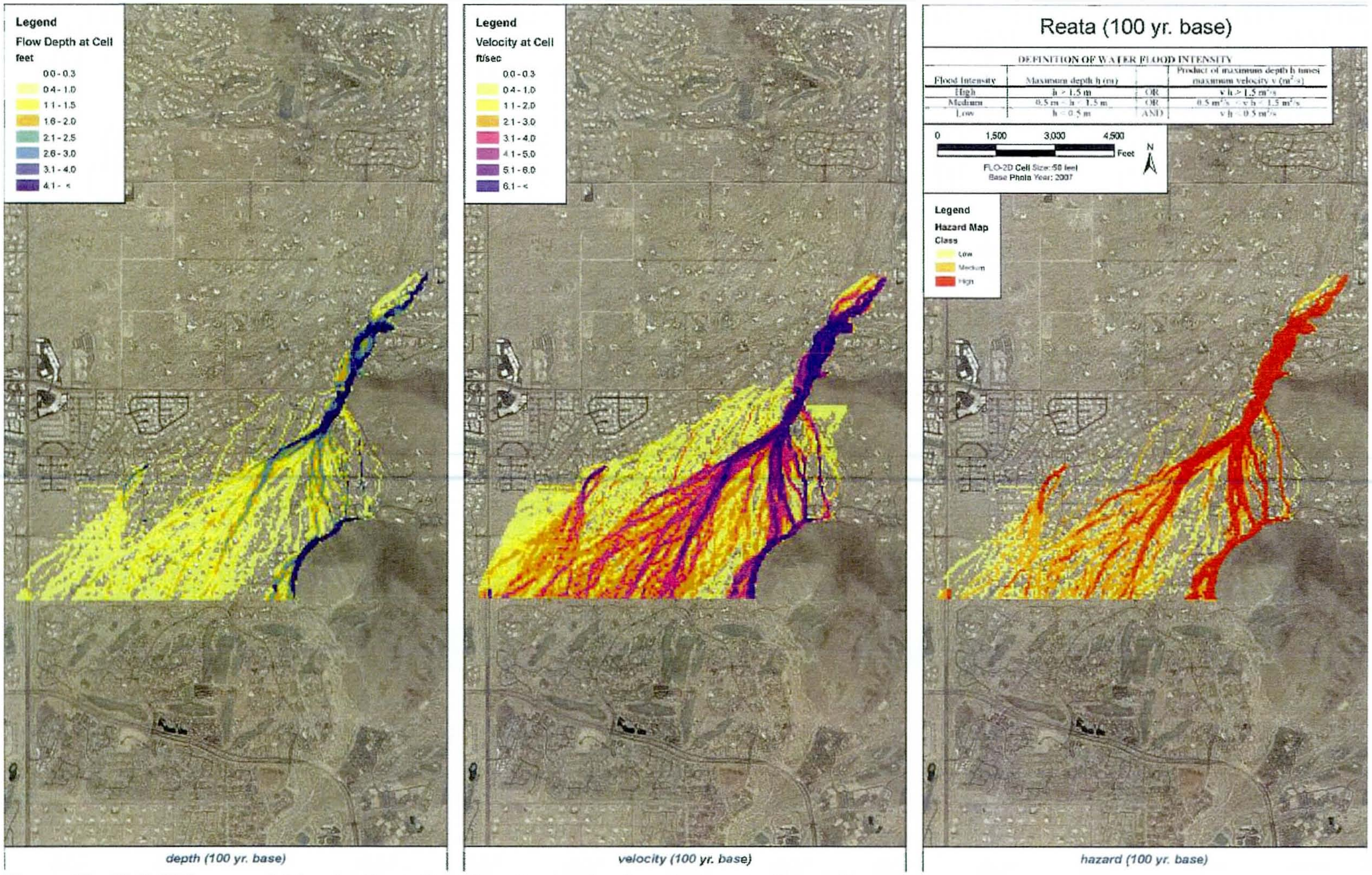

Figure 17. FLO-2D base model for the Reata Pass Fan site showing flow depth, velocity, and hazard.

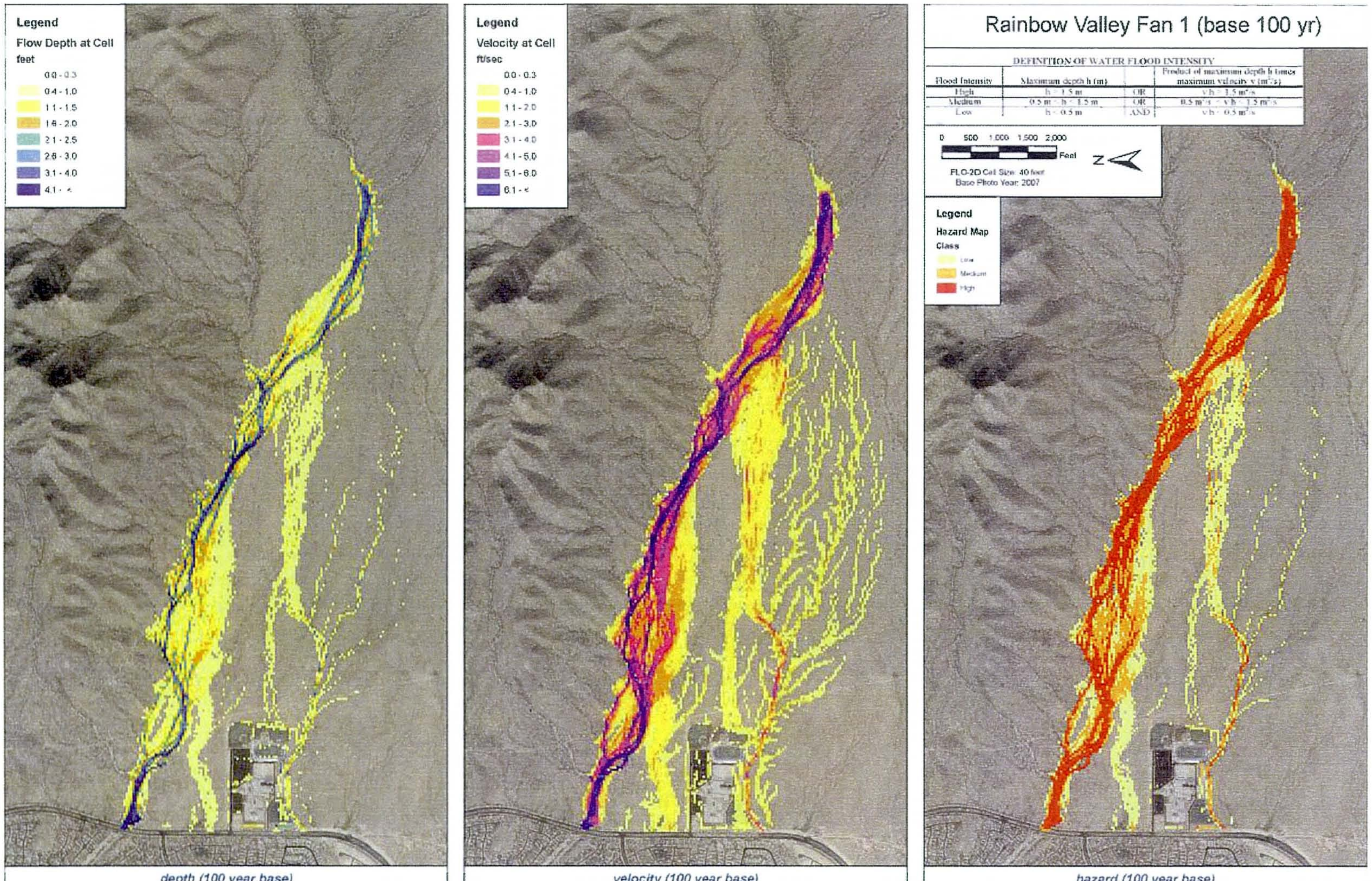

Figure 18. FLO-2D base model for the Rainbow Valley Fan 1 site showing flow depth, velocity, and hazard.

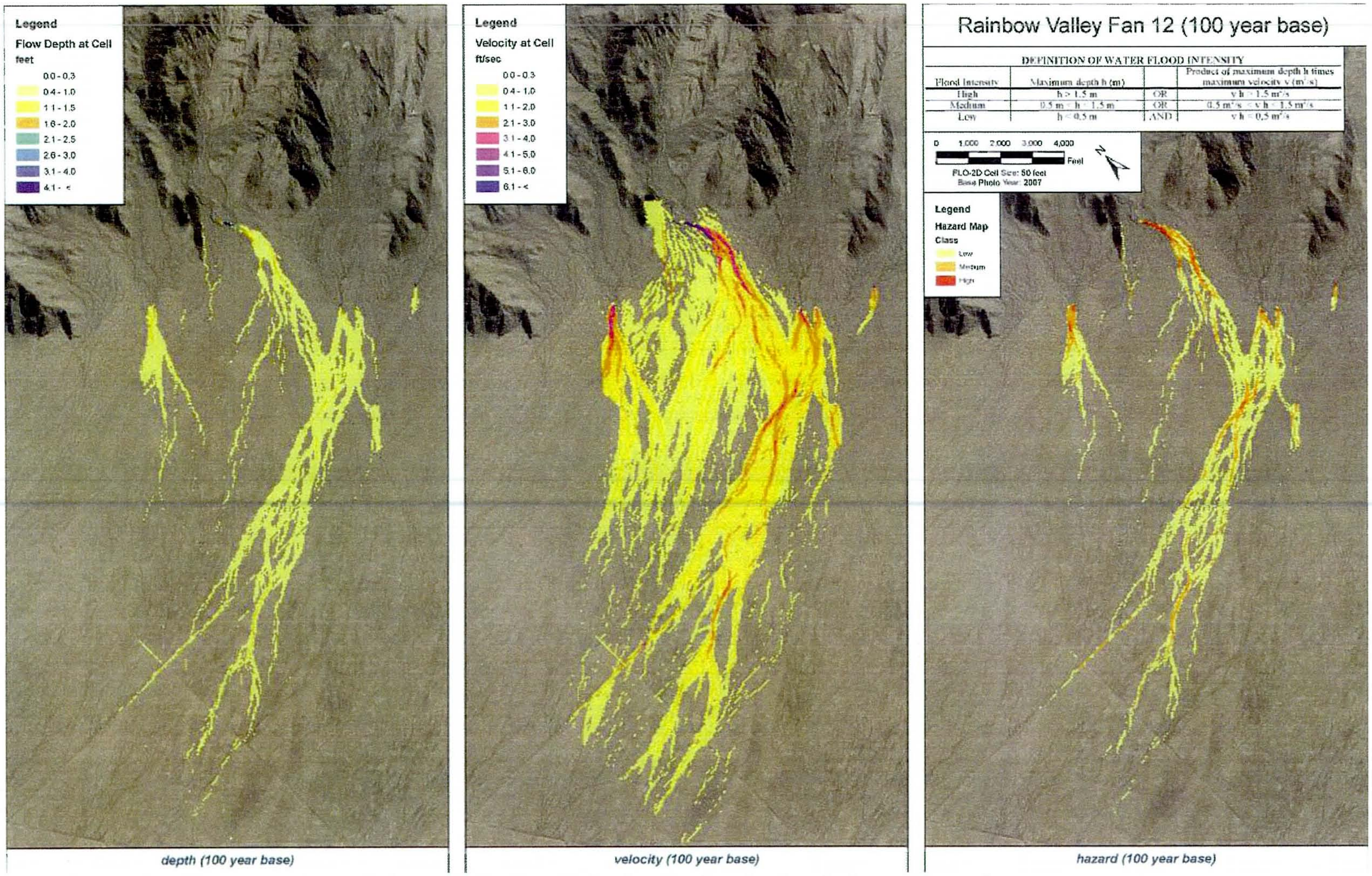

Figure 19. FLO-2D base model for the Rainbow Valley Fan 12 site showing flow depth, velocity, and hazard.

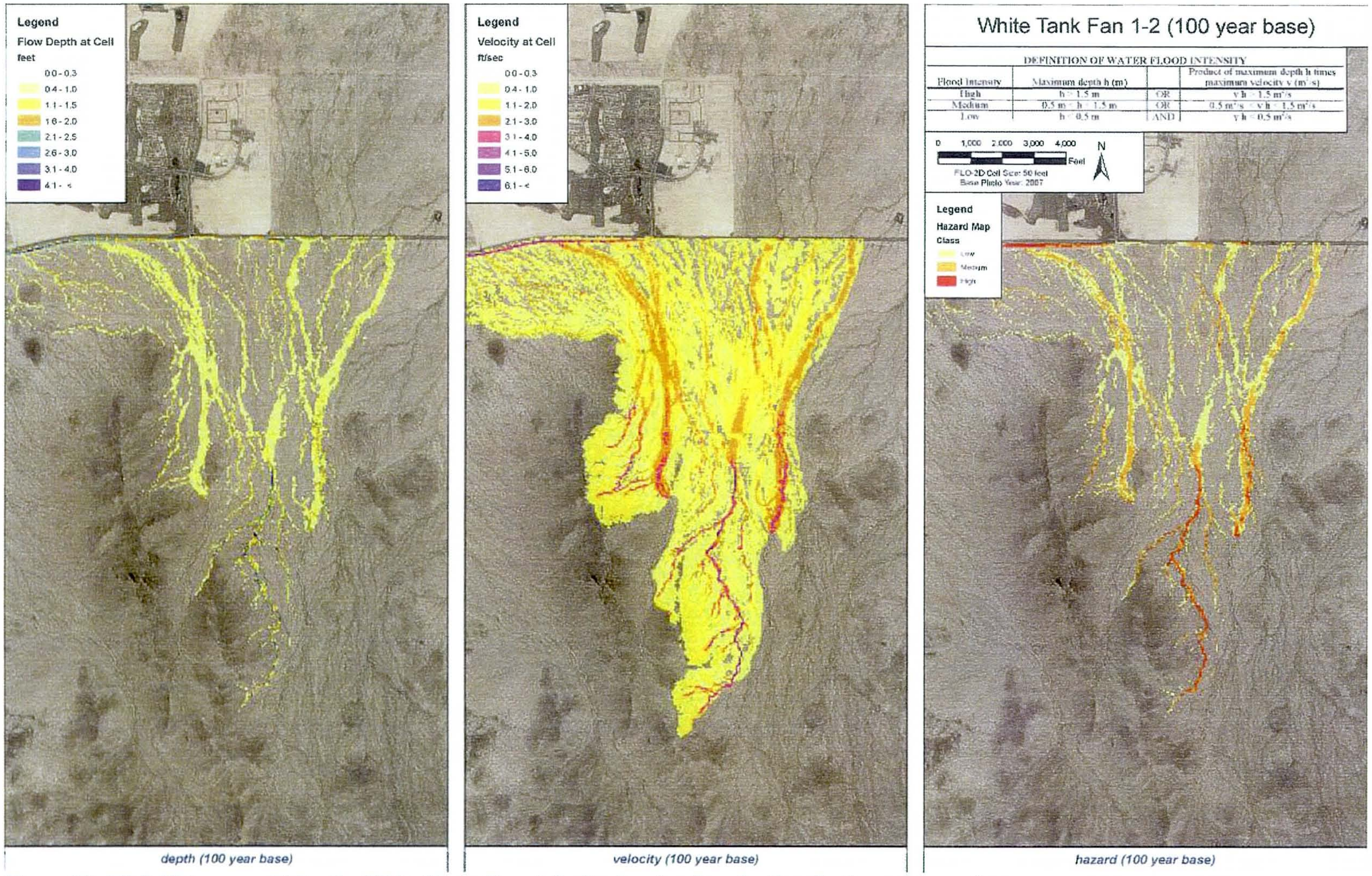

Figure 20. FLO-2D base model for the White Tanks Fans 1-2 site showing flow depth, velocity, and hazard.

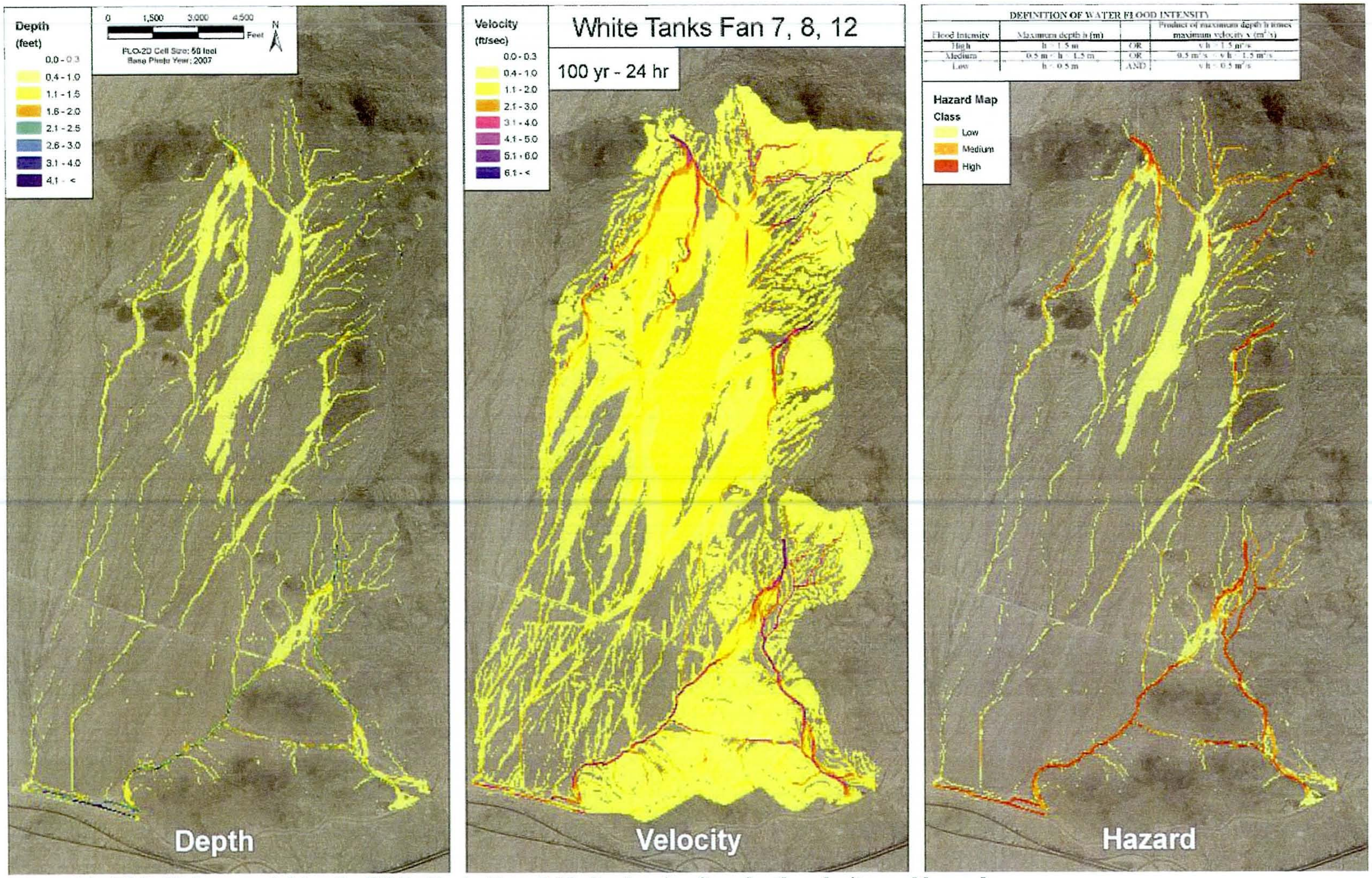

Figure 21. FLO-2D base model for the White Tanks Fans 7-12 site showing flow depth, velocity, and hazard.

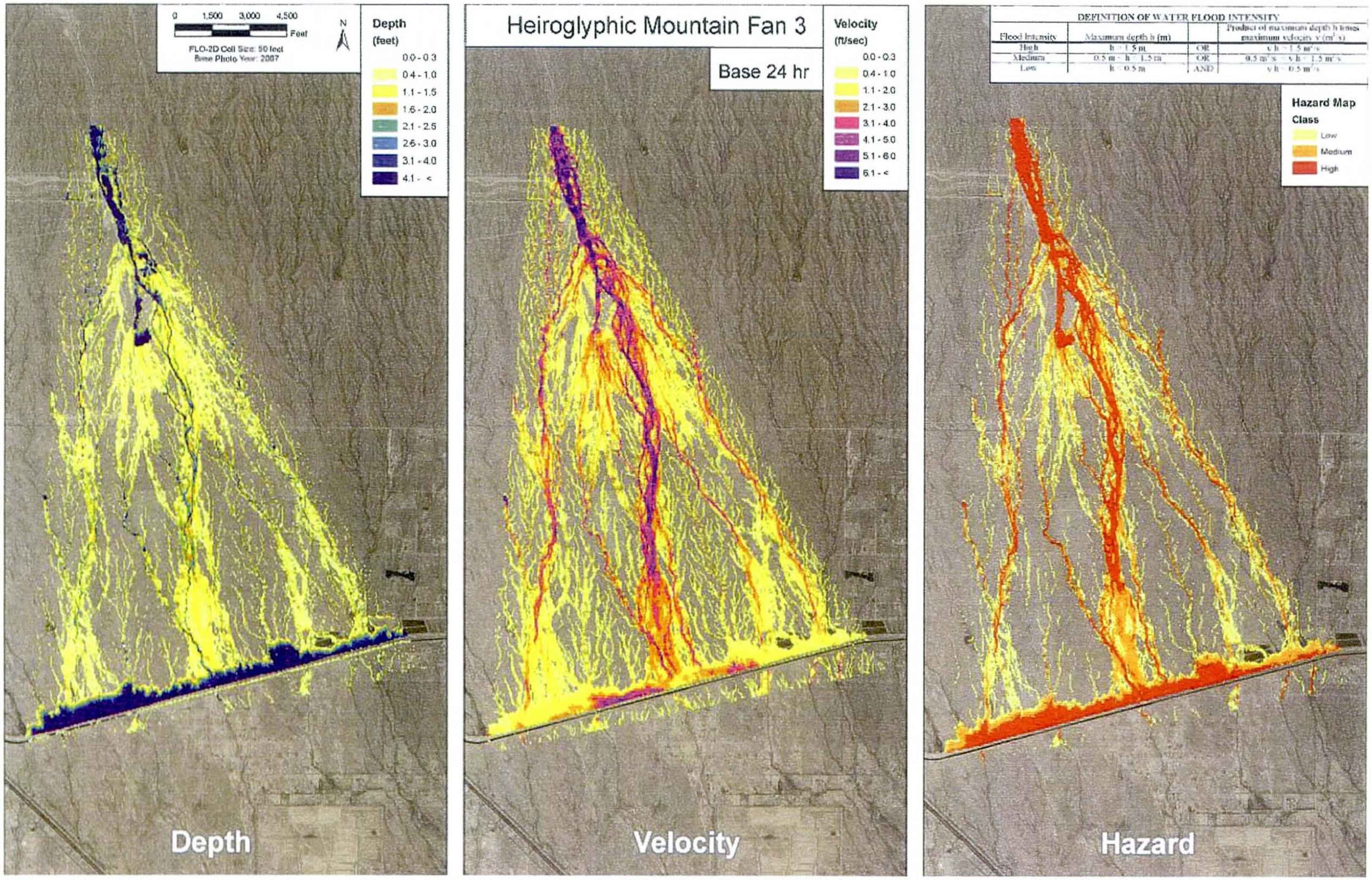

Figure 22. FLO-2D base model for the Hieroglyphic Mountain Fan 3 site showing flow depth, velocity, and hazard.

2.3.3.2. Multiple Frequency Models

Additional FLO-2D models were prepared for the four evaluation sites using 2-, 10-, 50-, and 500-year hydrographs. FLO-2D models also were prepared using probable maximum precipitation (PMP)[13] rates to simulate the potential behavior of an extreme flood event (>Q500) on the fan surface. The multiple frequency models were used to assess differences in potential impact to alluvial fan processes and hazards between large (infrequent) and small (frequent) floods. The following are some of the conclusions drawn from the FLO-2D multiple frequency model results shown in Figure 23 to Figure 26:

- Flow Pattern Similarity. Not surprisingly, FLO-2D results indicate that large floods inundate more of the fan surface, and at greater depths and velocities than small floods. However, despite the differences in depth and inundation, the overall pattern of flow inundation was nearly identical for large and small events. Regardless of flood magnitude, FLO-2D predicts that most flow occurs in distributary channels or as shallow sheet flooding.
- Extreme Floods. FLO-2D modeling indicates that the PMP event inundates nearly all of the Holocene surfaces at the four evaluation sites (Figure 27), particularly in the upper active fan areas. However, some surfaces in the mid- and distal-portions of the fan were not inundated, even at PMP flow rates. Therefore, the PMP FLO-2D runs may be useful for identifying non-floodprone surfaces within active portions of an alluvial fan. In addition, PMP (and 500-year) modeling results also help elucidate potential avulsive flow corridors, as described in Section 2.7.
- Flow Attenuation. The smallest floods tend to be completely attenuated on the active fan surfaces, and do not reach the fan toes. It can be assumed that if the flood water does not leave the fan surface, the entire sediment load (in those small events originating above the hydrographic apex) will be deposited on the fan surface. Furthermore, if the smaller, more frequent floods originating above the hydrographic apex do not reach the toe of the fan, then the drainage patterns in the lower fan areas are most likely the result of on-fan runoff alone. On-fan runoff events may transport sediment downfan, or in some cases, off the active fan surface.

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[13] The PMP rainfall depths and distributions were obtained from HMR 49 (NOAA, 1984).

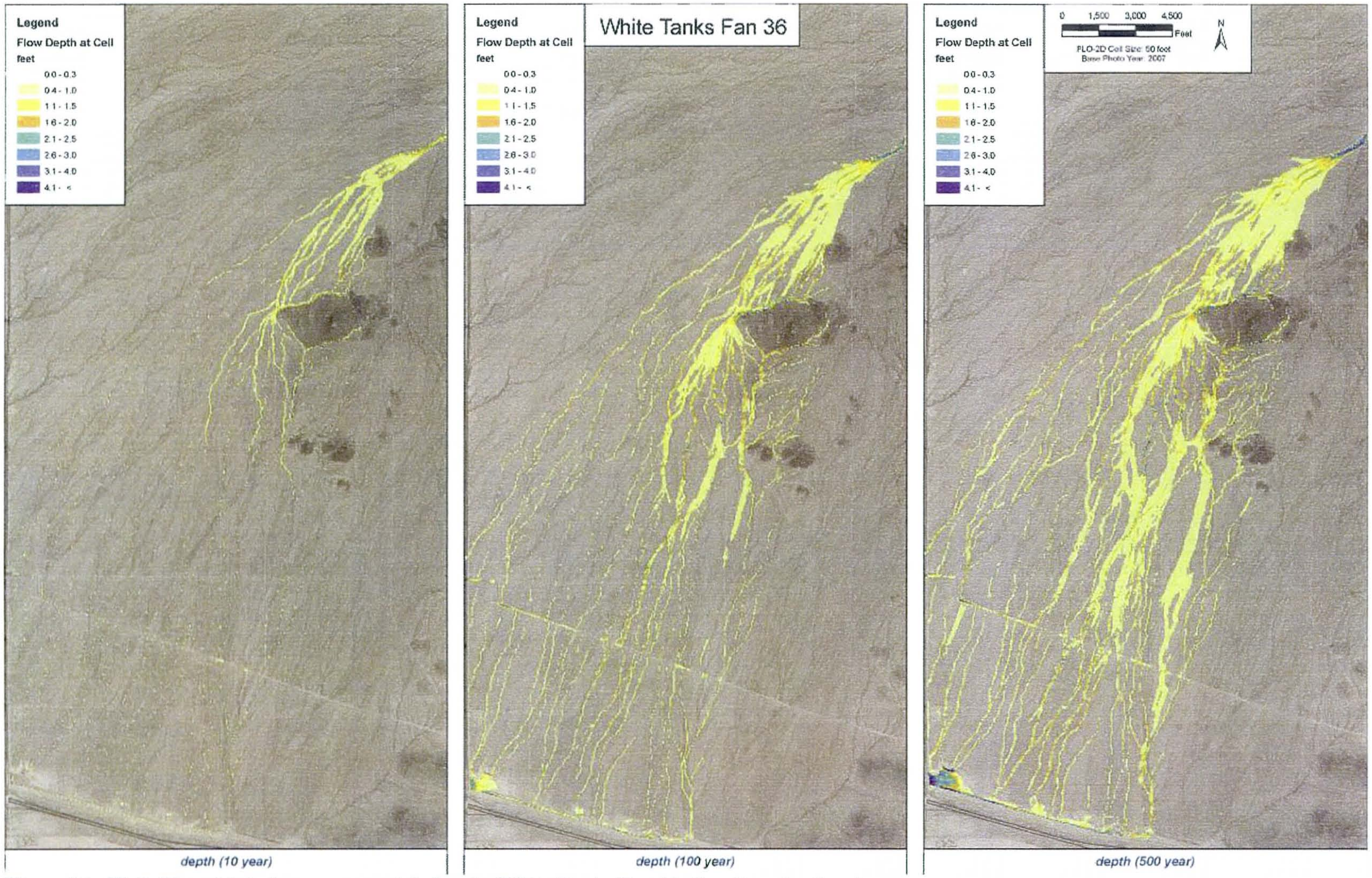


Figure 23. FLO-2D multiple frequency models for the White Tanks Fan 36 site - flow depth only.

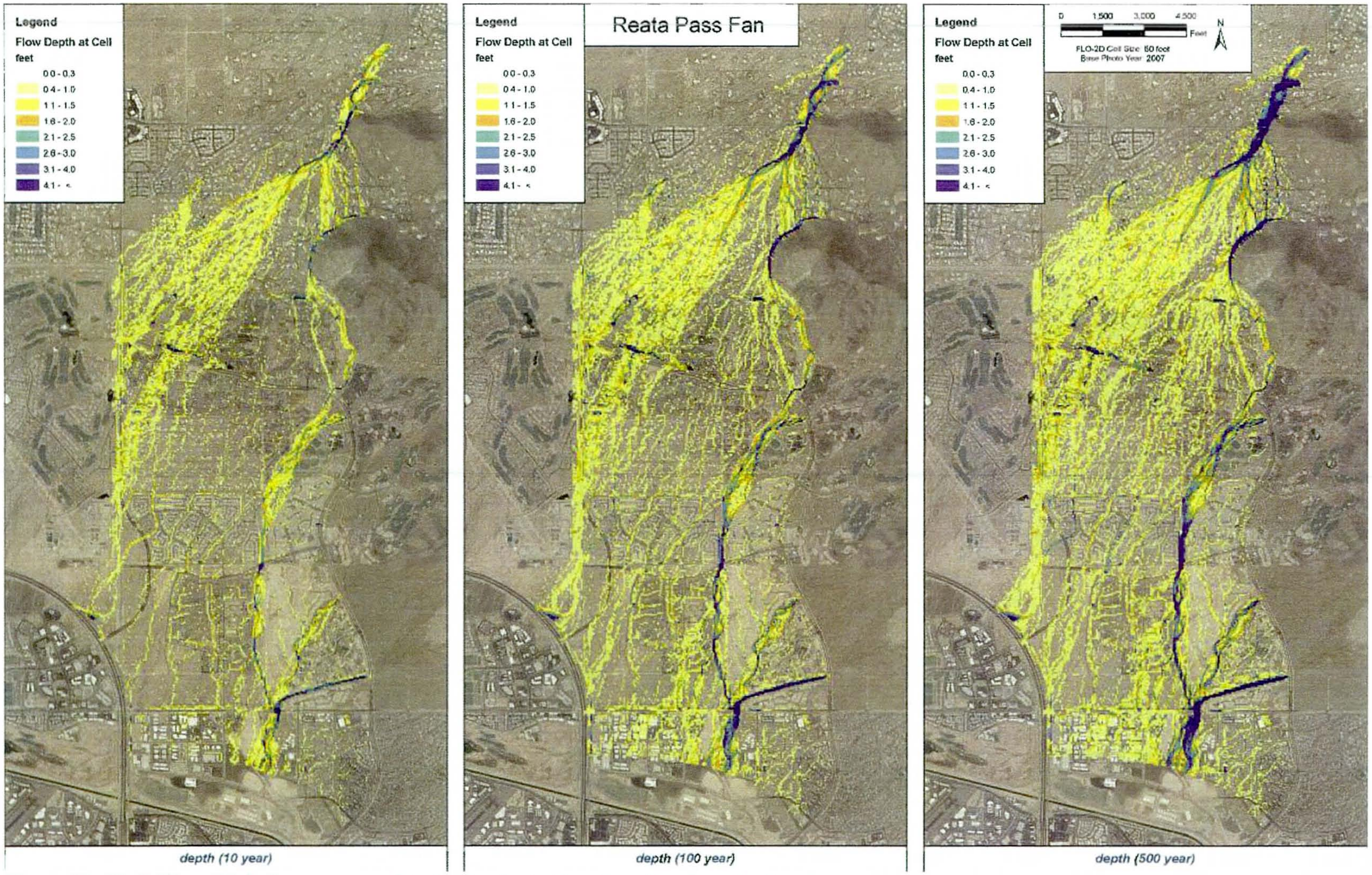


Figure 24. FLO-2D multiple frequency models for the Reata Pass Fan site - flow depth only.

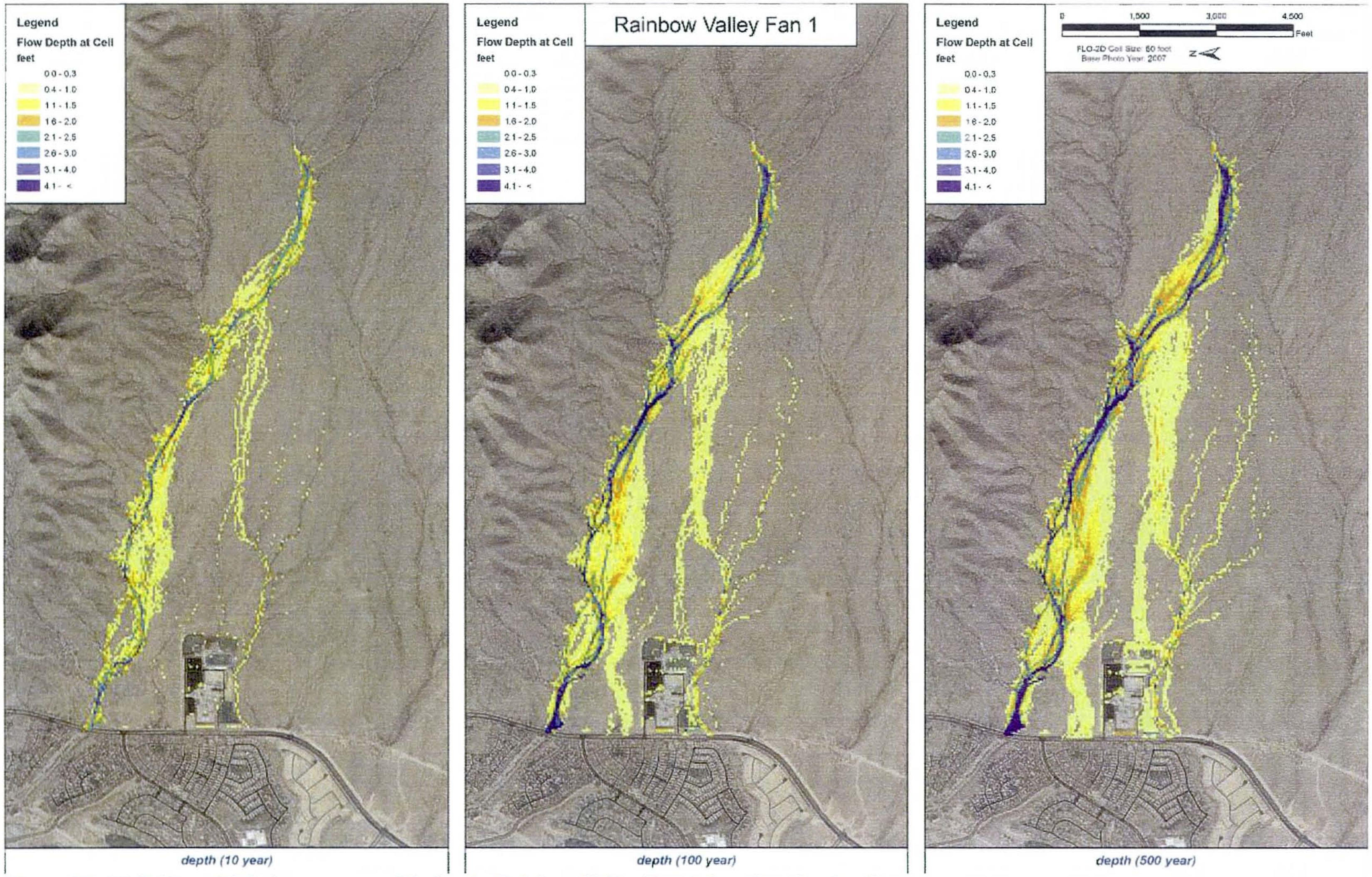


Figure 25. FLO-2D multiple frequency models for the Rainbow Valley Fan 1 site - flow depth only.

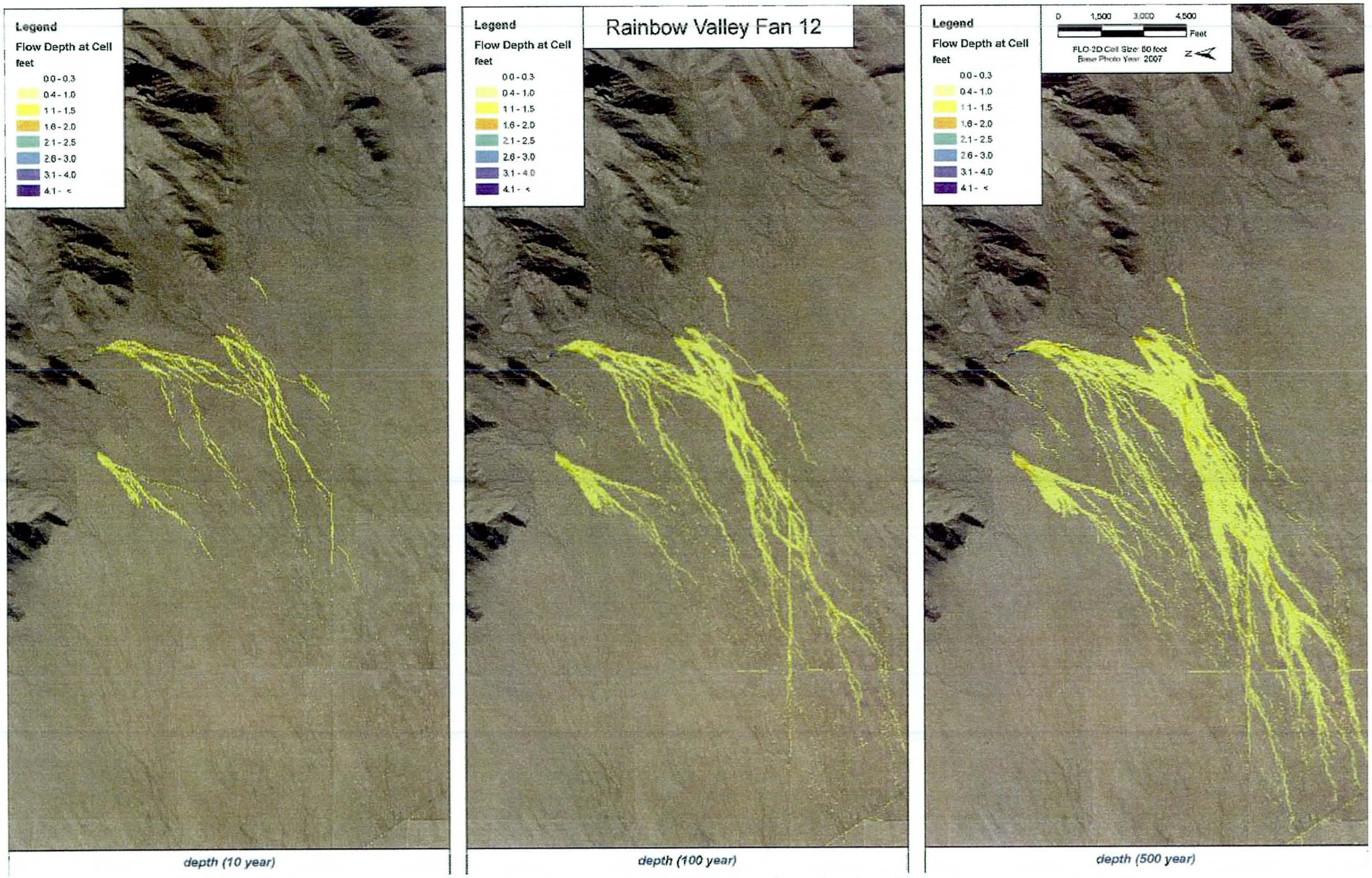


Figure 26. FLO-2D multiple frequency models for the Rainbow Valley Fan 12 site - flow depth only.

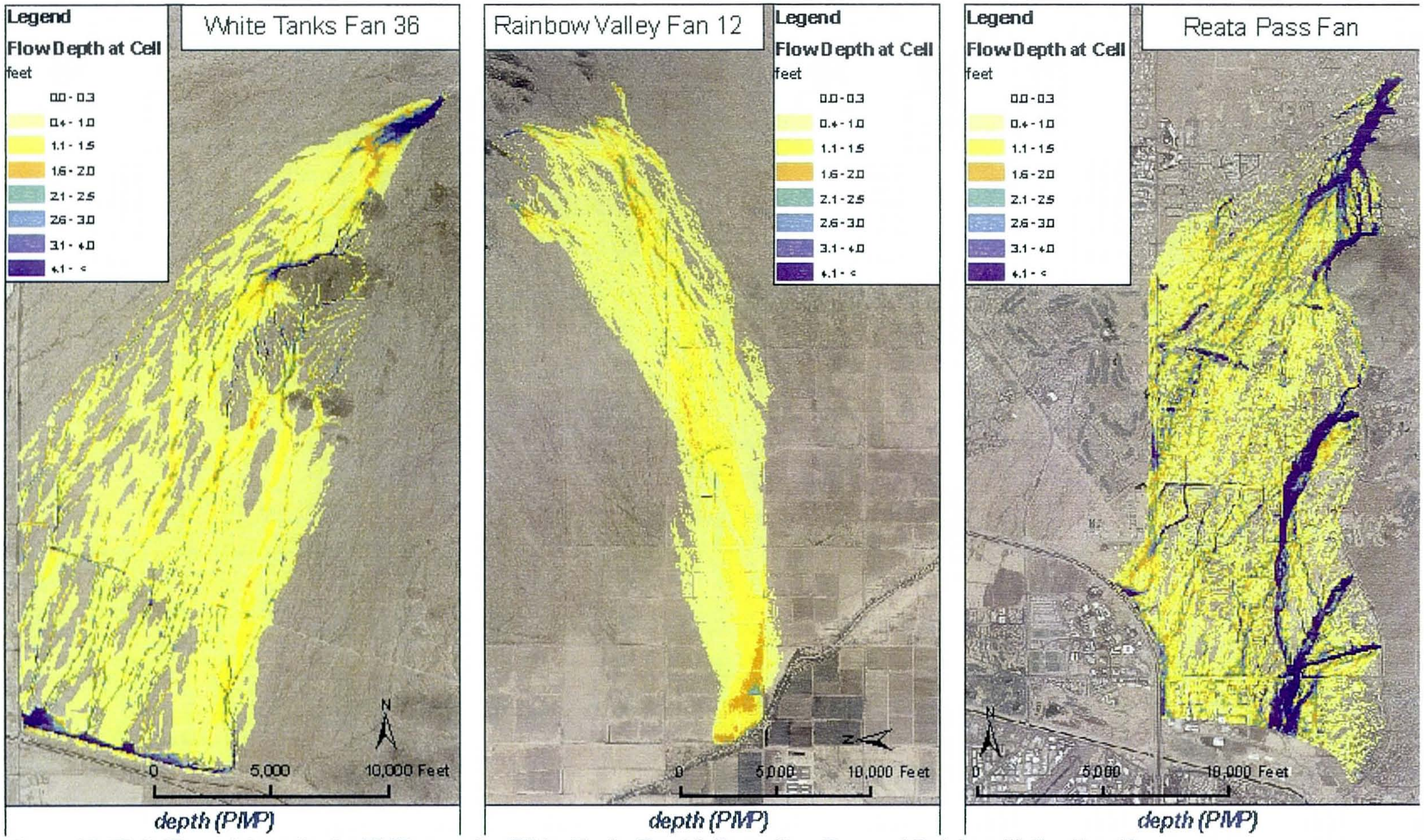


Figure 27. FLO-2D model results for PMP event for White Tanks Fan 36, Reata Pass Fan, and Rainbow Valley Fan 12.

2.3.3.3. Model Sensitivity Runs

A number of model sensitivity runs were prepared to evaluate the accuracy of the FLO-2D results. The following are some of the conclusions drawn from the FLO-2D model sensitivity results shown in Figure 28 to Figure 31:

- Multiple Channel Option (Figure 28). The multiple channel option in FLO-2D was developed to recognize that flow over the sheet flooding portions of a fan surface may occur in fine-textured, self-formed channels that might not be well-expressed using a coarse FLO-2D grid. The FLO-2D multiple channel option allows the model to develop a regime channel for routing the hydrograph through a grid cell. More detail on the modeling procedures are available in the FLO-2D user's manual (FLO-2D, 2010). Accordingly, use of the FLO-2D multiple-channel option in the WTF36 base model increased the volume of runoff delivered to the toe of the fan, increased the rate at which flow travelled across the fan, and increased the overall area of inundation on the fan surface. These results indicate that the multiple-channel option should be carefully evaluated prior to finalizing the recommendations for the proposed PFHAM methodology.
- Grid Size (Figure 29). Compared to the 50-foot grid used in the FLO-2D base model, use of a 25-foot grid size increased the resolution of the FLO-2D results, resulted in inundation of more land within the active area, and facilitated identification of more channelized flow paths, as well as potential avulsive flow corridors within the active area. Therefore, it was concluded that use of a smaller grid results in more accurate depiction of flood conditions. It is noted that smaller grid sizes can significantly increase the model run times for large alluvial fans, and that selection of the appropriate grid size requires experience, engineering judgment, and knowledge of site conditions. In cases where the topographic data resolution is poor, use of a smaller grid system may not be justified. In this study, modeling performed using 40- and 50-foot grid cells was found to achieve the study goals. More guidance on grid size selection is available in the FLO-2D User's Manual, and will be provided (and supplemented with District guidelines) in the revised PFHAM document, after the completion of this study.
- Topographic Data (Figure 30). Similarly, use of 2-foot topographic data in the WTF 36 site FLO-2D model increased the resolution of the predicted inundation area relative to the 10-foot topographic data used in the base models. In all cases, use of the most detailed topographic data available is recommended. Where more detailed topographic mapping is available, the smallest possible grid size relative to run time should be used to optimize the modeling results.
- No Infiltration and On-Fan Rainfall (Figure 31). To test the validity of the high rates of flow attenuation predicted by FLO-2D, additional models were prepared in which no on-fan rainfall was simulated and the infiltration option was turned off. These changes did not significantly change the FLO-2D results, leading to the conclusion that the levels of predicted flow attenuation are due primarily to the extensive storage volume available on the inundated portions of an alluvial fan relative to the flood volume, and the slow rate of hydrograph progression downfan at low depths and velocities across the fan surface.

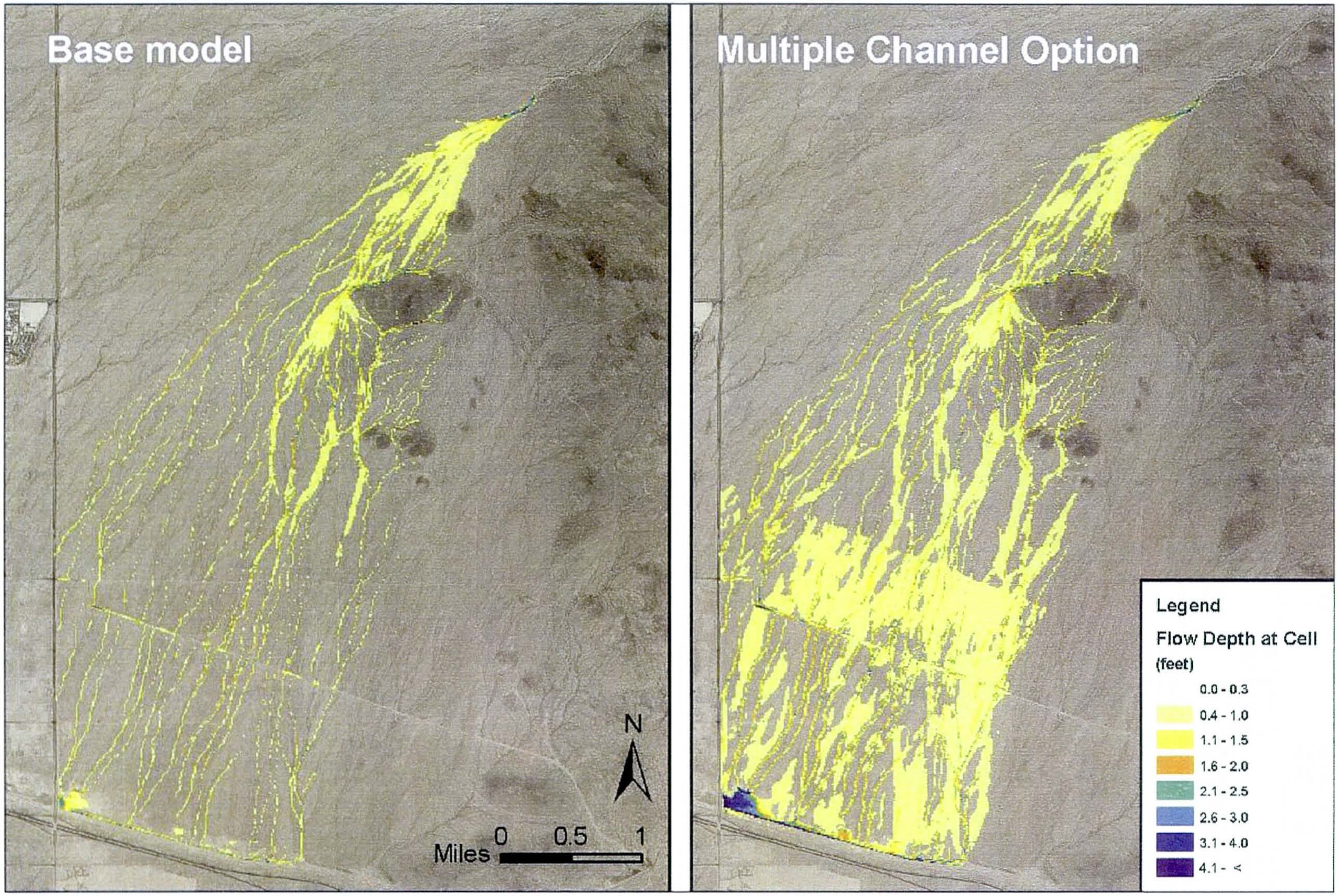


Figure 28. FLO-2D results for White Tanks Fan 36 – multiple channel vs. base model (Q100).

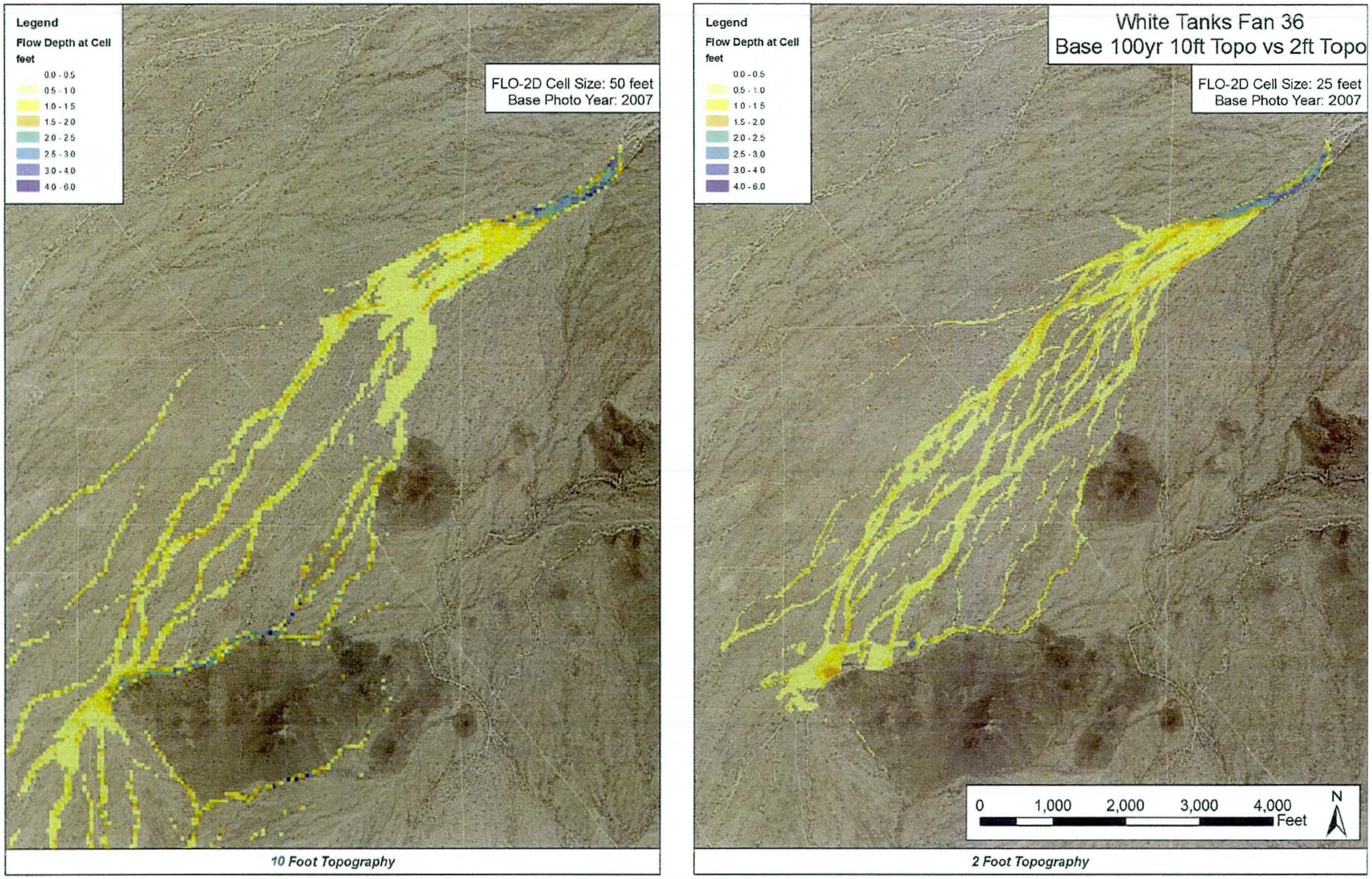


Figure 29. FLO-2D results for White Tanks Fan 36 – 25-ft vs. 50-ft. grid size (Q100).

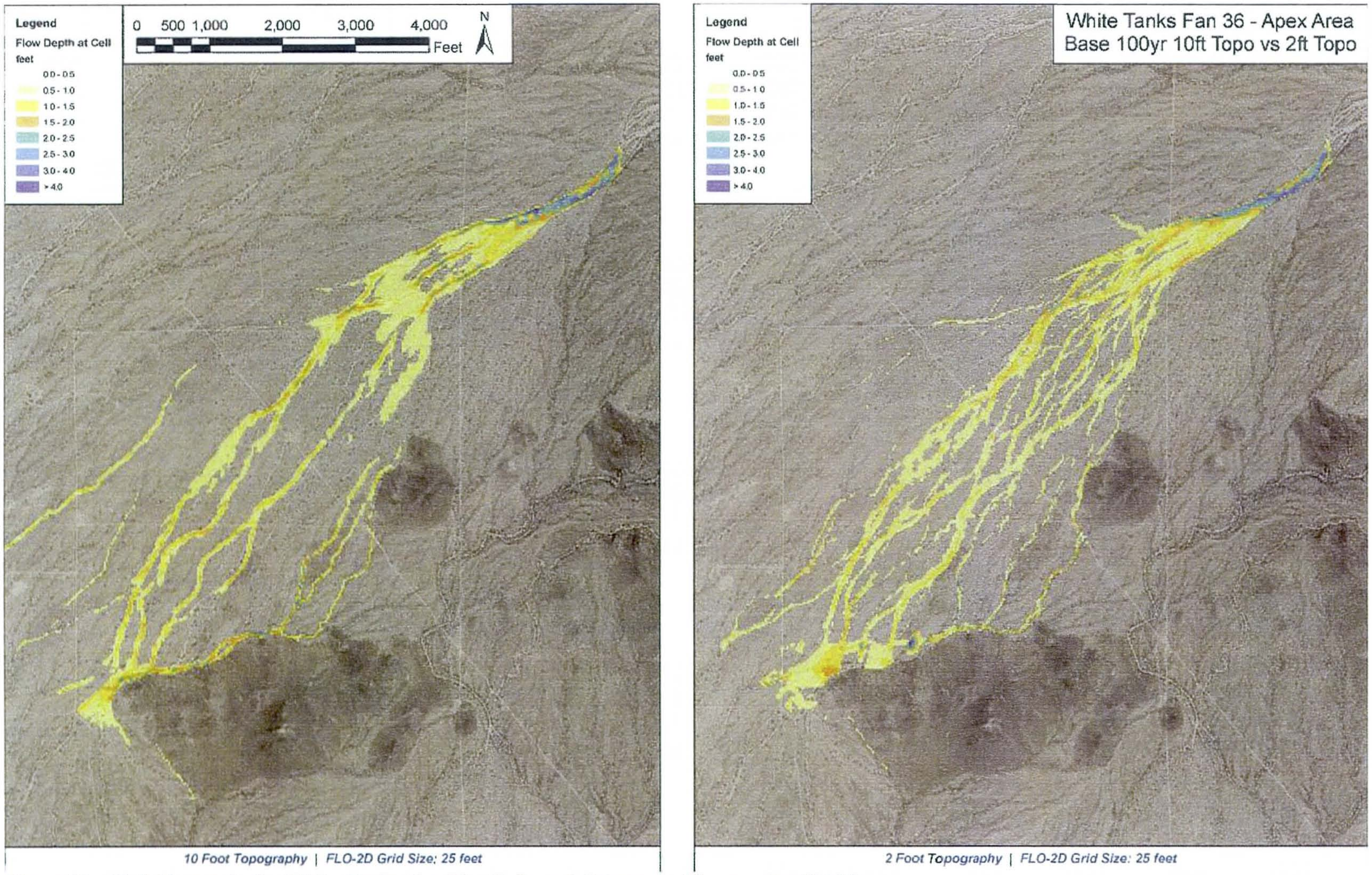


Figure 30. FLO-2D results for White Tanks Fan 36 – 10 ft. vs. 2 ft topographic mapping (Q100).

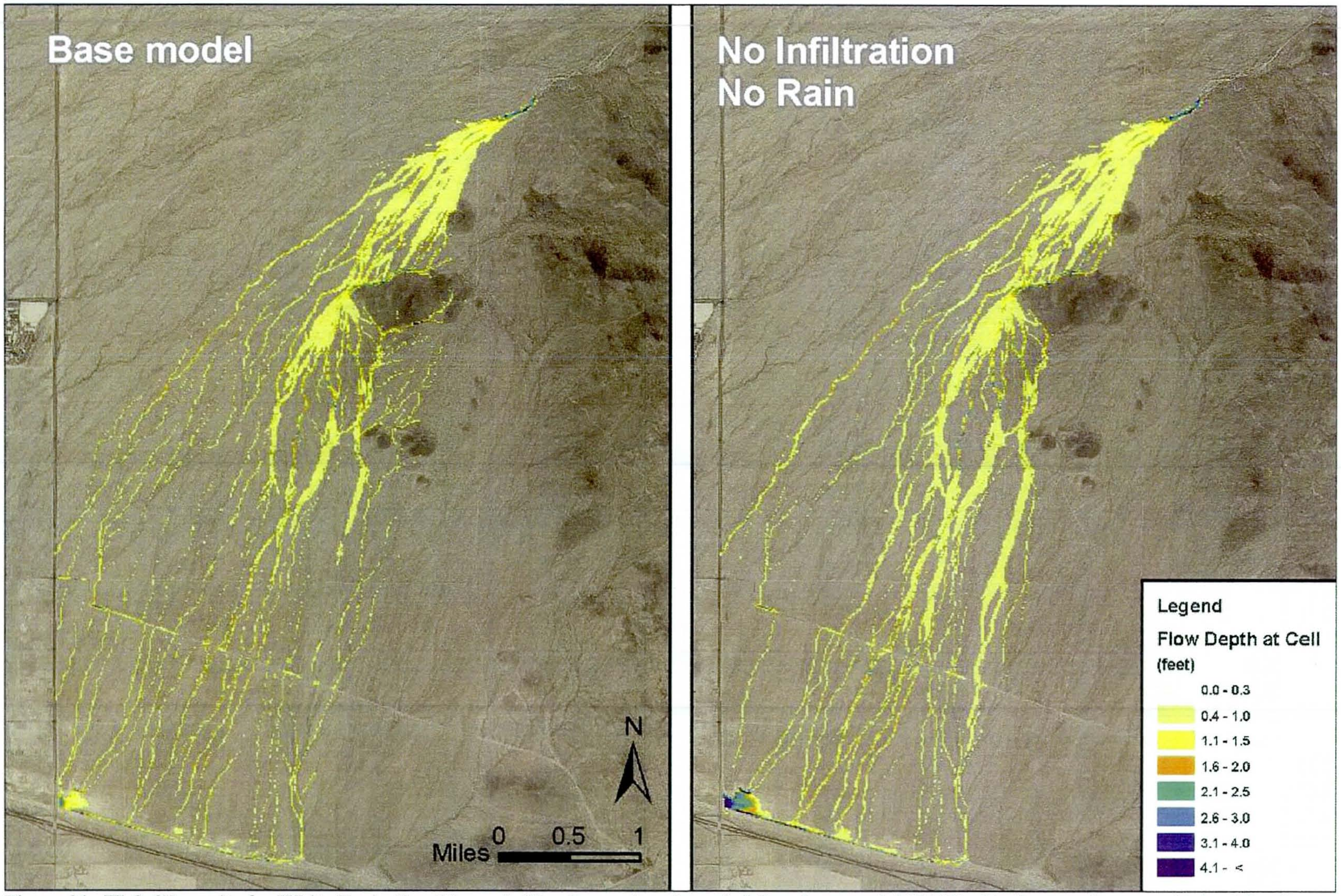


Figure 31. FLO-2D results for White Tanks Fan 36 – no infiltration and on-fan rainfall vs. base model (Q100). Similar results were obtained for the other fan evaluation sites (see Appendix F)

2.3.3.4. Encroachment Impact Models

A FLO-2D model simulating the impact of encroachment by development of the active alluvial fan was prepared for the WTF 36 (Figure 32) and RVF 12 (Figure 33) sites. To simulate the potential impact of encroachment by development on the active fan surface, the high hazard portion of the upper fan area was blocked, leaving only a conveyance channel that mimicked the width of the channel above the hydrographic apex. This approach was used to simulate the hydrologic and hydraulic impacts of protecting the developed area from flooding from upstream sources. The developed areas were allowed to generate runoff that was conveyed downstream, but no runoff from upstream sources was allowed to enter the simulated developments.

The encroachment impact models demonstrated that, as expected, loss of natural attenuation areas on the active fan surface resulted in adverse increases in peak discharge, flood depth, and flood velocity on downstream properties, as well as diversion and concentration of natural flows. Other potential adverse impacts of encroachment include changes in sediment delivery rates to areas below the encroachment, scour and headcutting along channels not adjusted to the new supply of flood water and sediment, and cutting off flow to riparian corridors formerly supplied by now-obstructed distributary channels. The alteration of the natural flow distribution may be particularly problematic since the mid- and distal-portions of the fans tend to lack any well-defined significant flow corridors.

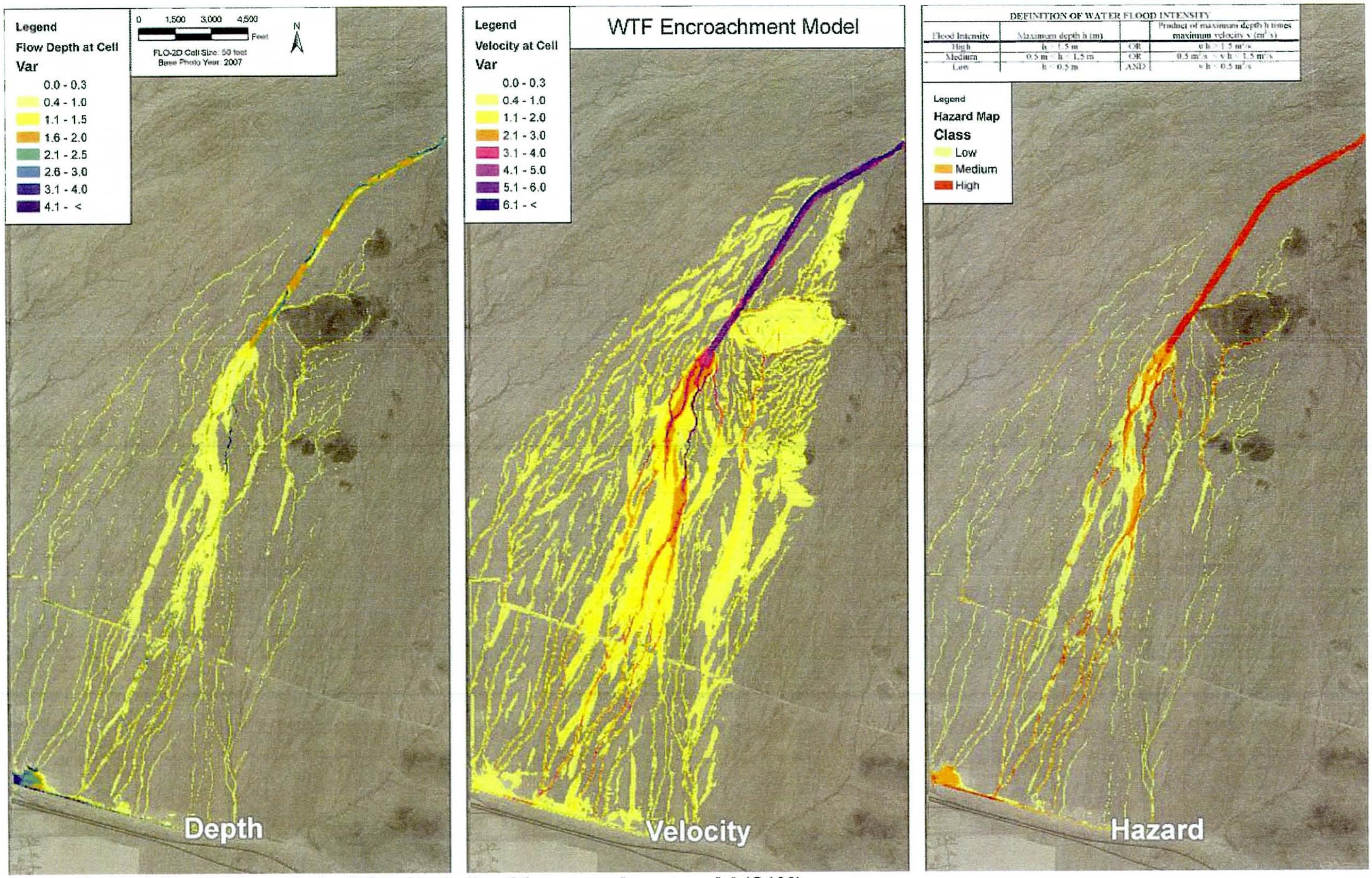


Figure 32. FLO-2D model results for White Tanks Fan 36 – encroachment model (Q100).

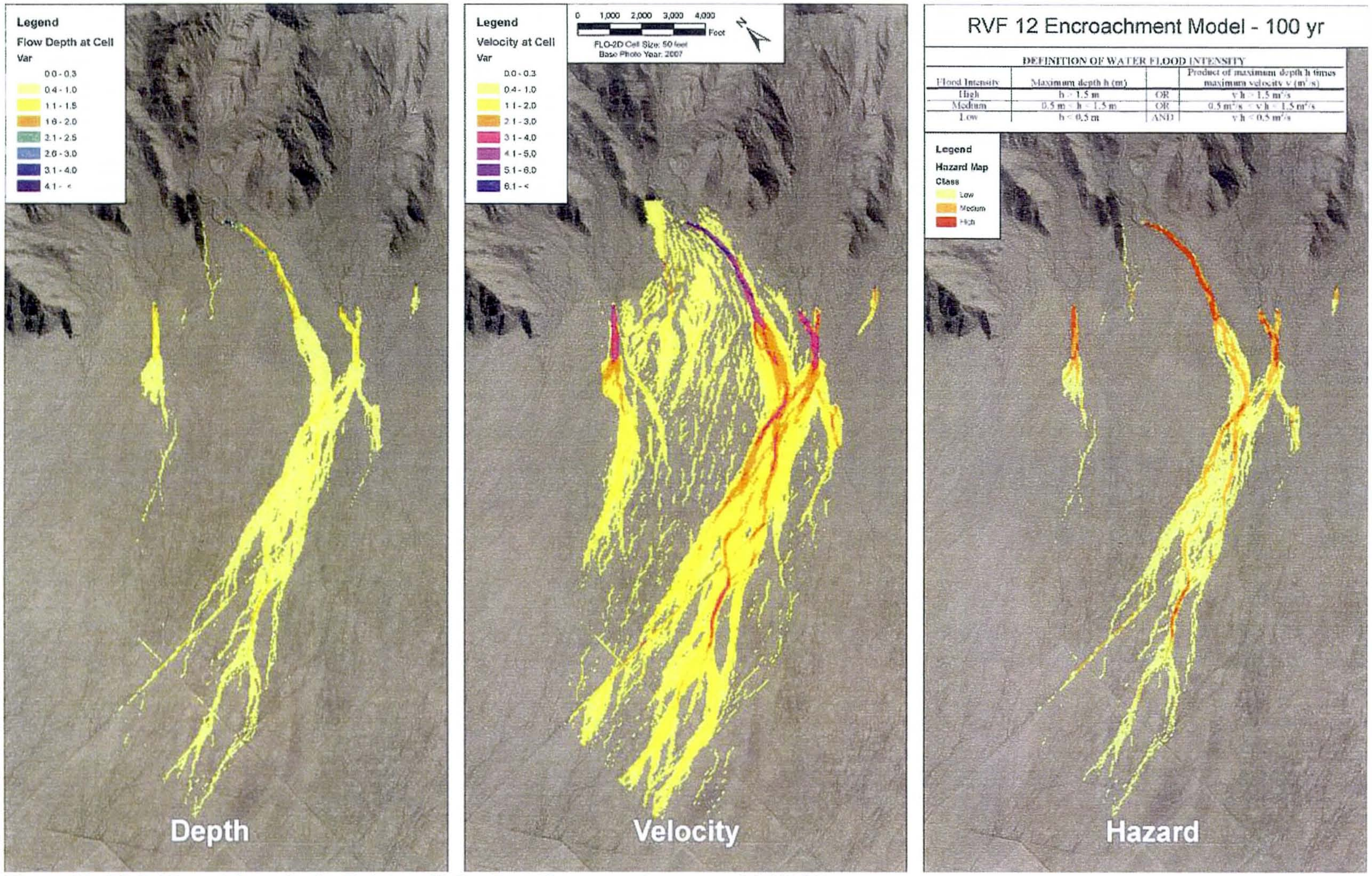


Figure 33. FLO-2D model results for Rainbow Valley Fan 12 – encroachment model (Q100)

2.3.3.5. Flood Hindcast Models

Large floods occurred at the WTF 36 site in 1951 (JEF, 2000) and on the Tiger Wash alluvial fan in 1997 (Pearthree et. al., 2004). For the WTF 36 site, there was good correlation between the FLO-2D base model inundation area relative to flood evidence visible on the 1953 aerial photographs. For the Tiger Wash alluvial fan, neither the reconstructed 1997 hydrograph (Pearthree et. al., 2004), nor the 500-year FLO-2D inundation area adequately inundated areas of known avulsions, indicating that the cause of the Tiger Wash avulsions was due to more than just simple water flooding processes. Conclusions drawn from the FLO-2D flood hindcast model results are summarized below.

White Tanks Fan 36 (Figure 34). There is good correlation between the inundation areas visible on the 1953 aerials and the FLO-2D base model results, indicating that the overall topography of the WTF 36 site has probably not changed significantly since the 1951 flood. However, there are a number of differences between the 1951 and FLO-2D base model inundation areas. First, there a several readily identified channels visible on the 1953 aerials that are not shown as flooded in either the 100- or 500-year FLO-2D results. These channels have either aggraded since they were exploited in the 1951 flood, or other parts of the fan surface have changed sufficiently to re-direct flow away from them. Second, some avulsive flow corridors along the northern margin of the active fan area near the hydrographic apex identified from the FLO-2D modeling results do not appear to have been inundated during the 1951 flood. These potential avulsion corridors picked up by the FLO-2D model either did not exist as topographic lows in 1951 or changes in ground elevations near the apex since 1951 now direct flow towards them. Third, avulsions in the distal portion of WTF 36 occurred in areas shown by FLO-2D modeling to have extremely low flow depths and velocities. Finally, it is known that the 1951 event flooded portions of the Town of Buckeye and was one of the reasons for construction of the Buckeye FRS#1. However, the FLO-2D base models indicate that relatively little flow reaches the Buckeye FRS. Therefore, either the 1951 event was larger than a 100-year event (either by peak or volume), other sources contributed to the flooding in Buckeye, and/or the FLO-2D model is over-estimating losses on the fan surface. Given the results of the multiple channel modeling, it is likely that at least part of the difference is due to over-estimated losses in the FLO-2D base models.

Tiger Wash (Figure 35 and Figure 36). The 1997 Hurricane Nora flood on Tiger Wash resulted in at least two major channel avulsions as well as inundation of significant portions of the alluvial fan surface. Because the 1997 flood reached the ponding area upstream of the Central Arizona Project (CAP) canal, the event provided an opportunity to test whether the default FLO-2D modeling parameters accurately predicted flow losses on the fan surface. As shown in Figure 35, initial FLO-2D modeling predicted much less ponding at the CAP than was observed, indicating that FLO-2D is probably over-estimating the routing losses on the fan. Note that this study firmly concludes that significant hydrograph attenuation occurs on alluvial fans (See Section 2.3.2 of this report). The rough verification exercises summarized above merely indicate that the initial base modeling procedure may require minor adjustments to decrease the predicted rates of attenuation.

To attempt to hindcast the occurrence and locations of the 1997 avulsions, FLO-2D models were also prepared using pre-1997 topographic mapping and the 1997 flood hydrograph estimated by Pearthree et. al. (2004), a 100-year inflow hydrograph, a 500-year inflow hydrograph, and a hydrograph based on PMP rainfall. As shown in Figure 36, the FLO-2D results do not clearly predict the location of the 1997 avulsions. For the estimated 1997 hydrograph, the FLO-2D results indicate that the areas where avulsions occurred were inundated by flows less than 0.3 feet deep. Even for an extreme flood discharge like the PMP event (Figure 37), the FLO-2D results did not predict highly erosive flow depths and velocities along the avulsion alignments. Unfortunately, the poor quality[14] of the only available pre-1997 topographic mapping makes it impossible to draw firm conclusions about the ability of FLO-2D to predict alluvial fan avulsions.

[14] The only available pre-1997 topography was a USGS 10 meter DEM from circa 1951.

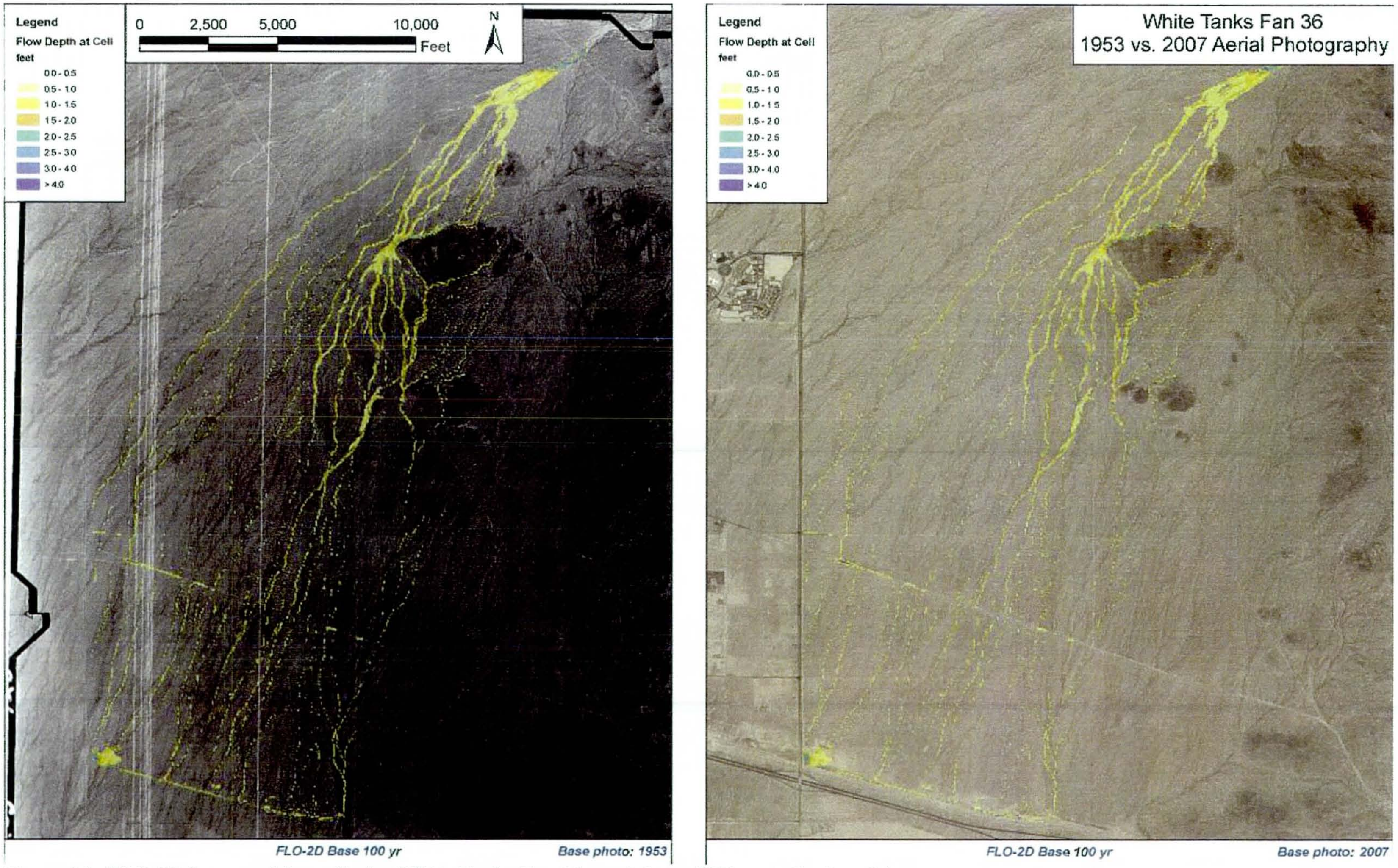


Figure 34. FLO-2D base model results for White Tanks Fan 36 overlain on 1953 post-flood aerial.

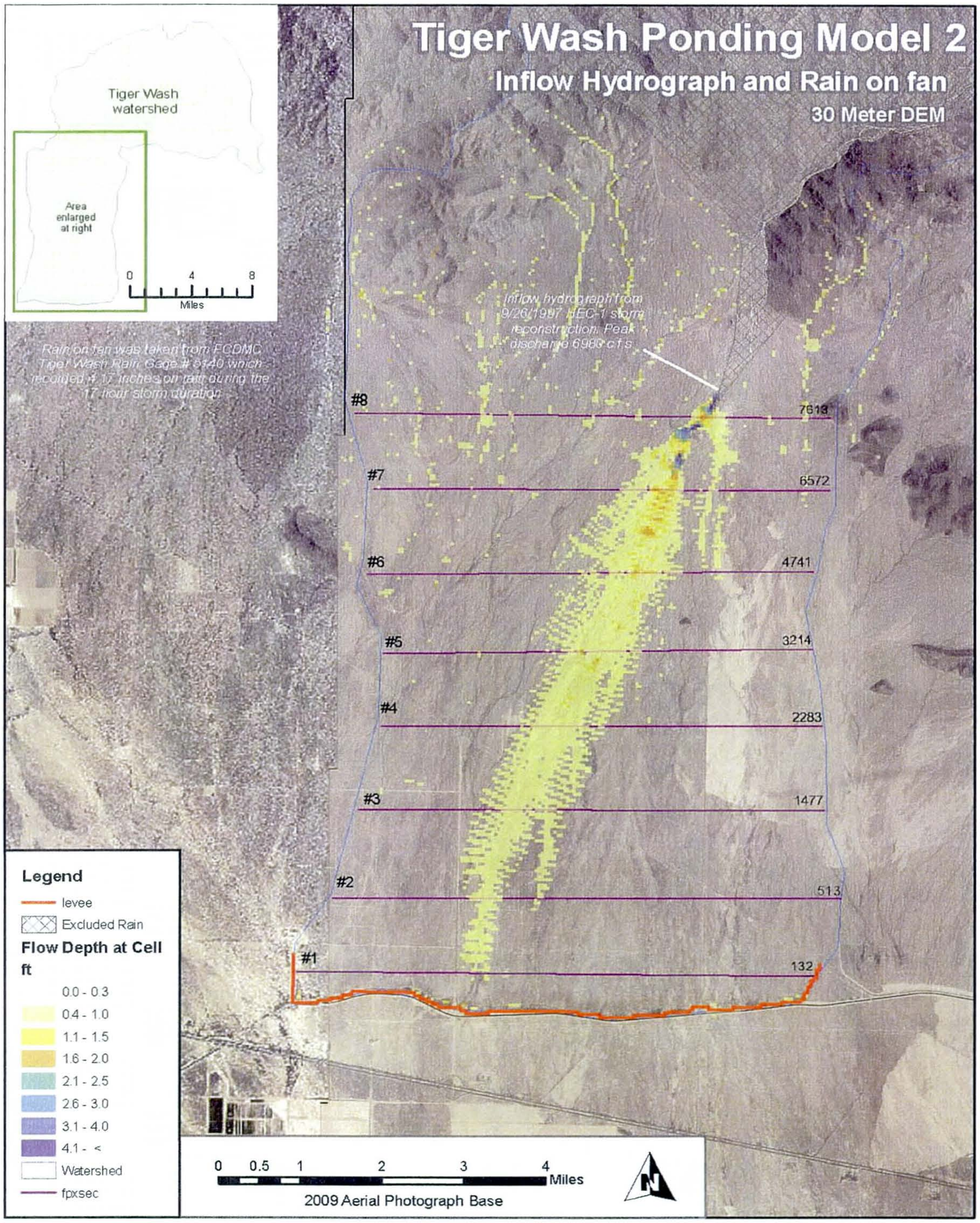


Figure 35. FLO-2D 1997 flood model of entire fan landform to CAP ponding area.

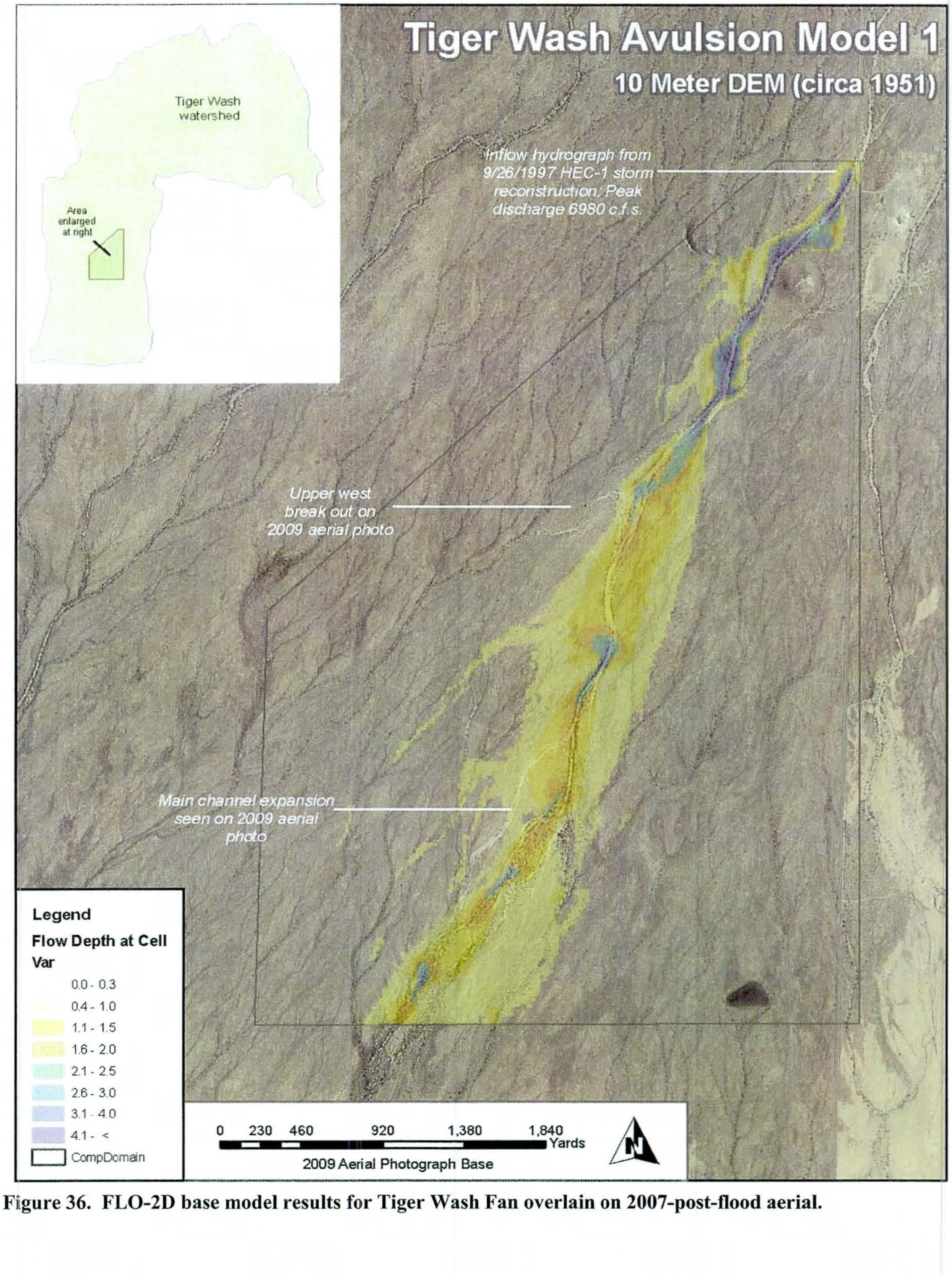


Figure 36. FLO-2D base model results for Tiger Wash Fan overlain on 2007-post-flood aerial.

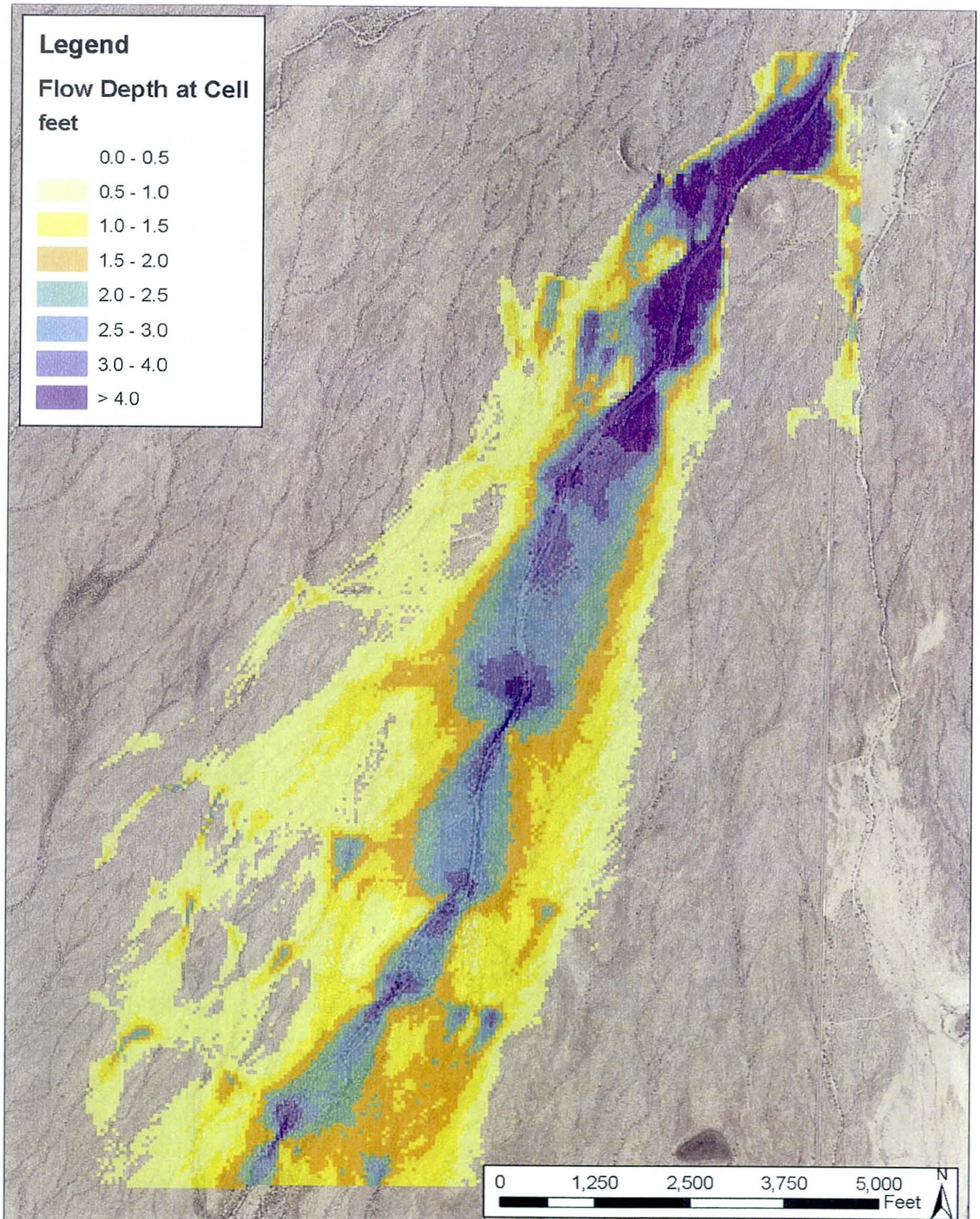


Figure 37. Tiger Wash Q500 FLO-2D modeling result

2.3.3.6. Avulsion Simulation Models

Several types of FLO-2D models were prepared to simulate the affects of channel avulsions in the active fan area. These models included runs for the WTF 36 site in which the main channel was blocked at likely sediment deposition points or channel bends to force flow into the floodplain, and use of hydraulic data from 100-year and extreme flood FLO-2D runs from all four evaluation sites to identify potential avulsive corridors (i.e., areas of high flow depths and velocity that do not correspond to existing channel locations). The results of the avulsion scenario models are described in more detail in Section 2.7 and Appendix I of this report. The following conclusions were drawn from the FLO-2D avulsion modeling results shown in Figure 38 to Figure 40:

- Channel Blockage (Figure 38). For all of the trials for the WTF 36 site, blockage of a well-defined channel forced flow out of the main channel into the floodplain. The blockages were simulated by raising the grid elevations to match the channel bank and overbank ground elevations. However, for most of the trials, FLO-2D predicted that all of flow returned to the main channel immediately downstream of the blockage. Only where the fan sloped steeply away from main channel at the blockage point (i.e., where the radial contours had a shorter arc length) did flow leave the parent channel and flow along a new alignment. However, even where flow did not immediately return to the main channel, it was quickly captured and conveyed along other existing channels on the fan surface.
- Avulsion Flow Path Tool (Figure 41). FLO-2D results were used as part of the avulsive flow path methodology (formerly called the slope-walk method) for identifying potential avulsive flow corridors. The avulsive flow path methodology uses FLO-2D velocity vectors and steepest slope paths to identify potential flow corridors outside the existing channel network on a fan surface. The tool does not specifically model the avulsion process, but instead identifies flow paths that might direct flow away from existing channel alignments if overbank flow were to occur. As currently formulated, the avulsive flow path tool differs from other drainage path identification tools in that it works in the downstream direction and utilizes FLO-2D hydraulic result vectors to identify potential flow paths. This methodology is described in more detail in Appendix I.
- Flow Corridor Identification (Figure 39). As described in Section 2.7 and Appendix I of this report, FLO-2D depth, velocity and hazard results for the 100- and 500-year floods were compared to the existing channel pattern visible on recent aerial photographs. Since FLO-2D routes flow along topographic lows, subject to momentum and energy conservation principles, areas where FLO-2D predicts significant conveyance that do not correspond to existing defined channels were hypothesized to be potential avulsive flow corridors. Examples of such potential avulsive corridors were identified at the four fan evaluation sites.
- Perched Channel Identification (Figure 40). FLO-2D results were also used to identify channels visible on recent aerial photographs for which the model predicted no inundation. These results were hypothesized to represent channels that were perched above the surrounding terrain and that were therefore candidates for avulsive abandonment.

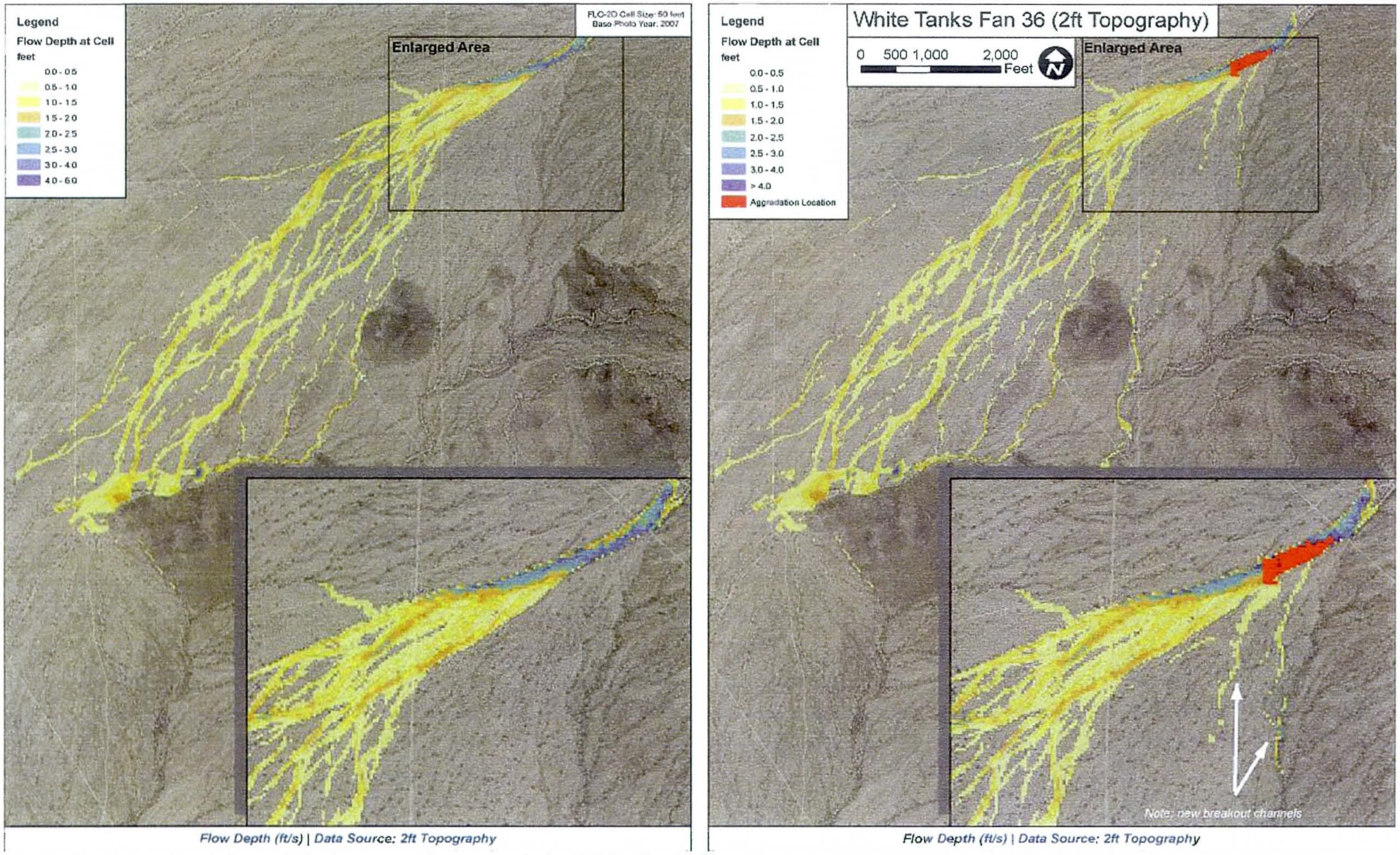


Figure 38. Example of channel blockage avulsion scenario for White Tanks Fan 36.

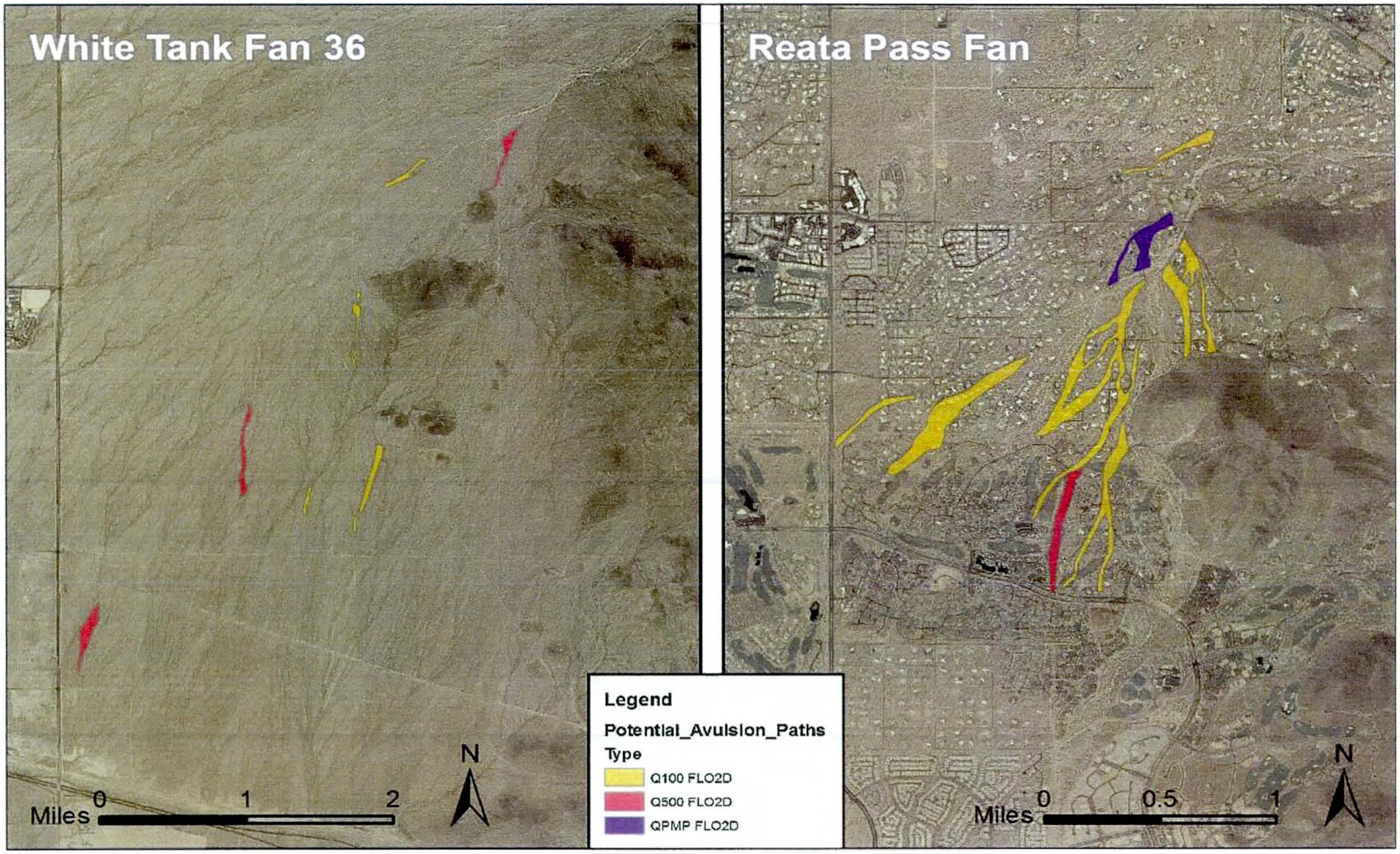


Figure 39. Example of potential avulsive flow corridor identified from a extreme flood FLO-2D model.

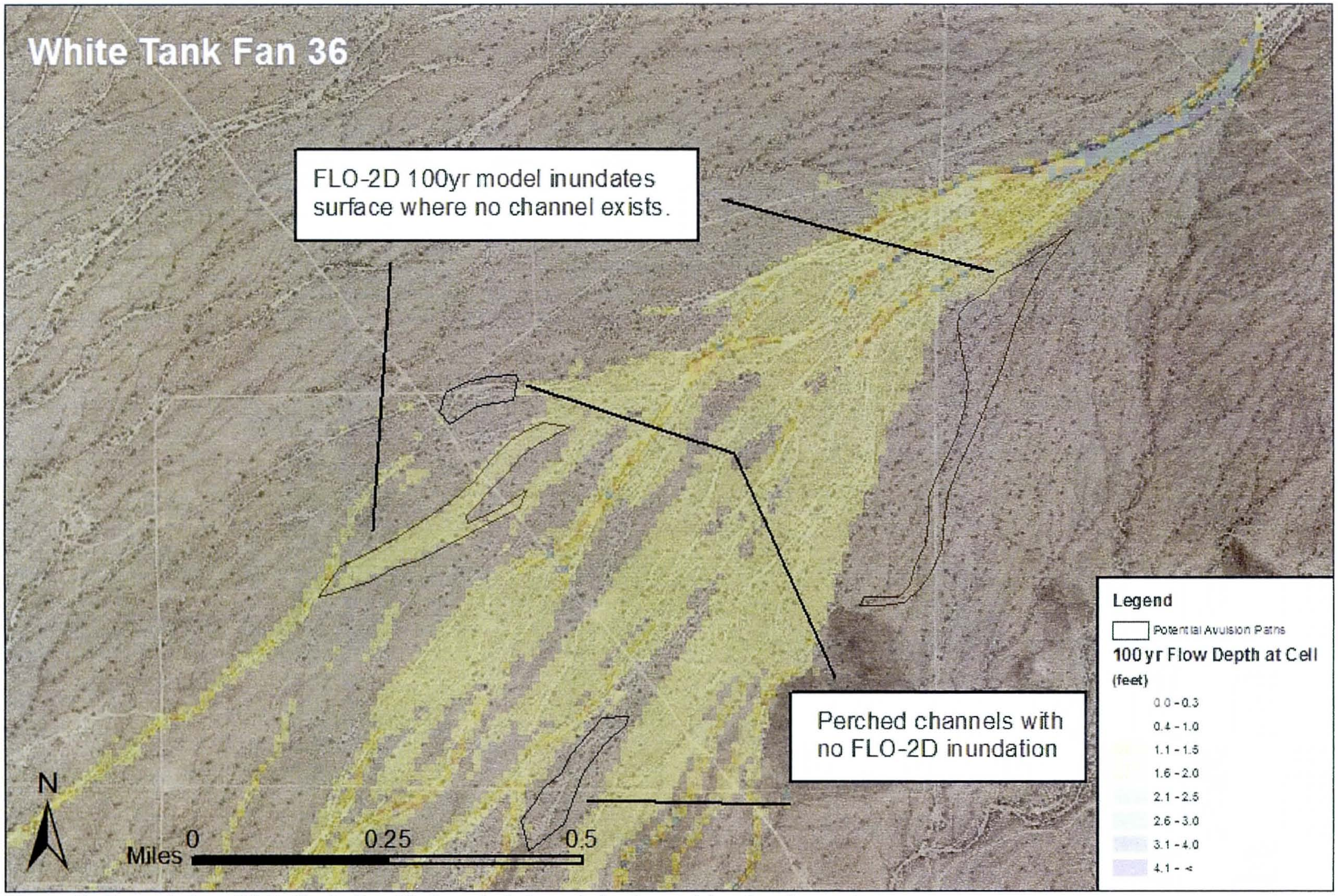


Figure 40. Example from White Tanks Fan 36 of perched channel ripe for avulsive abandonment.

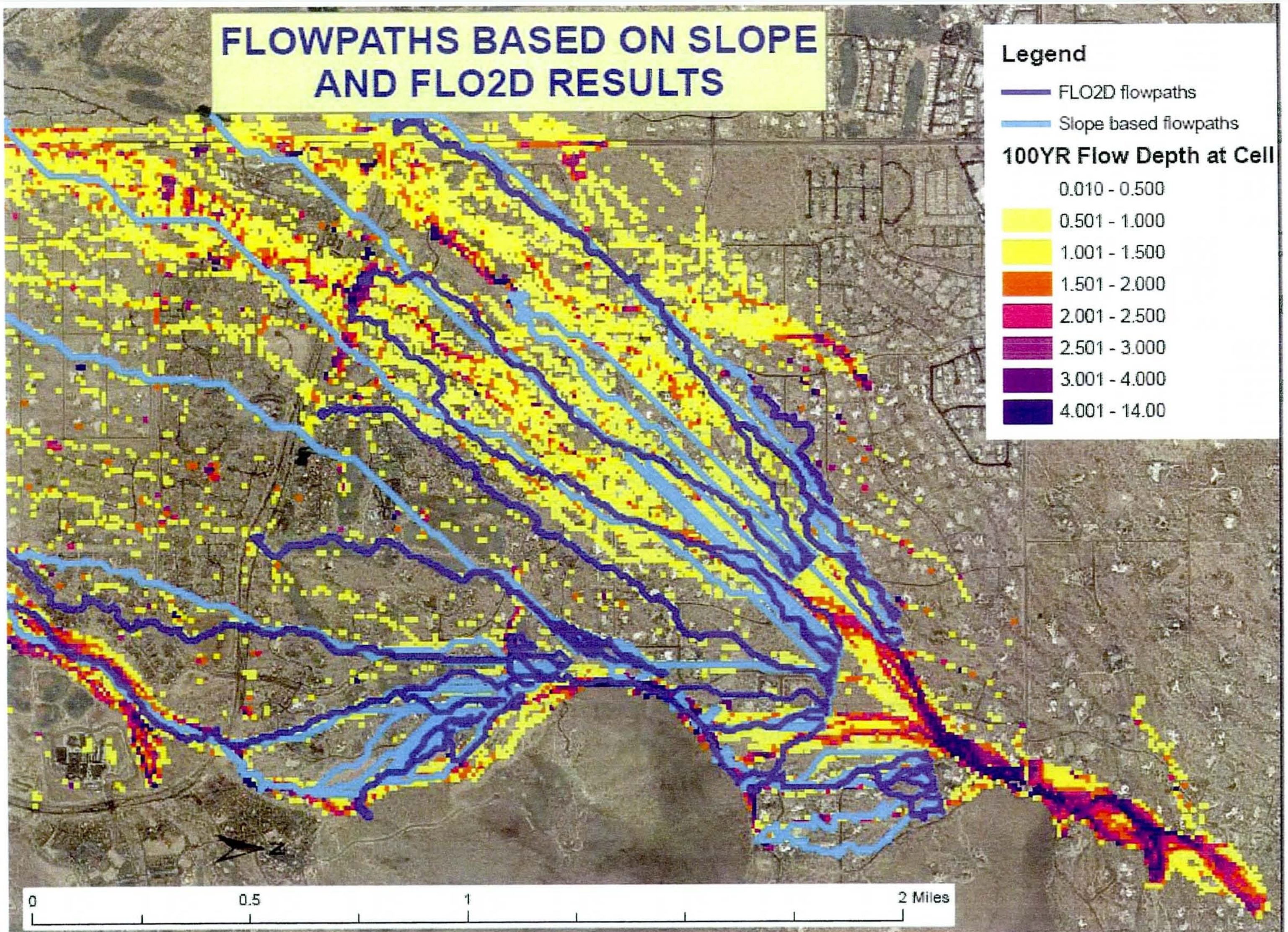


Figure 41. Avulsive flow path model flow paths for Reata Pass Fan

2.3.3.7. Virtual Levee Scenario Models

FLO-2D models applying the virtual levee methodology, as described in Section 2.7 and Appendix I of this report, were prepared to simulate the possible impacts of avulsions on flood hydrology and hydraulics on the active fan, to distinguish active and inactive parts of the alluvial fan landform, and to identify what portions of the active alluvial fan are subject to one percent chance flooding. The virtual levee scenario methodology does not attempt to model the avulsion process explicitly, but instead attempts to simulate the possible affect on downstream hydrology and hydraulics of an avulsion by forcing flow toward specific parts of the fan using "virtual" levees coded into the FLO-2D input file. The following are some of the conclusions drawn from the virtual levee scenario FLO-2D modeling results (Figure 42):

- Upper Fan Areas. For the portion of the alluvial fan in which the virtual levees are placed, FLO-2D results should be used with caution. There is some potential for flow to "pile up" along the levees, particularly where the levee alignment is more oblique than parallel to the primary flow direction. However, since the virtual levees are typically placed in the portion of the fan most likely to experience sedimentation aggradation, scour and avulsion, water-only FLO-2D depth predictions are already less reliable than on other, less hazardous portions of the fan.
- Mid-Fan Areas. The impact of the virtual levees is expressed most strongly in the mid-fan areas immediately downstream of the virtual levee footprint. Differences in flow depths and velocities between the base model and virtual levee models were greatest in this region. The maximum (worst-case) depths and velocities from all scenarios probably best represent the flood hazard in this region.
- Distal-Fan Areas. One of the more important results from the PFHAM study is that regardless of the virtual levee scenario modeled, flow in the distal portions of the fan is relatively unchanged. That is, flow returns to a shallow sheet flooding condition near the toe of the fan regardless of how it is re-routed by avulsions near the apex of the fan. This interpretation is not only supported by the FLO-2D modeling results, but also by geomorphic interpretation of channel geometry and spacing in the distal fan areas.

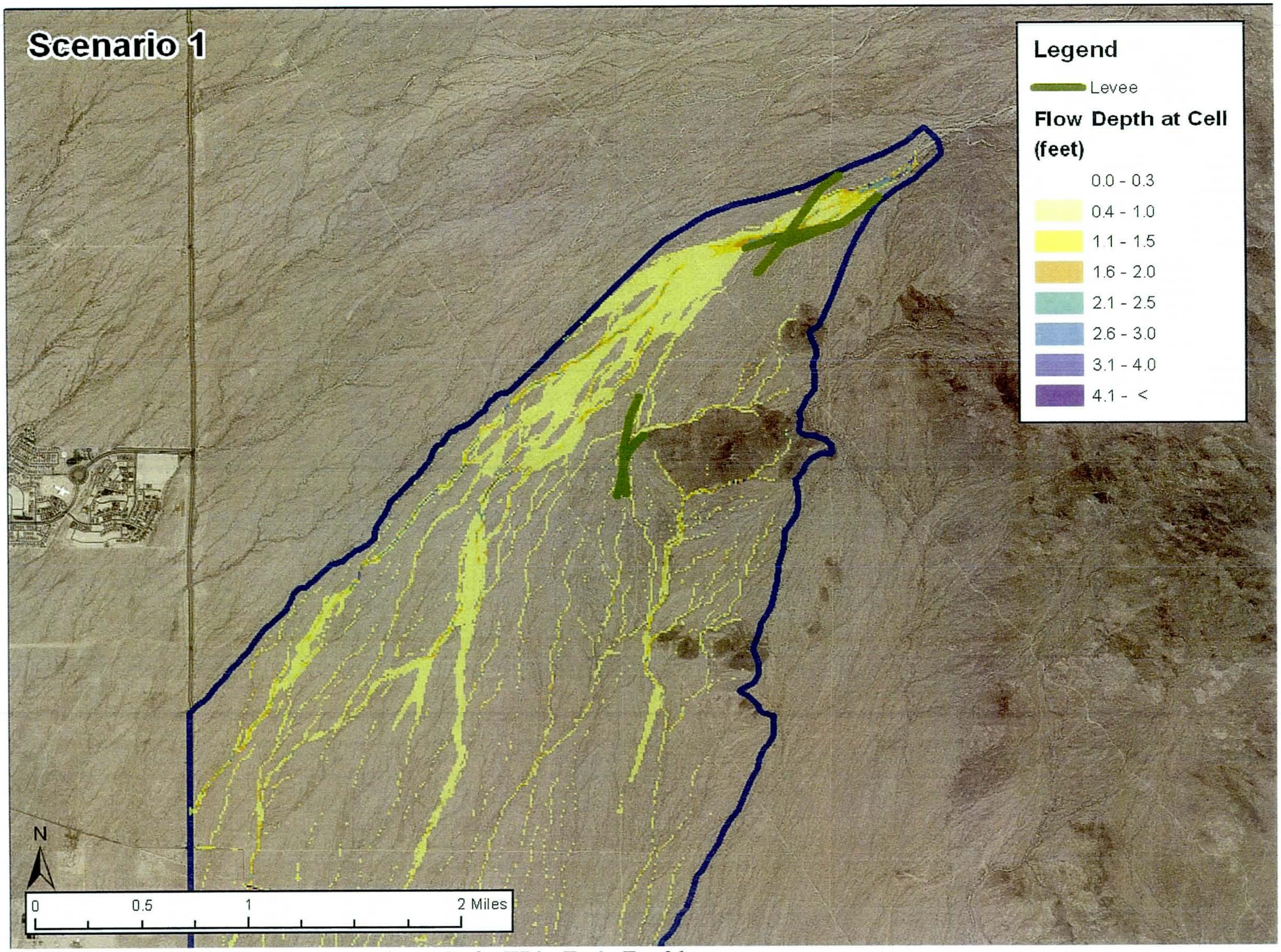


Figure 42. Example of virtual levee scenario results for White Tanks Fan 36

2.3.3.8. Sediment Transport Models

FLO-2D sediment transport models were prepared for each of the four alluvial fan evaluation sites, as described in Section 2.4 below.

2.3.3.9. Flood Hazard Zone Classification

One of the District's primary goals for the PFHAM study was to quantify the level of flood hazards on active alluvial fans. Several established hazard classification methodologies were considered and evaluated and the following were selected for application to the four alluvial fan evaluation sites:

- USBR (1988) Flood Danger Level (Figure 2, Building Foundation)
- USBR (1988) Flood Danger Level (Figure 6, Small Children)
- FLO-2D Default Method (FLO-2D, 2007; Fieberger, 1997)

It is noted that after initially selecting the flood hazard classification method described in this section, the District decided to abandon this approach in favor of relying solely on FLO-2D depths. Therefore, the methodologies described in the following paragraphs are provided for reference only, and as documentation of work products prepared in this study.

USBR Flood Danger Level Charts. The Bureau of Reclamation (USBR) ACER Technical Memorandum No. 11 includes a series of charts that are intended to depict flow hazards downstream of dams. These charts relate flow depth and velocity to hazards to buildings on foundations, mobile homes, motor vehicles, adult pedestrians, and children. The two end members of these categories of flood hazards were quantified for the four alluvial fan test sites for the PFHAM study – hazards to buildings on foundations (USBR, 1988 - Figure 2) and hazards to children (USBR, 1988 - Figure 6). The USBR charts subdivide flood hazards into "high" and "low" categories, with an intermediate "judgment" zone between them, as shown in Figure 43 and Figure 44.

The boundaries of the USBR hazard zones on the Tech Memo No. 11 figures were approximated using a polynomial function, and the resulting equations were applied to the FLO-2D output for each grid cell in the 100-year base model results for each alluvial fan evaluation site. The corresponding hazard zones were then determined for each cell from the function results (e.g. above or below the lines), and were plotted using ArcGIS. The results for each site are shown in Figure 45 to Figure 48.

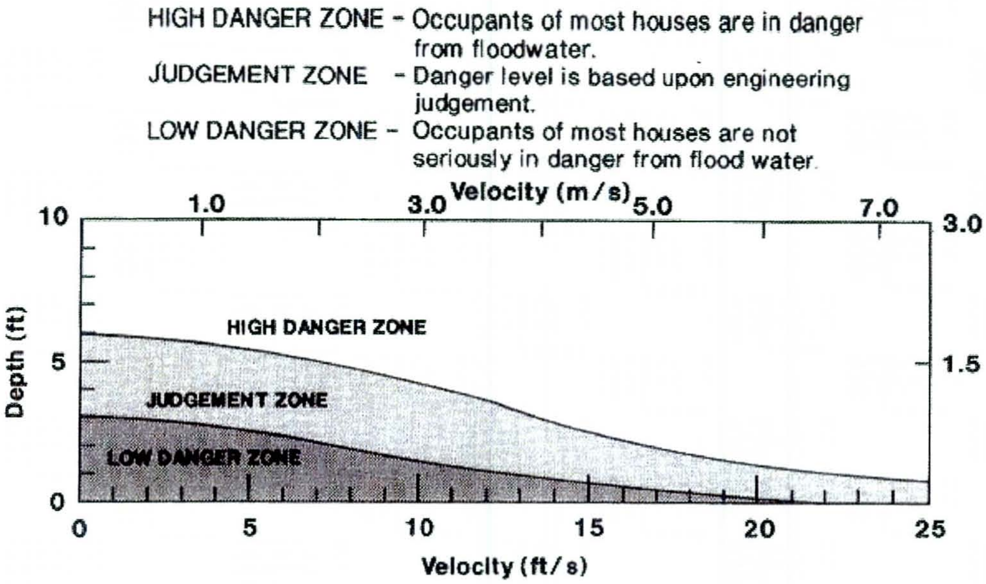


Figure 2. – Depth–velocity flood danger level relationship for houses built on foundations.

Figure 43. USBR ACER Tech Memo No. 11 Figure 2

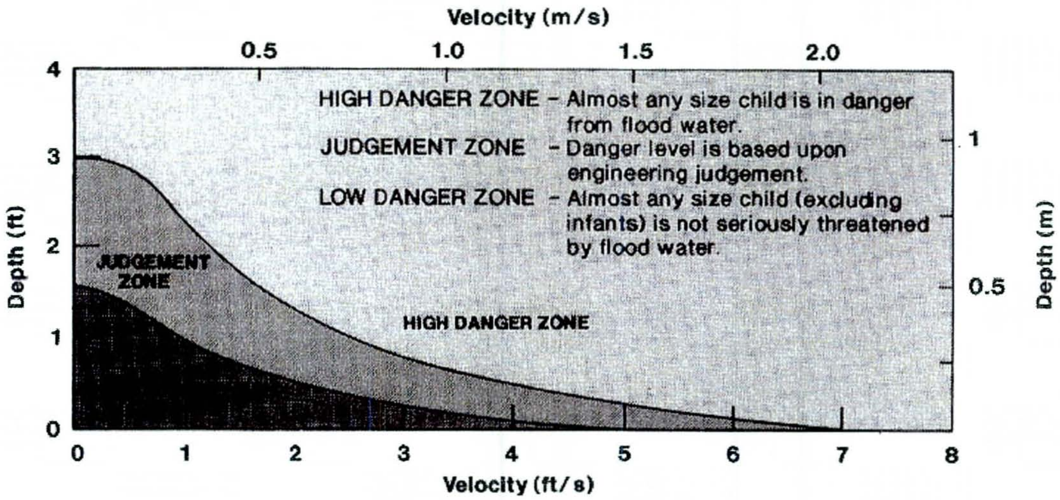
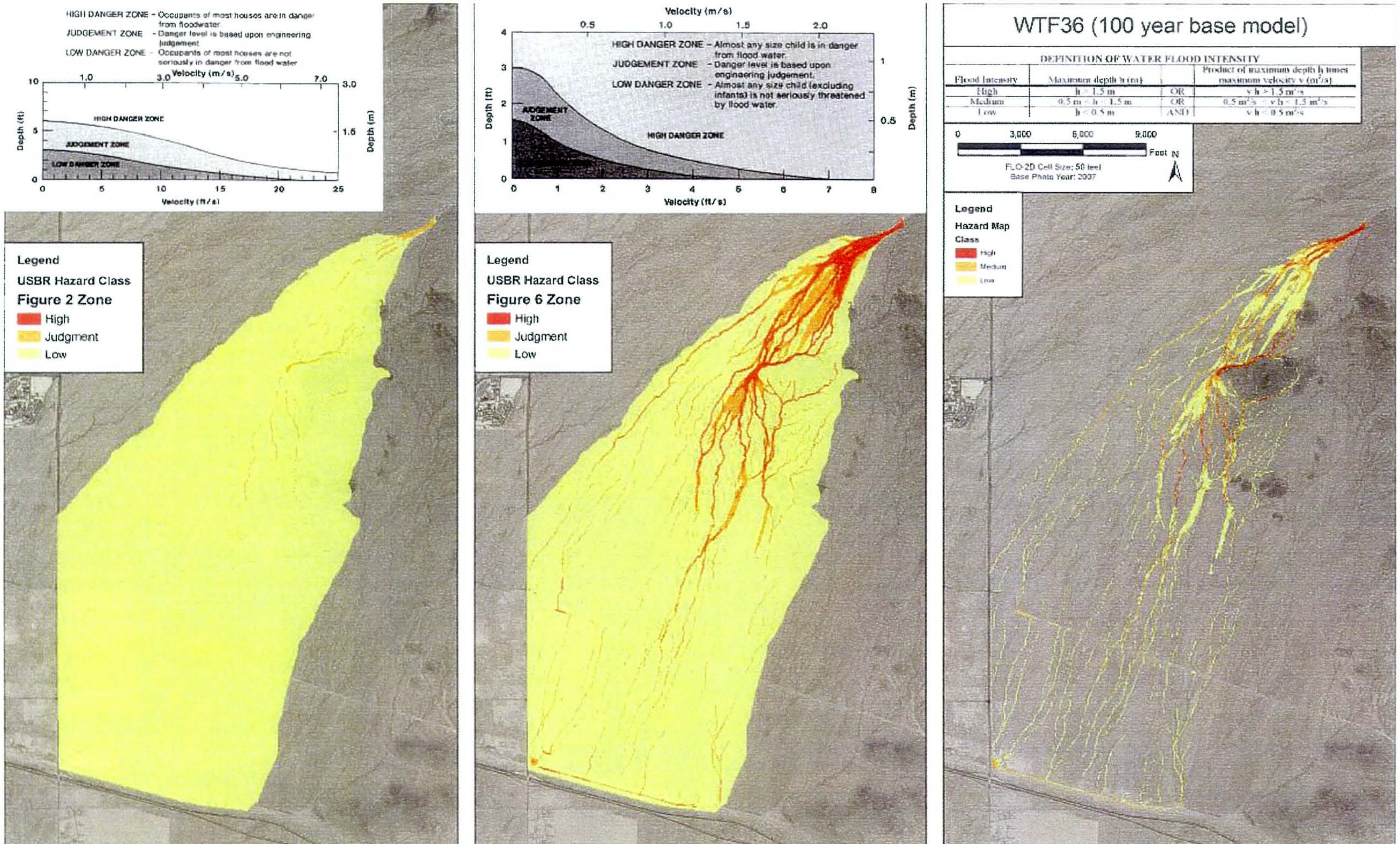


Figure 6. – Depth–velocity flood danger level relationship for children.

Figure 44. USBR ACER Tech Memo No. 11 Figure 6.



USBR ACER Tech Memo 11 - Figure 2 Hazard (buildings) | *USBR ACER Tech Memo 11 - Figure 6 Hazard (children)* | *FLO-2D Hazard (100 year base model)*

Figure 45. USBR Figure 2 (Buildings on Foundations) and Figure 6 (Small Children) hazard zones, with FLO-2D Hazard Map results for White Tanks Fan 36 FLO-2D base model.

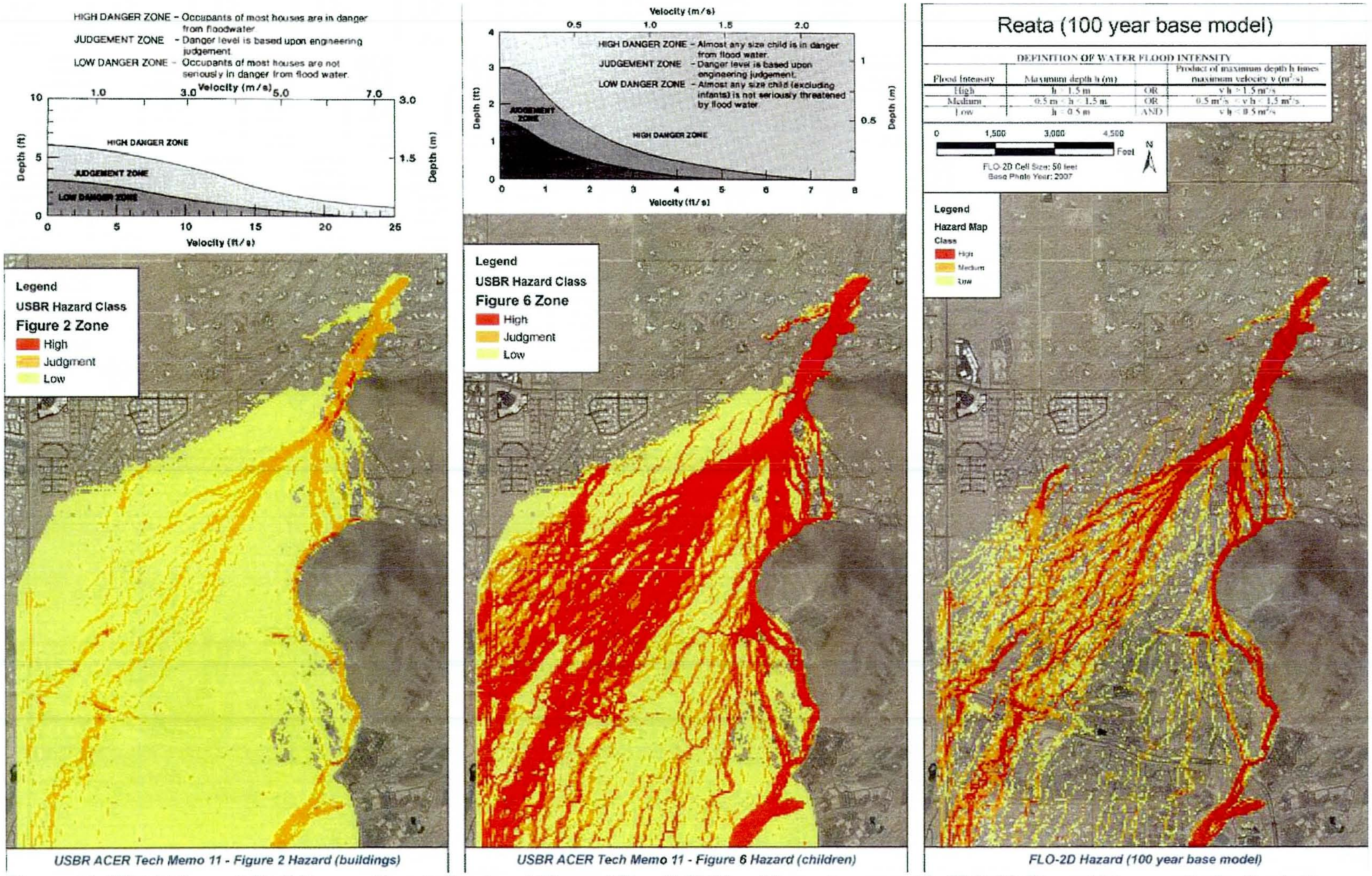


Figure 46. USBR Figure 2 (Buildings on Foundations) and Figure 6 (Small Children) hazard zones, with FLO-2D Hazard Map results for Reata Pass Fan FLO-2D base model.

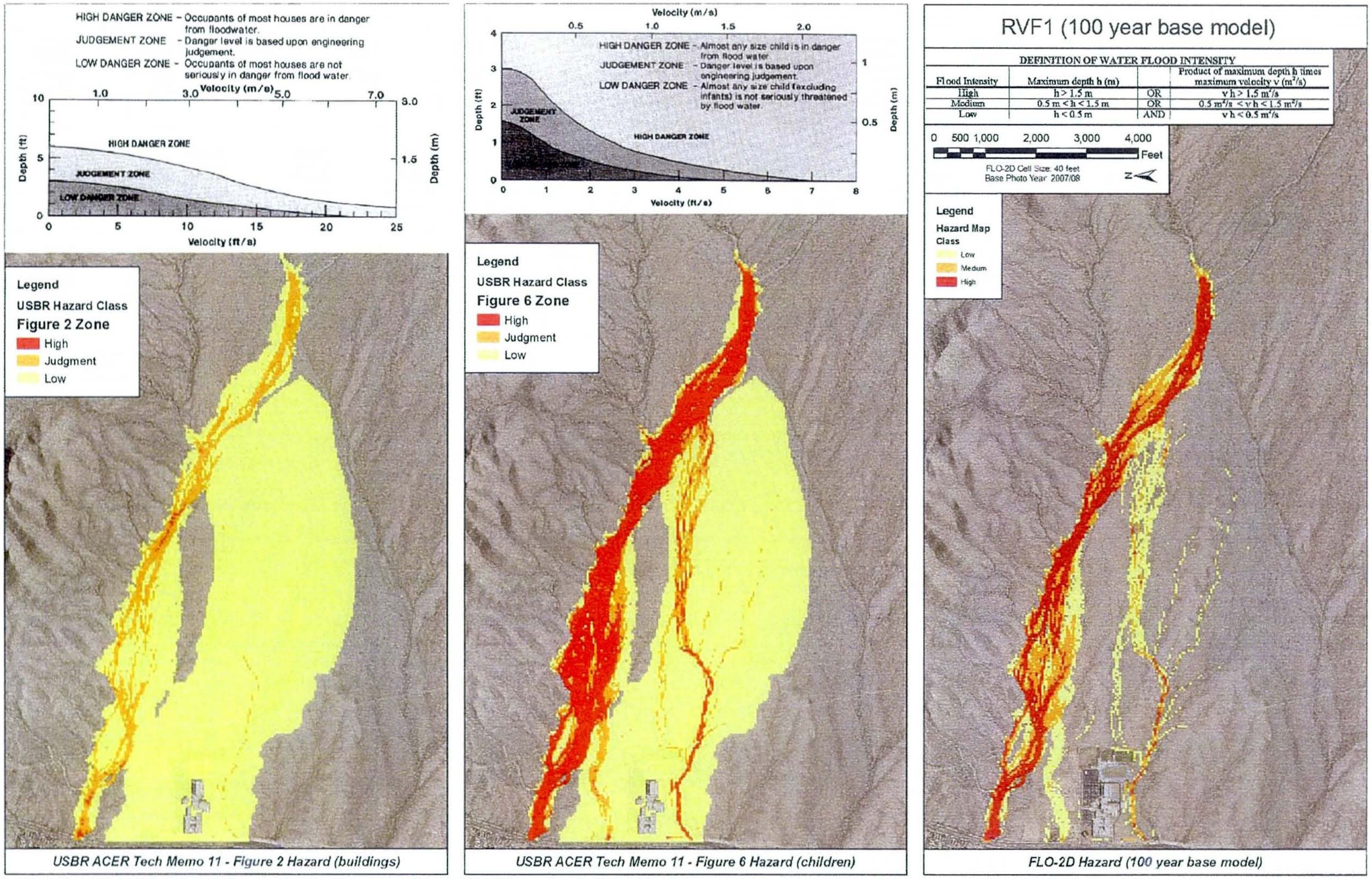


Figure 47. USBR Figure 2 (Buildings on Foundations) and Figure 6 (Small Children) hazard zones, with FLO-2D Hazard Map results for Rainbow Valley Fan 1 FLO-2D base model.

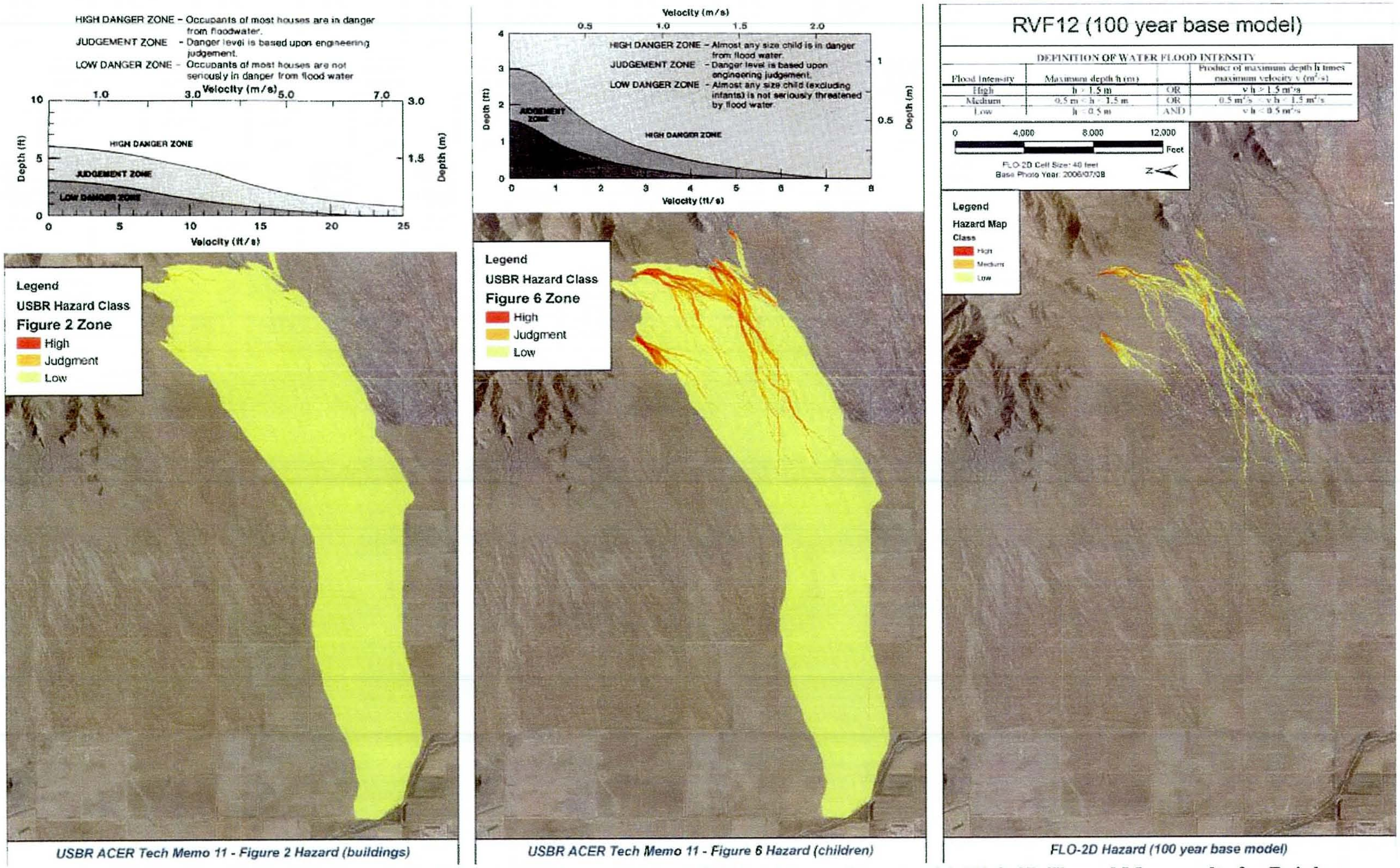


Figure 48. USBR Figure 2 (Buildings on Foundations) and Figure 6 (Small Children) hazard zones, with FLO-2D Hazard Map results for Rainbow Valley Fan 12 FLO-2D base model

FLO-2D Mapper Hazard Classification. The "Hazard Map" classifications as presented in the FLO-2D Mapper program (FLO-2D, 2007) were computed for the 100-year base models. The FLO-2D hazard classifications are based on work by Fieberger (1997) and have been used by a variety of regulatory agencies worldwide. In addition, a composite or combination hazard classification was also computed by combining the 10-, 100-, and 500-year FLO-2D base model results using the frequency-weighting procedure illustrated in Figure 49 and described in Table 9 and Table 10, as well as in the FLO-2D user's manual. The results of the FLO-2D methodology for each fan site were shown in Figure 45 to Figure 48.

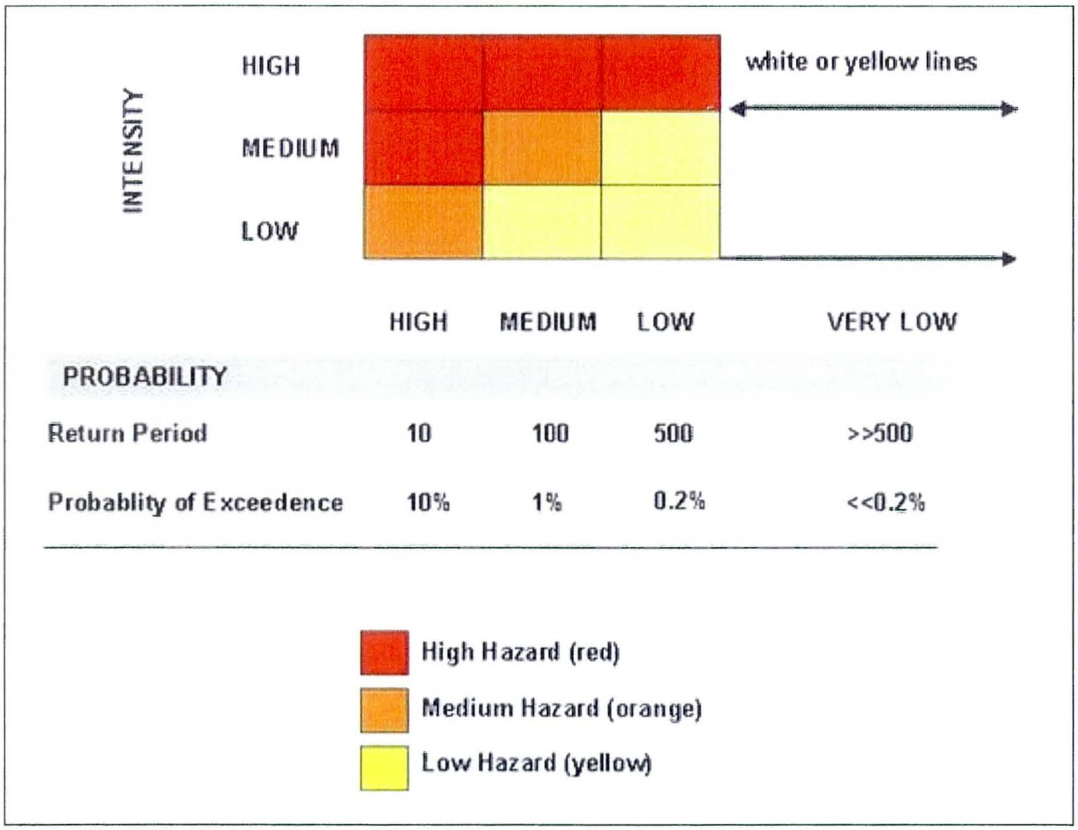


Figure 49. FLO-2D frequency-weighted hazard classification system

Table 9. FLO-2D Hazard Classification descriptions

Flood Hazard Definition		
Hazard Level	Map color	Description
High	Red	Persons are in danger both inside and outside their houses. Structures are in danger of being destroyed.
Medium	Orange	Persons are in danger outside their houses. Buildings may suffer damage and possible destruction depending on construction characteristics.
Low	Yellow	Danger to persons is low or non-existent. Buildings may suffer little damages, but flooding or sedimentation may affect structure interiors.

Table 10. FLO-2D Hazard Classification computational basis

Definition of Water Flood Intensity			
Flood Intensity	Maximum depth h (m)		Product of maximum depth h times maximum velocity v (m^2/s)
High	h > 1.5 m	OR	v h > 1.5 m^2/s
Medium	0.5 m < h < 1.5 m	OR	0.5 m^2/s < v h < 1.5 m^2/s
Low	0.1 m < h < 0.5 m	AND	0.1 m^2/s < v h < 0.5 m^2/s

Conclusions. As expected, the USBR Figure 6 hazard classification (Figure 44) produces the largest extent of hazards on all four example fan sites, because it has the lowest thresholds for the hazard classifications of the three methods considered. The USBR Figure 6 hazard threshold was determined to be the most appropriate for application in Maricopa County for several reasons. First, engineering judgment and field observations indicate that such flow depths and velocities are were sufficient to transport the fine- to medium-grained sediment (i.e., erosion) found on most active alluvial fans in Maricopa County. Second, the USBR Figure 2 was determined to be too high a threshold since significant property damage could occur long before flows exceeded the threshold to damage a building with a solid foundation. Third, District staff strongly recommended use of hazard classification methodology that had been developed by the federal government, in order to provide more credibility. However, District staff also preferred the frequency-weighted approach used by the FLO-2D Mapper. Therefore, the District PFHAM team decided to use the FLO-2D frequency-weighting procedure (Q10-Q100-Q500), but use USBR Figure 6 thresholds to categorize the low-judgment-high hazard classifications. District staff will work with FLO-2D Software, Inc. under a separate contract to modify the FLO-2D code to include the USBR curves as an alternative to the default methodology. Finally, as a result of the recommendations of the PFHAM Blue Ribbon Panel (Section 4.7, Appendix J), the USBR Figure 2 (Buildings) hazard classification will also be used in the recommended integrated methodology, as part of the method for identifying the "ultrahazardous" portion of an alluvial fan.

Subsequent to preparation of the draft report, the District elected to not use the USBR-based hazard classification in favor of direct use of flow depths from the FLO-2D modeling tasks.

2.3.4. Normal Depth Modeling

The PFHAM study found that normal depth modeling, e.g. HEC-RAS is not an appropriate method for hydraulic evaluation of flood hazards within active alluvial fan floodplains, except in certain specific situations, such as local site analyses, as described later in this report (Sections 3.3.2 and 4.4). Normal depth modeling has the following deficiencies when applied on active alluvial fan floodplains:

- Horizontal water surface elevation. A normal depth rating assumes that the water surface within a cross section is horizontal, and that all flows within the cross section are hydraulically connected. Post-flood observations reveal that flows on an active fan surface often have multiple disconnected flow paths across a given contour, each with its own water surface elevation and hydraulic characteristics.

- Cross section alignment. Active alluvial fans typically have a radial contour pattern with perched and/or abandoned flow paths and floodplains. It would be very difficult to correctly align a cross section to accurately reflect the flow distribution across an active fan surface. Failure to correctly align the cross section would inaccurately distribute flow into the lowest part of the section.
- Topographic containment. Active alluvial fans typically have relatively planar surfaces, resulting in inadequate topographic containment at the margins of any given cross section.
- One-dimensional flow. Field observations and FLO-2D modeling prepared for this study indicates that alluvial fan flooding has a strong two-dimensional component. A normal depth rating assumes flow is one dimensional.
- Continuity. Flow reaching any given part of a cross section of an active alluvial fan is highly dependent on the distribution of flow between upstream distributary channels and sheet flooding areas. A normal depth rating does not take into account the distribution of flow in upstream areas.
- Fixed-bed model. A key characteristic of active alluvial fan floodplains is changing topography due to scour, erosion and sediment deposition. Normal depth models typically do not consider mobile-bed or bank hydraulics.
- Flow path uncertainty. A normal depth rating is not capable of evaluating the potential affect of channel avulsions or flow distribution changes on the fan surface, and thus is not appropriate for a whole-fan analysis.

Despite the deficiencies listed above, a normal depth hydraulic analysis may be appropriate for a single site if the following conditions exist:

- Design discharge. A design discharge must be provided by the methods recommended in this report. The discharge used should correctly reflect any uncertainty in the flow rate reaching the site where the normal depth rating is to be applied.
- Site-specific analysis. A normal depth rating may be appropriate where it is used to generate hydraulic data for a specific localized channel reach. A normal depth analysis is not appropriate for fan-wide evaluations.
- Detailed topography. A normal depth rating may provide more accurate hydraulic data if more detailed topographic data are available for a specific site or channel reach on an alluvial fan than was used in a whole fan model, such as FLO-2D.
- Apex channel. A normal depth rating is appropriate for estimating the capacity of a defined channel at or above the hydrographic apex.

2.3.5. Fan Site Evaluation Conclusions

The following conclusions are supported by the hydrologic and hydraulic modeling performed for the four alluvial fan evaluation sites:

- Two-Dimensional Modeling. Two-dimensional modeling is the preferred method for evaluating the hydrology and hydraulics of alluvial fans. For the PFHAM study, the FLO-2D model was selected as the best available model, a finding which is consistent with the findings of other agencies (USACE, 2000). However, any two-dimensional model that has the same capabilities as FLO-2D would be acceptable for the purposes of floodplain delineation and flood hazard identification.

- Flow Attenuation. Attenuation of the hydrograph peak is an important process on active alluvial fans in Maricopa County. Therefore, use of the full apex discharge at any point other than the hydrographic apex is unnecessarily conservative and is not supported by the scientific analyses conducted as part of the PFHAM study. In many cases, the degree of flow attenuation is such that many small floods are completely stored on the fan surface, never reaching the toe, and resulting in deposition of the entire sediment load on the fan. The following are also noted with respect to flow attenuation:
    - Antecedent moisture condition. With increased antecedent moisture, the degree of rainfall losses and re-infiltration is likely to decrease compared to a dry antecedent condition. However, given the very high degree of flow attenuation computed for the "no-infiltration" sensitivity models, antecedent moisture condition is not likely to be a significant factor relative to the volume of flow storage provided on the fan surface. Also, if the FLO-2D results are compared HEC-1 results, the conclusion that flow attenuation is an important process on active alluvial fans is still supported. The District intends to provide specific guidance on the recommended antecedent moisture condition.
    - Storm sequence. Sequencing of back-to-back storms produces the same conditions as discussed above for antecedent moisture.
    - On-fan precipitation. The occurrence of on-fan precipitation was included in the FLO-2D simulations and did not affect the conclusion that significant flow attenuation occurs on active alluvial fan surfaces, although it is intuitively obvious that more attenuation is likely if no on-fan precipitation occurs.
    - Local (non-apex) inflow sources. The occurrence of local inflows to the fan surface was included in several of the FLO-2D simulations and did not significantly affect the degree of flow attenuation predicted.
- Sheet Flooding. Large portions of active alluvial fans in Maricopa County are affected only by shallow sheet flooding with minimal flow depths, flow velocities, and aggradation rates. The majority of the land area on the active alluvial fans specifically evaluated for this study is dominated by shallow sheet flooding. The extent of sheet flooding is both a cause and result of significant flow attenuation that occurs on active alluvial fans.
- 100-Year Inundation. Not all of the active portions of the alluvial fan sites will be inundated by the 100-year flood in a single event.
- Flood Hazard Zone Classification. Flood hazard zones on alluvial fans in Maricopa County can be classified using a frequency-weighted technique based on USBR (1988) hazard classification charts and FLO-2D hydraulic data.
- High Hazard Zones. On active alluvial fans in Maricopa County, high hazard zones are limited in extent and are generally limited to the region immediately downstream of the hydrographic apex. The extent of the high hazard zones is a function of fan slope, drainage area, and discharge.

- Modeling Results. FLO-2D depth and velocity output represent average values for the grid size used in the model. Therefore, some interpretation of results is necessary to determine design data for specific sites that may not be well represented by the grid elevations. In these cases, site specific step-backwater modeling is recommended to obtain structure design data.
- Modeling Guidelines. The accuracy of topographic data may affect the modeling results. Use of the best available topographic mapping is recommended. In some cases, the county-wide 10-foot mapping may not produce sufficiently accurate results. In addition, the FLO-2D grid size used also affects the model output. The use of the finest grid size feasible with respect to model run time and topographic data is recommended.
- FLO-2D Grid Size. The modeler should chose a grid size that reflects required model precision, model run time, topographic data precision, and unique site characteristics. For this study, 40- to 50-foot grids achieved adequate results.

2.4. Sedimentation Evaluation

The objectives of the PFHAM study sedimentation analysis were to quantify how sediment delivery, transport and deposition across an active alluvial fan surface can be quantified, and how sediment processes influence flood hazards on alluvial fan landforms in Maricopa County. The sedimentation evaluation consisted of the following two elements: (1) sediment yield, and (2), sediment transport modeling.

2.4.1. Sediment Yield Analysis

Sediment yield to the hydrographic apex of each of the four alluvial fan evaluation sites was computed using the District's sediment yield methodology described in Chapter 11 of draft *Drainage Design Manual for Maricopa County: Hydraulics*. Calibration, verification, or evaluation of District's sediment yield methodology was not included in the scope of services for this study, and the methodology was applied per the District guidelines. The computed sediment yields for the four evaluation sites are shown in Table 11. To relate the computed sediment yields to potential fan aggradation, Table 11 also lists an estimate of the active alluvial fan area and the resulting deposition during a 100-year design flood as well over a 100 year time period. The active fan acreage is a rough estimate based on visual inspection of an aerial photograph and the default FLO-2D hazard zones (high and moderate). It is unlikely that all of the sediment yield would be deposited in the high hazard zone, nor is it likely that deposition would be uniform over the entire active area. Furthermore, at least some of the deposited material would be transported or removed during subsequent floods. Nevertheless, the rough prediction indicates that the estimated sediment yield to the fan apex is probably insignificant for the 100-year flood, but may be of consequence over longer planning periods on some parts of an active alluvial fan.

The District's sediment yield methodology estimates the sediment load delivered from the upper-watershed to the alluvial fan apex. The load delivered to the fan apex is transported across or deposited on the alluvial fan surface. The rate of deposition is a function of the transport capacity, as expressed by hydraulic data and site conditions. Sediment delivered to unchannelized floodplains may deposit on the fan surface if runoff is stored or infiltrates into the soil. If it is assumed that sediment transport occurs primarily in the channels and high depth-velocity overbank areas, and that sediment deposition primarily occurs in shallow, overbank areas, an estimate of fan deposition can be made by combining the sediment yield estimates with FLO-2D hydraulic data, as described in Appendix F of this report. Using this approach, sediment deposition was estimated for the 2-, 10-, 50- and 100-year events by using FLO-2D results. The estimated sediment deposition volumes were then probability-weighted by recurrence interval to estimate the average annual sediment deposition. The results indicated that average annual sediment deposition would be less than 0.01 foot for most of the fan surface, with slightly larger values in areas adjacent to the significant wash corridors. When compared with stratigraphic interpretations of trench profiles from the WTF 36, RVF 12, and Tiger Wash site (CH2M HILL, 1992), the data indicated recent sediment deposition rates at the trench locations of 0.005 ft/yr, 0.003-0.005 ft/yr, and 0.005-0.03 ft/yr, respectively.

Table 11. MUSLE Sediment Yield to Fan Apex & Simplistic Projection of Deposition Rates

Fan Site	100-Year (AF)	Average Annual (AF)	Active Fan Area (Ac)	Potential Deposition (ft)	
				100-Yr Flood	100 Year Period
WTF 36	34.2	4.9	>185	< 0.2	< 2.6
RPF	49.7	7.0	>250	< 0.2	< 2.8
RVF 1	33.9	4.9	>115	< 0.3	< 4.3
RVF 12	14.6	2.1	>110	< 0.1	< 1.9

2.4.2. Sediment Transport Modeling

Sediment modeling was performed using FLO-2D. The modeling evaluation found that FLO-2D performed the sediment transport calculations adequately, and that the model is the best available for the purposes of quantifying flood hazards on active alluvial fans in Maricopa County. FLO-2D was used to investigate the following aspects of sediment transport on alluvial fans:

- Multiple Frequency Models
- Sediment Gradation
- Sediment Inflow
- Sediment Transport Functions
- Series of Events
- Comparison to Water-Only Models

The sediment transport modeling effort is summarized in the following paragraphs. For the purposes of the sediment transport analyses, the 100-year model with the Zeller-Fullerton transport function was considered the "base" model. All sensitivity models were evaluated relative to this base model.

2.4.2.1. Multiple Frequency Models

FLO-2D models were prepared for the 2-, 10-, 50-, and 100-year events. Not surprisingly, FLO-2D modeling indicates that smaller events impact smaller areas, similar to the results of the without-sediment runs described in Section 2.3.3.2 above. Also, smaller events not only inundated a smaller percentage of the fan surface, but more of the flow was attenuated or infiltrated on fan surface (Figure 50). Therefore, it is likely that a

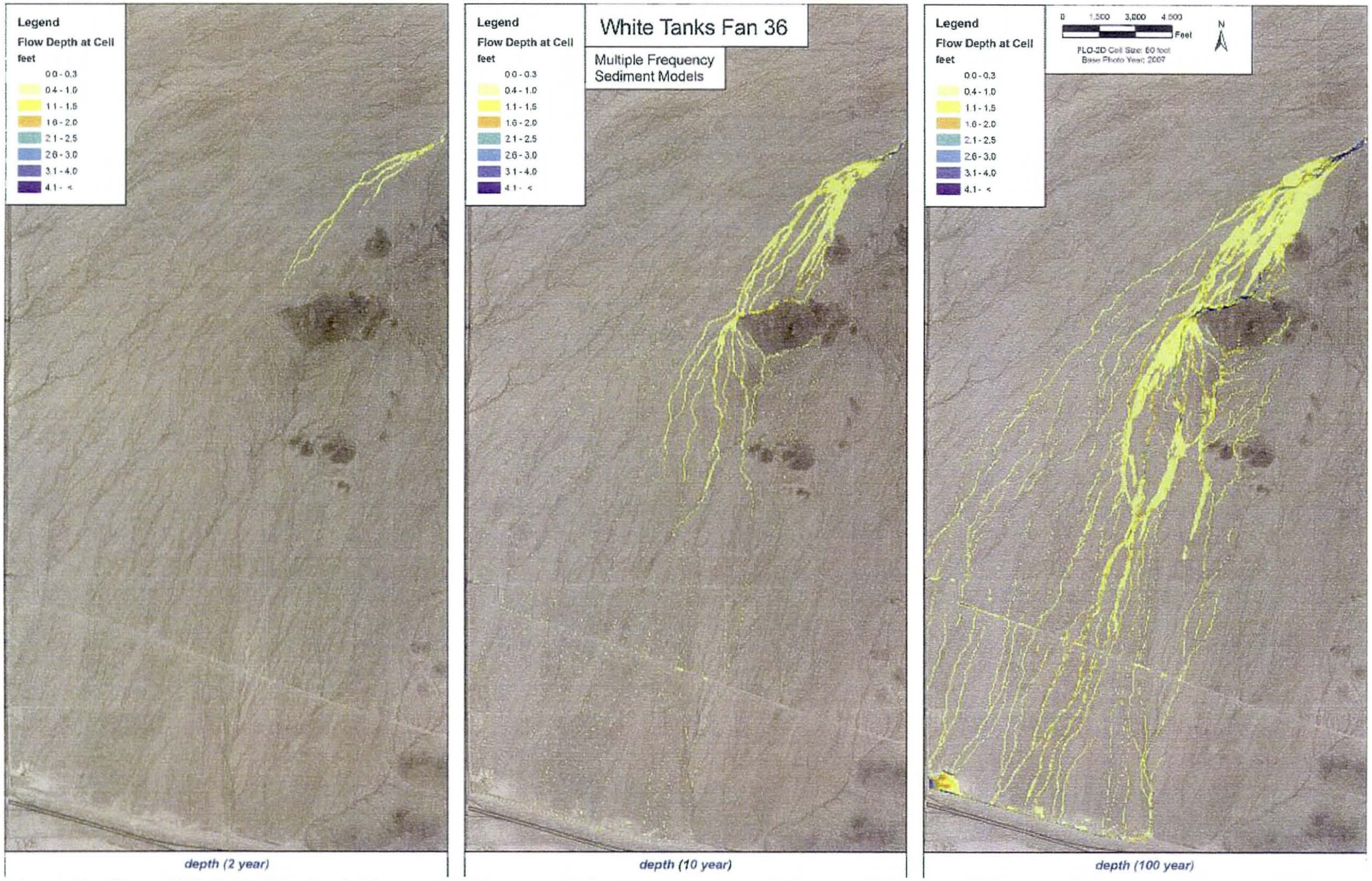


Figure 50. Plots of FLO-2D flow depths for multiple frequencies for White Tanks Fan 36.

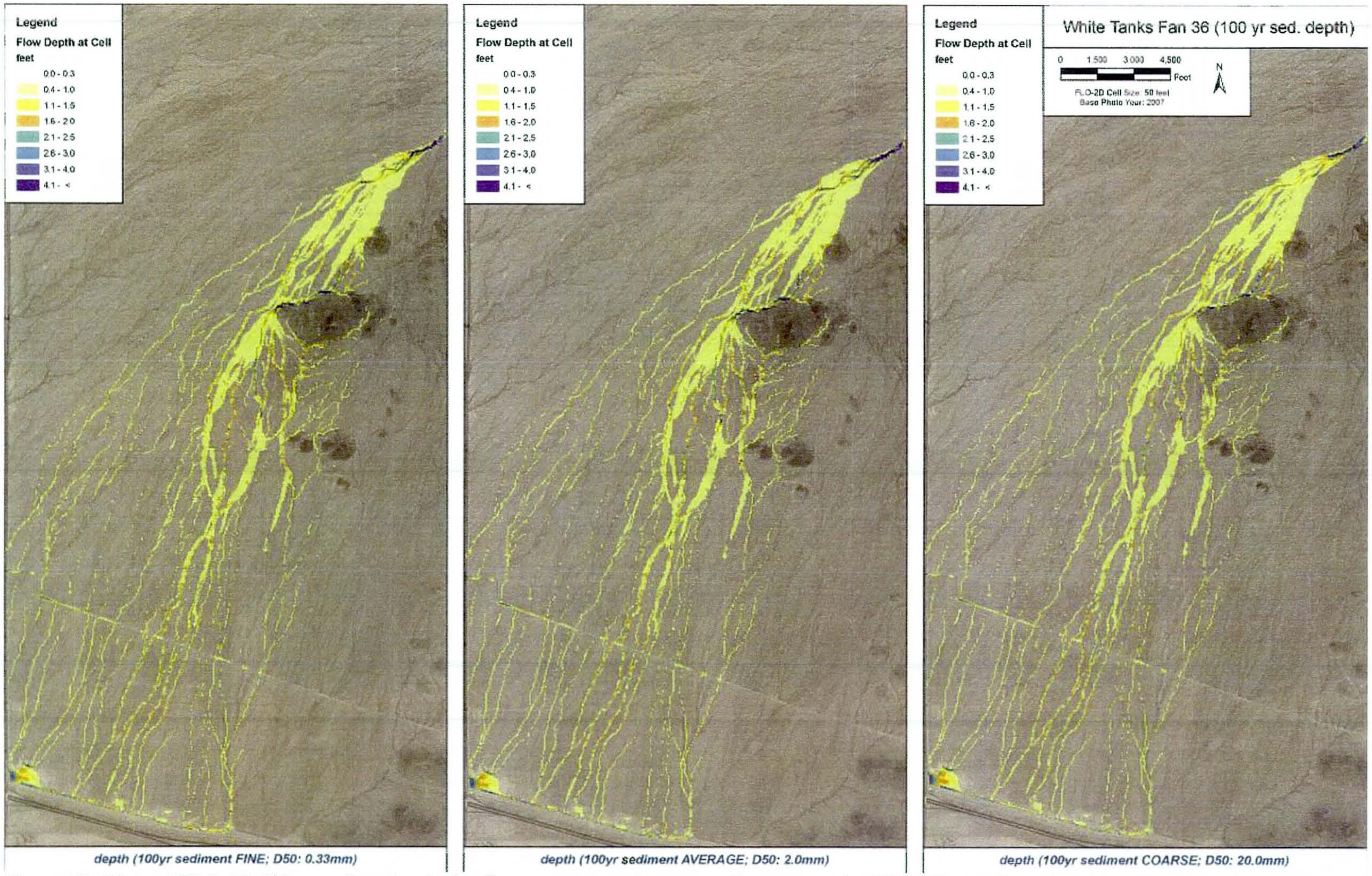


Figure 51. Plots of FLO-2D 100-year flow depths for fine, average, and coarse sediment runs for White Tanks Fan 36.

higher percentage of the sediment load delivered by the frequent events is deposited on the fan surface, possibly creating conditions more conducive to avulsion in subsequent larger floods. The water-only simulations of large floods such as the 100- and 500-year events could be interpreted to identify possible alternate (avulsive) flow-paths that could be exploited in rare floods, as described in Section 2.7 below.

2.4.2.2. Sediment Gradation

A variety of FLO-2D sediment runs were made to test the model's sensitivity to sediment size. The model results indicated that sediment size does impact the predicted flow hydraulics, scour and deposition, although the overall area of inundation was essentially identical to water-only modeling (Figure 51). In general, use of a finer sediment size resulted in greater predicted scour along the main watercourses, and overall larger high and moderate hazard zones. Use of a coarser sediment distribution resulted in lower net bed elevation changes. Given that the current formulation of FLO-2D only allows a single sediment distribution for the fan area, the selection of the appropriate sediment distribution should be made to reflect the purpose of the modeling as well as the specific area of concern within the fan boundaries. Use the distribution for the area of concern.

2.4.2.3. Sediment Inflow

The impact of available sediment supply at locations upstream of the apex was investigated by comparing the clear-water inflow simulations with equilibrium sediment inflow simulations. The results indicated that overall, the fan areas immediately downstream of the apex are not affected by the sediment inflow rate, as long as the model domain extends far enough upstream of the apex for the sediment transport rate to normalize before it reaches the fan. The only impact due to sediment inflow occurs immediately below the sediment inflow location. Therefore, the inflow locations were intentionally located further upstream of the apex so that such impacts diminish as the flow approaches the apex and the area of interest on the fan surface. The hazard delineations obtained from either approach were very similar, leading to the conclusion that sediment inflow impacts are minimal and can be addressed by shifting the inflow location further upstream from the areas of interest.

2.4.2.4. Sediment Transport Functions

Sensitivity to the sediment transport function used by FLO-2D was investigated by testing different sediment transport equations in the Reata Pass Fan models. Various sensitivity-type simulations were performed using the Zeller-Fullerton, Yang, MPM-Woo and Englund-Hansen equations. The results indicate a high sensitivity of the hazard zones to the transport equation used, as shown in Figure 52. The Zeller-Fullerton appears to predict the most reasonable results based on the following:

- Standard of Practice – for other types of sediment transport analyses, the District has recommended using the MPM and/or Zeller-Fullerton equations. The ADWR Manual also uses the Zeller-Fullerton equation.
- Engineering Judgment – lacking data for calibration or verification, the engineer must rely on experience and judgment to select the best results.

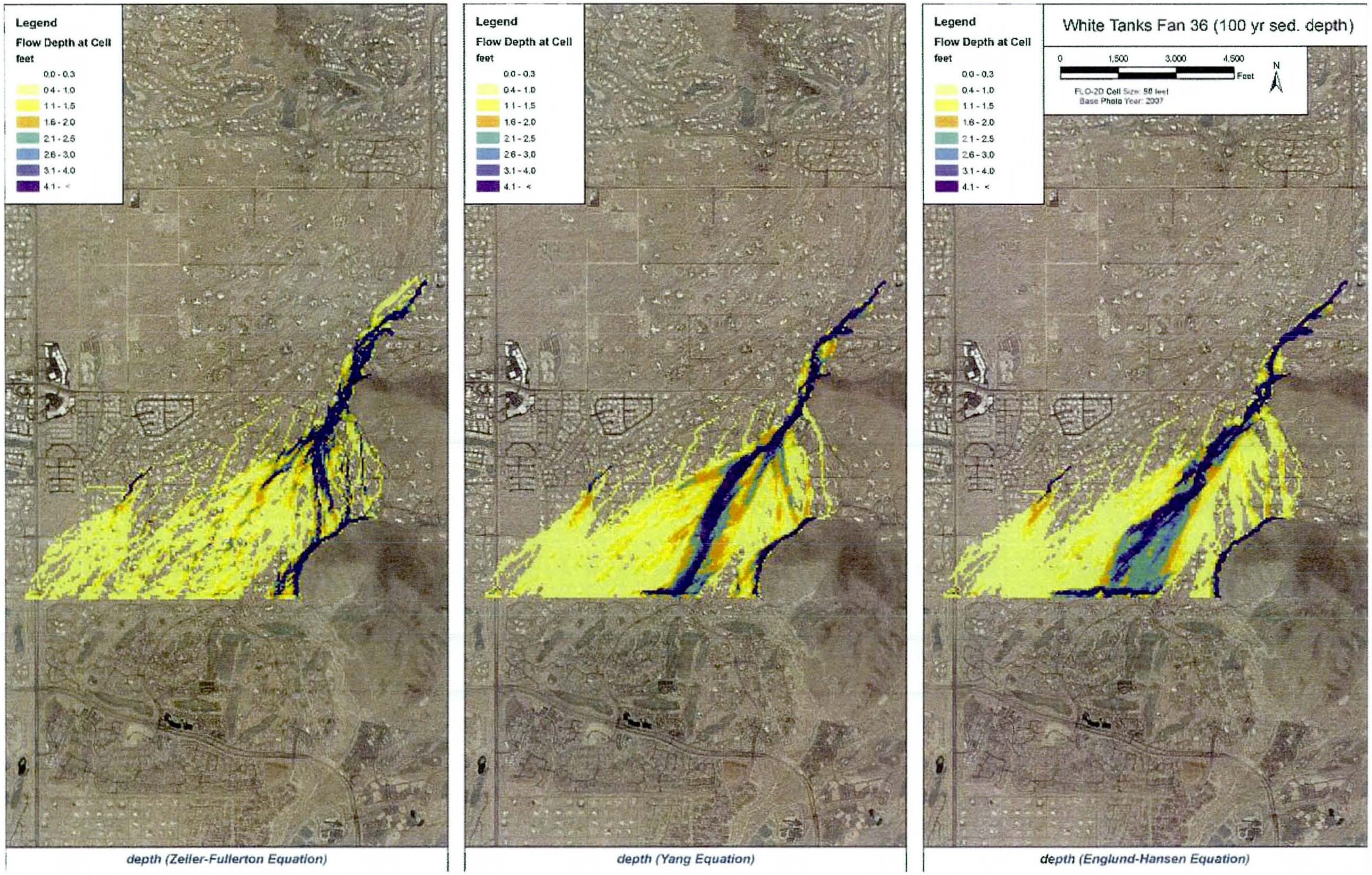


Figure 52. Plots of FLO-2D 100-year flow depths for various sediment transport functions for Reata Pass Fan.

It is recommended that the District continue to explore sediment transport modeling options for alluvial fans and to develop data for model verification. Dr. O'Brien15 notes that all of the available equations were developed for riverine, not alluvial fan, modeling

2.4.2.5. Series of Events

Two attempts to simulate long-term behavior of active alluvial fans were made using the FLO-2D model. The first attempt consisted of probability-weighting the results of 2-, 10-, 50- and 100-year models and projecting the average annual result over a long planning period. Unfortunately, this approach resulted in predictions of unrealistically excessive scour and deposition in some locations (e.g., greater than 25 feet). Future use of this methodology may be possible if subroutines are developed to cull out unrealistic results through an area-weighting or local averaging procedure. The second attempt consisted of running a series of flood hydrographs back-to-back in the model. However, since the FLO-2D model processing time is already slowed considerably by inclusion of sediment transport modeling, the addition of even longer duration flows caused the model to slow to the point where it was no longer practical. As computers get faster in the future and the FLO-2D algorithm is improved, it is more likely that a two-dimensional modeling based approach can be used to predict long-term behaviors in addition to single event models.

2.4.2.6. Comparison to Water-Only Models

Comparison of the flow rates from water only and sediment FLO-2D models at index cross sections on the fan surface indicated only minor differences (Table 12). Therefore, use of water only models probably results in acceptable estimates of peak discharge. Differences in predicted flow depths between water-only and sediment models are illustrated in Figure 53 to Figure 62. The FLO-2D modeling results indicate that there are differences in predicted flow depths and hazard levels caused by consideration of sediment transport. The greatest differences tend to occur near the hydrographic apexes in the high hazard zones. Further downfan, the differences are less significant, and are generally less than one foot. Note that the overall area of inundation is not significantly different between water-only and sediment models, but the predicted depths within those zones have some differences. At this time, there are insufficient data from which to conclusively judge the accuracy of the sediment modeling results.

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[15] Email to Jon Fuller on 7/18/10.

Table 12. Comparison of FLO-2D 100-year discharge estimates for water-only and sediment models.				
Site	FLO-2D Water Only		FLO-2D Water & Sediment	
	Q (cfs)	Vol (AF)	Q (cfs)	Vol (AF)
White Tanks Fan 36				
Section 10	2802	339	2861	345
Section 1020	538	81	313	25
Section 1050	921	103	1164	165
Section 10100	1150	125	1084	118
Section 20	35	11	50	9
Section 33	14	2	22	2
Section 34	0	0	0	0
Section 43	12	2	14	2
Section 44	0	0	0	0
Section 50	18	4	23	5
Section 60	41	7	49	9
Section 74	0	0	0	0
Section 80	58	13	65	19
Section 100	1615	157	1758	180
Section 100110	934	86	1162	114
Section 100140	532	54	413	45
Section 110	101	19	203	40
Section 140	349	59	276	52
Section 140110	90	10	101	22
Section 140150	256	51	234	32
Rainbow Valley Fan 1				
Section 30	3763	429	3549	424
Section 40	3739	481	2831	470
Section 60	172	26	115	20
Section 30-60	332	25	246	13
Section 40-60	207	10	163	8

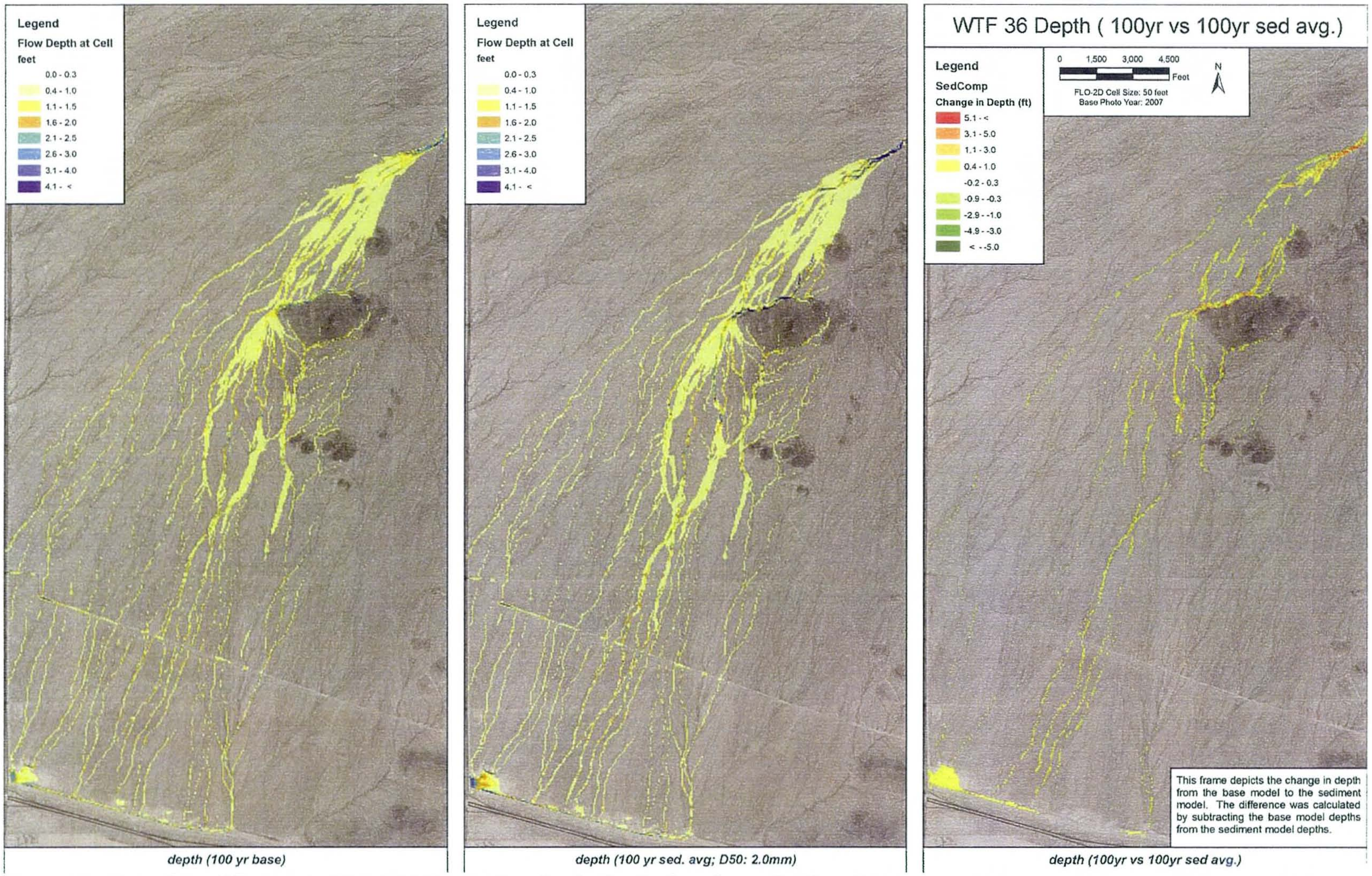
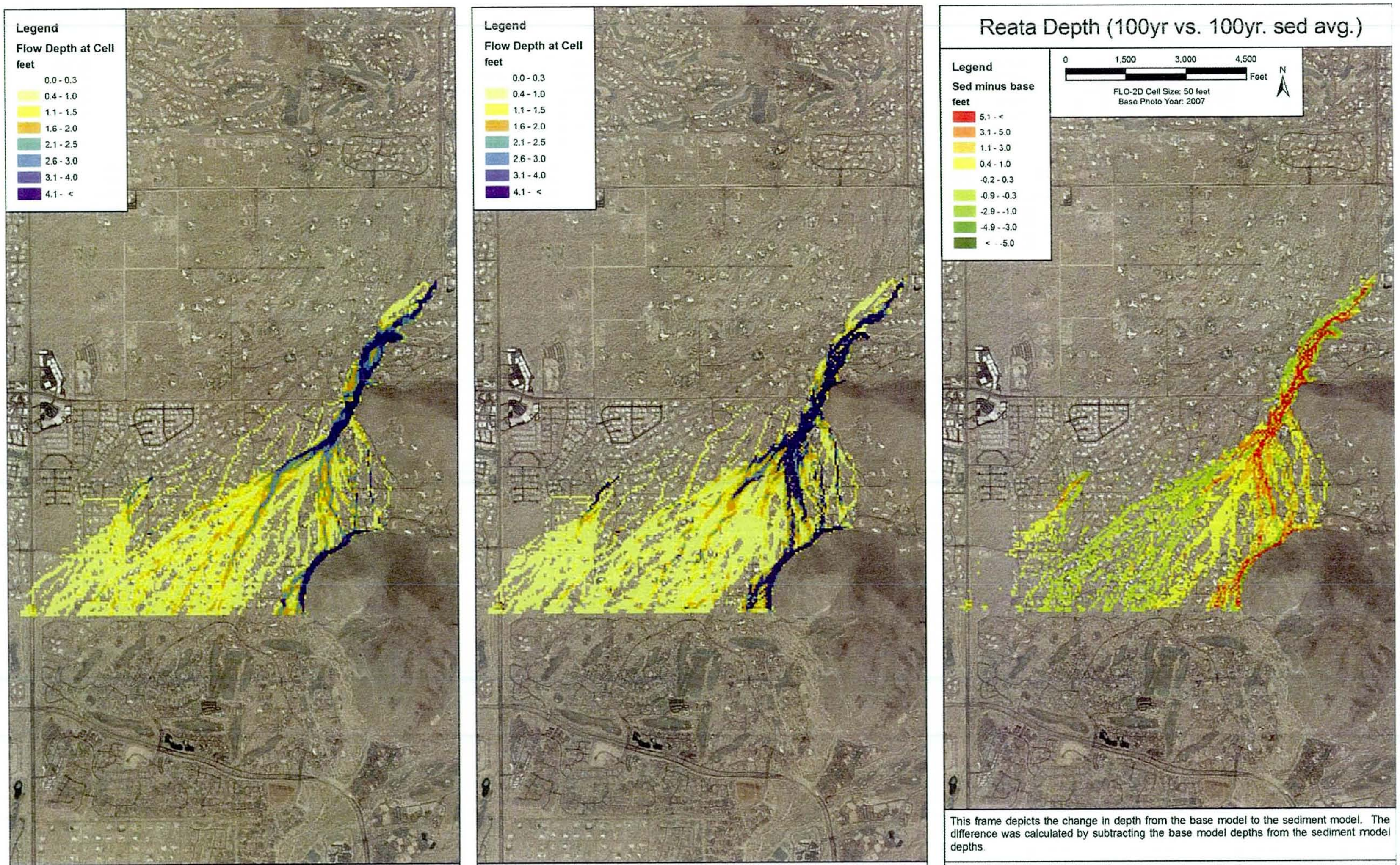


Figure 53. Plots of the difference in FLO-2D 100-year flow depths for the four fan evaluation sites.



depth (100 year base) | *depth(100 yr sed-average; D50: 2.0mm)* | *change in depth (100 yr base vs. 100 yr sed. avg)*

Figure 54. Plots of the difference in FLO-2D 100-year flow depths for the four fan evaluation sites.

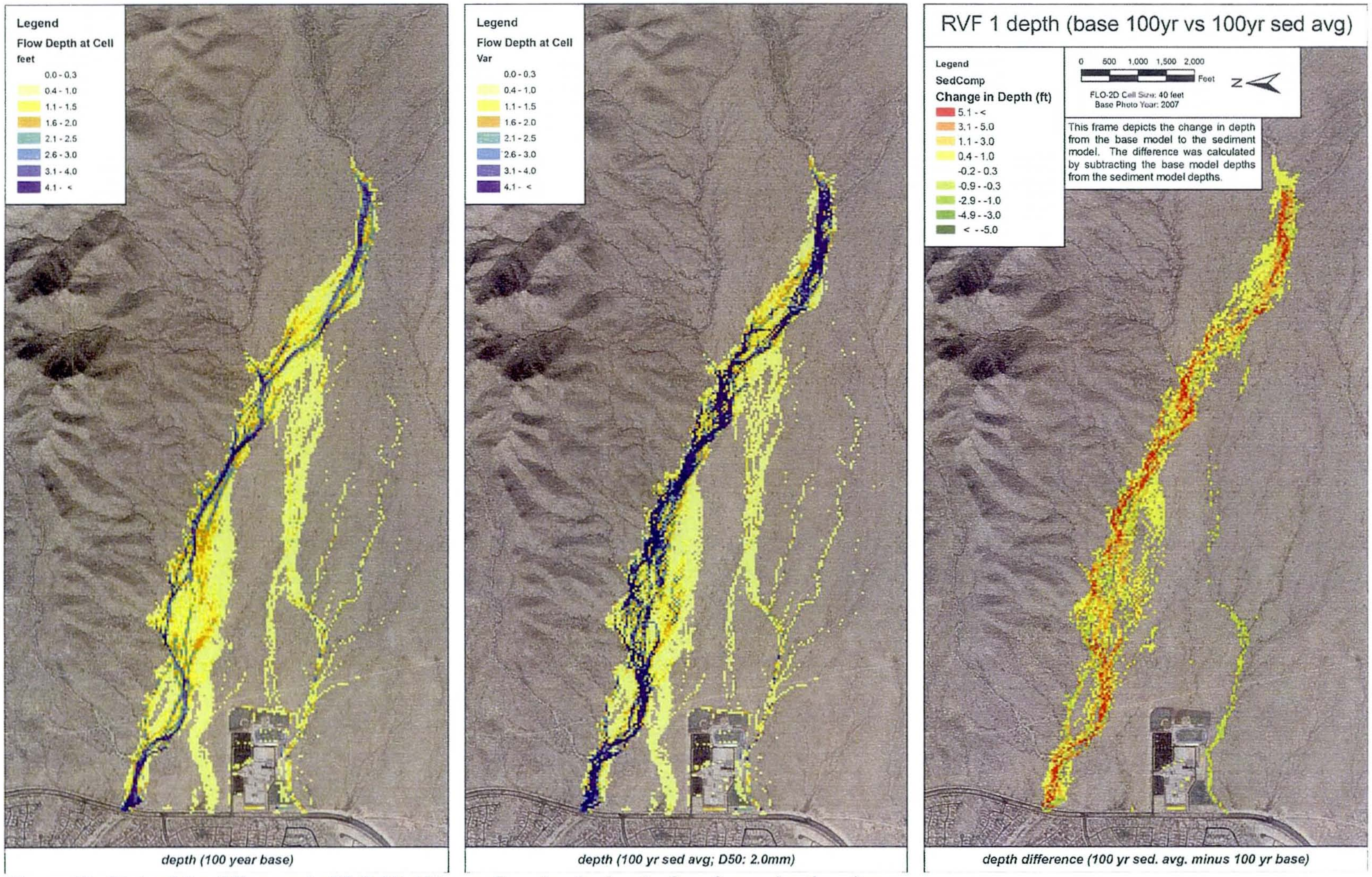


Figure 55. Plots of the difference in FLO-2D 100-year flow depths for the four fan evaluation sites.

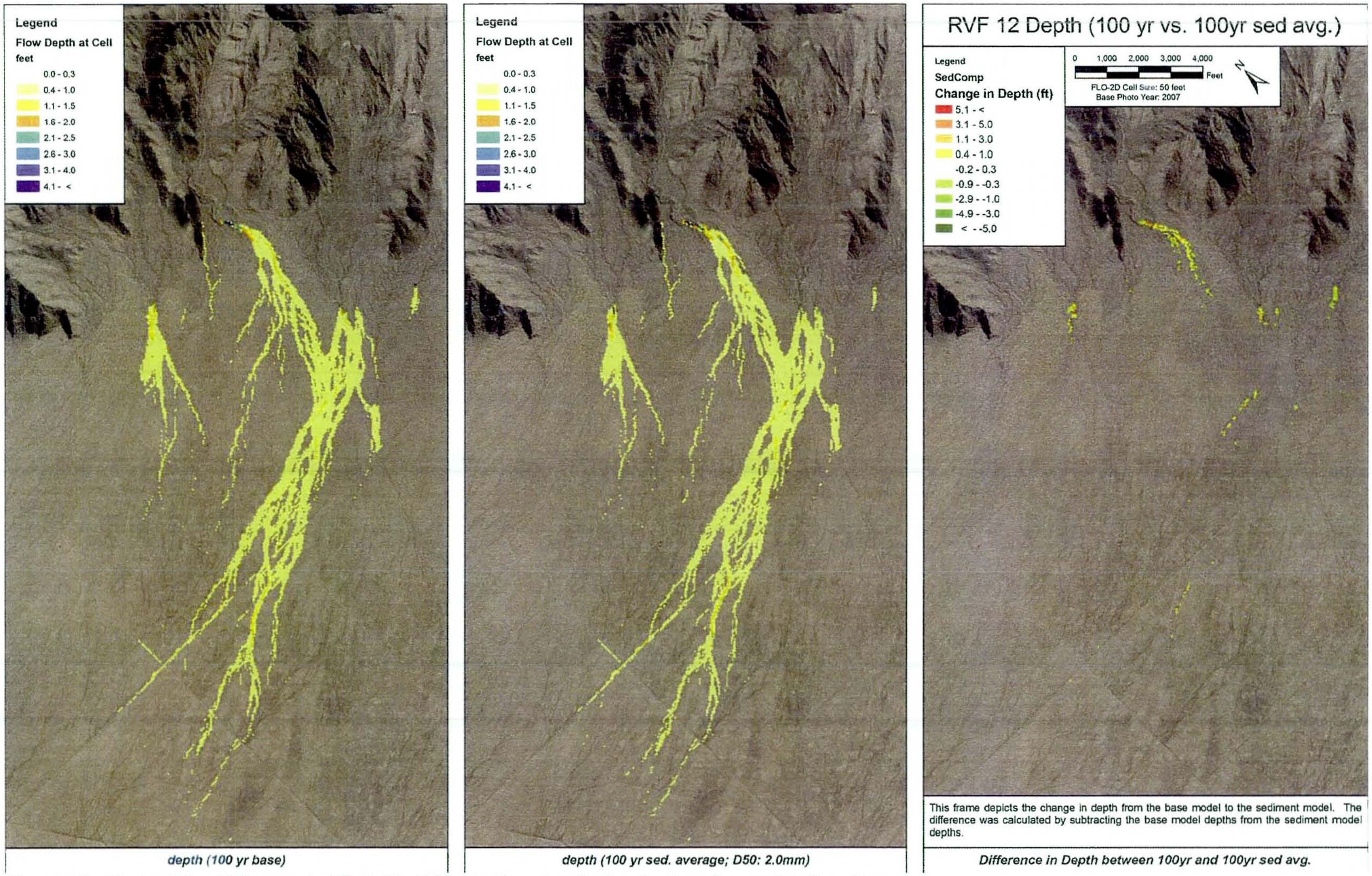


Figure 56. Plots of the difference in FLO-2D 100-year flow depths for the four fan evaluation sites.

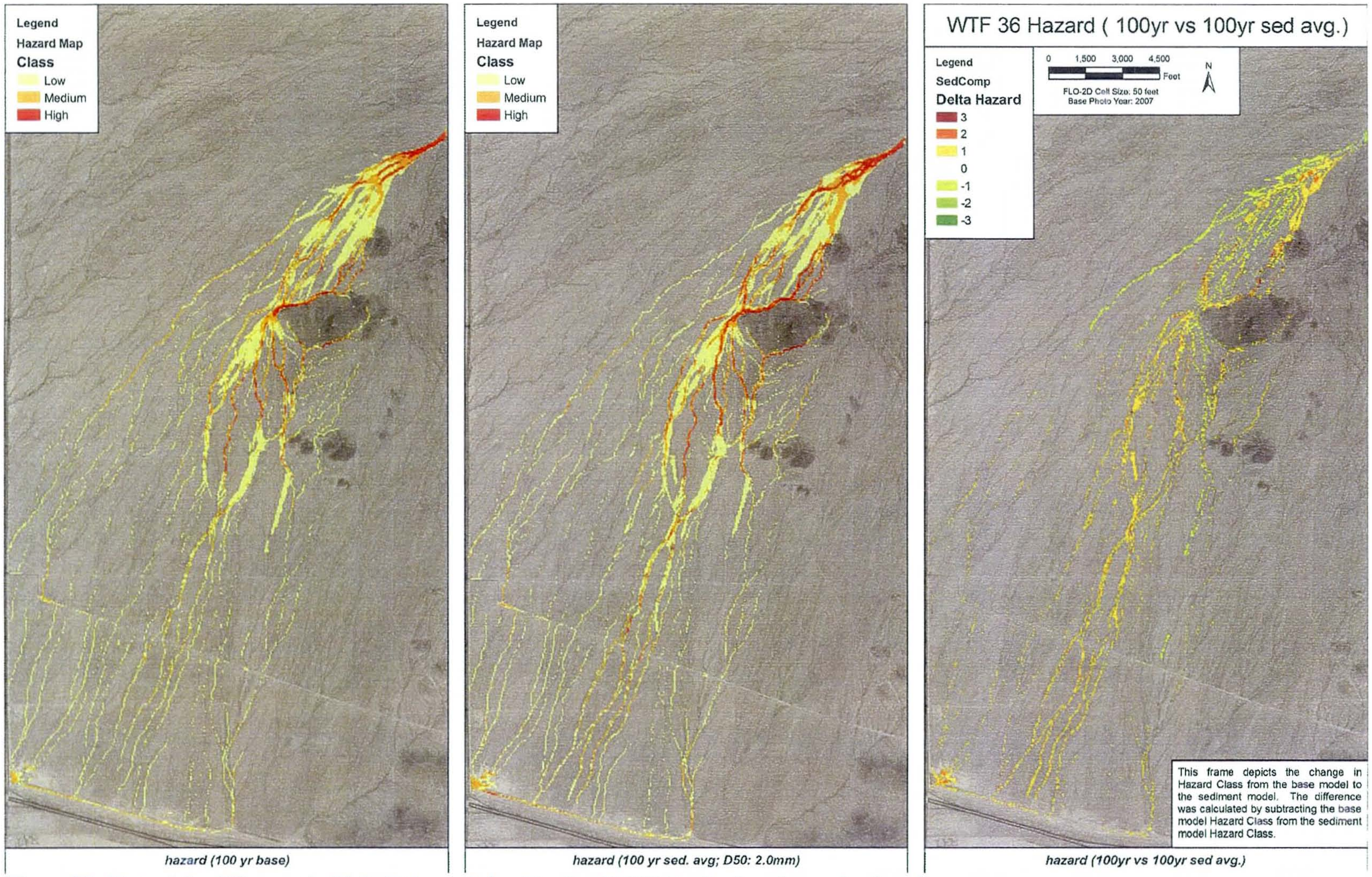


Figure 57. Plots of the difference in FLO-2D hazard classification (Q100) for the four fan evaluation sites.

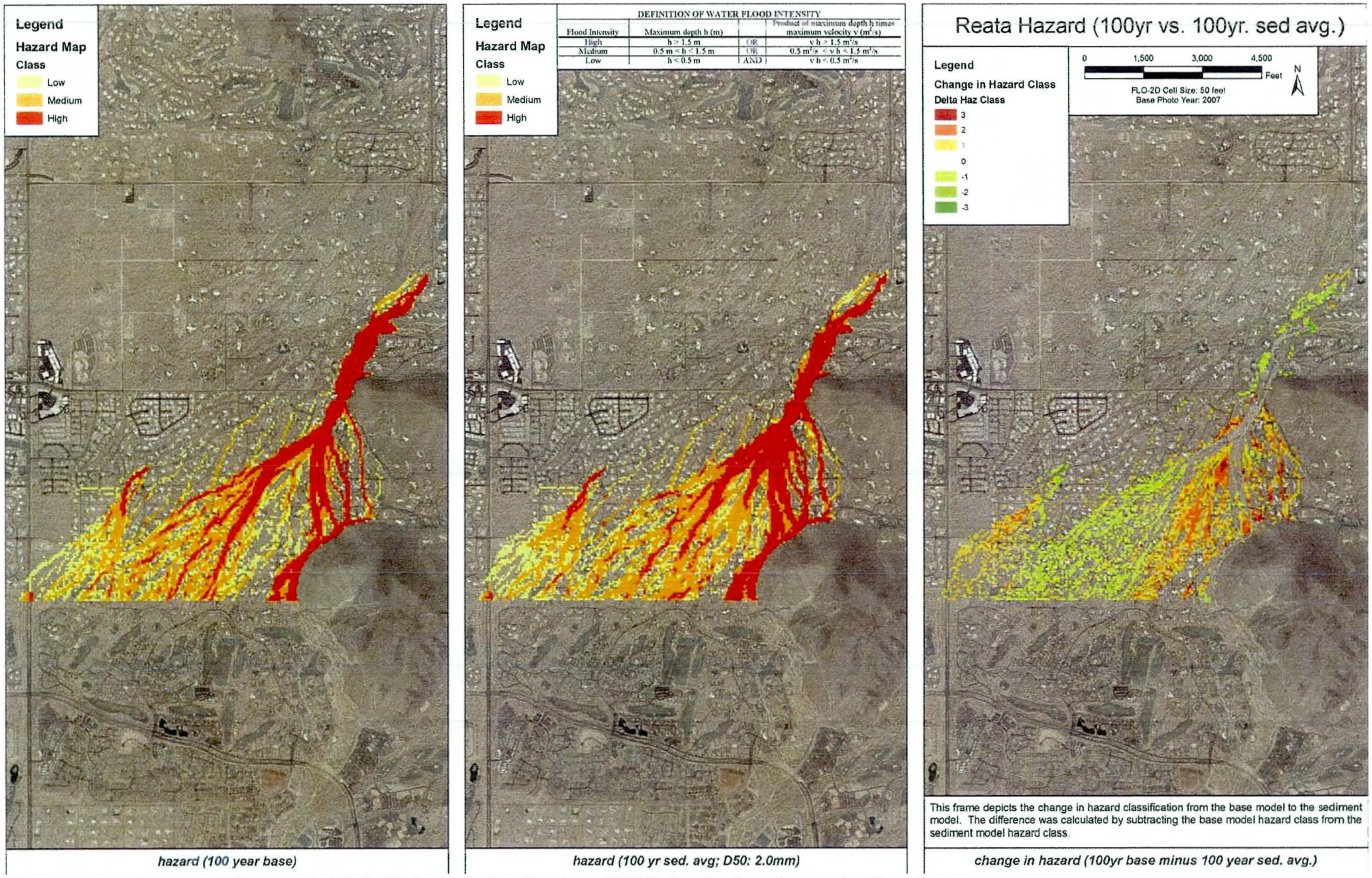


Figure 58. Plots of the difference in FLO-2D hazard classification (Q100) for the four fan evaluation sites.

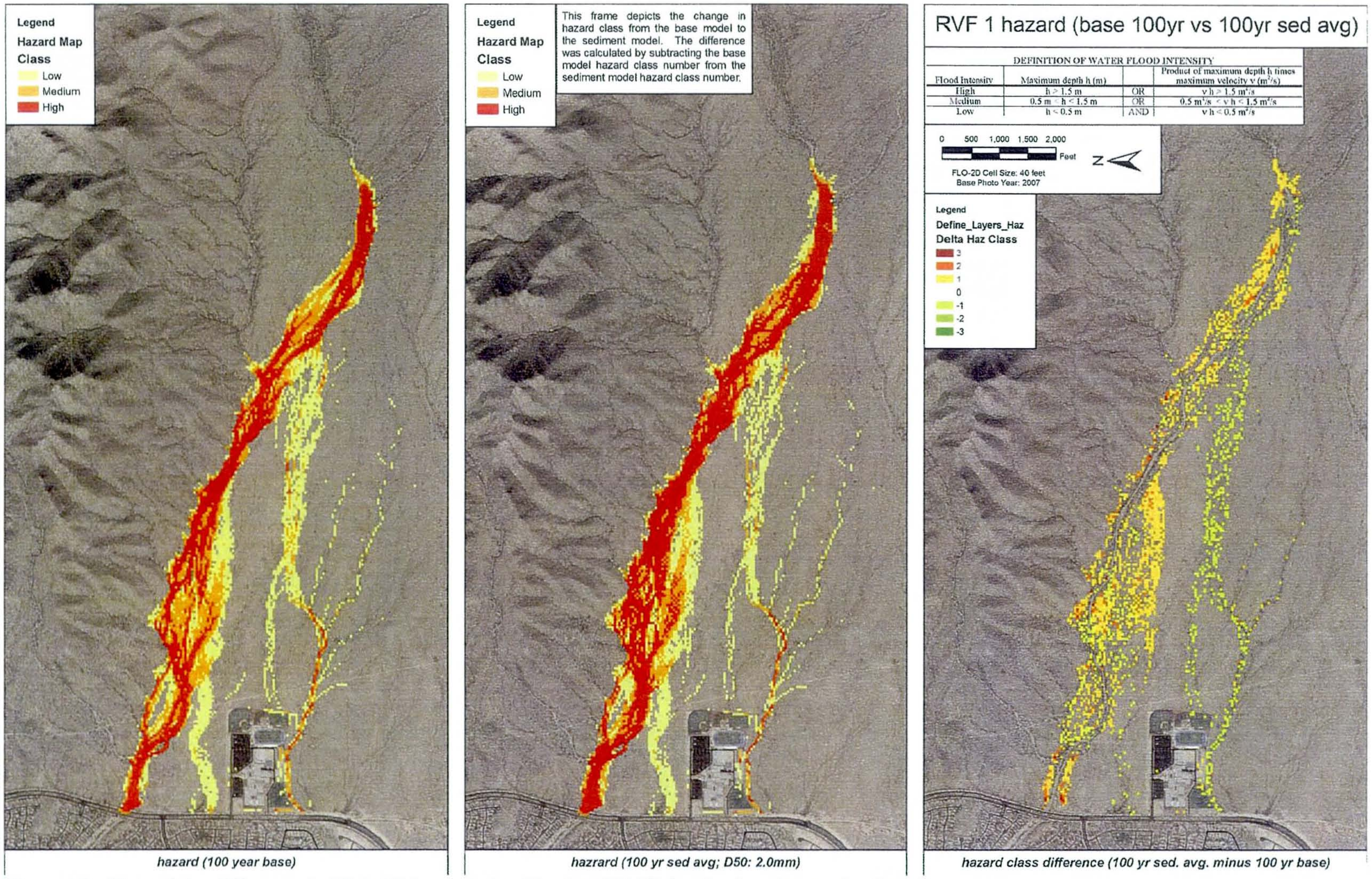


Figure 59. Plots of the difference in FLO-2D hazard classification (Q100) for the four fan evaluation sites.

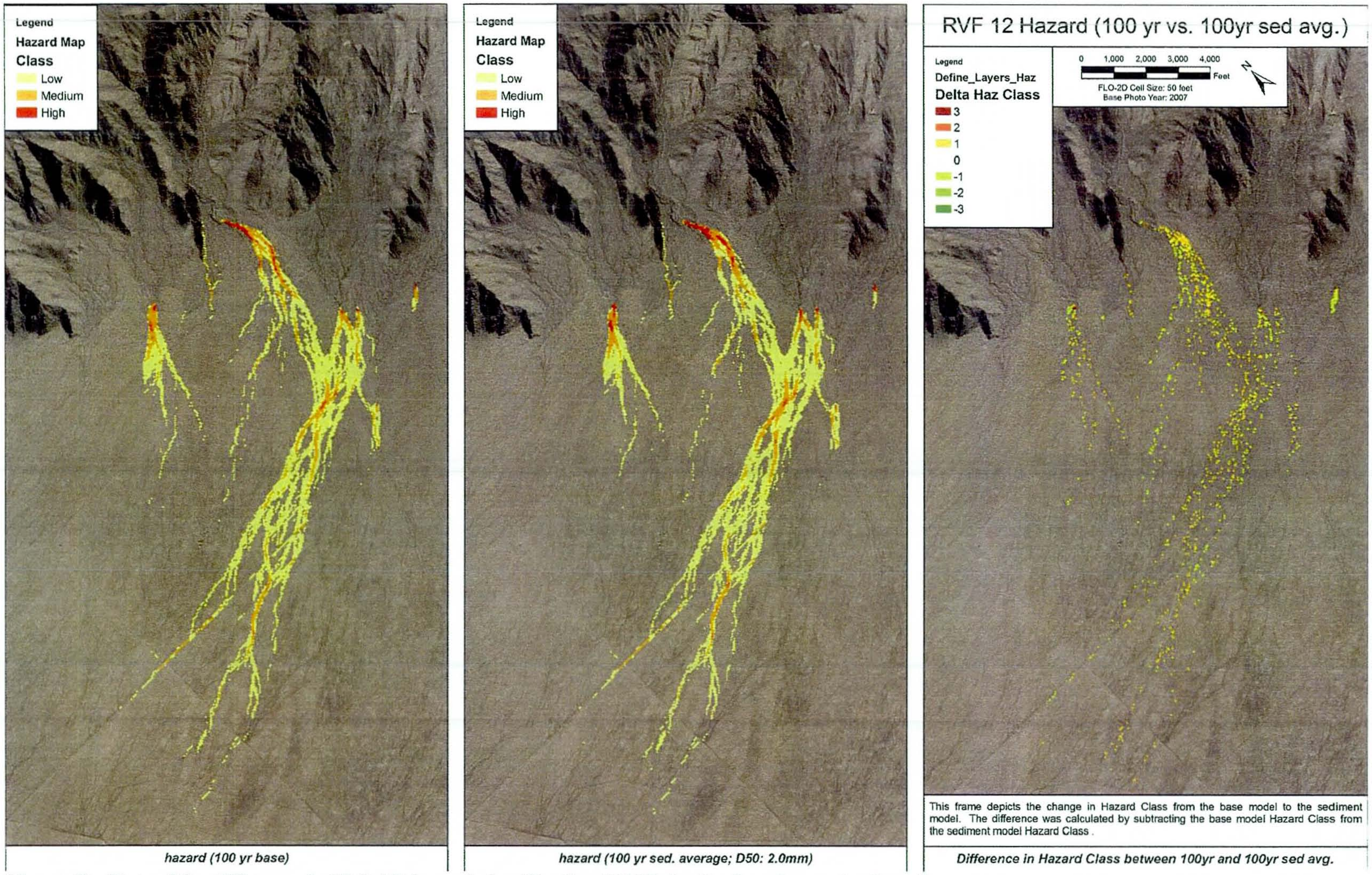


Figure 60. Plots of the difference in FLO-2D hazard classification (Q100) for the four fan evaluation sites.

2.4.3. Conclusions

Conclusions drawn from the sedimentation evaluation of the four alluvial fan sites included the following:

- Frequent floods, such as the 2- to 10-year events, induce channel changes which may not be significant on a single event basis, but may have important cumulative impacts, particularly when large, rare floods occur. However, long-term cumulative sediment impacts are difficult to simulate using any available modeling tool, including FLO-2D.
- The impact of the sediment supply was not found to be significant if the sediment inflow point was placed sufficiently upstream of the area of concern. Clear-water inflow and sediment laden inflow models resulted in nearly identical results for the areas downstream of the fan apex.
- Modeling results reinforce the importance of accurate, detailed topography and appropriate grid size when performing FLO-2D modeling on alluvial fans.
- FLO-2D is highly sensitive to the transport function used. The Zeller-Fullerton was judged to predict the most reasonable results, but more investigation and model calibration is recommended.
- The upstream sediment supply was found to have a minor impact on fan topography, at least for single flood events.
- Use of sediment transport subroutines slows the FLO-2D model considerably.

In order to enhance the effectiveness of the two-dimensional sediment transport models, further calibration of sedimentation results to measurements is needed. Presently, there is lack of data to verify the adequacy of the models to predict reliable results from a qualitative as well as a quantitative point of view. The collection of such data may be difficult and expensive.

2.5. Holocene Dating Techniques

An assessment of Holocene[16] surficial dating techniques was completed to demonstrate how landform surface age estimates can be used in the evaluation of alluvial fan flood hazards in Maricopa County, Arizona. Surface age estimates are used to help identify active (young) and inactive (old) portions of alluvial fan landforms, and are a major component of the Stage 2 PFHAM methodology. Detailed geomorphic mapping of alluvial fan surfaces combined with surface age estimates reveal the degree of flood hazards by identifying the most recently active flooding areas. Geomorphic mapping and application of relative dating methods (surface morphology, degree of soil and desert pavement development, vegetation type and density, carbonate content and structure) should be performed prior to applying any numerical dating techniques. A more detailed discussion of Holocene dating techniques as applied to alluvial fans in Maricopa County is presented in Appendix G.

[16] The Holocene Epoch consists of the past ~10,000 years of earth history. Some of the dating techniques described extend into the Pleistocene Epoch (> 10,000 yrs before present), though the focus of this report is only on the more geologically recent Holocene dates.

The dating techniques considered included relative, numerical, and correlative methods, but the evaluation focused on methodologies that could provide better age-resolution of Holocene surfaces. The following methodologies which are considered applicable to alluvial fan landforms in Maricopa County were evaluated:

• Optically Stimulated Luminescence (OSL)	(Numerical)
• Radiocarbon (C-14)	(Numerical)
• Cosmogenic Nuclides (CND)	(Numerical)
• Thorium-Uranium (Th-U)	(Numerical)
• Varnish Micro-Lamination (VML)	(Correlative)
• Pedogenesis	(Relative)
• Rock weathering	(Relative)
• Surface Morphology	(Relative)
• Gully diffusion	(Relative/Correlative)
• Palynology	(Correlative)
• Archaeology	(Correlative)

Of the dating techniques listed above, the OSL and radiocarbon dating methods were found to be the most applicable numerical dating methods for dating alluvial fan sediments on fan landforms in Maricopa County. CND and VML are the most applicable methods for estimating surface ages. VML is a correlative method which should be evaluated further for application in Maricopa County. The types of dating techniques considered, as well as their resolution and age ranges are shown in Figure 61.

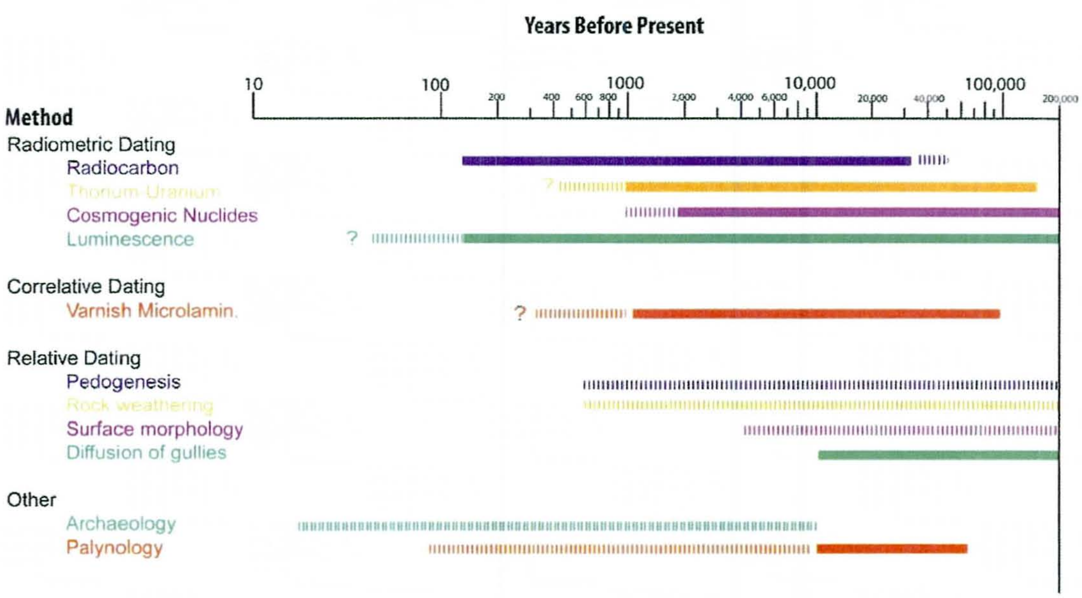


Figure 61. Dating techniques and age-resolution available for use on alluvial fans in Maricopa County.

While relative, numerical and correlative dating methods can be used to date Holocene alluvial fans in Maricopa County, accurately estimating the ages and establishing a chronology of alluvial fan development in Maricopa County will require a multi-step approach which relies on several methodologies. Relative dating methods are always an important first step, and are used to generate a contextual geomorphic interpretation, as well as detailed maps that define the physical framework of the alluvial fan system. The relative dating results provide a basis for evaluating what type of material and surface to sample and what dating methods would be most useful. Numerical dating methods should always be coupled with relative age indicators. If numerical ages are obtained from alluvial fan sediments and surfaces like those found in Rainbow Valley or Tiger Wash, then indirect dating techniques like VML, weathering rind thickness measurements, surface roughness and degree of soil formation can be calibrated from those same sediments and surfaces. When relative dating methods have been calibrated at several sites within Maricopa County, a regional chronology of fan and surface development could be constructed that would apply throughout Maricopa County. The process of constructing a regional chronology could take several years to complete, and would require the involvement of several types of dating and surficial geology experts. It may be possible to complete this task using research staff from Arizona Universities in conjunction with the Arizona Geological Survey. Once completed, it would provide useful guidelines in the PFHAM for dating and delineating young alluvial fan surfaces.

2.5.1. Conclusions

This study concludes that there are methods for quantifying surface age that are applicable to alluvial fans in Maricopa County. OSL and AMS radiocarbon dating methods are the most applicable numerical dating methods for dating alluvial fan sediments on fan landforms in Maricopa County. Cosmogenic nuclide dating and varnish microlamination correlation are the most favorable methods for estimating surface ages. Varnish microlamination (VML) is a correlative method and should be evaluated further in Maricopa County. It is recommended that a combination of relative and numerical methods be applied, in conjunction with conventional surficial mapping techniques, to most accurately determine surface age on alluvial fans in Maricopa County. It is further recommended that a regional chronology be constructed so that more cost-effective relative dating techniques can be used to determine correlative ages.

2.6. Debris Flow Potential Assessment

An assessment of the potential for debris flows to influence alluvial fan flood hazards in Maricopa County was conducted as part of the PFHAM study. Specifically, the assessment evaluated and recommended methods for determining potential debris flow occurrence and run-out onto alluvial fan flood hazard areas. Other debris-flow hazard issues such as expected magnitude, frequency, or direct impacts on developments located at the base of steep slopes (Péwé, 1978) are not directly addressed in this report. A more detailed discussion of the debris flow assessment is provided in Appendix H.

Debris flows are unsteady, non-uniform, very poorly sorted sediment slurries that are generated when hillslope soils become saturated and fail. While there is some evidence that debris flows have occurred in Maricopa County on very steep slopes of mountainous watersheds, there are no documented cases of historic debris flows impacting flood hazards on any mid-piedmont alluvial fans within the County. Based on known general characteristics of debris-flow behavior, as well as on the specific climatic and geologic conditions in Maricopa County, the expected recurrence interval for debris flows in Maricopa County, even in the mountainous areas, probably exceeds 1,000 years. Furthermore, because of the regional physiography and watershed characteristics, it is likely that future debris flows will have low volumes because of limited sediment supplies, will travel only short distances from their point of initiation due to their coarse sediment composition and low clay content, and that most will not reach the active areas of alluvial fans, particularly the fans that are located well away from the mountain front.

Based on the PFHAM study requirement to develop a method for assessing potential debris-flow impacts on alluvial fan flooding, the following steps are recommended for detailed evaluations of debris flows on specific alluvial fan landforms in Maricopa County:

- Step One: Initial Assessment of Alluvial Fan
- Step Two: Geologic Reconnaissance
- Step Three: Debris-Flow Runout Hazard Modeling

Step One: Initial Assessment. The first step in the recommended approach is to select a fan of interest and determine if the alluvial fan is adjacent to or distant from the mountain front. If the alluvial fan is distant from the mountain front, it is highly unlikely that debris flows will impact alluvial fan flooding. Thus, there is no need to proceed with further assessment of debris flow impacts on the alluvial fan floodplain. If the alluvial fan is adjacent to the mountain front, then the next step is a geologic reconnaissance to determine if debris flows have occurred in the basin of interest, and if any debris flow deposits are found on the fan.

Step Two: Geologic Reconnaissance. The second step in the recommended approach is geological reconnaissance. Geologic reconnaissance of the watershed and alluvial fan, especially near the fan apex, will confirm the presence or absence of debris-flow deposits, and provide details of the basin and piedmont conditions that will be useful for calculating and evaluating potential debris-flow volumes. Geologic mapping will provide data regarding minimum number of deposits, relative ages, and travel distances of past debris flows. If debris-flow deposits are not found in the watershed or on the alluvial fan, it is not a debris-flow producing basin, and no further debris flow hazard evaluation is warranted. If debris-flow deposits are in found in the basin and/or on the fan, then the deposits should be geologically mapped. Detailed field mapping of young debris flow deposits at and below canyon mouths can provide real data to help constrain estimates of debris flow volumes and runout distances using the procedures outlined in Youberg and others (2008). This field-mapping step is critical to realistically assess the potential impacts of debris flows on alluvial fan flooding under modern climatic conditions. If debris-flow deposits are found on the alluvial fan then additional modeling will be required to assess the potential impacts to alluvial fan flooding hazards.

Step Three: Modeling. The third step, if deemed necessary based on the results of step two, is to model various debris-flow volumes using LAHARZ[17] as shown in Figure 62. The first phase of the recommended LAHARZ methodology uses the lahar function, where deposition zone begins at the apex of the active fan area. Various flow volumes should be modeled, in half order-of-magnitude increments, to estimate potential volumes required to emplace debris-flow deposits at the farthest distance the youngest deposits (late Holocene to modern) were mapped. Debris-flow maps will provide the basis for determining potential deposition zones and modeling flow volumes. Results from LAHARZ can also then be used to identify potential hazard zones on alluvial fans.

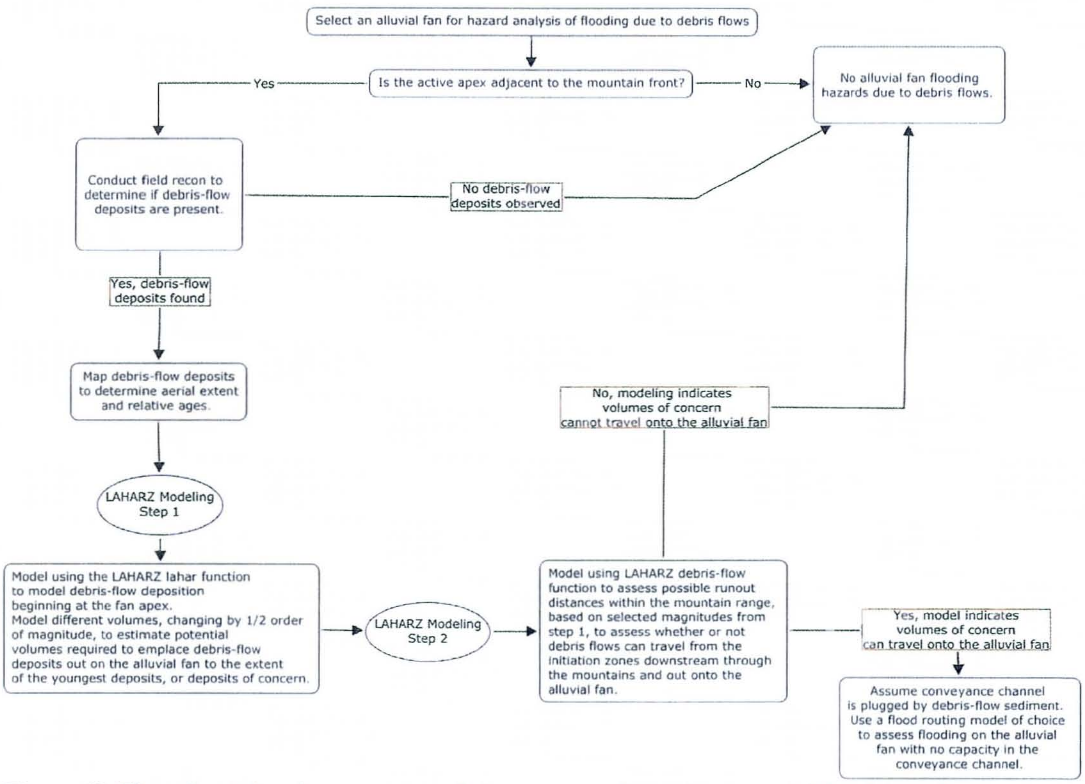


Figure 62. Flow chart showing recommended steps to evaluate the potential for debris flows to impact alluvial fan flooding.

Once the potential debris flow volumes have been estimated, a geologic analysis of material available is required. For example, if the model indicates 100,000 cubic yards of material are required to emplace debris-flow deposits on the active fan surface, then that volume can be compared to the average depths of hillslope soils, as well as to the material volume stored in upstream channels. The sediment production rate should also

[17] LAHARZ (Schilling and Iverson, 1997; Griswold and Iverson, 2008) is an empirical area-volume model. It is a GIS-based runout prediction model originally developed for volcanic-related debris flows (lahars) and recently revised to predict runout distances for non-volcanic debris flows and rock avalanches (Griswold and Iverson, 2008). It uses an empirical approach based on observations that the debris-flow inundation area is proportional to flow volume raised to the 2/3 power (Schilling and Iverson, 1997).

be compared to the required volume to determine if the basin can produce enough material to reach the modeled volumes. If sufficient sediment material is available, then the second phase of LAHARZ modeling should be conducted using the debris flow function.

The purpose of the second phase of LAHARZ modeling is to determine if debris flows produced in the basin can actually travel to the alluvial fan. Deposition zones for this phase will be based on field- and GIS-derived data, such as minimum contributing area and slopes, channel gradients, and soils data, if available. The second phase of modeling will take several iterations, as the modeler will need to consider the effects of coalescing debris flows. If the modeling indicates that debris flows cannot reach the alluvial fan, then it is unlikely that debris flows will impact alluvial fan flooding. If the modeling indicates that debris flows can reach the fan, then the assumption that the conveyance channel can become blocked with sediment should be made, at which point more traditional distributary alluvial fan flooding models (e.g., FLO-2D) can be applied. The greatest impact debris flows may have on flooding is to block existing channels with sediment, forcing the following floods onto other areas on alluvial fans.

Application of debris-flow runout models like LAHARZ will provide hazard information regarding potential travel distances, as well as the volumes required to reach those distances. It should be noted that these methods will not provide any information to quantify frequency-magnitude relationships or the actual risk of debris-flow occurrence or expected volumes. Initiation modeling to evaluate the likelihood of debris-flow occurrence would require significant resources in terms of time commitments to set up and run the models, and collect field data with which to calibrate the models. In addition, these models need debris flow inventories for calibrating model results. Because no such inventory currently exists for Maricopa County, one would have to be developed by qualified personnel. Without such an inventory, initiation modeling is not recommended.

Model results from LAHARZ should be locally validated and calibrated with debris-flow data from Maricopa County. LAHARZ has been calibrated using the limited data set from southeast Arizona to model the 2006 debris flows in the Santa Catalina Mountains with reasonable success. It may be possible to test LAHARZ in Maricopa County on alluvial fans with young debris-flow deposits by making generalized assumptions regarding location of debris-flow initiation, and volume estimates. The 2006 southern Arizona debris flows may act as a proxy for initiation locations and volumes. If results from these tests are satisfactory, LAHARZ can be considered ready to use in Maricopa County. Otherwise, additional calibration LAHARZ coefficients will have to be developed from newer debris flows as they occur, or other modern debris flows in Arizona that have not yet been studied in detail.

2.6.1. Conclusions

This study concluded that debris flows are unlikely to impact regulatory flood hazards on alluvial fans in Maricopa County for two primary reasons: (1) they occur so infrequently or, (2) when they do occur they do not runout far enough to reach the hydrographic apex of the alluvial fan. Nevertheless, as directed by the project scope of work, a three-step procedure for evaluating debris flow potential and hazards was developed for use on piedmont surfaces in Maricopa County.

2.7. Avulsion Potential Evaluation

The objective of the avulsion potential evaluation was to determine and quantify how channel avulsions influence flood hazards on alluvial fan landforms in Maricopa County. This information is to be used to refine the Integrated Alluvial Fan Hazard Assessment Methodology that may be used in future revisions of the Flood Control District of Maricopa County's (District) Piedmont Flood Hazard Assessment Manual (PFHAM). The results of the avulsion potential evaluation are described in detail in Appendix I.

An avulsion is the process by which flow is diverted out of an established channel into a new course on the adjacent floodplain (Slingerland & Smith, 2004). Avulsions divert flow from one channel into another, leading to a total or partial abandonment of the previous channel (Field, 2001; Bryant et. al., 1995), or may involve simple flow path shifts in a braided or sheet flooding system (Slingerland & Smith, 2004). An example from Maricopa County of avulsive channel change that occurred on the Tiger Wash alluvial fan during the 1997 Hurricane Nora flood is shown in Figure 63. Avulsions are commonly associated with alluvial fan flooding, but are also known to occur on riverine systems and river deltas (Slingerland & Smith, 2004). Some of the terminology associated with alluvial fan avulsions is shown in Table 13.

The occurrence of avulsions is what makes an alluvial fan "active." Avulsions give the alluvial fan the ability to distribute water and sediment over the surface of the landform, which results in the radial "fan" shape. Avulsions influence flood hazards on an alluvial fan landforms by changing the location, concentration and severity of flooding on the fan surface. That is, an area not previously inundated by flooding (or inundated only by shallow flow) may in a subsequent flood become the locus of flood inundation, sediment deposition, and/or erosion. If an alluvial fan has no risk of avulsion, flood hazard delineation and mitigation become much simpler engineering problems, consisting only of modeling two-dimensional flow and/or normal riverine hydraulic and sedimentation issues.

The occurrence of major avulsions in an alluvial fan drainage system introduces the following complications into an engineering analysis of the flood hazard:

- Uncertain and changing flow path locations, during and between floods
- Continually changing channel and overbank flow path topography
- Inundation and/or sedimentation hazards in previously unflooded areas
- Uncertain and changing flow rate distribution for areas downstream of avulsions
- Uncertain and changing watershed boundaries for areas downstream of avulsions
- Aggrading, net depositional land surfaces and channel with diminishing capacity
- Unsteady, rapidly-varied flow conditions
- High rates of infiltration and flow attenuation across the fan surface

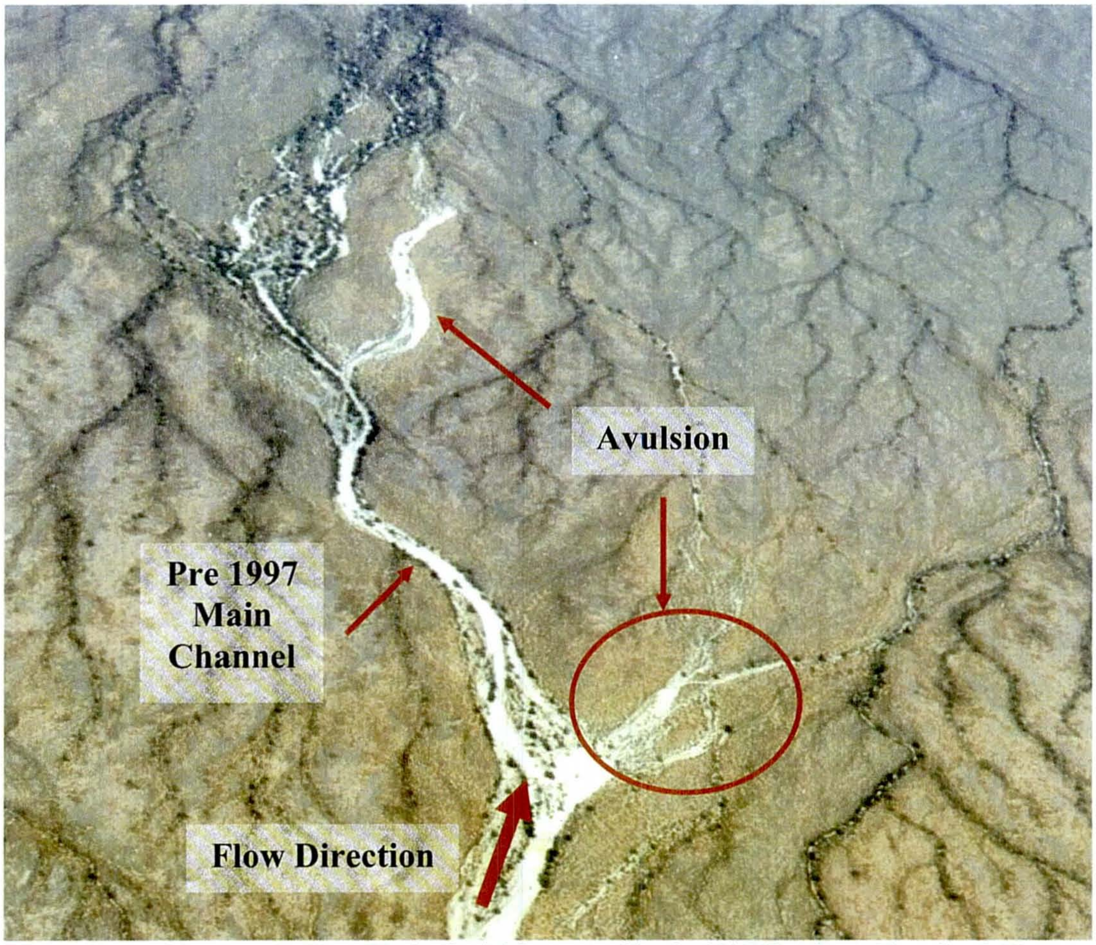


Figure 63. *Avulsions on the Tiger Wash alluvial fan caused by the 1997 Hurricane Nora flood. View looking southwest across active fan surface.*

Table 13. Avulsion Terminology & Classification Continuum **End Member ←---→ End Member**	
Major Avulsion Occurs near the apex Diverts > 50% of flow from the parent channel	**Minor Avulsion** Does not meet the major avulsion criteria
Full Avulsion All of flow is diverted Parent channel abandoned	**Partial Avulsion** Part of flow is diverted Parent and avulsive channel coexist
Nodal Avulsion Recurring at fixed point, e.g., a fan apex	**Random Avulsion** Occurs anywhere along an active channel system
Local Avulsion Avulsive channel rejoins parent downstream	**Regional Avulsion** Large scale event Affects all of system downstream of origin
Abrupt Avulsion Full avulsion occurs in single event	**Gradual Avulsion** Avulsion completed over decades or more
Anastamosing Avulsions return to parent downstream	**Distributary** Avulsions do not return to parent channel

Most importantly, there is a lack of appropriate engineering standards for evaluation of flood hazards or design of flood mitigation measures on alluvial fans with avulsion potential. Despite the importance of avulsions to the assessment of flood hazards on alluvial fans, the causes and frequency of avulsions have not been extensively studied (Slingerland & Smith, 2004).

Avulsions have been observed on several alluvial fans in Maricopa County, including some of the four fan evaluation sites selected for the PFHAM study. The avulsion history of the four PFHAM fan evaluation sites and Tiger Wash are documented and described in Appendix I. It is likely that there are other examples of major avulsions in Maricopa County, but no comprehensive evaluation of avulsion frequency or occurrences has been made. Historical records clearly indicate that avulsions do occur on the types of alluvial fans found in Maricopa County. The data available indicate that avulsions are relatively rare events, and that they are often associated with the occurrence of large floods. However, further documentation of the avulsion history of local alluvial fans is warranted to better assess the recurrence interval and frequency of avulsions. Almost all of the known causative factors for avulsions exist on alluvial fans in Maricopa County, and thus it is likely that avulsions will continue to occur in the future.

While there is much yet to be understood about avulsion prediction, avulsion frequency, and avulsion mechanics, there is general consensus about many of the factors that are conducive to forming avulsions (Table 14). Because of the number of variables that affect the occurrence of avulsions, accurate prediction of their occurrence may always elude modelers. Similarly, any given avulsion may be caused to some degree by a large number of variables.

Other important considerations in assessing the cause of alluvial fan avulsions include the following:

- Aggradation is a necessary condition for riverine avulsions (Slingerland & Smith, 2004). Most avulsions occur on aggrading landforms or channels.
- Overbank flooding is a necessary condition (Slingerland & Smith, 2004) for avulsions. Therefore, avulsions tend to occur during large floods (Wells & Dorr, 1987; Field, 2001; Pearthree, 2004). However, not all large floods cause avulsions (Pearthree et. al., 1992; Whipple et. al., 1998; Field, 2004), even if conducive set up conditions exist (Tornqvist & Bridge, 2002).
- It is important to distinguish between the set-up conditions (those conducive to avulsion) and the triggering event (e.g., a flood, debris blockage, or bank failure).
- The radial topographic pattern is evidence that avulsions have occurred (Beaty 1963). Avulsions on alluvial fans will tend to be directed toward topographically lower areas, i.e., slopes steeper than the parent channel, in areas that haven't received recent sediment deposition (Hooke 1967).

Table 14. Physical Variables Which Affect Alluvial Fan Avulsions	
Factor	**Comments**
Fan Physiography	
• Fan Slope	Steeper fans experience more frequent avulsions (P)
• Floodplain morphology	Size and configuration of invaded flood basin (SS)
• Floodplain vegetative cover	Affects conveyance and resistance (SS, M)
• Erosion resistance	Less cohesive floodplain soils more prone to avulsion (SS)
• Presence of existing channels	Overbank flows exploit on-fan flow paths (SS, F)
• Wide, unobstructed floodplain	Open conveyance more conducive to avulsions (SS)
• Drainage area	Large drainage area generates higher peaks and volumes (P)
Discharge	
• Size and duration of avulsion	Large, long overbank flows form more complete avulsions (SS)
• Flood magnitude	Large peaks after proper set-up condition (SS, F)
• Frequency	Floods are of limited duration, avulsions at finite rate (SS)
• Flood ratio	High flood ratio watersheds prone to high overbank floods
• Flood volume	High flood volume capable of more geomorphic work (P)
• Flood sequence	Sequence of floods important for set-up conditions (F)
Channel Pattern	
• Outside of bends	Avulsions more likely on outside of bends (SS, F)
• Sheet flooding	Avulsions likely in sheet flooding areas (F)
• Splays	Avulsion likely in braided channel splays (F)
• Near channel tributaries	Piracy more likely when channels close to parent (F)
Sediment Transport	
• Sediment partitioning	Between parent and avulsion affects closure rate (SS)
• Suspended sediment	Initial overflow high in water column, is sediment deprived (F)
• Bed material load	Occurs on channel bottom, deep avulsions only (SS)
• Small floods aggrade	Results in set-up conditions, loss of capacity (F)
• Total supply	More sediment supply, more frequent avulsions (SS)
• Debris flow potential	Avulsions common on debris flow fans
Breach Geometry	
• Avulsion vs. parent bed elevation	Sediment distribution affected, rate of completion (SS, F)
Slope	
• Downstream vs. cross slope	If slope ratio > 5 avulsion will occur (SS)
Channel Conditions	
• Low bank height; channel depth	Low bank height causes overbank flow (F, SS)
• Aggrading	Main channel aggradation lowers capacity (SS)
• Debris blockage	Lowers capacity (SS, F)
• Bed elevation vs. overbank	Overbank flow needed for avulsion (SS)
• Bank vegetation	Increases channel stability, leads to aggradation (SS, S)
• Height of alluvial ridge	Inversely related, higher ridge when overtopped avulses (SS)
• Bank stability	Directly related (M, S)
Allogenic Factors	
• Change in sediment supply	Increased sediment supply increases avulsion risk (S)
• Change in water supply	Increased water supply increases avulsion risk (S)
• Change in base level	Initiates regional aggradation or degradation (S)

References:

SS = Slingerland & Smith, 2004	F = Field, 1994; 2001	S = Southamer, 2007
M = McCarthy et. al., 1992	P = Pearthree et. al, 2004	M = Mohrig, 2000

There have been few published studies of avulsion frequency, and fewer still that are applicable to alluvial fans in Maricopa County. The following statements summarize the current understanding of avulsion frequency:

- Field (1994) estimated a 50 to 650 year return period for avulsions at five active alluvial fan sites in central and southern Arizona. His estimates were based on interpretation of historical and recent aerial photographs, post-flood inundation mapping, interpretation of soil trench profiles, and limited radiocarbon dating of organic material from two sites.
- Kesel and Lowe (1987) estimated an avulsion recurrence interval of several hundred years for humid region alluvial fans, based on radiocarbon dates.
- Parker et. al. (1998), Whipple et. al. (1998), Schumm et. al. (1987), and Hooke (1967) found that avulsions occurred rapidly and continuously in physical modeling studies of alluvial fans.
- Pelletier et. al. (2005) noted that rapid avulsions occur on a decadal time scale, with a lower frequency on fluvial fans compared to debris flow fans.
- Pearthree et. al, (1992) found that 13 of 19 off-channel soil pits on the Tortolita piedmont near Tucson, Arizona had channel deposits that could be at least tentatively interpreted as evidence of past avulsions.
- DMA (1985), in their verification analysis of FEMA's FAN model (Dawdy, 1978), determined that avulsions occurred on 18 sites in California and Nevada. However, inspection of their records as part of this study indicates that as few as two of the 18 sites had solid evidence of avulsions. DMA further reported that the avulsion coefficient of 1.5 in FEMA's FAN model means that a major avulsion occurs in every other 100-year event.
- Slingerland & Smith (2004) report avulsion frequency ranges from 28 years on the Kosi River in India to 1400 years on the Mississippi River, but that rates may be less in glacial outwash streams and more on non-aggrading rivers.

A number of methodologies to predict avulsions on active alluvial fans were explored as part of this study, and are summarized in more detail in Appendix I. These methodologies attempted to identify two types of avulsive characteristics: (1) non-channelized portions of an active fan surface in which formation of an avulsion is likely, or (2) portions of the existing channel network that are ripe for being abandoned by avulsive processes. The results of these analyses were verified by comparing their predictions to conditions observed in the field and on aerial photographs, as well as by comparing their results to channel changes observed during known avulsive floods on White Tanks Fan 36 and the Tiger Wash alluvial fan. The following methodologies were applied to the four alluvial fan evaluation sites:

- Interpretation of Historical Aerial Photographs
- Field Methods for Identifying Avulsions
- FLO-2D 100-Year Models
- FLO-2D Extreme Flood Models
- FLO-2D Depth-Velocity Zones
- FLO-2D Hazard Classification
- FLO-2D Virtual Levee Scenarios
- FLO-2D Sediment Transport Models

- FLO-2D Channel Blockage Models
- Topographic Analysis: Avulsive Flow Path Models

Based on the results of the analyses and information summarized above, the recommended procedure for evaluating the potential for avulsions on active alluvial fans in Maricopa County consists of the following steps:

- Step One: Historical Analysis. The most reliable means of determining if an alluvial fan is subject to avulsions is to identify evidence of historically recent avulsions. Documentation of past avulsions can be completed by comparing channel locations and conditions on historical and recent (or pre- and post-flood) aerial photographs. In addition to the presence of historical avulsion, the extent, location on the fan surface, and types of avulsions should be described and related to the flood history.

- Step Two: Geomorphic Analysis. An evaluation of the surficial geology of the alluvial fan should be conducted that includes field observations, surficial mapping of active and inactive surfaces, and assessment of debris flow potential. If possible, the geomorphic analysis should include interpretation of stratigraphic data from subsurface soil profiles to estimate fan aggradation rates and occurrence of channel sediments outside the existing channel corridors. If debris flows have the potential to impact that active fan surface, then a detailed debris flow analysis should be conducted using the procedures outlined in Section 2.6 and Appendix H, prior to proceeding to Step Three.

- Step Three: FLO-2D Modeling. FLO-2D models of the fan surface from the hydrographic apex to the downstream limit of the active alluvial fan should be prepared. At minimum, FLO-2D models for the 100-year base condition and a 500-year "extreme flood" should be prepared. Potentially avulsive flow corridors can be identified by overlaying 100- and 500-year FLO-2D flow depths and velocities and hazard classification zones over a recent aerial photograph and identifying disparities from the existing channel network. For specific sites where concerns about avulsion exist, channel blockage FLO-2D models can be prepared to estimate overflow frequency and behavior. Finally, FLO-2D modeling results should be used to prepare an avulsive flow path model analysis.

- Step Four: Sediment Modeling. The sediment yield at the hydrographic apex should be computed and used to estimate potential deposition along the fanhead channel. The sediment yield values should be used to help identify the location of the hydrographic apex as the point where flow is no longer contained in a single channel, and where alluvial fan flooding begins. At some point in the future, improvements in sediment transport modeling tools for alluvial fans may progress to the point which such modeling will improve our ability to predict alluvial fan avulsions. Until such time, detailed sediment transport modeling of the alluvial fan downstream of the hydrographic apex should be used only to identify broad sedimentation trends and likely locations of single-event sediment deposition or possible changes in flow distribution on the fan surface.

- Step Five: Floodplain Delineation. The potential for future avulsions should be considered when delineating an active alluvial fan floodplain. To this end, the virtual levee scenario method results should be incorporated into the predicted inundation limits.

The avulsion analysis task identified the following three primary gaps in the knowledge base required to develop a robust methodology for quantifying alluvial fan flood hazards in Maricopa County:

1. Avulsion Frequency. To resolve this knowledge gap, the District should conduct a study of avulsion frequency on active alluvial fans in Maricopa County, as recommended by the Blue Ribbon Panel.
2. Modeling Methodology. To address the lack of a universally accepted methodology for evaluating avulsion potential, the District should adopt the recommended methodology presented in this report as a first step. Subsequent steps include testing the methodology on alluvial fans in Maricopa County and vetting the methodology with FEMA.
3. Engineering Design Standards. The District should include engineering and design guidelines for development on active alluvial fans in the updated PFHAM.

2.7.1. Conclusions

The objective of the avulsion potential evaluation was to determine and quantify how channel avulsions influence flood hazards on alluvial fan landforms in Maricopa County. This information is to be used to refine the Integrated Alluvial Fan Hazard Assessment Methodology that may be used in future revisions of the District PFHAM methodology. The following conclusions can be made from the evaluation summarized in this report:

- Avulsions Occur on Alluvial Fans In Maricopa County. The occurrence of past alluvial fan avulsions on alluvial fans in Maricopa County is well documented in the literature, by past District studies, and by aerial photographs.
- Avulsion Frequency. The frequency of avulsions on alluvial fans in Maricopa County is not well known, although it is likely that avulsions are relatively rare events. A systematic study of avulsion frequency is strongly recommended. If avulsions are found to be sufficiently rare, avulsions could be eliminated from the recommended integrated methodology, greatly simplifying the required analyses. If avulsion frequency is better quantified, it can be more precisely evaluated.
- Avulsions Affect Flood Hazards on Alluvial Fans. When avulsions occur, they change the distribution of flood peaks and volumes downstream, lead to extensive erosion of the fan surface, and redistribute areas of sediment deposition. Consideration of avulsion impacts should be included in any revisions the District's PFHAM methodology.
- Methodology. There is no broadly accepted technique for identifying and predicting the location or nature of future avulsions. A multi-step methodology for use on alluvial fans in Maricopa County has been proposed as part of this study

3. General Recommendations

3.1. Recommended Definitions of Terms

One of the key findings of the PFHAM study is the importance of using terminology precisely when discussing alluvial fan flood hazards. This is especially true for the term "alluvial fan." Because of the high potential for miscommunication when dealing with regulatory agencies, it is strongly recommended that the current NFIP and FEMA definitions be used for the terms listed in Table 15. This approach will also assure conformity with the rest of the floodplain management community. However, the District should work with FEMA in conjunction with other affected communities to improve FEMA definitions and guidance, where needed.

3.1.1. Definition of Alluvial Fan

The PFHAM scope of services calls for "clear administrative guidance based on technical definitions of what is an alluvial fan." Within the floodplain community, there is near universal agreement that an alluvial fan landform can be defined or identified by the following three criteria:

- Composition. An alluvial fan is a sedimentary deposit composed of alluvium.
- Morphology. An alluvial fan has the shape of fan.
- Location. Alluvial fans are usually located at mountain front or topographic break.[18]

The three criteria listed above are technically sufficient to allow any competent investigator to be able to identify an alluvial fan landform. Unfortunately, there is not universal agreement on how to identify an <u>active</u> alluvial fan. The differences in opinion on how to define an active alluvial fan stem mostly from the floodplain management consequences of delineating an area as an active alluvial fan floodplain. Absent the NFIP insurance regulations for development in areas subject to alluvial fan flooding (e.g., elevation on fill is normally insufficient to remove the insurance requirement), there is general agreement on the defining characteristics of an active alluvial fan. The key characteristics of active alluvial fans include the following:

- Location on an alluvial fan landform
- Flow path uncertainty
- Net depositional environment
- Geologically young surface where flooding is possible

Disagreements over what constitutes an active alluvial fan come primarily from the third aspect of the NFIP definition of active alluvial fan flooding: "An environment where the combination of sediment availability, slope, and topography creates an ultrahazardous condition for which elevation on fill will not reliably mitigate the risk." The key (and most perplexing) term in the quoted portion of the NFIP definition is "ultrahazardous."

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[18] See NRC (1996; cf p. 55 and Examples, p. 83-125) for further discussion of what constitutes a topographic break.

Table 15. Existing FEMA Definitions of Key Terms		
Term	**NFIP or FEMA Definition**	**Comments**
Alluvial Fan	An alluvial fan is a sedimentary deposit located at a topographic break such as the base of a mountain front, escarpment, or valley side, that is composed of streamflow and/or debris flow sediments and has the shape of a fan, either fully or partially extended. (FEMA Appendix G, p. G-6)	This is the definition of the alluvial fan landform. The definition in the Maricopa County Floodplain Regulations uses the old NFIP definition.
Active Alluvial Fan	The term active refers to that portion of an alluvial fan where deposition, erosion, and unstable flow paths are possible. If flooding and deposition have occurred on a part of an alluvial fan in the past 100 years, clearly that part of the fan can be considered to be active. (FEMA Appendix G, p. G-8)	It is recommended that the District work with FEMA to clarify contradictory language in the FEMA Guidelines regarding the defining criteria for active alluvial fans.
Alluvial Fan Flooding	Alluvial fan flooding means flooding occurring on the surface of an alluvial fan or similar landform which originates at the apex and is characterized by high-velocity flows; active processes of erosion, sediment transport, and deposition; and, unpredictable flow paths (44 CFR, Part 59.1)	This is the only definition currently in the NFIP Code of Federal Regulations.
Active Alluvial Fan Flooding	An active alluvial fan flooding hazard is indicated by the following three related criteria: 1) Flow path uncertainty below the hydrographic apex; 2) Abrupt deposition and ensuing erosion of sediment as a stream or debris flow loses its ability to carry material eroded from a steeper, upstream source area; 3) An environment where the combination of sediment availability, slope, and topography creates an ultrahazardous condition for which elevation on fill will not reliably mitigate the risk. (FEMA Appendix G, p. G-2)	This definition closely parallels the "active alluvial fan hazard" definition in the Maricopa County Floodplain Regulations. "Active alluvial fan flooding" applies only to the ultra-hazardous portions of the floodplain of an active alluvial fan. Part 65.13 conditions apply to ultrahazardous areas.
Active Alluvial Fan Floodplain	The extent of the 1-percent-annual-chance (100-year) flood within any floodprone area on an active alluvial fan identified during Stage 2. (FEMA Appendix G, p. G-11)	Only a portion of the active alluvial fan is within the regulatory floodplain.
Inactive Alluvial Fan	For a given area of the alluvial fan, if the situations described in Subsection G.2.2.1 do not exist, then the area is considered inactive and not subject to the deposition, erosion, and unstable flow path flooding that builds alluvial fans. (FEMA Appendix G, p. G-9)	This definition basically states that inactive fans are those that do not meet the definition of active, i.e., inactive = not active.
Inactive Alluvial Fan Flooding	Inactive alluvial fan flooding is similar to traditional riverine flood hazards, but occurs only on alluvial fans. (FEMA Appendix G, p. G-2)	Flooding on inactive alluvial fans can be addressed using riverine modeling techniques. Stable distributary flow areas may require fixed-bed 2d modeling.

Table 16. Definitions of Key Terms Not in FEMA Guidelines		
Term	**NFIP or FEMA Definition**	**Comments**
Alluvial Plain	Not defined in NFIP or FEMA Appendix G. Defined in PFHAM Glossary as "a level or gently sloping tract or a slightly undulating land surface produced by extensive deposition of alluvium, usually adjacent to a river that periodically overflows its banks; it may be situated on a flood plain, a delta, or an alluvial fan."	Note that alluvial plains can occur on alluvial fan landforms, or may be a unique landform type. See discussion below regarding District interpretation of alluvial plain.
Uncertain Flow Path Flooding	A broad category of flooding in which the location of channels and/or the distribution of flooding across a landform cannot be known with certainty.	See NRC (1996)
Sheet Flooding	Any broad expanse of unconfined runoff moving downslope.	See Section 2.1.3 & Appendix C
Distributary Flow Areas	Any landform on which the drainage pattern consists of channels that split, divide, or branch in the downstream direction.	May be stable (flow paths not subject to avulsion) or unstable (uncertain flow path).
Mountain Front	A line defined by the intersection of the steep sloping bedrock mass of a mountain range with the flatter sloped piedmont.	The alluvial fan landform topographic apex is usually located at mountain front.
Re-Infiltration	The continued infiltration of surface runoff as it moves across a land surface, as distinguished from the initial infiltration that occurs as an element of rainfall losses.	Term defined for use in this report. See Section 2.3.2.
Major Avulsion	A major avulsion occurs near a hydrographic apex and has the potential to divert more than 50% of the flow from the parent channel.	See Section 2.7 and Table 13

Unfortunately, the guidance in FEMA Appendix G does little to clarify the intended meaning of "ultrahazardous." On the one hand, the definition states that active alluvial fan flooding reaches a level of hazard so great that elevation on fill cannot mitigate it. On the other hand, FEMA Appendix G (p. G-11) states the following, "Because such sheetflows [near the toe of the fan]...follow unpredictable flow paths, they are classified as active alluvial fan flooding." It is hard to reconcile the characteristics of sheet flooding (shallow, low velocity) found on much of the four alluvial fan sites in the PFHAM study with an ultrahazardous condition for which elevation on fill would not mitigate the risk.

The FEMA Guidelines further complicate the definition of "active alluvial fan," stating that an active alluvial fan may include older alluvial fan surfaces where areas upstream could lead to sheet flood across the surface (p. G-9, 3rd bullet), or parts of the alluvial fan where flooding and deposition have occurred in the past 1,000 years (p. G-8). Comparison of these criteria to riverine conditions is problematic since elevation on fill is considered a reliable means to mitigate flood risk in shallow, low velocity riverine floodplains (and even in deep, high velocity riverine floodplains).

The resolution to these apparently contradictory definitions may be found in the difference between the terms "active alluvial fan flooding" and "active alluvial fan." The NFIP only defines "active alluvial fan flooding," which refers to the actual floodplain delineation (i.e., Zone A determined during Stage 3 of the delineation process). The term "active alluvial fan" is described in FEMA Appendix G and refers to the second stage of the floodplain delineation process. An active alluvial fan, per se, is not regulated by

FEMA. Active alluvial fan flooding, which may occur on a portion of the active alluvial fan, is regulated by FEMA, and consists of the portion of the floodplain that has "ultrahazardous" conditions. Therefore, there must be parts of an active alluvial fan that are subject to a one percent risk of inundation that are not ultrahazardous and thus not subject to "active alluvial fan flooding." This interpretation is consistent with the conclusion of the NRC Report (1996), as well as the opinions of the members of the NRC Alluvial Fan Committee who participated in the PFHAM Blue Ribbon Panel (See Section 4.7 and Appendix J).

To resolve the question regarding definition of active alluvial fans, it is recommended that the District take the following actions:

- FEMA Coordination. The District should work with FEMA to clarify apparent contradictions in FEMA Appendix G guidance. Specifically, differences between "active alluvial fans" and "active alluvial fan flooding" should be clarified. One potential avenue for FEMA coordination is the Association of State Floodplain Managers (ASFPM) Arid Regions Committee White Paper (ASFPM, 2010) recommending improvements to FEMA Appendix G. The District should participate in and support the ASFPM effort, and encourage the Arizona Floodplain Management Association (AFMA) and other local communities to do so as well.
- District Definition. The District should make an affirmative statement that active alluvial fan flooding applies only to the areas of ultrahazardous flood conditions on an active alluvial fan. That is, there are portions of active alluvial fans that are not subject to ultrahazardous flood conditions, and these areas should be distinguished as such.
- Quantify Ultrahazardous. The District should use the USBR Figure 2 hazard classification criteria, as outlined in Sections 2.3.3.9 of this report to define the portions of the active alluvial fan that are subject to ultrahazardous flood conditions.
- Inactive Alluvial Fan. The District should continue use the FEMA Appendix G definition of the term "inactive alluvial fan." Efforts to re-define "inactive" will create confusion in the Stage 2 delineation, as well as potential roadblocks for FEMA approval of the recommended methodology.

3.1.2. Definition of Alluvial Plain

The District also has concerns regarding definition of alluvial plains, and would like clear guidance on how to distinguish active alluvial fans from alluvial plains. Alluvial plains can occur on piedmont and alluvial fan landforms, but are most commonly identified along river corridors. There is also an alluvial plain landform that is transitional in character (as well as spatially) between alluvial fan landforms and riverine alluvial plains. While it is relatively easy to distinguish riverine alluvial plains from piedmont landforms, these transitional alluvial plains are not easily distinguished from alluvial fan landforms as there is generally an irregular, gradational boundary between the alluvial fan and the piedmont alluvial plain. Normally, smaller alluvial plain surfaces that occur on the piedmont are considered part of the alluvial fan landform, as indicated by the last part of the PFHAM definition[19] of alluvial plain.

Some of the defining characteristics of alluvial plains include the following:

- Smooth or gently undulating terrain
- Dominated by unconfined, non-channelized flow, which may consist of sheet flooding or shallow overbank flooding
- Uniform vegetative characteristics
- Lack of well-defined channels or flow paths
- Fine-grained sediment substrate
- Non- or marginally erosive velocities
- High rates of flow attenuation due to extensive floodplain storage and infiltration
- Parallel rather than radial contour pattern
- Location far enough from a mountainous watershed that the dominant flow originates on the alluvial surface itself, though some contribution of runoff from a distant mountainous watershed is possible

Note that some of the characteristics listed above also apply to some alluvial fans. In practice, there is a very gradual transition from an active alluvial fan to an alluvial plain on a piedmont landform for which no clear demarcation may exist. FEMA Guidelines indicate that sheet flooding on an alluvial fan landform is alluvial fan flooding. Therefore, the occurrence of sheet flooding is not a reliable diagnostic characteristic for distinguishing alluvial fans and alluvial plains.

This study evaluated ways to demarcate a boundary between an alluvial plain and an alluvial fan landform both in Stage 1 and Stage 2 of the delineation process. While this can easily be done at Stage 1 for boundaries between riverine alluvial plains and alluvial fan landforms, it would be problematic in Stage 2 when attempting to demarcate an active alluvial fan from an alluvial plain on an alluvial fan landform. If the motivation for making this distinction in Stage 2 is to minimize the area that could be classified as subject to "alluvial fan flooding," as that term is currently defined by FEMA, then the approach outlined in Section 3.1.1 above may circumvent the need for such a distinction. If not, there are a number of challenges to delineating a physical boundary between alluvial plains and active alluvial fans on alluvial fan landforms, including the following:

- There is no established regulatory procedure for making such a distinction.
- Descriptions of the two features in the literature are not precise enough to eliminate subjectivity in such a delineation.
- Alluvial plains and the toes of active alluvial fans have similar characteristics (sheet flooding, planar topography, parallel and distributary drainage paths, etc.)
- It is clear from the literature that neither alluvial plains nor active alluvial fans are identified based solely on slope. While alluvial plains typically have flat slopes (< 2%), alluvial fans described in the literature have slopes ranging from far less

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[19] PFHAM Glossary: An alluvial plain is a level or gently sloping tract or a slightly undulating land surface produced by extensive deposition of alluvium, usually adjacent to a river that periodically overflows its banks; it may be situated on a flood plain, a delta, or an alluvial fan (p. 164).

than 1% to well above 10%. By itself, slope is not a diagnostic feature for distinguishing alluvial plains and alluvial fans.

As the District completes more alluvial fan floodplain delineations and collects more data, it may be possible to define measurable characteristics that can be used to distinguish active alluvial fans from alluvial plains in Maricopa County. Possible parameters for consideration include developing a relationship describing the geometric change of slope in the downfan direction, measurements of drainage density, or other forms of contour analyses. At this time, sufficient data do not exist.

Because of the similarities between active alluvial fans and alluvial plains located downstream of active alluvial fans, it is recommended that the proposed integrated methodology be applied to both feature classifications. The similarities include the following: (1) both are subject to uncertain flow paths, (2) both are subject to uncertain flow rate, and (3) neither is subject to ultrahazardous flood conditions.

3.2. Recommended Design Frequency

The 100-year (1%) design frequency is recommended for regulation of alluvial flood hazards in Maricopa County for the following reasons:

- FEMA Standard. The 100-year event is firmly established in federal regulations as the standard of design for floodplain management. Deviation from the federally-mandated minimum criteria would require broad political support. NFIP member communities are allowed to adopt more stringent standards.[20]
- Maricopa County Standard. The 100-year event is the standard of regulation and design for all other types of floodplains in Maricopa County. This study has documented that although alluvial fan flooding hazards are different than riverine floodplain hazards, they are not so hazardous as to require a different design standard. The unique aspects of alluvial fan flooding in Maricopa County can be addressed by applying the integrated technical approach outlined in this report.
- Maricopa County Cities and Towns. Use of a higher design standard may complicate District involvement with the regulatory policies and flood control planning with other Maricopa County incorporated communities.
- State of Arizona Criteria. No other community in Arizona currently regulates anything other than the 100-year event. All of the ADWR State Standards are based on the 100-year flood.
- Regulatory Authority. It is not clear whether the State of Arizona's floodplain management enabling legislation would allow Maricopa County to use a higher design standard without action by the State Legislature. This matter should be discussed with the District's legal counsel.
- Technical Criteria. While there are hazards that are unique to alluvial fan floodplains in Maricopa County, no technical bases were identified that would justify raising design standards for alluvial fans. Attempts to replace some of the recommended procedures with 500-year and PMP-based floods were found to inadequately depict the flood hazard.

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[20] The State of California recently adopted a 200-year standard of design for levee floodplains.

- Debris Flows. Some communities in North America and Europe regulate debris flow hazards using a 200-year or higher design standard. However, the PFHAM study determined that debris flows were not a significant risk for alluvial fan flooding in Maricopa County. Therefore, for the few instances in which there is a risk of debris flow, a site-specific analysis of those hazards using the procedures outlined in this report is recommended.
- Distributary Flow Areas. No technical basis for applying a different design standard for distributary flow floodplains was identified during the course of this study. The 100-year event is recommended as the standard of design.
- Risk-Based Analysis. As an alternative to the 100-year design standard, the District could follow the lead of some federal agencies and move toward risk-based design. Risk-based analysis of alluvial fan flooding is already one of the approved methodologies listed in the FEMA Guidelines (2003, Appendix G, Table G-1).

It is recommended that the District follow FEMA guidance for selecting the regulatory design standard for alluvial fan flooding. Currently, the 100-year event is the standard of design.

3.3. Engineering Tools for Alluvial Fan Flood Hazard Assessment

Task item 2.9.3.1 of the PFHAM study scope of work requires that a matrix or list of engineering tools and methodologies be recommended for assessing the type and degree of flood hazards on alluvial fans landforms in Maricopa County. The recommended engineering tools matrix is shown in Table 17 below. Note that Table 17 only lists the engineering tools, as directed by the District scope of work. Other tools may exist and may be added to the list in the future. A brief outline of how the recommended engineering tools listed in Table 17 can be applied is described in the following paragraphs. The description of the recommended Integrated Alluvial Fan Hazard Assessment Methodology in Maricopa County, that incorporates all the engineering, geomorphic, and other tools, is provided in Section 4.

Table 17. Recommended Engineering Tools for Alluvial Fan Flood Hazard Assessment

Discipline	Recommended Engineering Tool		
	Active Alluvial Fan	**Alluvial Plain**	**Inactive Alluvial Fan**
Hydrology	FLO-2D	FLO-2D	Current District Hydrology Manual
Hydraulics Whole Fan Local Site	 FLO-2D HEC-RAS	 FLO-2D HEC-RAS	 Current District Hydraulics Manual
Sediment Transport Whole Fan Local Site	 FLO-2D HEC-RAS, HEC-6	 FLO-2D HEC-RAS, HEC-6	 Current District Hydraulics Manual
Debris Flow	LAHAR-Z	Not applicable	Not applicable
Surficial Dating	Optical Stimulated Luminescence Cosmogenic Nuclide	Radiocarbon – AMS Varnish Microlamination	
Avulsions	FLO-2D Avulsive Flow Path Tool Sediment Yield (District)	FLO-2D	Not applicable

Note: FLO-2D was selected for use in the PFHAM study (See Section 2.3.3). However, any two-dimensional model with similar or superior capabilities may be used.

3.3.1. Hydrologic Modeling

The recommended engineering tool for hydrologic modeling of active alluvial fans and alluvial plains in Maricopa County is FLO-2D. Upstream of the hydrographic apex and on inactive alluvial fans, the current District modeling practices should be followed. HEC-1 or other lumped parameter, unit hydrograph flood routing models are not recommended for active parts of alluvial fans. There may valid reasons to select FLO-2D for modeling the entire watershed, as well as for the active alluvial fan area, but that decision should be coordinated with the District prior to beginning the modeling effort. A few of the reasons for using FLO-2D to model the hydrology of areas above a hydrographic apex might include: (1) better representation of spatial variation in watershed parameters, (2) simplification of the modeling process – use of one model instead of multiple models, (3) better accounting for attenuation and infiltration in low-sloping watersheds with poorly defined flow paths, (4) deficiencies in the unit-hydrograph approach for generating runoff in low-sloping watersheds with poorly defined flow paths, (5) presence of stable distributary or sheet flooding areas upstream of the hydrographic apex, and (6) presence of multiple poorly defined watersheds that contribute runoff to the active alluvial fan area downstream of the hydrographic apex.

In addition, the following special conditions should be considered for active alluvial fans:

- Virtual levee scenario method. The virtual levee scenario method should be used to estimate peak discharge at all points downstream of the hydrographic apex. Use of the full apex discharge is not recommended for design purposes. The maximum discharge from the cumulative virtual levee scenarios should be used for design purposes.
- Coalescing alluvial fans. Where one or more active alluvial fans coalesce, combination of discharges from adjacent fans should be estimated using the virtual levee scenario method.
- Future conditions. For planning studies, future condition discharges should be estimated by applying full-build out of the fan surface with normal retention requirements and whatever current District (or local community) development policies exist at that time.
- Flood conveyance corridor. For planning purposes, it may be useful to identify a flow corridor that could be used to convey upstream and local runoff from the hydrographic apex to the toe of the alluvial fan landform.
- Sheet flooding areas. Where runoff is expected to occur as unconfined sheet flooding, peak discharge estimates should reflect the total flow reaching the upstream boundaries of a site, or flow across the entire sheet flooding area, rather than the point discharge at a single concentration point or grid cell.
- Model sensitivity. Given the potential for uncertainty in hydrologic modeling, it may be necessary to run a number of modeling scenarios with different input parameters to build confidence in the final predicted results.

Other hydrologic modeling recommendations were provided in Section 2.3.2.4 of this report.

3.3.2. Hydraulic Modeling

The recommended engineering tools for (water-only) hydraulic modeling on active alluvial fans and alluvial plains are FLO-2D and HEC-RAS. The scenarios in which each model should be used are summarized in Table 18. In general, FLO-2D should be used for overall modeling of the fan surface, including estimation of peak (design) discharges. HEC-RAS should be used to estimate hydraulic parameters in individual channels at specific sites in most circumstances. The District employs this same division of hydraulic modeling tools in the highly distributary channel networks near the Rio Verde area in northern Maricopa County. However, if the District submits a floodplain delineation to FEMA with the Zone AE designation, the FLO-2D model results must be used to set finished floor elevations, per FEMA guidance. Additional freeboard should be provided to account for potential sediment deposition (aggradation), as discussed in Section 3.3.3 below.

Table 18. Selection of Hydraulic Modeling Tools

Modeling Scenario	Recommended Tool
Design Discharges	FLO-2D – virtual levee scenario method
Flow Distribution over Active Fan Surface	FLO-2D
Flow Distribution over Alluvial Plain	FLO-2D
Water Surface Elevations at Building Site	HEC-RAS* Use FLO-2D discharge Include sediment deposition
Hydraulic Design Data (depth, velocity, etc)	HEC-RAS Use FLO-2D discharge
Notes: * Unless delineation submitted as Zone AE. See text above for discussion.	

HEC-RAS (or any similar model) is preferred over FLO-2D for site-specific hydraulic analyses where the following conditions exist:

- The modeling reach has fine-textured topography that cannot be readily defined by grid-based topographic data. If HEC-RAS is used, topographic data and cross section spacing should be coded into the model in a manner that accurately portrays the subtleties of the local terrain.
- Flow is primarily one-dimensional and gradually-varied flow conditions exist.
- A single design discharge (steady flow) reasonably approximates flow conditions.
- Flow is conveyed in a relatively well-defined natural or engineered channel.
- The modeling reach is short enough that flow volume conservation is not a factor.

FLO-2D is preferred for the following types of hydraulic modeling exercises on active alluvial fans and alluvial plains:

- Determining flow hydraulics in broad sheet flooding areas
- Modeling of the entire alluvial surface
- Identifying preferred, alternative or avulsive flow corridors
- Identifying low relief "islands" within the active fan (use extreme flood discharges)
- Estimating impacts of development in active fan attenuation areas

3.3.3. Sedimentation Modeling

A variety of tools are recommended for sedimentation modeling on active alluvial fans and alluvial plains. First, prediction of sediment yield to the hydrographic apex should be completed using the procedures outlined in the District's Hydraulics Manual. Similarly, the District's Hydraulics Manual lists specific methodologies for the computation of scour that should be used in channel and site design. The PFHAM study did not identify any reasons to replace any of the District's currently approved methodologies for scour and sedimentation. Second, use of FLO-2D and HEC-RAS should be partitioned in a similar manner as described above for hydraulic modeling (Section 3.3.2). FLO-2D should be used in broad scale surface analyses, and HEC-RAS should be used for site-specific evaluations that meet the conditions listed above. Where sediment continuity modeling is needed, HEC-6 or HEC-6T is recommended.

The sediment modeling tasks performed for the PFHAM study led to the conclusion that FLO-2D results are sensitive to the transport function selected, and that sediment transport will affect the single event maximum flow depths and velocities, at least in the high hazard zones near the fan apex. Long-term sediment deposition and scour may similarly impact hydraulic conditions in the high hazard zone over longer planning periods. The study also identified the need to further refine the sediment modeling routines in FLO-2D and to collect data for calibration of its application to alluvial fans. Based on the results summarized in this report, use of the Zeller-Fullerton sediment transport equation is recommended, at least until more data are available from which to make a more refined evaluation.

For site specific analyses in the ultra-hazardous and high hazard portions of active alluvial fans, the District's current guidelines should be applied to estimate the potential for long-term aggradation at a proposed development, and the estimated deposition should be added to the water surface elevations as freeboard.

3.3.4. Surficial Dating

The recommended methodologies listed in Table 17 probably are better classified as quantitative geologic techniques, rather than engineering tools, but are described in this section because they are numerical techniques. These geomorphic dating tools may be used to better refine estimates of surface age, and therefore may inform on the degree of alluvial fan activity, as well as help distinguish between active and inactive alluvial fan surfaces. A combination of relative and numerical methods may be applied where more detailed age resolution is needed, in conjunction with conventional surficial mapping techniques, to most accurately determine surface age on alluvial fans in Maricopa County. OSL and AMS radiocarbon dating methods are the most applicable numerical dating methods for dating alluvial fan sediments on fan landforms in Maricopa County. Cosmogenic nuclide dating and varnish microlamination correlation are the most favorable methods for estimating surface ages. Varnish microlamination (VML) is a correlative method and should be evaluated further in Maricopa County. As noted in Section 2.5 and Appendix G, the recommended quantitative dating techniques have varying degrees of precision, and would be improved by development of a regional dating chronology for Maricopa County.

3.3.5. Debris Flow Assessment

This study concluded that debris flows are unlikely to impact regulatory flood hazards on alluvial fans in Maricopa County for two primary reasons: (1) they occur so infrequently or, (2) when they do occur they do not runout far enough to reach the hydrographic apex of the alluvial fan. Nevertheless, to complete the project scope of work a three-step procedure for evaluating debris flow potential and hazards was developed for use on piedmont surfaces in Maricopa County in the event that a debris flow hazard is identified at a specific fan site.

For evaluation of debris flow hazards, the recommended engineering tool is the LAHAR-Z model, as described in Section 2.6 and Appendix H. Again, this study found that it is unlikely that debris flows will impact flood hazards on active alluvial fans in Maricopa County. Furthermore, use of the LAHAR-Z model is recommended only after completion of more foundational analyses in the recommended multi-step process.

3.3.6. Avulsion Assessment

Two engineering tools are recommended as part of the assessment of avulsion potential on active alluvial fans: (1) FLO-2D and (2) an avulsive flow path tool, both of which are discussed in more detail in Section 2.7 and Appendixes F and I. A variety of FLO-2D modeling scenarios are used to help predict the location and occurrence of avulsions, including the following: (1) 100-year base models, (2) extreme flood models, (3) hazard classification models, (4) sediment models, and (5) channel blockage models. The avulsive flow path tool uses topographic data and FLO-2D flow vector data to identify potential avulsive corridors, as defined by slope and conveyance, which are located outside the existing channel network.

3.3.7. Limitations of the Geomorphic (Only) Approach

The overall recommendation of the PFHAM study is for a methodology that integrates engineering and geomorphic techniques to achieve a more robust, comprehensive analysis of flood hazards on active alluvial fans. The existing PFHAM methodology follows the lead of the NRC (1996) and FEMA Appendix G in relying heavily on geomorphic methodologies for delineating alluvial fan floodplains. However, over-reliance on geomorphic interpretation alone may result in the following weaknesses:

- Urbanized Alluvial Fans. It is difficult to apply geomorphic assessment techniques on urbanized alluvial fans for several reasons. First, urbanization obscures many of the natural landscape feature used to support a geomorphic assessment. Second, grading of the natural topography often accompanies urbanization, changing the natural distribution, rate and volume of runoff. Third, road and building construction typically obstructs, diverts and alters natural flood and sediment transport processes. Finally, urbanization usually alters the natural balance of sediment and water supply, resulting in significant changes to the pre-development stream morphology. Therefore, in urbanized or developing areas, it is more important to include engineering methodologies in the overall assessment procedures.
- Quantitative Results. As currently formulated, the geomorphology-based PFHAM methodology does not provide quantitative engineering data needed for

design of structures, implementation of structural flood control measures, and performance of standard floodplain management tasks such as setting safe finished floor elevations. Note that the existing PFHAM methodology was originally intended primarily for alluvial fan hazard zone delineation, not development of engineering design data.

- Subjectivity. While there are varying degrees of subjectivity in all types of engineering analyses, there is a relatively high degree of applied judgment inherent in the geomorphic methodologies in the current PFHAM manual that has complicated its implementation.
- Expertise. Use of geomorphic methodologies requires special training, extensive field experience, and understanding of natural surficial processes that are outside the practice of many civil engineers. Therefore, any methodology that relies solely on geomorphic expertise will be difficult to implement among practitioners without such skill sets.

3.4. Flood Hazard Classification Matrix

3.4.1. Flood Hazard Zones on Alluvial Fans in Maricopa County

Based on the results of the PFHAM study tasks, the project team was able to reach consensus and definitively conclude the following with respect to classification of flood hazards on alluvial fans in Maricopa County:

- Ultrahazardous Levels. It is possible, though unlikely, that there may be ultrahazardous flood zones that meet FEMA's criteria for "active alluvial fan flooding" on small portions of some alluvial fans in Maricopa County.
- Conveyance & Uncertain Flow Path Flooding. On alluvial fans in Maricopa County, there are areas characterized by channelized flow, higher flow depths and velocities, and uncertain flow paths which typically have higher flood hazards.
- Sheet Flooding & Ponding. On alluvial fans in Maricopa County, there are areas of relatively low flood hazards dominated by sheet flooding.
- Engineering Tools. There are engineering tools, such as FLO-2D, that are capable of predicting areas of high and low hazards on alluvial fans.
- Geomorphic Tools. There are geomorphic tools that are capable of identifying areas of high and low hazards on alluvial fans.
- Integrated Approach. The best way to evaluate alluvial fan flooding hazards is an approach that integrates engineering and geomorphic tools.
- Key Variables. There is a relatively small set of variables that are most important for predicting the degree of flood hazards on alluvial fans in Maricopa County.
- Floodplain Management. Floodplain management restrictions and guidelines for development on alluvial fans should reflect the degree of flood hazard.

Based on the criteria listed above, the District decided to use the hazard classification scheme described in Section 2.3.3.9 of this report as the basis for evaluating avulsion potential in alluvial fan flooding areas, and elected not to use the USBR hazard classification curves in the final recommended procedure. The final hazard classification selected by the District is based on FLO-2D estimates of flow depth, as summarized in Table 19, and the following additional criteria:

- 100-Year Discharge. If the 100-year peak discharge is less than 50 cfs, Maricopa County Floodplain Regulations dictate that the floodplain is not regulatory. Below the hydrographic apex of an active alluvial or on an alluvial plain, the 100-year discharge is measured as flow along individual defined channels or the sum of flow approaching the upstream boundary as sheet flooding.
- Debris Flow. All areas subject to debris flow hazards are deemed ultrahazardous zones, regardless of other criteria. The recommended procedures for identifying debris flow risk are outlined in Section 2.6 of this report.
- Avulsion. Portions of active alluvial fans at risk of major avulsions are considered high or ultrahazardous zones. The recommended procedures for identifying avulsion risk are outlined in Section 2.7 of this report. The following avulsion characteristics are used in Table 19:
    - Major avulsions occur near a hydrographic apex in areas of high flow depths and velocities, involve major channel relocations or formation of significant channels, or have the capability of diverting 50 percent or more of the hydrograph, and are often caused by excessive sediment deposition.
    - Minor avulsions occur in distal or medial portions of the active fan area, divert smaller parts of the parent channel flow, involve formation of new distributary linkages (as opposed to abandoning the parent channel), or occur in areas of medium or low flow depths and velocities, and are often caused by piracy or erosion.
    - Frequent avulsions occur with a less than 50-year recurrence interval.
    - Infrequent avulsions occur with a 50- to 200-year recurrence interval.
    - Rare avulsions occur with a greater than 200-year recurrence interval.
- Multiple Criteria. In the unlikely event that the criteria in Table 19 indicate different hazard levels, the highest hazard level should be used.

Table 19. Recommended Hazard Zone Classification Criteria
(Applies only if Q100 > 50 cfs and FLO-2D Depth > 0.3 ft)

Hazard Level	Ultra-Hazardous (Active Alluvial Fan Flooding)	Areas of Conveyance & Uncertain Flow Paths	Areas of Sheet Flooding
Risk of Debris Flow	Yes	No	No
Avulsion Characteristics	Major - Frequent	Major – Infrequent Minor - Frequent	Minor - Infrequent Minor - Rare

Notes:
1. If the apex 100-year discharge is less than 50 cfs, the floodplain is non-regulatory, and no delineation is required.
2. If the 100-year depth from FLO-2D modeling is less than 0.3 ft, the floodplain is non-regulatory, and no delineation is required.

The following variables known to affect the severity of alluvial fan flooding were considered for use in Table 19 but were ultimately abandoned, for the reasons explained below:

- Fan Slope. The slope of the alluvial fan surface is both the result of and cause of the degree of flood hazard on alluvial fans. In general, steep alluvial fans are more hazardous than low-sloped alluvial fans. However, there are no widely accepted slope thresholds published in the literature or in practice that can be used to classify alluvial fan flooding hazards.

- Flow Depth. Flow depths in all of the plots of FLO-2D results in this report use depth category thresholds of 0.3 feet, 0.6 feet, and 1.0 feet (and above) because of technical references indicating that flows less than 0.3 feet deep tended to be non-erosive (i.e., non-avulsive). On that basis, flow depth was considered as one of the categories for the hazard zone classification criteria in Table 19. However, FLO-2D plots of discharge indicate that in some cases, areas of shallow flow (< 0.3 ft) may still convey discharges well in excess of the County's 50 cfs threshold. Also, it is noted that the FLO-2D depths reported represent averages over the grid cell width, and may underestimate actual maximum flow depths in channels smaller than the grid size. Therefore, to avoid discounting very real flood hazards associated with (predicted) low FLO-2D depths, use of depth alone as a criteria was initially discontinued. However, the District decided that flow depth shall be used as part of the FEMA floodplain classification.
- Watershed Area. In general, alluvial fans with large watersheds tend to have large peak discharges, which in turn result in more severe flood hazards. However, watershed area per se is not a factor for determining flood hazard. It is the flood discharges the watershed produces that affect flood hazard levels.
- Peak Discharge. Alluvial fans with large peak discharges tend to have higher hazard levels than alluvial fans with small peak discharges. However, it is really the flow depths and velocities which define the hazard, not the discharge alone. That is, a large discharge spread over a wide area at shallow depth is normally less hazardous than that same discharge when concentrated in a defined channel.
- Stream Power & Shear Stress. These variables definitely impact the ability of flooding to transport sediment, but for the purposes of assessing broad hazard classifications, they are adequately captured by evaluating flow depth and velocity.
- Distance from Apex. The degree of flood hazard generally decreases with distance from the hydrographic apex. However, no consistent relationship between flood hazard and distance from the apex was observed in the field, in post-flood observations, or in FLO-2D modeling results.
- Sediment Yield. Fans with high sediment yields to the fan apex tend to be more vulnerable to avulsions, and thus may have higher flood hazards. However, difficulties in predicting sediment yield, as well as sediment transport on active alluvial fans, make use of this variable problematic, at least using the currently available technology. The impacts of sediment delivery are adequately captured in the debris flow potential and avulsion analysis.
- Channel Capacity. Stream channels with low capacity (relative to the flow rate and sediment supply) on active alluvial fans are more prone to overflow and cause avulsions, and thus may be more hazardous than fans with higher capacity channels. However, channel capacity is adequately captured by the FLO-2D modeling used to establish the USBR hazard classifications. Channel capacity is also a factor in the avulsion potential analyses. Note that channel capacity is one of the key factors in identifying the location of the hydrographic apex.

The PFHAM study scope of work Task 2.9.2 requires that a "flood hazard classification matrix based on engineering parameters" be developed to distinguish the degree of alluvial fan flood hazards. A draft flood hazard classification matrix was presented to the District PFHAM task force at a brainstorming meeting on April 21, 2009. The original intent of the flood hazard classification matrix was to identify specific measurable or predictable characteristics indicative of the degree of flood hazard, such as flow depth, velocity, fan slope, stream power, shear stress, debris flow potential, watershed size, distance from the hydrographic apex, sediment transport capacity, flood frequency, avulsion potential, surface age, sediment yield, historical channel movement, and channel capacity.

In addition, the District identified the following necessary characteristics for the flood hazard classification matrix:

- Be simple, concise, implementable, and understandable
- Be usable by "journeyman" engineers and regulators
- Provide unambiguous regulatory guidance
- Contain specific criteria for defining hazards
- Support responsible and appropriate regulation
- Provide mitigation guidance
- Provide reliable, repeatable quantitative measures that address uncertainty
- Be technically supportable
- Include tools for different types of alluvial fan flooding hazards

The District PFHAM team also outlined a general description of what might constitute high and low hazard levels on alluvial fan floodplains in Maricopa County, as summarized in Table 20. While the descriptions of the characteristics listed in Table 20 are broadly informative, they are qualitative, and do not meet the District's goal of quantifying flood hazards on alluvial fan. Ultimately, while the highly detailed draft flood hazard classification matrix concept was used to guide the investigations summarized in Section 2 of this report, the final version evolved into the more simplified form shown in Table 19 for the following reasons:

- Variables. The large numbers of variables that affect the degree of flood hazard on active alluvial fans make application of a matrix too complicated and impractical.
- Precedent. No published information was identified that clearly and definitively categorized the degree of hazard relative to many of the specific variables considered.
- Consensus. The project team was unable to reach consensus on how to classify many of the variables as to the degree of hazard.
- Results. The results of the technical analyses performed for the PFHAM study pointed toward a more feasible way to classify flood hazards on alluvial fans in Maricopa County, as presented in Section 3.4.1 and Table 19.

Table 20. General Characteristics of High and Low Hazards on Alluvial Fan Floodplains in Maricopa County		
Characteristic	**Areas of Conveyance & Uncertain Flow Path Zones**	**Sheet Flooding & Ponding Zones**
Velocity	High	Low
Sediment Transport Capacity	High	Low
Channel Stability	Low	High
Debris Flow Risk	High	None
Drainage Area	Large	Small
Fan Slope	Steep	Flat
Distance from Mountain Front	Short	Long
Roads & Development	Affect Flooding	No Effect on Flooding
Danger to Life	Yes	No
Danger to Property	Yes	Some
Ease of Management	Difficult	Normal
Elevation on Fill Adequate	No	Yes
Sheet Flooding	No	Yes
Flood Control Measures	Regional	Site
Floodway	Yes	No

Discussion of how the hazard classification is incorporated into the overall recommended methodology is provided in Section 4.4.

3.5. Recommended Design Guidelines

Development on active alluvial fans should be designed so that structures are not damaged by the regulatory flood and so that it has no adverse impacts to adjacent properties. That is, development on active alluvial fans should be held to the same development standards in any other type of floodplain in Maricopa County. Because some flood hazards are unique to active alluvial fans, the flood hazard analyses techniques for hydrology, hydraulics, sedimentation, debris flow, avulsion, and floodplain delineation described above (Sections 3.3 and 4) should be applied, as outlined in Table 17 and Table 24. Some additional design guidelines for development on active alluvial fans include the following:

- Design Discharge. The 100-year event should be used as the standard of design, as discussed in Section 3.2 above. When determining adverse impacts, a range of discharges (Q2-Q10-Q100) should be considered to assure that impacts to adjacent properties do not occur either in frequent floods or the regulatory flood.
- Debris Flow Hazards. Debris flows are not a risk factor for the vast majority of alluvial fans in Maricopa County. However, if steep alluvial fans near mountain slopes vulnerable to mass movement are identified in Maricopa County, the portions of the alluvial fans vulnerable to debris flow impacts should be managed as ultrahazardous flood zones, and major engineered flood control mitigation measures should be mandated prior to any development.
- Analysis Required. In the areas of conveyance, uncertain flow paths, sheet flooding and ponding, no development should occur without a detailed engineering analysis that uses the flood hazard assessment methodologies described above, and that is sealed by an applicable Arizona registrant.

- Conveyance Corridors.[21] For large active alluvial fans where development is expected to occur, the District should identify conveyance corridors with sufficient right-of-way to convey flood discharges from the hydrographic apex to a downstream watercourse with sufficient capacity, and/or detention basin sites required to reduce peak discharges to meet downstream conveyance limits. Identification of conveyance corridors is fundamentally a planning activity, rather than a floodplain delineation task.
- FEMA Criteria. For development in mapped active alluvial fan floodplains,[22] the County has traditionally required that the FEMA floodplain be changed through the CLOMR/LOMR process. To revise a FEMA floodplain for an area subject to active alluvial fan flooding, the requirements of 44 CFR, Part 65.13 must be met, which include the following:
    - Elevation on fill alone *generally* (emphasis added) is not sufficient to revise a FEMA active alluvial fan floodplain delineation. Typically, major structural flood control measures are required.
    - Engineering analyses must be prepared that address the potential for erosion, scour, deposition, sediment, debris flow, and local inflow.
    - An operations and maintenance plan underwritten by a public agency is required for any structural flood control measures relied on to alter an active alluvial fan floodplain.
- Operations and Maintenance. Any structural measures relied on for flood control should have well-documented operations and maintenance plan that demonstrate continued safe functioning of the flood protection measures.
- Sheet Flooding Zone. Development in sheet flooding areas of active alluvial fans and alluvial plains may be allowed if the following criteria are met:
    - Runoff enters and leaves the developed area in the same manner as in pre-development conditions. This requirement may mean that a portion of some lots remain undeveloped.
    - Finished floors for single lot homes are elevated 2 feet above the 100-year water surface elevation.
    - Drainage openings are provided in any wall or obstruction of flow sufficient to prevent capture of sheet flooding and ponding that will adversely impact a structure.
    - Fill pads that may be impacted by off-site runoff should be protected against scour and erosion.
- Single Lot Development. The District should develop rules of development for single lot construction using the Rio Verde ADMP regulations as a template. Implementation of single lot development guidelines for active alluvial fans may require revision of the County Floodplain Regulations and/or development of a County-wide Area Drainage Master Plan for active alluvial fan areas.

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[21] Through-flow corridors are existing well-defined channels on active alluvial fans that convey flow from an active area toward the toe of the alluvial fan landform. Conveyance corridors may or may not follow existing through-flow corridor channels.
[22] The District intends that only the ultra-hazardous areas be subject to NFIP Part 65.13 criteria. Other (non-ultra-hazardous) parts of an alluvial fan floodplain would be subject to the NFIP Part 65.10 criteria.

- Performance assessment. The District should systematically monitor the performance of flood control measures constructed on active alluvial fans to provide feedback for refining and upgrading their design guidelines.

3.6. Recommended PFHAM Refinements

One of the primary objectives of the PFHAM study was to "make recommendations for updating the PFHAM."[23] Actual revision of the PFHAM, if necessary, will be completed by the District in the future. General recommendations for analyzing and quantifying flood hazards on active alluvial fans have been made throughout this report, and are summarized in Section 5 below. Recommendations specific to the PFHAM manual are provided in the following paragraphs.

3.6.1. Definitions

The definitions of terms used in the PFHAM Manual should be consistent with the definitions used in FEMA guidelines and NFIP regulations, as discussed in Section 3.1. The District should work with FEMA, ASFPM, AFMA, and other local communities to improve FEMA description and definition of an active alluvial fan (See Section 3.6.5).

3.6.2. Stage 1 Refinements

The following recommendations apply to the Stage 1 methodology as described in the existing PFHAM:

- Focus on Alluvial Fan Landforms. The PFHAM Stage 1 methodology should focus on distinguishing alluvial fan landforms from non-alluvial fan landforms. Identifying relict fans and pediments should be part of the Stage 2 (Active / Inactive) analysis.
- Simplify. Identification of alluvial fan landforms should be a relatively simple task that requires a minimal level of effort. The Stage 1 methodology should be simplified to the three basic criteria: composition, morphology, and location.
- Fan Boundaries. The guidelines for delineating the boundaries of alluvial fan landforms should be improved, particularly with respect to the following:
  - Identifying the toe of alluvial fan landforms
  - Identifying the boundaries of coalescing alluvial fans (bajada)
  - Identifying the topographic apex along embayed mountain fronts
- Alluvial Plains. Techniques for distinguishing alluvial plain landforms[24] from alluvial fan landforms should described, and examples should be provided. Note that because many alluvial plains are subject to flow path uncertainty due to unconfined sheet flooding, some of the floodplain analysis techniques for active alluvial fans described in this report may be more applicable than traditional riverine modeling techniques. Separate (Stage 3) floodplain delineation techniques for alluvial plains should be developed, perhaps as a separate chapter in the PFHAM.

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[23] PFHAM Study Scope of Work, Task 1.1.2.

[24] As opposed to alluvial plain surfaces on alluvial fan landforms, identification of which is part of the Stage 2 analyses.

- Countywide Delineation. The District should perform a Stage 1 landform delineation for the entire County, or at least the potentially developable lands within the County. This exercise could be completed with minimal effort, would provide valuable information on where alluvial fan flood hazards exist, and would be useful for District drainage master planning studies. The Stage 1 delineation could be incorporated into the floodplain information GIS available on the District's website.

3.6.3. Stage 2 Refinements

The following recommendations apply to the Stage 2 methodology as described in the existing PFHAM:

- Active/Inactive. The PFHAM should be written using the active-inactive terminology used by FEMA, the NFIP, and most other floodplain management agencies. The terms "stable/unstable" carry connotations related to development and are typically not used to describe undisturbed natural systems.
- Inactive Fans. Detailed discussion of types of inactive fans (relict, inactive, etc.) is unnecessary. Since the methodology currently only describes floodplain delineation techniques for active alluvial fans, the PFHAM Stage 2 methodology should focus on identifying active alluvial fans. Anything that is not an active alluvial fan simply falls out of the PFHAM process, and requires little, if any, detailed description. Any distinction between an inactive alluvial fan and relict alluvial fan is more of an academic exercise, and may not be relevant for floodplain delineation purposes, since both can be evaluated using delineation methodologies described in other District manuals.
- Stable Distributary Flow Areas. Criteria for distinguishing stable distributary flow areas from active alluvial fans should be developed and described. Guidelines for delineating flood hazards (Stage 3) on stable distributary flow areas also should be developed (See Section 3.6.5).
- Pediments. The discussion of pediments in the Stage 2 PFHAM methodology should be rewritten or removed. Pediments are geologic landforms characterized by sloping planar surfaces underlain by shallow or exposed bedrock. Pediments may have stable tributary drainage patterns (inactive), stable distributary drainage patterns (inactive), or small inset active alluvial fan floodplains (active). The presence of shallow bedrock, although interesting from a geologic perspective, may not affect surface flooding if it is buried by more than a meter of unconsolidated alluvium. Therefore, the PFHAM Stage 2 methodology should focus on whether active or inactive flooding occurs on a pediment, rather than on identification of the pediment itself. If there are unique floodplain characteristics on pediments that are substantively different from those on active or inactive alluvial fans, the recommended process for delineating such hazards should be discussed in a separate chapter of the PFHAM.
- Debris Flows. A discussion regarding debris flow potential on alluvial fans in Maricopa County should be added to the PFHAM, as well as a description of the recommended methodology to perform debris flow assessments for specific study areas where debris flow potential exists. When documenting the level of alluvial

fan activity (Stage2), the potential for debris flows is an important consideration for FEMA.

- Approximate vs. Detailed Method. A description of the recommended approximate and detailed Stage 2 methodologies should be added to the PFHAM.
- Countywide Delineation. The District should consider performing an approximate method Stage 2 delineation for the entire County. This exercise could be completed with a moderate effort, would provide valuable information on where active alluvial fan flood hazards exist that require special analysis techniques, and would be useful for District drainage master planning studies. The Stage 2 delineation could be incorporated into the floodplain information GIS available on the District's website.

3.6.4. Stage 3 Refinements

The following recommendations apply to the Stage 3 methodology as described in the existing PFHAM:

- Methodology. The existing PFHAM Stage 3 description should be rewritten to include the composite engineering and geomorphic methodologies outlined in this report, including both approximate and detailed methods.
- Flood Hazard Zones. The Stage 3 methodology should result in at least the following types of flood zones on active alluvial fans (See Table 19):
    - Ultrahazardous zone (may not occur on all fans in Maricopa County)
    - Areas of conveyance and uncertain flow paths
    - Areas of sheet flooding
    - Riverine through-flow corridors
- Active Alluvial Fans Flood Zones. The District needs to evaluate the local administrative zones for relationship to how they are currently administered.

Table 21. Hazard Classification vs. Floodplain Delineation Zone Designation

Hazard Classification	Detailed PFHAM Method	Approximate PFHAM Method
Ultra-Hazardous FIRM Panel FCDMC Work Map	 Zone A (Alluvial Fan) Administrative Floodway AFAN	 Zone A (Alluvial Fan) Administrative Floodway AFAN
Areas of Conveyance and/or Uncertain Flow Paths FIRM Panel	AE	Zone A (unnumbered)
Areas of Sheet Flooding & Ponding FIRM Panel	AE or AO1, Shaded X	Zone A
Riverine / Through-Flow FIRM Panel FCDMC Work Map	AE	Zone A

- Terminology. As recommended by some members of the Blue Ribbon Panel, the District may wish to consider different terminology for portions of active alluvial fans that does not meet the recommended ultrahazardous criteria, and thus does not meet the NFIP definition of "active alluvial fan flooding." For example, shallow or moderate depth uncertain flow path flooding on an active alluvial fan could be called “active piedmont flooding” or “uncertain flow path flooding.” It is recommended that the District conduct additional coordination efforts with FEMA and FEMA technical reviewers to determine whether this approach has merit or would achieve the intended outcome.

3.6.5. General Refinements

In addition to the recommendations for each of the three stages of the PFHAM, the following general recommendations are made for the PFHAM:

- Examples. The example studies provided in the PFHAM (Chapter 5) should be updated to illustrate the integrated analysis techniques described in this report, and should closely follow the three-stage process outlined in the PFHAM.
- Appendixes. The existing PFHAM appendixes should be provided in a separate document to reduce the file size. Appendixes which contain copies of reports available elsewhere should be removed and simply listed in the bibliography.
- Alluvial Plain Chapter. The District should consider adding a new chapter to the PFHAM which describes how the recommended flood hazard assessment techniques described in this report could be applied to floodplain delineations on alluvial plains.
- Stable Distributary Flow Chapter. The District should consider adding a new chapter to the PFHAM which describes how to identify stable distributary flow areas, as well as the recommended method for estimating design discharges, hydraulic data, and floodplain limits on stable distributary flow areas.
- Pediment. If further analysis indicates that pediments have flood hazards that are substantively different from active alluvial fans, inactive alluvial fans, alluvial plains, and stable distributary flow areas, the District should consider adding a new chapter to the PFHAM specifically oriented at pediment surfaces.
- Debris Flow Assessment. A description of how to apply the recommended debris flow assessment technique to the Stage 3 delineation, for both approximate and detailed approaches should be added to the revised PFHAM.
- Sediment Modeling. A detailed description of how to incorporate the recommended sediment yield and sediment modeling approaches to estimate potential fan aggradation rates, impact on avulsion, fan activity, and flood hazards should be added to the revised PFHAM. In general, the sediment yield is used to predict the average fan aggradation rate, and the 100-year FLO-2D model results are used to: (1) identify potential avulsive flow paths, (2) determine differences in flow distribution and extent from the 100-year water-only FLO-2D models, and (3) identify area of more rapid sediment accumulation trends (or scour).
- Geotechnical Testing. Additional guidance on more detailed geotechnical testing such as erodibility measurements (cohesion, soil strength, material size, etc.) that could potentially be used to supplement more detailed Stage 3 analyses should be added to the revised PFHAM.
- FEMA Coordination. The Integrated Alluvial Fan Hazard Assessment Methodology described in this report is consistent with current FEMA guidelines and regulations. However, there are some possible differences in how some FEMA officials have traditionally interpreted their guidelines, as well as some needed clarifications of FEMA guidance. Therefore, it is recommended that the

District continue to work with staff from FEMA Region IX and FEMA headquarters to coordinate the findings of this study with ongoing efforts to update FEMA alluvial fan delineation and management practices. Specific coordination efforts should focus on the following:

- Recognize that there are different types of active alluvial fans, such debris flow fans and fluvial fans.
- Recognize that portions of active alluvial fans are subject to differing degrees of hazard, such as debris flows, channelized flow, avulsions, and sheet flooding.
- Clarify terminology in Appendix G, specifically for that relating to characteristics of active alluvial fans and active alluvial fan flooding.
- Improve technical guidance for delineating active alluvial fan floodplains.
- Improve technical guidance for engineering support of CLOMR/LOMR requests on active alluvial fan flooding areas.
- Recognize the importance of flow attenuation and infiltration on active alluvial fans.
- Recognize the occurrence and importance of sheet flooding on active alluvial fans.
- Recognize the need for continued training on alluvial fan methodologies.
- Identify improvements in the alluvial fan review process to assure consistency and thoroughness.
- Recognize the need to quantify the risk of avulsion on active alluvial fans.

- Engineering Analyses. The PFHAM should be expanded to include guidelines for engineering analysis of specific development sites. The current PFHAM is oriented primarily at floodplain delineation and does not directly address the types of analyses required to remove a site from an alluvial fan floodplain using structural methods, or how to design flood control mitigation measures in active alluvial fan floodplains.

4. Recommended Integrated Methodology

Revision of the existing PFHAM Manual is not part of the current PFHAM study scope of work. However, Task 2.9.3.2 of the PFHAM study does require preparation of a "decision tree that maps the engineering, investigation, and analyses required for flood hazard assessment and mitigation on alluvial fans." The recommended methodology represents the decision tree, also shown in Figure 64, which was developed using the following goals and assumptions:

- Quantified Flood Hazards. The recommended methodology should be (and is) based on engineering principles that are able to quantify the level of flood hazard on alluvial fan landforms.
- FEMA Guidelines. The methodology should be compatible with NFIP requirements (44 CFR, Chapter 1, Part 65.13) and FEMA Guidelines (Appendix G). The proposed integrated method is fully compatible with the composite methodology described in the FEMA Appendix G Guidelines.
- Maricopa County. The methodology is intended for use only in Maricopa County, Arizona. Application of the recommended methodology in other geographic areas may be possible, but was not specifically investigated as part of this study.

4.1. Methodology Overview

An overview of the recommended Integrated Alluvial Fan Hazard Assessment Methodology in Maricopa County is presented below. The outline follows the three-stage process developed in the NRC (1005) Report and adopted in FEMA Appendix G (2003), which can be summarized as follows:

- **Stage 1: Landform Identification**. In Stage 1, it is determined whether a study area lies on an alluvial fan landform, as opposed to a riverine floodplain or alluvial plain landform. Only alluvial fan landforms are advanced forward for analysis in Stage 2.

- **Stage 2: Definition of Active and Inactive Areas**. In Stage 2, the active portions of an alluvial fan landform are distinguished from inactive portions. Only the active portions of alluvial fan landforms are advanced forward for analysis in Stage 3.

- **Stage 3: Delineation of Regulatory Floodplain**. In Stage 3, the portions of an active alluvial fan that are subject to inundation during a 100-year flood is delineated. The result of the Stage 3 is a regulatory floodplain delineation map.

Identification of a study area as an alluvial fan landform (Stage 1) or an active alluvial fan (Stage 2) does not dictate any special requirements by FEMA. FEMA jurisdiction only extends to those areas delineated within the 100-year floodplain (Stage 3). The recommendation integrated methodology is illustrated on the decision tree shown in Figure 64.

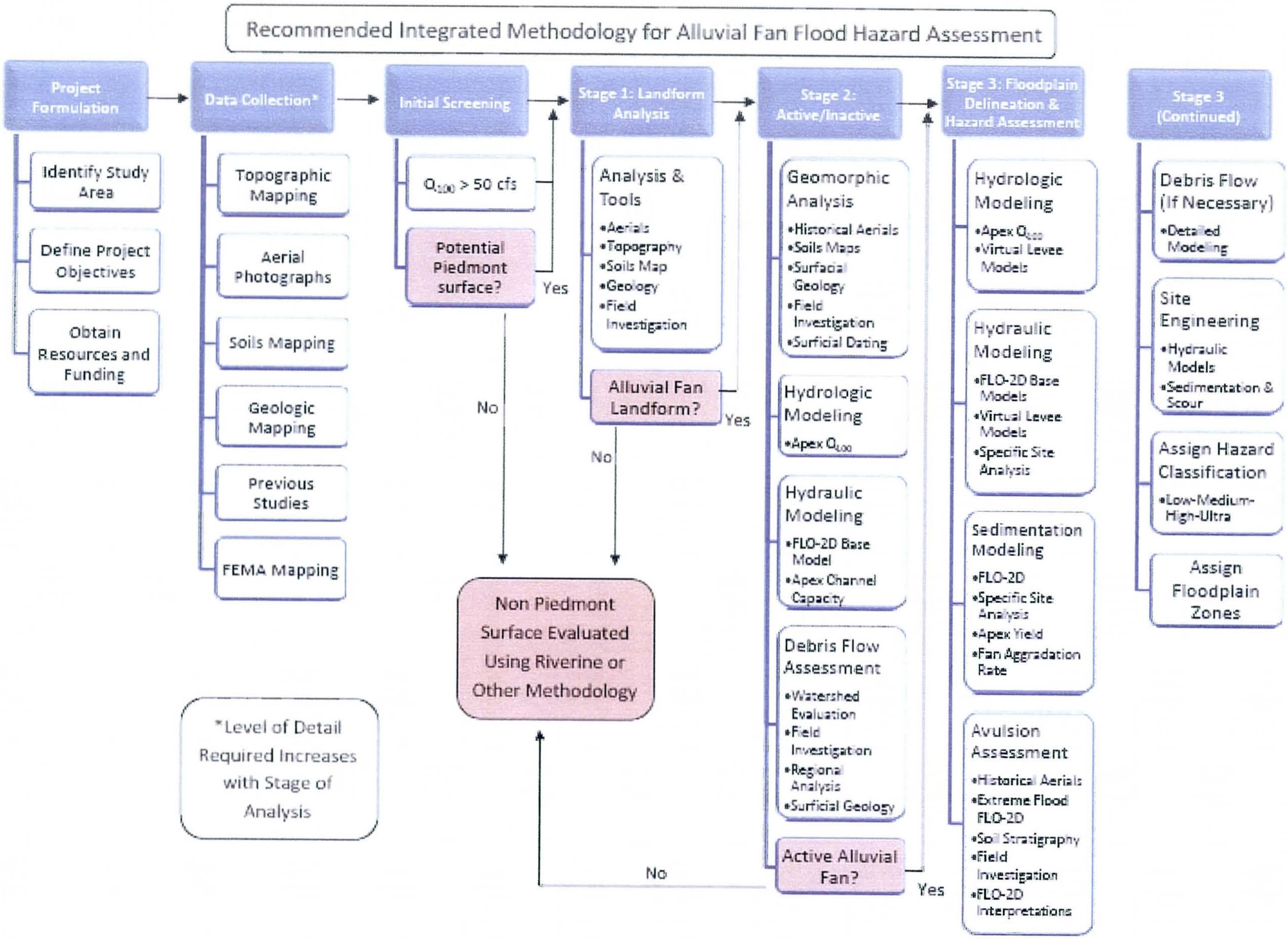

Figure 64. Decision tree illustrating the recommended Integrated Alluvial Fan Hazard Assessment Methodology for alluvial fans in Maricopa County.

4.2. *Stage 1: Landform Identification*

In the Stage 1 analysis, alluvial fan landforms are distinguished from other landform types. Other landform types that may occur in Maricopa County include mountains, riverine alluvial plains, piedmont alluvial plains, and riverine floodplains. The methodologies and tools required for a Stage 1 analysis are listed in Table 22. Suggested modifications to the existing PFHAM Manual Stage 1 procedures are provided in Section 3.6. Alluvial fan landforms are identified using the three basic criteria: (1) composition, (2) morphology, and (3) location.

Table 22. Overview of Stage 1 Methodology.
GOAL: IDENTIFY LANDFORM TYPE

Methodology	Tools
Interpretation of Aerial Photographs	Recent aerial photographs
Interpretation of Topographic Maps	USGS quadrangle maps (or other source)
Interpretation of Geologic Maps	Surficial or bedrock geologic maps
Interpretation of Soils Maps	NRCS soil survey map
Field reconnaissance (optional)	

As indicated in Table 22, the Stage 1 analysis is relatively straightforward, and can be completed by interpretation of aerial photographs, topographic maps, soils and geologic maps, and field reconnaissance. None of the elements of a Stage 1 evaluation can be readily quantified given the existing data sets for alluvial fan landforms in Maricopa County. Furthermore, use of additional numerical analyses, if any could be developed, would probably unnecessarily complicate the Stage 1 evaluation, which is intended to be a preliminary screening that generally should be accomplished with a minimal effort and resources. If a landform is identified as an alluvial fan landform in Stage 1, then it is advanced for a Stage 2 analysis. Other non-fan landforms can be evaluated using traditional floodplain delineation tools which are described in other Maricopa County manuals.[25]

4.3. *Stage 2: Definition of Active & Inactive Areas*

In the Stage 2 analysis, the active portions of an alluvial fan landform are distinguished from inactive portions. Definitions of active and inactive alluvial fans are discussed in Section 3.1 above. The recommended integrated methodology for Stage 2 includes an approximate and detailed approach, as shown in Table 23. The approximate method approach relies primarily on geomorphic techniques and is best applied where a coarse, non-quantified Stage 2 delineation is acceptable. The detailed method incorporates all of the approximate method techniques, but also includes a base two-dimensional model, as well as more detailed or quantified geomorphic, soils and geotechnical analyses. The detailed Stage 2 methodology requires a higher level of effort and expertise than the approximate method, and is therefore recommended in areas where finer distinctions between active and inactive areas are warranted, such as where the boundary between

[25] Note that some members of the Blue Ribbon Panel suggested that the recommended integrated methodology would probably be applicable to other landform types where flow path uncertainty exists.

active and inactive is not obvious and finer resolution delineation would eliminate the need for a detailed Stage 3 application.

Table 23. Overview of Stage 2 Methodology GOAL: IDENTIFY ACTIVE & INACTIVE PORTIONS OF ALLUVIAL FAN LANDFORMS	
Methodology	**Tools**
Approximate Method (Geomorphic)	
Interpretation of Aerial Photographs	Recent aerial photographs
Interpretation of Topographic Maps	USGS quadrangle maps (or other source)
Interpretation of Geologic Maps	Surficial or bedrock geologic maps
Interpretation of Soils Maps	NRCS soil survey map
Field Reconnaissance	Field equipment, maps and aerials
Debris flow potential assessment	Expertise in field, aerial & map interpretation
Surficial geologic mapping	Expertise in soils & geomorphology
Estimate apex channel capacity	Manning's equation, other hydraulic modeling
Estimate apex 100-year discharge	Regression equation, other hydrologic modeling
Detailed Method (Composite of Engineering & Geomorphology)	
All approximate method tools	See above
Hydraulic/hydrologic modeling	FLO-2D - may be simplified base model
Detailed soils mapping	Expertise in soil description & classification Trenching equipment
Detailed surficial geologic mapping	Expertise in geomorphology Field mapping tools
Detailed topographic mapping	Low contour interval mapping
Numerical surficial dating	Expertise in sampling & dating techniques AMD, VML, CND, TLD Access to specialized dating laboratories
Geotechnical testing of soil characteristics	Erodibility & resistance sampling equipment Expertise in geotechnical engineering Access to specialized testing laboratories
Debris flow potential evaluation	Expertise in field, aerial & map interpretation Expertise in slope stability & geomorphology

The objective of the Stage 2 analysis is to identify active and inactive portions of the alluvial fan landform. Therefore, the level of effort for each analysis type listed in Table 23 should be limited to the level required to achieve the objective. For example, at Stage 2, it is sufficient to determine that a risk of debris flow exists for the alluvial fan landform in question. It is not necessary to quantify the extent of the debris flow hazard, the potential runout distance, or potential flow volume. Similarly, FLO-2D models conducted for the Stage 2 analysis may be somewhat less refined than the FLO-2D modeling required for the Stage 3 hazard assessment. Thus, what might appear to be a duplication of effort between Stages 2 and 3 is actually a scaled level of effort that reflects the different objective of each stage of analysis. Likewise, the use of engineering analyses is incorporated into both the approximate and detailed Stage 2 methodologies, although the level of engineering analysis increases significantly for the detailed Stage 2 approach.

Descriptions of how to apply many of the recommended Stage 2 delineation techniques are provided in the existing PFHAM, and thus are not repeated in this report. A brief description of how the following methods that are listed in Table 23, but are not discussed in detail in the existing PFHAM, is provided below:

- Approximate Methods.
    - Debris Flow Assessment. Steps One and Two of the recommended methodology described in Section 2.6 and Appendix H of this report should be applied. Any areas found to be potentially subject to debris flow risk should be considered active.
    - Apex 100-Year Discharge. The 100-year discharge at the (potential) hydrographic apex may be estimated using any of the procedures outlined in the District Hydrology Manual. The 100-year discharge is then used as part of the analyses to define the location of the hydrographic apex.
    - Apex Channel Capacity. The channel capacity at the hydrographic apex may be estimated using Manning's equation. The channel just upstream of the hydrographic apex should contain the 100-year discharge, including any applicable freeboard to account for potential sediment deposition and/or sediment bulking. The hydrographic apex can then be defined using the channel capacity modeling in conjunction with surficial geology to demonstrate flow containment (lack of flow path uncertainty).
- Detailed Methods. The following detailed Stage 2 methods are similar to the approximate methods, but use more detailed, less generalized information, or are performed at a smaller scale:
    - Debris Flow Evaluation
    - Detailed Soils Mapping
    - Detailed Surficial Mapping
    - Detailed Topographic Mapping

  The following tools are unique to the detailed Stage 2 methodology:
    - FLO-2D Modeling. A base 100-year FLO-2D model can be used to generate rough estimates of the transition from channelized to sheet flooding, high depth and velocity zones versus shallow, low velocity zones, and the extent of inundation over the alluvial fan landform. Extensive interpolation and extrapolation of the FLO-2D results will be required to assure that the impacts of flow path uncertainty, avulsion, and sedimentation are not overlooked by use of a single event, single recurrence interval model. That is, one should avoid over-reliance on the Stage 2 FLO-2D results alone. The base FLO-2D model results can also be used to distinguish topographically low, older surfaces that can be flooded from topographically elevated older surfaces that can safely be considered inactive.
    - Numerical Surficial Dating. In some cases it may be beneficial to apply higher resolution numerical dating techniques (See Section 2.5 and Appendix G) to create a more refined geomorphic surfaces map. Surfaces not flooded for long time periods (> 1,000+ yrs) may be considered inactive, if hydraulic modeling also indicates that are not at risk of inundation.
    - Geotechnical Testing. In some cases geotechnical testing of soils may yield information that helps distinguish active and inactive surfaces. Such geotechnical information may include soil erodibility, cohesiveness, soil profile development, or sediment size.

If a portion of an alluvial fan landform is identified as an active alluvial fan in Stage 2, then it is advanced for Stage 3 floodplain delineation. Inactive alluvial fan floodplains identified in Stage 2 can be evaluated using traditional floodplain delineation tools described in other Maricopa County manuals.

4.4. Stage 3: Floodplain Delineation and Hazard Assessment

In Stage 3, the portion of an active alluvial fan that is subject to inundation during a 100-year flood is delineated. In conjunction with the floodplain delineation, a hazard assessment is performed for use in engineering design and analysis. The bulk of the work performed for the PFHAM study is reflected in the recommended Stage 3 methodologies. Like the Stage 2 methodology, the recommended integrated Stage 3 methodology includes an approximate and detailed approach, as shown in Table 24.

Table 24. Overview of Stage 3 Methodology
GOAL: IDENTIFY ACTIVE ALLUVIAL FAN FLOODPLAIN LIMITS

Methodology	Tools
Approximate Method (Geomorphic)	
Use of Stage 2 active area boundary	See Table 23 tools (approximate or detailed) Engineering judgment
Flow depth estimates	Manning's ratings (apex & fan surface)
Debris flow assessment	If debris flow potential exists, use detailed methods Field and map reconnaissance, surficial mapping
Detailed Method (Composite of Engineering & Geomorphology)	
Hydrologic modeling	FLO-2D below hydrographic apex FLO-2D or HEC-1 above hydrographic apex
Hydraulic modeling	FLO-2D 100-year base model 10-, 50-, 500-, PMP water only model Sediment transport model (100-yr) Virtual levee scenario models
Sediment modeling Sediment yield Sediment transport on fan surface Estimate 100-year deposition Estimate long-term deposition	 Current District Hydraulics Manual guidelines FLO-2D (100-yr) Sediment yield, FLO-2D Sediment yield, FLO-2D, soil trench descriptions
Debris flow potential assessment	Field and map reconnaissance Historical debris flow assessment Surficial geologic mapping Regional debris flow evaluation LAHAR-Z modeling
Avulsion analysis	FLO-2D – 100-yr, 500-yr, sediment, channel blockage, hazard classification Avulsive flow path tool Aerial photo interpretation & historical analysis Surficial geology interpretation Field investigation Topographic map evaluation Soil trench stratigraphy
Engineering Analysis of Development Sites (Not Floodplain Delineation)	
All analyses listed above Hydraulic modeling of site features Sedimentation analysis of site features	 HEC-RAS HEC-6, District Hydraulics Manual methods

The approximate method approach relies primarily on geomorphic techniques and is best applied where a coarse, non-quantified Stage 3 floodplain delineation is acceptable. In general, an approximate method Stage 3 delineation will be similar in extent to limits of the Stage 2 active alluvial fan delineation. Therefore, the approximate Stage 3 delineations are likely to be more conservative in extent than a detailed Stage 3 delineation.

The detailed method incorporates most of the approximate method techniques, but also includes more sophisticated hydrologic, hydraulic, and sediment transport modeling, as well as modeling of debris flows and avulsions where needed. The detailed Stage 3 method may also require more detailed field investigation and more detailed topographic mapping. The detailed Stage 3 methodology requires a much higher level of effort and expertise than the approximate method, and is therefore recommended in areas where quantitative data are needed for floodplain management or engineering design purposes that justify the increased investment of labor and capital.

Use of engineering analyses is incorporated into both the approximate and detailed Stage 3 methodologies, although the level of engineering analysis increases significantly for the detailed approach. The portion of any active alluvial fans identified as within the 100-year floodplain is delineated using the procedures outlined above. Areas of an active alluvial fan that are outside the 100-year floodplain limits are not under FEMA or District jurisdiction. Recommendations for assignment of alluvial fan floodplain zones are discussed in Section 3.6.4.

Descriptions of how to apply many of the recommended Stage 3 delineation techniques are provided in the existing PFHAM, and thus are not repeated in this report. A brief description of how the following methods that are listed in Table 23, but are not discussed in detail in the existing PFHAM, is provided below:

- Approximate Methods.
  - Debris Flow Evaluation. Where evidence of debris flows are identified in the Stage 2 analysis, the detailed Stage 3 method should be used.
  - Flow Depth Estimates. Coarse estimates of depth made using the full apex discharge and Manning's equation can be used to verify geomorphic-based floodplain delineations and estimates of the limits of the high hazard zones, as well as to identify the transition from channelized flow above the hydrographic apex to uncertain flow path flooding below the hydrographic apex.
- Detailed Methods.
  - Debris Flow Evaluation Step Three of the recommended methodology described in Section 2.6 and Appendix H of this report should be applied. Any areas subject to debris flow risk should be considered ultrahazardous zones.
  - Hydrologic Modeling. See Section 2.3.2.
  - Hydraulic Modeling. See Section 2.3.3. The results of the FLO-2D modeling should be composited and interpolated to provide a reasonable

depiction of the potential flood hazard, considering avulsions, sedimentation, flow path uncertainty, and normal flow across the fan surface.
    - Sediment Modeling. The results of the sediment modeling support the floodplain delineation in the several ways. First, estimates of the average annual and 100-year sediment yield can be distributed over the active fan surface using the methodologies described in Appendix F to determine the relative magnitude of potential aggradation. Where potential aggradation is minimal relative to the flow depths predicted, it can be assumed to not affect water surface elevations. Second, the distribution and extent of predicted flow depths from a sediment-enabled FLO-2D model can be compared to the FLO-2D base and virtual levee scenario models to identify potential impacts of sediment on flood hazards, and the floodplain delineation adjusted according to account for the differences. Third, areas of high predicted scour or deposition can be included as factors for identifying high hazard zones and flow conveyance corridors. Fourth, the sediment model results can be included in the avulsion risk analysis as described in Section 2.7 and Appendix I of this report.
    - Avulsion Analysis. The floodplain delineation should envelop all areas potentially subject to flooding due to avulsions. Predicted 100-year flow depths and/or water surface elevations should be a composite of the maximum depths predicted by all the 100-year FLO-2D models prepared for the site. Some interpolation and extrapolation of the virtual levee scenario results, base models, other avulsion models, and sediment models will be necessary to composite the modeling results appropriately.

4.5. Virtual Levee Scenario Methodology

The virtual levee scenario methodology is a key element of the recommended Integrated Alluvial Fan Hazard Assessment Methodology in Maricopa County. The virtual levee scenario methodology is required to address the flow path uncertainty element of the hazard analysis. A discussion of the virtual levee scenario methodology is provided in Section 2.3.2.3 (p. 38), and more detailed information about its application in the PFHAM modeling exercises was provided in Sections 2.3.3.7 and Appendix F. Because of its importance to the recommended integrated methodology, the following cursory guidelines on implementation of the virtual levee scenario methodology are provided:

- Not a Cookbook. Because of the unique hazards associated with flooding and sedimentation on active alluvial fans, implementation of the virtual levee scenario methodology requires engineering judgment, modeling finesse, and a thorough understanding of the dynamics of flooding on alluvial fans in Maricopa County.
- Foundational Analyses. The following analyses should be completed prior to beginning the virtual levee scenario modeling:
    - Stage 2 Analysis. Active and inactive areas should be delineated, as well as areas of flow path uncertainty and potential avulsion

- Base FLO-2D Model. The results of a preliminary base FLO-2D model completed in Stage 2 can be used to help identify channelized and sheet flow zones, as well as areas of potentially high flow depth and velocity.
- Geomorphic Assessment. The most active surfaces, areas of channelized flow, high velocity areas, and surfaces with the youngest soils should be identified as potentially avulsive areas to be covered by virtual levees.
- Avulsion Analysis. A full avulsion potential analysis should be essentially complete prior to beginning the virtual levee scenario modeling. This includes interpretation of historical aerial photographs (to identify past avulsions and likely avulsion areas such as bends or piracy points), as well as a range of FLO-2D models up to extreme discharge models (to identify high depth/velocity zones, perched or abandoned channels, and overbank flow concentrations), as described in Section 2.7 and Appendix I.

- Preliminary Avulsion Hazard Area. It is useful to outline a preliminary avulsion hazard area based on the composited results of the foundational analyses listed above. The virtual levees should extend from a point of full flow containment upstream of the hydrographic apex to the downstream limit of preliminary avulsion hazard area to simulate the affect of possible avulsions within the ultrahazardous and high hazard zones.
- Levee Modeling. The overall objective of virtual levee modeling is to force flooding in directions that would simulate avulsions, and to estimate a maximum (reasonable) delivery of routed flow to concentration points in the lower fan area. The number, geometry, and alignment of the virtual levees should be selected to achieve those objectives. In addition, the following apply:
  - Levee Length. The virtual levees should extend from a point of full flow containment upstream of the hydrographic apex and extend downstream to the beginning of the sheet flooding area (shallow depth in FLO-2D results). The levees should extend across the entire preliminary (and final) ultra- and high hazard zones.
  - Number of Levee Scenarios. The number of virtual levee scenarios modeled depends on level of detail required, the number of obvious existing or potential avulsive flow paths, whether there are coalescing adjacent fans to be considered, the number of concentration points being evaluated, and other site-specific factors. Engineering judgment and coordination with affected regulatory agencies is recommended.
  - Alignment. The virtual levees should be aligned at moderate angles to the fan axis so that they do not cause a significant "pile up" of flow in the model results.
  - Drainage Pattern Interpretation. The existing condition drainage pattern on the active (and inactive) surfaces downstream of the hydrographic apex(es) can be used to provide clues as to the number and alignment of virtual levees needed. At minimum, flow should be directed at the primary existing flow corridors defined by the drainage network.
  - Coding. The virtual levees should be coded to not overtop or fail.

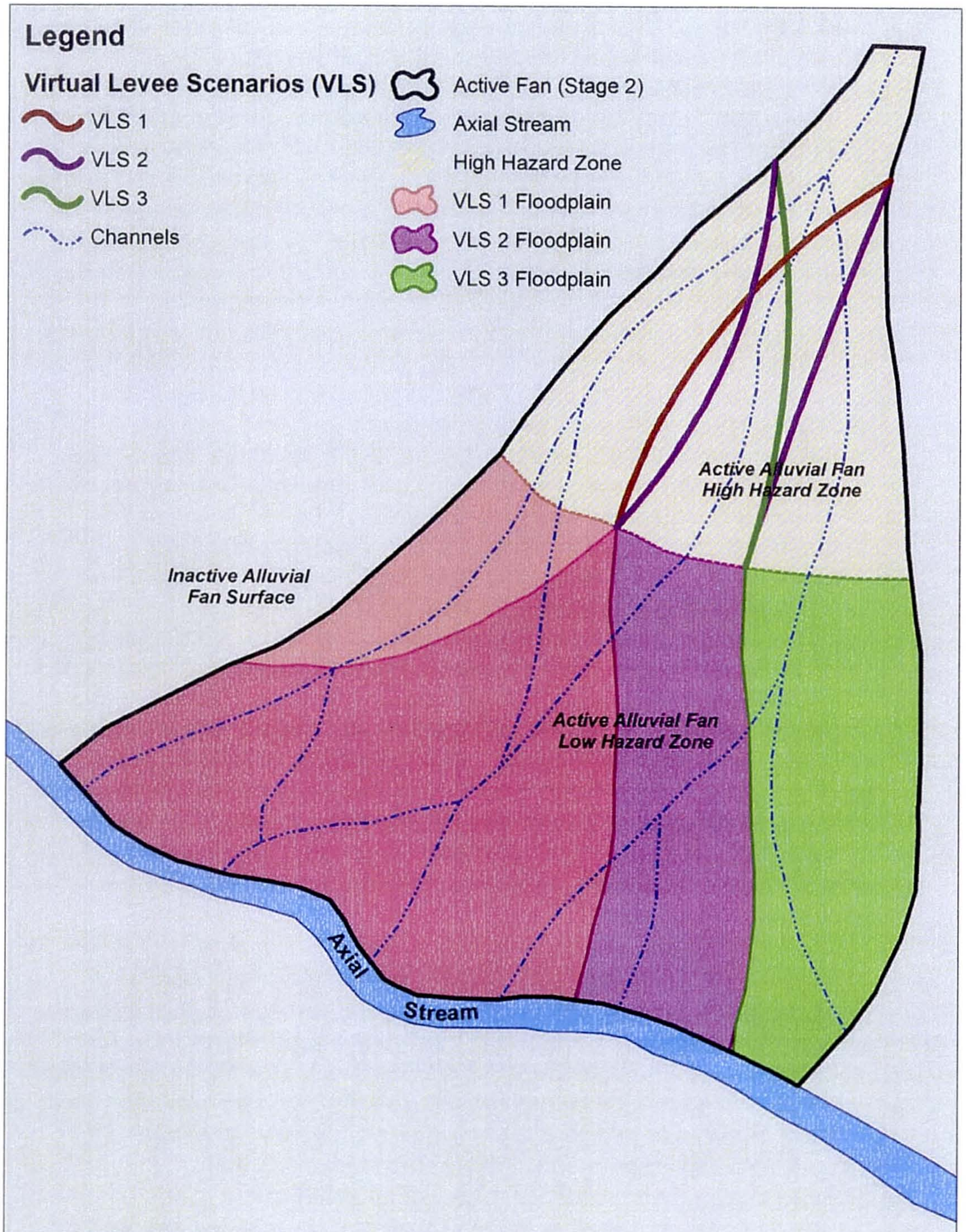

Figure 65. Illustration of virtual levee scenario methodology application.

- Model Iteration. After the initial virtual levee scenarios are modeled, the results may dictate that additional iterations are required, particularly if the FLO-2D results appear to contradict the preliminary avulsion hazard area delineation.
- Secondary Apex. If multiple apexes exist on the alluvial fan, the virtual levee scenario modeling should be repeated for each secondary apex using the upstream levee combination(s) that deliver maximum flow rate to secondary apex
- Hazard Delineation. In the simplest case, the maximum depth at each grid cell from a combination of virtual levee scenario runs can be used as the regulatory flood depth. In most cases, however, delineation of the flood depths from the virtual levee scenario modeling results will require interpolation and extrapolation of FLO-2D output, at least for the high hazard zone, to produce a reasonable depiction of the hazard. Outside the high hazard zone, it is likely that the virtual levee scenario results will have similar depths regardless of the upstream scenario. The following also may apply:
    - Pile-Up. Avoid mapping the "pile up" depth against the virtual levees, which should be easy to identify by its location and alignment, as well as the depth relative to surrounding grid cells.
    - Islands. Avoid mapping islands of low or high hazard that are significantly different than surrounding grid cells, unless they are topographically or geomorphically justified.
    - Uniformity. Interpolated depths should be laterally uniform near the hydrographic apex, with increasing lateral variation possible in downfan direction.
- Conservative Results. If properly modeled, the virtual levee scenario produces somewhat conservative flood depths, particularly given the (probable) low frequency of avulsion on fans in Maricopa County, as well as the fact that actual avulsions do not completely divert the entire hydrograph along a particular alignment. The method requires application of engineering judgment and understanding of alluvial fan flood processes to assure that the results are reasonable.

4.6. Integration of Stage 3 Results for Floodplain Delineation

The recommended integrated methodology does not produce a single, definitive model output file from which a floodplain delineation can be automated. Therefore, some engineering judgment will be required to synthesize the results from the various elements of the recommended Stage 3 methodology listed in Table 24. In most cases, the results won't necessarily all coincide perfectly, and will thus require some integration. The following general guidelines may be useful when integrating the results:

- When delineating flood zones, err on the side of public safety.
- Consider the consequence of an error in mapping when drawing zone limits.
- Be mindful of the uncertainty in each of the methodologies used.
- Results with the least uncertainty may be most reliable.
- Weight documented historical evidence of flooding over theoretical results.
- Allow for application of engineering judgment and experience.

4.7. *Blue Ribbon Panel Review of the Recommended Methodology*

The recommended integrated methodology was presented to a panel of experts (the "Blue Ribbon Panel") for peer review. The Blue Ribbon Panel meeting was held at the Flood Control District of Maricopa County on June 2-3, 2010, and was facilitated by District staff. The Blue Ribbon Panel consisted of experts from a variety of engineering, scientific, and regulatory disciplines associated with alluvial fan flood hazard assessment. In general, the Blue Ribbon Panel endorsed the recommended methodology. A detailed summary of the Blue Ribbon panel meeting and a list of the panelists are provided in Appendix J.

The Blue Ribbon Panel concluded the following with regard to the recommended Integrated Alluvial Fan Hazard Assessment Methodology:

- The methodology as proposed in the draft report (May 25, 2010 version) was reasonable, defensible, and scientifically sound.
- The proposed methodology may have applicability to similar fan areas elsewhere in the semi-arid west, but it should be adopted specifically for Maricopa County.
- The proposed methodology should be applied on a local alluvial fan and sent to FEMA as a test-case delineation (with documentation) for review and approval.
- The 100-year flood should be used as the basis of engineering design and floodplain delineation on alluvial fans in Maricopa County.
- Two-dimensional modeling is strongly recommended for alluvial fan flood hazard assessment.
- Flow attenuation is a key process on alluvial fans in Maricopa County and should be accounted for the methodology.
- The virtual levee scenario is an important and necessary component of the proposed methodology.
- The proposed hazard assessment methodology (BUREC Figure 6, FLO2D depth-velocity, frequency-weighted) is acceptable. Depth and velocity are the best variables for assessing the hazard level, if uncertainty is addressed through the virtual levee scenario method.
- Avulsions are a key process for alluvial fan flooding hazards. Avulsion methodology should distinguish between major avulsions, minor avulsion and simple lateral channel erosion. Recent occurrence of avulsions may preclude formation of new avulsions in the near term.
- The recommended avulsion risk assessment methodology is acceptable.
- The slope-walk method is a useful tool.[26]
- "Active alluvial fan flooding" refers to an ultrahazardous flooding condition characterized by very high velocities and flow depths, active transport of boulder-sized sediment, high avulsion potential, rapid aggradation, and debris flow potential. New terminology, such as "piedmont active flooding," may be needed to address uncertain flow path flooding on active alluvial fans that is not ultra-hazardous.

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[26] The name of the slope-walk method was changed to "avulsive flow path method" at the request of District staff.

- There is no known physical characteristic that could serve as the minimum threshold of concern to identify alluvial fan landforms or the potential for alluvial fan flooding. Hazards can be quantified based on the flow depths and velocities predicted by the proposed methodology
- There is no need to quantify the Stage 1 delineation process using variables such as minimum slope, velocity, etc.
- Some quantification of flood hazards is needed in the Stage 2 delineation process. Flow depth and velocity estimates are needed to identify "active alluvial fan flooding" as defined by FEMA.
- Alluvial fans in Maricopa County are not unique, though they differ from steep alluvial fans bounding tectonically active mountain ranges. The fans in Maricopa County are typical of alluvial fans formed near tectonically inactive mountain ranges in semi-arid climates.
- Areas on active fans outside the 100-year floodplain should be designated as having some hazard potential, but should not be mapped as part of the FEMA floodplain
- Development in low hazard areas on alluvial fans is acceptable as long as it is adequately regulated for impacts to adjacent areas. High hazard areas should be regulated with higher restrictions. Policies to prevent loss of attenuation (downstream impacts) should be developed.
- There are significant problems with the Dawdy Method (FAN model).
- FEMA's current plan to revise the NFIP provides a rare window of opportunity for also revising the FEMA Appendix G methodology to incorporate the recommendations of the PFHAM study.
- There is a need for high quality topographic mapping when performing floodplain delineations.

The Blue Ribbon Panel also voiced the following concerns and recommendations regarding alluvial fan flood hazard assessments:

- "Point-in-time" modeling may not adequately characterize long-term fan behavior and flood risks because fan processes evolve dynamically over time. Because we do not yet have the ability to reliably predict how those processes will change the landscape or impact other functions such as flow attenuation over time, a composite methodology (combining engineering and geomorphic techniques) is needed.
- The recommended integrated methodology would be improved if clarification of mechanics of virtual levee scenario methodology – length of levees, orientation, number of scenarios, approach at secondary apexes, etc. – were provided.
- The District should endeavor to determine avulsion frequency on alluvial fans in Maricopa County.
- The District should work to document infiltration parameters on alluvial fans. The values used in the PFHAM Study modeling need verification.
- If and when large floods occur on alluvial fans in Maricopa County, they should be thoroughly documented & studied, and compared with proposed methodology.

- The District should develop and provide documentation on how "risk" is quantified by the proposed methodology. This documentation of risk will be important for FEMA approval.
- When an application of the recommended integrated methodology is submitted to FEMA for review and approval, the methodology should be characterized in RiskMAP language.
- Additional work should be done to clarify which sediment transport function produces best results.
- The District should explore the definition of hazard level relative to no-build zones and/or floodways. No-build zones could be based on hazard classification as well as the "ultrahazardous" areas, but also could be incorporated into zoning overlays.

Additional information on the Blue Ribbon Panel meetings is provided in Appendix J.

5. Summary of Recommendations

The following paragraphs reiterate and summarize the recommendation of the PFHAM study presented earlier in this report.

5.1. Definitions

The following recommendations were made with respect to terminology:

- Sheet Flooding. The term "sheet flooding" is preferred over "sheet flow."
- FEMA Definitions. Current NFIP and FEMA definitions relating to alluvial fan flooding should be used wherever possible (Table 15). Where necessary, the District should work with FEMA in conjunction with other affected communities, to improve FEMA definitions and guidance.
- Active Alluvial Fan Flooding. The District should make an affirmative statement that the term "active alluvial fan flooding," as defined in the NFIP, applies only to the areas of ultrahazardous flood conditions on active alluvial fans. The District should use the hazard classification criteria outlined in Sections 2.3.3.9 and 3.4 of this report to define the term "ultrahazardous" with respect to alluvial fans.
- Inactive Alluvial Fans. The District should use the FEMA Appendix G definition of the term "inactive alluvial fan."

5.2. Hydrology

The following recommendations were made with respect to hydrologic analyses of alluvial fans:

- Two-Dimensional Modeling. Two-dimensional modeling is recommended for all hydrologic modeling below the hydrographic apex of active alluvial fans in Maricopa County. The recommended engineering tool for hydrologic modeling of active alluvial fans and alluvial plains in Maricopa County is FLO-2D.
- Virtual Levee Scenario. The virtual levee scenario method should be used to estimate peak discharge at all points downstream of the hydrographic apex. Use of the full apex discharge is not recommended for design purposes. The maximum discharge from the cumulative virtual levee scenarios should be used for design purposes.
- Coalescing Alluvial Fans. Where one or more active alluvial fans coalesce, a combination of discharges from adjacent fans should be estimated using the virtual levee scenario method.
- Future Conditions. For planning studies, future condition discharges should be estimated by applying full-build out of the fan surface with normal retention requirements and whatever current District (or local community) development policies exist at that time.
- Conveyance Corridors. For planning purposes, it may be useful to identify a flow corridor that could be used to convey upstream and local runoff from the hydrographic apex to the toe of the alluvial fan landform.
- Sheet Flooding. Where runoff is expected to occur as unconfined sheet flooding, peak discharge estimates should reflect the total flow reaching the upstream

boundaries of a site, or flow across the entire sheet flooding area, rather than the point discharge a single concentration point or grid cell.

- Modeling Guidelines. The District should develop two-dimensional hydrologic modeling guidelines that specifically address:
    - Point rainfall depths
    - Loss rate parameters
    - Limits on re-infiltration volume
    - Pre- and post-processing tools for modeling coalescing alluvial fans
- Above Apex. Hydrologic modeling upstream of the hydrographic apex should be completed as dictated by current District modeling guidelines and standards. Based on the findings of this study, it is recommended that the District develop guidelines for using FLO-2D to model watersheds upstream of the hydrographic apex, particularly for small watersheds or where tributary inflows to the active fan surface occur over broad areas, rather than at discrete concentration points.
- Flow Attenuation. Attenuation of the hydrograph peak is an important process on active alluvial fans in Maricopa County. Therefore, use of the full apex discharge at any point other than the hydrographic apex is unnecessarily conservative and is not supported by the scientific analyses conducted as part of the PFHAM study. In many cases, the degree of flow attenuation is such that many small floods are completely stored on the fan surface, never reaching the toe, and resulting in deposition of the entire sediment load on the fan.
- Design Frequency. The 100-year (1%) design frequency is recommended for regulation of alluvial flood hazards in Maricopa County.

5.3. Hydraulics

The following recommendations were made with respect to hydraulic analyses of alluvial fans:

- Model Selection. The recommended engineering tools for (water-only) hydraulic modeling on active alluvial fans and alluvial plains are FLO-2D and HEC-RAS. The scenarios in which each model should be used are summarized in Table 18. For the PFHAM study, the FLO-2D model was selected as the best available model, a finding which is consistent with the findings of other agencies (USACE, 2000). Any two-dimensional model that has the same (or better) capabilities as FLO-2D would be acceptable for the purposes of floodplain delineation and flood hazard identification.
- FLO-2D. FLO-2D is preferred for the following types of hydraulic modeling exercises on active alluvial fans and alluvial plains:
    - Determining flow hydraulics in broad sheet flooding areas
    - Modeling of the entire alluvial surface
    - Identifying preferred, alternative or avulsive flow corridors
    - Identifying low relief "islands" within the active fan (use extreme flood discharges)
    - Estimating impacts of development in active fan attenuation areas
- HEC-RAS. HEC-RAS may be used for evaluation of channel capacity near the hydrographic apex as part of the methodology for identifying the hydrographic

apex location. In addition, HEC-RAS (or any similar model) is preferred over FLO-2D for site-specific hydraulic analyses where the following conditions exist:

  - The modeling reach has fine-textured topography that cannot be readily defined by grid-based topographic data. If HEC-RAS is used, topographic data and cross section spacing should be coded into the model in a manner that accurately portrays the subtleties of the local terrain.
  - Flow is primarily one-dimensional and gradually-varied flow conditions exist.
  - A single design discharge (steady flow) reasonably approximates flow conditions.
  - Flow is conveyed in a relatively well-defined natural or engineered channel.
  - The modeling reach is short enough that flow volume conservation is not a factor.

- Further Research. The District should continue to investigate improvements in FLO-2D modeling techniques as applied to active alluvial fans and alluvial plains in Maricopa County. Specifically, the use of the multiple-channel option in FLO-2D and the effect of topographic resolution should be explored.
- Modeling Results. FLO-2D depth and velocity output represent average values for the grid size used in the model. Therefore, some interpretation of results is necessary to determine design data for specific sites that may not be well represented by the grid elevations. In these cases, site specific step-backwater modeling is recommended to obtain structure design data.
- Modeling Guidelines. The accuracy of topographic data may affect the modeling results. Use of the best available topographic mapping is recommended. In some cases, the county-wide 10-foot mapping may not produce sufficiently accurate results. In addition, the FLO-2D grid size used also affects the model output. The use of the finest grid size feasible with respect to model run time and topographic data is recommended.
- Sheet Flooding. Large portions of active alluvial fans in Maricopa County are affected only by shallow sheet flooding with minimal flow depths, flow velocities, and aggradation rates. Most of the land area on the active alluvial fans specifically evaluated for this study is dominated by shallow sheet flooding. The extent of sheet flooding is both a cause and result of significant flow attenuation that occurs on active alluvial fans.

5.4. Sediment Transport

The following recommendations were made with respect to sediment transport analyses on alluvial fans:

- Modeling Tools. A variety of tools are recommended for sedimentation modeling on active alluvial fans and alluvial plains.
  - Sediment Yield. Prediction of sediment yield to the hydrographic apex should be completed using the procedures outlined in the District's Hydraulics Manual.
  - Scour. The District's Hydraulics Manual lists specific methodologies for the computation of scour that should be used in channel and site design.

- Model Selection. Use of FLO-2D and HEC-6 should be partitioned in a similar manner to that described above for hydraulic modeling (Section 3.3.2). FLO-2D should be used in broad scale surface analyses, and HEC-6 should be used for site-specific evaluations that meet the conditions listed above.

- Further Research. The District should conduct additional research on calibration of FLO-2D sediment modeling results and sediment transport functions for use on active alluvial fans.

5.5. Debris Flows

The following recommendations were made with respect to debris flow analyses on alluvial fans:

- Risk. The PFHAM study concluded that the risk of debris flow impact on flood hazards on most alluvial fans in Maricopa County is much less than one percent. In the vast majority of cases, no detailed investigation of debris flow potential will be needed. For the few cases of possible concern, a recommended methodology was developed.
- Methodology. Based on the District's goal of assessing debris-flow potential to impact alluvial fan flooding, the following steps are recommended for detailed evaluations of debris flows on specific alluvial fan landforms in Maricopa County:
    - Step One: Initial Assessment of Alluvial Fan
    - Step Two: Geologic Reconnaissance
    - Step Three: Debris-Flow Runout Hazard Modeling
- Engineering Tools. For evaluation of debris flow hazards, the recommended engineering tool is the LAHAR-Z model, as described in Section 2.6 and Appendix H. Use of the LAHAR-Z model is recommended only after completion of more foundational analyses in the recommended multi-step process.

5.6. Avulsions

The following recommendations were made with respect to avulsion risk assessment on alluvial fans:

- Methodology. The recommended method of evaluating avulsion potential on active alluvial fans in Maricopa County consists of the following multi-step process (Section 2.7):
    - Step One: Historical Analysis.
    - Step Two: Geomorphic Analysis.
    - Step Three: FLO-2D Modeling.
    - Step Four: Sediment Modeling.
    - Step Five: Floodplain Delineation.
- Engineering Tools. Two engineering tools are recommended as part of the assessment of avulsion potential on active alluvial fans: (1) FLO-2D and (2) an avulsive flow path tool, both of which are discussed in more detail in Section 2.7 and Appendixes F and I. A variety of FLO-2D modeling scenarios are used to help predict the location and occurrence of avulsions, including the

following: (1) 100-year base models, (2) extreme flood models, (3) hazard classification models, (4) sediment models, and (5) channel blockage models.

- Avulsion Frequency. The frequency of avulsions on alluvial fans in Maricopa County is not well known, although it is likely that avulsions are relatively rare events. A systematic study of avulsion frequency is strongly recommended.

5.7. Surficial Dating

The following recommendations were made with respect to dating of alluvial fan surfaces:

- Regional Chronology. This study recommends that a combination of relative and numerical methods be applied to most accurately determine surface age on alluvial fans in Maricopa County. It is further recommended that a regional chronology be constructed so that more cost-effective relative dating techniques can be used to determine correlative ages.
- The recommended methodologies listed in Table 17 are better classified as quantitative geologic techniques, rather than engineering tools. These geomorphic dating tools can be used to better refine estimates of surface age, and therefore may inform on the degree of alluvial fan activity, as well as help distinguish between active and inactive alluvial fan surfaces.

5.8. Policy

The Consultant recommended use of flood hazard zone classifications to determine floodplain zones; however, the District after careful consideration, has directed that floodplain management policies follow the current FEMA practice and be based on depth of flow.

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Memorandum JE Fuller/ Hydrology & Geomorphology, Inc.

DATE: June 30, 2008

TO: Kathryn Gross, CFM/FCDMC

FROM: Jon Fuller, PE

RE: FCD2007C051 – Assignment #1, Task 1.2.3

CC: File

In 1995, the National Research Council (NRC) was authorized by FEMA to investigate methodologies for evaluating alluvial fan flood hazards. A panel of eight experts with diverse backgrounds selected by the NRC convened over the course of twelve months and generated the report *Alluvial Fan Flooding* (1996). The three-stage methodology for evaluating alluvial fan flooding hazards described in the NRC report was the foundation of the District's *Piedmont Flood Hazard Assessment Manual* (PFHAM) as well as the *FEMA Appendix G* guidelines.

Task 1.2.3 of the above-referenced contract includes the following language:

> *The CONSULTANT shall interview former members of the NRC Alluvial Fan Task force to follow up on their opinions on the success/failure of the 1996 NRC study results and identify any recommendations for further study, alternative approaches, or new research that may be important for the methodology assessment.*

Accordingly, the following NRC Committee members were interviewed:

- Stan Schumm, PhD, Committee Chair
- Vic Baker, PhD
- Peggy Bowker, PE
- Tom Dunne, PhD
- Joe Dixon, PE
- Win Hjalmarson, PE
- Doug Hamilton, PE
- Dorothy Merritts, PhD

The panel members were unanimously enthusiastic about the success of the NRC Committee in achieving its goals and for having changed how alluvial fan flood hazard assessment is done. The committee members stressed the importance of founding any technical assessment of alluvial fan flooding on site-specific geomorphic and historical information and following the three stage approach. The committee members applaud the District's effort to expand their work to include development guidelines and include more detailed guidance for implementing the three stage process.

More detailed interview notes are provided in the appendix to this memorandum.

Maricopa County PFHAM Fan Delineations

- Skyline Wash Fan
- White Tank Fan 36
- Tiger Wash
- White Tank Fans 1, 2, 3, 4, 5, 6, 7, 8, 10, 11, 12, 13, 14, 15, 16, 17, 18, 19, 20, 21
- White Tank Fans 37, 38, 39
- Hieroglyphic Mountain Fan #3
- Rainbow Valley Fans 1-25 (in progress)

Most alluvial fan CLOMR/LOMR submittals submitted since that time attempt to revise the older delineations using structural flood control methods.

Table 1. Summary of Methods

Method	Count	Percent of Total
Three Stage Method (NRC/FEMA)	2	13
Structural Measures	5	33
Fan Model (Dawdy)	1	7
HEC-RAS (unsuccessful approach)	3	20
Dropped Cases (unknown method)	4	27
TOTAL	15	
Note: Does not include 52 FCDMC PFHAM on-going or completed delineations		

Table 2. LOMR/CLOMR Submittals Reviewed by JE Fuller, Inc.

Case No.	Approval	Method Used	Community
05-09-0844A	Not approved	HEC-RAS	Ojai, CA (Ventura County)
08-09-0405R	Not approved	PFHAM & Structural Methods	Buckeye, AZ (Elianto Village IV)
08-09-0919P	Approved	Structural Methods by USACE. HEC-RAS	Las Vegas, NV
07-09-1133P	Not approved	HEC-RAS originally, then Composite Method	Yuma County, AZ (Wash C Tributary to Fontana Wash)
08-09-1260R	Not approved	Structural Methods. HEC-RAS	Clark County, NV (Laughlin Area)

Table 3. Mohave County (Data Supplied by MapMOD Team)

Case No.	Approval	Method Used	Community
03-09-1611R	issued	Channelization – HEC-RAS	City of Bullhead City, AZ Community No.: 040125
04-09-1533P	dropped		City of Bullhead City, AZ Community No.: 040125
05-10-0586P	dropped		Mohave County, AZ Community No.: 040058
05-09-0973R	issued	HEC-2	Mohave County, AZ Community No.: 040058
05-09-2100494P	dropped		City of Bullhead City, AZ Community No.: 040125
06-09-B164P (Follows Case No.: 05-09-A494P)	issued	Fan Program –HEC-RAS	City of Bullhead City, AZ Community No.: 040125
06-09-B664R	Dropped		Mohave County, AZ Community No.: 040058
07-09-0043R	issued	HEC-RAS	Mohave County, AZ Community No.: 040058
07-09-0557R	issued	HEC-RAS—Channelization	City of Bullhead City, AZ Community No.: 040125
07-09-0800R	issued	HEC-RAS – Channelization	City of Lake Havasu City, AZ Community No.: 040116

Memorandum JE Fuller/ Hydrology & Geomorphology, Inc.

DATE: July 11, 2008; revised March 20, 2009

TO: Kathryn Gross, CFM/FCDMC

FROM: Jon Fuller, PE, RG

RE: FCD 2007 C051
Assignment #1, Task 1.2.2
Summary of FEMA CLOMR/LOMR Methodologies

CC: File

Scope Summary for Task 1.2.2. FEMA CLOMR/LOMR Methodologies.

> *FEMA CLOMR/LOMR Methodologies. The CONSULTANT shall obtain readily available records from FEMA and/or their technical review contractor regarding the number of alluvial fan floodplain delineation submittals in recent years and the types Stage 3 methodologies used to delineate the regulatory floodplain on the alluvial fan.*

Summary of Findings

FEMA and Michael Baker Jr. (MBJ) did not provide digital or physical access to their library of CLOMR/LOMR submittals. Instead, they required that individual submittals be requested by name and/or file number. Unfortunately, this results in a Catch-22 situation, since one cannot know whether a given submittal is for an alluvial fan without the submittal name or file number. However, one of the MBJ MapMOD team members graciously volunteered to provide a list of alluvial submittals from the two counties with the most alluvial fan submittals in Region IX, Mohave & Maricopa Counties. To date, we have received only the data for Mohave County (Table 3).

Through my role as a MapMOD team member responsible for review of alluvial fan submittals, I have personal knowledge of a number of CLOMR/LOMR's fan submittals, which are listed below in Table 2. In addition, I have had discussions with MapMOD team members from other regions, who have stated that new alluvial fan delineations are extremely rare. These team members were unable to recall any specific submittals or what delineation methodologies had been used.

Table 1 summarizes the methods used in the 15 cases collected from the FEMA files either from JEF reviews or provided by the MapMOD team. The District should have the Maricopa County records for alluvial fan submittals, presumably all of which used the PFHAM three stage methodology.

The data suggest that most new alluvial fan delineations have originated in Maricopa County. Alluvial fans in other parts of the country were delineated prior to publication of the 1996 NRC Report, and were mapped using the FEMA Fan Model (Dawdy Method).

REFERENCES

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Non-Agency Analyses

A few other studies have been performed delineating alluvial fan floodplains by non-agency investigators. House (2005) performed a detailed geomorphic investigation of flood hazards near Laughlin, NV. He contrasts his findings with the effective FEMA floodplain for the area. Another paper by Pelletier, et al. (2005) examined two-dimensional, fixed bed modeling of the Tortolita piedmont near Tucson for various frequencies. The results are presented and compared to work by previous investigators. An earlier study by French (1992) developed a modified version of the Dawdy method for delineation of alluvial fan floodplains.

A series of other articles address flood hazards on alluvial fans whether by water floods and/or debris flows. These articles are identified by key words in the excel spreadsheet provided on a DVD developed under Task 1.2.4 & 1.2.7 for FCD 2007C051. Most of these studies relate depth and velocity of water and/or debris flows for a specific frequency to depict the spatial distribution of flood hazards on a particular fan under study but do not address FEMA floodplain delineation concepts. Many of these studies used FLO-2D as a hydraulic model. Many considered depths greater than 1 meter and flow velocities in excess of 1 m/s as high hazard areas.

Summary

- The *FEMA Appendix G* methodologies are uniformly being applied to alluvial fan floodplain delineation thought the southwest.
- No agency researched for this study is employing alluvial fan floodplain delineation methodologies outside of those described in *FEMA Appendix G*.
- The Flood Control District of Maricopa County is consistently viewed as the agency with the most advanced, up-to-date, forward-thinking policies and actions regarding alluvial fan floodplain delineation.
- The California agencies that are actively dealing with alluvial fan floodplain issues are anxiously waiting for the California Alluvial Fan Task Force to provide ordinance language recommendations.

Recommendation

The FCDMC is currently revising their *Piedmont Flood Hazard Assessment Manual* (PFHAM). The revisions include an updated literature search, collection of technical reports on alluvial fan flooding, documentation of historical development on alluvial fans, and alluvial fan site evaluations within Maricopa County. The results of these analyses will be summarized in a series of technical memorandums that will culminate in recommended revisions to the PFHAM. Whereas the PFHAM revision study is a more comprehensive analysis of alluvial fan delineation methodologies than was conducted for this memo, the recommendation here is to wait for the completion of the PFHAM revision study, at which time the revised delineation methodology(ies) be adopted.

Level of Documentation Required

Structural solutions require significant documentation for each phase of the project.

Mitigation Design Recommendations

Whole-fan structural solutions in Coachella Valley are designed to mitigate the alluvial fan flood hazard.

Agency
Coachella Valley Water District
Contact: Georgia Calahar

Document Title-Year
Coachella Valley Water District (CVWD) has no formal manual/document.

Methodology Summary
The CVWD recognizes and accepts alluvial fan delineation methodologies described in *FEMA Appendix G.* To date, the CVWD has not proactively mapped alluvial fan hazards within their jurisdiction using *FEMA Appendix G.* The CVWD has constructed a series of flood control structures on several alluvial fans within Coachella Valley. The structures include levees, channelization, and debris basins at fan apexes.

The Thousand Palms Flood Control Project is a joint project with the CVWD and the U.S. Army Corps of Engineers. The project consists of a series of flood control structures including debris basins, levees, and fine sediment basins to control flooding on alluvial fans in Coachella Valley. The project is currently in the design phase.

Applicability to Fan Types in Maricopa County
The principle methodology employed by CVWD is structural mitigation. Such mitigation is applicability to fan types in Maricopa County.

Compatibility with FEMA Guidelines and NFIP Regulations
The methodologies are compatible with FEMA guidelines NFIP regulations.

Data Availability
Structural solutions require significantly different data than FEMA Appendix G delineation methodologies.

Reproducibility
N/A

Ease of Use
Requires specialized engineering services for the structural design.

Cost
Structural solutions are often the most expensive solution and require continued budgets for operations and maintenance.

Ability to Identify Risk Level
Structural solutions generally significantly reduce or remove the risk of alluvial fan flooding.

Compatibility with FEMA Guidelines and NFIP Regulations
The methodologies are compatible with FEMA Appendix G.

Data Availability
Data availability is dependent on which methodology or combination of methodologies is employed (see Table 2).

Reproducibility
The reproducibility of the results is dependent on which FEMA Appendix G methodology (or combination of methodologies) is employed. The more quantitative approaches (risk-based, FAN program, and hydraulics) may be more reproducible than the qualitative geomorphic approach. The AFTF draft report strongly emphasizes the geomorphic approach in determining the 100-year floodplain on alluvial fans.

Ease of Use
Methodology dependent (see Table 2).

Cost
Methodology dependent (see Table 2).

Ability to Identify Risk Level
Methodology dependent (see Table 2).

Level of Documentation Required
Methodology dependent (see Table 2).

Mitigation Design Recommendations
Step 3 through *Step 5*in the AFTF draft report addresses the following with respect to mitigation design recommendations:

Step 3: Identify Project Design and Resource Value Considerations
Step 4: Evaluate Potential Consequences, Costs and Benefits and Identify Strategies
Step 5: Integrate Alluvial Fan Data to Identify Multiple Objective Opportunities

Agency
California Department of Water Resources Alluvial Fan Task Force
Document Authors: Alluvial Fan Task Force
Contact: Mark Stuart – Chair: Alluvial Fan Task Force

Document Title-Year
Five-Step Process for Application of Local Planning Tools and Model Ordinance – July 2008

The Alluvial Fan Task Force (AFTF) was charged with developing comprehensive planning tools and a model ordinance that communities could use to address future development on alluvial fans. The AFTF convened a series of plenary meeting beginning in December 2007 and concluding March 27, 2009. The meetings included series of presentations on alluvial fan flooding issues presented by various public and private entities. The presentations available as of the date of this memo are included in the accompanying data disc under the *misc* folder.

As of the date of this memo, the AFTF Five-Step report was still in draft form and the model ordinance had not yet been completed. A copy of the AFTFdraft report is also included on the data disc.

Methodology Summary
The AFTF draft report presents a five-step process for floodplain management on alluvial fans. However, only steps one and two address identification and delineation of alluvial fan hazards. These steps are described below.

Step 1: Identify Alluvial Fan Presence – this step mirrors the *FEMA Appendix G* State 1 process. The AFTF draft report emphasizes the use of geologic maps, soil maps, field borings, site inspections, and general morphology of the landscape to identify alluvial fan landforms.

Step 2: Identify Existing Hazards on Alluvial Fans (Active vs. Inactive areas) – this step mirrors the Stage 2 process from *FEMA Appendix G.* The AFTF draft report recommends the use of field reconnaissance, aerial photography, historical flooding, and all the sources listed under *Step 1*to identify active and inactive areas on an alluvial fan. *Step 2* also includes defining the 100-year floodplain (FEMA Stage 3). The AFTF draft report discusses the use of all the sources described in *Step 1* and *Step 2* in identifying the 100-year floodplain. The draft report also recommends consideration of post-fire debris flow and erosion, and earthquake faults when defining the 100-year floodplain. All of these factors would fit into the Geomorphic Method category as defined in *FEMA Appendix G.*

Applicability to Fan Types in Maricopa County
The methodologies outlined in the AFTF draft report are applicable to fan types in Maricopa County.

development on alluvial fans[1], mitigation measures have been employed for existing development. These include:

- Land use planning (alluvial fan hazard zones)
- Land acquisition
- Site-specific land use regulations
- Forest Management Plan
- Active warning system
- Watershed stabilization
- Landslide/Earthflow monitoring
- Debris flow mitigation structures
  - Debris basins
  - Debris barriers
  - Deflection berms

It should be noted that the preferred mitigation measures as both discussed in the Jones Creek and Canyon Creek reports, and in personal communication with Paul Pittman (6/30/08), are non-structural (e.g. buy-outs, land acquisition, land use, warning systems, etc.). Major structures built within the past decade have deteriorated rapidly due to the volume and frequency of debris impacting the structures. WCFCZD has transferred responsibility of some of these structures to private entities due to the extremely high costs of maintenance (Paul Pittman personal communication, 6/30/08).

Other Comments
Unlike Maricopa County, Whatcom County has significant problems with large woody debris during debris flow and debris flood events. The woody debris causes aggradation on an accelerated scale in comparison with Maricopa County. Although both the Jones Creek and Canyon Creek studies resulted in a detailed hazard assessment including multiple hazard zones accompanied by individual development guidelines, a FEMA submittal of the hazard delineations would result in a blanket Zone A designation (Paul Pittman personal communication, 6/30/08).

[1] Paul Pittman (WCFCZD) personal communication, 6/30/08.

These delineations were based on both geomorphic methods and two-dimensional hydraulic modeling. Copies of these studies are available in their entirety from the WCFCZD website[1] and on the DVD included with Task 1.2.4 and 1.2.7.

Methodology Summary
WCFCZD currently recognizes and accepts alluvial fan delineation methodologies described in *FEMA Appendix G*. Although like FCDMC they regulate to more detailed delineations, alluvial fan floodplain delineations are submitted to FEMA as Zone A.

Applicability to Fan Types in Maricopa County
The methodologies accepted are applicable to fans in Maricopa County.

Compatibility with FEMA Guidelines and NFIP Regulations
The methodologies are compatible with *FEMA Appendix G*.

Data Availability
Data availability is dependent on which methodology or combination of methodologies is employed (see Table 2).

Reproducibility
The reproducibility of the results is dependent on which *FEMA Appendix G* methodology (or combination of methodologies) is employed. The more quantitative approaches (risk-based, FAN program, and hydraulics) may be more reproducible than the qualitative geomorphic approach.

Ease of Use
Methodology dependent (see Table 2).

Cost
Methodology dependent (see Table 2).

Ability to Identify Risk Level
Methodology dependent (see Table 2).

Level of Documentation Required
Methodology dependent (see Table 2).

Mitigation Design Recommendations
Both the Canyon Creek and Jones Creek studies provide design recommendations for mitigation of the hazard. Although the WCFCZD no longer allows subdivision

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Kerr Wood Leidal Associates, LTD, 2004, *Jones Creek Debris Flow Study*. Whatcom County Flood Control Zone District, Whatcom County, Washington.

[1] http://www.co.whatcom.wa.us/publicworks/riverflood/index.jsp

Agency

Whatcom County Flood Control Zone District, Washington
Contact: Paul Pittman, PG

Document Title-Year

In 1990 the State of Washington established legislation titled the Washington State Growth Management Act (GMA). Specific geological hazards (including alluvial fans) were outlined within the GMA. The purpose of the geological hazards designation was to establish minimum guidelines to aid in classification of critical areas. One of the guideline mandates was to identify and regulate hazards on alluvial fans. The Act provides considerable latitude in how geologically hazardous areas are to be regulated.

IN 1997 Whatcom County adopted its Critical Areas Ordinance (CAO) following an inventory assessment and identification of 150 alluvial fans in the county. The CAO defined alluvial fan hazard areas as:

> *"...those areas on alluvial fans where flooding, boulder floods, and/or debris torrents have the potential to damage or harm the health or welfare of the community. They include the area generally corresponding to the path of recent and potential future stream flooding, boulder flooding, and/or debris torrents as determined by local topography, hydrology, and depositional history on the fan. Alluvial fan hazard areas are geologically hazardous areas and therefore critical areas."*

Section 16 of the CAO includes specific regulatory requirements for alluvial fan hazard areas:

- A. *No critical facilities shall be constructed or located in geologically hazardous areas without fully mitigating the hazard.*
- C. *Projects shall be engineered and/or constructed to fully mitigate the hazard, and protect the building and occupants from the hazard.*
- H. *All projects on an alluvial fan hazard area must be engineered and constructed to withstand alluvial fan hazards and/or flooding equivalent to the largest known event evident on the fan as determined by professional assessment.*
- I. *Clearing within alluvial fan hazard areas is prohibited without adequately addressing the significance of tree retention in an assessment report.*

Whatcom County currently recognizes and accepts alluvial fan delineation methodologies described in *FEMA Appendix G*. Like the FCDMC, Whatcom County has been proactive in attempting to identify and describe alluvial fan hazards beyond those outlined in *Appendix G*. Whatcom County completed two studies[1] in which they identified and delineated hazard zones within alluvial fans.

[1] Kerr Wood Leidal Associates, LTD, 2003, *Canyon Creek Alluvial Fan Risk Assessment*. Whatcom County Flood Control Zone District, Whatcom County, Washington.

Ability to Identify Risk Level

The methodology results in flood zones based on depth and velocity as applied across the entire width of the fan. Risk level is applied broadly. The methodology does not consider the geology which, when considered, could impact the actual risk.

Level of Documentation Required

The level of documentation is minimal and should consist of equations used, results of equations, and a flood hazard map.

Mitigation Design Recommendations

The document provides recommendations for both structural and non-structural methods of flood protection on alluvial fans.

1. Non-Structural – the document recommends this method when proposed construction will not cause a major change to the natural alluvial fan process, or when buildings and other obstructions to flow are spaced such that flood and sediment flow can go around them without a major disturbance.
2. Structural – the document recommends this method when proposed construction does not fit the non-structural criteria. The documents required the following to be submitted to the county when structural methods are used:
    a. 1"=200' scale work maps showing alternative plans for flood control using county topographic maps.
    b. Evaluation summary for each alternative based on the criteria above.
    c. Design criteria: hydraulics, sediment transport, and erosion protection
    d. Computations and specific methods for developing recommendations.

Agency
San Diego County – Department of Public Works
Document Authors: Boyle Engineering Corporation

Document Title-Year
Borrego Valley Flood Management Report - 1989

The purpose of the report was to provide a broad background on alluvial fan flooding in the Borrego Springs area. The report contains a general discussion of alluvial fans, flood hazards and the environmental setting in Borrego Valley. Methods of non-structural flood protection and a description of flood control structures for alluvial fans are included. The document also includes an alluvial fan floodplain delineation map produced by FEMA.

Methodology Summary
The methodology recommended by the document is based on the assumption that the probability of an event of a particular magnitude striking a specific point on an alluvial fan decreases with increasing distance from the apex as the fan widens out. The actual flood hazard is defined in the document in terms of lines of equal depth and velocity of flooding across the fan. The combination of depth, width, and velocity related to a specific discharge which has a one percent chance of being equaled or exceeded in a given year.

Applicability to Fan Types in Maricopa County
This methodology is applicable to fan types in Maricopa County.

Compatibility with FEMA Guidelines and NFIP Regulations
The methodology is presented in the document is similar to using the FEMA FAN software program as shown in Figure G-4 in *FEMA Appendix G*. *FEMA Appendix G* recognized this methodology as valid for identifying and delineating alluvial fan flood zones.

Data Availability
Data required for this methodology is: hydrology (X-year discharge estimate at the fan apex), and topography of the fan surface.

Reproducibility
The methodology is quantitative and highly reproducible.

Ease of Use
The FEMA FAN software allows for a more simplified use of this methodology.

Cost
Cost is relatively low assuming hydrology and topography are readily available for little or no cost.

manual available. Specifically, the FCDMC is seen as "ahead of everyone else" in alluvial fan assessments according to Mike Fox. San Bernardino County is also looking to the California Alluvial Fan Task Force to eventually provide specific guidance, recommendations, and ordinance language on alluvial fan hazard determination and mapping.

Agency
Flood Control District of San Bernardino County, California
Contact: Mike Fox – Floodplain Manager

Document Title-Year
San Bernardino County has no formal, county-specific manual/document.

Methodology Summary
San Bernardino County currently recognizes and accepts alluvial fan delineation methodologies described in *FEMA Appendix G*. The county is not actively reviewing any alluvial fan floodplain delineations, nor have they reviewed any within the recent past.

Applicability to Fan Types in Maricopa County
The methodologies accepted are applicable to fans in Maricopa County.

Compatibility with FEMA Guidelines and NFIP Regulations
The methodologies are compatible with *FEMA Appendix G*.

Data Availability
Data availability is dependent on which methodology or combination of methodologies is employed (see Table 2).

Reproducibility
The reproducibility of the results is dependent on which *FEMA Appendix G* methodology (or combination of methodologies) is employed. The more quantitative approaches (risk-based, FAN program, and hydraulics) may be more reproducible than the qualitative geomorphic approach.

Ease of Use
Methodology dependent (see Table 2).

Cost
Methodology dependent (see Table 2).

Ability to Identify Risk Level
Methodology dependent (see Table 2).

Level of Documentation Required
Methodology dependent (see Table 2).

Mitigation Design Recommendations
There are no design recommendations provided in *FEMA Appendix G*.

Other Comments
Like Kern County, San Bernardino County views the FCDMC as the leader in alluvial fan floodplain management in the southwest and sees the PFHAM as the most advanced

as the most advanced manual available. Riverside County is also looking to the California Alluvial Fan Task Force to eventually provide specific guidance, recommendations, and ordinance language on alluvial fan hazard determination and mapping.

Agency
Flood Control and Water Conservation District of Riverside County, California
Contact: David Garcia – Floodplain Manager

Document Title-Year
Riverside County has no formal, county-specific manual/document.

Methodology Summary
Riverside County currently recognizes and accepts alluvial fan delineation methodologies described in *FEMA Appendix G*. The county is not actively reviewing any alluvial fan floodplain delineations.

Applicability to Fan Types in Maricopa County
The methodologies accepted are applicable to fans in Maricopa County.

Compatibility with FEMA Guidelines and NFIP Regulations
The methodologies are compatible with *FEMA Appendix G*.

Data Availability
Data availability is dependent on which methodology or combination of methodologies is employed (see Table 2)..

Reproducibility
The reproducibility of the results is dependent on which *FEMA Appendix G* methodology (or combination of methodologies) is employed. The more quantitative approaches (risk-based, FAN program, and hydraulics) may be more reproducible than the qualitative geomorphic approach.

Ease of Use
Methodology dependent (see Table 2).

Cost
Methodology dependent (see Table 2).

Ability to Identify Risk Level
Methodology dependent (see Table 2).

Level of Documentation Required
Methodology dependent (see Table 2).

Mitigation Design Recommendations
There are no design recommendations provided in *FEMA Appendix G*.

Other Comments
Like Kern County and San Bernardino County, Riverside County views the FCDMC as the leader in alluvial fan floodplain management in the southwest and sees the PFHAM

Mitigation Design Recommendations
There are no design recommendations provided in *FEMA Appendix G.*

Agency
Pima County Flood Control District, Arizona
Contact: Terry Hendricks – floodplain manager

Document Title-Year
Pima County has no formal, county-specific manual/document.

Methodology Summary
Pima County currently recognizes and accepts alluvial fan delineation methodologies described in *FEMA Appendix G*. Pima County is not currently reviewing any alluvial fan floodplain delineations; however the City of Marana (within Pima County) is currently reviewing alluvial fan floodplain delineations for the Tortolita Mountain piedmont. The document is titled *Volume 2: Geomorphic Analysis for the Tortolita Mountain Piedmont* (CMG Drainage Engineering, 2008). The document summarizes a geomorphic assessment of the Tortolita piedmont resulting in a Stage 1 and Stage 2 determination. The third volume of the study is still in progress, but upon completion will summarize the comparison of the geomorphic mapping with two-dimensional hydraulic modeling of the piedmont.

Applicability to Fan Types in Maricopa County
The methodologies accepted are applicable to fans in Maricopa County.

Compatibility with FEMA Guidelines and NFIP Regulations
The methodologies are compatible with FEMA Appendix G.

Data Availability
Data availability is dependent on which methodology or combination of methodologies is employed (see Table 2).

Reproducibility
The reproducibility of the results is dependent on which FEMA Appendix G methodology (or combination of methodologies) is employed. The more quantitative approaches (risk-based, FAN program, and hydraulics) may be more reproducible than the qualitative geomorphic approach.

Ease of Use
Methodology dependent (see Table 2).

Cost
Methodology dependent (see Table 2).

Ability to Identify Risk Level
Methodology dependent (see Table 2).

Level of Documentation Required
Methodology dependent (see Table 2).

Mitigation Design Recommendations

There are no design recommendations provided in *FEMA Appendix G.*

Other Comments

Kern County views the FCDMC as the leader in alluvial fan floodplain management in the southwest and sees the PFHAM as the most advanced manual available. Kern County is looking to the California Alluvial Fan Task Force to eventually provide specific guidance, recommendations, and ordinance language on alluvial fan hazard determination and mapping.

Agency
Kern County Engineering & Survey Services Department, Kern County, California
Contact: Aaron Leicht – Assistant Engineer

Document Title-Year
Kern County has no formal, county-specific manual/document.

Methodology Summary
Kern County is actively reviewing new alluvial fan floodplain submittals and CLOMR requests for alluvial fan delineations. These submittals are using a combination of the *FEMA Appendix G* geomorphic approach combined with detailed 2-dimensonal hydraulic analysis. Two specific recent submittals include:

- Indian Wells Alluvial Fan
- Lake Isabella Alluvial Fan

The Indian Wells fan was mapped by FEMA in the 1990s using the FEMA Fan Model. The recent CLOMR submission to Kern County for the Indian Wells fan is in support of reducing the floodplain area.

Applicability to Fan Types in Maricopa County
The methodologies being applied are applicable to fans in Maricopa County.

Compatibility with FEMA Guidelines and NFIP Regulations
The methodologies are compatible with *FEMA Appendix G*.

Data Availability
See Table 2 for data requirements of two-dimensional hydraulic modeling and geomorphic methodologies.

Reproducibility
The reproducibility of the results is dependent on which *FEMA Appendix G* methodology (or combination of methodologies) is employed. The more quantitative approaches (risk-based, FAN program, and hydraulics) may be more reproducible than the qualitative geomorphic approach (see Table 2).

Ease of Use
Methodology dependent (see Table 2).

Cost
Methodology dependent (see Table 2).

Ability to Identify Risk Level
Methodology dependent (see Table 2).

Level of Documentation Required
Methodology dependent (see Table 2).

The level of documentation is minimal and should consist of equations used, results of equations, and discharge estimates for the site of interest.

Mitigation Design Recommendations
Alluvial fan flood hazard mitigation is described in the document for transportation alignments crossing three alluvial fans in Southern Nevada and California. The methodology described in the document was applied to estimate the 100-year recurrence interval discharge at a number of drainage crossings along each alluvial fan.

Agency
Desert Research Institute, Reno, Nevada
Authors: French, R.H, W.A. McKay, J.W. Fordham

Document Title-Year
Chapter 3: Identification and Mitigation of Flood Hazard on Alluvial Fans – 1996

Methodology Summary
This document discusses and provides examples of a stochastic methodology developed by the authors. This methodology uses conditional probability to determine the discharge at a desired point or an arc of finite length on the alluvial fan. The methodology computes a synthetic Log-Pearson Type III (LP3) probability distribution skew (G), a synthetic LP3 standard deviation (S), and a synthetic mean ($\overline{X}$). The following example problems are discussed in detail in the document:

- Flow to a point on a single fan
- Flow to a point on coalescent fans
- Flow to a line of finite length on a single fan
- Flow to a line of finite length on coalescent fans

Applicability to Fan Types in Maricopa County
This methodology is applicable to fan types in Maricopa County.

Compatibility with FEMA Guidelines and NFIP Regulations
The methodology is similar to the FEMA FAN software program as discussed in *FEMA Appendix G*.

Data Availability
General data required for this methodology includes: hydrology (X-year discharge estimates at the fan apex), topography of the fan surface.

Reproducibility
The methodology is quantitative and highly reproducible.

Ease of Use
The numerous example problems in the document make this methodology easy to use.

Cost
Cost is relatively low assuming hydrology and topography are readily available for little or no cost.

Ability to Identify Risk Level
This methodology results is discharge estimates for site-specific locations on the alluvial fan. The methodology does not consider the geology.

Level of Documentation Required

methodology does not consider the geology which, when considered, could impact the actual risk.

Level of Documentation Required

The level of documentation for the FEMA FAN model is minimal and should consist of equations used, results of equations, and a flood hazard map.

Mitigation Design Recommendations

Whole-fan structural solutions in Clark County are designed to mitigate the alluvial fan flood hazard. Two example projects include the Red Rock Detention Basin[1] and F1 and F2[2] Basins at the apices of two alluvial fans within the Las Vegas Wash hydrologic system.

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[1] http://breccia.ccrfcd.org/pdf_arch3/ProjectFiles/USCOE/COER1%20-%20Red%20Rock%20Detention%20Basin/COER1%20-%20Design%20Memorandum%20Red%20Rock%20Detention%20Basin.pdf

[2] http://breccia.ccrfcd.org/pdf_arch3/ProjectFiles/USCOE/COEF3%20-%20%20F1%20and%20F2%20Basins%20and%20Channels/COEF3%20-%20F-1%20Channel%20Final%20Design%20-%20Sept.%201998.pdf

Agency
Clark County Regional Flood Control District, Nevada
Contact: Kevin Eubanks – Asst. General Manager

Document Title-Year
Hydrologic Criteria and Drainage Design Manual – 1999

- Section 1405: Alluvial Fan Flood Protection Measures[1]

Methodology Summary
Clark County's approach to alluvial fan flooding has historically involved structural, whole-fan solutions at fan apices. Such structural solutions outlined in the manual include: levees, channels, detention basins, debris basins, fences, deflectors, and dams. FEMA FAN model methodology is described in the manual for achieving the hydraulic parameters required for the structural design. At the time of this report, Clark County was not actively reviewing any alluvial fan floodplain delineations, not have they in the recent past. All alluvial fan hazards are mitigated by structural solutions (Kevin Eubanks person communication, 7/1/2008).

Applicability to Fan Types in Maricopa County
The structural approach is applicable to Maricopa County; however land ownership of the fan apex often precludes whole-fan solutions.

Compatibility with FEMA Guidelines and NFIP Regulations
The methodologies are compatible with FEMA guidelines NFIP regulations.

Data Availability
Structural solutions required significantly different data than *FEMA Appendix G* delineation methodologies.

Reproducibility
N/A

Ease of Use
Required specialized engineering services for the structural design. The FEMA FAN software is relatively simple to use.

Cost
Structural solutions are often the most expensive solution and require continued budgets for operations and maintenance. Cost of the FEMA FAN methodology is relatively low assuming hydrology and topography are readily available for little or no cost.

Ability to Identify Risk Level
The FEMA FAN methodology results in flood zones based on depth and velocity as applied across the entire width of the fan. Risk level is applied broadly. The

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[1] http://breccia.ccrfcd.org/pdf_arch1/hcddm/Sec1400.pdf

Mitigation Design Recommendations

There are no design recommendations provided in FEMA Appendix G.

Agency
Albuquerque Metropolitan Arroyo Flood Control Authority (AMAFCA)
Document Authors: Resource Consultants & Engineers, Inc.
Contact: Jerry Lovato – Drainage Engineer

Document Title-Year
Sediment and Erosion Design Guide - 1994
The purpose of the manual was to provide guidance for the analysis of sediment and arroyos for use in determining a lateral erosion limit. Although alluvial fan landforms are mentioned in the document, no guidance for floodplain delineation or general flood hazard determination on alluvial fans is discussed.

Methodology Summary
AMAFCA currently recognizes and accepts alluvial fan delineation methodologies described in *Guidelines and Specifications for Flood Hazard Mapping Partners – Appendix G: Guidance for Alluvial Fan Flooding Analyses and Mapping* (FEMA, 2003) (hereafter referred to as *FEMA Appendix G*).

Applicability to Fan Types in Maricopa County
This methodology is applicable to fan types in Maricopa County.

Compatibility with FEMA Guidelines and NFIP Regulations
The methodologies are compatible with FEMA Appendix G.

Data Availability
Data availability is dependent on which methodology or combination of methodologies is employed (see Table 2).

Reproducibility
The reproducibility of the results is dependent on which FEMA Appendix G methodology (or combination of methodologies) is employed. The more quantitative approaches (risk-based, FAN program and hydraulics) may be more reproducible than the qualitative geomorphic approach.

Ease of Use
Methodology dependent (see Table 2).

Cost
Methodology dependent (see Table 2).

Ability to Identify Risk Level
Methodology dependent (see Table 2).

Level of Documentation Required
Methodology dependent (see Table 2).

Each of the agency sources studied for this task were evaluated for each of the characteristics listed in the scope. Specifically, the categories were divided into the following:

- *Agency* – name of agency and floodplain administrator contact
- *Document Title-Year* – title of document/manual outlining alluvial fan floodplain delineation procedures
- *Methodology Summary* – which methodologies are required and/or accepted by the agency?
- *Applicability to Fan Types in Maricopa County* – whether the accepted methodologies are compatible to Maricopa County fans. Not all methods are applicable to all fan types.
- *Compatibility with FEMA Guidelines and NFIP Regulation* – are the required/accepted methodologies specific to the agency or are they compatible with FEMA and NFIP standards?
- *Data Availability* – is the data required by the methodologies readily available or highly specialized?
- *Reproducibility* – are the methodologies reproducible or highly interpretational?
- *Ease of Use* – are the methodologies relatively simple to follow and implement or do they require highly specialized expertise?
- *Cost* – what are the relative costs of the methodologies?
- *Ability to Identify Risk Level* – do the methodologies result in a clearly identified risk for flooding , sedimentation, and erosion?
- *Level of Documentation Required* – do the methodologies require extensive, detailed documentation or simplified documentation?
- *Mitigation Design Recommendations* – does the document/manual outline specific mitigation design requirements/recommendations?

The following pages within this section describe the results of the evaluation for each agency.

Table 2. FEMA Appendix G methodologies

FEMA Appendix G Methodology	**Task 1.2.1 Characteristics**							
	Applicability to Maricopa County	Compatibility with FEMA and NFIP	Availability of Data	Reproducibility of Results	Ease of Use	Cost to Apply Methodology	Ability to Identify Risk	Level of Documentation Required
FEMA FAN Model	Applicable	Compatible	Data requirements include: • Flood-frequency data • Avulsion factor • Slope (multiple channel option) • Manning's *n* (multiple channel option) • Discharge (multiple channel option) All this information is relatively simple to compute and/or readily available.	Assuming the input values are constant, the reproducibility is high.	The program is simple to use with most of the input values being yes or no questions.	Relatively low.	Model results in velocity and depth "zones" within the fan boundaries. Results indicate the further down-fan the less the risk.	Low. Documentation should include flood-frequency computations and sources of discharge estimates.
Sheetflow[1]	Applicable	Compatible	Data requirements include: • Topography • Hydrology at head of sheetflow area	Assuming the input values are constant, the reproducibility is high.	Simple. Basic one-dimensional step-backwater modeling can be used to compute depths.	Relatively low.	Results in inundation depth risks.	Moderate. A simple FIS Report is required.
Hydraulic Analytical								
One-Dimensional	Not applicable to active alluvial fan flooding (*FEMA Appendix G*)	Compatible for stable flow paths only	Detailed hydrology (rainfall, soils, landuse) and topography required.	Assuming the input values are constant, the reproducibility is high.	Complex modeling requiring specific knowledge.	Relatively high.	Not applicable to active fan flooding.	High. Hydrology and Hydraulics Report.
Two-Dimensional	Applicable	Compatible	Detailed hydrology (rainfall, soils, landuse) and topography required.	Assuming the input values are constant, the reproducibility is high.	Complex modeling requiring specific knowledge.	Very High.	Results in detailed velocity and depth for entire fan surface.	High. Hydrology and Hydraulics Report.
Geomorphic	Applicable	Compatible	Data requirements include: • Recent/historical aerial photographs • Topography • Soils mapping • Geologic mapping • Detailed field analysis	Results are mostly qualitative.	Less complicated than hydraulic method, but requires knowledge of geology and geomorphology.	Lower than hydraulic methods, likely higher than FAN and Sheetflow methods.	Results in absolute or relative age relationships of landforms and flood frequency on geologic time scale. Site-specific risk is relative.	Moderate. Geomorphic Assessment Report required.
Composite	Applicable	Compatible	Methodology dependant	Methodology dependant	Methodology dependent	Methodology dependent	Methodology dependent	Methodology dependent

[1] *FEMA Guidelines and Specifications for Flood Hazard Mapping Partners: Appendix E: Guidance for Shallow Flooding Analyses and Mapping* (https://www.fema.gov/pdf/fhm/frm_gstc02.pdf)

Table 1. Agency sources for this study

Agency	General Geographic Location	Comments
Albuquerque Metro. Arroyo Flood Control Authority (AMAFCA)	Southwest	
California Dept. of Water Resources Alluvial Fan Task Force	Southwest	
Clark County, NV	Southwest	
Coachella Valley Water District	Southwest	
Desert Research Institute	Southwest	
Kern County, CA	Southwest	
Pima County, AZ	Southwest	
Riverside County, CA	Southwest	
San Bernardino County, CA	Southwest	
San Diego County, CA	Southwest	
Whatcom County, WA	Northwest	Not a similar geographic area, but found to be relevant.

Collecting information from the agencies consisted of researching their online electronic document libraries for manuals/documents related to alluvial fan flooding, and speaking with the floodplain administrator or other relevant party responsible for review of alluvial fan floodplain delineations. Communication with agency personnel was conducted via telephone. The information gathered by online research and telephone communication is summarized in the agency evaluation pages found later in this document.

Summary of Findings

The scope of work for this task listed eight characteristics with which each alluvial fan floodplain delineation methodology identified should be described. The characteristics include:

- *Applicability to fan types in Maricopa County*
- *Compatibility with FEMA Guidelines & NFIP Regulations*
- *Availability of necessary data to apply method*
- *Reproducibility of results*
- *Ease of use*
- *Cost to apply methodology*
- *Ability to identify the activity (risk level) of alluvial fan flooding*
- *Level of documentation required for methodology*

The methodologies described in FEMA Appendix G represent those sanctioned by FEMA, thus represent the baseline from which any additional methodology be built. It is therefore instructive to first apply the eight characteristics above to each of the methodologies described in FEMA Appendix G before applying them to any additional methodologies. Table 2 lists the methodologies and their applicability to the eight characteristics.

Source: FEMA Appendix G

Figure 1. Three-stage process of FEMA Appendix G

FEMA Appendix G outlines four general methodologies for alluvial fan floodplain delineation, with a fifth method being composed a combination of the four. The methods described are:

1. FEMA FAN Computer Model
2. Sheetflow
3. Hydraulic Analytical
4. Geomorphic
5. Composite

It is not the purpose of this document to describe in detail each of these methodologies and the reader is referred to FEMA Appendix G for more detail.

Task Approach

The bulk of this study was composed of identifying and researching current methodologies being employed for alluvial fan floodplain delineation. The first task was to identify which agencies to research. The scope of work specifically recommends several sources. The scope also specifies the research be focused in "*potentially similar geographic areas*". Table 1 lists the agencies that were the focus of this study.

Introduction

This memorandum summarizes the results of research and documentation on alluvial fan floodplain methodologies that are presently being employed by agencies and municipalities within the western U.S with a specific emphasis on the southwestern U.S. At present, the Federal Emergency Management Agency (FEMA) recognizes and accepts multiple alluvial fan floodplain delineation methodologies as described in *Guidelines and Specifications for Flood Hazard Mapping Partners – Appendix G: Guidance for Alluvial Fan Flooding Analyses and Mapping* (FEMA 2003); hereafter referred to as FEMA Appendix G.

Appendix G presents a three-stage analysis approach to alluvial fan floodplain delineation. Each of the three-stages must be thoroughly documented. Each of the successive stage processes builds on the previous, so FEMA recommends close coordination with the FEMA reviewing partner throughout the entire process. The three-stages are described as follows:

- Stage 1 – Recognizing and characterizing alluvial fan landforms.
- Stage 2 – Defining the nature of the alluvial fan environment and identifying active and inactive areas of the fan.
- Stage 3 – Defining and characterizing the 1-percent annual change (100-year) flood within the defined areas.

Figure 1 illustrates the different types of information that are required to complete each of the three stages.

DATE: July 11, 2008; revised March 20, 2009

TO: Kathryn Gross, CFM/FCDMC

FROM: Jon Fuller, PE, RG

RE: FCD 2007 C051
Assignment #1, Task 1.2.1
Existing Alluvial Fan Floodplain Delineation Methodologies

CC: File

Scope Summary for Task 1.2.1. Existing Alluvial Fan Delineation Methodologies

Existing Alluvial Fan Floodplain Delineation Methodologies. The CONSULTANT shall identify Stage 2 and Stage 3 alluvial fan floodplain delineation methodologies already in use by regulatory agencies in potentially similar geographic areas. The methodologies considered shall include the DISTRICT's current Stage 2 and Stage 3, the FEMA FAN software, and up to ten (10) other alluvial fan floodplain delineation methodologies selected from technical papers/reports that describe alluvial fan flood hazard mapping. Potentially similar geographic areas include, but are not limited to, northern New Mexico (Albuquerque area), southern Nevada (Clark County), and Southern California. Alluvial fan methodologies described in engineering design manuals for Clark County, counties in Southern California, and Albuquerque Metropolitan Arroyo Flood Control Authority (AMAFCA) shall be evaluated for applicability to Maricopa County. The DISTRICT will provide a bibliography and copies of alluvial fan literature and manuals already collected by District staff that relate to this task. The CONSULTANT will prepare a report discussing methodologies and case studies in geographically similar alluvial fan areas and will recommend the most appropriate delineation methods for use in Maricopa County. The evaluation of methodologies will be based on the following:

- *Applicability to fan types in Maricopa County*
- *Compatibility with FEMA Guidelines & NFIP Regulations*
- *Availability of necessary data to apply method*
- *Reproducibility of results*
- *Ease of use*
- *Cost to apply methodology*
- *Ability to identify the activity (risk level) of alluvial fan flooding*
- *Level of documentation required for methodology*

floodplain delineation studies rely on geomorphic methods. The literature search did identify several methodologies that may be useful for quantifying some elements of alluvial fan floodplain delineation studies and flood hazard assessments. However, none of these methodologies were developed specifically for floodplain delineation purposes, and none have been formally adopted by regulatory agencies, including FEMA. Therefore, it is likely that the District will be charting new territory as it revises the PFHAM.

Overview of Literature Search DVD

The enclosed DVD includes the following information which can be automatically accessed by inserting the disk into a DVD drive:

- FCD2007C051 Literature Search Summary
  Includes a series of memoranda summarizing the findings for literature research on seven specific topics included in the 2007C051 scope of services.

- Reference List
  Consists of an Microsoft Excel spreadsheet listing every literature source identified, bibliographic reference information, key words, significance relative to alluvial fan flooding in Maricopa County, and a hot link to the scanned article on the DVD (or an applicable website).

- Collected Literature
  Scanned articles in pdf format for literature sources available for collection. The literature sources are organized by type. Specific sources can be easily found by scanning or searching the Excel spreadsheet and clicking on the hot link.

Executive Summary

In 2008, JE Fuller/Hydrology & Geomorphology, Inc. performed a specialized literature review focused on the following research topics relating to alluvial fans:

1.2.1 Existing Alluvial Fan Floodplain Delineation Methodologies
1.2.2 FEMA CLOMR/LOMR Methodologies
1.2.3 Interview NRC Committee Members
1.2.4 Debris Flow Hazard & Risk Assessment
1.2.5 Frequency of Alluvial Fan Channel Avulsion
1.2.6 Mitigation Measures
1.2.7 Hazard Quantification Methods

For each research topic, separate memoranda were provided to the District. These memoranda have been revised in response to District comments and are included on the DVD attached to this summary.

The literature research revealed that Maricopa County is in the forefront of alluvial fan flood hazard assessment. Floodplain delineation methods are following criteria set out to comply with FEMA Appendix G, including one- and two-dimensional fixed bed hydraulic modeling, geomorphic methods, and composite methods. Of the CLOMR and LOMRs obtained, structural mitigation measures are the primary approach to alluvial fan hazard mitigation. Follow-up with the original NRC Alluvial Fan Task Force Committee members revealed little new in the fan hazard assessment world. Review of debris flow hazard and risk assessment revealed a large body of work in Europe. Hazard assessment techniques relate hydraulic characteristics to degree of hazard with depths greater than 1 meter and velocities greater than 1 meter per second. Some studies have added elements related to impact forces and extent of debris runout. Very few studies of avulsion frequency were identified. Examples of avulsions on Tiger Wash and on the western White Tank Mountain piedmont are found in work by the Arizona Geological Survey and related studies for the District. However, relationships to statistical frequency of such events were not discovered. Mitigation measures for debris flows and landslides are found in the European literature. Several references are provided in the accompanying electronic disc. Examples from American fans were found in US Army Corps documents and were summarized in tabular form. Finally, a spreadsheet and electronic disc were compiled with all of the relevant abstracts, journal articles, and reports collected in an electronic format.

The District's Piedmont Flood Hazard Assessment Manual (PFHAM) is essentially a floodplain delineation methodology, and does not address quantification of alluvial fan flood hazards for engineering design. The literature search identified three basic types of alluvial fan floodplain delineation methods: (1) the FEMA FAN model, a.k.a., the Dawdy Method, (2) so-called geomorphic methods, of which the PFHAM is one, and (3) composite methods that attempt to combine elements of the geomorphic method and hydraulic modeling techniques. Because of FEMA's acceptance of the geomorphic method developed by the National Research Council (NRC), most new alluvial fan

Executive Summary

Literature Search & Data Collection

FCD2007 C051 – Work Assignment #1

Deliverable for Work Assignment No. 1, Task 2.1, FCD2008C007
Refinement of Methodology: Alluvial Fan Hazard Identification & Mitigation Methods

March 31, 2009

JE FULLER
HYDROLOGY & GEOMORPHOLOGY, INC.

Appendix A:

Executive Summary of Literature Search
FCD2007C051, Task 1

Memorandum JE Fuller/ Hydrology & Geomorphology, Inc.

DATE: March 31, 2009

TO: Kathryn Gross, CFM

FROM: Ted Lehman, PE

RE: FCD 2007 C051
Assignment #1, Task 1.2.4 – Debris Flows

CC: File

Scope Summary for Task 1.2.4. Debris Flow Hazard & Risk Assessment

> *Debris Flow Hazard & Risk Assessment. The CONSULTANT shall identify and summarize literature accounts of debris flows on alluvial fans, descriptions of physical characteristics of debris flow deposits (vs. fluvial deposits), methodologies for predicting debris flow occurrence, estimates of debris flow frequency, and mapping of known debris flows in central Arizona compiled by the Arizona Geological Survey*

Debris Flows

The literature on debris flows is extensive. Several international conferences have been held in the past 10 years. The proceedings from these conferences contain excellent sources of information on case studies of debris flows, studies on debris flow mechanics, and discussions of debris flow mitigation measures.

DEBRIS FLOW 2008, Second International Conference on Debris Flow including all aspects of Debris Flow Monitoring, Modelling, Hazard Assessment, Mitigation Measures, Case Studies, and Extreme Events, Erosion, Slope Instability and Sediment Transport, 17 - 19 June, 2008, The New Forest, UK

Conference website

Chen, C. editor, 1997, Debris-flow Hazards Mitigation: Mechanics, Prediction, and Assessment, Proceedings from the First International Conference, San Francisco, CA Aug. 7-9, 1997, published by ASCE, New York, NY.

This was the first of several international conferences on debris-flows. Numerous excellent papers of case studies on debris flows, mechanics, hazards, and defenses were presented. A hard copy is available at JEF.

Rickenmann, D. & Chen, C. editors, 2003, Debris-flow Hazards Mitigation: Mechanics, Prediction and Assessment, Proceedings of the Third International Conference on Debris-Flow Hazards Mitigation, Davos, Switzerland, Sept. 10-12, 2003.

Abstract, Table of Contents, conference website

Chen, C. & Major, J., editors, 2007, Debris-flow Hazards Mitigation: Mechanics, Prediction, and Assessment, Proceedings from the Fourth International Conference, Chengdu, China, Sept. 10-13, 2007

Abstract, conference website

Another excellent collection of papers on debris flows is found in:

Jakob, M. & Hungr, O., editors, 2005, Debris-flow Hazards and Related Phenomena, Springer, Berlin, 739 p.

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For a person new to the subject, Chapter 2 defines and classifies debris flows and provides a good overview of the issues.

Cannon, S.H., 1997, Evaluation of the Potential for Debris and Hyperconcentrated Flows in Capulin Canyon as a Result of the 1996 Dome Fire, Bandalier National Monument, NM, USGS Open-File Report 97-0136.

Griffiths, P.G., Webb, R.H., & Melis, T.S., 1996, Initiation and Frequency of Debris Flows in Grand Canyon, Arizona, USGS Open-File Report 96-491.

This report notes the importance of lithology, especially shale or other clay rich sources, as important to generation of debris flows.

Debris flow frequency

In Switzerland, a design frequency of 200 years is used for all flood hazard assessment, including debris flows. A 200-year recurrence interval is also recommended in British Columbia. Several investigations in the Pacific Northwest have shown debris flow frequency ranging from several hundred to a few thousand years (KWL, 2003; KWL, 2004). Whatcom County, Washington, where the KWL studies were performed, recommends a 500-year design frequency for debris flows. In New Zealand, no critical facilities, such as hospitals, are allowed in areas subject to at least the 1,000-year flood hazards, including debris flows on alluvial fans. Evacuation sites are recommended to be safe from the 2,500-year event (McSaveney, M.J., Beetham, R.D., 2006).

Debris flows in Arizona

In addition to the USGS Open File Report on the Grand Canyon noted above, the USGS and Arizona Geological Survey (AZGS) have described and documented recent debris flows in southern Arizona. Personal communications with Dr. Phil Pearthree (AZGS) reveal additional yet unpublished observations of debris flows throughout other parts of Arizona. Dr. Pearthree noted that most of the debris flows they have observed lie in very steep areas, especially at the base of near vertical bedrock exposures. Another common element has often been the occurrence of debris flows following severe fire in the watershed.

Conversely, Field (2001) notes that debris flows were not observed in the western piedmont of the White Tank Mountain alluvial fans he investigated. He also cites other investigators mention of lack of debris flow activity in central Arizona since the early Holocene (1994b).

Memorandum JE Fuller/ Hydrology & Geomorphology, Inc.

DATE: June 30, 2008; revised March 20, 2009

TO: Kathryn Gross, CFM/FCDMC

FROM: Jon Fuller, PE, RG

RE: FCD 2007 C051
Assignment #1, Task 1.2.5
Summary of Alluvial Fan Flood Mitigation Measures

CC: File

Scope Summary for Task 1.2.5. Frequency of Alluvial Fan Channel Avulsion.

The CONSULTANT shall identify and summarize literature accounts of channel avulsions on alluvial fans, especially in regard to the frequency of occurrence.

Summary of Findings

We identified only one literature source that identified long-term studies of alluvial fan channel avulsions from which estimates of frequency of occurrence could be derived (Field, 1994). Using historical photographs, stratigraphic information, and field observations, Field estimated that the frequency of significant avulsions range from 50 to 600 years on fans in central and southern Arizona. There are also a number of flume and stream table studies that describe mechanisms of avulsions and evaluate the importance of variables thought to cause avulsions. Most of these experimental studies are directed at riverine avulsions, but most authors also note the potential application to avulsions on streamflow dominated fans. Of the studies cited and summarized below, the work by John Field is the most applicable to Maricopa County, having been completed on the White Tank Mountain Piedmont and elsewhere in Arizona.

The following summarize the more salient conclusions from the research cited below:

- Avulsions are known to occur on alluvial fans.
- Avulsions occur on both fluvially-dominated and debris flow-dominated fans.
- Avulsion frequency increases with increased slope and sediment supply.
- Avulsion frequency is also directly related to debris blockage of channels, high flood ratio (e.g. Q2/Q100), the flood sequence, climatic change or shifts, and channel depth.
- Avulsion frequency on large river systems ranges from decadal to millennial cycles.
- Avulsions occur both in aggrading and sheetflow portions of a fan.
- Avulsions occur preferentially on the outside of channel bends.

We recommend that the project team continue to search for literature and research studies regarding avulsion frequency and mechanisms.

Summaries of Key Literature Sources

Field, John J., 1994, Surficial Processes, Channel Change, and Geological Methods of Flood-Hazard Assessment on Fluvially Dominated Alluvial Fans in Arizona, Ph.D Dissertation, University of Arizona Department of Geosciences, Tucson, Arizona.

- Study examined White Tank, Tiger Wash & Tortolita alluvial fans in Arizona.
- Channel avulsions (diversions) occur at low channel banks and bends where overland flow is generated. (p. 13)
- Channel migration occurs through stream capture (piracy). (p. 13)
- Recurrence interval of major channel shifts exceeds 100 years. (p. 13)
- Flood hazard assessments should be updated after each flood because small floods can affect the location and timing of avulsions. (p. 13)
- Debris flows do not occur on the White Tank and Tiger Wash fans. (p. 18)
- Mechanism of avulsion: (p. 18)
    - Small floods aggrade channel
    - Subsequent floods overflow channel and enter secondary channels
    - New channels form along secondary overbank paths which capture the main channel by piracy
- Channel Migration Processes (p. 138)
    - Based on field data, aerial photos, stratigraphic sections
    - Incipient (on-fan) drainage channel network is incorporated into main fan channel through capture as they approach the distributary network, often during a flood.
    - Captured channels widen with larger discharges
    - Small floods into "new channels" with high w/d ratio have high transmission loss, deposit sediment (only largest floods have energy to convey sediment through system).
    - Aggradation occurs, lowering bank height & allowing overbank flow.
    - Overbank flow is single most important component of channel migration.
    - Captured channels are often lower topographically than aggrading distributary area, leading to effective captures
- Factors that affect channel migration
    - Initial depth of main channels
    - Flood magnitude
    - Sequence of flood magnitudes
    - Location of on-fan channels
    - Composition/resistance of bank materials
- Definition of "Active." Active surfaces are those portions of the fan having a finite, though in some areas a low probability of being flooded in any given year (Hooke, 1972). Active surfaces are not necessarily inundated entirely by each flood, and portions of the active surfaces may not be flooded for several thousand years. (p. 24)

Additional References in Field (1994):

- Beatty (1963) – debris blockage avulsions, especially at bends
- Pack (1923), Chawner (1935), Kochel & Johnson (1984) – debris flow avulsions
- Griffiths & McSaveney (1986) – aggradation precedes avulsion
- Eckis (1928) – stream flow avulsion
- Schumm (1989) - ephemeral stream avulsion
- Chawner (1935) – debris flows fill channels
- Kesseli & Beaty (1959) – avulsion frequency higher on steeper fans
- Blair (1987) – catastrophic floods form entirely new channels (not along network)
- Gole & Chitale (1966) – avulsion frequency

See Also: Field, John, 2001, "Channel avulsion on alluvial fans in southern Arizona," *Geomorphology*, Vol 37, p. 93-104.

Ashworth, Philip J., Best, James L., and Jones, Merron, 2004, "Relationship between sediment supply and avulsion frequency in braided rivers," *Geology*; Vol. 32; No. 1; p. 21-24; (ashworth_etal_2004_geology_v32_no1_p21-24.pdf)

> Abstract: The interplay between sediment supply (S_s), sedimentation rate (S_r), and the frequency of channel avulsion (A_f) exerts a primary control on alluvial architecture. In order to investigate the effect of sediment supply on avulsion frequency, four Froude-scale model experiments of an aggrading braided river were undertaken in which the magnitude of S_s was progressively increased over an eightfold range. The value of A_f increases at a rate slower than the increase in S_s, contrary to the trend previously reported by Bryant, Falk, and Paola (1995) in their experimental study on alluvial-fan dynamics. These results suggest that the relationship between A_f and S_s is dependent upon bed slope and that the response of A_f to an increase in S_s in unconfined braided rivers may be different than that on steep alluvial fans.
>
> The authors define an avulsion as channel movement over a lateral distance greater than the mean channel width, within a short period of time, and with some degree of permanence of the channel at the new location (i.e., not progressive rapid lateral movement). Bryant et. al. (1995) had defined avulsion as creation of a new channel that carries at least 50% of the old channel capacity. Avulsion frequency increases with sediment supply and channel slope because at high slopes and high supply rates, flow outside the defined channel network is most likely. The results suggest that other factors that increase overbank flow would similarly increase avulsion frequency.

Ashworth, P. J., Best, J.L., Jones, M., 2007, "The relationship between channel avulsion, flow occupancy and aggradation in braided rivers: insights from an experimental model," *Sedimentology*, Vol. 54, No. 3, p. 497-513, (ashworth_etal_2007_sed_v54_no3_p497-513.pdf)

> Abstract: Experimental modeling of an aggrading braided river has allowed investigation of the relationship between the frequency of channel avulsion (Af), the duration of time that the braidplain is occupied by flow, the spatial pattern of braidplain sedimentation and how these respond to a change in sediment supply (Ss). Model results demonstrate a strong, positive relationship between Ss and Af and that there is no downstream change in Af over the short braidplain distances (ca 100 m) modeled herein. Although Af is strongly dependent on Ss, the degree of channel switching does not influence the rate, or

spatial pattern, of braidplain sedimentation. All experiments used a single, central input for water and sediment, and the channels occupied the centre of the alluvial basin for a longer period of time than the margins for all sediment supply rates and distances downstream. Despite this spatio-temporal pattern in flow occupancy, braidplain sedimentation rates were nearly uniform both downstream and across the basin, and increased at approximately the same rate as increases in Ss. As a consequence, less frequent, and possibly short-lived, flows at the margins of the braidplain deposited and preserved more sediment per unit time in comparison with the centre of the basin where flow occupancy was higher. An approximate order of magnitude change in sediment supply resulted in only a factor of two change in bed slope, probably due to both an increase in channelization and adjustment of the channel form that maintained sediment transport through the basin. This result suggests that linear diffusion models are unlikely to be applicable in landscape evolution models that possess aggrading multi-thread rivers, which are capable of self-adjustment in channel number and form.

The study is based on experimental results, similar to previous work by the authors (above) and does not provide estimates of the temporal frequency of real streams or fan channels.

Bryant, M., Falk, P., Paola, C., 1995, Experimental Study of Avulsion Frequency and Rate of Deposition, *Geology*, Vol. 23, No. 4, p. 365-368, (bryant_etal_1995_geology_v23_no4_p365-368.pdf)

Abstract: In existing models of alluvial architecture it is typically assumed that mean avulsion frequency is independent of sedimentation rate. However, if avulsion is driven by superelevation of a river bed above its surrounding flood plain, one might expect avulsion rate to increase with sedimentation rate. We have carried out a series of experiments with laboratory-scale fluvial fans in which we measured the frequency of apical avulsions as a function of mean sedimentation rate on the fan. Avulsion frequency increased strongly with increasing sedimentation rate and then stabilized as mass flows began to influence deposition. In the regime of increasing avulsion frequency, the added volume of sediment needed to trigger an avulsion decreased with increasing sedimentation rate. Although our experimental results cannot simply be scaled up to natural rivers, they suggest the possibility of coupling between avulsion frequency and sedimentation rate that would be strong enough to change qualitatively the results of existing models of alluvial architecture. These models should be applied with caution until avulsion mechanics are better understood.

In this laboratory experiment the authors concluded that the fundamental criterion for avulsion is addition of a critical volume of sediment to the system. They also hypothesize that avulsion frequency will increase with increased fan slope, probably due to decreased bankfull flow depth (for a given discharge & channel width).

Leier, A.L., DeCelles, P.G., Pelletier, J.D., 2005, "Mountains, monsoons, and megafans," *Geology*, Vol. 33, No. 4, p. 289-292, (leier_etal_2005_geology_v33_no4_p289-292.pdf)

Abstract: In certain cases, the rivers draining mountain ranges create unusually large fan-shaped bodies of sediment that are referred to as fluvial megafans. We combine information from satellite imagery, monthly discharge and precipitation records, digital elevation models, and other sources to show that the formation of fluvial megafans requires particular climatic conditions. Specifically, modern fluvial megafans in actively aggrading basins are produced by rivers that undergo moderate to extreme seasonal fluctuations in discharge that result from highly seasonal precipitation patterns. The

global distribution of modern megafans is primarily restricted to 158–358 latitude in the Northern and Southern Hemispheres, corresponding to climatic belts that fringe the tropical climatic zone. No relationship exists between megafan occurrence and drainage-basin relief or area. The tendency of rivers with large fluctuations in discharge to construct megafans is related to the instability of channels subject to such conditions. Because of the correlation between seasonal precipitation and megafan occurrence, the recognition of fluvial megafan deposits in ancient stratigraphic successions may provide critical information for paleoclimate reconstructions.

Clearly, there are no megafans in Maricopa County. Some applicable principles from the study for Maricopa County relate to avulsion drivers and mechanisms. Specifically, avulsions are thought to be: (1) related to large fluctuations in discharge rate (i.e., high flood ratios), (2) floods, which are avulsion triggering events, (3) high sediment yields either from the watershed or lateral erosion, (4) sparse bank vegetation density.

Morhig, D., Heller, P.L., Paola, C., Lyons, W.J., 2000, "Interpreting avulsion process from ancient alluvial sequences: Guadalope-Matarranya system (northern Spain) and Wasatch Formation (western Colorado)," *Geological Society of America Bulletin*, Vol. 112, No. 12, p. 1787-1803, (mohrig_etal_2000_gsabull_v112_no12_p1787-1803.pdf)

Abstract: Alluvial deposits of the Guadalope-Matarranya system (Oligocene, Ebro basin, Spain) and the Wasatch Formation (Eocene, western Colorado), provide time-integrated records of the process of river channel avulsion. These sequences consist of isolated channel-belt sandstones incised into, and abruptly overlain by, flood-plain siltstones, indicating deposition by avulsive river systems. The geometry and distribution of channel incisions suggest that avulsion was not controlled by tectonics, climate, or base-level changes, but formed by auto cyclic processes. Measurements from 221 channel fills in the Guadalope-Matarranya system and 38 from the Wasatch Formation allow us to statistically characterize channel geometries we infer to be associated with establishment and abandonment of individual river avulsions. Paleoflow depths in both systems average 1.4 to 1.6 m. Aggradation height (superelevation) of channel margin levees are, on average, 0.6 and 1.1 times paleoflow depth in the Guadalope-Matarran- ya and Wasatch systems, respectively. These results are consistent with values from recently avulsed modern rivers and suggest that (1) flow depth is the appropriate parameter against which to scale the critical superelevation necessary for channel avulsion; and (2) the increase in potential energy due to channel perching drives the lateral instability that is needed for avulsion to be successful. Numerous stacked channel fills indicate repeated reoccupation of the same site by avulsing channels. These reoccupation channels indicate that inherited flood-plain topography, here abandoned channel forms, was an important control on the arrival site of newly avulsed channels. Comparison of our results to others suggests two end-member types of avulsion can take place. Incisional avulsion, seen here, is characterized by an early incision phase followed by infilling by migrating bar forms. Aggradational avulsion begins with aggradation followed in time by stream integration into a single down-cutting channel. We suggest that the type of avulsion is strongly influenced by whether or not the adjacent flood plain is well or poorly drained. In both cases subsequent aggradation and channel perching increase the chances that some triggering event will lead to avulsion.

The application to alluvial fans in Maricopa County is in the description of several mechanisms for formation of avulsions, the importance of perching of the channel bed above the floodplain prior to avulsion, and the potential for avulsions to later reoccupy a previous channel alignment.

Weissmann, Gary S., Mount, Jeffery, and Fogg, Graham E., 2002, Glacially Driven Cycles in Accumulation Space and Sequence Stratigraphy of a Stream-Dominated Alluvial Fan, San Joaquin Valley, California, U.S.A., *Journal of Sedimentary Research*; Vol. 72; No. 2; p. 240-251. weissman_etal_2002_jrnlsedres_v72_no2_p240-251.pdf

High-resolution sequence stratigraphy provides a framework to interpret unconformity-bounded depositional sequences in the stream-dominated Kings River alluvial fan, located near Fresno, California. Depositional units in the fan are analogous to systems tracts described from marine deposits. Fan sequences reflect changes in accumulation space (Blum and Törnqvist 2000) associated with Pleistocene glacial cycles in the Sierra Nevada and preservation space created by tectonic subsidence in the San Joaquin basin. Adjustments in accumulation space are driven by changes in the ratio of sediment supply to discharge during glacial advances and retreats. At the end of glacial periods and the beginning of interglacial periods, declines in the ratio of sediment supply to discharge led to fan incision, a basinward shift in the fan intersection point, and loss of accumulation space. In mid- and upper-fan settings, incised valleys and laterally extensive, moderately mature paleosols formed, marking the unconformable base of the depositional sequence. Throughout the interglacial period, relatively low accumulation space existed and deposition was confined to the distal areas of the fan. Rapid aggradation and, thus, accumulation space increase, in response to increased sediment supply during the next glacial event initially filled the incised valley with a fining-upward succession of relatively coarse-grained channel and overbank deposits that contain rare, immature paleosols. Upon filling of the incised valley, the intersection point stabilized near the fan apex. This led to unconfined, open-fan deposition, indicating that widespread accumulation space was available across most of the fan surface. These high-accumulation-space units consist of fluvial deposits from multiple, large glacial outwash channels that radiated outward from the proximally located intersection point. Sequence boundaries and units associated with accumulation-space cycles can be used to understand and predict facies distributions and stratigraphic packaging within glacially influenced fans similar to the Kings River alluvial fan.

Heller, Paul L., and Paola, Chris, 1996, Downstream Changes In Alluvial Architecture: An Exploration of Controls on Channel-stacking Patterns, *Journal of Sedimentary Research*, Vol. 66.

Various, but related, models have been proposed to explain the architectural arrangement of channel stacking patterns in avulsion-dominated alluvial sequences. The early models published by Leeder, Allen, and Bridge (LAB) addressed the role of changes in sedimentation rate (a proxy for subsidence rate) as a control on stacking patterns. The models decouple avulsion frequency from sedimentation rates, resulting in an inverse relationship between stacking density (or interconnectedness) and sedimentation rates. A key element missing from these models is the likely dependence of avulsion frequency on local sedimentation rate within the active channel belt. We consider a simple model whereby avulsion takes place only when a minimum, critical, relief is developed between a channel bank and the adjacent flood plain. If avulsion frequency increases at rates slower than the increase in sedimentation rate, then stacking density increases with decreasing sedimentation rate, similar to that predicted by the LAB models. However, if avulsion frequency increases linearly with sedimentation rate, then there is no change in stacking pattern with changes in sedimentation rate. If avulsion frequency increases faster than sedimentation rates, as seen in some data sets, then stacking patterns become more dense with increasing sedimentation rates, a result that is the exact opposite of that predicted by the LAB models. Therefore sensitive dependence on the relationship between avulsion frequency and sedimentation rate calls into question the veracity of some previous interpretations of re active subsidence made in alluvial architecture studies.

Dan Cazanacli, Chris Paola, and Gary Parker, 2002, Experimental Steep, Braided Flow: Application to Flooding Risk on Fans, *J. Hydr. Engrg.*, Vol. 128, Issue 3, pp. 322-330.
cazanacli_etal_2002_jrnlhydeng_v128_p322-330.pdf

> Flooding processes occurring on alluvial fans are considerably different from those occurring along single thread rivers with well defined floodplains. Active erosion, rapid sedimentation, and the uncertainty in flow path make the prediction of flood evolution and extent difficult. Based on a large scale experiment, this study investigates the long term evolution of the flow on a steep, non-cohesive sediment surface resembling a complex of merged alluvial fans. The results are pertinent to the assessment of flooding hazard on alluvial fans. At any given time, the average flow occupancy was 21% of the surface. However, the flow was characterized by active channel switching and overflow processes. The percentage of the surface remaining dry was found to decay harmonically with time. A reworking time was defined as the time at which half of the surface that was initially dry remained dry, whereas the other half was inundated at least once. An empirical expression was developed in which reworking time is proportional to the average cross sectional area of flow and inversely proportional to the sediment supply.

Pamela F. Scott, Wayne D. Erskine, 1994, Geomorphic effects of a large flood on fluvial fans, *Earth Surface Processes and Landforms*, Vol. 19, Issue 2, p. 95–108.

> Abstract: The response of 12 fluvial fans near Sydney, Australia to a large storm between 2 and 4 February 1990 was determined by repeating previously surveyed longitudinal profiles and by undertaking detailed field observations of erosion and deposition. Peak rainfall intensities occurred on 3 and 4 February when between 173 and 193·8 mm were recorded. Return periods for 24 h duration peak rainfall ranged between 5·7 and 11·0 years on the annual maximum series at six stations within the study area and return periods for 48 h peak rainfall ranged between 13·5 and 29·4 years. Of the 12 fans, seven were trenched and five untrenched. The most significant geomorphic effects of the storm were recorded on the proximal region of the fans. However, fan response was highly variable, with one fan exhibiting no detectable change, three fans localized deposition, two fans spatially disjunct erosion and deposition, two fans channel avulsions, and seven fans fanhead trench reworking. Some fans exhibited more than one type of response. A four-stage, tentative cyclical model of fanhead development was constructed from the field data. Stage 1 refers to the episodic aggradation of the fanhead by localized deposition, spatially disjunct erosion and deposition and/or channel avulsions. Stage 2 represents the initiation of a fanhead trench when progressive aggradation locally exceeds a threshold slope leading to localized erosion. This erosion initially creates one or more discontinuous flow-aligned scour pools. Over time, the scour pools widen, deepen and extend both up- and downfan. Stage 3 refers to the coalescence of discontinuous scour pools into a continuous trench by the removal of intervening log and boulder steps. Stage 4 represents the backfilling phase of the trench once it has been overwidened and/or slope reduced. Aggradation then continues as for stage one.

Terence C. Blair, 1987, Sedimentary Processes, Vertical Stratification Sequences, and Geomorphology of the Roaring River Alluvial Fan, Rocky Mountain National Park, Colorado, *Journal of Sedimentary Research*, Vol. 57.
blair_1987_jrnlsedpet_v57_no1_p1-18.pdf

> ABSTRACT: The Roaring River alluvial fan formed on 15 July 1982, in Rocky Mountain National Park, Colorado, by a catastrophic flood that was generated by a dam failure. The fan covers an area of 0.25 square km, has a radial length of 0.7 km, and is up to 14 m thick. Sedimentation occurred in three phases, each producing a distinct fan lobe.

Initial sedimentation was by a noncohesive sediment-gravity flow which deposited two levees on the proximal boundaries of Lobe I. The levees consist of a poorly sorted mixture of logs, sand, pebbles, cobbles, and boulders. The first two lobes were built primarily by sheet flooding, which deposited imbricated boulders in trains behind obstacles that formed as jams between boulders or logs and upright trees. Horizontally laminated granule and sand sedimentation took place down-fan from the boulders due to deceleration of the expanding sheet flood. Thin-to-medium interbedded sand and cobble-pebble gravel couplets were deposited by sheet flooding on the third lobe. Gravel was transported as bedload by supercritical flow and deposited locally where antidunes broke. Sand was transported as suspended load and deposited where flood velocity locally decreased due to destruction of antidunes, increased roughness, or flow separation around the low-amplitude gravel bed forms. The flood rechannelized at the distal end of Lobe III due to constriction between the fan and the valley margin. Deposits in the upper rechannelized reaches consist of crudely bedded cobble and pebble gravel, and interstratified pebble gravel and backset-bedded sand. Deposition was by supercritical flow. In the lower reaches, planar-cross-bedded, sandy pebble gravel and climbing ripple, horizontal, trough-cross-bedded, and backset-bedded sand were deposited by supercritical and subcritical flow. The flood deposit was modified during waning flood stage and during the three years following the flood by noncatastrophic discharge events. These events formed braided distributary channels by erosion into the top of the sheet flood deposits. Fan building took place mostly by catastrophic unconfined discharge, whereas much of the present fan surface consists of braided channels that formed by erosion into the sheet flood deposits by noncatastrophic discharge.

Rudy Slingerland and Norman D. Smith, 2004, River Avulsions and Their Deposits, Annual Review of Earth and Planetary Sciences, Vol. 32, p. 257-285.

Abstract: Avulsion is the natural process by which flow diverts out of an established river channel into a new permanent course on the adjacent floodplain. Avulsions are primarily features of aggrading floodplains. Their recurrence interval varies widely among the few modern rivers for which such data exist, ranging from as low as 28 years for the Kosi River (India) to up to 1400 years for the Mississippi. Avulsions cause loss of life, property damage, destabilization of shipping and irrigation channels, and even coastal erosion as sediment is temporarily sequestered on the floodplain. They are also the main process that builds alluvial stratigraphy. Their causes remain relatively unknown, but stability analyses of bifurcating channels suggest that thresholds in the relative energy slope and Shields parameter of the bifurcating channel system are key factors.

Memorandum **JE Fuller/ Hydrology & Geomorphology, Inc.**

DATE: June 30, 2008; revised March 20, 2009

TO: Kathryn Gross, CFM/FCDMC

FROM: Jon Fuller, PE, RG

RE: FCD 2007 C051
Assignment #1, Task 1.2.6
Summary of Alluvial Fan Flood Mitigation Measures

CC: File

Scope Summary for Task 1.2.6. Mitigation Measures.

> The CONSULTANT shall prepare a ***brief*** summary of types of alluvial fan flood hazard mitigation measures, where such measures are used on the fan landform (apex, toe, etc.), and what design criteria should be applied for each structure type. The summary shall be based on previous research and the experience of the CONSULTANT, rather than a new literature search. *(16 hrs scoped for Task)*

Summary of Findings

This memorandum describes flood mitigation measures for active alluvial fans, i.e., those subject to alluvial fan flooding as that term is defined by FEMA. Flooding on inactive alluvial fans generally can be mitigated using measures common to riverine systems. Because the District already has adopted guidelines for riverine flood protection measures, no further discussion of measures for riverine or inactive alluvial fan systems is presented in this memorandum. Mitigation measures for active alluvial fan flooding can be grouped into the following main categories:

1. Structural Measures
2. Non-Structural Measures

Structural measures are defined as flood mitigation strategies that require construction and maintenance activities. Structural measures can be implemented on a regional or single lot basis. Structural measures tend to work against or alter natural flood and geomorphic processes and therefore require regular maintenance and are likely to have adverse impacts to adjacent properties that require further mitigation measures. Structural flood control measures built on alluvial fans generally consist of some combination of basins (storage) and channels (conveyance) that capture the water and sediment load and discharge it in a manner that removes the uncertainty associated with alluvial fan flooding. In Maricopa County, implementation of structural measures funded by the District requires compatibility with scenic resource, open space and recreation values in addition to standard hydrologic and hydraulic design requirements.

Non-structural measures are defined as those that require no construction or maintenance to mitigate the flood hazard. Some entities include measures such as elevating the finished floor or anything done on a single lot basis as non-structural flood control. However, for the purposes of this summary, any construction practice that differs from construction practice in non-flood hazard areas is considered a structural flood control measure.

Brief descriptions of common structural and non-structural flood control measures are provided in Table 1.

Sources of Information

1. Hydrologic Engineering Center, October 1993, Assessment of Structural Flood-Control Measures on Alluvial Fans. Report prepared for the Federal Insurance Administration, FEMA.

   This report summarizes a variety of structural flood control measures that have been implemented on alluvial fans, primarily in the western United States. The report includes some case histories of large floods, most of which occurred on riverine systems, rather than alluvial fans. It also describes the performance, design issues, and common failure mechanisms for various classes of structural flood control measures. Several case histories and examples from central Arizona are cited.

2. US Army Corps of Engineers, September 2004, Flood Proofing: Alluvial Fans & Arid Regions. Report to the National Non-Structural Flood Proofing Committee.

   This report summarizes non-structural and structural measures that have been used on alluvial fans in the southwestern United States. The report includes a number of site photographs for single lot protection measures. Few engineering details and bibliography are provided in the report.

3. Code of Federal Regulations, 44 CFR, Part 65.13.

   This section of the NFIP Regulations outline submittal requirements and general engineering analyses required to support CLOMR/LOMR requests for areas mapped as alluvial fans. The requirements are not detailed or specific, leaving much to the judgment of individual engineers and agency reviewers. Key elements include evaluation of impacts to adjacent lands, consideration of sediment deposition and scour, evaluation of flow path uncertainty, and structural engineering analyses of constructed plan elements.

4. Flood Control District of Maricopa County, 2005, Alluvial Fan Flooding Symposium, Speaker Presentations & Conference Summary.

   Speakers from Arizona, California, and Nevada presented flood control strategies used on alluvial fans in their communities. Regional detention basins and/or channels are the most frequently used method of flood control on alluvial fans.

Table 1. Mitigation Measures for Alluvial Fan Flooding

Type	Description	Where	Definition	Application		Design Criteria
				Regional	Single Lot	
Structural Measures	Detention Basins (on-line)	Above apex	Any constructed reservoir that captures flooding, stores it, and releases it at a reduced rate. Includes retention basins which merely detain flood water for longer periods or discharge via evaporation, infiltration, or very small outlets. Basins are usually located above the fan apex, are connected to constructed outlet channels, and incorporate a debris and sediment trapping (basin) element. Basins built below the fan apex require upstream channels or diversion to capture flow.	X		Hydrologic modeling Hydraulics Sediment yield/transport Maintenance Dam safety Spillway Outlet capacity/clogging Downstream channels Environmental permitting Risk analysis Geotechnical
	Diversion Basins (off-line)	Above apex	A peak-scalping basin built near, but not directly on the primary flow path leading to the alluvial fan. Off-line basins provide some low flow and sediment continuity to the lower portions of the fan, while attempting to lower the peak of major floods. Hydraulic performance of the side weir over the long-term and impact on sediment delivery below the diversion are major design concerns.	X		Hydrologic modeling Hydraulics Diversion hydraulics Sediment yield/transport Sediment capture Maintenance Basin drainage Downstream sediment Geotechnical
	Debris Basins	Above apex	Any basin designed specifically to capture sediment and debris rather than flood water. Debris basins typically have large outlets with debris traps designed to remove the sediment load from the flood. Basins are usually located above the fan apex, and are often used as emergency measures after wildfires.	X		Hydrology/Hydraulics Estimating debris supply Outlet capacity/clogging Maintenance No peak reduction Risk analysis
	Debris Barriers	In watershed above apex	Structures built in the watershed to stop or reduce debris movement through the channel system to the alluvial fan. Barriers are often used as temporary measures after wildfires.	X		Location Sediment yield/transport Sizing Durability Maintenance No peak reduction
	Channels	On fan	Construction of any type of flow conveyance system. May include collection channels, diversion channels, through-flow channels, or bypass channels. Channel materials may range from natural materials to reinforced concrete.	X		Toe protection depth Bank protection durability Scour Sediment deposition

Table 1. Mitigation Measures for Alluvial Fan Flooding

Type	Description	Where	Definition	Application: Regional	Application: Single Lot	Design Criteria
						Long-term sediment anlys Freeboard Supercritical flow Grade control Channel transitions Tributary confluences Slope breaks Maintenance
	Levees	Along fan channels	A form of channelization where flow is contained by constructed banks elevated above the surrounding ground.	X	X	Freeboard Aggradation vs. capacity Erosion protection Scour Deposition Maintenance Levee failure scenarios Geotechnical Risk analysis
	Floodwalls	Along fan channels	Structural flood walls function like levees to increase channel capacity and prevent flood overflow.	X		Structural stability Aggradation vs. capacity Erosion protection Scour Deposition Maintenance Levee failure scenarios Geotechnical Risk analysis
	Retaining Walls	On fan	Structural walls intended to deflect flooding and debris from individual structures. Typically used in lower, less hazardous portions of fans.		X	Structural stability Aggradation vs. capacity Erosion protection Scour Deposition Maintenance Levee failure scenarios Geotechnical Risk analysis
	Elevation	Sheet flow	Raising the finished floor of habitable structures above flood		X	Not accepted by FEMA

Table 1. Mitigation Measures for Alluvial Fan Flooding

Type	Description	Where	Definition	Application: Regional	Application: Single Lot	Design Criteria
		areas, fan toe	elevations. Elevation on fill may be effective in less hazardous portions of the fan (near fan toe), but is not recognized by FEMA as acceptable for LOMR's on designated alluvial fans.			Long-term aggradation
	Flood-Proofing	Shallow flow areas	Designing structures to withstand flood inundation with minimal damage. Generally considered ineffective for alluvial fan flooding.		X	Ineffective for fan floods Maintenance Cost effectiveness
	Composite Methods	Whole fan	Most constructed structural flood control projects are composites of several means of flood protection.	X	X	See above
Non-Structural Measures	Avoidance (no development)	Whole fan	Preservation of active fan flooding areas as undisturbed open space, with a goal of allowing the active areas to function naturally. Construction of golf, parking, or other non-habitable uses in the fan floodplain is not avoidance, since significant damage may occur to structures, requiring maintenance and/or additional design measures. Can be accomplished by zoning, density transfers, or other means.		X	Cost Property rights issues
	Acquisition	Whole fan	Purchase of flood-prone lands for preservation, open space, low-impact recreation, or other uses that preclude habitable structures and disturbance of the natural system and function.	X	X	Cost
	Zoning	Whole fan	Zoning of fan floodplains as open space, recreational, or other uses that preclude habitable structures. Zoning density may vary between high & low hazard portions of fan.	X		Pre-development only
	Density Transfer	Whole fan	Transfer of zoned density from flood-prone to non-flood-prone portions of a development. Can create institutional difficulties for some community's zoning boards.	X		Large parcels needed Political/zoning issues
	Flood Warning	Whole fan	Flood warning is most effective in large watersheds with large times of concentration.			Lead time in flash floods
	Composite Methods	Whole fan	Composite methods include a combination of the measures listed above. The measures applied may vary with defined degree of hazard.	X	X	See above

Memorandum JE Fuller/ Hydrology & Geomorphology, Inc.

DATE: March 31, 2009

TO: Kathryn Gross, CFM

FROM: Ted Lehman, PE

RE: FCD 2007 C051
Assignment #1, Task 1.2.7 – Hazard Quantification Methods

CC: File

Scope Summary for Task 1.2.7. Hazard Quantification Methods

> *Hazard Quantification Methods. The CONSULTANT shall identify from published literature any methods for quantifying engineering properties of flow (depth, velocity, shear, slope, stream power, or force) using physics-based equations, empirical equations, and hydraulic modeling for alluvial fan flood hazards. Of particular interest shall be literature describing differences in flood characteristics on the upper and lower portions of the piedmont, impacts by man-made features, and development criteria, as well modeling tools used to estimate engineering properties.*

Hazard Quantification Methods

The hazard quantification discussion reveals an extensive developing literature on flood risk assessment. Some of the literature is more generally related to flood hazards of any or all types. There is also a separate body of literature more specifically related to debris flows which often includes landslides, rock slides, and avalanches. Evaluation of risk, probability, uncertainty, and acceptable risk embodies a significant portion of the research.

Most of the alluvial fan specific literature is related to debris flow hazard quantification. Degree of hazard is often related to the depth, velocity, frequency, and/or intensity of the debris flow. Intensity is often expressed as the size of the largest particle moved or through a computation of an impact force. The extent of debris run-out is also used to evaluate relative flood risk in many studies.

One often cited article is:

Fiebiger, G., 1997. "Hazard Mapping in Austria." Journal of Torrent, Avalanche, Landslide and Rockfall Engineering, No.134, Vol.61.

These methods have apparently been adopted for use in Austria and Switzerland. The FLO-2D software has incorporated the methods from Fiebiger (1997) into its post-processor. Several studies have applied these methods around the world.

In Italy, another related set of hazard assessment approaches can be found. One of potential special interest is by D. Fontan and his colleagues (2004; undated). Two more recent articles by Toyos, et al. (2007; 2008) provide additional excellent work on debris flow hazard assessment methods in Italy.

Another body of literature relates hazards based on methods similar to those used in ACER Technical Memorandum No. 11 (USBR, 1988) for assessment of hazards downstream from dams.

USBR, 1988, Downstream Hazards Classification Guidelines, ACER Technical Memorandum No. 11.

ANCOLD, 1997, Guidelines for the Design of Dams for Earthquake, Australian National Committee on Large Dams, Melbourne, 98 p.

Referred to in some literature as source of determination of hydraulic hazards. Probably similar to USBR ACER Tech. Memo. No. 11.

Hjalmarson & Kemna (1991) provide another potential relative hazard framework for piedmont landforms.

Other resources of possible interest:

Resources Information Standards Committee, 1997, Terrain Stability Mapping in British Columbia, Province of British Columbia.

New South Wales, Australia, 2005, Floodplain Management Program.

Environment Waikato, NZ, 2003, Thames Coast Flood Risk Assessment Report, prepared by URS.

Contains extensive discussion of flood risk assessment in New Zealand. Some areas include alluvial fans with debris flow potential.

Finally, two excellent studies have been performed in Whatcom County, Washington by consultants to assess alluvial fan hazards (KWL, 2003; KWL, 2004). The two fans investigated in these studies are primarily debris-flow dominated fans. The studies used FLO-2D to model hazards along with extensive field investigations and C14 dating of debris –flow deposit

Review of Literature Search and Data Collection Prepared by JE Fuller Hydrology and Geomorphology, Inc. Work Assignment No. 1, Task 2.1, FCD2008C007, March 31, 2009

Review prepared by Mussetter Engineering, Inc. May, 22nd 2009

Introduction

As part of Task 2.1, JE Fuller Hydrology and Geomorphology, Inc. (JEF) collected and collated about 250 papers and reports that dealt with various aspects of alluvial fan morphology, process, risk assessment, mitigation measures and hazard quantification methods. These publications were compiled into a comprehensive electronic data base. On reviewing the data base, Dr. S.A. Schumm was able to identify additional alluvial fan literature (89) that has been compiled into the attached Excel spreadsheet and that could be integrated into the JEF data base.

Comments on the individual JEF memoranda follow.

Task 1.2.1. Existing Alluvial Fan Delineation Methodologies

Table 2. FEMA Appendix G methodologies:

Under the Hydraulic Analytical Methodology the cost is categorized as Very High, but recent developments that include LiDAR mapping and automated grid generation have significantly reduced the costs of most 2-D applications.

Under the Geomorphic Methodology, the reproducibility is described as qualitative, but should also include commentary regarding individual experience and the quality of the available information.

Under the Geomorphic Methodology, it should be noted that there is a major discrepancy between the geologic timescale and the engineering time-scale for which risk is being assessed. Further, it should be noted that geologic uncertainty is always considered to represent increased risk.

p.7. Assessment of the AMAFCA Sediment and Erosion Design Guide, 1994

The Sediment and Erosion Design Guide has been recently up-dated (2008) by Mussetter Engineering, Inc. (MEI) for the Southern Sandoval County Arroyo Flood Control Authority. Geomorphic conditions on the alluvial fans in the Albuquerque area are dissimilar enough to those in Maricopa County that the AMAFCA/SSCAFCA methodology may not be appropriate for use in Maricopa County. The channels/arroyos are extremely sensitive to changes in the water-sediment ratio that inevitably occurs as a result of urbanization because the channel slopes are steep (about 4%) and the bed material is primarily sand-sized (D_{50}~0.2-0.3 mm). Coarser, as well as more cohesive bed material on the medial and distal portions, respectively of the Maricopa County fans probably make them less susceptible to incision.

p.8. Clark County Regional Flood Control District

In the Ability to Identify Risk Level section, comment is made regarding the lack of consideration of "geology", which could impact the actual risk. Should geomorphic characteristics be substituted for geology?

p.11. Desert Research Institute

In the Ability to Identify Risk Level section, comment is made regarding the lack of consideration of "geology", which could impact the actual risk. Should geomorphic characteristics be substituted for geology?

p.21. San Diego County Department of Public Works

The methodology does not seem to take into account the fact that fans can both incise and aggrade and thus the spatial relationships of erosion and deposition and associated risks can change through time.

In the Ability to Identify Risk Level section, comment is made regarding the lack of consideration of "geology", which could impact the actual risk. Should geomorphic characteristics be substituted for geology?

p.23. Whatcom County Flood Control Zone District, Washington

Because of topographic, climatic and geologic conditions there is very heavy emphasis on debris flow hazards which are unlikely to be applicable to the Maricopa County area.

Task 1.2.4 Debris Flow Hazard and Risk Assessment

In the context of the alluvial fans in Maricopa County, it appears that the potential for debris flow generation from basins underlain by relatively erosion-resistant volcanic rocks under current climatic conditions is extremely low. Given the distance between the topographic and hydrographic apexes of most of the incised fans the potential for debris flow impacts on the medial and distal portions of the fans is also extremely low. Although debris flows have been reported in other parts of Arizona, for the most part they are restricted to areas with higher sediment yields and more erodible rocks where the precipitation is sufficient to support some vegetation on very steep slopes (e.g. the granite-underlain basins in the Mazatzal Mountains). Following the occurrence of fires, significant sediment is delivered to the channels and debris flows have been reported during high intensity thunderstorm runoff (Laird and Harvey, 1986; Heede, Harvey and Laird, 1988).

References:

Heede, B.H., Harvey, M.D. and Laird, J.F., 1988. Sediment delivery linkages in a chaparral watershed following fire. Environmental Management, v.12, no.3, pp.349-358.

Laird, J.F. and Harvey, M.D., 1986. Complex response of a chaparral drainage basin to fire. Proc. Int. Symposium on Drainage Basin Sediment Delivery, IAHS Spec. Publ. No. 159, pp. 165-184.

Task 1.2.5. Frequency of Alluvial Fan Avulsions

On the medial portion of the fans that are located downstream of the hydrographic apex, the key factor in determining the frequency of channel avulsion, and thus the associated risk to structures and developments on both the medial and distal portions of the fan is the sediment supply from the upstream basin. The higher the sediment supply, and thus the potential for aggradation below the hydrographic apex, the higher the potential for frequent channel avulsions. However, even if the sediment supply is low, avulsions may still occur but the frequency will be lower. Therefore, on the Maricopa County alluvial fans, the majority of which are incised, emphasis should be placed on better defining the sediment yield from the contributing basin and sediment delivery to the hydrographic apex of the fans. In the arid setting of Maricopa County the rate of sediment production is most likely slow. As a result, event sequencing should also be takewn into account. If a sediment exporting event from the basin has occurred in recent times it is highly unlikely that subsequent events will have high sediment yields.

The results from experimental studies of alluvial fans (Weaver, 1984; Schumm et al., 1987) suggest that the probabilities of erosion and deposition, and hence channel avulsion, during an event are conditional on the preceding state. Probability matrices were developed to predict the likelihood of future conditions at the fan apex, midfan and fan toe areas. If sufficient historical data are available, this approach may well help to resolve the uncertainty associated with channel avulsions, especially in those areas located downstream of the hydrographic apex.

On the distal portions of the fan where the slopes are very low, sheet flooding is the predominant process, the sediments are finer grained and the fan surface merges with the trunk stream floodplain, the avulsion potential and frequency will be conditioned by the presence or absence of a cross-fan topography and mobility of the sediments. Quantification of the potential for avulsion could possibly be related to unit discharge at a given location.

Task 1.2.6. Mitigation Measures

The literature review focused on methodologies used by various organizations within the U.S. A significant body of engineering and geomorphic literature is available from the Japanese Disaster Prevention Agency (SABO) and from flood control agencies in Taiwan and New Zealand (NIWA) Although these countries are located in tectonically active and very humid regions, it might be worth reviewing some of the methodologies they use to control alluvial fan flooding and sedimentation.

Task 1.2.7. Hazard Quantification Measures

European, mainly Swiss (Greminger, 2003) attempts to quantify hazards have been recently incorporated into flood and mudflow hazard assessments where FLO-2D models have been used. Garcia et al (2003) incorporated a modified version of the Swiss hazard assessment (OFEE, 1997) that was based on flow depths and depth-velocity products to assess hazards on Venezuelan fans. A similar approach was taken by MEI to assess the hazards associated with mudflows on the highly developed Cornet Creek alluvial fan in Telluride, Colorado (MEI, 2009).

References:

Garcia, R, Lopez, J.L., Noya, M., Bello, M.E., Gonzales, N., Paredes, G., Vivas, M.I. and O'Brien, J.S., 2003. Hazard mapping for debris flow events in the alluvial fans of northern Venezuela. In Rickmann, D. and Chen, C-L (eds), Debris flow Hazards Mitigation, Millpress, Rotterdam, Netherlands, ISBN 907701778X.

Greminger, P., 2002. Managing the Risks of Natural Hazards. In Rickmann, D. and Chen, C-L (eds), Debris flow Hazards Mitigation, Millpress, Rotterdam, Netherlands, ISBN 907701778X.

Mussetter Engineering, Inc., 2009. Cornet Creek Watershed and Alluvial Fan Debris Flow Analysis. Prepared for the Town of Telluride, May, 2009.

Appendix B:

Alluvial Fan Characteristics Data Collection Summary
FCD2007C051, Task 4

Memorandum **JE Fuller/ Hydrology & Geomorphology, Inc.**

DATE: September 18, 2009

TO: Kathryn Gross, CFM / FCDMC

FROM: Jon Fuller, PE

RE: FCD2007C051 – Task 4 Deliverable

CC: File

Registered Geologist Certificate No. # 38732 JONATHAN E. FULLER Date Signed 9-18-09 ARIZONA, U.S.A. Expires 3/31/2012

Registered Professional Engineer (Civil) Certificate No. # 26846 JONATHAN FULLER Date Signed 9-18-09 ARIZONA, U. S. A. Expires 3/31/2011

This memorandum summarizes the results our review of the literature collected in Work Assignment #1. The objectives of this review was to document the characteristics of alluvial fans described in the literature sources, and to investigate whether the methodologies and information identified in the literature search are appropriate for assessment of local alluvial fan flood hazards in Maricopa County.

Methodology

To complete this assignment, each article listed in the Work Assignment #1 bibliography was reviewed. The individual alluvial fans discussed in each literature source were entered in a Microsoft Excel spreadsheet, and were also plotted by location in an ArcGIS map database.

Alluvial Fan Characteristics. The following information was obtained for each fan site(s) discussed in each literature source cited:

- Fan location
- Geographic information for the fan location (Country, State, County, Lat/Long)
- Physiographic descriptors:
    - Apex elevation
    - Maximum watershed elevation
    - Climate type
    - Vegetative cover & type
- Fan slope (landform and channel)
- Watercourse channel bed slope for drainage area above the apex
- Watershed drainage area (above the apex)
- The distance from the apex to the mountain front
- Fan area below the apex

The following types of information were also collected only if they were included in the literature source:

- Discharges and estimated depth of flow
- Calculated velocities
- Flooding history including observed depth, velocity, sediment deposition, scour, and damage
- Annual rainfall depth
- Sediment sizes for fan channel bed, fan overbank, and watershed watercourse

- Sediment yield
- The implemented mitigation measures
- FEMA floodplain delineations for the fan area

The methodologies and procedures used to identify and quantify these characteristics are discussed in more detail below. The spreadsheet records whether the information was provided in the literature source or was obtained by direct measurement using the ArcGIS. Most of the literature provided no information beyond a rough description of the fan location. Only alluvial fans located in the United States were recorded. Although some fans in the literature search database were located outside of the United States, nothing but the name of the fan and the country is listed on the spreadsheet, due to a lack of supporting GIS data. If the location of an alluvial fan was not provided, then only the information listed in the literature source was recorded in the spreadsheet. However, none of this partial information was included in the summary of the results shown below.

ArcGIS Data. ArcGIS data are provided with this memorandum. First, a point file is provided that marks the approximate apex location of each alluvial fan. Second, two shape files are provided that delineate the approximate fan and watershed areas. The apex point has a FID number in ArcGIS which is listed in the spreadsheet as "Fan_ID," which is used to identify that alluvial fan elsewhere. If the literature source did not specifically map or describe the alluvial fan boundaries (which is the case for the vast majority of sites), a delineation was created using ESRI on-line topographic mapping and aerial imagery sources. Similarly, a watershed delineation shapefile was created using the ESRI topographic map sources.

Fan Slope (Landform). The fan landform slope was estimated using the ArcGIS software, although occasionally it was provided in the article. The topographic contour lines shown on USGS quadrangle maps were used to compute the slope. The horizontal distance was measured between two contour lines and the vertical distance was provided by the topography. Typically, the distance was taken between the two closest major contours in the fan area; however exceptions were made for fan sizes that were either very large or very small. This measurement is intended to capture the overall slope of the most active part of the fan. The slope is recorded as a percent.

Fan Slope (Channel). The fan channel slope was estimated using the ArcGIS software if it was not stated in the article. The distance of the main channel on the alluvial fan was measured and the vertical change in elevation was found using the topographic map. Typically, the distance was taken between the two closest major contours in the fan area; however exceptions were made for fan sizes that were either very large or very small. This measurement is intended to capture the overall slope of the most active part of the fan. This measurement is always taken from the same two points that were used to find the fan slope for the landform. The slope is recorded as a percent.

Profile. As reported here, the profile is a qualitative description of whether the slope of the alluvial fan flattens or steepens from the apex to the toe, as indicated by the contour spacing on the topographic mapping. This characteristic was recorded as "flatter," "steeper," or "can't tell."

Drainage Area. The drainage area was either given in the article or found using ArcGIS software. This value is recorded in square kilometers and is the area of the watershed above the apex of the alluvial fan.

Channel Slope above the Apex. The channel slope above the apex was typically found using the ArcGIS software, although occasionally it was given in the article. The reach of channel evaluated was located between the apex and where the channel becomes noticeably different in slope. In most cases, the closest two major contour lines were used as end points. The horizontal distance was measured and the vertical distance was found using contour lines. The slope is recorded as a percent.

Fan Area. The fan area, recorded in square kilometers, was either given in the article or found using ArcGIS software. This is the area of the alluvial fan which is outlined in the GIS map. If the article value is noticeably different from the value that the ArcGIS software calculated, then the ArcGIS value is used for the sake of consistency in the summary of the results. The article value is still reported in the spreadsheet. The objective of the alluvial fan delineation was to capture the area that the author discussed. In many cases, the fans were not active. The FEMA delineations rarely coincide with the fan delineation.

Q_{100} Discharge. The discharge for the 100-year event, in cubic feet per second, is only recorded if given in the article.

Other Discharge Values. Other discharges such as the 2-year, 5-year, 10-year, and maximum flood events are included only if provided by the article. The units for the values were reported as they were stated by the authors.

Depth of Flow. The depth of flow, in meters, is only recorded if given in the article.

Calculated Velocities. Velocities of flow, in meters per second, were only included if provided by the article.

Flooding History. If the article included an account of historical floods, a summary was reported in the spreadsheet.

Location. The locations of the alluvial fans were found using information in the article and GIS maps. The location listed was generally given as the mountain range or valley which contains the fan. In some cases, simply finding the fan location was a significant challenge.

Apex Elevation. The elevation of the fan apex was found using information from the article or the ArcGIS topographic maps. This value given the spreadsheet is in feet.

Maximum Watershed Elevation. The maximum elevation of the watershed was found using information from the article or the ArcGIS topographic maps. This value is in feet.

Climate. The climate for the alluvial fan is based on its location, and was classified in one of the following categories: desert/arid west, humid, or alpine. The climate of the alluvial fan was either stated in the article or inferred from its general location.

Vegetation. The vegetation of the alluvial fan is based on the article's description (if provided), or interpreted from its location and the ArcGIS aerial imagery. It was placed in one of the following categories: desert, range, or forested.

Annual Rainfall Depth. The annual rainfall depth, in centimeters, was only recorded if stated in the article.

Sediment Size. The sediment size, in centimeters, was only included if stated in the article.

Sediment Yield. The sediment yield was only reported if provided in the article. It was entered in the units used by the author.

Distance from Apex to Mountain Front. The distance from the apex to the mountain front, in kilometers, was measured using ArcGIS software unless this value was stated in the article. The mountain front is defined by the protrusion of bedrock from the alluvial surface of the piedmont.

Country- State- County. This data describing the fan location was obtained from the GIS. Only fans located in the United States are considered.

Latitude/Longitude. The latitude and longitude of the apex were recorded using the values provided by the ArcGIS software. These values are reported in decimal degrees.

Mitigation Measures. Any mitigation measures stated in the article are included.

FEMA Delineated. The spreadsheet states whether the alluvial fan has been delineated by FEMA. This was determined using a layer in ArcGIS called Web Map Service NFHL. The shaded red areas are FEMA delineations.

Assumptions

Some articles did not clearly convey where a specific alluvial fan is located. Therefore it was assumed that the alluvial fan was located at the mouth of the creek or canyon with the same name. Typically, the articles described a mountain range or valley that contained the alluvial fan without going into further detail.

Results & Conclusions

The following charts and figures quantify the results of the investigation.

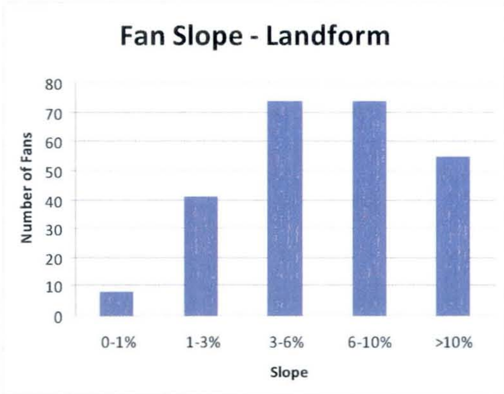

Figure 1. Slope (measured along fan profile) range classification for fans described in the literature search.

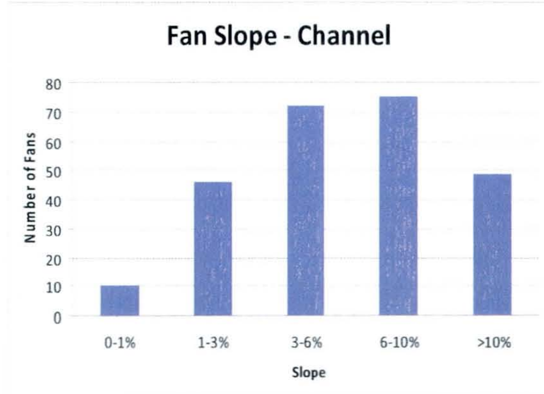

Figure 2. Slope (measured along channel alignment) range classification for fans described in the literature search.

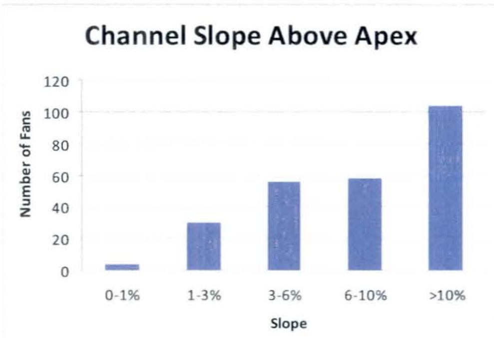

Figure 3. Slope of the main channel upstream of the apex at head of fan.

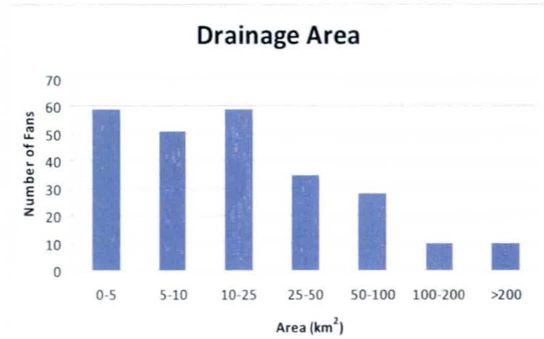

Figure 4. Drainage area above the fan apex.

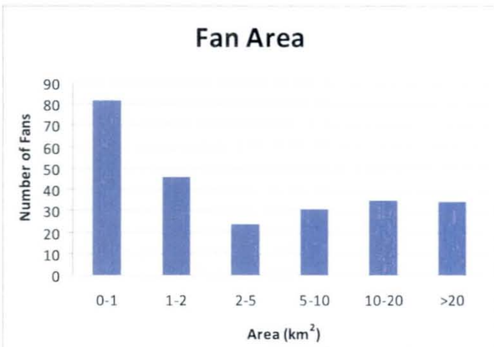

Figure 5. Areas of the fan landforms described in the literature sources.

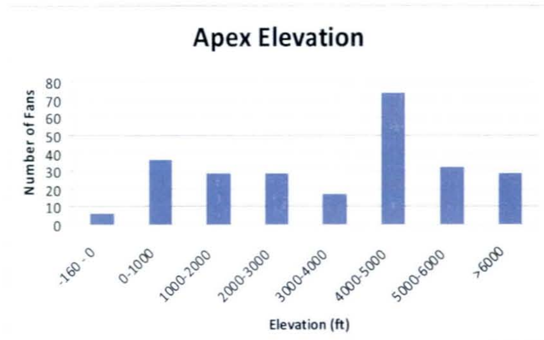

Figure 6. Elevation of the fan apexes for fans described in the literature sources.

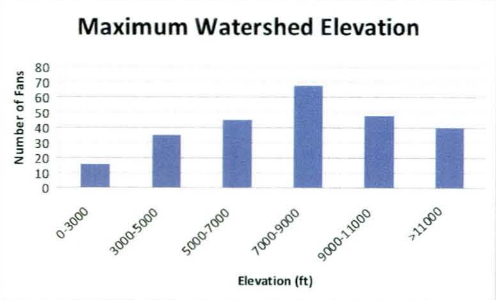

Figure 7. Maximum elevations in watersheds above fan apexes for fans described in the literature sources.

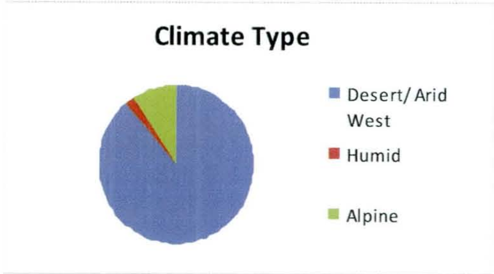

Figure 8. Range of climatic types for fans in literature sources.

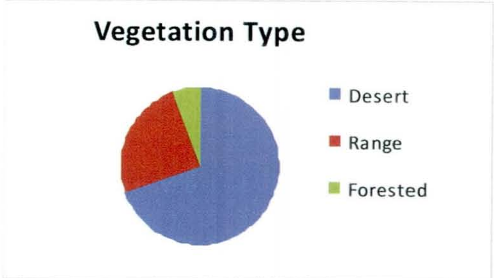

Figure 9. Range of vegetative types for fans in the literature sources.

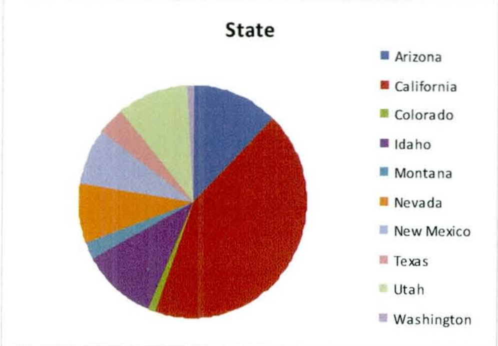

Figure 10. States represented in the literature sources. Arizona was the second most common area in the literature.

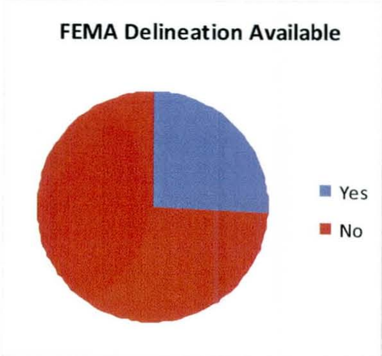

Figure 11. Approximately ¼ of the fans sites had some form of FEMA floodplain delineation.

Too few of the literature sources provided data on the following characteristics to allow meaningful analysis:

- 100-Year Discharge
- Flow Depth
- Flow Velocity
- Flood History
- Annual Rainfall
- Sediment Size
- Sediment Yield

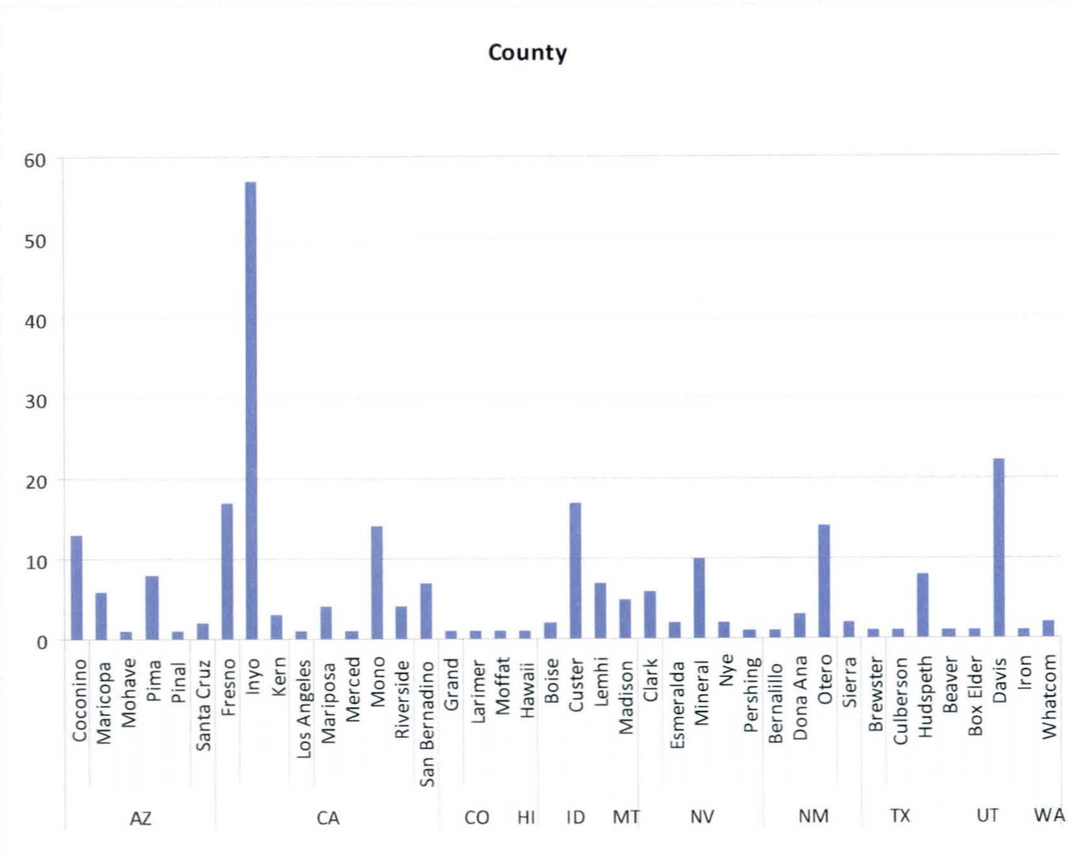

Figure 12. Distribution of States & Counties for Fan Sites Considered.

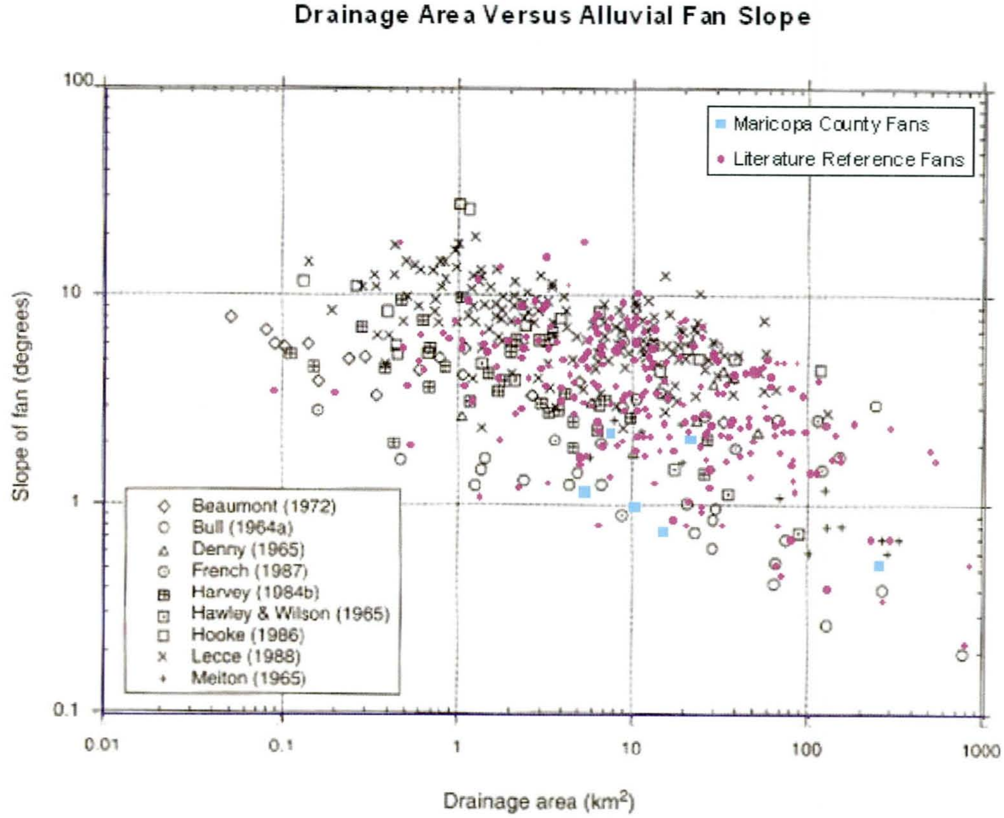

Figure 13. Plot of fan slope (degrees) vs. drainage area (km2) from Givens (2004) with data from Maricopa County fan sites superimposed (blue squares).

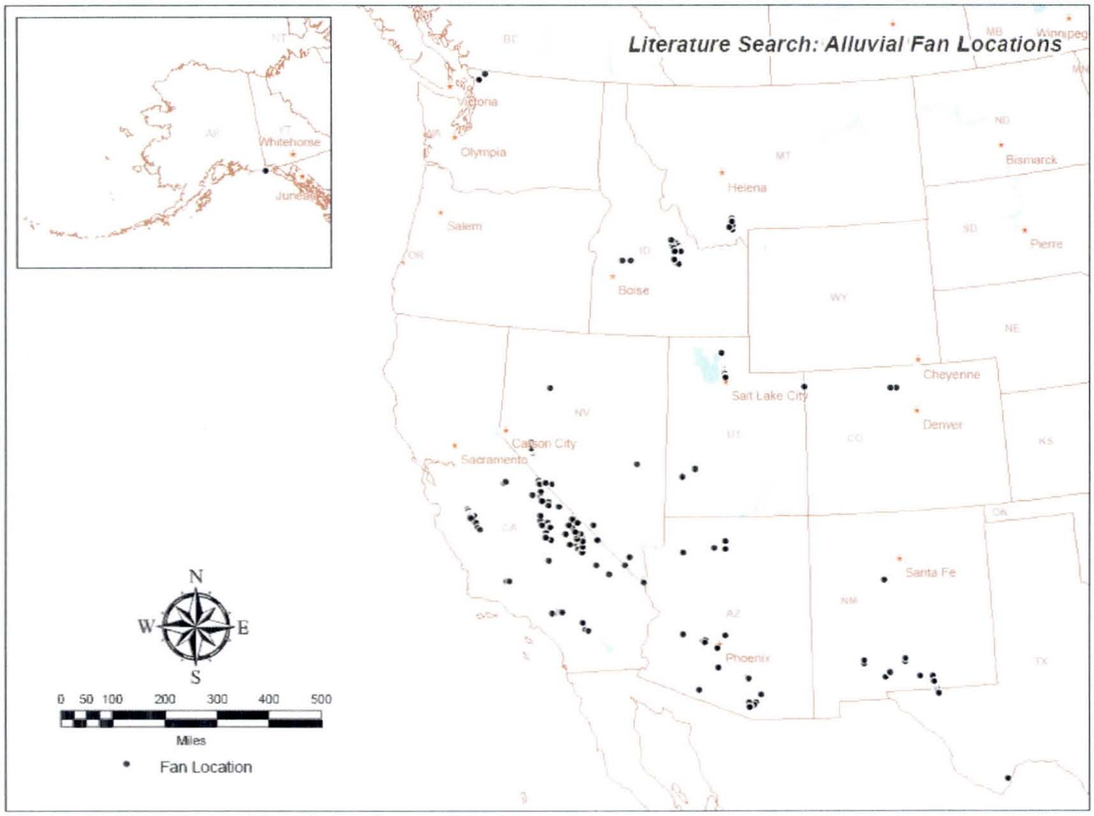

Figure 14. Locations of fan sites referenced in this task.

Appendix C:

Supplemental Literature Search: Sheet Flooding
FCD2007C051, Task 6

Executive Summary

Literature Search & Data Collection
FCD2007 C051 – Work Assignment #6

Deliverable for Work Assignment No. 6, FCD 2007CO51
Supplemental Literature Search – Sheet Flooding

February 2010

JE FULLER
HYDROLOGY & GEOMORPHOLOGY, INC.

FCDMC 2007C051 Task WA No. 6. Supplemental Literature Search – Sheet Flooding

1.1 Executive Summary

JE Fuller/Hydrology & Geomorphology, Inc. (JEF) performed a specialized literature review focused on the following research topics relating to sheet flooding:

1. Definition(s) of sheet flooding
2. Defining characteristics of sheet flooding
3. Characteristics that can be used to distinguish general sheet flooding and sheet flooding on alluvial fan surfaces
4. Flood hazards, including erosion and sedimentation that are unique to sheet flooding areas
5. Hydrologic and hydraulic modeling tools developed specifically for sheet flooding areas
6. Existing floodplain regulations or development guidelines adopted by public agencies specifically for management of sheet flooding areas

A literature search was conducted to identify published articles that describe sheet flooding issues. The literature search was conducted in three phases. The first phase researched scholarly journals. The second phase researched published books and textbooks. The third phase investigated sheet flow management practices used by neighboring counties, states and agencies. The literature search was conducted from September to October 2009, and includes literature sources available prior to those dates.

The first phase of research focused on engineering literature, such as ASCE journals, journals and academic research in hydraulics, fluid mechanics and physics. Research was primarily conducted using the online academic research databases at the Hayden Library and Nobel Science and Engineering Library at Arizona State University (ASU). Use of ASU's online academic research databases provided a mechanism by which to systematically research sheet flow and sheet flooding.

Initial research was conducted searching both "sheet flow" and "sheet flood" as keywords. However, it became immediately apparent that authors use the term "sheet flow" rather imprecisely. Most articles found using the keyword "sheet flow" only discussed "sheet flow" as a hydraulic process (such as laminar flow over parking lots or in computation of lagtime), rather than as a flood phenomenon. More germane articles were found searching the keyword "sheet flood." Therefore, as the literature research progressed, we emphasized the keyword "sheet flood" more than "sheet flow."

The second phase of research included searching published books and textbooks for sections on the topic of sheet flooding. The third phase of research utilized the internet to identify how neighboring counties, states or agencies regulated sheet flooding.

Once an article germane to the research topic above was identified, a PDF of the article was obtained or created. Every journal article, book chapter, manual or report that was identified as part of this literature search has been included in the bibliography and as a PDF on the enclosed DVD.

Below is a brief written summary of the key literature collected as it relates to the topics bulleted above. Following that is an annotated bibliography listing chronologically key scholarly works on sheet flooding. Articles are referenced by last name and date both in this document and the Sheet_Flow_Literature_Reference.xls

Key Findings & Recommended Action Items

Based on the results of the literature search, the following key findings and action items are recommended for inclusion in the overall PFHAM Revision study:

- The term "sheet flooding" should be used rather than "sheet flow."
- A revised definition of the term "sheet flooding" should be added to the PFHAM and should be incorporated into the Floodplain Regulations for Maricopa County. The precise wording of the definition will be finalized as part of the PFHAM Revision Study final report.
- Sheet flooding occurs on active alluvial fans, as well as on landforms that are not active alluvial fans.
- The mere presence of sheet flooding is not diagnostic for identifying active or inactive alluvial fans.
- The literature does not distinguish between the characteristics of sheet flooding on active alluvial fans and the characteristics of sheet flooding on other types of landforms.
- There are known flood hazards associated with sheet flooding, but none of them are specific or unique to active alluvial fans or other landforms.
- FLO2D is an adequate tool for modeling the hydrology and hydraulics of sheet flooding. There are no engineering models developed specifically for sheet flooding.
- If sheet flooding regulations are developed as part of future PFHAM revisions, Maricopa County will be the first community to develop detailed engineering guidance and regulations for sheet flooding areas.

Overview of Literature Search DVD

The enclosed DVD includes the following information which can be automatically accessed by inserting the disk into a DVD drive:

- Reference List

  Consists of a Microsoft Excel spreadsheet listing every literature source identified, bibliographic reference information, key words, and significance relative to sheet flooding in Maricopa County.

- Collected Literature

  Scanned articles in pdf format for literature sources available for collection. Sources are listed using the following nomenclature. Author_Date_Journal_Volume_Page.

1.2 Summary of Research Topics Relating to Sheet Flooding

1. Definition(s) of Sheet Flooding

Blair and McPherson 1994 contains the most comprehensive definition of the term sheet flood. "A sheet flood is defined as a broad expanse of unconfined runoff moving downslope (McGee 1897). The flow event is of relatively low frequency and high magnitude (Hogg 1982), while the flow itself is generally shallow and short-lived and has a limited travel distance. Sheet flooding is produced by catastrophic discharge, most commonly from high-intensity rainfall, combined with the absence of channelized drainage." (Blair & McPherson 1994)

Also, the Arizona Department of Water Resources (ADWR) State Standard 4-95 defines types of sheet flooding. The ADWR definitions conform to Blair and McPherson's definition given above. The Maricopa County Floodplain Regulations do not have a definition for sheet flooding (or sheet flow), but notes in the definitions section that sheet flooding occurs on portions of alluvial fans.[1]

Key References: Blair & McPherson, 1994
Hogg, 1982
McGee, 1897

2. Defining Characteristics of Sheet Flooding

Defining elements of sheet flooding include the following:

- Flood waters occur as a broad unconfined sheet (FEMA, 2002 Appendix G)
- Flat or low slope (ADWR, 1995)
- Few or no well defined washes or where flood water is not contained in one well defined channel (PCRFCD, 2007)
- Flood flow conveyed over an un-channelized land surface (ADWR, 1995)
- Flow depths ranging from several inches to several feet (PCRFCD, 2007)
- Ability to transport sediment over large distances on low slopes (ADWR, 1995)
- Significant loss of flow volume due to infiltration and other abstractions (ADWR, 1995)
- Highly unpredictable flow direction because of low relief, shifting channels, and/or debris loads (FEMA, 2003 Appendix E)

Key References: McGee, 1897
ADWR, 1995
PCRFCD, 2007
FEMA, Appendix G
FEMA, Appendix E

3. Characteristics that Distinguish General Sheet Flooding From Alluvial Fan Sheet Flooding

The literature search did not yield any articles that distinguish general sheet flooding from sheet flooding on an alluvial fan surface. A wide variety of literature sources affirm that sheet flooding does occur on alluvial fans (e.g., NRC, 1995; FEMA, 2003), but none were found that proposed that alluvial fan sheet flooding has characteristics unique to alluvial fans. The first use of the term sheet flooding (McGee, 1897) described flooding on a piedmont surface, so at least historically, there is a strong link between alluvial fans and the process of sheet flooding.

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[1] See definitions for Alluvial Fan Uncertain Flow Distribution (AFUFD) and Alluvial Fan Zone A (AFZA).

4. Flood Hazards, Including Erosion and Sedimentation, Unique to Sheet Flooding Areas.

Sheet flood hazards identified in the literature include the following:

- Structure inundation - development above channel banks does not guarantee adequate flood protection because of the high percentage of flow carried outside the defined channels (ADWR, 1995).
- Obscure flow paths - casual observers may miss the flood potential prior to developing a property because flow is conveyed overland outside of defined channels (PCRFCD, 2007).
- Flow concentration problems – concentration of flow into collector channels or by obstructions created by development may result in channel (arroyo) erosion, initiating headcuts that could propagate upstream, or cause downstream scour and inundation (ADWR, 1995).
- Roadway inundation - sheet flooding over long roadway stretches may prevent emergency vehicle access. Sediment deposition on roadways may also delay access and prevent road travel (ADWR, 1995).
- Roadway drainage crossings - significant backwater conditions may occur upstream of roadway drainage structures not sized for the 100-year flood, particularly where the road embankment is elevated. Flood depths resulting from these backwater conditions may exceed depths indicated by local geomorphology (ADWR, 1995).
- Erosion and scour – sheet floods have been known to undercut building foundations and erode fence posts, resulting in property damage (PCRFCD, 2007).
- Hydrodynamic forces - flow of unconfined flood water against structures can cause damage (PCRFCD, 2007).
- Sediment deposition – sheet floods carry significant sediment loads which can be deposited, particularly upstream of obstructions (McGee, 1897) and (ADWR, 1995).
- Channel avulsion – concentration of sheet flow can lead to formation of avulsive flow paths (Field, 2001).

Key References: ADWR, 1995
PCRFCD, 2007
Field, 2001

5. Hydrologic and hydraulic modeling tools developed specifically for sheet flooding areas.

The literature search did not yield any articles about hydrologic or hydraulic modeling tools developed specifically for sheet flooding areas. There are numerous models which can model shallow flooding (e.g., HEC-RAS, FLO2D, etc.), although none of them were developed specifically to evaluate sheet flooding conditions. ADWR State Standard 4-95, in the "Methods of Flow Analysis" section, describes methods which range from a simple finished floor elevation (Level 1), to a single section Manning's rating (Level 2), to two- or three-dimensional hydraulic modeling (Level 3). No detailed procedures are provided in State Standard 4-95 for the Level 3 modeling approach. FEMA (2003, Appendix E) provides some cursory guidelines for floodplain delineation in "sheet runoff" areas. The FEMA guidelines stress the importance of accurate topographic mapping, use of historical flood records (inundation mapping), interpretation of topographic maps and aerial photographs, field reconnaissance, and application of engineering judgment. FEMA recommends that more detailed methods be used if flow depths are expected to exceed 1.0 foot. Although no specific models are cited, the approximate method procedures outlined by FEMA imply that a step-backwater model (e.g., HEC-RAS) may be used.

Reference: ADWR, 1995
FEMA, 2003 (Appendix E)

6. Existing Sheet Flooding Floodplain Regulations or Development Guidelines

The Maricopa County Floodplain Regulations only mention sheet flooding in the context of alluvial fan flooding, with no specific regulations relating solely to management of sheet flood areas. The Maricopa County Drainage Regulations do not use the term "sheet flood." The Maricopa County Drainage Policies and Standards (2007) reference sheet flooding in Section 3.8.3 (Erosion Hazard Management – Sheet Flow/Unconfined Flow Areas). Maricopa County recommends minimizing vegetation disturbance and flow concentration, and returning flow to pre-development conditions before exiting a developed property.

ADWR State Standard 4-95 lists a number of development standards for sheet flooding areas. These include elevated finished floors, foundation scour protection, site grading, elevating or gapping fences to allow through flow drainage, setting back fences from property lines, aligning construction parallel to flow (minimizing obstructions), lowering building densities, and avoiding impacts to adjacent properties due to flow concentration.

Pima County AZ, Pinal County, AZ, San Diego County CA, and Clark County NV have all developed floodplain regulations and guidelines for sheet flood, sheet flow or shallow flood areas. Regulations include elevation on fill, CLOMR/LOMR, flood proofing of utility and sanitary facilities, limitations on the type and extent of walls and fencing, and providing adequate drainage around and away from the structure.

The Pima County Regional Flood Control District (PCRFCD, 2007) delineated potential sheet flooding areas in portions of Pima County (federal, state, and tribal lands were excluded) using a process of geomorphic mapping and landform interpretation. No new land use and floodplain management guidelines were developed as part of the PCRFCD study, although these areas are regulated under the County's floodplain ordinance. As such, new development (buildings, fences, grading, etc.) requires a floodplain use permit and is subject to normal floodplain restrictions. Pima County restricts the type of fencing and walls in floodplains, including those in sheet flooding areas. Pima County regulates all floodplains with 100-year peak discharges greater than 100 cfs, not just floodplains delineated by FEMA.

Pinal County, Arizona has adopted rules of development that describe best management practices for development in sheet flooding areas. Guidance for single lot development, concentration of flow, methods of analysis, setting finished floor elevations, structure alignment, and development density are provided. The Pinal County Rules of Development rely heavily on the ADWR (1995) State Standard.

San Diego County's floodplain management plan (2007) mentions sheet flooding as a hazard, but does not have any specific regulations for sheet flooding areas that are different from any other floodplain area. Clark County's Uniform Regulations for the Control of Drainage (2007, Section 10.020.C) identifies specific criteria for development in "Areas of Shallow Flooding." Sheet flooding is one of the types of shallow flooding identified by Clark County, which requires elevated finished floors and consideration of adequate flow paths around structures located in FEMA-mapped flood zones.

<u>Key References</u>: ADWR, 1995
PCRFCD, 2007
CCRFCD, 2007
Pinal County, 2009
San Diego County, 2007

1.3 Chronological Annotated Bibliography of Key Articles on Sheet Flooding

Following is a brief annotated bibliography of the key articles written on sheet flooding. Articles are listed chronologically starting with McGee 1897 who coined the term "sheet flooding" to present day.

McGee, W.J. 1897. Sheetflood Erosion. Geologic Society of America Bulletin. 8: 87-112

- McGee 1897 contains the first known use of the term "sheet flood" in scientific literature. William J. McGee a geologist working for the United States Geologic Survey used the term sheet flood to describe an aspect of flooding he witnessed first hand in the Sonoran District of south-western Arizona.

Davis, W. M. 1938. Sheetfloods and Streamfloods. Geologic Society of America Bulletin. 48: 1337-1416

Ives, R.L. 1938. Desert Floods in the Sonoyta Valley. American Journal of Science. 5th Series; 32: 349-360

- Ives 1938 contains the second well documented first-hand observation of a sheet flood that occurs in scientific literature.

Blissenbach, E. 1954. Geology of Alluvial Fans in Semiarid Regions. Geologic Society of America Bulletin. 65: 175-190

- Blissenbach 1954 writes that there are three depositing agents on alluvial fans: sheet floods, stream floods and streams.

Rahn, P.H. 1967. Sheetfloods, Streamfloods, and the Formation of Pediments. Annals of the Association of American Geographers. vol. 57, no.3, p.593-604

- Rahn 1967 contains the third well documented first-hand observation in scientific literature of a sheet flood. Rahn describes and photographs sheet flooding in southwestern Arizona during the summer of 1963

Hogg, S.E. 1982. Sheetfloods, Sheetwash, Sheetflow, or ...? Earth Science Reveiws. Vol. 18, p.59-76

- Hogg 1982 contains an in-depth review of the various terms used for 'sheet flood' since McGee first used the term in 1897. Hogg defines the three terms sheet flood, sheet flow and sheet wash (p. 59) as: "A *sheet flood* is a sheet of unconfined flood water moving down a slope. The frequency of a sheet flood is relatively low while its magnitude is relatively great. *Sheet flow* is defined as relatively high-frequency, low-magnitude overland flow occurring in a continuous sheet and is restricted to laminar flow conditions. *Sheet wash*, a term of geomorphic origin, is considered to be redundant and is superseded by the more meaningful term *rainwash* defined as the washing action of rain on slopes."

Blair, T.C. 1994. Alluvial Fans and their Natural Distinction from Rivers based on Morphology, Hydraulics Processes, Sedimentary Processes, and Facies Assemblages. Journal of Sedimentary Research. Vol. A-64, No. 3 (July 1994), p. 450-489

- Blair 1994 contains thorough descriptions of sedimentary sheet flood deposits as well as sheet flood facies in the sedimentary record.

Blair, T.C. and McPherson J.G. 1994. Chapter 14: Alluvial Fan Processes and Forms. Geomorphology of Desert Environments: edited by Abrahams A.D. and Parsons A.J., Chapman & Hall, 1994 1st ed.

- On page 368 Blair and McPherson expand on Hogg's 1982 definition of sheet flood by defining it as "a broad expanse of unconfined runoff moving downslope (McGee 1897). The flow event is of relatively low

frequency and high magnitude (Hogg 1982), while the flow itself is generally shallow and short-lived and has a limited travel distance. Sheet flooding is produced by catastrophic discharge, most commonly from high-intensity rainfall, combined with the absence of channelized drainage."

ADWR 1995, Arizona State Standard 4-95: State Standard for Identification of and Development Within Sheet Flow Areas.

- The State Standard on Sheetflow first defines different types of sheet flow and identifies their key characteristics. The State Standard then identifies Sheet Flow Flood Hazards and covers development standards for Sheet Flow areas. The State Standard then identifies three methods of flow analysis.

Field, J. 2001, Channel avulsion on alluvial fans in southern Arizona. Geomorphology. vol. 37 (2001) 93-104

- Field 2001 draws a correlation between sheet flooding areas on alluvial fans and the increased potential for channel avulsion in those areas.

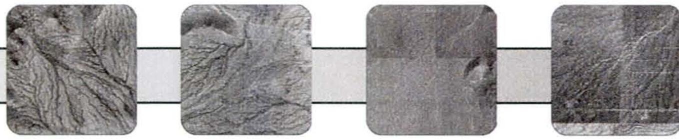
PCRFCD 2007. Fact Sheet: Sheet Flood Hazard Areas. Pima County Regional Flood Control District.

- Pima County defines Sheet flooding areas as (p. 2) "… areas that are flat or have a low slope and where there are no or few well defined washes or where washes are not large enough to contain all of the water delivered during storm events. As a result, flood waters flow in a broad sheet across the entire ground surface. For this reason, sheet flooding is likely to affect all or most of your property." Sheet flood depths can range several inches to several feet in depth depending on location. (p. 2). PCRFCD then defines requirements for building in sheet flow floodplains. (p.3)
- Homes and other structures in Pima County that are not elevated have been flooded by water less than six inches deep. Sheet flooding has been known to undercut building foundations, causing potentially significant building stability problems, and rip out fences with posts buried in 2 feet of concrete and move them over 100 feet away. In addition, even shallow moving water exerts a tremendous amount of force on objects that obstruct its movement. (p.2)

CCRFCD 2007. Uniform Regulations for Drainage. Clark County Regional Flood Control District

- The Clark County Uniform Regulations (p 26, 27 & 62) contain the regulatory policies for "Areas of Shallow Flooding." Regulations include elevation on fill, CLOMR/LOMR, flood proofing of utility and sanitary facilities, and providing adequate drainage around and away from the structure.

Appendix D:
Report on Historical Development on Alluvial Fan Landforms



2008C007 Task 2.3

Historical Development on Alluvial Fans

Prepared for: Flood Control District of Maricopa County

By: JE Fuller Hydrology & Geomorphology

December 2, 2009

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1. Executive Summary

The purpose of this technical memorandum is to assess the successes, failures, and/or drainage problems associated with historical development on alluvial fan landforms in Maricopa County, Arizona. The primary objective of this memorandum is to assess the nature of flood hazards and damages associated with development on alluvial fans in Maricopa County.

Four individual site locations (Ahwatukee, Pima Canyon, Reata Wash & Lost Dog) were chosen and approved by the District staff for the study of historical development on alluvial fan landforms (Figure 1-1). The study site locations were identified using historical and recent aerial photographs, NRCS soils mapping and topographic mapping. The four study sites include areas of dense urbanization, single lot development, and developments with major structural drainage measures.

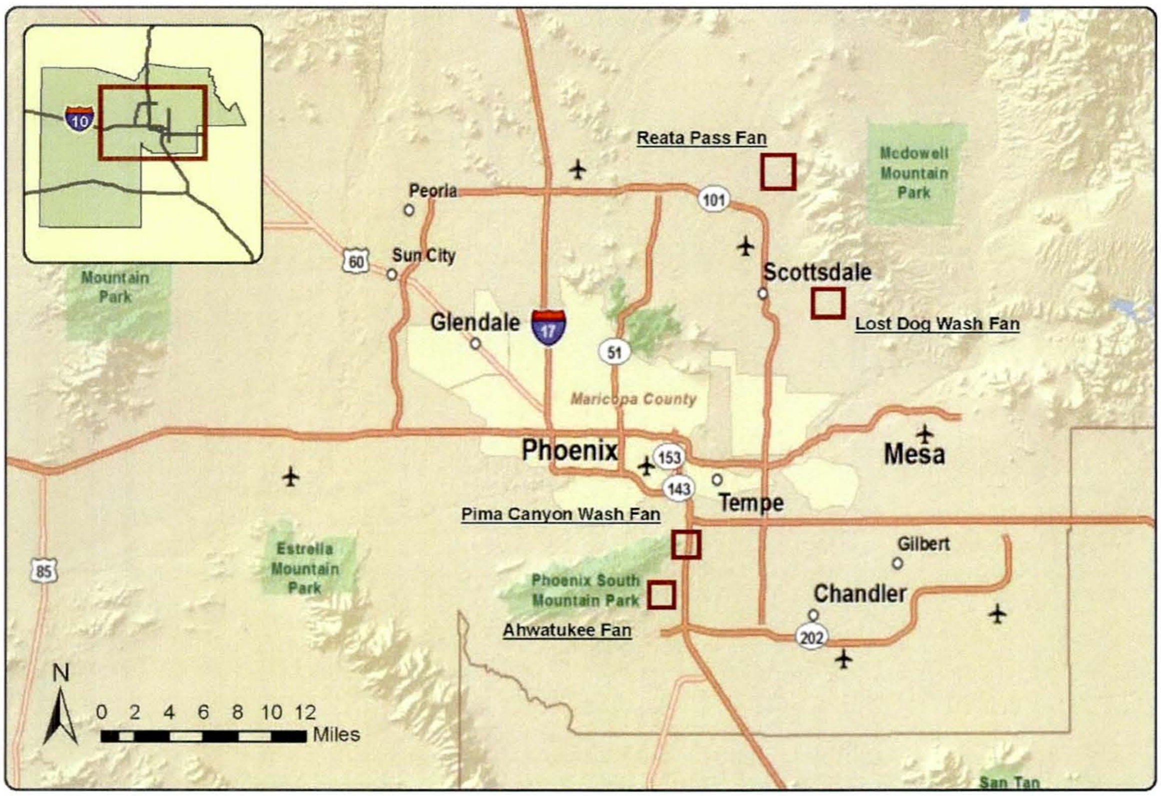

Figure 1-1 Location map showing all four historical fan sites.

The Ahwatukee alluvial fan was an active alluvial fan prior to development in the late 1980's. Prior to development, the Ahwatukee fan wash lost both capacity and definition at its hydrographic apex, as previously contained flow was converted to broad sheet flow over much of the upper fan area. The upper fan had been the site of repeated sediment deposition over time as water spread out and lost both depth and momentum giving this area distinctive geomorphic texture. The alluvial fan landform remained undeveloped until the mid-1980's when rapid and dense suburban single-family-unit development over the entire fan landform occurred. Upstream of the apex flows were dammed and floodwaters were routed to the toe via a concrete-lined trapezoidal channel. No homes or structures on or around the fan have been flooded to date. The concrete-lined channel, despite being heavily damaged during the large 2005 flood event, has never overtopped. The problems with sedimentation in the channel and expansion / contraction issues surrounding the channel are addressed routinely by the channel owners, a private home owners' association, through regular channel maintenance. We anticipate that sediment and channel maintenance needs will continue indefinitely.

The Pima Canyon Wash alluvial fan was an active alluvial fan prior to development in the late 1980's. Due to low topographic relief at the toe of the fan, the town of Guadalupe had been repeatedly flooded by shallow sheet flow and sediment, resulting in damaged homes and infrastructure from at least the 1930's to the 1980's when a regional flood control dam was constructed. Since the 1930's, extensive development has taken place on the fan including the construction of I-10 and the Guadalupe Flood Retarding Structure (FRS), channelization of Pima Wash, construction of residential subdivisions and transportation infrastructure, and development of a golf course in the wash bottom and alluvial fan floodplain. Development-related improvements have been tested by one very large rainfall event (on the fan surface, not the upper watershed), which was estimated at about a 350-year event in July 2008. This storm sent a record amount of both floodwater and sediment along Pima Canyon Wash to the Guadalupe FRS. Several homes near the fan were flooded, although the inundation was not a result of flooding along the main channel on the Pima Canyon alluvial fan. In addition, the flooded homes were not located within the limits of the historically active alluvial fan area. Although record rainfall was recorded on parts of the fan, the actual damage to structures on the fan were minimal. Sedimentation and erosion in the channel both in and around the golf course will continue to occur in the future.

The Reata Pass alluvial fan has a moderately large watershed, a large active distributary flow area downstream of the hydrographic apex, and a classic fan shape. To date the largest problem area on the fan is the Pima Acres subdivision where no drainage infrastructure was built within the 1960's-style rectangular grid development. Construction of homes in Pima Acres started in the early 1990 and the area was 75% built out by spring 2009. Elsewhere on the fan, sedimentation has clogged culverts and blanketed dip crossings during small floods, creating a maintenance burden on both the City and the local home owners' associations. Development on the upper portion of Reata Pass fan preserved much of the natural, distributary drainage patterns of the fan landform, with the natural wash corridors designated and protected by City regulations as environmentally sensitive wildlife habitat. While no significant flood damages have been reported on the Reata Pass Fan, neither have there been any storm events greater than a 10-year event since development began, and the flood mitigation infrastructure is largely untested. It is likely that the existing low flow sediment maintenance problems will persists. Future large floods may cause significant damage to flood-prone homes on active parts of the alluvial fan landform.

The Lost Dog Wash, until modern development in the area between 1997 and 2005, was a small active alluvial fan characterized by unconfined distributary flow downstream of the apex. Development confined Lost Dog Wash to an engineered channel that routes flood water down the western portion of the fan, under the intersection of 120th Place and Via Linda Road to the Central Arizona Project Canal (CAP) where the water is ponded and routed northwest to the nearest crossing of the CAP canal. Lost Dog Wash has not seen any significant rainfall since the fan landform was developed, and the drainage structures remain substantially untested over the last 10 to 15 years. Minimal sedimentation and maintenance concerns are expected in the future, with the possible exception of the area upstream of the CAP canal, and then only in the event of a large flood.

Based on our analysis, we conclude that the engineered drainage systems at the four historical alluvial fan study sites have performed adequately during the 20 year period of record, at least with respect to controlling the flow uncertainty and sedimentation associated with active alluvial fans. The range of structural measures used included a peak-scalping detention basin, a concrete-lined channel, an earthen channel with drop structures, mass grading (golf course & development), a regional detention basin (at the fan toe), levees, diversion dikes, culverts, dip crossings, and bridges, as well as some non-structural regulatory measures. Although there has been only one near-regulatory type event on only one of the fans, and the systems remain largely untested, the record indicates the following:

- No homes on the fans have been damaged by alluvial fan flooding in the past 20 years.
- The structural measures, while they have sustained some damage and required sediment maintenance, have essentially performed their intended function thus far.
- No evidence of adverse impacts from channel avulsions, excessive sedimentation or scour have been recorded.
- Periodic sediment removal is required, especially near the upper end of the fans, but has not been excessive or beyond the capacity of the HOA's or the local jurisdiction.

Given the episodic and probable low return frequency of fan-altering (avulsive, excessive sedimentation, etc.) flood events, the conclusions listed above should be carefully weighed in light of the short period of record at the four fan sites.

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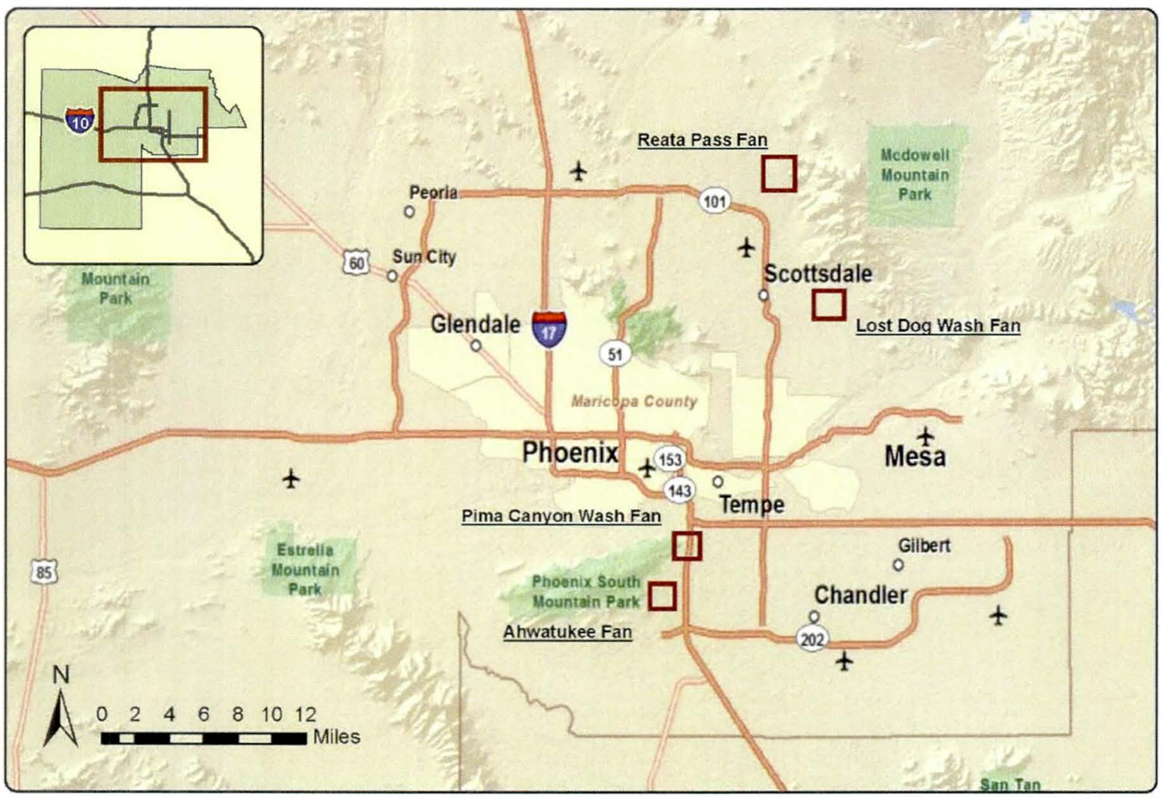

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2. Introduction

2.1 Study Purpose

The purpose of this technical memorandum is to assess the successes, failures, and/or drainage problems associated with historical development on alluvial fan landforms in Maricopa County, Arizona. The primary objective of this memorandum is to assess the nature of flood hazards and damages associated with development on alluvial fans in Maricopa County.

2.2 Study Authorization

This study is performed for the Flood Control District of Maricopa County (FCDMC, or the District) under Contract No. 2008C007 Task 2.3.

Project 2008C007 is a refinement to the current Piedmont Flood Hazards Assessment Manual (PFHAM) methodology. The purpose of the refinement is to identify engineering procedures to determine flood hazards on alluvial fan landforms, recommend hazard mitigation measures, further refine the landform designations and make recommendations for updating the PFHAM.

2.3 Study Introduction

Four individual site locations were chosen (Ahwatukee, Pima Canyon, Reata Wash, and Lost Dog) to study the effectiveness of flood mitigation measures that have been used historically on alluvial fan landforms in the metropolitan Phoenix area (Figure 2-1). The study site locations were identified using historical and recent aerial photographs, NRCS soils mapping and topographic mapping. The four areas include areas of dense urbanization, single lot development, and developments with major structural drainage measures. Study sites were selected that covered the longest period of development, had varying types of development and had different flood mitigation measures. The pre-development landforms were then classified using the District's PFHAM Stage 1 categories.

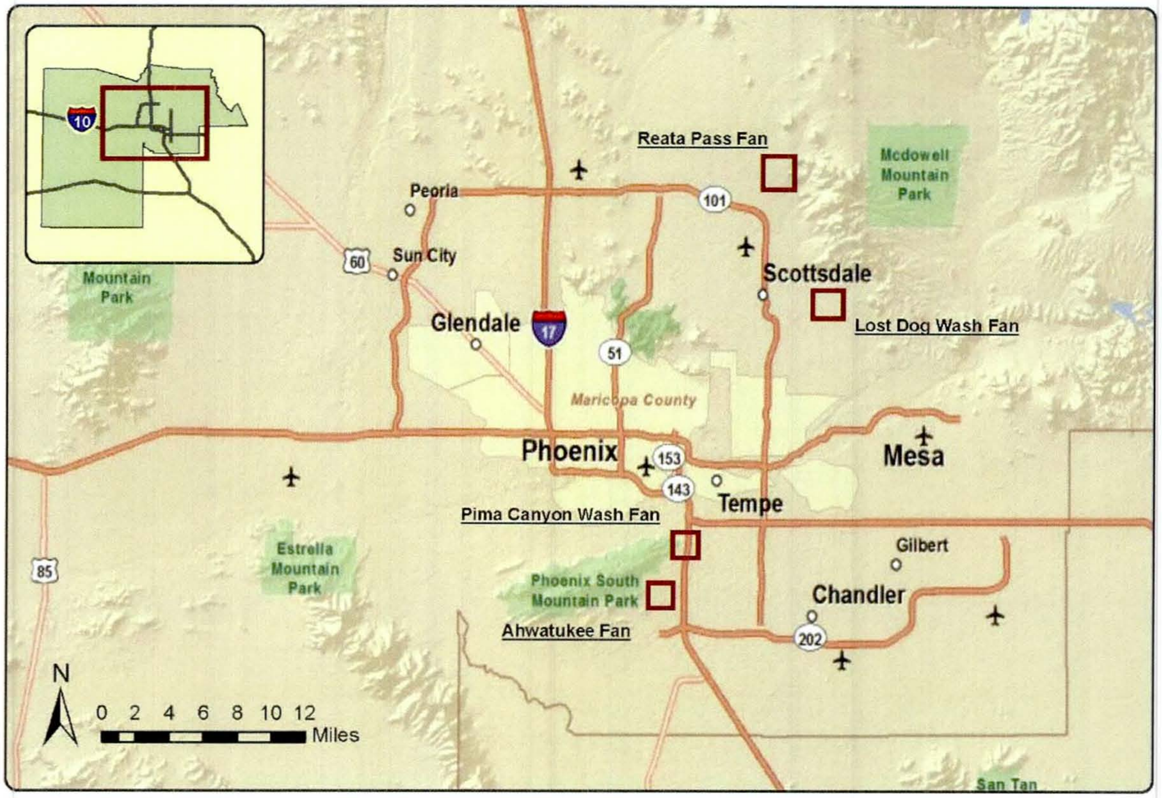

Figure 2-1 Location map showing all four historical fan sites.

Changes in the historical landform characteristics were documented for each site. To find anecdotal or systemic information regarding the performance of drainage structures, maintenance problems, and flood damages Investigation of each study site included the following: review of: historical and recent aerial photographs, construction plans-if available, historical and recent topography, and rainfall records, as well as interviews with maintenance staff, long-term residents, local floodplain managers, and home owners associations.

Finally, the effectiveness of structural or non-structural flood mitigation measures at each study site were documented based on the information collected. Preliminary recommendations on how to apply these findings to the Integrated Alluvial Fan Hazard Assessment Methodology are made within the discussion for each historical fan site.

3. Ahwatukee Fan

3.1 Site Location

The Ahwatukee Alluvial Fan site is located within the southeast valley of Phoenix, Arizona. Both the alluvial fan and apex are located within T1N R3E Section 24 of the Gila & Salt River Meridian (G&SRM). The fan is located in the community of Ahwatukee which is within the City of Phoenix incorporated limits. The alluvial fan apex is located approximately two miles west of I-10 at about the Warner Road alignment (Figures 3-1 and 3-2).

Figure 3-1 Location Map: Ahwatukee Fan.

The Ahwatukee Fan watershed is 1.7 square miles in area, and drains a portion of the southeast flanks of South Mountain. The watershed, up to the apex of the fan, is contained within Phoenix South Mountain Park and remains undeveloped.

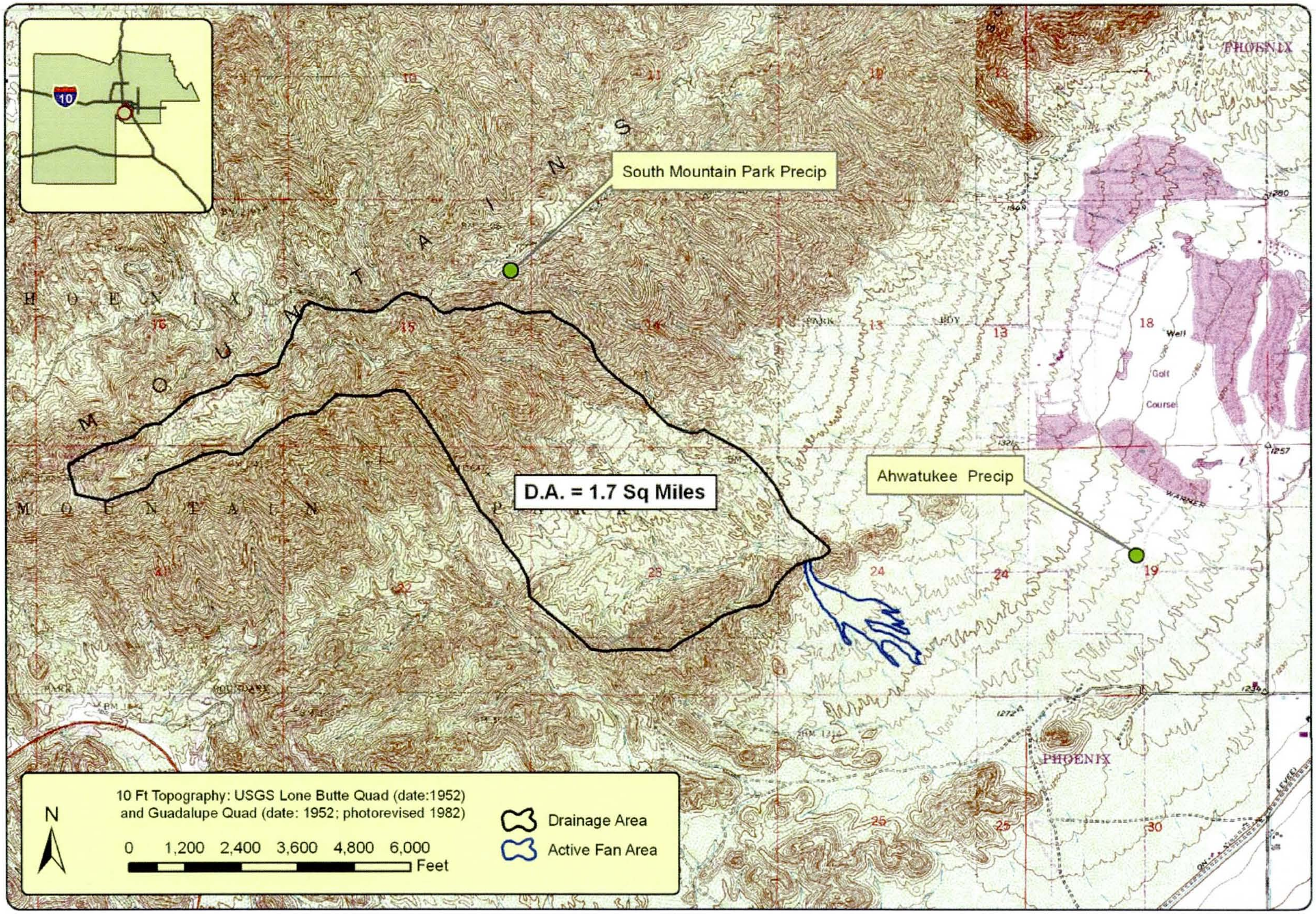

Figure 3-2 Ahwatukee Fan Drainage Area Map.

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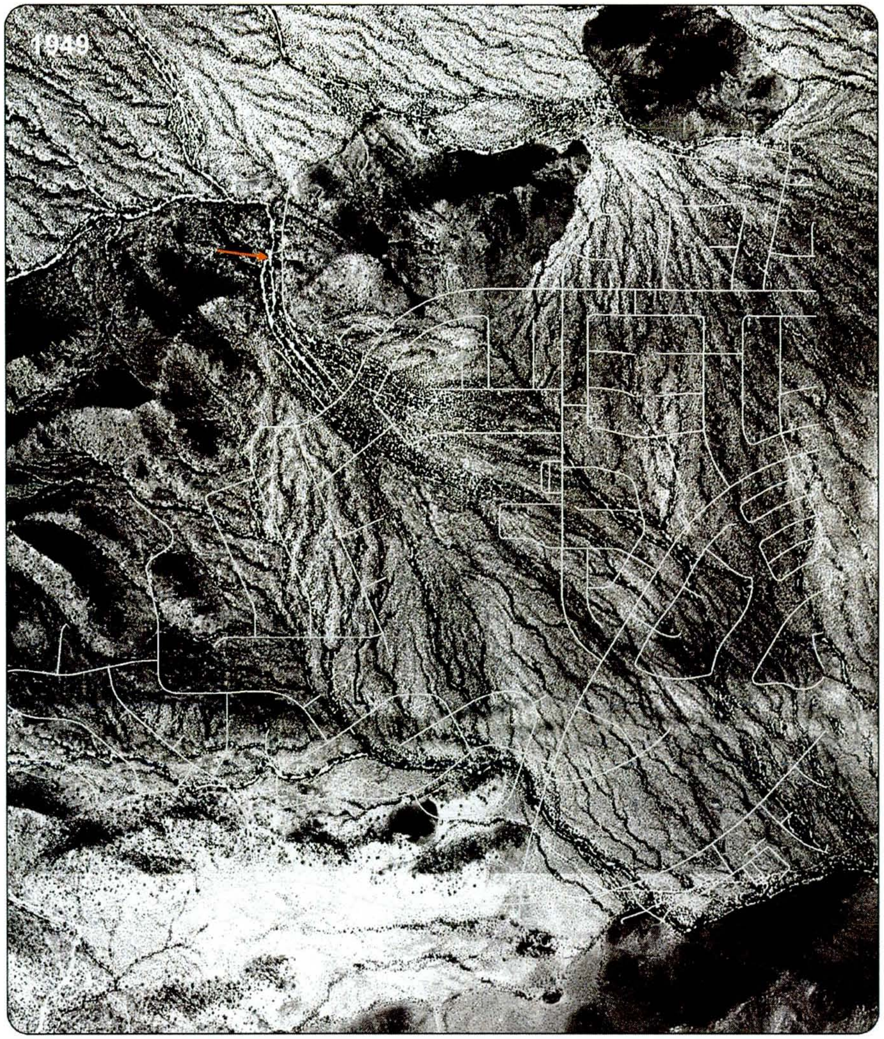

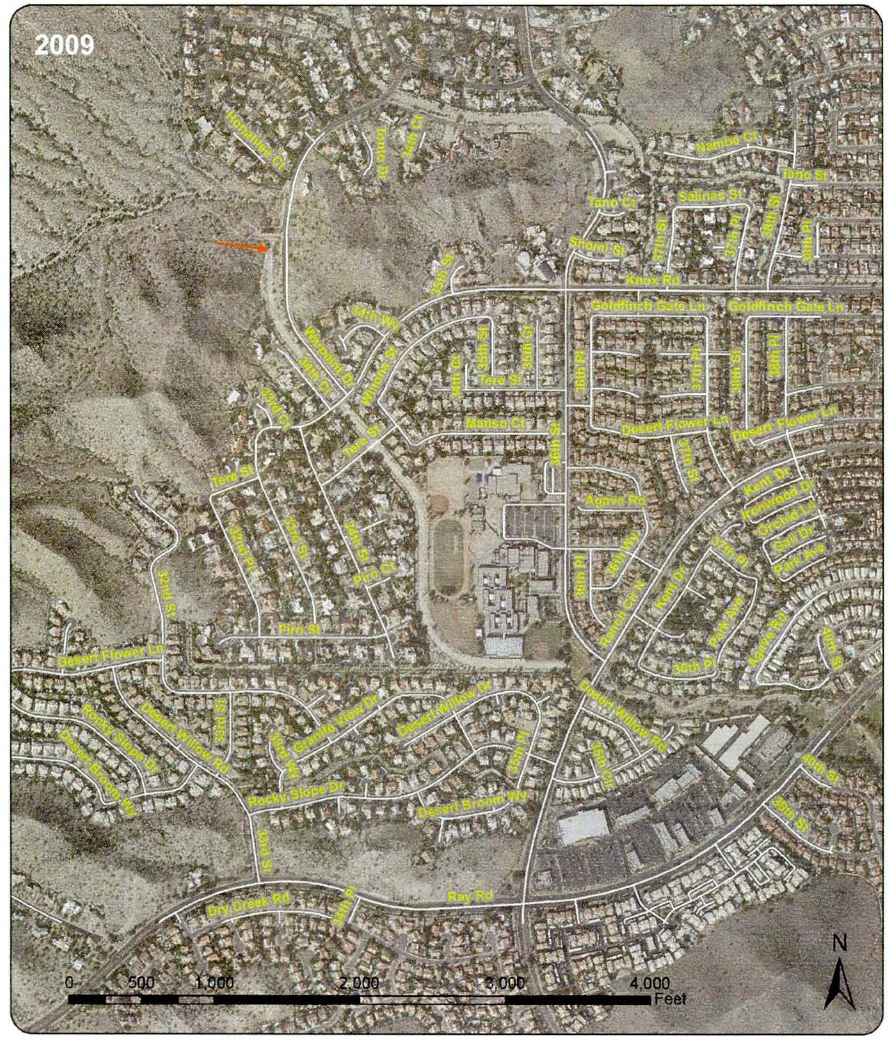

Figure 3-3 Ahwatukee Fan (before development).

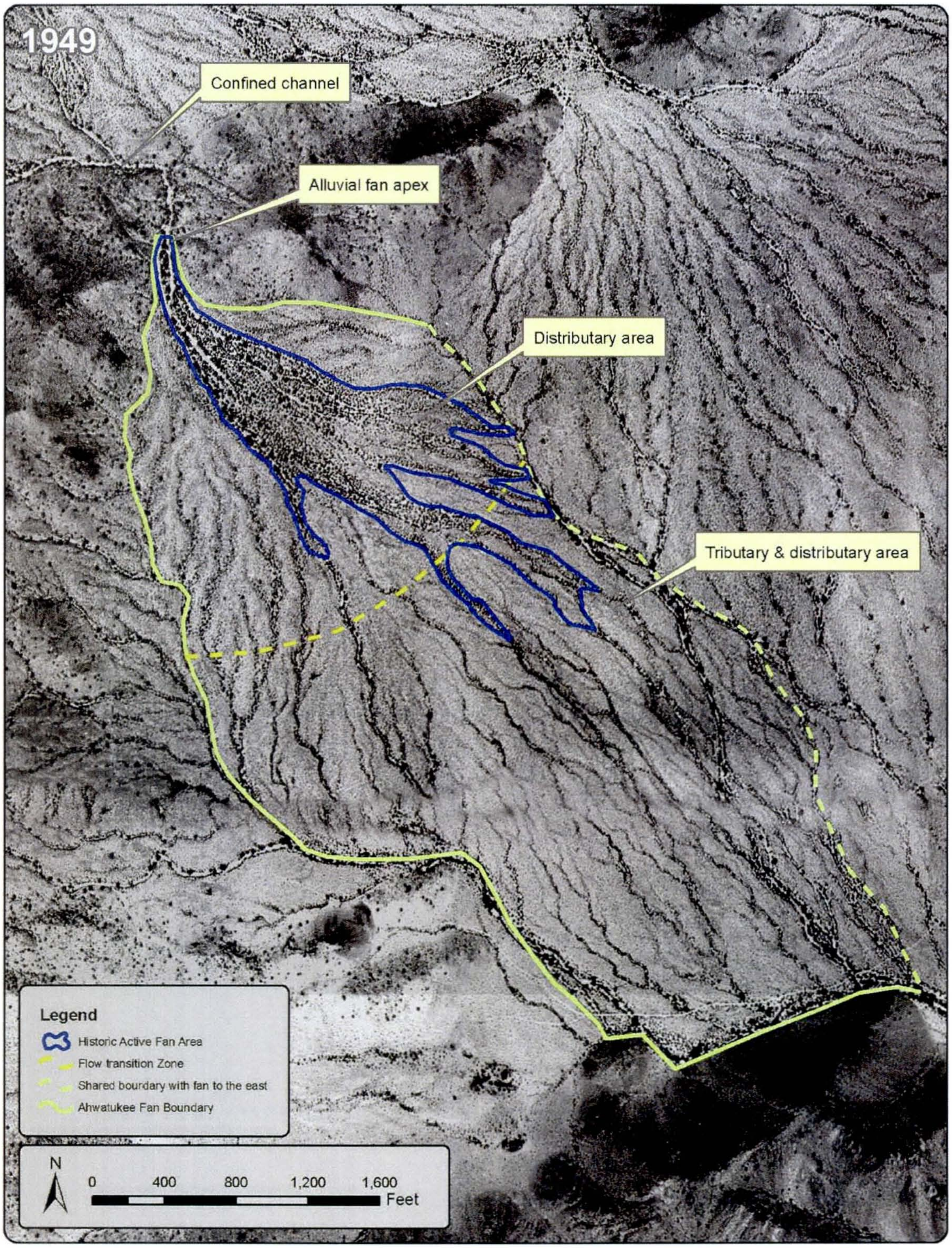

Figure 3-4 Ahwatukee Fan Landform Boundary (pre-development).

Figure 3-5 Ahwatukee Fan Points of Interest & Photo Locations.

As seen in Figure 3-4 and Figure 3-5, the apex of the historical alluvial fan is located approximately 1,000 feet northwest of the present day intersection of Knox Road and Warpaint Drive. The wash, unnamed on USGS quads, collects flows off South Mountain, enters the historical photograph from the west (on the upper left) then makes a sharp right turn to the south (river right) through a narrow canyon, the present day location of Warpaint Drive. The wash then loses capacity and spreads out as distributary flow over much of the upper portion of the fan. In the 1949 photograph (Figure 3-3) the active portion of the fan can is characterized by a "salt and pepper" stippled pattern characteristic of distributary and shallow sheet flow areas. The active portion of the fan extends down fan approximately as far as the present location of North Ranch Circle Drive.

After flood water flows down fan over the distributary areas, in the upper third of the fan, the sheet flow is conveyed into more defined, slightly incised flow paths. The flow paths are both tributary and distributary but do not contain the same "salt and pepper" stippled pattern as the active areas upstream. These incised flow paths convey the flood water to the toe of the fan where they join another wash, flowing from the west, and continue downstream.

3.1.1 NRCS Soils Mapping

Figure 3-6 presents the soil survey information for the Ahwatukee Fan study area. The source of the soil survey data is the NRCS (formerly the SCS) Soils Survey of Eastern Maricopa and Northern Pinal Counties, Arizona, 1974. In Figure 3-6 the historically active alluvial fan area was delineated from the 1949 aerial and is included as a blue outline on the 2009 aerial photograph background. This was done to provide perspective of where the historical active alluvial fan surface was in comparison to modern residential development in the area. Soil survey units are labeled individually but also grouped by major landform type that each unit typically represents.

Upstream of the apex are two soil units: Ro (Rock Land) and Ru (Rough Broken Land). Both these units have been shaded brown in the figure and classified as 'Mountain Slopes.' Rock Land consists of areas that are 50 to 70 percent exposed rock, and is used to describe steep sloping bedrock mountains in the study area. Runoff is typically very rapid and erosion active in these areas. Rough Broken Land (Ru) is moderately sloping to very steep. This unit is often dissected by many intermittent V-shaped drainage channels and separated by irregular narrow ridges.

The entire alluvial fan landform is composed of Antho gravelly sandy loam (AoB), and bordered on each side by Tremant gravelly loam (TrB). Antho gravelly sandy loam (AoB) forms on gentle, 1-3 percent slopes, on the upper portions of alluvial fans. Tremant gravelly loam (TrB) consists of well drained soils on old alluvial fans. In Figure 3-6, the (AoB) Antho Series has been shaded yellow to depict alluvial fans while the (TrB) Tremant Series has been shaded blue to depict older, inactive alluvial fans. The Ahwatukee alluvial fan is composed of soils typically found on alluvial fans and bordered by older fan terrace soils.

3.1.2 Surficial Geology

Figure 3-7 presents the surficial geology of the Ahwatukee Fan study area, as mapped on the AZGS Phoenix South Geology 100,000 scale, Issue DI-5 June 1997, by Reynolds and Skotnicki. In Figure 3-7 the historically active alluvial fan area was delineated from the 1949 aerial and included as a blue outline on the 2009 aerial photograph background.

The bedrock units of the ridgeline that lies to the north of the study area are composed of granite and breccia (Tg and Tcb). Tg (Tertiary Granite) is the same unit that composes most of the South Mountain Range and formed in the middle Tertiary, roughly 65 million to 2 million years before the present.

The majority of the Ahwatukee alluvial fan landform lies within the Qy geologic unit. Qy (Quaternary Young Alluvium) forms low terrace and alluvial fan deposits. Qy, a Holocene unit less then 10,000 years old, is the youngest geologic unit in the study area.

Bordered on both the east and the west, the Qy unit is bounded by the older Qm2. Qm2 is an upper to middle Pleistocene alluvium. The Pleistocene Epoch dates from approximately 1.8 million to 10,000 years before present.

3.1.3 Topography

Figure 3-8 presents the topography for the Ahwatukee alluvial fan study area. The topography shown is USGS 10-foot topography from the Lone Butte quadrangle dated 1952. In Figure 3-8 the historically active alluvial fan area was delineated from the 1949 aerial and included as a blue outline on the 2009 aerial photograph background.

The contours immediately downstream of the apex of the fan are smooth, radial in shape and bend in the downstream direction. Topographic contours become more crenulated downstream of the outlined blue distributary area indicating more defined flow paths near the toe of the fan.

Figure 3-6 NCRS Soils: Ahwatukee Fan.

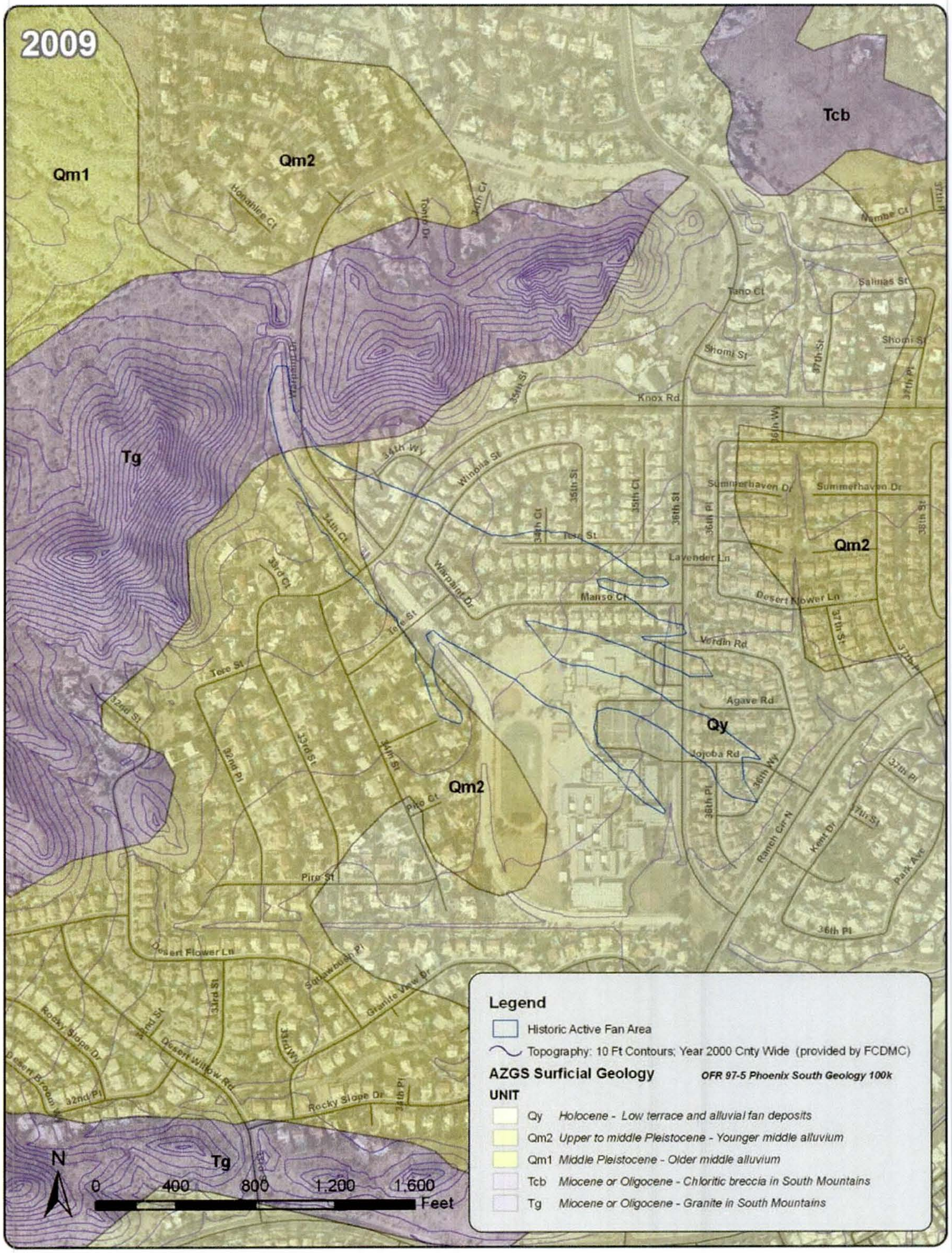

Figure 3-7 AZGS Geology: Ahwatukee Fan.

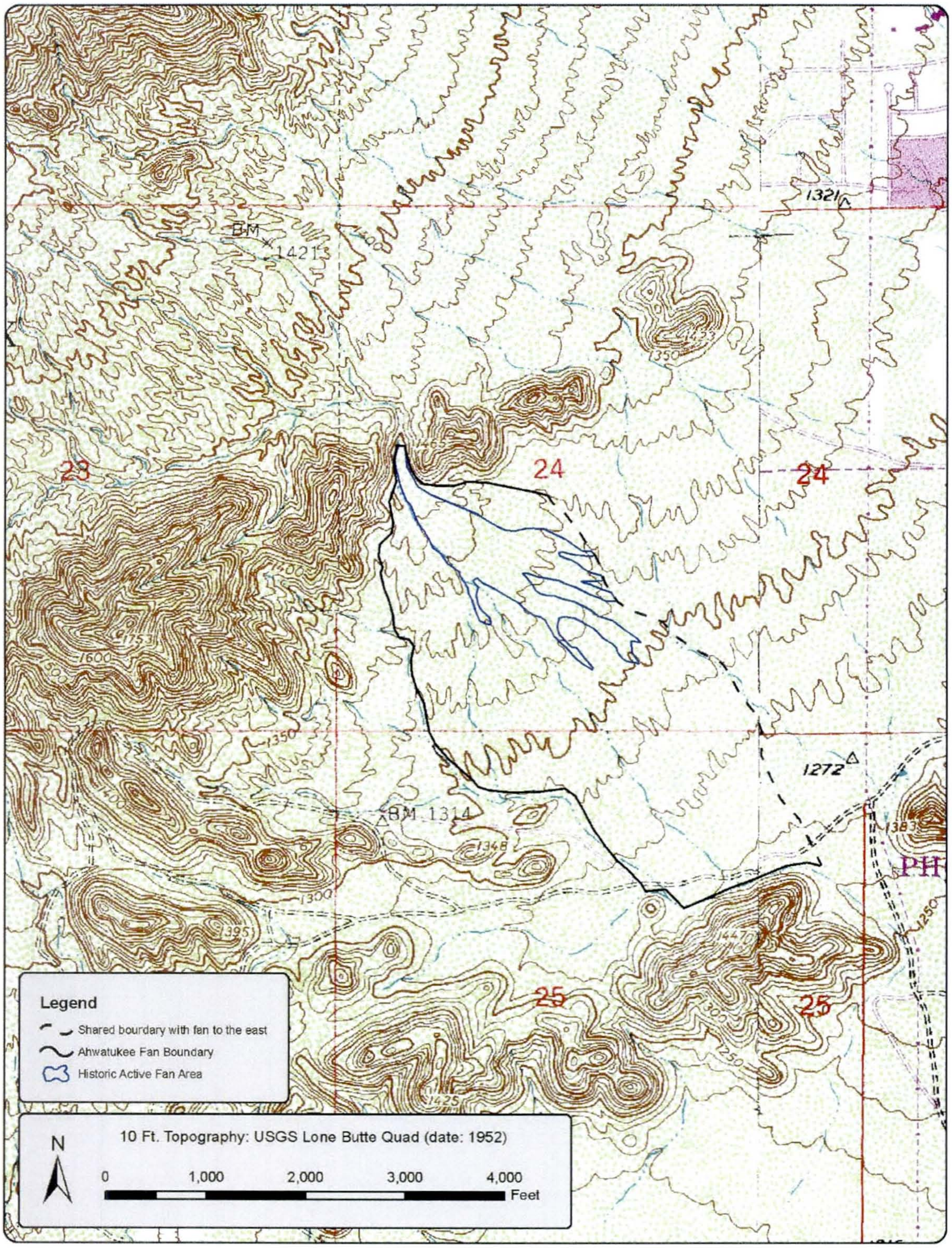

Figure 3-8 Topographic Mapping: Ahwatukee Fan.

3.1.4 Watershed and Fan Parameters

The following tables enumerate specific statistics about the watershed and fan area. Details are also included about the type and location of engineered structures within the study area.

Item	Value	Source
Watershed area (apex)	1.7 square miles	USGS Quad
Watershed slope Upstream of apex (3.3 – 1.2 miles) Upstream (1.2 miles to apex) Channel Slope Apex to 0.5 miles downstream ACE-8 Channel	 8.1 percent slope 3.8 percent slope 1.8 percent slope 1.5 percent slope	 USGS Quad USGS Quad USGS Quad FCDMC year 2000 ten foot topography
Q100 at apex	2778 cfs	USGS Water Supply Paper 2433 (Drainage Area = 1.7 Sq. Miles, Median Elevation: 1800 ft)
Fan Profile Shape	Concave up	USGS Quad
Max Elevation in Drainage Area	2586 ft	USGS Quad
Elevation at apex	1350 ft	USGS Quad
Minimum Elevation in fan	1270 ft	USGS Quad

Table 3-1 Watershed and Fan Parameters

Structure	Type	Location
Dam, two 6'x 6' box culverts	Roller-Compacted Concrete (RCC) dam	Upstream of apex
ACE -8 Channel (Ahwatukee Custom Estate 8)	Concrete-lined trapezoidal channel	From apex to Ranch Circle Rd. (continues downstream in a network of engineered channels until Pecos Rd
Knox Rd Crossing	RCBC Culvert crossing	Intersection of Knox Rd and ACE-8 Channel (1200 feet downstream of the dam)
Piro St Channel	Trapezoidal channel feeder channel to ACE-8 channel	Channel running parallel to and south of Piro St.
Retention Basin	0.8 acre grass lined basin	At termination of ACE-8 channel, West of intersection of 36th St and Ranch Circle Rd.
Sediment Ramp	Sediment ramp – later covered with gunite	At termination of ACE-8 channel, at entrance to retention basin
Ranch Circle Road Culverts	Drop inlet RCBC culvert crossing	South of intersection of 36th St and Ranch Circle Rd.

Table 3-2 Structure Parameters

3.1.5 PFHAM Stage I Landform

Task 2.3.3 requires that the pre-development landform be classified as to the "probable" landform type using the PFHAM Stage 1 categories. A PFHAM Stage 1 landform classification for an alluvial fan consists of the following elements:

- *Composition*. The landform is composed of alluvium (sediment material transported by the streams that formed the landform.
- *Morphology*. The landform has the shape of a fan, either partially or fully extended.
- *Location*. The landform is located at a topographic break where the primary watercourse loses capacity.

The Ahwatukee Fan landform is shown to be composed of alluvium, as shown by the NRCS detailed soils mapping (Figure 3-6) and AZGS surficial geology mapping (Figure 3-7). As shown in Figure 3-8, the landform has the radial contours characteristics of a partially extended fan. The site is located at the topographic break formed where the main wash traverses the narrow canyon along the Warpaint Drive alignment and the channel changes from a single thread channel to a bifurcated distributary pattern (Figures 3-4 and 3-8). Therefore, the landform is properly classified as an alluvial fan landform.

3.2 Development History

3.2.1 Development History Timeline

Historical aerial photographs of the Ahwatukee Fan are shown on the following pages on Figures 3-9 to 3-12. On each photograph is the delineation of the active fan area (as delineated from the 1949 aerial). This delineation is included as a point of reference because the landform becomes quite obscured with build-out of residential developments in the area. All of the following aerial photography was obtained from the FCDMC.

The oldest aerial image of the study area is from 1937. The 1937 aerial photograph resolution is not as crisp as the following set, taken in 1949, but still evident is the active area in the upper portion of the fan. It is represented in the photograph as a consistent gray-toned area with a lack of defined drainage paths.

The 1949 photograph is the highest resolution pre-development aerial photograph of the study area. In 1949, there was no development, roads, or even paths in the study. According to the U.S. Census Bureau the population of metropolitan Phoenix was only about 332,000 people in 1950, and the community of Ahwatukee did not exist. Besides dense residential growth, other changes on the fan surface since 1937 include a more clearly distinguishable flow split area in upper middle portion of the distributary flow area. The channel that flows from the apex along the northeastern edge of the fan is more clearly visible in this photograph also.

By 1979, the first minor paths and roads are visible in the area. Two paths cross the fan, one crosses the fan at the apex, and the second road crosses the fan at the eastern extents of the active fan portion, but most of the alluvial fan landform remains undisturbed. Changes since 1949 on the landform also include: (1) denser vegetation near the fan apex and, (2) a smoother texture in the area between the two south-western fingers of the distributary. This may indicate that the area had been inundated and subject to sedimentation prior to the date of the later aerial.

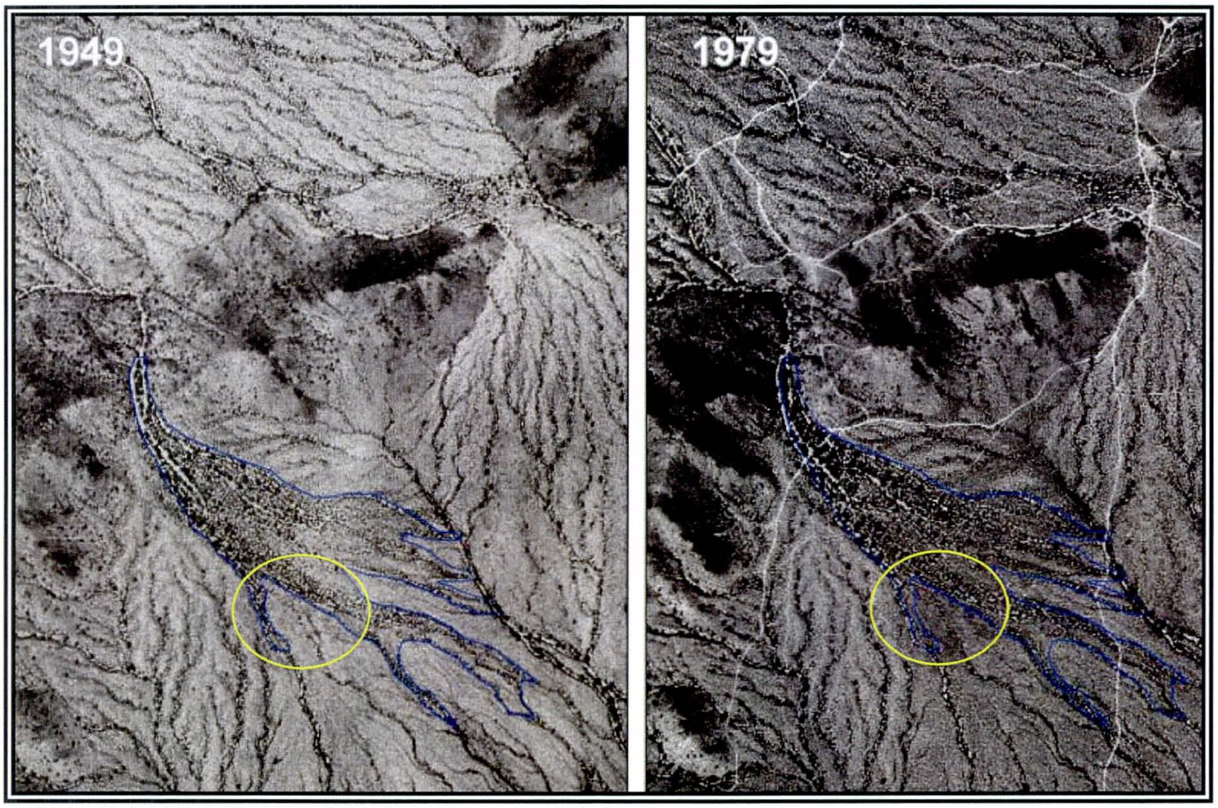

Figure 3-9 Ahwatukee Fan Landform Changes 1949 -1979.

In the late 1980's, an engineered drainage system was constructed across the fan surface. The drainage system consisted of a small, peak-scalping dam upstream of the hydrographic apex and a lined trapezoidal channel that traverses the fan landform. The exact year the dam was completed is not known.[1] Culverts were built through the dam to convey a metered flow into a concrete-lined trapezoidal channel that then conveys the flow toward North Ranch Circle Drive. From Ranch Circle North, flow continues into an engineered meandering lined channel owned by Mountain Park Ranch Home Owners' Association. From there, the flow continues through a series of channels owned by various home owners' associations and continues two miles, daylighting south of Pecos Road, at which point the channel flows into rangeland without engineered drainage facilities. Interestingly, while the lined channel follows the original channel alignment immediately downstream of the apex, it deviates significantly from the natural channel alignment after about 2,000 feet and follows a completely artificial alignment thereafter.

The 1993 aerial shows the aforementioned changes. Starting in the mid to late 1980's Ahwatukee began to be extensively developed. Within the study area dense suburban single lot development took place, major road improvements were designed and installed and drainage improvements where

[1] The City of Phoenix does not retain development plans older than 20 years. Thus development plans for the study area are not readily available.

constructed to route floodwaters through the development. The engineering firm listed on the Final Plat for the area "Ahwatukee Custom Estates-8" is Brooks Hersey & Associates Inc. The final plat is dated July, 1985. Brooks Hersey & Associates, now Brooks Strand Associates Inc., did not have any drainage reports on the channel built in the area, and identified as "Drainage Tract A" on the Final Plat. Although the plans for the dam could not be found, Art Brooks, the owner of Brooks Hersey & Associates, which designed the dam, stated that the purpose of the roller compacted concrete dam was to reduce flood peaks to 1600 cfs.

Kyrene de la Colina Elementary School and Centennial Middle School were built in the middle of the project area in 1990, immediately adjacent to the concrete-lined channel. The public schools are under the jurisdiction of the City of Phoenix, while the homes and drainage channel in the project area are managed by a Home Owners Association, the Ahwatukee Board of Management.

The concrete-lined trapezoidal channel continues south of the dam, routed under a set of box culverts at Knox Rd, continues southeastward until the Middle School property, at which time it turns south and then east adjacent to the middle school boundary. South of the middle school the channel empties into a grass lined drainage basin before crossing underneath Ranch Circle North Road. The drainage basin routes water under the road to connect with a meandering rock lined channel that conveys the flow further downstream out of the project area.

The 1997 photograph shows continued development south of the project area, with additional road improvements to 34th Way, which is northeast of the intersection of Knox Road and Warpaint Drive.

By 2003 with the completion of a few remaining homes in the area, development is completely built-out. The study area today is similar to the early 2000's, and is substantially unchanged with respect to the drainage system since the early 1990's. .

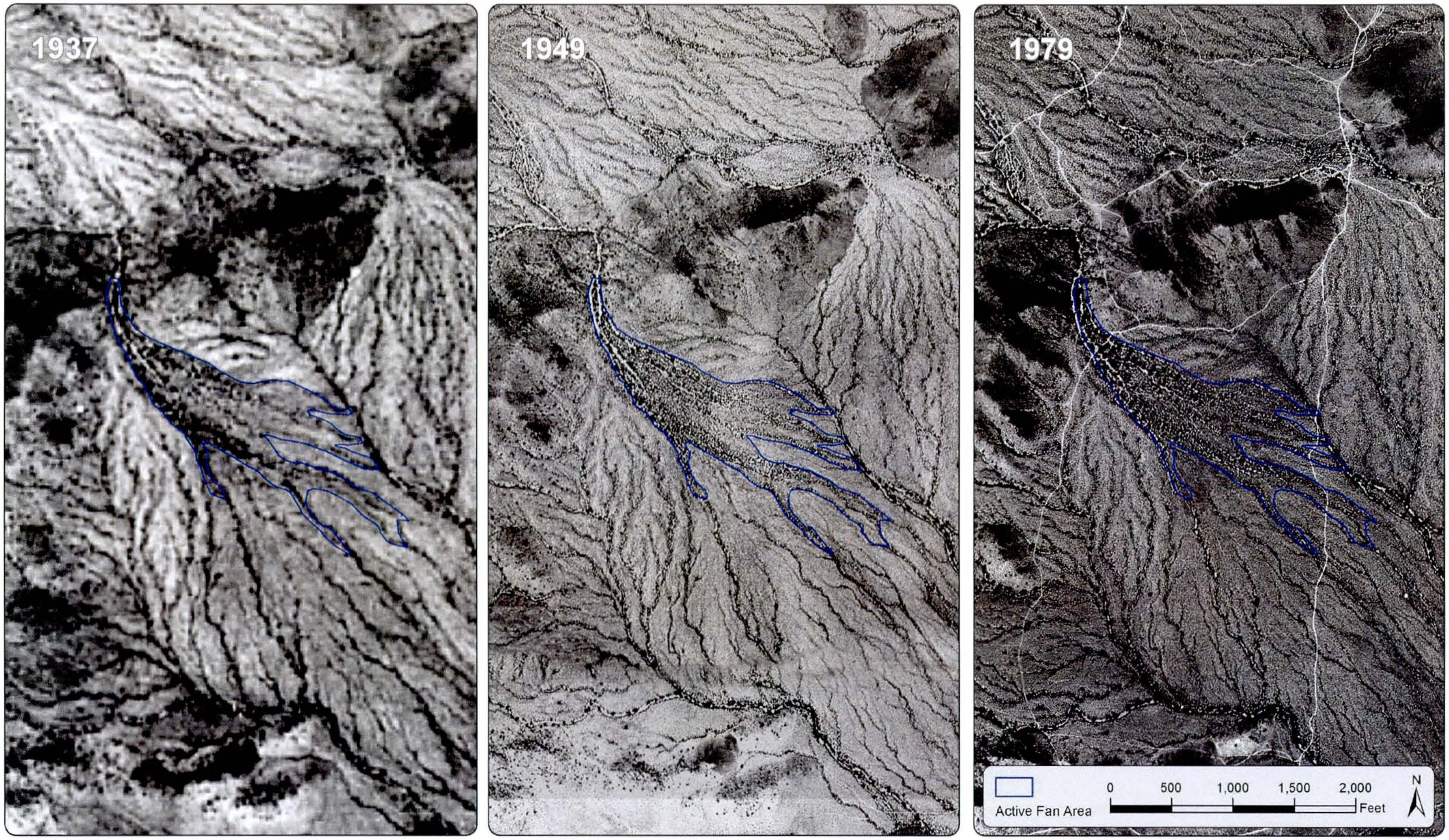

Figure 3-10 Historical Aerial Photos: Ahwatukee Fan 1937-1979.

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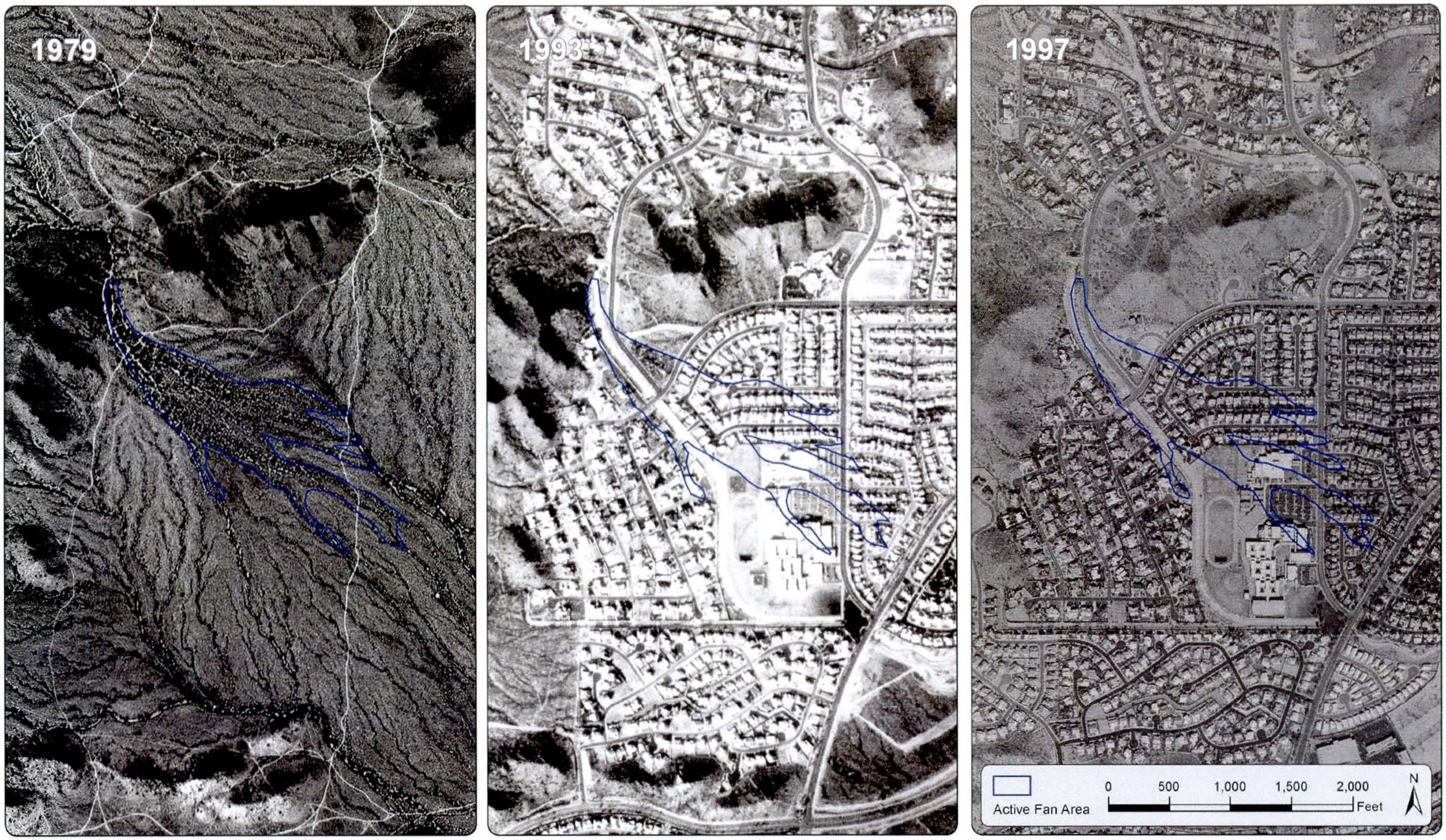

Figure 3-11 Historical Aerial Photos: Ahwatukee Fan 1979-1997.

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Figure 3-12 Historical Aerial Photos: Ahwatukee Fan 1997-2009.

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3.3 Hydrology

The locations of the nearest rain gages have been located in relation to the watershed boundary in Figure 3-2. The FCDMC rain gage closest to the study area is located 1.25 miles east, near the intersection of Warner Rd. and 44th St. (#6550). The gage has been continuously reporting data since March 1996. Since that time, the average rainfall per year is 6.74 inches with the wettest year on record being 2005 with 13.94 inches and the driest year on record being 2002 with 3.03 inches of rainfall reported. The FCDMC also has a rain gage located in South Mountain Park (#6510) and just 0.1 miles outside the upper limits of the study area watershed. This has been continuously reporting data since October 1982 (with only 3 months of missing or partial data). Since its installation, the median rainfall in the upper portion of the watershed has been 7.64 inches with the wettest years on record being 1983, 1993 and 2005 with total rainfall being 13.50," 13.33" and 13.27" respectively. The largest storms near the watershed have been:

- 30 year storm: 2.05" in 6 hours on 08-02-2005 (FCD #6550)
- 20 year storm: 1.46" in 1 hour on 07-13-2008 (FCD #6550)
- 50 year storm: 3.23" in 24 hours on 08-15-1990 (FCD #6510)
- 40 year storm: 2.01" in 3 hours on 08-15-1990 (FCD #6510)
- 35 year storm: 2.13" in 6 hours on 08-03-2005 (FCD #6510)

The General Manager of the Ahwatukee Board of Management, who has been working in the project area ever since it was built-out in the early 1990s, said that the largest event he could remember occurred during August 2005. During this event, the concrete-lined channel that routes water through the HOA flowed full, from bank to bank. The dam upstream, he said, was nearly overtopped. This was an intense, localized storm, which did considerable damage to the concrete-lined channel. Damage from this event will be covered in more detail in the next section of this report. The HOA did not report any damage to drainages that neighbor the study area.

3.4 Flood Mitigation Measures

3.4.1 History

As mentioned above, a concrete-lined trapezoidal channel was built on the fan to convey flood water through the project area from the apex to the toe. A roller compacted concrete (RCC) dam was built just above the apex, approximately 400 yards upstream of the Warpaint Drive / Knox Rd intersection. The concrete channel is 4100 feet in length from the dam to E. Ranch Circle North Drive.

Neither the design plans nor the party who has jurisdiction over the dam were identified. Both the City of Phoenix and the home owners' association (HOA) denied having any jurisdiction over the dam (the City was aware of its existence). The City has not retained any of the design plans for the dam, channel or surrounding communities. From field observations, the RCC dam appears to be about 20 feet wide at the top, 120 feet long, and is covered by a thin veneer of soil. A two-cell concrete box culvert serves as the principal outlet and meters flow into the concrete channel. The dam serves as the dividing point between the natural wash in the upstream watershed and the engineered channel downstream. The concrete trapezoidal channel downstream of the dam is locally referred to as the ACE-8 channel, as it runs through the Ahwatukee Custom Estates No.8 Subdivision.

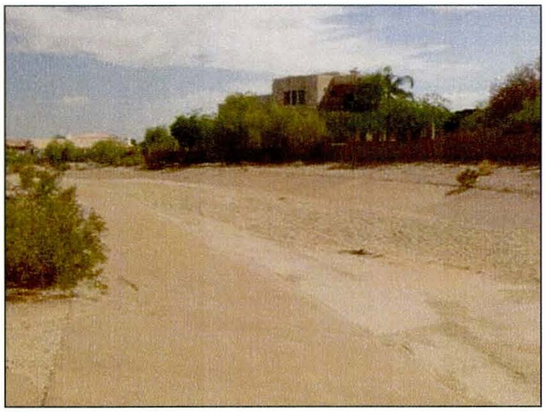
At the outlet of the culvert through the dam are 10-20 several ton boulders lying in the wash. Several of these boulders are attached to the channel bottom and sides with concrete, others are not. The intended purpose of these boulders at the outlet of the culverts is not known, but they may have been placed as energy dissipaters or for aesthetic reasons. Downstream of the dam for approximately 100 yards, sediment drops out in a series of sandy riffles. The ACE-8 channel crosses under Knox Road in a concrete box culvert, over Tere Street in a dip crossing, and passes Centennial Middle School heading first due south and then due east. As the channel takes a 90 degree turn left going from south to east it picks up flow from the Piro Channel which joins it from the west. The Piro channel, runs parallel to Piro St., and picks up local runoff from the development directly west of the active fan area.

After the channel turns east (at the south end of Centennial Middle School), the channel drops into an engineered grass-lined basin. Downstream of the drainage basin, the water flows under East Ranch Circle North Drive into a channel maintained by the adjacent Mountain Park Ranch HOA. The channel was designed and built with a four foot drop structure at the basin entrance. However, over the course of ten years, enough sediment has built up at the drop structure to create a ramp of sediment from the channel into the drainage basin. This sediment was later graded and gunite was laid over the top of the ramp, effectively eliminating the drop structure. The volume sediment stored in the ramp structure is estimated at about 7.4 cubic yards.

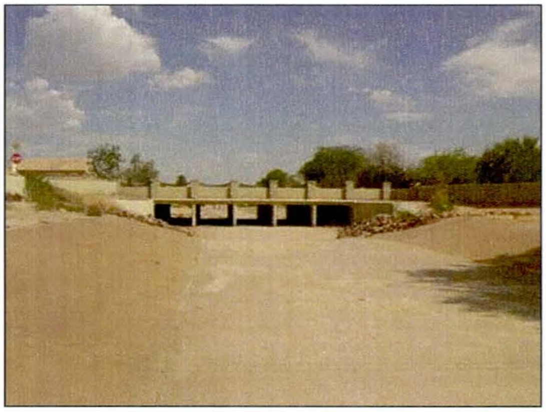
3.4.2 Photograph locations

Following is a set of field photos. The location of each photograph has been noted in Figure 3-5, which also labels other important reference locations in the study area.

1. ACE-8 Dam
Downstream of the dam, looking upstream

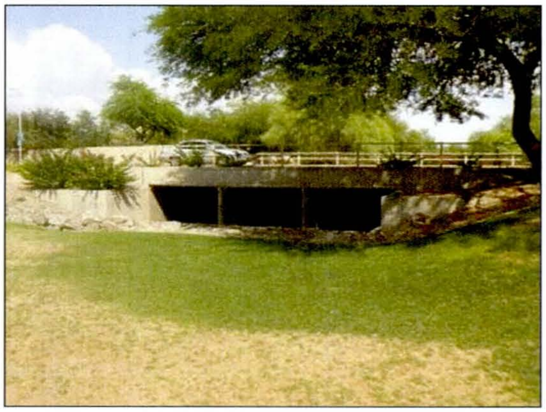


2. ACE-8 Channel
Downstream of the dam, looking downstream



3. Knox Road Crossing
Looking upstream

4. Drop / Ramp Structure
South of Centennial Middle School



5. Outlet to channel downstream
Culverts underneath Ranch Circle Road

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3.4.3 System Maintenance

The Ahwatukee Board of Management is responsible for the maintenance of the ACE-8 channel from the dam to where the wash crosses East Ranch Circle North. Maintenance is done on the channel on a routine basis twice a year and involves removing sediment from the channel, and inspecting for damage and debris. Sediment is removed from the channel bottom and graded out onto the overbank area, effectively removing it from the channel system. It is estimated that 10 - 15 cubic yards of sediment are removed from the channel per year. The channel downstream of the ACE-8 channel is a trapezoidal rock lined channel, with small engineered meander bends. The channel owner downstream, Mountain Park Ranch HOA, did not report sedimentation problems or maintenance needs with their section of the channel.

The ACE-8 channel has had recurring expansion and contraction problems at the channel joints. Joints that become offset from one another are routinely cut away with a concrete saw and patched.

The most severe damage to the channel occurred during a large storm in August 2005. The Ahwatukee Board of Management reports that during this event the dam was nearly overtopped and the channel flowed full. The flow had enough force to displace and carry as many as ten 6 to 8 ton boulders from the rock dissipater at the dam outlet a distance of about 1,500 feet downstream, as well as many smaller 3-4 ton boulders downstream as far as Centennial Middle School, which is several thousand feet downstream of the dam. One large boulder is still lodged in the culvert under North Ranch Circle Drive. In addition, approximately 200 feet of the channel bottom and sides were ripped out and damaged by the floodwaters and a large quantity of sediment was also deposited in the channel.

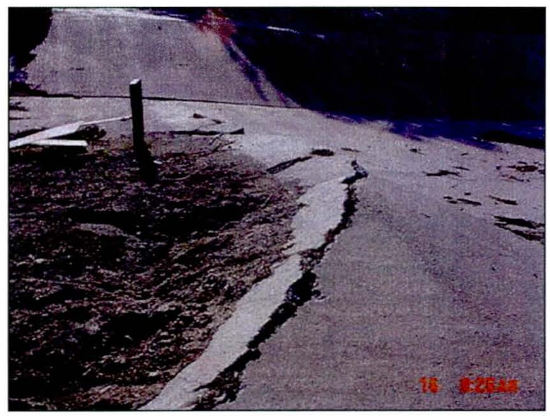
To estimate the magnitude of the 2005 flood, the ACE-8 Channel bankfull discharge was estimated using Manning's equation to be 2,555 cfs, with a velocity of 23 ft/s. This flow rate is lower than, but near the 100-year discharge estimate of 2,778 cfs obtained from regional regression equations. Given that this estimate is larger than the 1,600 cfs maximum outflow for the RCC dam, the estimate is considered crude and approximate with respect to the August 2005 flood.

- Manning's Equation: Q=V*A, V=k/n (A/P)^2/3 (S)1/2
- Area = 106.8 sq. ft., Wetted perimeter = 48 ft, k = 1.49
- Concrete channel slope = 0.015 (ft/ft), N value for concrete lined channel = 0.013

The Ahwatukee Board of Management estimates that about 10-12 truck loads of sediment (~50-120 cubic yards) were removed from the wash after that one event. The channel repair cost more than $25,000. The large boulders that had washed downstream were removed from the wash and placed back in their original position just below the dam.

It is theorized that the flood water was able to tear out the channel lining by getting underneath just one slab at first, most likely exploiting a weak joint or one that was slightly separated due to contraction / expansion. After one portion of the wash was torn away, the water was able to erode sediment out from underneath adjacent slabs, as shown in Photographs 6-9 below.

6. Concrete lining damaged
Downstream of the dam, looking upstream



7. Sedimentation
50-120 cubic yards of sediment

8. Scour under lining
Downstream of the dam, looking upstream

9. Sedimentation
25,000 dollars in total damages to channel

3.5 Conclusions

Prior to residential development in the late 1980's, the Ahwatukee alluvial fan landform had a moderate-sized active area near the apex. Development occurred as part of a master planned community, which was based in part on a regional-scale, privately funded drainage master plan. The engineered drainage master plan for the alluvial fan included a peak-scalping RCC dam and a concrete channel that only partially followed the pre-development channel alignment.

The drainage system has been tested by at least one large storm event in August 2005 that approached the magnitude of a 100-year event based on crude post-flood stage estimates, though rainfall measurements at the District gages were significantly less than 100-year depths. Since development began in the area, the largest rainfall events to happen at the two neighboring gages have been a 50-year 1-hour storm in the upper watershed in 1990 and a 30-year 6-hour storm in 2005 recorded just one mile to the east. While there have other flow events in the ACE-8 channel, such flows are rare and have typically been no more than a few cfs.

Based on our analysis, we conclude that the engineered drainage system has performed adequately during the 20 year period of record, at least with respect to controlling the flow uncertainty and sedimentation associated with active alluvial fans. No homes or structures on or around the fan have been flooded in the past 20 years. The concrete-lined channel, despite flowing full and being heavily damaged during the August 2005 event, has never overtopped. Sedimentation in the channel and expansion / contraction issues surrounding the channel joints are problems that are addressed routinely by a private home owners' association, the Ahwatukee Board of Management, who maintains the channel regularly. Sediment maintenance reported is only required in the upper portion of the channel system, with no maintenance reported downstream of North Ranch Circle Drive. The performance of the engineered drainage system is predicated on the following:

- Periodic sediment removal from the lined channel and basins.
- Regular repair of the concrete channel.
- Occurrence of floods that do not exceed the design frequency.

4. Pima Canyon Fan

4.1 Site Location

Pima Canyon Alluvial Fan is located at the northeast end of the Phoenix South Mountain Park, in T01S R04E Sections 4 and 5. Following the Guadalupe Road alignment the fan apex is located approximately 0.25 miles west of the I-10, near the intersection of Guadalupe Road and 48th Street.

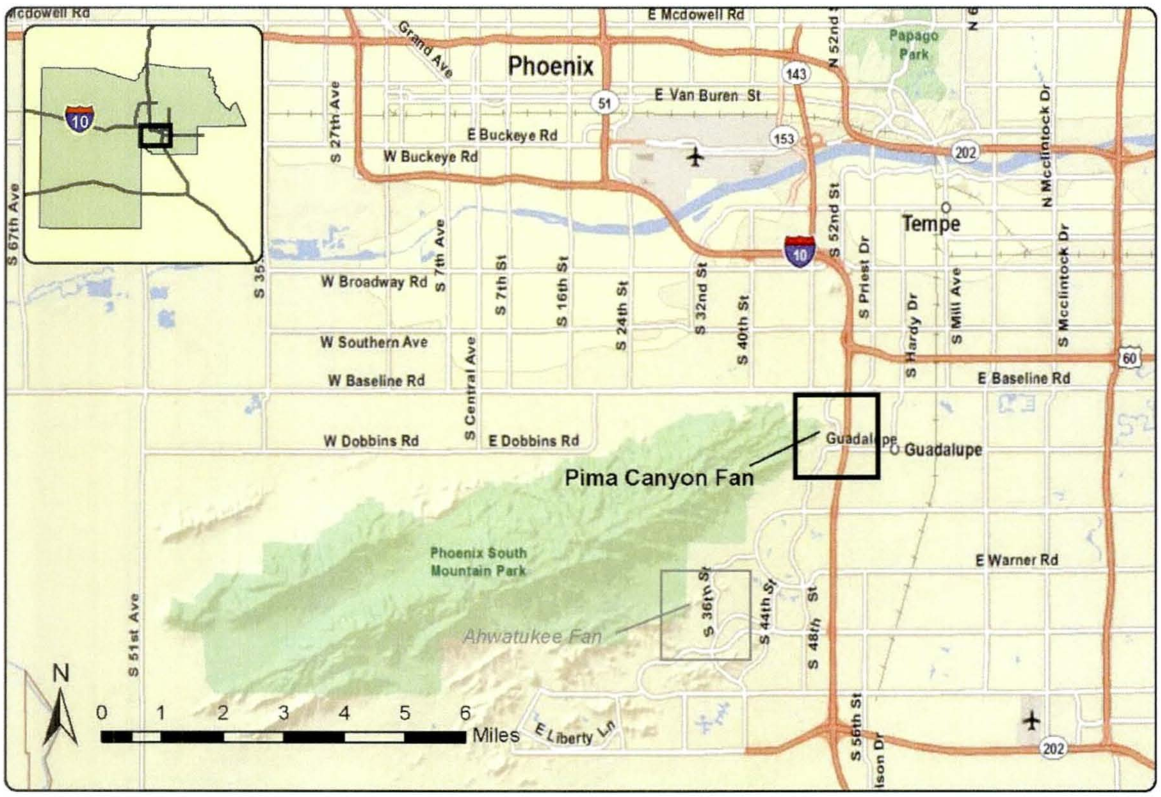


Figure 4-1 Location Map: Pima Canyon Fan.

The Pima Canyon Fan watershed is about 1.5 square miles in area and drains a portion of the northeast flanks of South Mountain. The main watercourse is called Pima Canyon Wash, which flows easterly out of South Mountain in a natural channel until about 2,000 feet upstream of the apex, where the wash crosses the Phoenix South Mountain Park boundary into the Arizona Grand Resort Golf Course and continues downstream. Within the golf course, the natural wash has been modified by grading with some channelization. The watershed within the Phoenix South Mountain Preserve remains undeveloped. The watershed downstream the park boundary is completely developed with golf course greens, homes and road infrastructure.

Although the study area is within the City of Phoenix, the roads, streets, culverts or drainage infrastructure are privately owned and maintained by the Pointe at South Mountain Home Owners' Association.

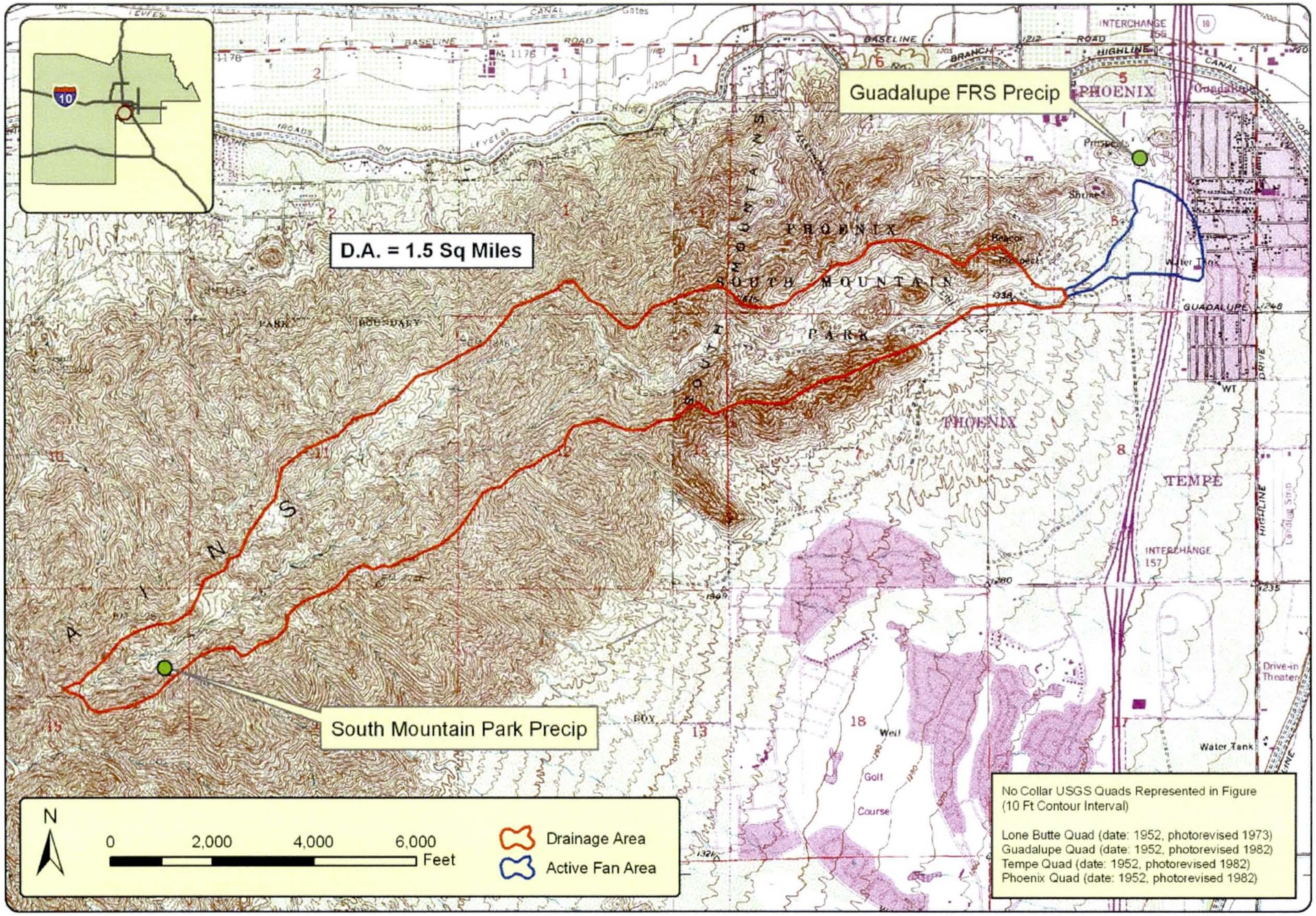


Figure 4-2 Drainage Area: Pima Canyon Wash.

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Figure 4-3 Pima Canyon Fan Before & After Development.

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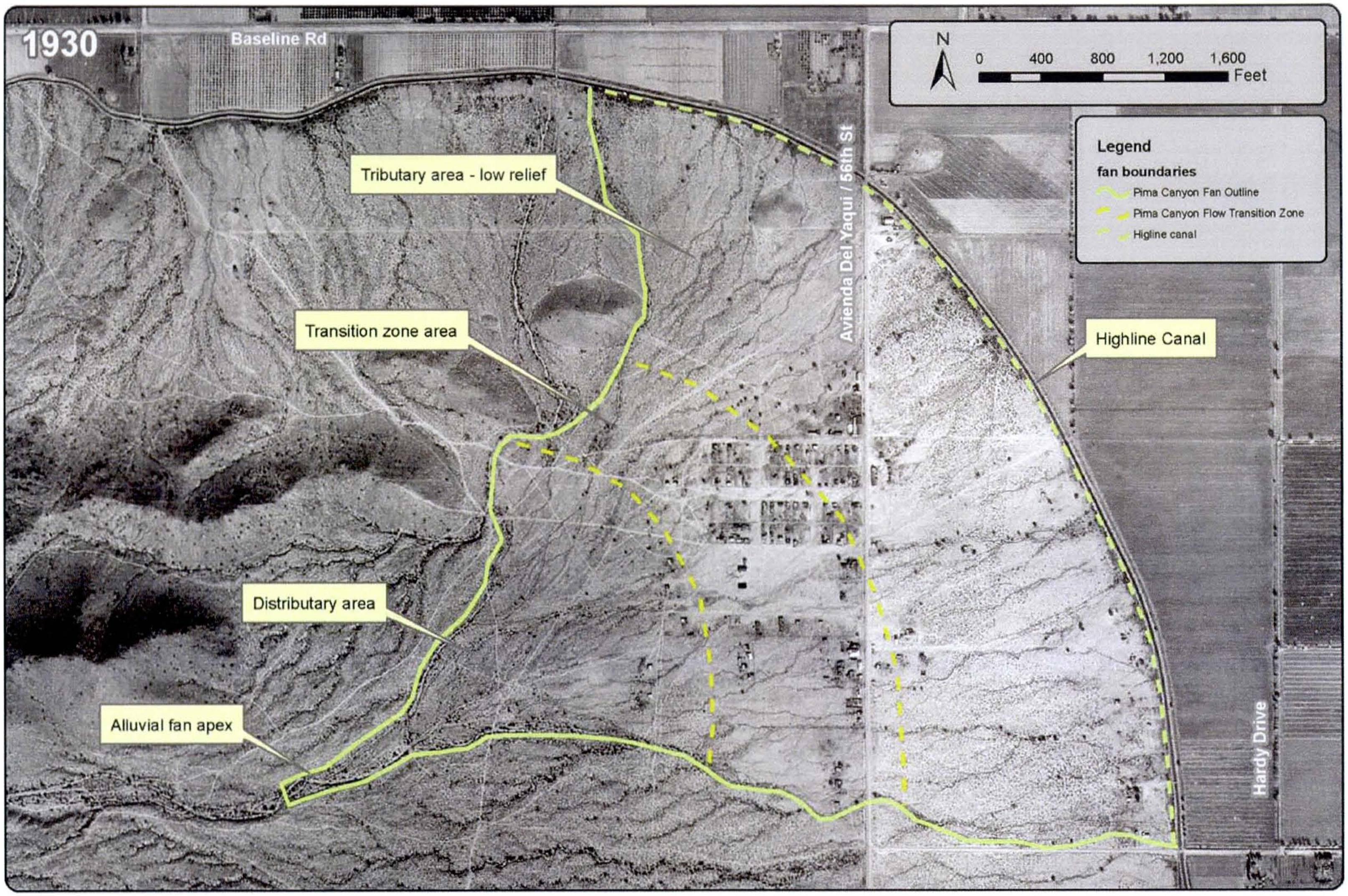

Figure 4-4 Pima Canyon Alluvial Fan Landform.

As seen in Figure 4-4, the apex of the alluvial fan apex in 1930 was approximately at the present 48th Street / Hazel Drive intersection. Historically, Pima Canyon Wash flowed easterly away from South Mountain and was contained within its natural channel until its apex, at which point the wash became distributary. As the flow paths of Pima Canyon Wash split from one another near the apex they become less defined in the downstream direction. Flood water leaving the poorly defined channels continued down fan as sheet flow inundating the Town of Guadalupe with flood water and sediment. This was a continuing problem for the Town of Guadalupe until the Guadalupe FRS (Flood Retarding Structure) was constructed in the mid 1970's.

4.1.1 NRCS Soils

Figure 4-5 presents the NRCS Soil Survey information for the Pima Canyon Fan study area. The source of the soil survey data is the Soil Survey of Eastern Maricopa and Northern Pinal Counties, Arizona (1974). In Figure 4-5 the historically active alluvial fan area was delineated from the 1930 aerial and included as a blue outline on the 2009 aerial photograph background. This was done to provide perspective of where the historical active fan surface was in comparison to modern residential development in the study area. Soil Survey units are labeled individually, and also grouped into the major landform that each unit typically represents.

The entire alluvial fan landform is contained within the Antho soil series, AoB and AnB. The Antho series is typically found on alluvial fans and contains well drained soils with shallow slope between 0 – 3 %. AnB (Antho sandy loam), found at the toe of the fan, is a soil that typically forms on alluvial fans. AoB (Antho gravelly sandy loam), while very similar to AnB, has between 15-35 % gravel by volume and is typically found on the upper portions of alluvial fans.

The linear green soil unit represented at the throat of the fan at the apex is the former location of a gravel pit. Mining on the gravel pit started in the late 1950's and the pit remained a geomorphic feature on the fan until development reclaimed the pit in the early 1980's.

Bordering the Antho series in the northern portion of the study area are Rock Land 'Ro' and Rough Broken Land 'Ru' soil units. Both these units have been shaded brown to represent Mountain Slopes. Rock Land consists of areas that are 50 to 70 percent exposed rock, and is used to describe steep sloping bedrock mountains in the study area. Runoff is typically very rapid and erosion active in these areas. Rough Broken Land is moderately sloping to very steep. This (Ro) unit is often dissected by many intermittent V-shaped drainage channels and separated by irregular narrow ridges.

The Antho series is bordered on the east by the Valencia sandy loam (Va), a well drained soil series on valley plains and alluvial fans, and southwest by the Tremant gravelly loam (TrB), a well drained soil on old alluvial fans and shaded light blue on the map.

4.1.2 Surficial Geology

Figure 4-6 presents the surficial geology for the Pima Canyon Alluvial Fan study area. The source of the geologic survey data is Arizona Geologic Survey (AZGS) Geologic Map of the Mesa 30' X 60' Quadrangle, by Kneale. In Figure 4-6, the historically active alluvial fan area was delineated from the 1930 aerial and included as reference in a blue outline on the 2009 aerial photograph background.

The bedrock unit that lies just to the west and north of the fan are composed of Granodiorite (Tg1). This is the same unit that composes most of the South Mountain Range. Tertiary Granite (Tg) formed in the middle Tertiary Period, sometime between 65 million and 2 million years before the present.

The whole of the Pima Canyon Alluvial Fan landform lies within the Quaternary Young Alluvium (Qy) unit. Qy forms low terrace and alluvial fan deposits. Qy, a Holocene unit (less then 10,000 years old), is the youngest geologic unit in the study area.

The Qy unit of the alluvial fan is bounded by the older Quaternary Middle Alluvium (Qm). Qm is an upper to middle Pleistocene alluvium, and often found on dissected alluvial fan and terraces. The Pleistocene Epoch dates from 1.8 Million to 10,000 years before present.

4.1.3 Topography

Figure 4-7 shows 10-foot contour interval topography of the Pima Canyon alluvial study area from the USGS quadrangle map. Within the traced blue outline of the fan landform one can see topographic contours on the alluvial fan bowing in the downstream direction with the classic extended fan shape.

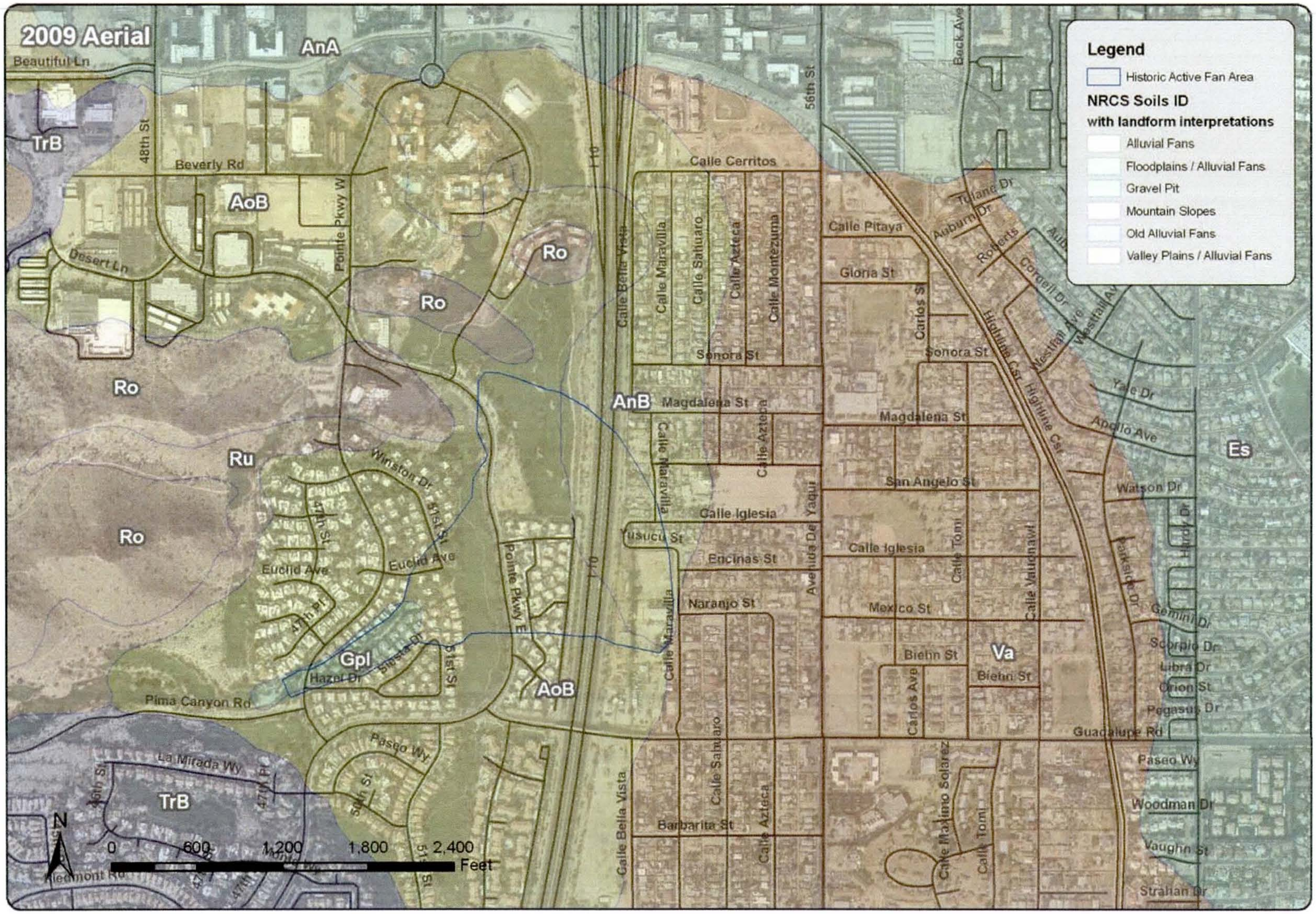

Figure 4-5 NRCS Soils: Pima Canyon Fan.

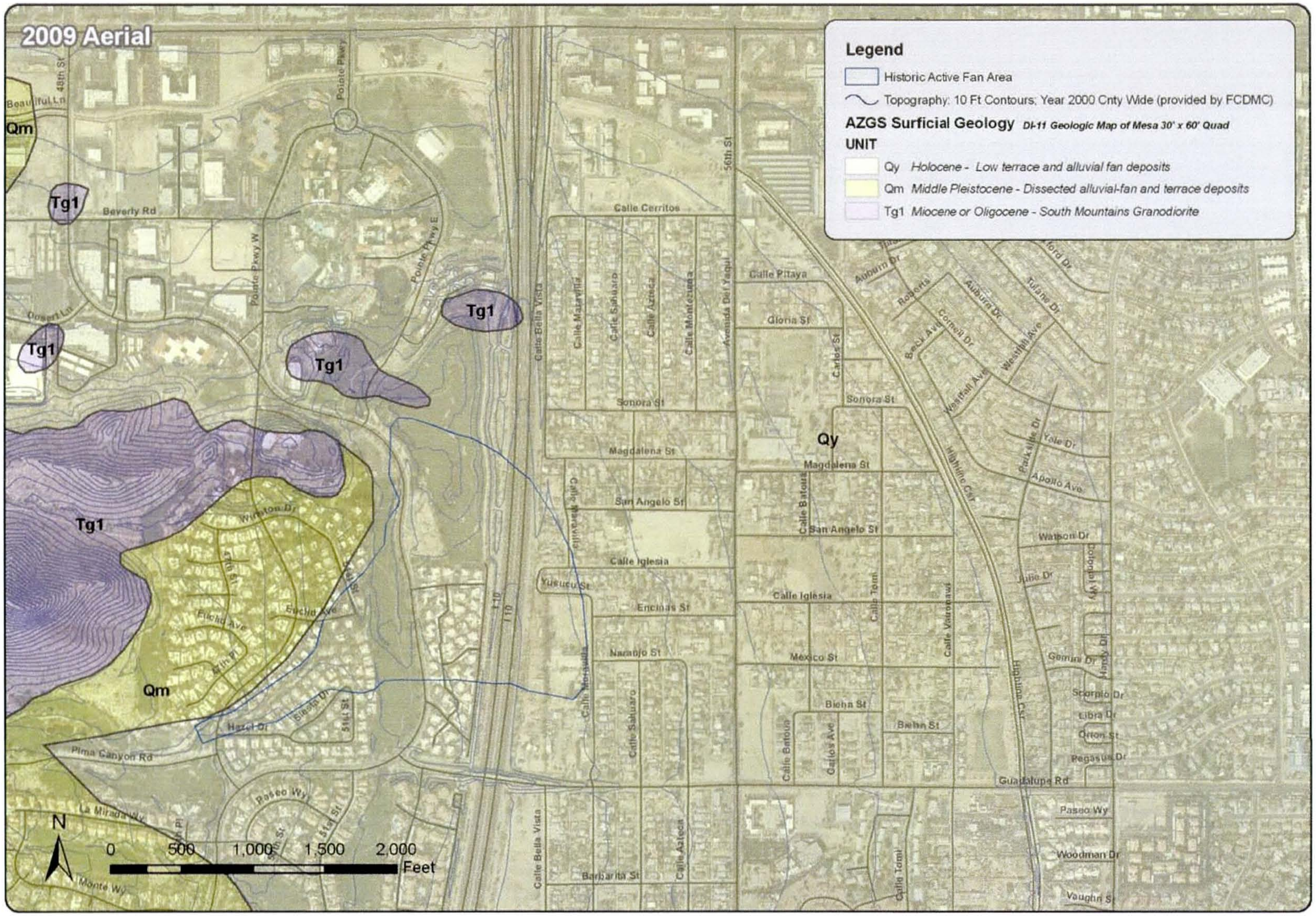

Figure 4-6 AZGS Geology: Pima Canyon Fan.

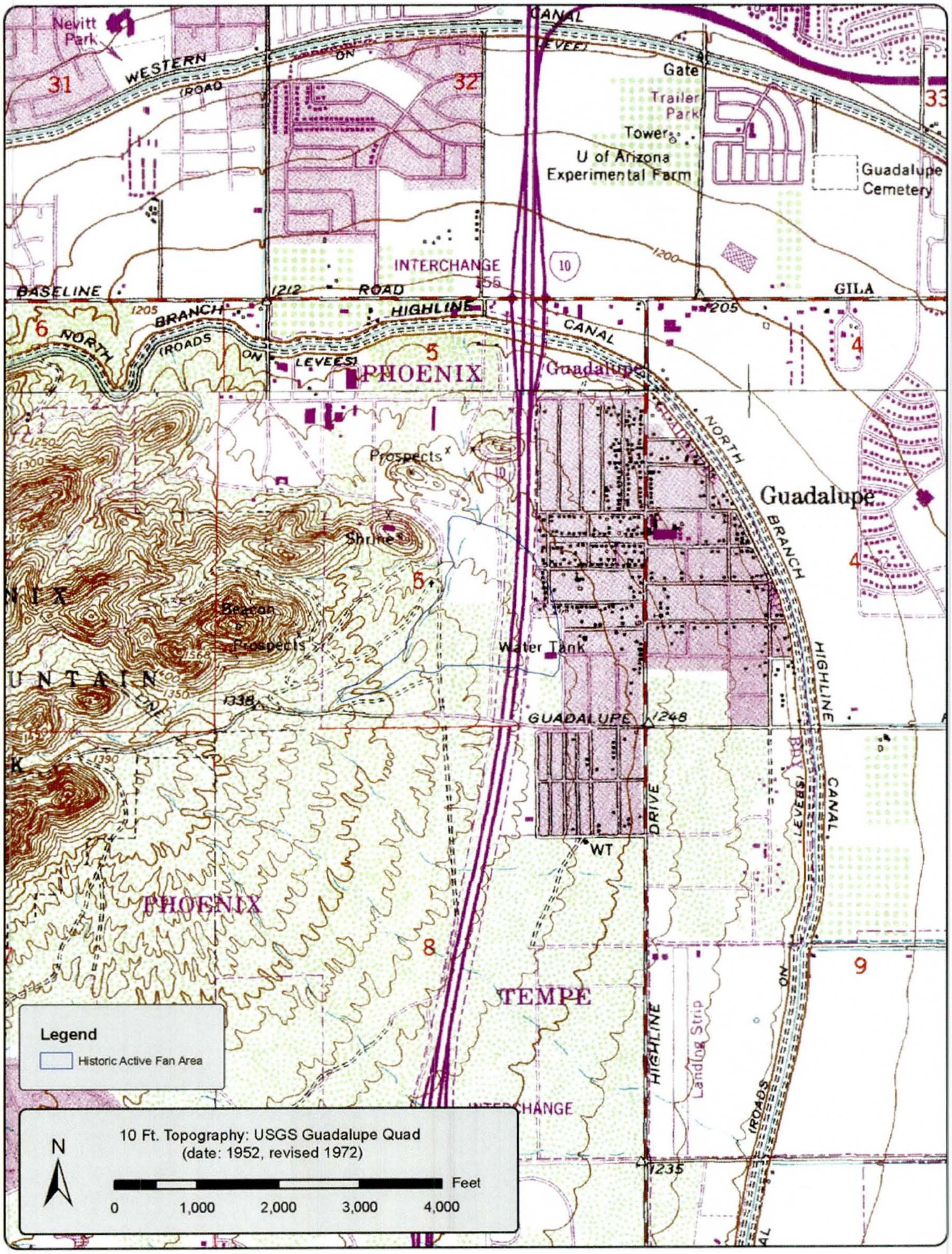

Figure 4-7 Pima Canyon Fan Topographic Mapping.

4.1.4 Watershed and Fan Parameters

The following tables enumerate specific statistics and about both the watershed and fan area. Details are also included about the type and location of engineered structures within the study area.

Item	Value	Source
Watershed area (apex)	1.5 square miles	USGS Quads
Watershed slope Upstream of apex (2.8 to 1.9 miles) Upstream of apex (1.9 to 0.5 miles) Upstream of apex (0.5 miles to apex)	 7.7 % 2.6 % 1.6 %	 USGS Quads USGS Quads USGS Quads
Fan slope (Apex to 0.25 miles downstream)	1.5%	USGS Quads
Q100 at apex	2525 cfs	USGS Water Supply Paper 2433 (D.A. =1.5, Median Elevation = 1800 feet)
Fan Profile Shape	concave	USGS Quads
Max Elevation in Drainage Area	2555 ft	USGS Quads
Elevation at apex	1310 ft	USGS Quads
Minimum Elevation in fan	1210	USGS Quad (at Highline Canal)

Figure 4-8 Watershed and Fan Parameters

Structure	Type / Date	Location
Interstate I-10	Constructed: 1959-1969	Transects fan 2000 feet below the apex
Gravel pit	Dug: 1949-1959	Below apex of fan
Guadalupe Flood Retarding Structure	Constructed: 1969-1979	Immediately west of I-10
Realignment of Pima Wash	Originally designed as grass lined channel, now natural gravel bottom	From apex to 1500 feet below
48th Street / Pima Wash crossing	8' foot CMP culvert	48th St / Pima Canyon Wash, at historical apex location
Development		
Town of Guadalupe	Pre-1930	On fan near the toe
Arizona Grande Resort Golf Course	Late 1980's, early 1990's	Upstream of apex and with-in the basins of the FRS downstream of the apex
Pointe South Mountain Development	Late 1980's to present	Upper portion of the alluvial fan.

Figure 4-9 Structures on Pima Canyon Wash

4.1.5 PFHAM Stage I

Task 2.3.3 requires that the pre-development landform be classified as to the "probable" landform type using the PFHAM Stage 1 categories. A PFHAM Stage 1 landform classification for an alluvial fan consists of the following elements:

- *Composition*. The landform is composed of alluvium (sediment material transported by the streams that formed the landform.
- *Morphology*. The landform has the shape of a fan, either partially or fully extended.
- *Location*. The landform is located at a topographic break where the primary watercourse loses capacity.

The Pima Canyon landform is shown to be composed of alluvium, as shown by the NRCS detailed soils mapping (Figure 4-5) and AZGS surficial geology mapping (Figure 4-6). As shown in Figure 4-7, the landform has the radial contours characteristics of a partially extended fan. The site is located at the topographic break formed where the main wash exits South Mountain Park and the channel changes from a single thread channel to a bifurcated distributary pattern (Figures 4-4 and 4-7). Therefore, the landform is properly classified as an alluvial fan landform.

4.2 Development History

A set of historical and recent aerial photographs are shown on the following pages. On each photograph, the delineation of the active fan area from the 1930 aerial is outlined in blue. This delineation is included as a point of reference because the natural features of the landform become obscured after development occurs in the area. All of the aerial photography was obtained from the FCDMC.

The oldest aerial image of the study area is from 1930. In 1930, Pima Canyon Wash flowed in a northeasterly direction out of South Mountain to the apex of the fan. At the apex of the fan, the primary Pima Wash channel split into roughly three less well defined channels. The first channel flowed north-toward Baseline Road, the second channel northeast toward the Town of Guadalupe and the third channel flowed east. Several break outs can be seen from each of these channels as they extend to the toe of the fan. At these break outs and other locations where the channels lose capacity, flood waters probably extended over the fan as sheet flow. The surface of the fan in 1930 appears to be relatively smooth with minimal lateral relief. This smooth surface characteristic is a distinctive contrast from the tributary incised drainage that can be seen on older fan terraces on both sides of the fan. By 1930, the Town of Guadalupe had roughly 15 homes built within the fan limits. At this time, there were no roads visible. Only a few small paths cross the fan. Interestingly, in 1930 the Baseline Road alignment is already visible as a linear feature in the upper most portion of the photograph.

By 1949, the Town of Guadalupe had approximately 50 homes built within the study area. The three channels that split at the apex are more defined; and the northeast channel has a wider bottom width than it did in 1930. This may be due to a major flood that occurred in 1934 (Guadalupe Watershed Work Plan, p. 10). Also, by 1949, two significant trails cross the fan, one at the toe and another mid-fan.

By 1959, a gravel pit had been dug near the apex, as shown on the NRCS Soil surveys. The Town of Guadalupe continued to expand to both the north and the south. Also visible in 1959, is the El Paso Gas line excavation across the fan. The gas line bisected the fan and the alignment can be seen running almost due north and south in the middle of the photograph.

By 1969, the I-10 had been built across the toe of the fan. The Guadalupe Watershed Workplan 1971 contains an excellent description of how the I-10 construction affected drainage downstream through the Town of Guadalupe. "The…construction of the Highway altered the paths of any flooding that occurred in past yeas so that flooding that will occur in the future will be different from what it has been in the past. The I-10 Highway provides for drainage from water running off of the upper portion of the watershed; however, there are no confined channels below the outlets of the culverts so when water leaves the end of the culvert it will again spread out to a fan flood condition" (Guadalupe Watershed Workplan, p. 52). Large storms on both September 14 and 16, 1969 also caused extensive flooding in Guadalupe, damaging homes, businesses, canals, and ditches, inundating crops, and damaging railroads and industrial property (Guadalupe Watershed Workplan, p. 12). The Guadalupe FRS (Flood Retarding Structure) was built in the early 1970's to help prevent future floods from devastating Guadalupe. The FRS was built on a north-south alignment along the west side of I-10. The Guadalupe FRS is clearly visible in the 1979 aerial photography.

By the early 1980's, the first residential development west of the I-10 was built and 48th Street was constructed across the fan near the apex. The gravel pit had been reclaimed with fill and Pima Wash had been realigned to preferentially follow only one of its historical flow paths. A large 8-foot circular corrugated metal culvert was placed under 48th Street to convey the wash. Pima Canyon Wash had been channelized as a grass-lined wash that conveyed runoff to the lower portions of the fan. About 600 feet downstream from the 48th Street crossing, a drop structure had been installed in the channel. The grass lined channel was constructed as far downstream as the El Paso gas line alignment. In addition, most of the alluvial fan landform had been extensively graded, with the construction of I-10, the Guadalupe FRS, realignment of Pima Wash, construction of 48th Street and the residential subdivision. By 1986, only a small portion of natural fan landform surface is visible.

In 1989 the Arizona Grand Resort Golf Course was built on the fan. Fairways were located in the vacant flood pool areas of the Guadalupe FRS and upstream of the apex of Pima Canyon Wash, both in and alongside the wash.

By the early 1990's both the golf course and the residential development on the alluvial fan were complete. No major development has taken place on the Pima Canyon alluvial fan landform since the mid 1990's. Pima Wash was engineered as a grass-lined channel up to the El Paso Gas pipeline alignment, at which point it empties completely into Fairway 6 of the Arizona Grand Resort Golf Course. Fairway 6 is located in the first of two large detention basins that are part of the Guadalupe FRS. Water then flows down Fairway 6 to Fairway 5, crosses under South Pointe Parkway in a large box culvert which also serves as a Golf Cart tunnel, and finally empties into the main FRS basin.

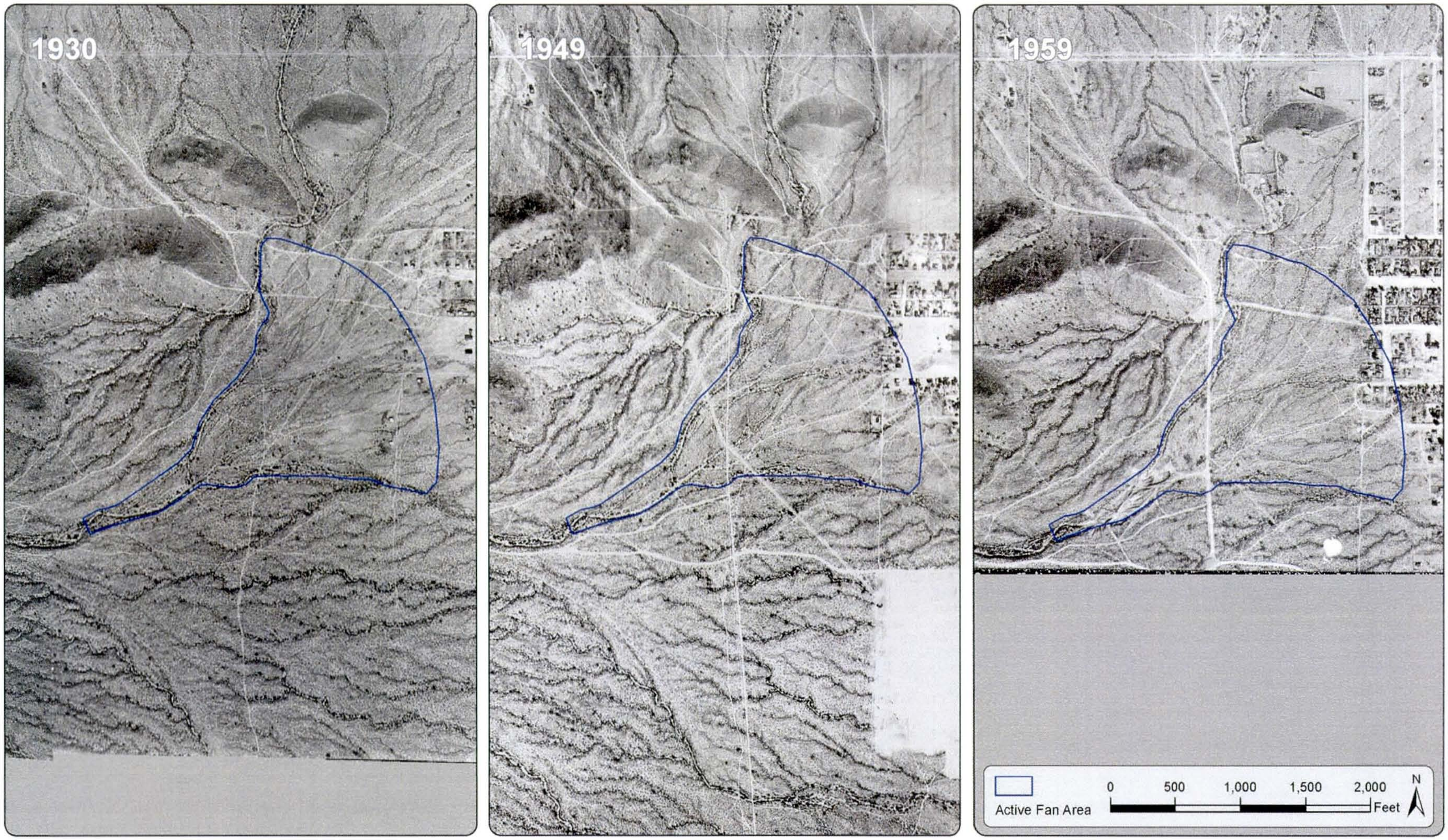

Figure 4-10 Historical Aerial Photos: Pima Canyon 1930 – 1959.

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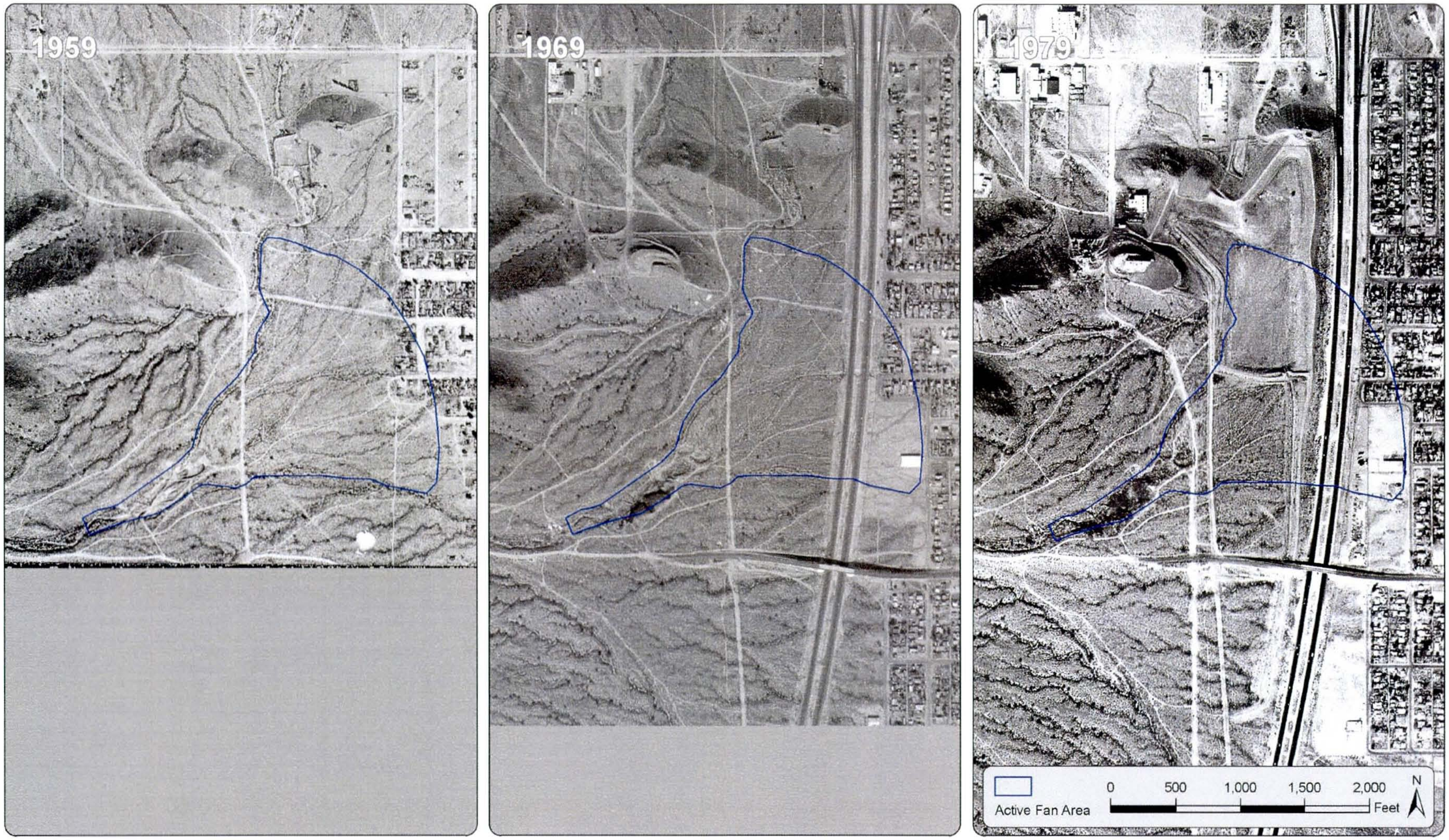

Figure 4-11 Historical Aerial Photos: Pima Canyon 1959 – 1979.

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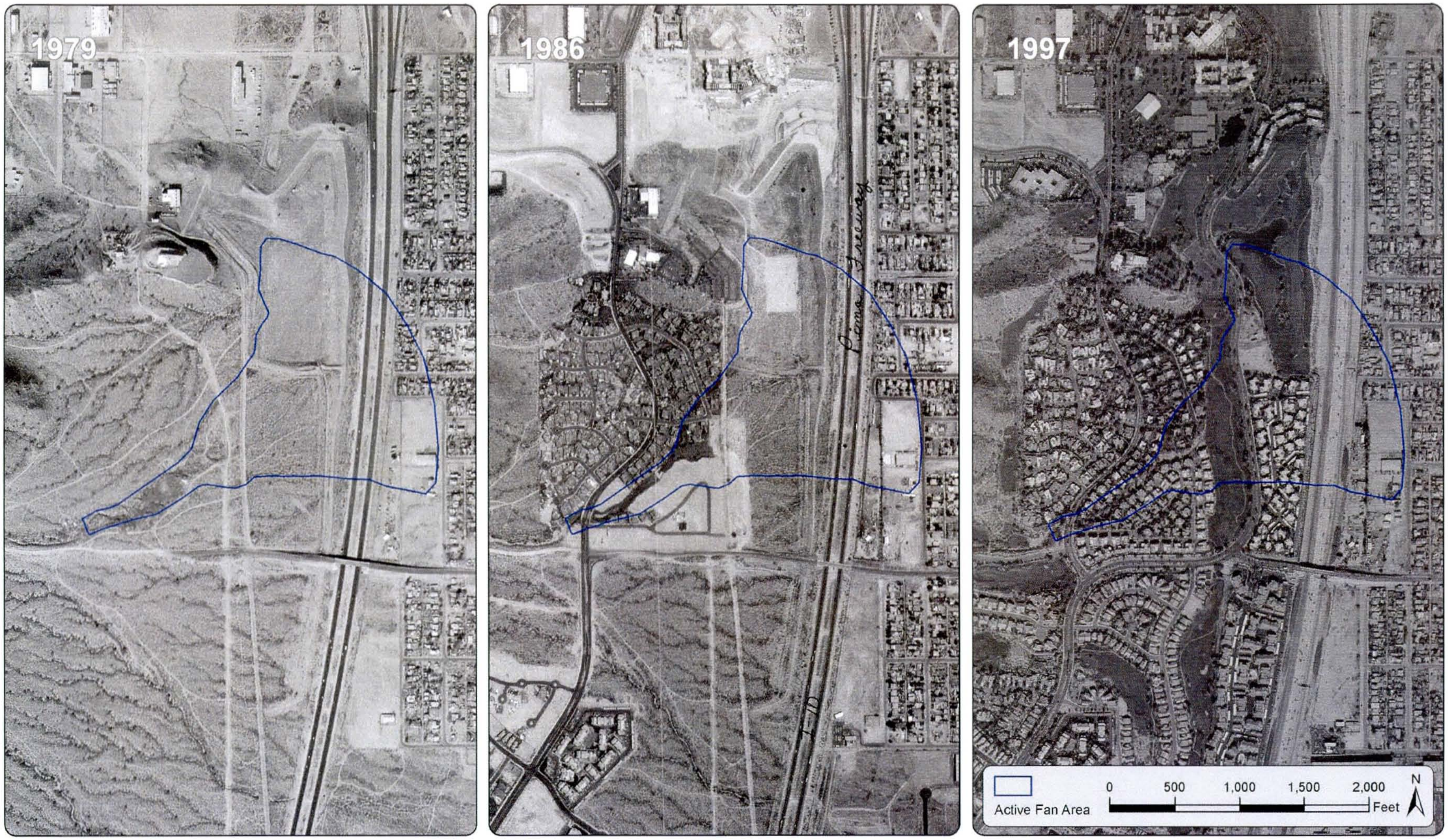

Figure 4-12 Historical Aerial Photos: Pima Canyon 1979 – 1997.

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Figure 4-13 Historical Aerial Photos: Pima Canyon 1997 – 2009.

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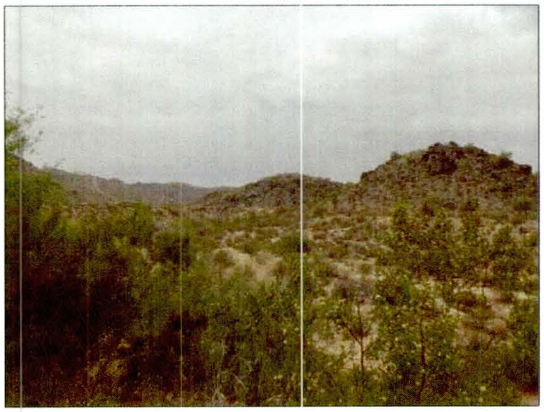
4.2.1 Photograph locations and areas of interest

The figure below is a reference key which includes the location of each field photo. Channel alignments, boundary, streets and major engineered structures within the study area also labeled below.

Figure 4-14 Pima Canyon Photo & Structure Locations.



1. Upper Watershed
View looking west into Phoenix South Mountain Preserve

2. South Mountain preserve boundary
View looking across Pima Canyon Wash as it enters Golf Course

3. Looking Downstream at Fairway #14
Pima Wash at Arizona Grande Resort Golf Course

4. Looking Downstream at Fairway #13
Pima Wash at Arizona Grande Resort Golf Course

5. Foot Bridge
Scour below dashed black line

6. Looking Downstream
Pima Wash at Arizona Grande Resort Fairway #13

7. Erosion at Fairway #13
Pima Wash erosion during July 13,2008

8. Looking Upstream at 48th St. crossing
Pima Wash at Arizona Grande Resort Golf Course

9. Looking Downstream
Pima Wash at Arizona Grande Resort Golf Course

10 Downstream side of 48th St. crossing
Pima Wash at Arizona Grande Resort Fairway #13

11. Design condition was grass lined channel
Looking downstream, Pointe South Mountain HOA

12. Looking Downstream at channel
Pointe South Mountain HOA

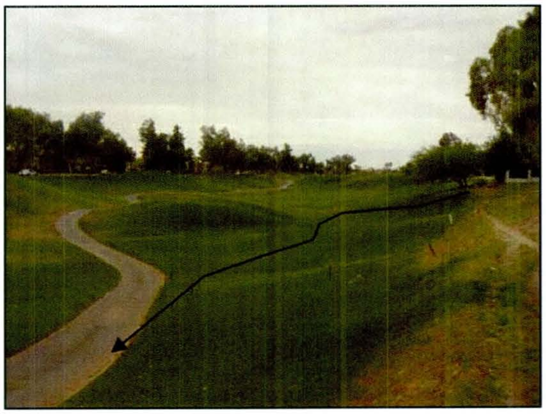
13. Looking Downstream
Grade control structure

14. Looking Upstream
Grade control structure

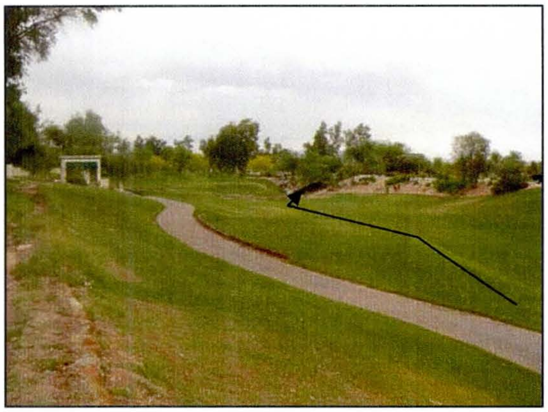
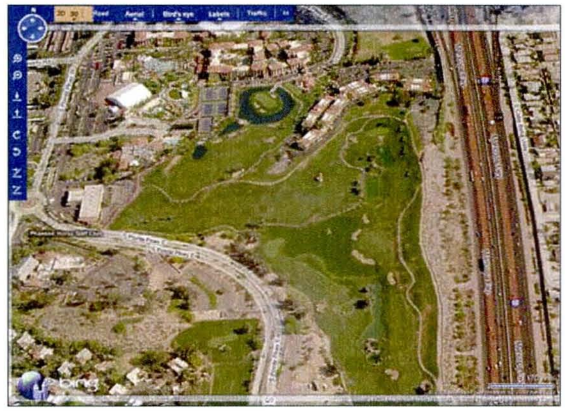
15. Looking at left bank of channel
Pointe South Mountain Home Owner's Association

16. Looking at right bank of channel
Pointe South Mountain Home Owner's Association

17. Looking at outflow of channel onto fairway # 6
Pointe South Mountain Home Owners' Association



18. Looking upstream, fairway #6, retention basin 1
Arizona Grande Resort Golf Course

	
19. Looking downstream, fairway #6, retention basin 1	20. Aerial view of FRS and final retention basin *(Source: bing.com)*

4.3 Hydrology

Modern development on and interaction with the Pima Canyon alluvial fan extends further back in history than any of the other three historical review sites. Aerial photograph records extend back to 1930. References in the literature to historical floods on the fan date back as far as 1934. The Guadalupe Watershed Workplan (p. 10) refers to major floods in 1934, 1952, 1965 and 1969.

The first FCDMC Rain / Stage gage was installed on the Guadalupe FRS in June 1989, and has been in continuous operation since that time. Since 1989 the average rainfall per year has been 6.34 inches per year, with the wettest year on record being 2008 with 11.34 inches of rainfall reported. The largest storms to occur in the project area since the gage was installed in 1989 have been:

- 307 year storm: 2.28 inches in 1 hour on 07-13-2008
- 18 year storm: 2.48 inches in 24 hours on 11-15-1993

The July 13, 2008 storm was the largest event in recorded history in the project area. The following statistics about the storm were provided by the FCDMC.

- 2.28 inches was measured at the Guadalupe FRS rain gage in one hour.
- The storm was greater than a 307-year storm point rainfall using NOAA Atlas 14.
- The average rainfall over the Guadalupe FRS watershed was 1.69 inches (using locally adjusted NEXRAD radar data).
- Two FCDMC observer network gages in the area recorded 3.75" and 2.98" for the storm.
- Estimated total runoff volume from the storm contained in the FRS was 30 acre-feet.
- The majority of the rain fell on the developed portion of the watershed.
- Peak discharge flow rates at the 48^{th} St. / Pima wash crossing were estimated to be between 200-300 cfs. (Estimates were made from high water marks in the natural portion of the watershed.)
- Inflow to the FRS is estimated to have averaged 1000 cfs during the most intense portion of the storm.

4.4 Flood Mitigation Measures

As mentioned above, an engineered drainage system was built on the fan that alters the natural alluvial fan landform geomorphology and drainage pattern. None of the structures referenced below are located upstream of the fan apex, although there are some undersized drainage crossings located within the golf course upstream of the historical apex. The drainage system consists entirely of constructed channels from the apex to the large basins that comprise the Guadalupe FRS, which is located near the toe of the fan. There is one principal outlet for the FRS that, when opened, releases water into a pipe that carries it north to the Highline Canal.

About half a mile upstream of the historical fan apex, Pima Canyon Wash exits the Phoenix South Mountain Park. At this point, the wash flows between and on the greens and fairways of the Arizona Grand Resort Golf Course. The historical course of the wash disappears in many places as the fairways have been designed in the wash bottom and in the surrounding floodplain. The wash continues east within the golf course fairways until it reaches the 48th Street crossing. The wash then passes underneath 48th Street in a large 8-foot corrugated metal pipe. Historically, in this area the wash had freedom to flow down several divergent flow paths from this point. Today, Pima Canyon Wash has been channelized down one of the historical flow path alignments. Levees and/ or fill have been placed around the channel to limit it from seeking its historical channels.

The section of Pima Canyon Wash from the 48th Street culvert to the golf course was designed to be a grass-lined channel. Today, it is no longer grass-lined, but rather has a sandy gravelly bed with weakly vegetated to un-vegetated side slopes. No documentation or anecdotal evidence was found indicating the reason for the change in channel condition. In many cases vertical retaining walls that bound residential yards or serve as structure foundations comprise the wash bank. Interestingly, the northern historical channel of the fan remains preserved in the present day topography but is cut off from channel flow by a levee and is severed by subdivision roads with no designed drainage crossings.

Approximately 600 feet downstream of the 48th Street crossing is a grade control structure. Built across the wash in the early 1980's, this drop structure is level with the wash bottom on the upstream side, then drops vertically two feet on the downstream side, effectively creating a stair step in the channel profile. Pima Wash continues downstream of the grade control structure for another 500 feet before it outfalls into a fairway of the Arizona Grand Resort Golf Course. There is a 16 foot, steeply sloped drop from the channel to the fairway as the wash empties out onto the fairway. The historical alignment of the

El-Paso gas line lies immediately upstream of the 16 foot drop. While no design drawings were available it is presumed that the wash was kept at grade until it crossed the gas-line alignment and was then allowed to empty out into the first designed basin of the Guadalupe FRS. There is no evidence of any grade control or erosion protection at the outfall onto the fairway. Once on the fairway the historical wash disappears as all the flow is then routed to the Guadalupe FRS embankment via the grassy golf course fairways.

During the July 13, 2008 storm the FCDMC recorded a peak stage impoundment at the Guadalupe FRS at 9.41 ft (Gage Height), with a peak volume of 36 acre-feet. The FCDMC did the post-flood clean up of the principal spillway / principal outlet after the storm. Approximately 1 CY of sand was removed. The minor amount of sediment debris at the outlet was probably caused by all the sediment deposited upstream in the lowest elevations of the final retention pond area. The golf course maintenance crews, who did the final clean up of the FRS retention area, estimated that as much as 240 cubic yards of sediment and debris were hauled away as a result of the July 13, 2008 impoundment event.

Upstream of the apex, during the same July 13, 2008 event, a series stair step headcuts moved upstream of 48th Street. These headcuts have been progressing upstream yearly during the largest storms of each rainy season. Sediment eroded from the headcuts was deposited in a series of bars immediately downstream. A large amount of sediment was deposited in the 48th Street culvert and the channel downstream of 48th Street during the event. Approximately 12-18 inches of sediment was deposited in the culvert, which had to be removed by a front-end loader to restore clearance for the horse path through the structure. Sediment from the 2008 event can be seen in bars and bed load deposits that dropped out downstream of the 48th Street crossing. The bed load deposited during this event decreases in size downstream from the 48th Street crossing to where the wash empties out onto the golf course.

Sedimentation is also an issue elsewhere on the fan. The residential developments in the area, including Pointe at South Mountain, which is located on historical fan surface, were designed primarily with underground storm drains. This infrastructure, according to a representative from Pointe South Mountain Home Owners' Association, was built undersized, quickly became plugged with sediment and is very difficult to clean out. The residential development in the area was also not designed to retain any water onsite. It was designed to convey 100 percent of the flow downstream. Note that this problem area is no longer hydraulically connected to the upper watershed of the alluvial fan.

The July 13, 2008 storm did flood several homes near the study area. These homes were not flooded by waters from Pima Canyon Wash, but rather by a parallel drainage directly to the south, known locally as Mulligan Wash. Flooding did occur and may have resulted from any of a number of factors including: clogged storm drains, overgrown drainage channels, poorly designed subdivision drainage, and the largest rainfall event on record.

4.4.1 Maintenance Needed

As the wash enters the golf course green and fairways it routinely drops some sediment on the grass and golf-cart paths. The cart paths are routinely cleared of sediment after any sizable storm event but the sediment on the greens and fairways, while occasionally raked and removed, is typically claimed by the quick growing Bermuda grass. This process of entrapping sediment in the growing grass has effectively raised the bed of Pima Wash in several places by as much as 12" where the bed of the wash is in the fairway itself. Also, the 48th St. wash crossing occasionally needs to be cleared of sediment.

4.5 Conclusions

Prior to residential development in the late 1980's, the Pima Wash alluvial fan had a large active area downstream of the apex, although it is likely that a significant portion of the lower fan surface was subject only to shallow sheet flooding. Flooding from the fan did cause damage to the nearby Town of Guadalupe. Development of the fan surface occurred as part of a master planned community, which was based in part on a regional-scale, privately funded drainage master plan. The engineered drainage master plan for the alluvial fan included earthen channels that extended from upstream of the apex to a golf course located within the impoundment of a regional FRS (dam) near the toe of the fan.

Since the development was completed in the mid 1990's the system has been tested by at least one very large magnitude storm. Estimated to be in excess of a 350 year storm (on the fan surface – the frequency was much less in the upper watershed above the apex), this event sent a record amount of floodwater and sediment down the Pima Canyon Wash. While record rainfalls were recorded, actual flood damage on fan was minimal and consisted primarily of sediment deposition that required removal. Both sedimentation and erosion in the channel and around the golf course occurred during the flood, and are likely to continue to occur in the future. However, there no record of a significant flood at or upstream of the fan apex during the 20 year period of record.

Based on our analysis, we conclude that the engineered drainage system has performed adequately during the 20 year period of record, at least with respect to controlling the flow uncertainty and sedimentation associated with active alluvial fans. No homes or structures on or around the formerly active portions of the fan have been flooded in the past 20 years. There is no record that the earthen channel overtopped or significantly eroded its banks. The sediment deposition that occurs during floods and rare flows from Pima Wash appears to be adequately handled by the private HOA and golf course maintenance crews. The performance of the engineered drainage system is predicated on the following:

- Periodic sediment removal from the channel and basins.
- Occurrence of floods that do not exceed the design frequency

5. Reata Wash Fan

5.1 Site Location

5.1.1 Location Map

The Reata Pass Fan site is located in northeast Scottsdale, Arizona within Sections, 16, 17, 19, and 20 of T4N R5E. The Reata Pass Fan is located along the western flank of the McDowell Mountains, approximately 3 miles northeast of the 101-Pima Freeway Curve. Since the Reata Pass alluvial fan landform is large, this historical analysis focuses on the upper portion of the landform from the apex near the intersection of Pinnacle Peak Road and Church Road to the Thompson Peak Parkway alignment.

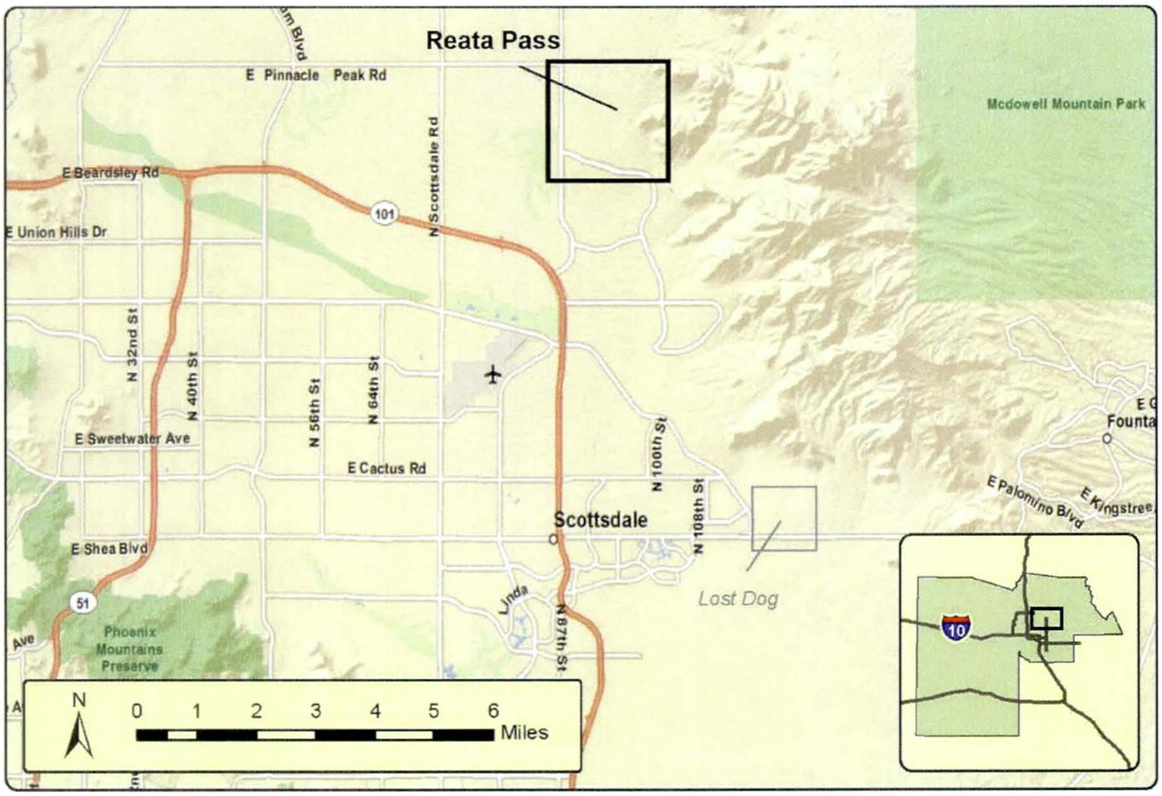


Figure 5-1 Location Map: Reata Pass Fan.

The Reata Pass Fan watershed area is approximately 8.0 square miles in area directly above the hydrographic apex,[2] and drains portions of the northern and western flanks of the McDowell Mountains, as well as the surrounding piedmont. The watershed includes steep mountain slopes, which are not

[2] Additional mountain drainage areas contribute below the primary hydrographic apex.

developed and gently sloping piedmont areas which are mostly developed with residential homes and golf courses. The upper half of the study area flows through the Pinnacle Peak Heights and Pinnacle Peak Vistas I and III subdivisions. The lower portion of the study area is occupied by the DC Ranch master planned community.

As seen in Figure 5-3 the primary hydrographic apex of Reata Pass alluvial fan is just south of the intersection of Pinnacle Peak Road and Via Ventosa. At the apex, flow splits in two main directions: (1) to the south, which is referred to as Reata Wash, and (2) to the southwest, which is locally referred to as Dobson Wash. Reata Pass Fan historically has been and still is an active alluvial fan, with significant sediment deposition and transport on the fan surface.

5.1.2 NRCS Soils Mapping

Figure 5-6 presents the soil survey information for the Reata Pass Fan study area. The source of the soil survey data is the NRCS Soil Survey of Aguila-Carefree Area, Parts of Maricopa and Pinal Counties, Arizona. In Figure 5-6, the lateral extents of the fan are delineated and included as a blue overlay on the 2009 aerial photograph background. This was done to provide perspective of where the historical lateral extent of the fan surface was in comparison to modern residential development in the area. Soil survey units are labeled individually in the figure but also grouped into major landform types.

The fan surface from the apex to Thompson Peak Parkway consists of four soil units. The apex, Reata Wash and Dobson Wash are composed of unit No. 8 (Arizo cobbly sandy loam). Arizo is "characterized by excessively drained soils on floodplains… [ ]. ..Runoff is slow, and the hazard of water erosion is severe…. [also] the riparian habitat in some areas of the Arizo unit is extremely important to wildlife" (Aguila-Carefree Soil Survey, p.16).

Downstream of the southwest branch, known as Dobson wash, is soil unit No. 6 (Anthony-Arizo complex), which is found on floodplains and drainageways. Between the Arizo (8) on the east and the Anthony-Arizo complex (6) on the west is the Tres Hermanos-Anthony complex (121). This soil unit is found on fan terraces, stream terraces, and their associated floodplains. Runoff is slow in this area and hazard of water erosion is slight. Downstream of the Anthony-Arizo Complex (6) is the Momoli gravelly sandy loam (90), which is also a deep well drained soil on fan terraces. Runoff is slow and the hazard of water erosion is slight.

Bordering the fan on the east are several rock outcrop soil units (31) which are part of the McDowell Mountains. On both the east and the west are other fan terrace soil units.

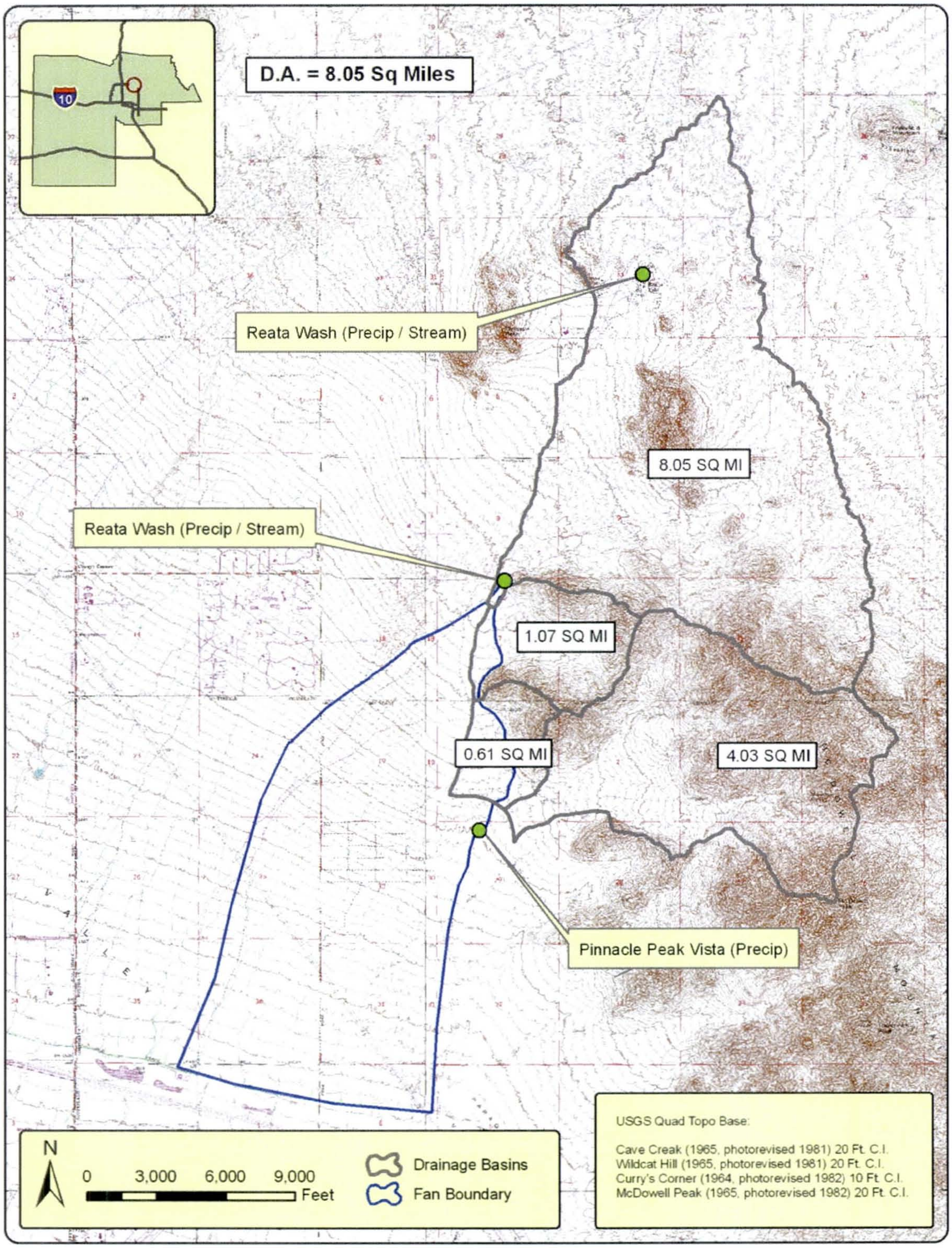


Figure 5-2 Reata Pass Fan Drainage Area & Gage Locations.

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Figure 5-3 Reata Pass Fan Before & After Development.

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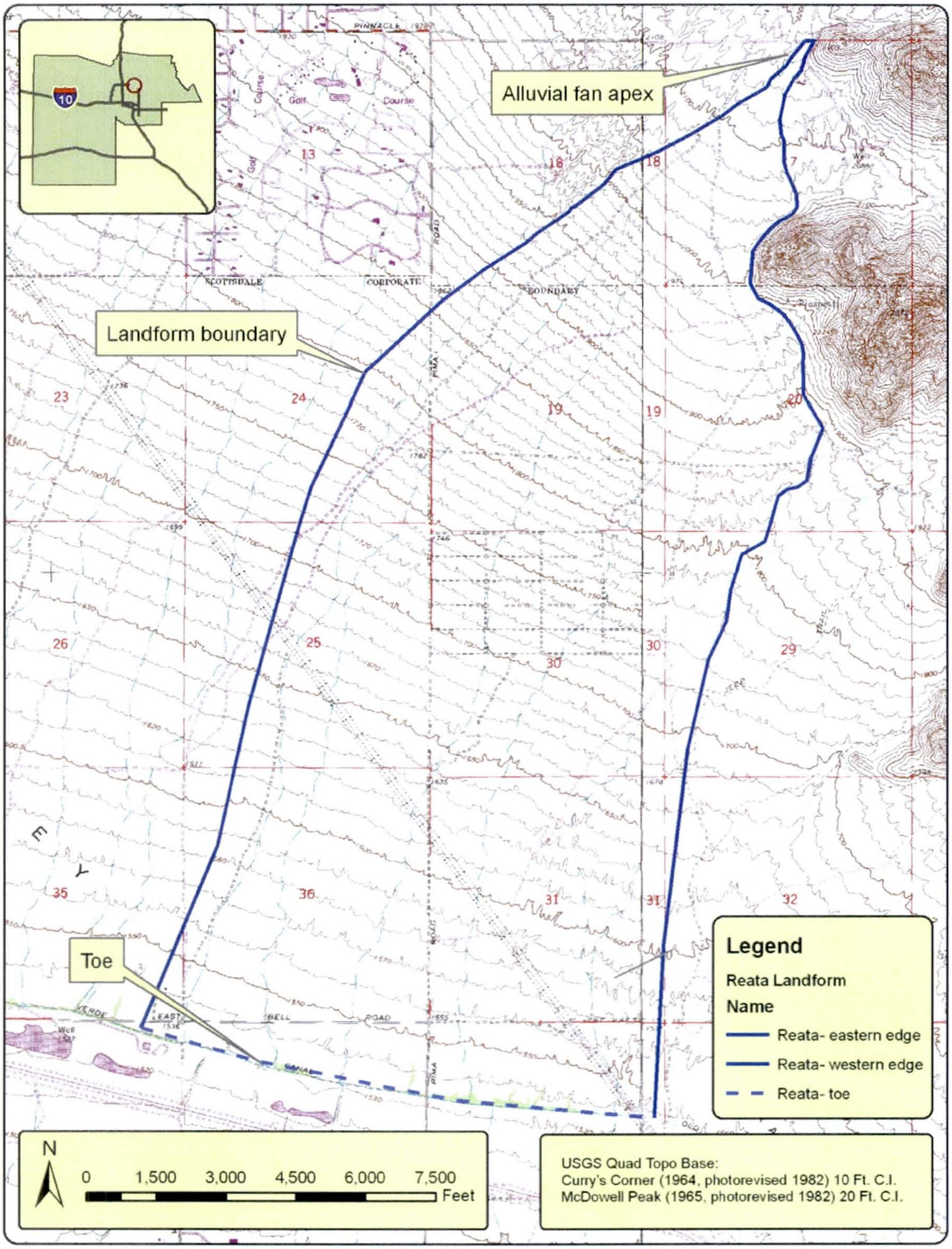

Figure 5-4 Reata Pass Fan Landform Boundary (whole fan).

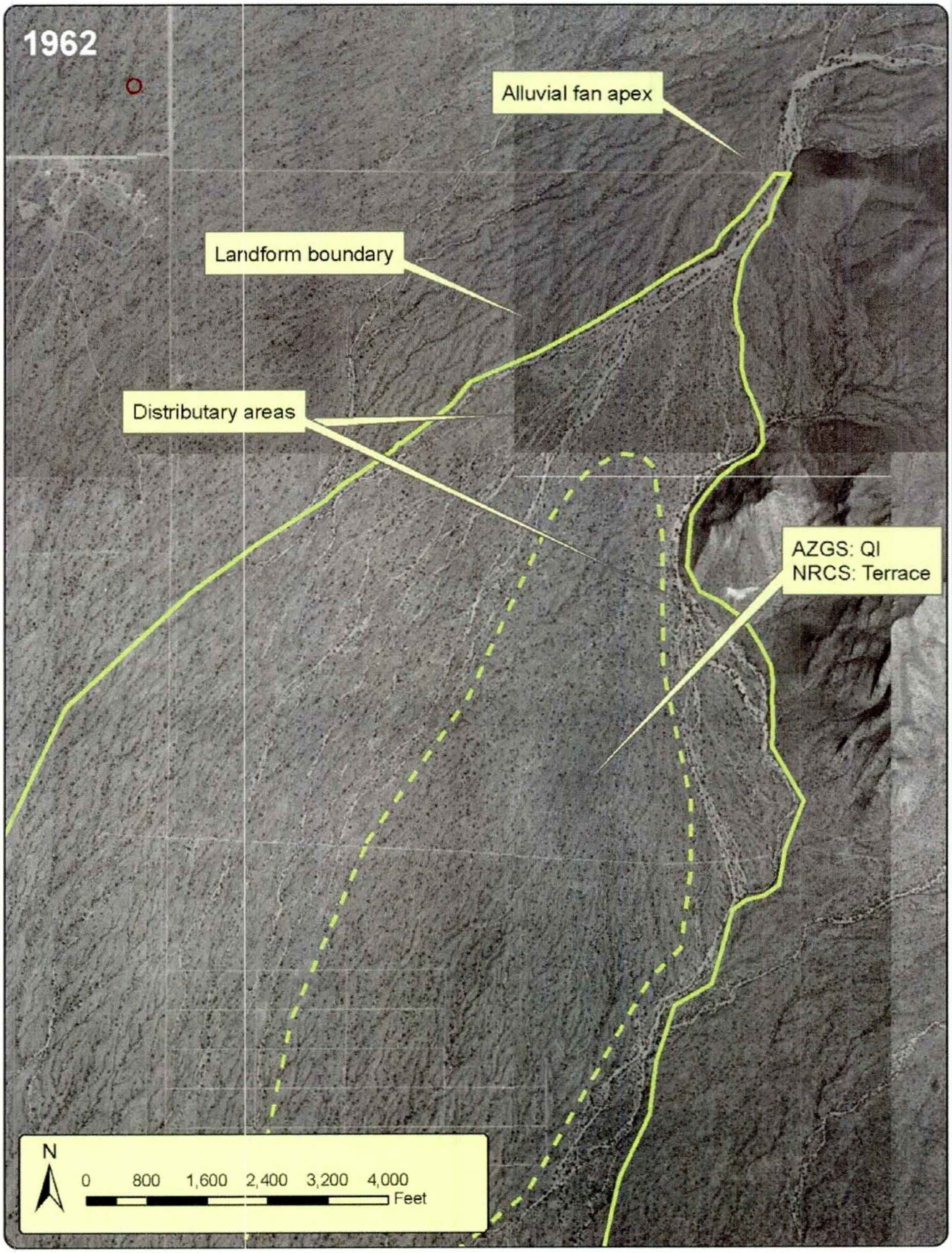

Figure 5-5 Reata Pass Fan Landform Boundary.

5.1.3 AZGS Surficial Geology

Figure 5-7 presents surficial geology mapping for the Reata Fan study area from the AZGS geologic map of portions of the Theodore Roosevelt Lake 30' x 60' Quadrangle, Richard and Spencer, 1998. The lateral extents of the historical alluvial fan area have been delineated from the 1962 aerial and included as a blue outline on the 2009 aerial background.

The bedrock units of the McDowells that lay to the east of the alluvial fan are composed of early Proterozoic Quartzite (Xsq). The three geologic units that compose the fan itself are: Qy, Qm and Ql.

Approximately half the study area is composed of the Qy unit. Qy (Quaternary Young Alluvium) forms low terraces and alluvial fan deposits. Qy, a Holocene unit (less than 10,000 years old) is the youngest geologic unit in the study area. Qy covers all the highly visible drainage pathways on the alluvial fan surface.

Portions of the fan that are not Qy are composed of Qm or Ql. Both of the units are Pleistocene in age: (Ql) late Pleistocene and (Qm) middle Pleistocene. These units are typically found on moderately dissected to dissected portions of alluvial fans and fan terraces. The oldest Quaternary unit found in the study area lies just to the west of the apex. This unit Qmo, middle to early Pleistocene in age, is found on older, heavily dissected fan terraces, evident by the heavily crenulated topographic contours in that area.

5.1.4 Topography

Figure 5-8 shows the topography for Reata Pass alluvial fan from 7.5 minute USGS quadrangle maps. As demonstrated in the topography and enumerated in the table below, Reata Pass fan has the steepest fan surface gradient of the four historical fan sites studied.

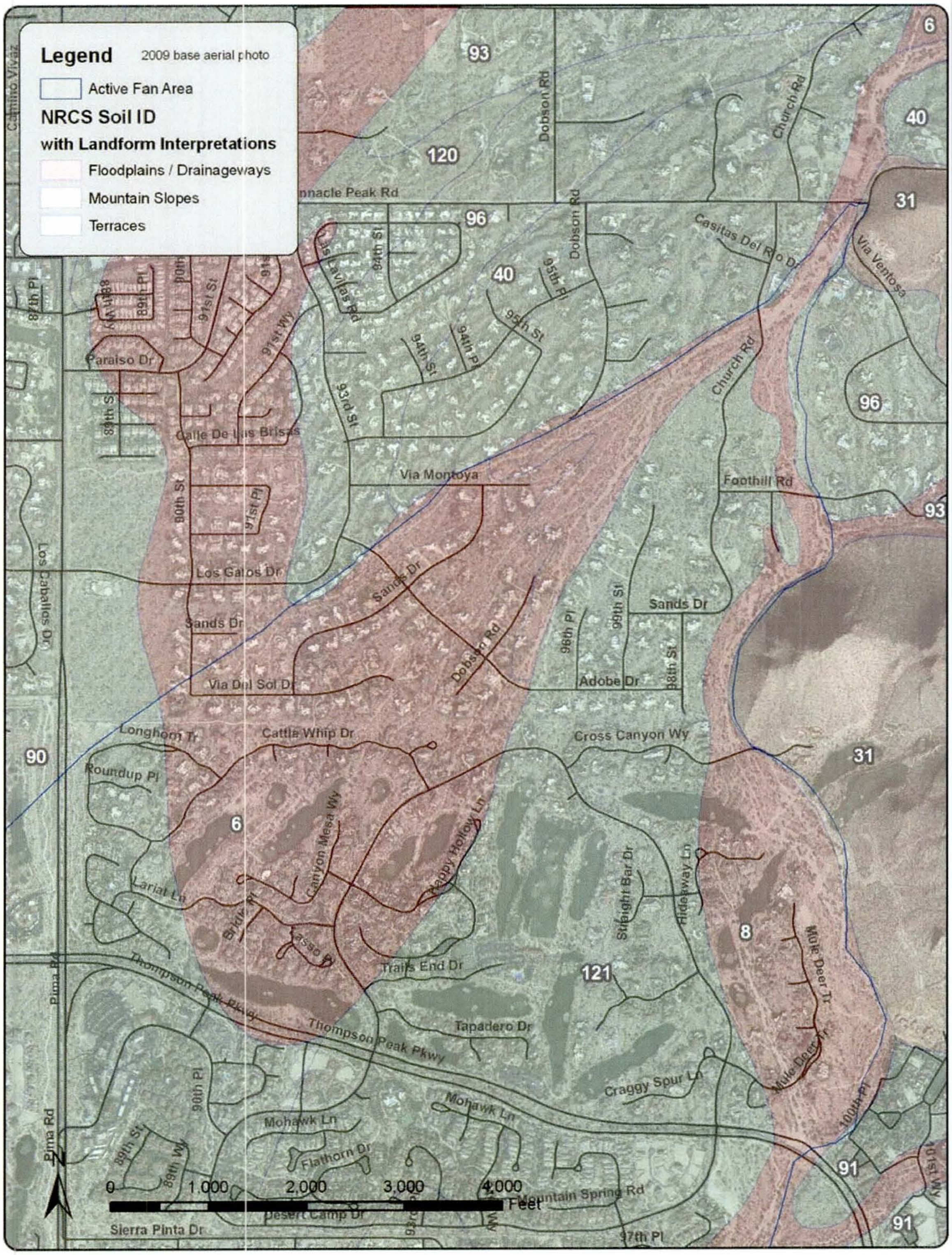

Figure 5-6 NRCS Soils: Reata Pass Fan.

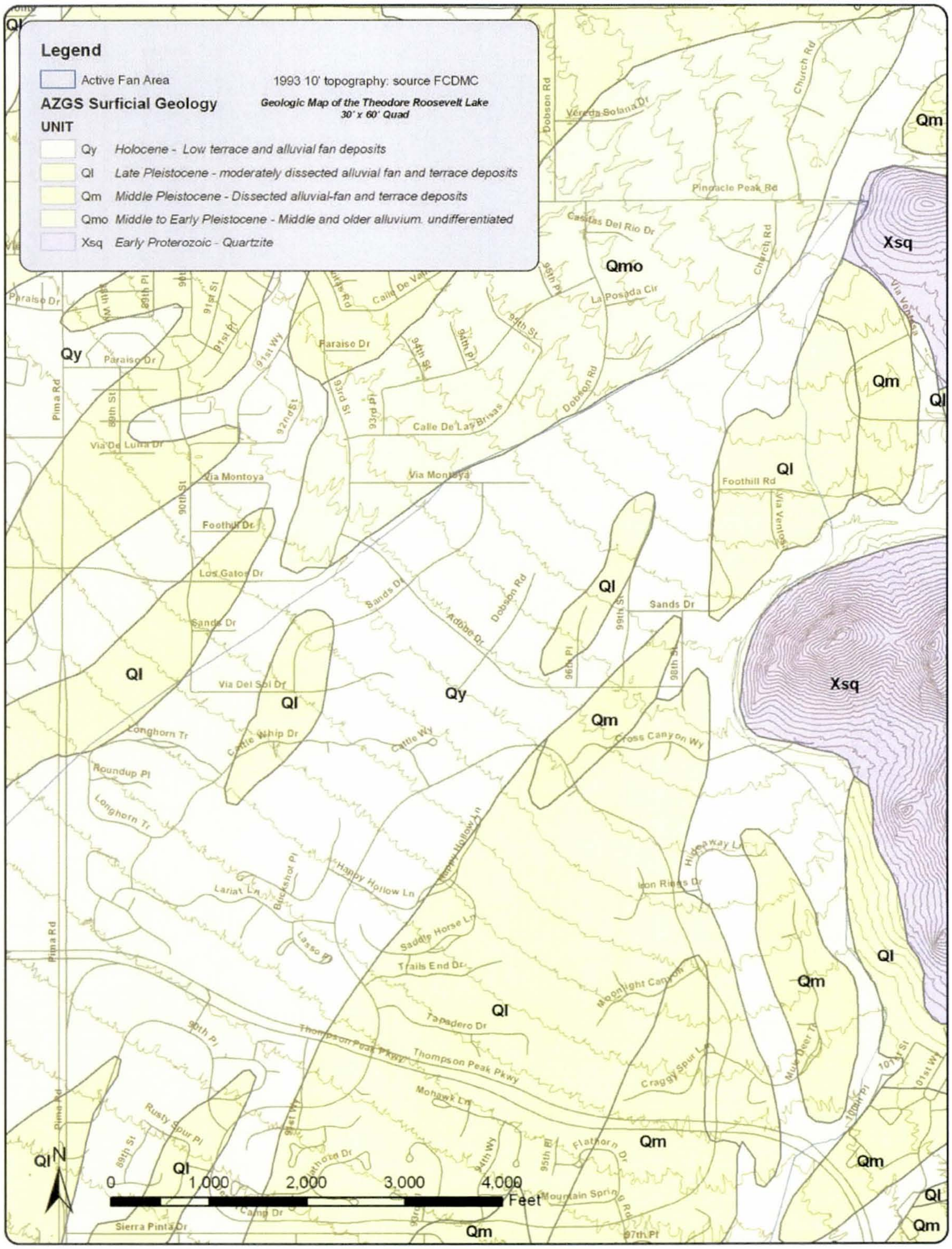

Figure 5-7 AZGS Geology: Reata Pass Fan.

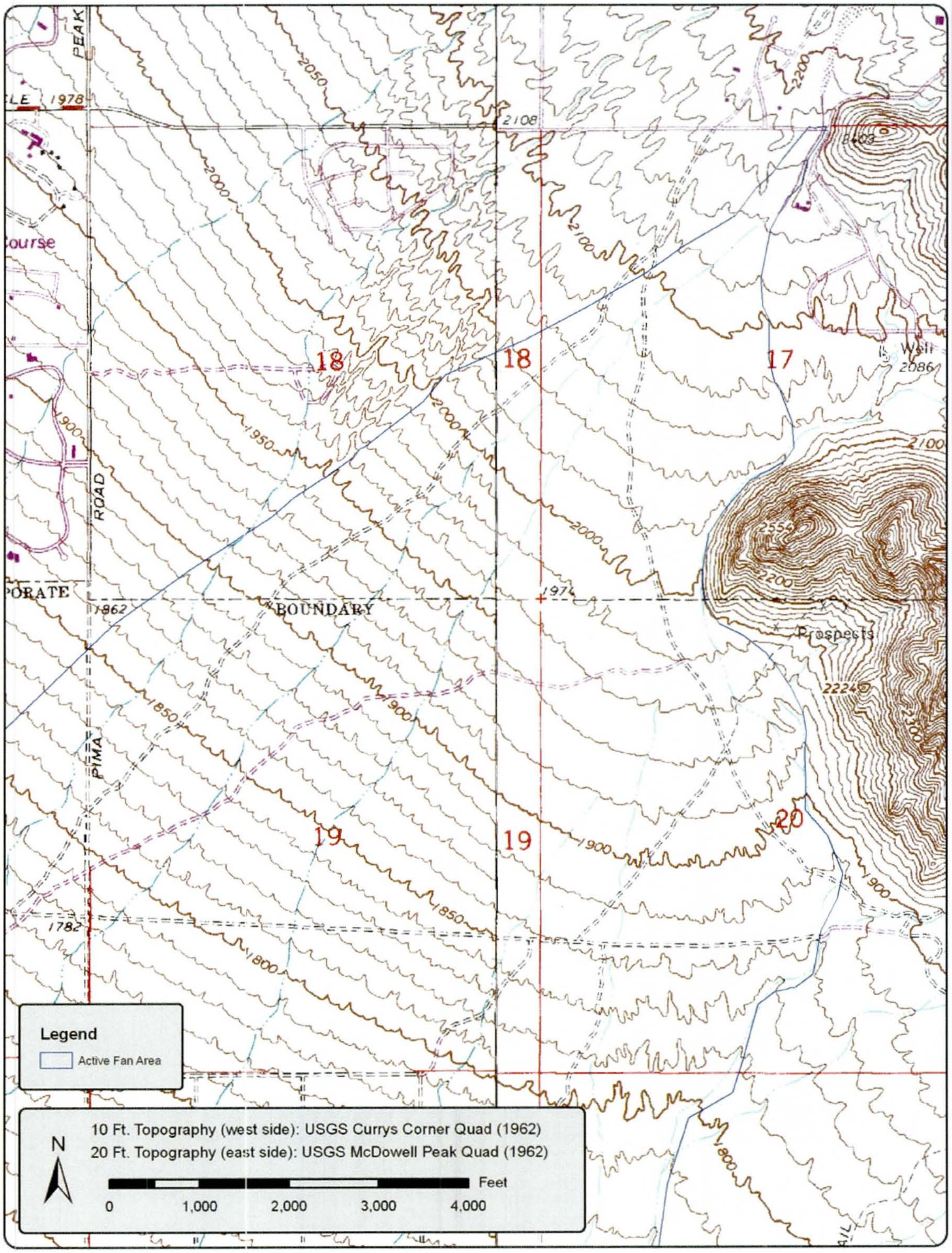

Figure 5-8 Topography: Reata Pass Fan.

5.1.5 Watershed and Fan Parameters

Item	Value	Source
Watershed area (upstream of apex)	8.1 square miles	USGS Quads
Watershed slope 3.2 miles upstream to apex	 3.4 %	 USGS Quads
Fan slope (Apex to 1.92 miles downstream) (1.92 miles to 4.65 miles ds)	3.3 % 2.0 %	USGS Quads
Q100 at apex	13,671 (24-hr)	City of Scottsdale Storm Water Master Plan
Fan Profile Shape	concave	USGS Quads
Max Elevation in Drainage Area	3880 ft	USGS Quads
Elevation at apex	2185 ft	USGS Quads
Minimum Elevation in fan	1520 ft	USGS Quads

Figure 5-9 Watershed and Fan Parameters

Structure	Type / Date	Location
Box culverts at apex	Concrete boxes	Pinnacle Peak Rd / Reata Pass Wash
Church Rd wet water crossing	Dip crossing	Church Road, south of Casitas Del Rio Dr
Foothills Rd culvert crossing	1 three foot dia. CMP	
Adobe Dr wet water crossing 1	Dip crossing	Between Los Gatos Drive and Sands Dr
Adobe Dr wet water crossing 2	Dip crossing	Between Sands Dr and Dobson Rd
Adobe Dr wet water crossing 3	Dip crossing	Between Dobson Rd and 96th Pl
Legacy (Union Hills) / 96th St Culvert	Two 8' x 4' box culverts	West of 96th St on Legacy

Figure 5-10 Structure Information

5.1.6 PFHAM Stage I

Task 2.3.3 requires that the pre-development landform be classified as to the "probable" landform type using the PFHAM Stage 1 categories. A PFHAM Stage 1 landform classification for an alluvial fan consists of the following elements:

- *Composition.* The landform is composed of alluvium (sediment material transported by the streams that formed the landform.
- *Morphology.* The landform has the shape of a fan, either partially or fully extended.
- *Location.* The landform is located at a topographic break where the primary watercourse loses capacity.

The Reata Pass Fan landform is shown to be composed of alluvium, as shown by the NRCS detailed soils mapping (Figure 5-6) and AZGS surficial geology mapping (Figure 5-7). As shown in Figure 5-8, the landform has the radial contours characteristic of a partially extended fan. The site is located at the topographic break formed where the main wash leaves the mountain canyons and enters the piedmont upstream of Pinnacle Peak Road and the channel changes from a single thread channel to a bifurcated distributary pattern (Figures 5-3 and 5-8). Therefore, the landform is properly classified as an alluvial fan landform.

5.2 Development History

Historical and recent aerial photographs of the study area are provided on the following pages. A delineation of the historical fan limits (delineated from the 1962 aerial) is outlined on each photograph to facilitate their comparison. This delineation is included as a point of reference because the landform becomes more obscured with subsequent years of development in the area. All of the aerial photography was obtained from the FCDMC.

5.2.1 Development History

The oldest aerial image of the study area is from 1962, which indicates that no development had taken place in the study area. The only man made features visible in the 1962 photograph are the alignments of Pima Rd (a north-south trace on the west side of the photo), Pinnacle Peak Rd (an east-west trace intersecting the fan at the apex), and an unnamed road transecting the fan near the bottom of the photograph. Interestingly, the subdivision outline (rectangular grid pattern) of Pima Acres is visible in the lower left hand corner of the photograph even though the first homes in that area where not built for another 20-25 years.

By 1976, there was only one home built near the fan landform. The home is located directly east of the apex outside the historical limits of the fan. The drainage channels at the apex and downstream appear more clearly defined than they do in the 1962 aerial, especially along Reata Wash as it heads south from the apex. This may be due in part to the large June 22, 1972 flood (See Appendix K of the 2003 PFHAM).

By the early 1990's, many custom homes had been built on the fan landform, primarily in the Pinnacle Peak Vistas and Pinnacle Peak Height subdivisions. According to a representative of the Pinnacle Peak HOA, the roads and homes in the upper portion of the fan were built to minimize disturbance to the natural channel conditions and to preserve the fan's natural drainage pattern. Restrictions were placed on modifying the wash in any way, and limitations were placed on where the lot structures were to be built. The site topography was also accounted for when choosing the building pad, which was required to be built on the topographically high portion of the lot. In addition, since all of Reata Pass fan is mapped in a FEMA AO zone, homes were required to be elevated on fill. Finally, each site plan was required to be engineered to ensure no rise in the regulatory floodplain.

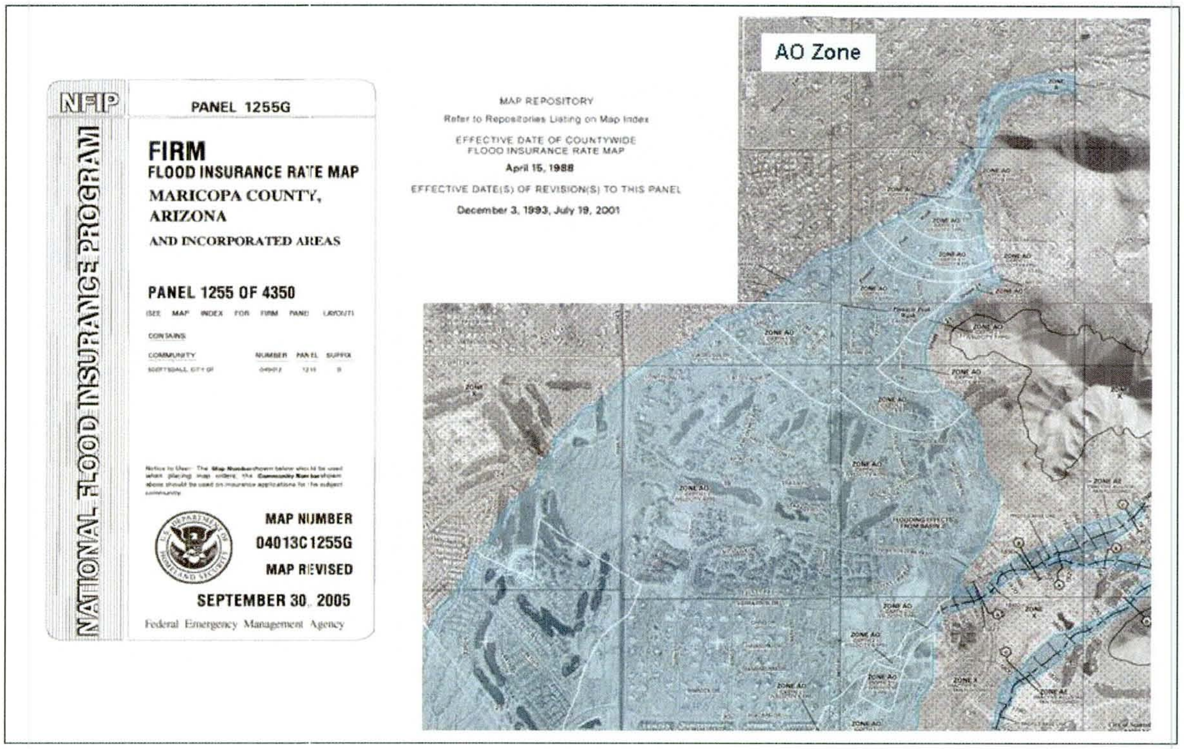

Figure 5-11 Reata Pass Fan FEMA Floodplain Map (FIRM).

All of the road crossings built on the upper portion of the fan, below the apex, but above the boundary of DC Ranch, are dip-crossings built at grade, with one exception. There is a culvert at the Foothill Road crossing of Reata Wash. Unlike the upper portion of the fan upstream of the DC Ranch boundary, the lower portion of the Reata Pass Fan has been highly modified and graded, including engineered channels, levees, and large bridge structures on Thompson Peak Parkway and other major roads.

The Greenbelt

Much of the development on the Reata Pass fan is tied up in the history of the City of Scottsdale's Desert Greenbelt project. The Desert Greenbelt project would have effectively channelized Reata Wash from apex and routed the flow down the Reata Wash corridor on the east side of the fan. A levee at the apex was designed to allow a limited amount of water to flow down Dobson Wash, the other historical fan flow path, to sustain the riparian habitat in those areas.

The DC Ranch community was designed and constructed using the Desert Greenbelt post-construction design discharges, which included the Reata Wash channelization element. However, for a variety of reasons, the citizens of Scottsdale and its City Council abandoned the Reata Pass elements of the Desert Greenbelt project and it was never built.

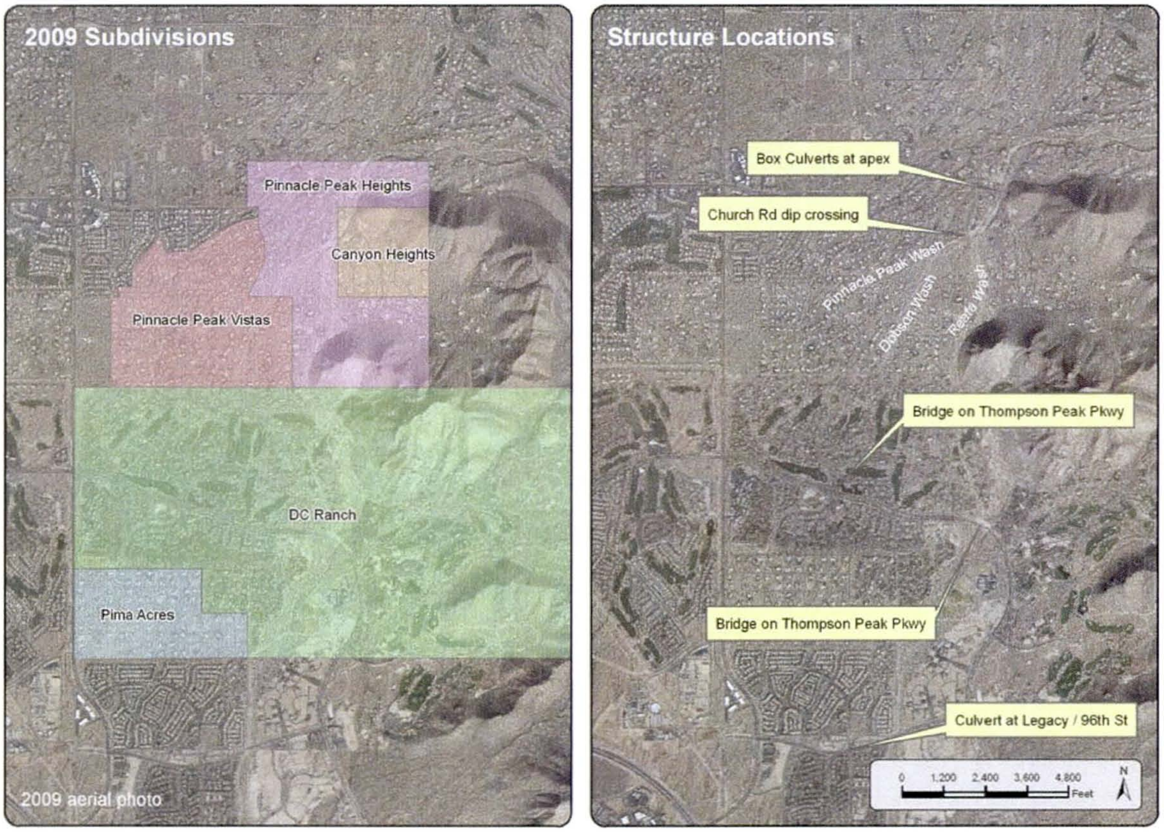

Figure 5-12 Reata Pass Fan Subdivisions and Structures.

During the late 1990's, DC Ranch began to develop the lower portion of the study area, north of Thompson Peak Parkway. DC Ranch is a master-planned golf course community with moderately dense residential development. Development in the late 1990's proceeded under the assumption that Reata Wash would be levied at the apex and the bulk of the flow would be channelized down Reata Wash on the east side of the fan. The result was that some residential homes in DC Ranch were built in the wash bottom with no protection from upstream flows even though the levee measures planned at the apex were never built. There have been no known flooding problems with these homes to date, probably due to the lack of significant rainfall in the ten years since their construction. Homes built in the wash may be inundated during large magnitude floods, potentially posing a risk to the safety, life and property of the residents. The homes in the wash may also restrict conveyance, potentially inundating adjacent areas.

Thompson Peak Parkway was built across the fan between 1993 and 1997, and included bridges to accommodate both Reata Wash on the east side of the fan and Dobson Wash (combined with other break offs from it) on the western side of the fan. Also, by this time, the golf course at DC Ranch had been built on the fan.

By 1999, development had begun at DC Ranch south of Thompson Peak Parkway, with construction continuing until present day. During the early 2000's, DC Ranch was completed upstream from Thomson Peak Parkway, and the custom home communities downstream of the apex were also completed.

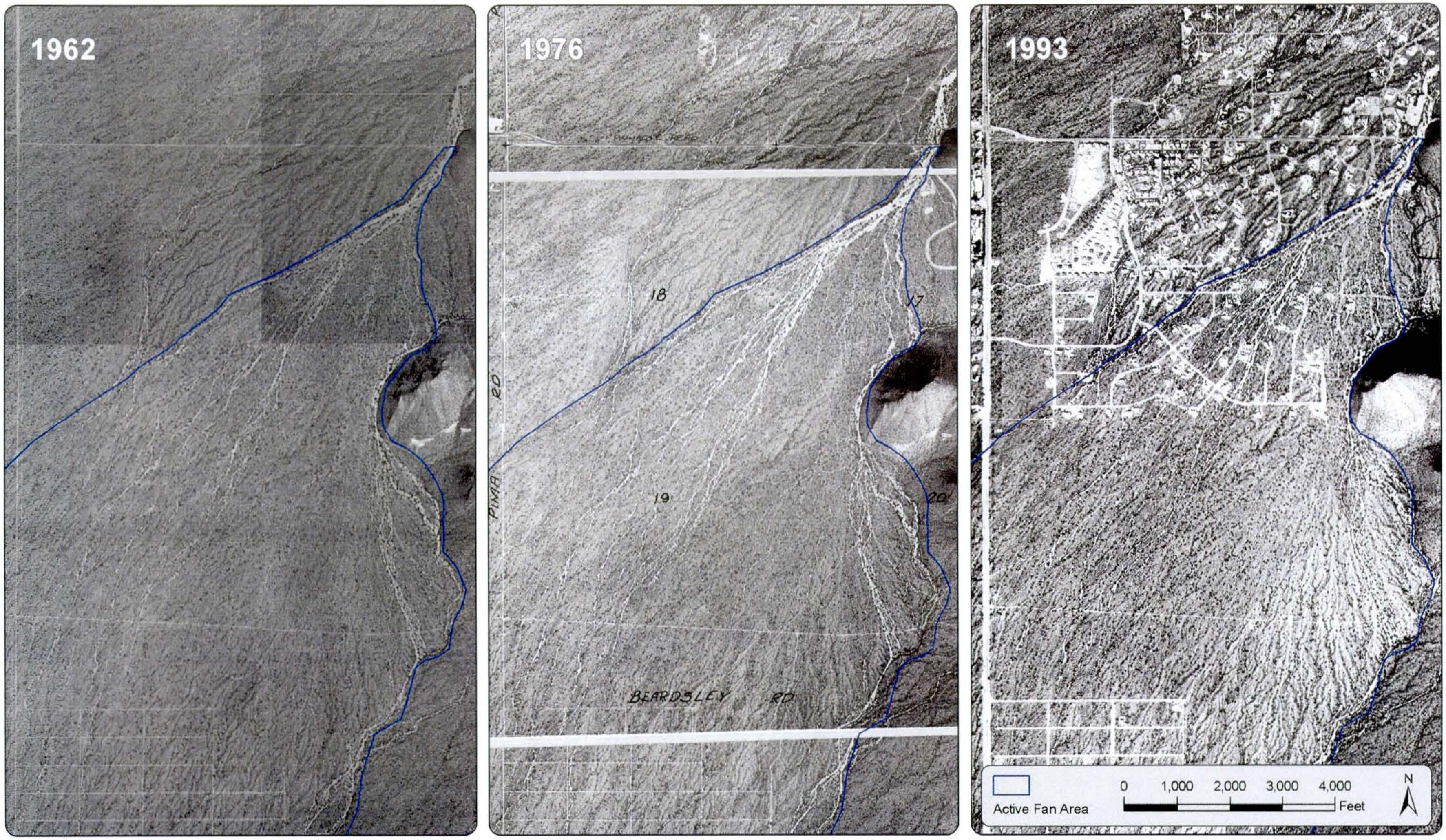

Figure 5-13 Historical Aerial Photos: Reata Pass Fan 1962 – 1993.

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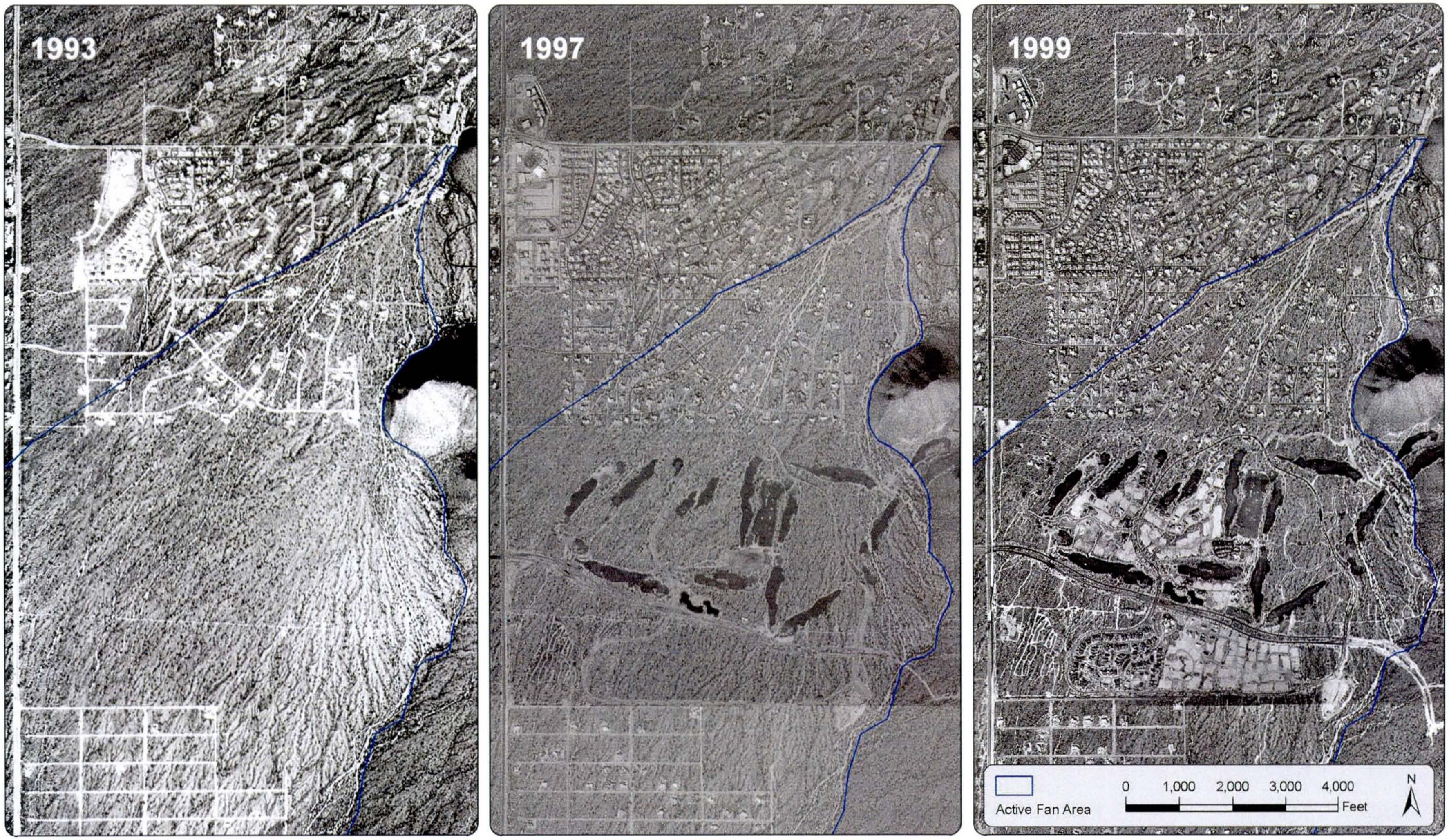

Figure 5-14 Historical Aerial Photos: Reata Pass Fan 1993 – 1999.

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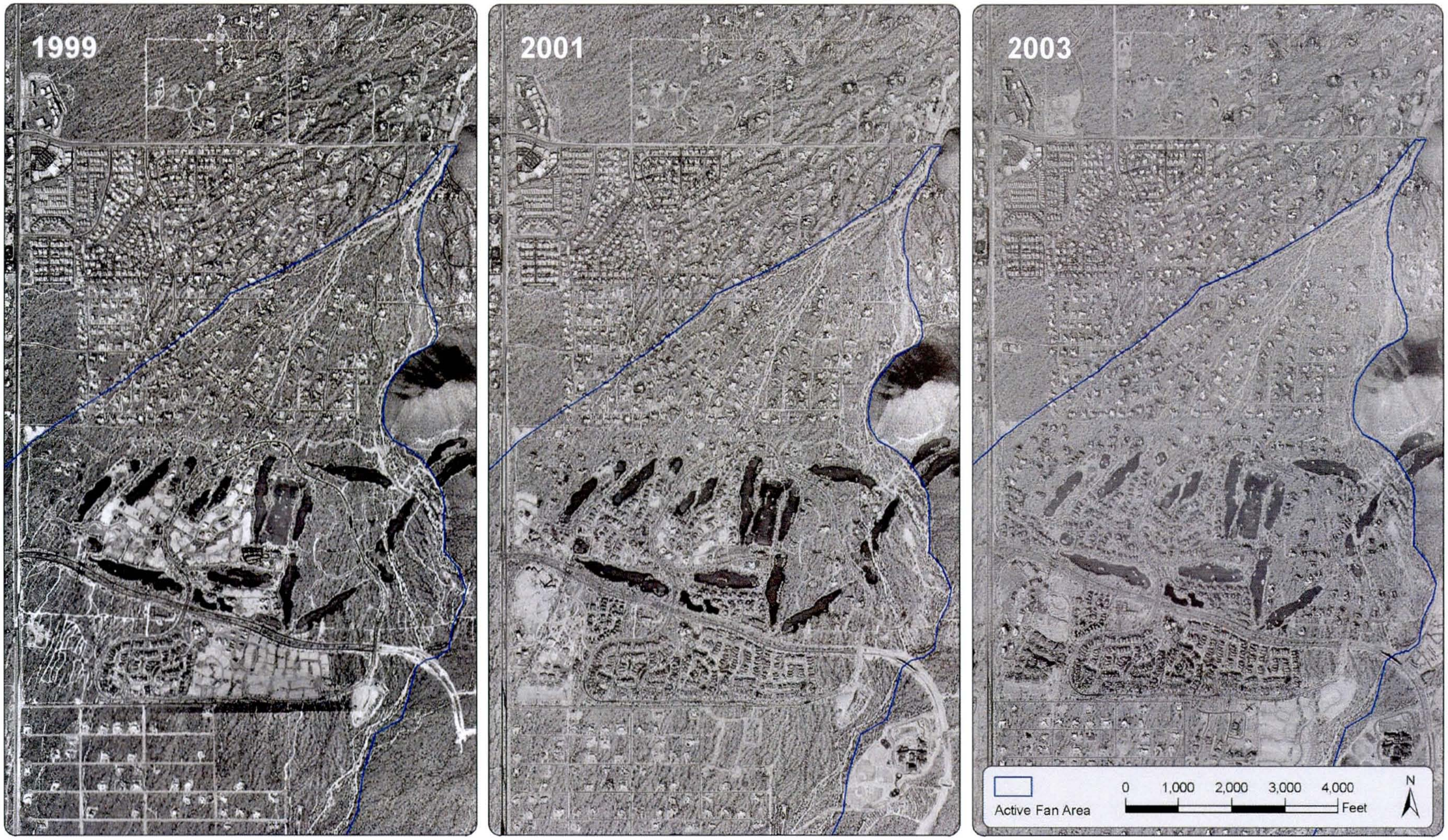

Figure 5-15 Historical Aerial Photos: Reata Pass Fan 1999 – 2003.

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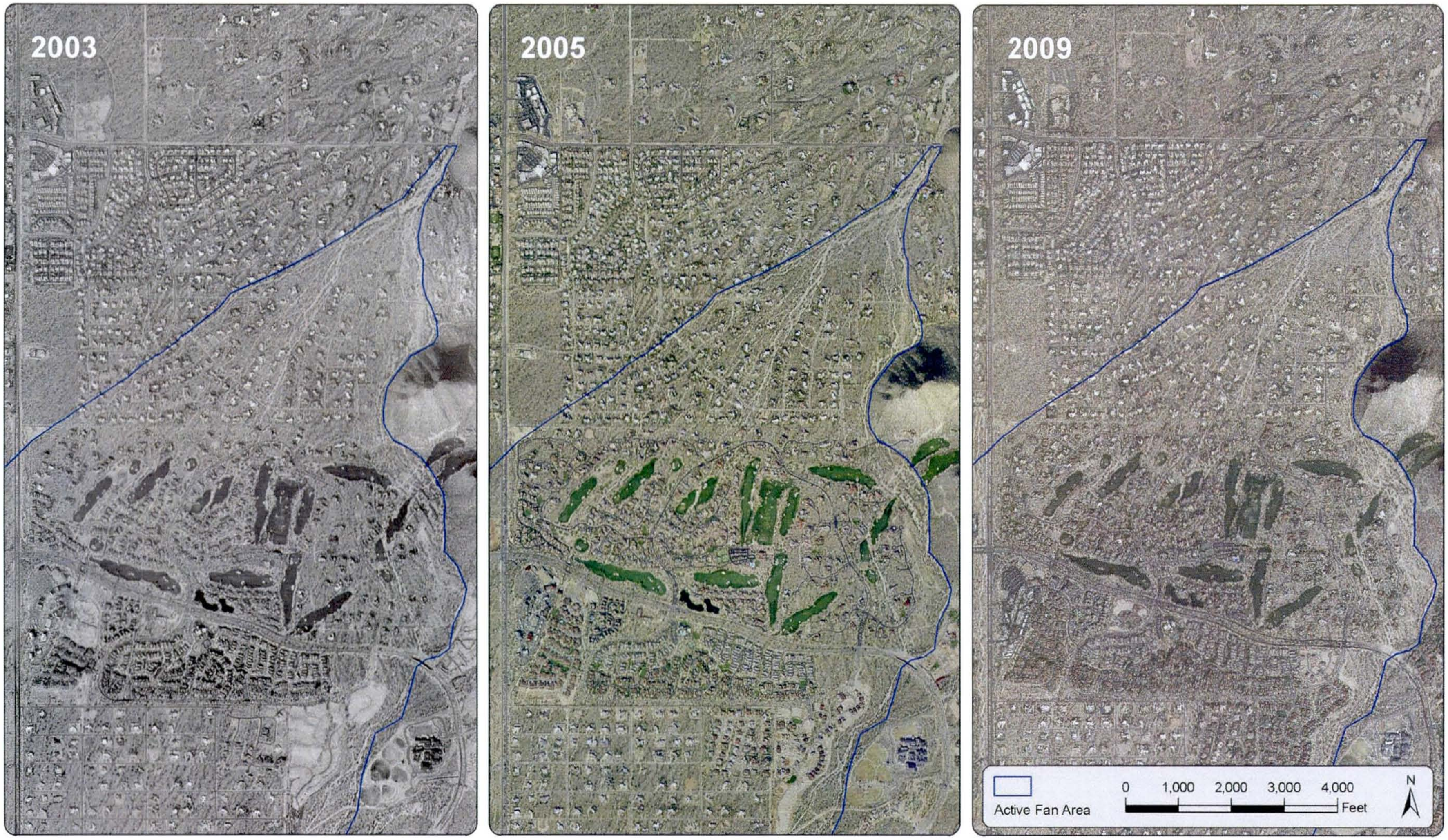

Figure 5-16 Historical Aerial Photos: Reata Pass Fan 2003 – 2009.

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5.2.2 Field Photograph Locations

The figure below includes the locations for each of the following field photos. Field photos are identified by the number in the caption below the photo.

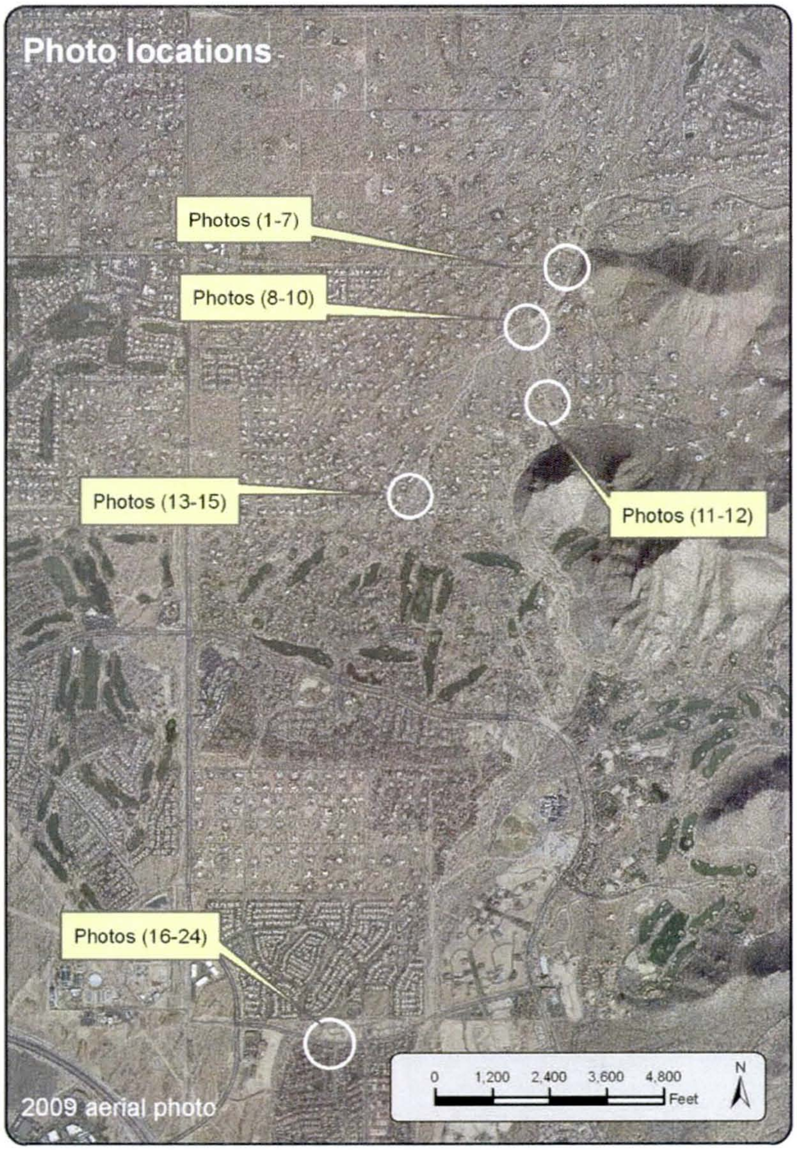
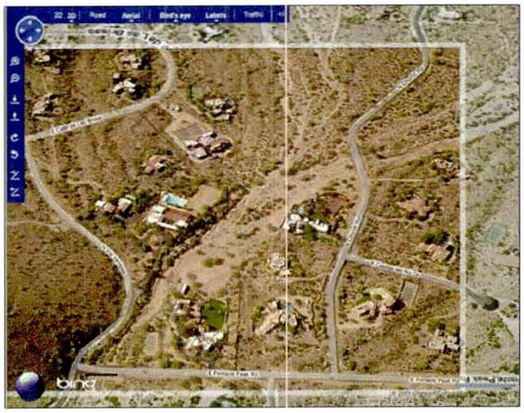
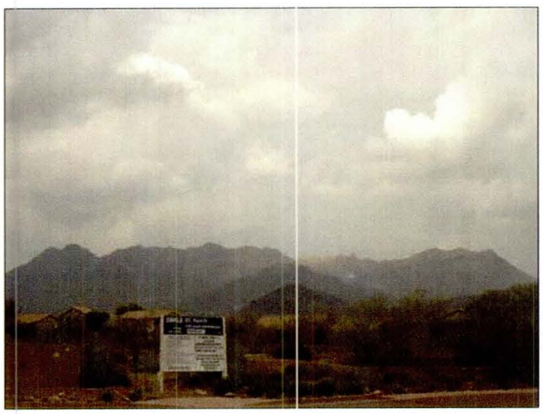


Figure 5-17 Reata Pass Fan Photo Locations

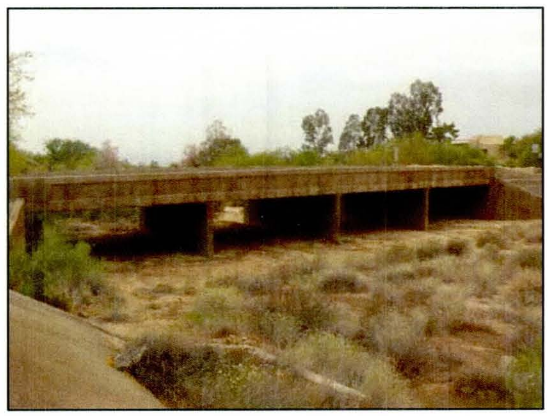


1. Oblique aerial view looking south at apex
Source: bing.com

2. Oblique aerial view looking south at Church Rd
Source: bing.com

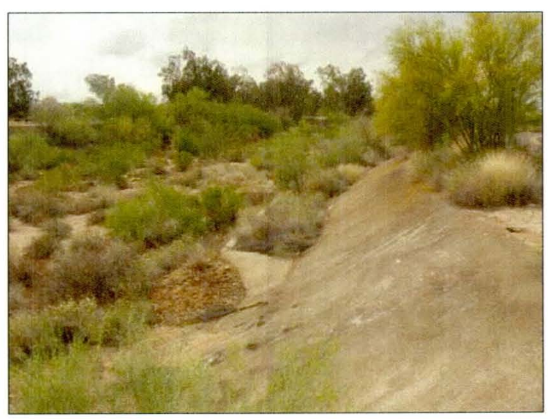


3. McDowell Mts.
Watershed contains the north slope of the McDowells

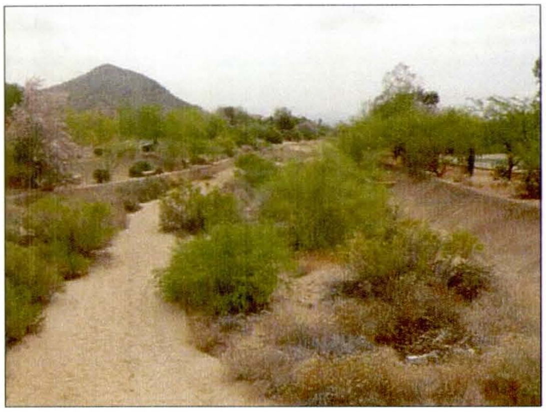


4. Crossing at the apex (Pinnacle Peak Rd)
Four 10' x 20' box culverts

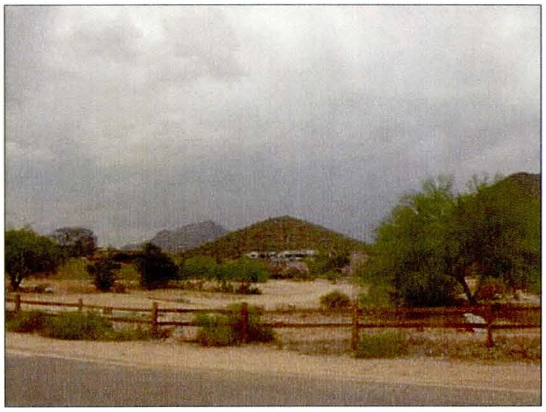
5. Looking downstream from Pinnacle Pk Rd culverts
Reata wash levied on both sides



6. Looking upstream from Pinnacle Peak Rd culverts
Reata wash levee on the left bank



7. Looking downstream from Pinnacle Peak Rd x-ing
Reata wash levied on both sides



8. At-grade crossing at Church Rd
Looking upstream

9. At-grade crossing at Church Rd
Looking downstream

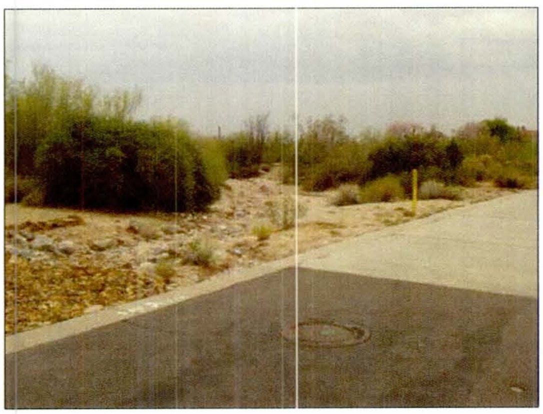
10. At-grade crossing at Church Rd
Looking downstream

11. Reata Wash at Foothills Drive
Two 3' CMP Culverts

12. Reata wash upstream of Foothills Dr. culverts
Looking upstream

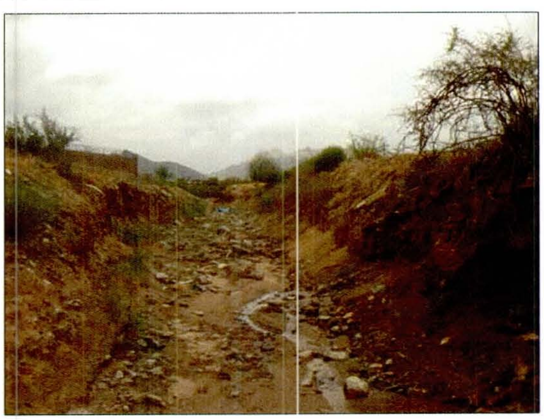
13. Dobson Wash dip crossing at Adobe Dr.
Looking upstream

14. Dobson Wash dip crossing at Adobe Dr.
Looking downstream



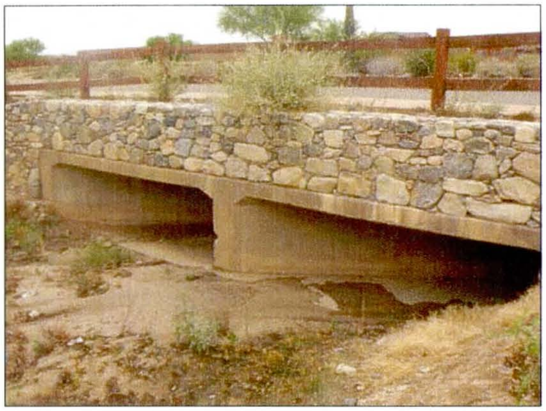
15. Dobson Wash dip crossing at Adobe Dr.
Looking downstream

16. Legacy road (Old Union Hills) / 96th St
Two 8' x 4' box culverts, As-built: Q = 511 cfs



17. Looking upstream
From the Legacy Road crossing

18. Looking Downstream
At the Legacy Road crossing

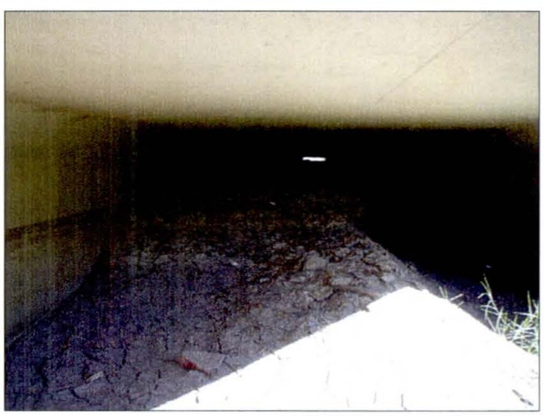


19. Union Hills / 96th St Culverts
Looking at the inlet

20. Looking Downstream
From the Union Hills culverts

21. Culvert clogged 2007-2008
Looking downstream

22. Culvert clogged 2007-2008
Looking downstream



23. Culvert clogged 2007-2008
Looking downstream

24. City of Scottsdale clearing sediment
Looking upstream

5.3 Hydrology

The nearest FCDMC rain gage is located at the apex of Reata Pass Fan. The combined rain and stream gage is located on the Pinnacle Peak Road crossing of Reata Pass Wash. The gage has been in continuous operation since it was installed on May 2001. Since that time the average rainfall per year has been 8.77 inches. The wettest year, in the limited record, was 2005 with a total water-year rainfall of 18.07 inches. The largest rainfall totals at this site have been:

- 5-10 year storm: 15 minute total: 0.91" on 09-03-2006
- 10-25 year storm: 1 hour total 1.61" on 07-31-2005
- 4 year storm: 24 hour total: 2.28" on 03-05-2004

The Reata Pass stream gage located at the same location recorded a maximum water level for the September 2006 event of 1.52 ft, or 649 cubic feet per second. The maximum water level, or extreme, outside the period of record was on August 29, 1996, of 1780 cubic feet per second. Using the rating table this flow rate would have been about 2.5 feet on the gage.

The second nearest FCDMC rain-streamflow gage is at Reata Pass Dam, which is located about 0.5 mile south of Dynamite Boulevard and 112th Street. Reata Pass Dam is located 2.8 miles northeast of the fan apex and is within the fan's watershed. The gage at Reata Pass Dam has been in continuous operation since August 1993. Since that time the average yearly rainfall at the gage site has been 10.38 inches. The two wettest years on record have been 2005 and 1995 with 16.89 and 16.81 inches of rain respectively. The largest rainfall totals at this site have been:

- 10 year storm: 1.54" in 1 hour on 08-29-1996
- 5 year storm: 2.64" in 24 hours on 11-15-1993

Appendix K of the PFHAM (2003) reports that large floods occurred in the area on June 22, 1972 and on August 29, 1996. Specific information on these previous events was not available.

The nearest FCDMC gage on the alluvial fan landform is a rain gage located about 2 miles due south of the apex, near the intersection of Thompson Peak Parkway and East Windgate Pass Drive. This gage has been in continuous operation since May 1998. Since that time the average rainfall per year has been 8.28 inches. The wettest year on record has been 2005 with 16.61 inches. The driest year on record was 2002 with 2.99 inches of rainfall. The largest rainfall totals at this site have been:

- 40 year storm: 1.89 inches in 1 hour on 10-10-2003
- 8 year storm: 2.56 inches in 24 hours on 12-07-2007

The 40 year 1 hour storm that was recorded on fan on 10-10-2003 was recorded at the apex as 1.26 inches in 24 hours. The recorded stream gage height at the apex during this event was 0.38 feet with a rating of 34 cubic feet per second. So while it rained a record intensity in the mid-fan area, it did not have a corresponding record rainfall in the watershed or a sizeable discharge at the apex.

The Reata Pass hydrologic data discussed above are also included below in Table 5-1. This table provides a way to see how a storm at one gage registered on the other nearby gages, or affected the flow at the apex.

Table 5-1 Reata Pass Fan Hydrology

Storm	Reata Pass Wash Stream / Precip (ID:4585)			Pinnacle Peak Vista Precip (ID: 4595)		Reata Pass Dam Precip (ID: 4935)	
	Rainfall Depth (Inches)	Stream Flow Stage = ft (Q in cfs)	Recurrence Interval (years)*	Rainfall Depth (Inches)	Recurrence Interval (years)	Rainfall Depth (Inches)	Recurrence Interval (years)
12/07/2007	0.47 (24 hour)	0.50 (57 cfs)	< 2 yr	2.56 (24 hour)	< 2 yr	0.75 (24 hour)	< 2 yr
09/03/2006	0.91 (15 min)	1.52 (649 cfs)	5-10 year	0.83 (24 hour)	< 2 yr	0.94 (24 hour)	< 2 yr
07/31/2005	1.61 (1 hour)	0.53 (63 cfs)	10-25 year	0.75 (24 hour)	< 2 yr	0.39 (24 hour)	< 2 yr
03/05/2004	2.28 (24 hour)	0.98 (238 cfs)	4 year	1.38 (24 hour)	< 2 yr	1.61 (24 hour)	< 2 yr
10/10//2003	1.26 (24 hours)	0.38 (34 cfs)	< 2 yr	1.89 (1 hour)	40 year	0.91 (24 hour)	< 2 yr
08/29/1996	no data	(1,780)	no data	no data	no data	1.54 (1 hour)	10 years
11/15/1993	no data	no data	no data	no data	no data	2.64 (24 hour)	5 years

*computed Precipitation Frequency Estimates using Reata Dam Site table. Reata Pass Wash Frequency Table not available.

5.4 Flood Mitigation Measures

The Reata Pass Fan is an example of a developed fan that remained similar to its historical condition, in contrast to the previous two sites where full structural measures were used to mitigate flood hazards. The upper portion of the Reata Pass Fan has no regional structural drainage measures to mitigate the flood hazard. Instead, flood mitigation measures were instituted on a lot-by-lot basis, and consisted of building on the natural topographic highs and by elevating structures on fill. Currently, the Home Owners Associations and local residents strictly adhere to regulations that keep the washes in their natural condition. As can be seen from a review of the historical aerial photographs the majority of drainage pathways remain unaltered and the fan still retains most of its pre-development distributary drainage pattern.

Through the DC Ranch development, in the lower portion of the study area, the natural historical channel patterns on the fan were not preserved. A few structures and homes have been built in wash bottoms, which may cause problems during future large magnitude flood events.

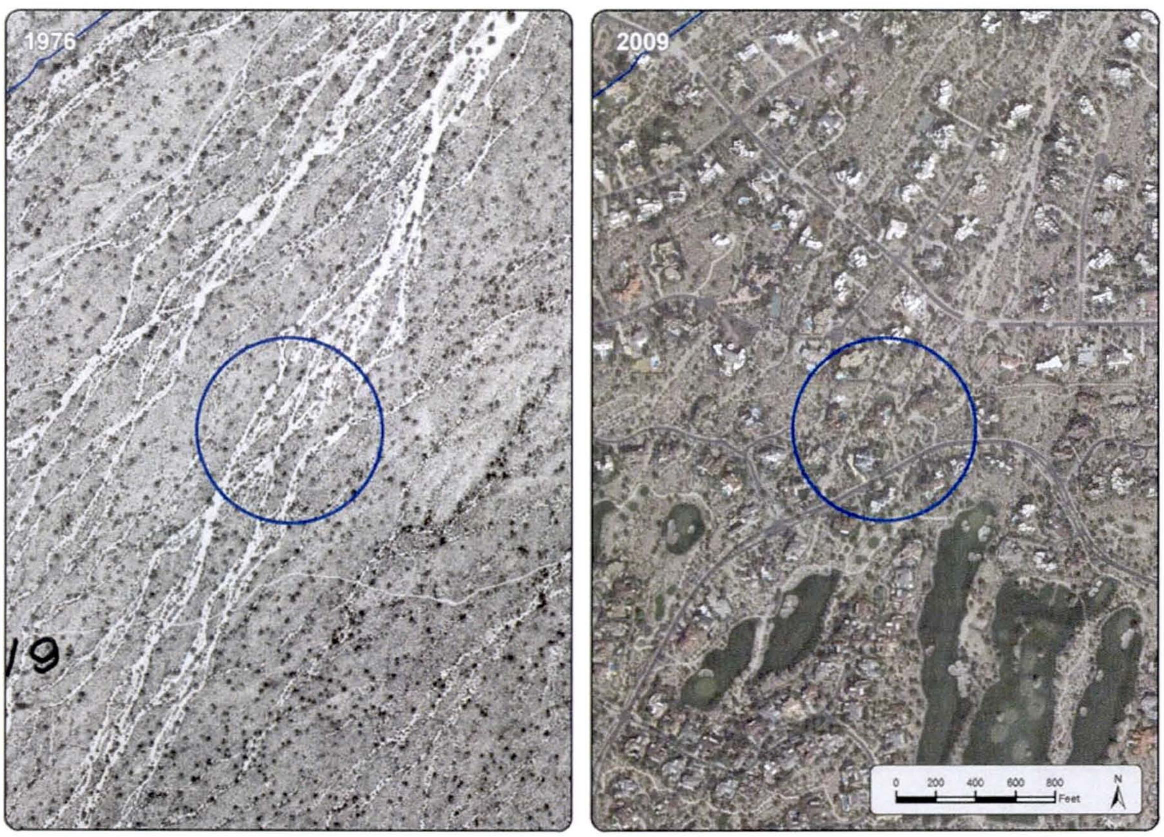


Figure 5-18 DC Ranch Homes Built in Washes.

To date, the largest known flooding problems on fan have occurred in the Pima Acres subdivision downstream of Thompson Peak Parkway. The grid outline of the lot layout at Pima Acres can be seen as early as 1962 on the historical aerial photographs. At the time it was developed, no drainage infrastructure was constructed in Pima Acres to deal with flooding through the area (source: City of Scottsdale, Department of Storm Water Management). Currently, the City is designing measures to mitigate flooding by intercepting the flow along the northern edge of the subdivision. The red dots, on the right side of the figure below depict the at-grade crossings on Reata Pass alluvial fan, the majority of which are within Pima Acres. Flooding problems in Pima Acres include sediment deposition and erosion on roads, damage to landscaping and flood debris.

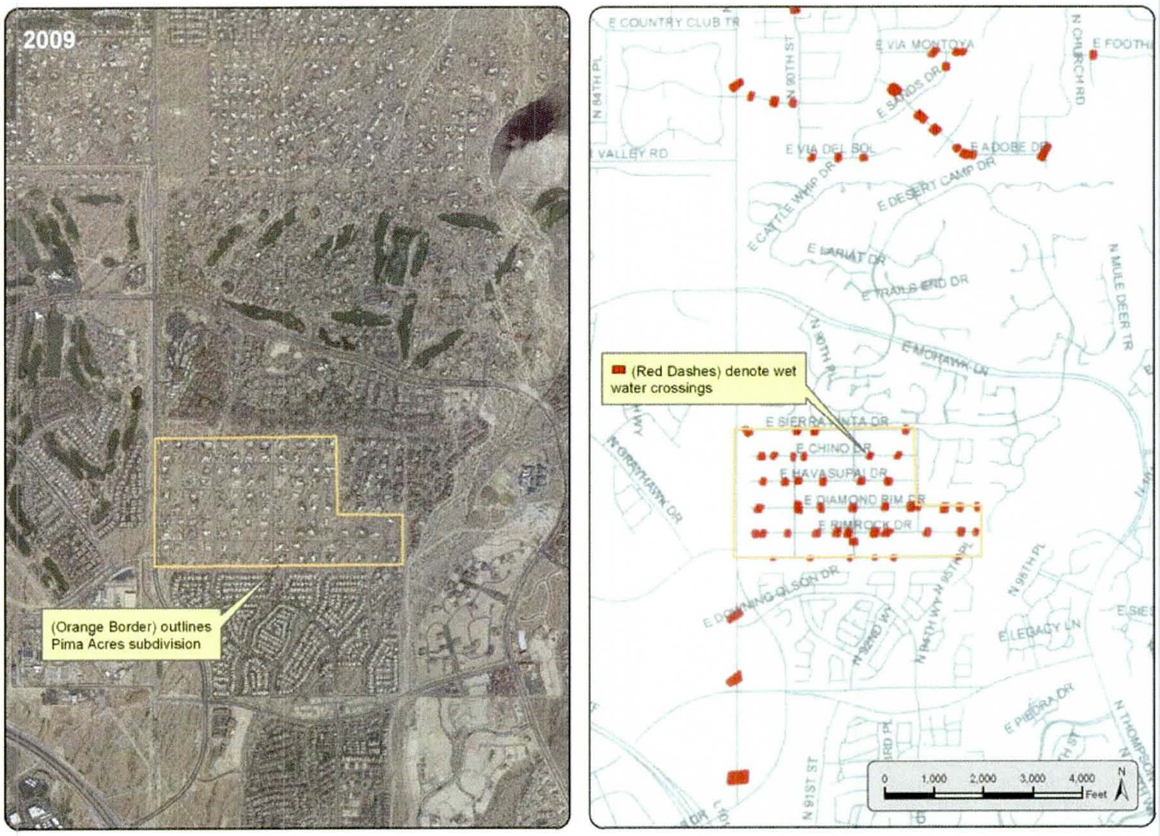


Figure 5-19 Location of Pima Acres Subdivision.

5.4.1 Maintenance Needed

The Chief Foreman of the Drainage and Street Operations Department at the City of Scottsdale commented that the biggest drainage and maintenance problems in the project area are that culverts frequently clog with sediment. Although there is only one culvert in the upper portion of the fan, there are many culverts, channels and engineered structures on the mid and lower portions of the fan. The culverts in the area, of which the culvert at Legacy / 96th St is a good example, were not designed to transport sediment during the 2- and 5-year events. Routine maintenance of the clogged culverts is a significant maintenance burden. The HOA's on the northern portion of the fan, where dip crossings are used rather than culvert crossings, report that the only maintenance required is clearing a small amount of sediment off the road surface after flow events. This is typically done with a street sweeper.

The natural channels upstream of DC Ranch are not actively maintained, but are regularly (though informally) monitored by the local residents to make sure that the HOA covenant regulations and ordinances to preserve the wash are observed.

The biggest flood-related problem the City of Scottsdale has had on the fan areas is with debris, vegetation or obstructions in the wash. This included landscaping and other debris dumped in washes. Another problem has been residents building small levees or flood walls within the floodplain, and in some cases building stables and horse facilities in the washes. The City of Scottsdale has taken a pro-active stance on dealing with these issues. The City currently employs two full time drainage-inspectors who constantly walk and patrol the washes in Scottsdale looking for violations, writing up citations in order to restore the wash to its natural unrestricted capacity as soon as possible. This program, although instituted recently, has been working very well to keep the washes functioning as designed.

5.5 Conclusions

Development on the upper, most active portion of the Reata Pass Fan preserved to a great extent the natural, distributary drainage patterns of the fan landform, with no development in the most active parts of the upper fan. Some large-lot residential construction has occurred in lower, less active parts of the upper fan, but only on higher ground outside the most prominent existing flow paths. The wash corridors are designated and protected as environmentally sensitive wildlife habitat to help assure their preservation. To date, no major flood damages have been reported in this area, although there have been no large magnitude floods during the period of record that would test the system.

The lower and mid-fan portions of the Reata Pass Fan were developed as mass-graded, master planned communities that significantly altered the natural character of the alluvial fan landform. Drainage problems in these areas have been limited to sedimentation at road crossings (both dips and culverts), local erosion, and minor surface inundation. Again, the lack of significant floods during the period of record may have contributed to the lack of major flood damages, but the record indicates that the system has performed moderately well during the small floods that have occurred.

Based on our analysis, we conclude that the structural and non-structural elements of the Reata Pass drainage system has performed adequately during the 20 year period of record, at least with respect to controlling the flow uncertainty and sedimentation associated with active alluvial fans. No homes on the fan have been flooded in the past 20 years. Sedimentation at road crossings is addressed routinely by home owners' association or the City of Scottsdale, though at some cost to taxpayers and residents. The past and future performance of the drainage system is predicated on the following:

- Periodic sediment removal from culverts and dip crossings.
- Occurrence of floods that do not exceed the design frequency.

6. Lost Dog Fan

6.1 Site Location

The Lost Dog Wash alluvial fan site is located in northeast Scottsdale, Arizona, in Sections 23 and 22 of T3N R5E. Lost Dog fan is located along the southwest flanks of the McDowell Mountains, approximately four miles east of the Loop 101 Freeway and about 0.5 mile north of Shea Boulevard. Historically, the apex of the alluvial fan was located near the present intersection of North 120th Place and East Via Linda Road.

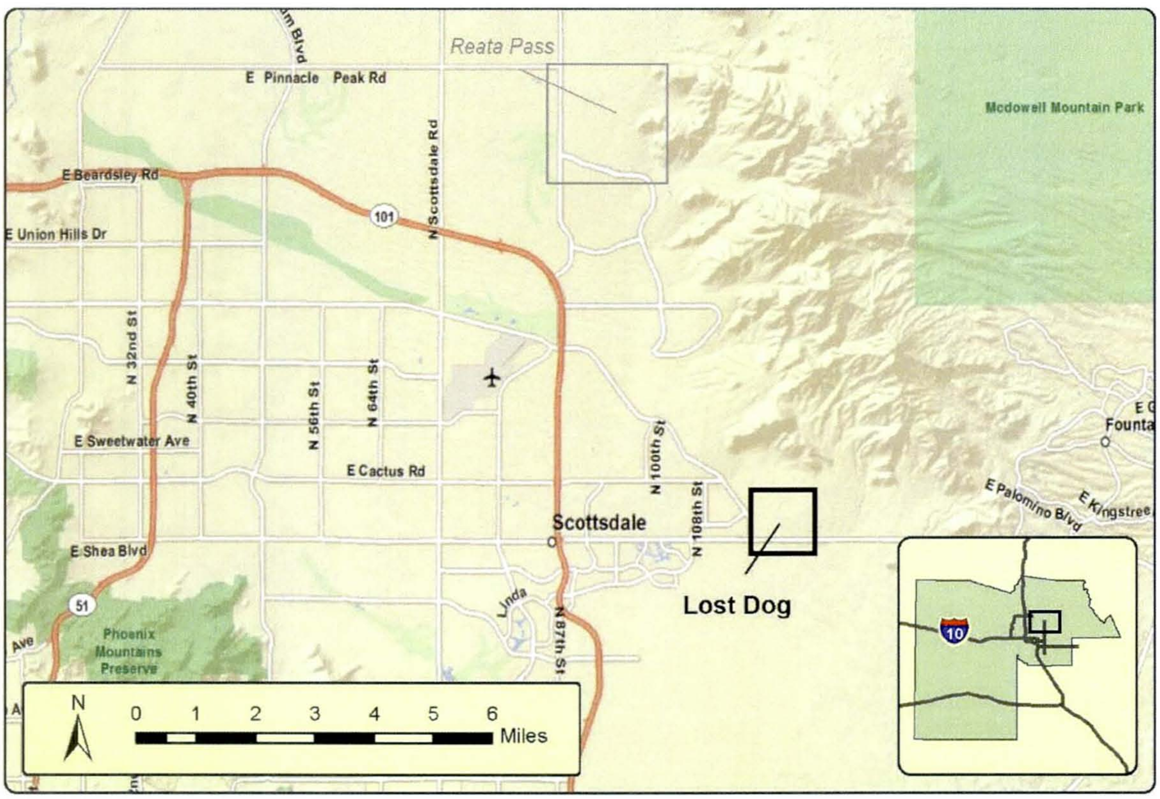


Figure 6-1 Location Map: Lost Dog Wash Fan.

The Lost Dog Wash watershed above the apex is 2.8 square miles, and drains a portion of the southern flanks of the McDowell Mountains. The Lost Dog watershed is located within the McDowell Sonoran Preserve, which remains undeveloped.

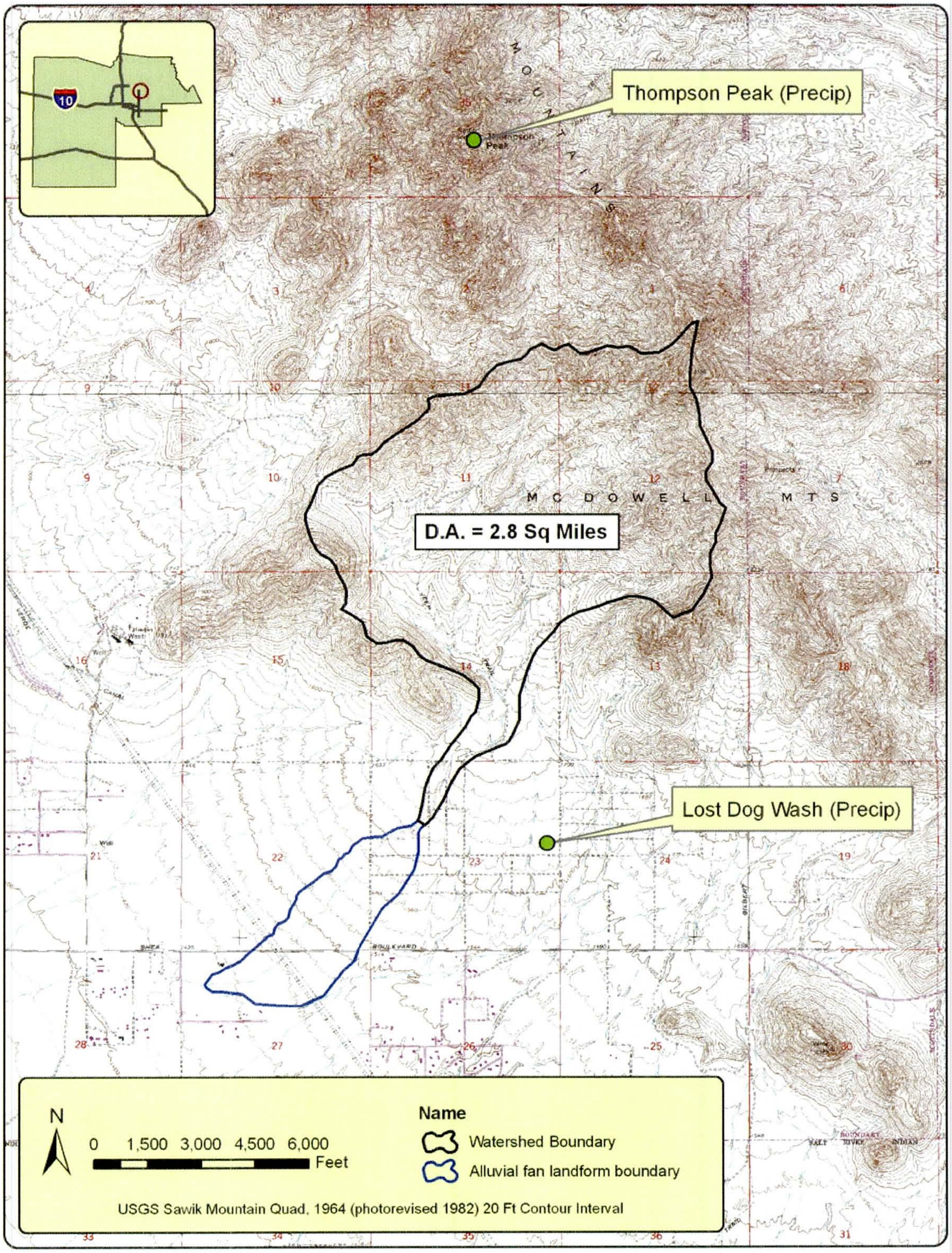


Figure 6-2 Lost Dog Fan Drainage Area & Gage Locations.

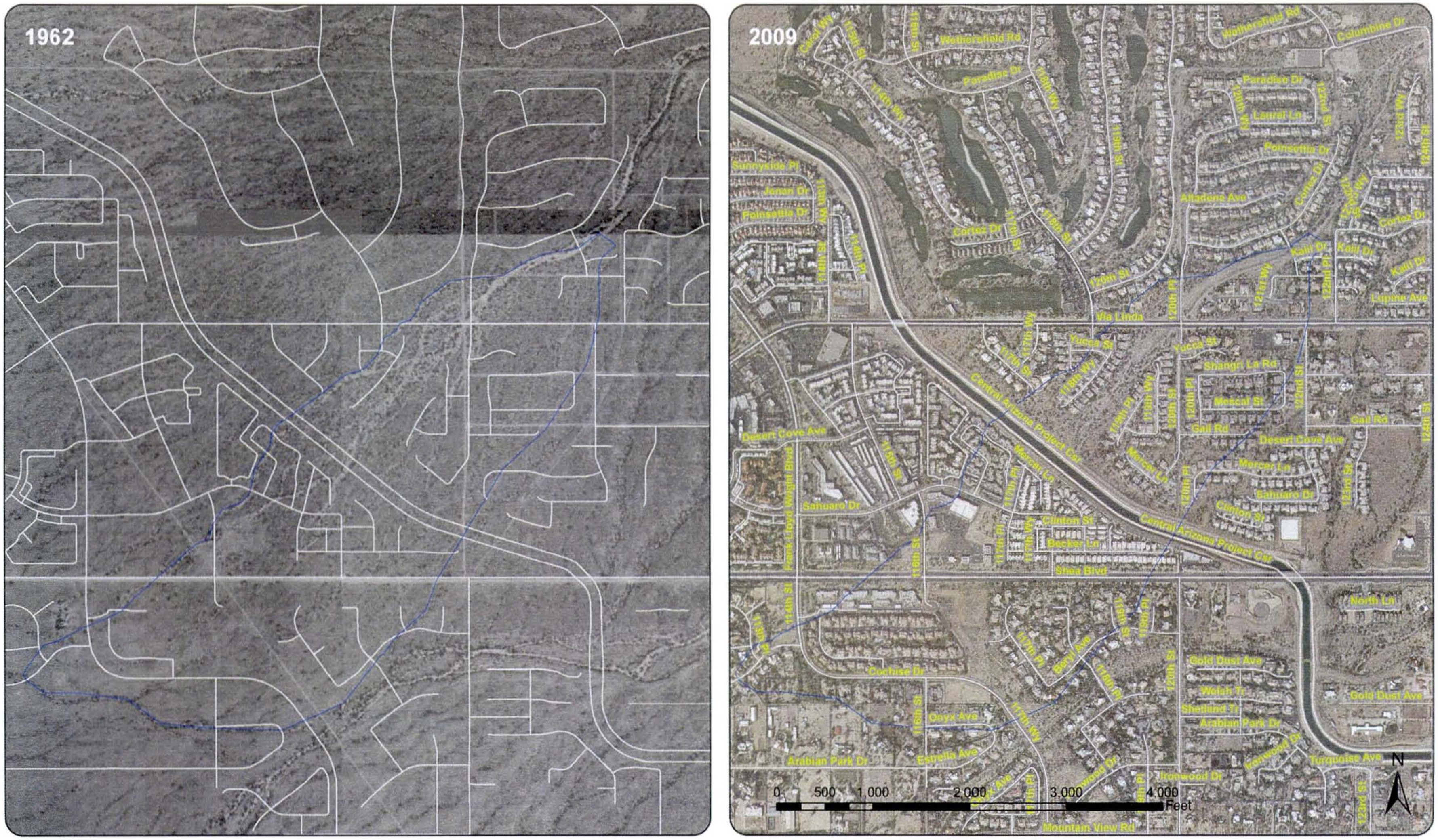


Figure 6-3 Lost Dog Fan Before and After Development.

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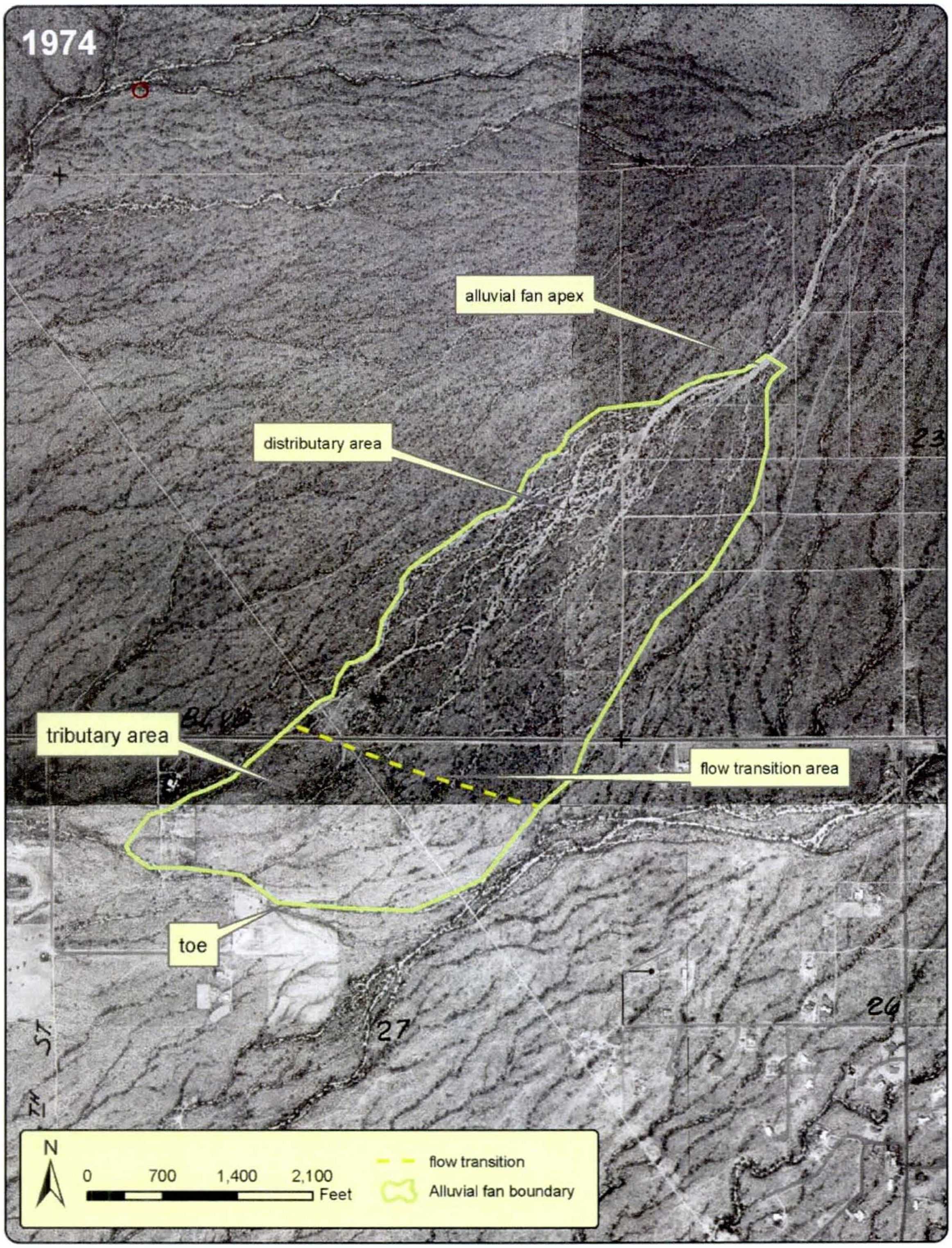

Figure 6-4 Lost Dog Fan Landform Characteristics.

As seen in Figure 6-4 the hydrographic apex of the Lost Dog Fan is located about 1,500 feet northeast of the present intersection of 120th Place and Via Linda Road. Lost Dog Wash, unnamed on USGS quads, flows out of the McDowell Mountains, and becomes distributary about 1.0 mile from the mountain front. Elevations range from 1,400 feet on the lower fan surface to 3,800 feet at the watershed divide in the McDowell Mountains. In the 1962 aerial photograph of Lost Dog the distributary areas can be seen extending down fan from the apex. These distributary channels continue down fan to about the Shea Boulevard alignment, at which point they lose definition and transition to shallow sheet flow. The toe of the fan is delineated where the sheet flow transitions to a low relief tributary drainage pattern before confluencing with a small wash that serves as the axial stream.

6.1.1 NRCS Soils Mapping

Figure 6-5 presents the soil survey information for the Lost Dog study area. The source of the soil survey data is the NRCS Soil Survey of Aguila-Carefree Area, Parts of Maricopa and Pinal Counties, Arizona. In Figure 6-5 the lateral extents of the fan are delineated and included as a blue outline on the 2009 aerial photograph background to provide perspective of where the historical lateral extents of the fan surface were in comparison to modern residential development in the area. Soil survey units are labeled individually in the figure, but are also grouped into major landform types.

The apex and the channel upstream occur within the Brios-Carrizo complex (10), a floodplain map unit. In both the Brios and Carrizo soils permeability is very rapid, and the hazard of water erosion is severe.

Below the apex, the entire alluvial fan landform is mapped in soil unit (3), the Antho-Carrizo-Maripo complex. This soil complex is found on drainageways and floodplains. Antho series is moderate in most respects: permeability is moderately rapid, available water capacity is moderate and hazard from water erosion is moderate. The Carrizo portion of the complex is excessively well drained, water hazard erosion is severe, and channelizing, deposition, and streambank erosion may occur during periods of flooding. The Maripo portion of the complex is deep and well drained, permeability is moderately rapid and run off is slow, and the hazard from water erosion is moderate. Interestingly, the description of this soil complex notes that “the soils in this unit are severely limited for urban use because they are in drainageways and on floodplains that are subject to flooding” (Aguila-Carefree Soil Survey, p. 14).

The units that border the fan landform on the east and the west are the Momoli-Carrizo complex (91) and the Ebon very gravelly loam (44). Both of these soil units are found on fan terraces and stream terraces.

6.1.2 Surficial Geology

Figure 6-6 presents the surficial geology for the Lost Dog Fan study area, as mapped on the AZGS Geologic Map of the Theodore Roosevelt Lake 30' x 60' Quadrangle, Richard and Spencer, 1998. The lateral extents of the historical alluvial fan area have been delineated from the 1962 aerial and are included as a blue outline on the 2009 aerial background.

The mapped extents of the Qy unit very closely represent the historical lateral limits of the alluvial fan landform. Qy (Quaternary Young Alluvium) forms low terraces and alluvial fan deposits. Qy, a Holocene unit (less than 10,000 years old) is the youngest geologic unit in the study area. Qy covers the entire active alluvial fan surface.

Just as in the NRCS mapping, terrace soil units border the fan on the east and west. The AZGS mapped the terrace soil units as Qm, Ql and Qmo, which are Pleistocene-aged: (Ql) late Pleistocene, (Qm) middle Pleistocene and Qmo middle to early Pleistocene. Qm and Ql are typically found on moderately dissected to dissected portions of alluvial fans and fan terraces. The oldest Quaternary unit found in the study area lies just to the southeast the apex. Qmo is found on older, heavily dissected fan terraces.

6.1.3 Topography

As seen in Figure 6-7 the topographic contours bow slightly in the downstream direction near the apex, although bowed contours are visible over a larger scale landform of which the Lost Dog Wash Fan is one element. The lack of well-defined contour bowing on the Lost Dog study area of this report is due to the scale of the USGS mapping and the affect of the coalesced bajada surface. It can also be seen that the slope decreases in the downstream directions because the contours in the toe of the fan are more widely spaced than the contours near the apex.

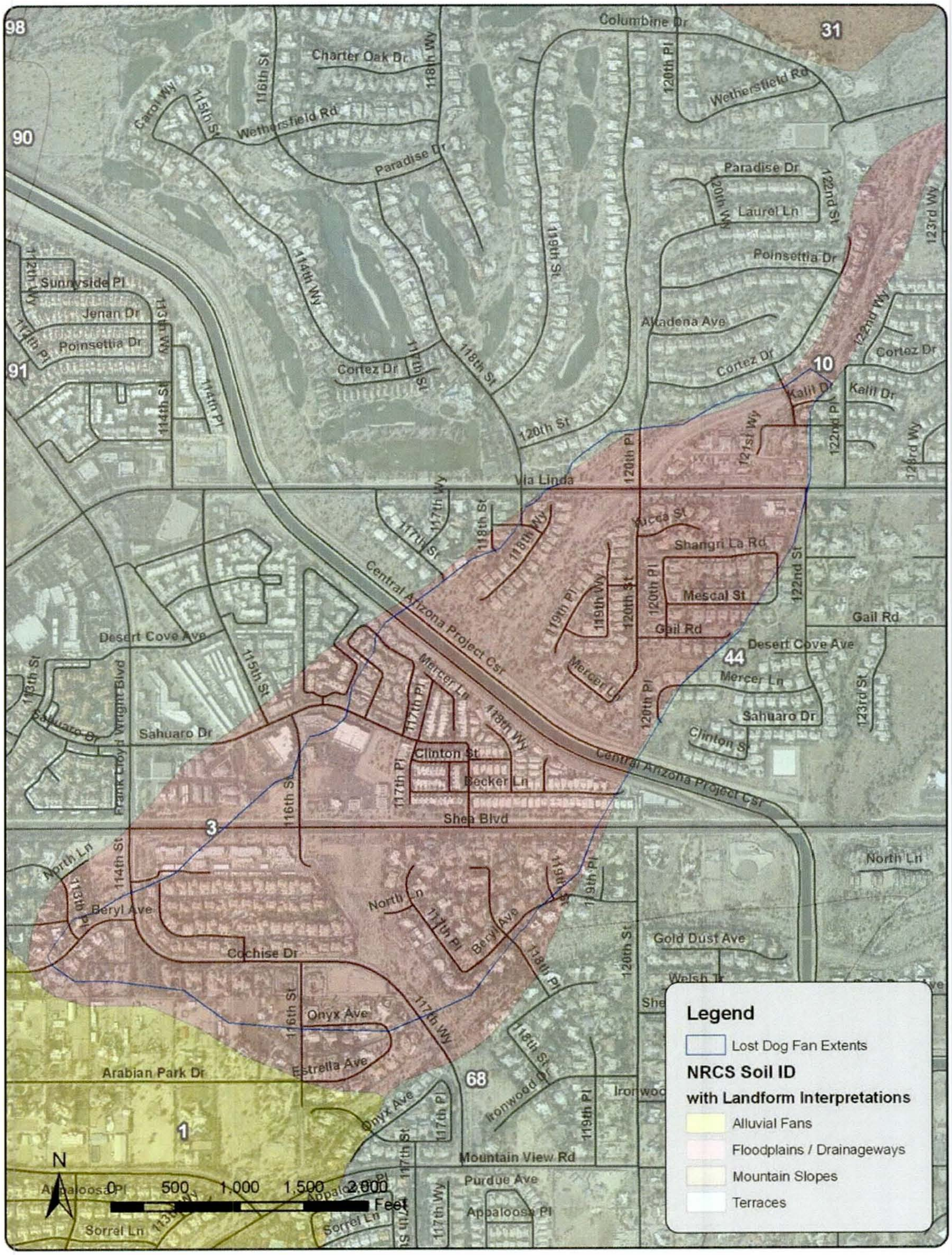

Figure 6-5 NRCS Soils: Lost Dog Fan.

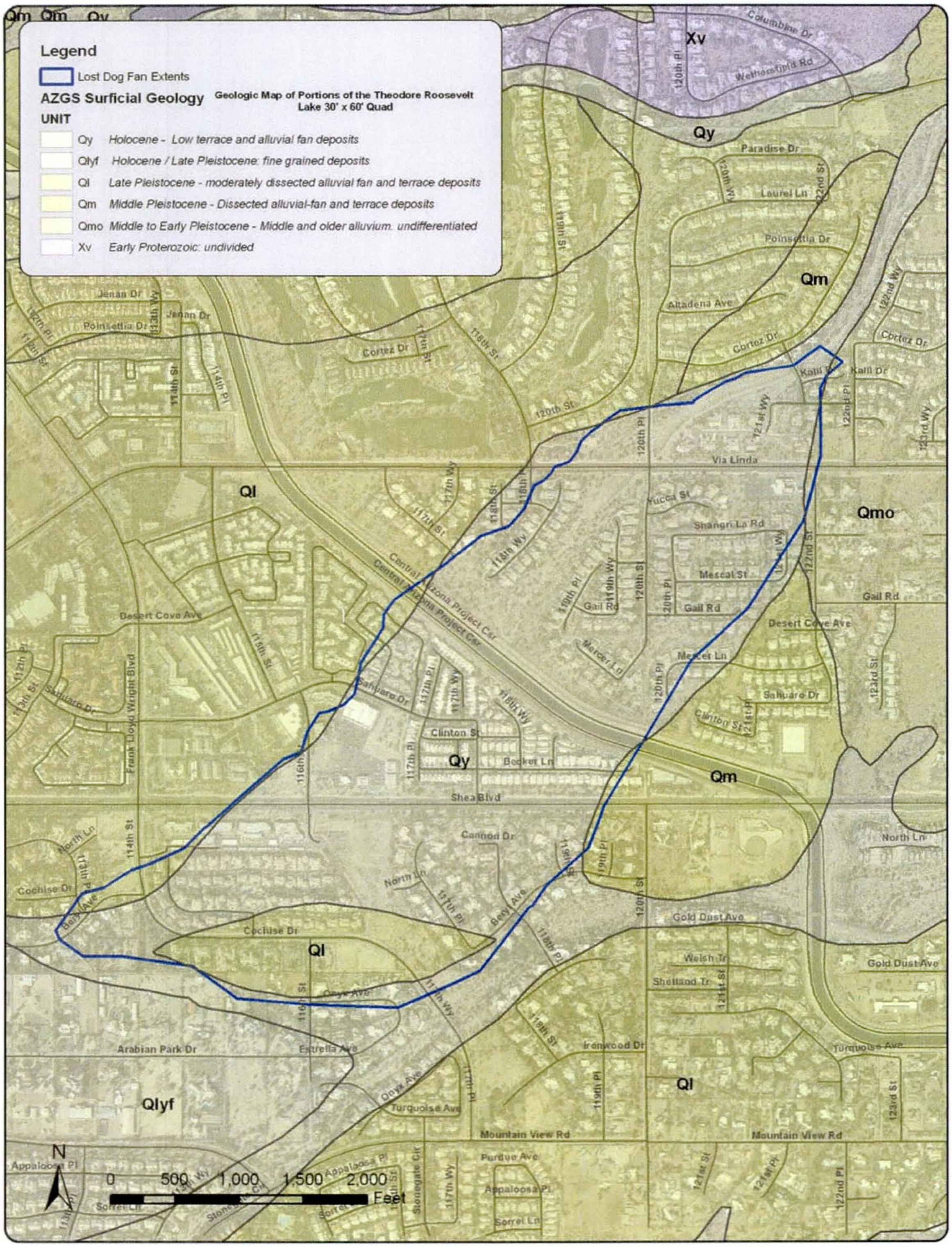

Figure 6-6 AZGS Geology: Lost Dog Fan

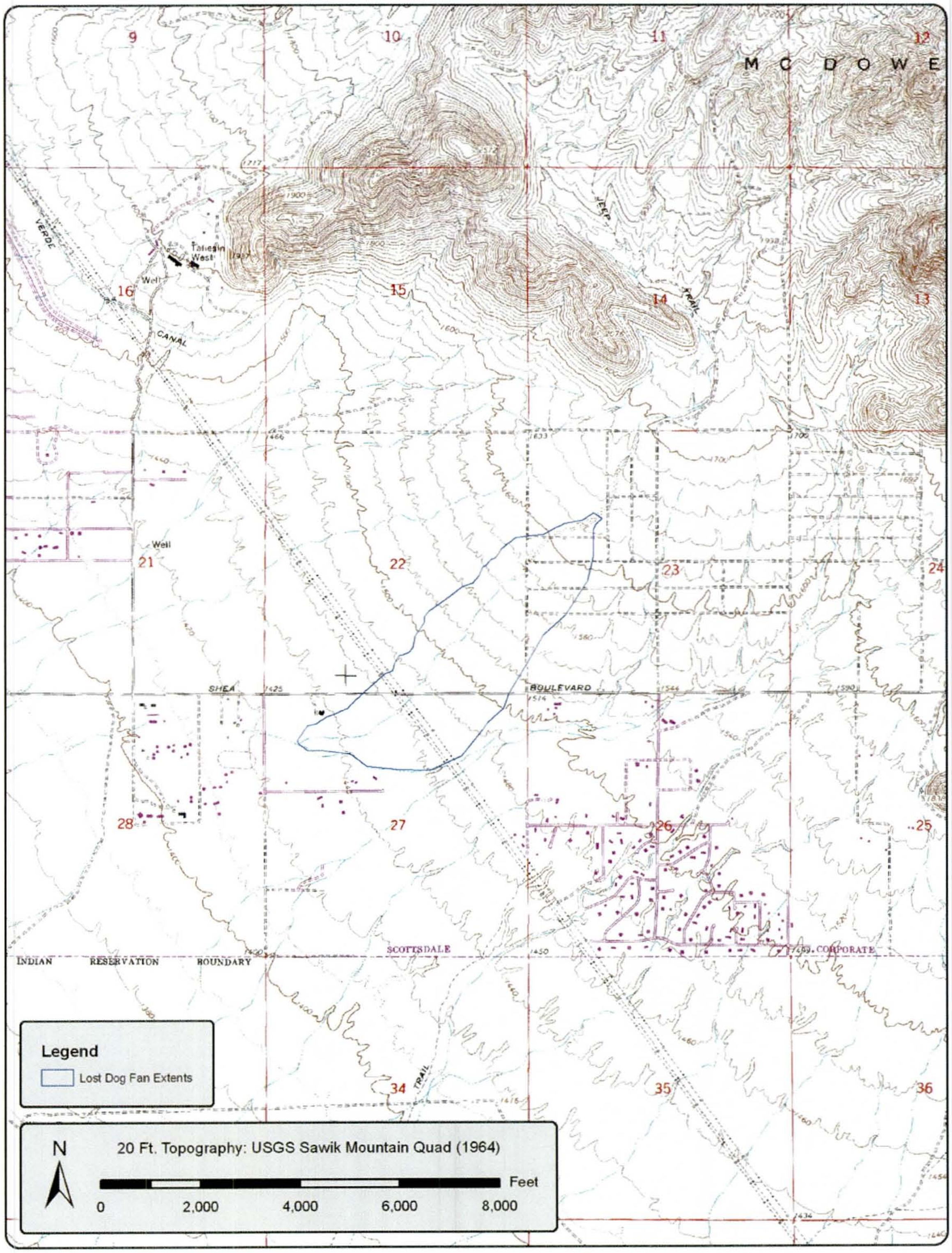

Figure 6-7 Lost Dog Fan Topographic Mapping.

6.1.4 Watershed Parameters

Item	Value	Source
Watershed area (upstream of apex)	2.8 square miles	USGS Quads
Watershed slope (3 miles to 1 mile up stream) (1 miles upstream to apex)	4.2 % 2.7 %	USGS Quads
Fan slope (Apex to toe)	2.5 %	USGS Quads
Q100 at apex	5,000 cfs	Lost Dog Wash Flood Control Project Concept Study [Aug 1995]
Q100 at apex	3,735 cfs	Hydrologic Analysis of Lost Dog Wash CAP [1991]
Fan Profile Shape	concave	USGS Quads
Max Elevation in Drainage Area	3,804	USGS Quads
Elevation at apex	1,625 feet	USGS Quads
Minimum Elevation in fan	1,440 feet	USGS Quads

Figure 6-8 Watershed and Fan Parameters

Structure	Type / Date	Location
CAP – Hayden-Rhodes Aqueduct Dike	Levee	Transverses mid fan
Via Linda / 120th St Con Arch Culverts	Three 20' x 8' Con-arch culverts	Via Linda Road / 120th St.
Channelization (120th / Via Linda to the CAP Dike)	Natural wash bottom, contained with retaining wall on left and right bank	Between the CAP dike and the crossing at Lost Dog Wash crossing at Via Lind Rd.
Channelization (122nd St Bridge to Via Linda)	Naturally lined trapezoidal channel	Lost Dog Wash between 122nd St Bridge to Via Linda Rd
Lost Dog Trailhead Con-arch culverts	Three 36' x 11' arch culverts	Upstream of the apex near the intersection of 124th St and Columbia St.
Development		
Via Linda Estates	Subdivision	On fan, upstream of the CAP and downstream of Via Linda Road.

Figure 6-9 Development & Structure Information

6.1.5 PFHAM Stage I

Task 2.3.3 requires that the pre-development landform be classified as to the "probable" landform type using the PFHAM Stage 1 categories. A PFHAM Stage 1 landform classification for an alluvial fan consists of the following elements:

- *Composition.* The landform is composed of alluvium (sediment material transported by the streams that formed the landform.
- *Morphology.* The landform has the shape of a fan, either partially or fully extended.
- *Location.* The landform is located at a topographic break where the primary watercourse loses capacity.

The Lost Dog Fan landform is shown to be composed of alluvium, as shown by the NRCS detailed soils mapping (Figure 6-5) and AZGS surficial geology mapping (Figure 6-6). As shown in Figure 6-7, the landform has the radial contours characteristics of a partially extended fan. The site is located at the topographic break formed where the main wash exits the shallow canyon that extends to the McDowells' mountain front and the channel changes from a single thread channel to a bifurcated distributary pattern (Figures 6-4 and 6-7). Therefore, the landform is properly classified as an alluvial fan landform.

6.2 Development History

6.2.1 Development History Timeline

Historical aerial photographs of the study area are provided on the following pages, each with an outline of the active alluvial fan delineated from the 1976 aerial photograph. This delineation is included as a point of reference because the landform becomes obscured with the build-out of residential development and transportation infrastructure. All of the aerial photography was obtained from the FCDMC.

The oldest aerial image of the study area is from 1962. At this time, the major flow paths were on the west side of the fan and can be seen as a network of distributary flow channels. There is no development in the study area in the 1960's. At this time, Shea Boulevard was an unpaved road, and its east-west alignment can be seen across the fan of toe. Local unpaved subdividing roads also can be seen dissecting the fan downstream of the apex.

By 1976, the only additional infrastructure in the study area was improvements made to Shea Boulevard. Documentation was unavailable in regards to whether the Shea Boulevard improvements of the time had installed dip crossings or culverts to convey the water past the road crossing. The distributary channels are more distinct on the western side of the fan in 1976. In addition, small channels that split from the apex at the upper north eastern portion can also be distinguished.

By the early 1980's, the Hayden-Rhodes Aqueduct, part of the Central Arizona Project (CAP) canal had been constructed across the midsection of the fan, and which intercepted flow from Lost Dog Wash. While the CAP was able to provide hydrologic design reports, no design construction plans for this reach were available. From field observation we know that no cross drainage was provided to allow flow from Lost Dog to cross the CAP. The CAP ponds water from Lost Dog Wash and routes it northwest along the CAP embankment to a large retention area where there is a water crossing underneath the CAP. Since the time the CAP was built, the alluvial fan landform downstream of the CAP has been effectively cut off from any future flow. A restudy of the hydrology of Lost Dog Wash was conducted by the CAP at the request of the City of Scottsdale in 1991. The estimated 100-year peak discharge at the alluvial fan apex was computed to be 3,735 cubic feet per second (Hydrology Analysis of Lost Dog Wash, p. 6).

By 1993, improvements were made to Via Linda Road. The Via Linda alignment is 0.5 miles north of Shea Boulevard and crosses the fan about 1,500 feet below the hydrographic apex. By 1993, much development has taken place near the fan but nothing, except Via Linda Road, had been built on the fan upstream of the CAP.

By 1997, homes had been built along both sides of the channel upstream of the apex in the Sonoran Arroyos development. The channel at the apex was levied on both sides before crossing under North 122 Street, which was built across the apex. The 122nd Street crossing is a two-span bridge, as seen in the site photographs that follow. In the following two years the fan downstream of the apex was channelized from the 122nd Street crossing to Via Linda Boulevard. This naturally lined trapezoidal channel takes flow from the apex along the west side of the fan surface. The Lost Dog channel then crosses underneath the intersection of Via Linda Road and North 120th Place in a large multi-cell arch culvert (80 feet wide by 300 feet long). Lost Dog Wash exits arch culverts and flows downstream 1,500 feet until it reaches the CAP ponding area. Between the culverts and the CAP, Lost Dog Wash is contained in what was labeled on the subdivision plans as a "Vista Corridor." Along this corridor homes now line each side of the channel downstream of the Via Linda crossing. The native predevelopment flora has been left in the wash bottom indicating that this portion of the wash is still at the natural grade.

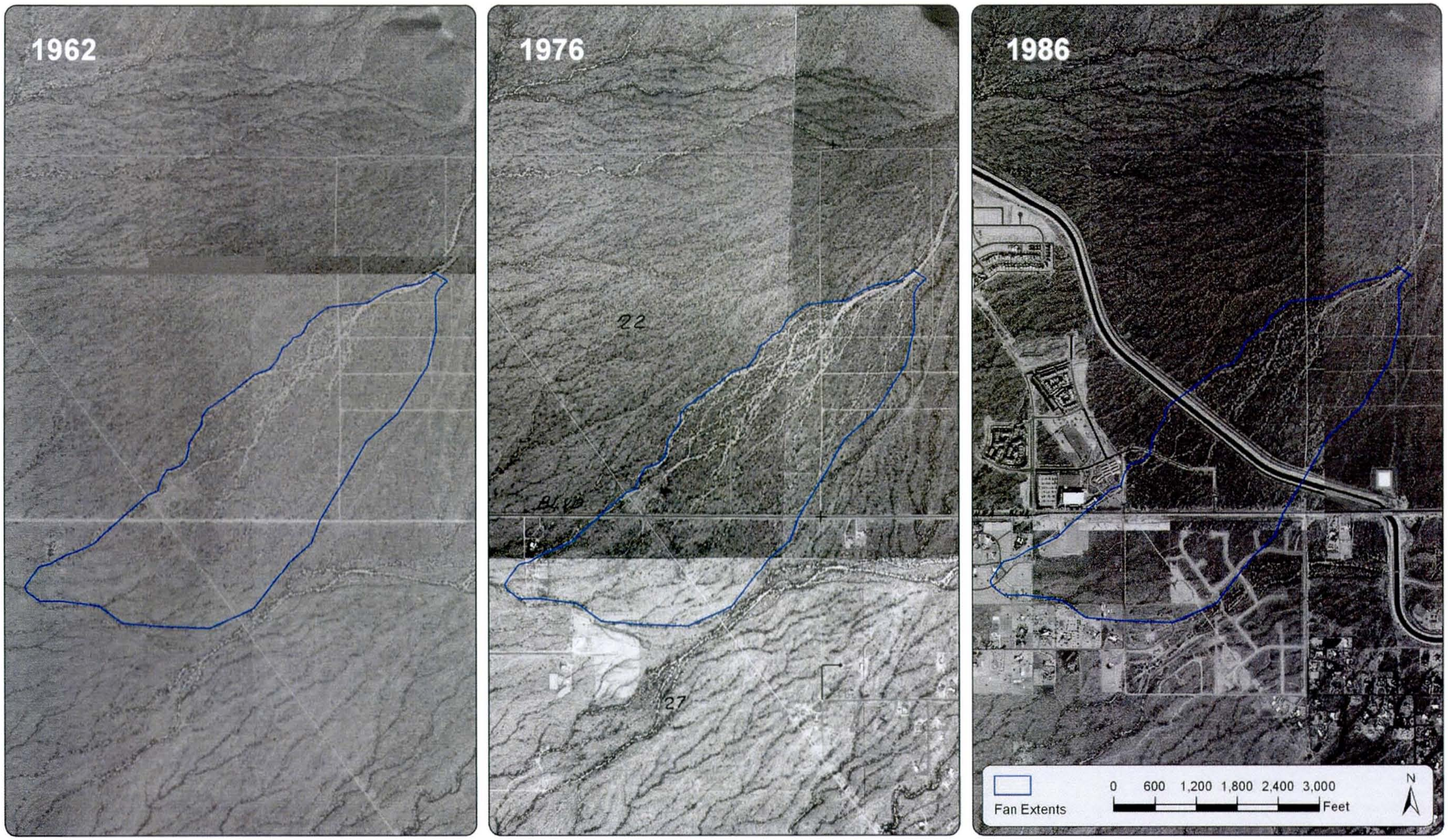

Figure 6-10 Historical Aerial Photos: Lost Dog 1962 – 1986.

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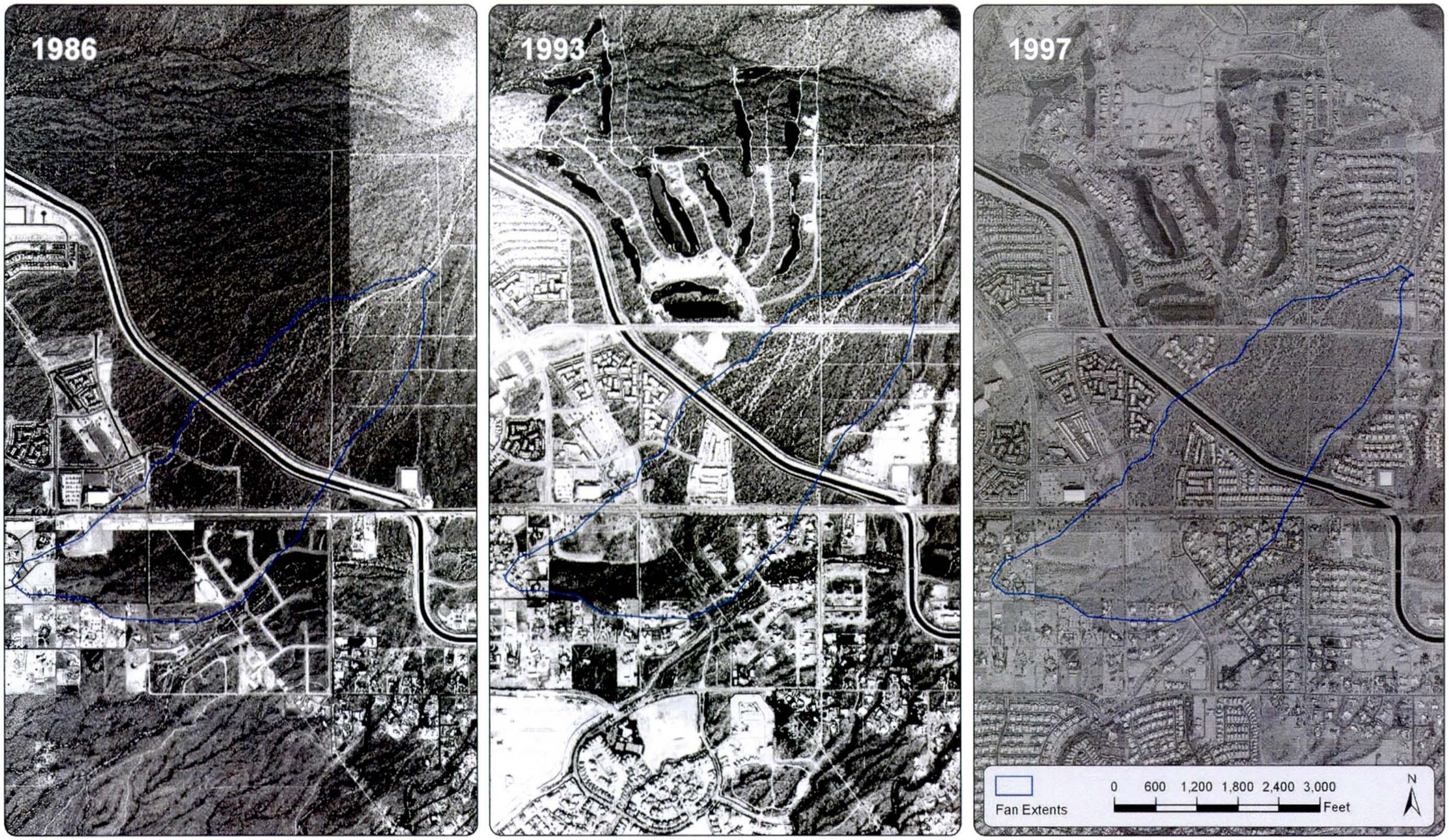

Figure 6-11 Historical Aerial Photos: Lost Dog 1986 – 1997.

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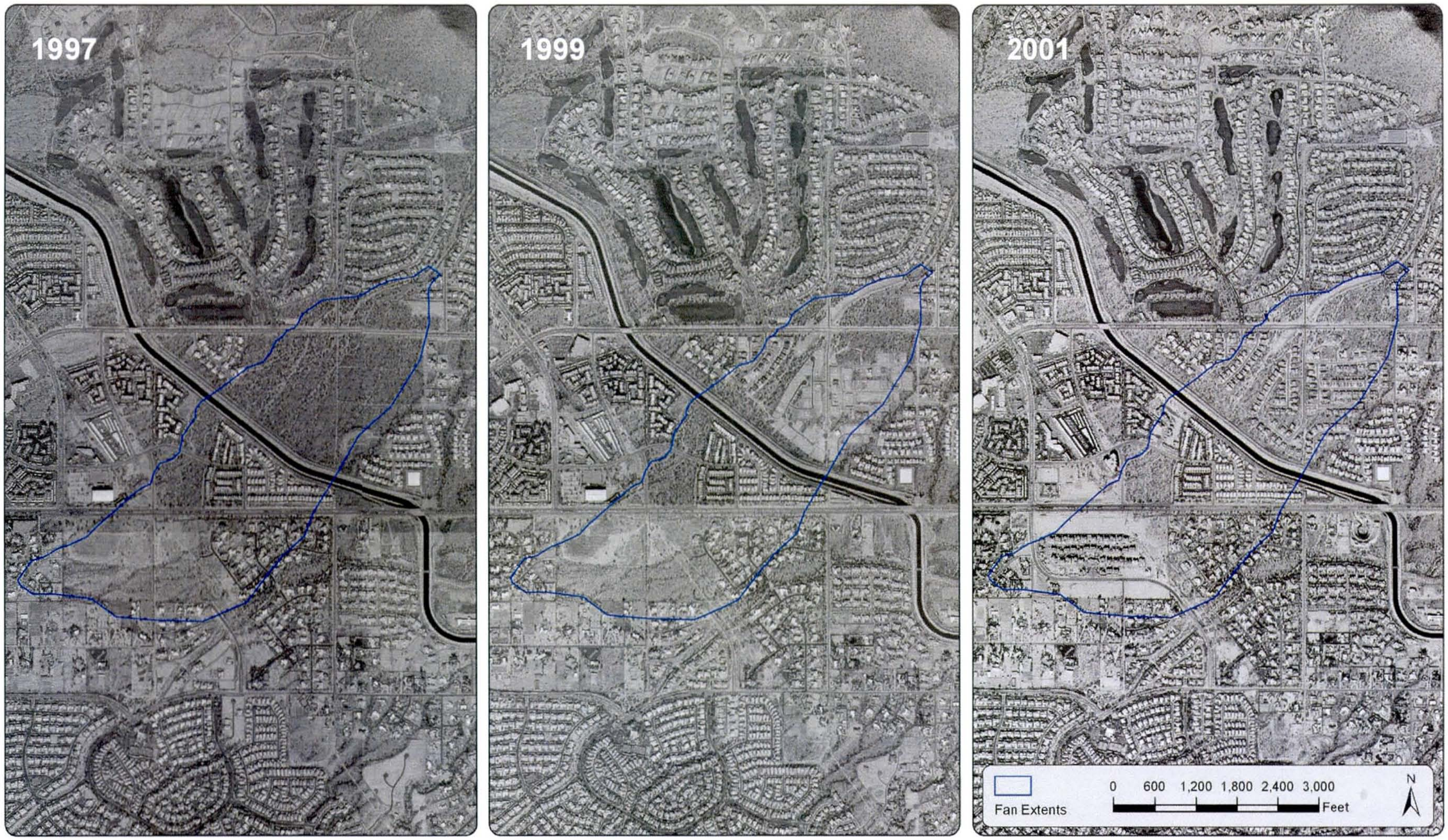

Figure 6-12 Historical Aerial Photos: Lost Dog 1997 – 2001.

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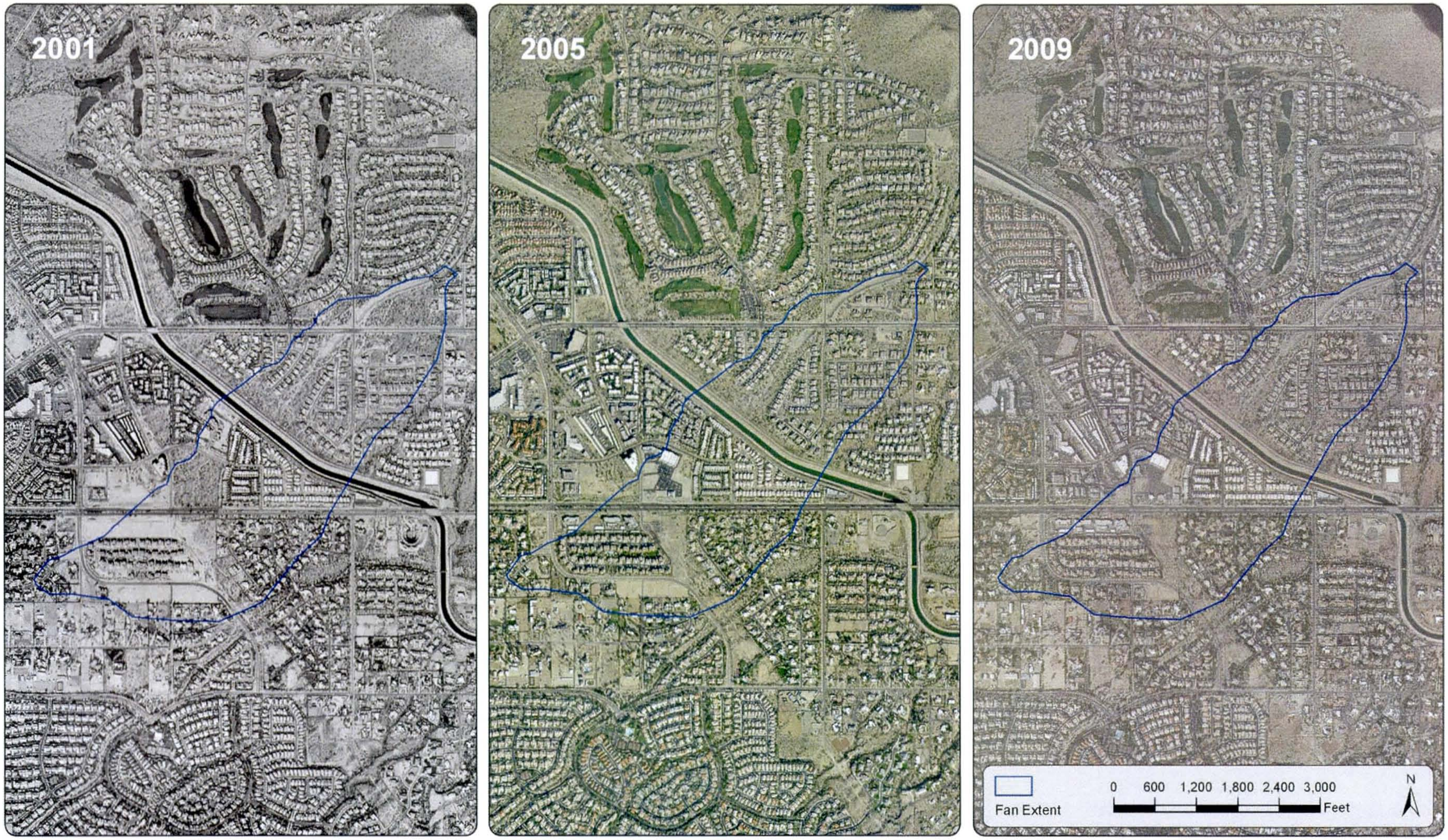

Figure 6-13 Historical Aerial Photos: Lost Dog 2001 – 2009.

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6.2.2 Field Photograph Locations

The figure below identifies the subdivision on the left hand side. The right hand side figure below identifies the major structures and channel reaches, along with the locations for each of the field photos. The number of each field photograph is included in the caption below the photograph.

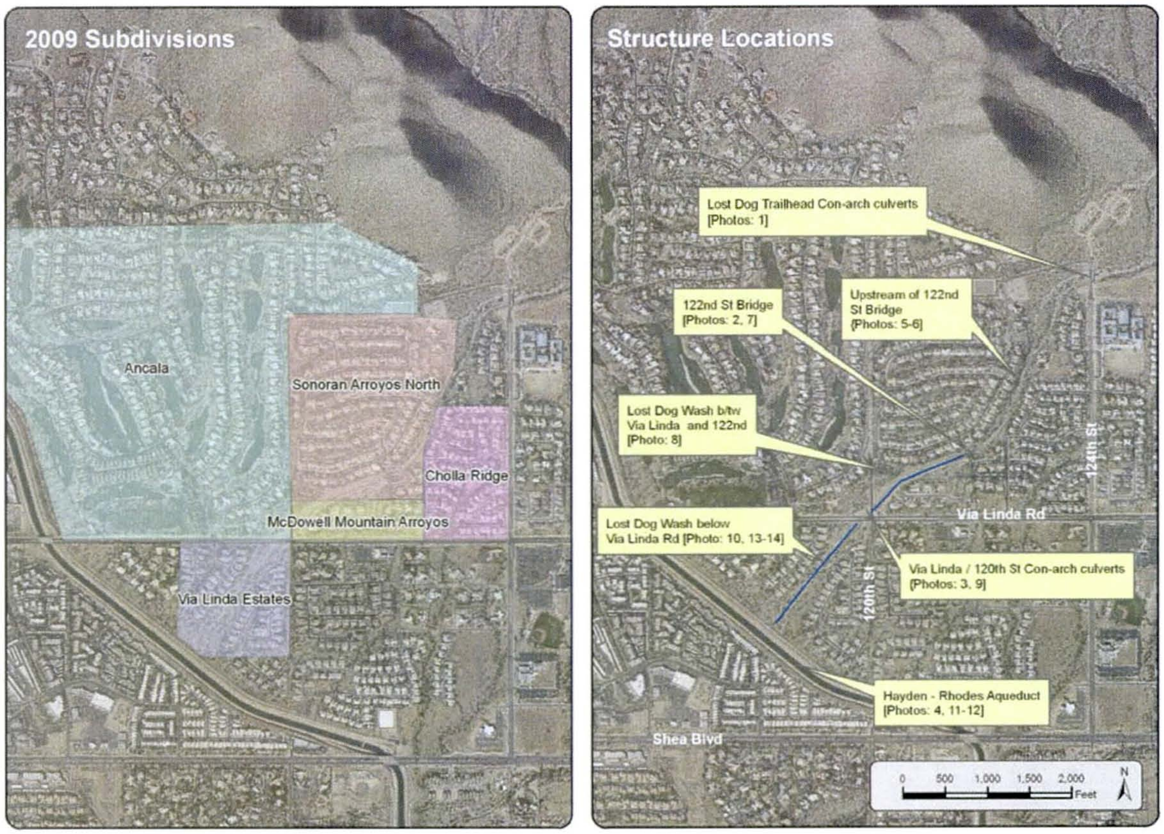
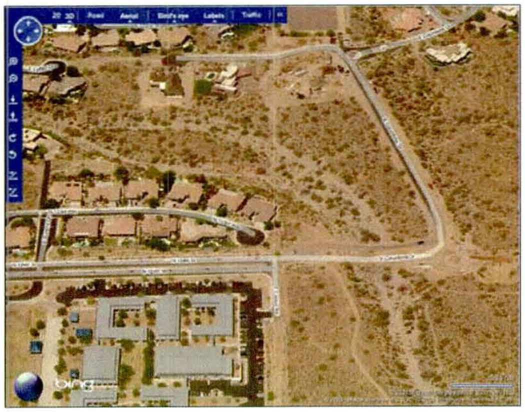
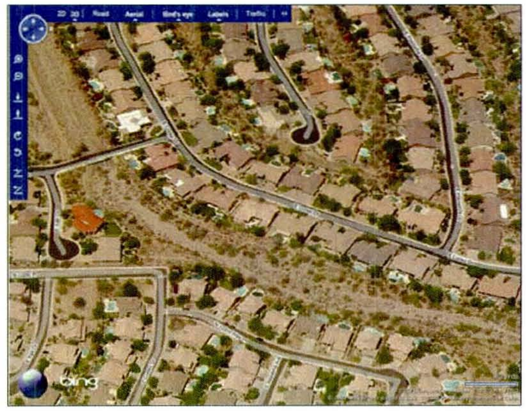


Figure 6-14 Lost Dog Fan Subdivisions & Structures.



1. Lost Dog Trailhead (124^{th} St / Columbia)
Source: bing.com



2. Looking Downstream at 124^{th} St bridge
Source: bing.com

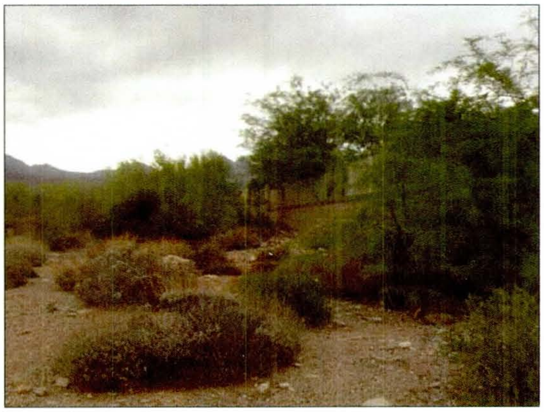
3. Via Linda / 120^{th} St culverts
Source: bing.com

4. Oblique view looking at CAP dike
Source: bing.com

5. Lost Dog Wash upstream of 122^{nd} St
Looking Upstream

6. Lost Dog Wash upstream of 122^{nd} St
Looking upstream

 7. Lost Dog Wash at 122nd St Bridge	 8. Lost Dog Wash at 122nd St *Looking downstream*
 9. Via Linda Rd / 120th St Structure *Three 20' x 8' Con-arch culverts, 225 L.F. in length*	 10. Lost Dog Wash Chnl downstream of Via Linda Rd *Looking downstream*
 11. Hayden-Rhodes Aqueduct levee (CAP levee) *Looking northwest along the levee*	 12. Hayden-Rhodes Aqueduct levee (CAP levee) *Looking northwest along the levee*

	
13. View from CAP levee looking upstream *Can see right bank*	14. Upstream of CAP levee looking upstream *Can see left bank*

6.3 Hydrology

The nearest FCDMC rain gage in the area is located one mile to the east of the Lost Dog fan, near the intersection of Via Linda and 128th Street. The gage has been in operation since July 1990. Since that time, the average annual rainfall has been 8.17 inches, with the wettest years on record in 1992 and 2005 with 15.55 inches and 12.80 inches per year, respectively. The two largest storms to occur in the project area have been:

- 20 year storm: 1.57" in 1 hour on 07-29-2001
- 12 year storm 1.69" in 3 hours on 08-18-1996

The FCDMC also has a gage at Thompson Peak approximately one mile north of the northern boundary of the Lost Dog watershed. The average yearly rainfall at Thompson Peak is 8.29 inches, with a record 16.3 inches of rain recorded in 1993 and 12.36 inches in 2005. The largest storm on record at Thompson Peak was an event on 08-22-1992.

- 60 year storm: 1.30" in 15 minutes on 08-22-2005, the 24 hour total for this storm was 3.27" giving it a 15 year recurrence interval.

Table 6-1 Lost Dog Wash Fan Hydrology

Storm	Lost Dog Wash Precip (ID: 4595)		Thompson Peak Precip (ID: 5945)	
	Rainfall Depth (Inches)	Recurrence Interval (years)	Rainfall Depth (Inches)	Recurrence Interval (years)
7-29-2001	1.57" (1 hour)	20 years	0.43 (24 hours)	<2 yr
08-18-1996	1.69" (3 hours)	12 years	0.91 (24 hours)	<2 yr
08-22-1992	No data	No data	1.30" (15 min)	60 years

6.4 Flood Mitigation Measures

As a result of development on the Lost Dog Wash alluvial fan, the alluvial fan landform no longer conveys flow in its pre-development state. Development on the fan included bridges, elevated roads, culverts, dikes and levees. Flows from Lost Dog Wash were effectively cutoff mid-fan in the early 1980's by the construction of the Hayden-Rhodes aqueduct (CAP). The aqueduct was built with dikes on either side to protect the CAP from cross drainage, including Lost Dog Wash. No design drawings of the CAP dike were available. Field observations combined with measurements taken from recent FCDMC topography of the area indicate that the CAP dike is raised about five feet above the toe of Lost Dog Fan surface. Subdivision plans for Via Linda Estates indicate that any water flowing down Lost Dog Wash is designed to pond at the CAP dike and then flow northwest approximately 1.2 miles to the nearest CAP water crossing. Lost Dog is now completely channelized from the apex with flows routed down fan to be ponded by the CAP embankment. Residential development has taken place over the entire fan surface with homes lining the channelized wash on both sides. The CAP dike has since the early 1980's effectively cut off the lower portion of the alluvial fan from receiving any flow from the apex. After the dike was installed the lower portion is no longer considered part of the active alluvial fan landform as it no longer receives any flow or sediment from the apex.

Besides the CAP dike, the largest engineered structures on the fan are two channelized sections of the wash with the Via Linda culvert crossing connecting the two. The Via Linda Crossing is at the intersection of Via Linda Rd and 120th St. It consists of three 20' x 8' concrete arch culverts. The City of Scottsdale Street / Field Operations Department inspects the structure once per year and is not aware of any flooding or sedimentation issues associated with that structure.

6.4.1 Maintenance Needed

A representative from the Via Linda Estates (south of Via Linda Rd, north of the CAP) contracts out maintenance of the properties bordering the wash. These maintenance companies do not do any work in the wash itself. No sedimentation, channeling, or flooding issues were reported. The City of Scottsdale Street / Field Operations is also unaware of any maintenance issues associated with the structures on Lost Dog Wash. Also the CAP, Central Arizona Project, was unaware of any damage to the dike due to the Lost Dog Wash fan crossing

6.5 Conclusions

Lost Dog Wash, until modern development in the area was an active alluvial fan with an unconfined distributary flow downstream of the apex. Development in the area has confined Lost Dog to a designed channel that routes flood water down the western portion of the fan, under the intersection of 120th Pl and Via Linda Rd. to the CAP where it is ponded up routed and to the northwest to the nearest CAP crossing.

Like the Reata Pass Fan, the Lost Dog Fan has not seen any significant rainfall / runoff events since the fan has been developed to test its drainage structures. The 60 year-15 minute rainfall occurred in 1992, prior to any residential development on the fan. Since that time the largest event was a 20 year rainfall in 2001 and no available source was aware of any problems resulting from that rainfall. The Lost Dog alluvial fan is a site that is substantially untested due to the lack of significant rainfall in the area in the last 20 years.

Based on our analysis, we conclude that the engineered drainage system has performed adequately during the 10 to 20 year period of record, at least with respect to controlling the flow uncertainty and sedimentation associated with active alluvial fans. No homes or structures on or around the fan have been flooded during the period of record. No sediment or erosion concern were reported or identified in this study.

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7. References

Data Structure for Arizona Geologic Survey Digital Geologic Maps, by Stephen M. Richard and Jennifer P. Thieme. Open-File Report 97-5 version 1.3. Arizona Geological Survey. 1997.

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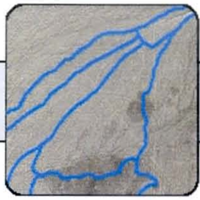
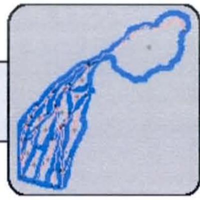
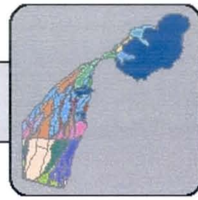
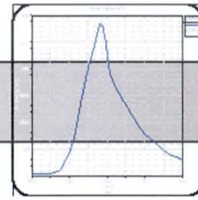
Watershed Work Plan Guadalupe Watershed, Maricopa Arizona, U.S. Department of Agriculture, Soil Conservation Service, January 1971.

Hydrology Analysis of Lost Dog Wash, Central Arizona Project (CAP Archives), 1991

Appendix E:
HEC-1 Modeling Results PowerPoint Presentation

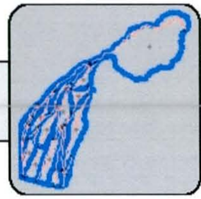





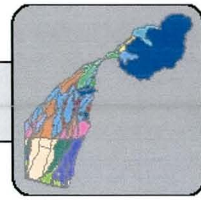
2008C007 Task 2.4

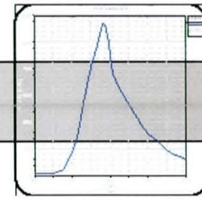
HEC-1 Modeling for Alluvial Fans in Maricopa County

Prepared for: Flood Control District of Maricopa County

By: JE Fuller Hydrology & Geomorphology

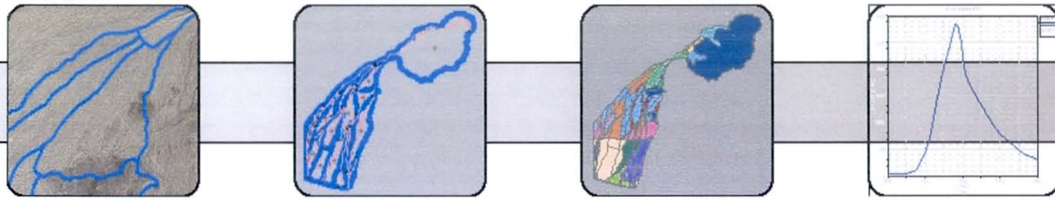






HEC-1 Modeling for Alluvial Fans in Maricopa County

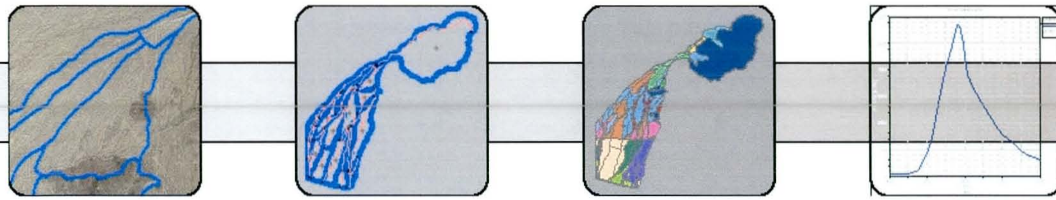
- Overview
- White Tank Fan #36
- Rainbow Valley Fan 12
- Rainbow Valley Fan 1
- Reata Pass Fan



Modeling Approach Overview

Watershed Delineation

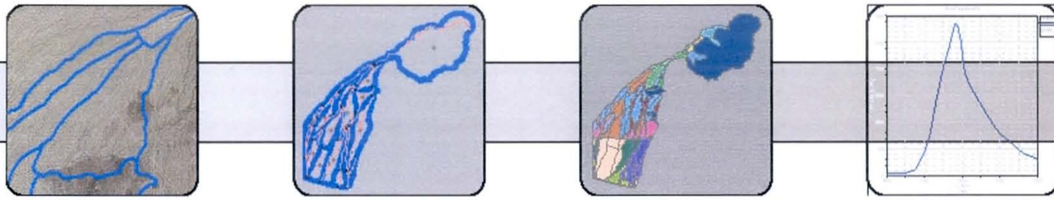
- Simpler is better
- Less is more
- Landform lateral boundaries
- Subbasin size
- Split flow locations



Modeling Approach Overview

Rainfall

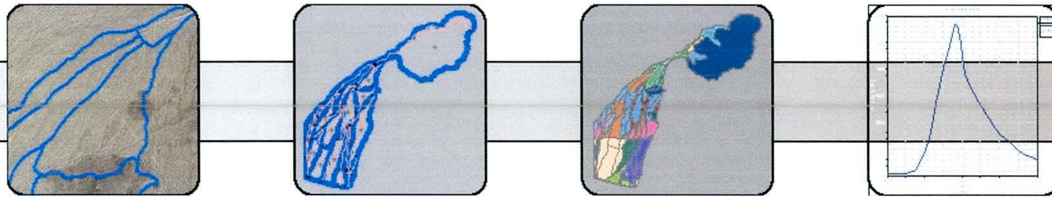
- NOAA 14 Point Rainfall Values
- Mountain vs. Piedmont
- JD Records & Storm Size
- Storm Duration



Modeling Approach Overview

Rainfall Losses

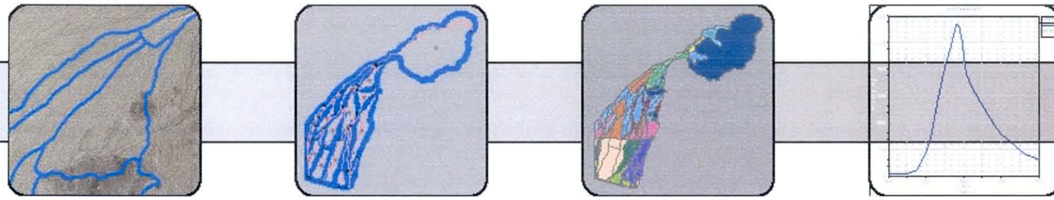
- Green-Ampt
- Rock outcrop assumed 50% effective
- Land use for natural areas based on slope
- DDMSW to compute subbasin average parameters



Modeling Approach Overview

Unit Hydrographs

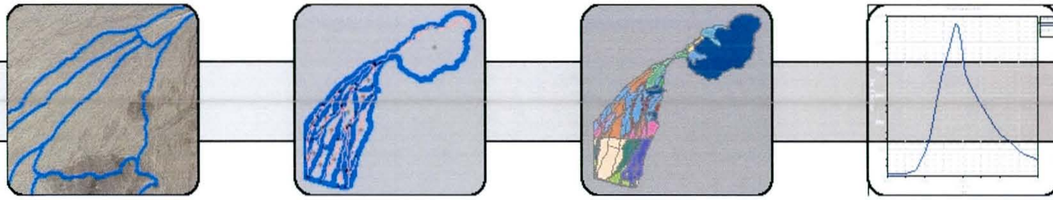
- S-Graph method used
  - Phoenix Mountain
  - Desert/Rangeland
  - Phoenix Valley for developed areas
- Kn based on land use
- DDMSW to compute lag time



Modeling Approach Overview

Channel Routings

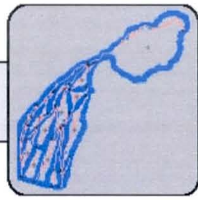
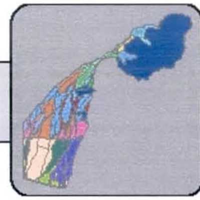
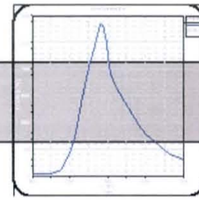
- Normal-Depth method used
- 8-point cross sections
- RL Records for transmission losses over active areas
  - PERCT = 1.0 cfs/ac ≈ 1 in/hr



Modeling Approach Overview

Diversions / Split Flows

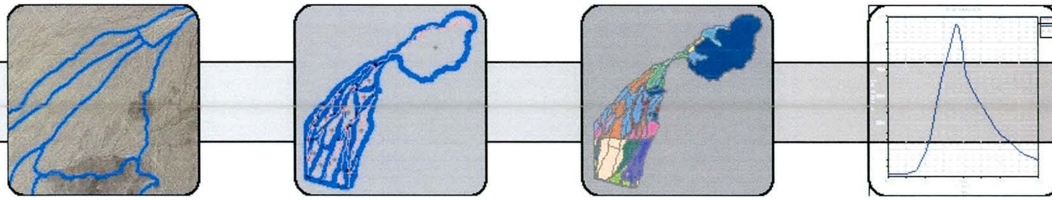
- Over-account in active areas – but not 100-100
  - e.g. 70-70 or 60-60-60
- Hydrographs Hard-coded (QI records)
- Conventional (fixed) diversions in inactive areas

Modeling Approach Overview

Mechanics

- Iterative process with multiple models
  - Mountain & Piedmont
  - Over-Accounting Splits
- Hydrographs Hard-coded (QI records)
  - Use of DSS (ZW)
  - Use of JR
  - Use of KO 7 (PUNCH)



White Tank Fan #36

Summary of Key Data

Drainage Area to Apex = 5.72 sq. mi.

Piedmont Area = 9.9 sq. mi.

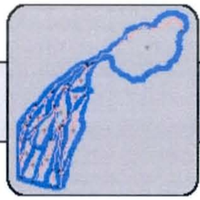
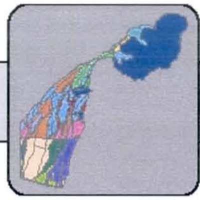
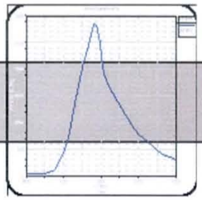
Fan Slope = 0.022

Above Apex Point Rainfall = 4.071 in

Piedmont Point Rainfall = 3.715 in

Apex Q100 = 2,836 cfs

3-way split at apex – 60/60/60 assumed

White Tank Fan #36

Special Elements

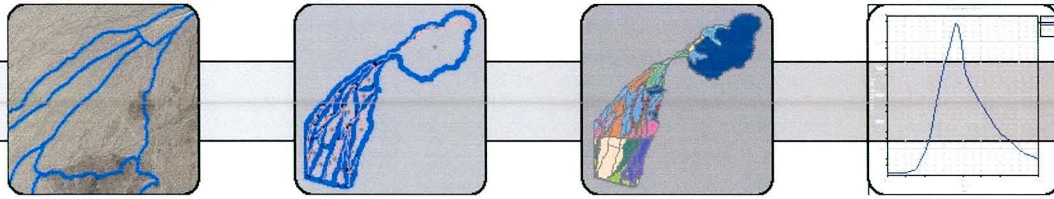
Multiple active areas

Inactive splits too

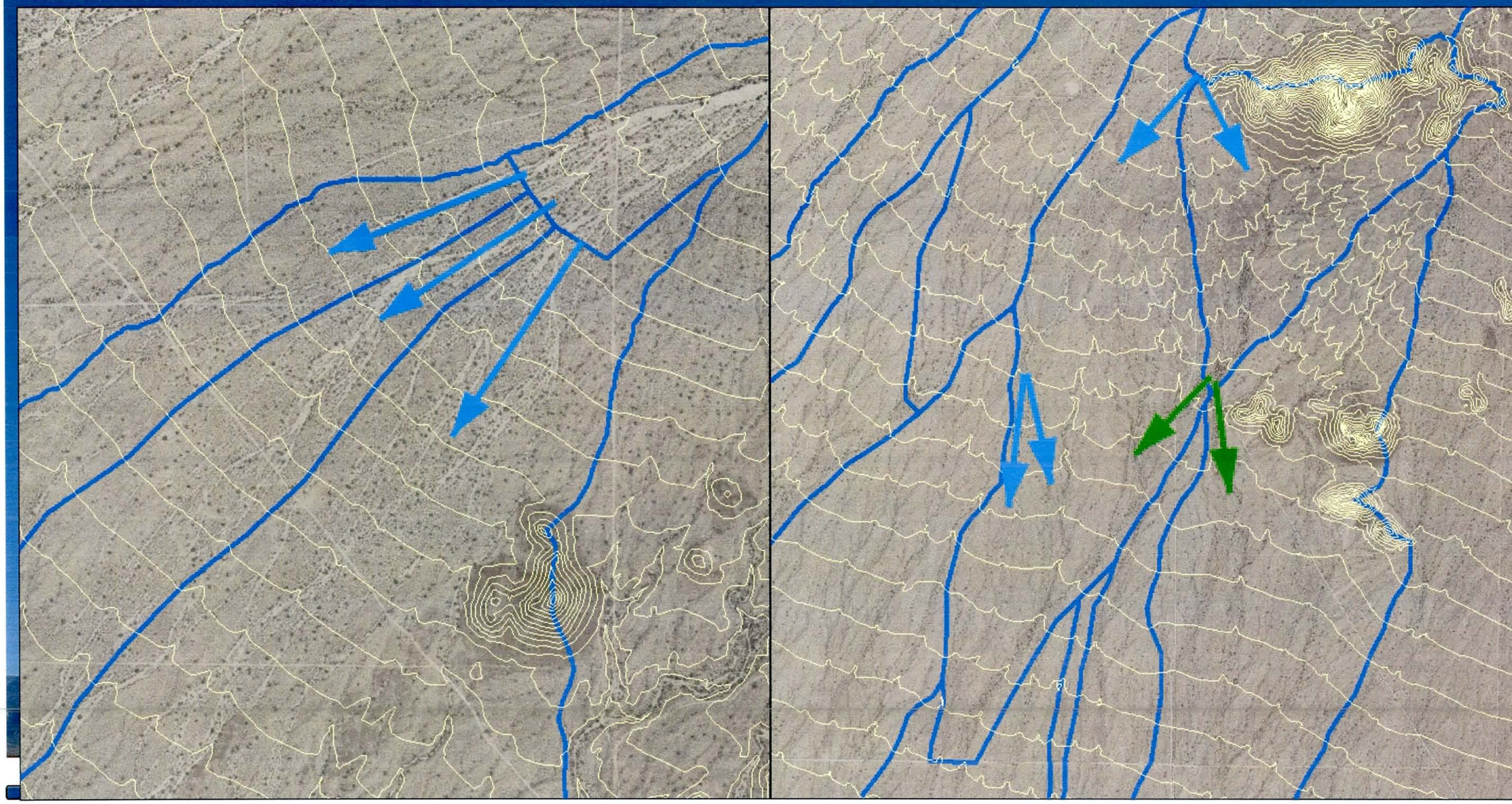
Lateral limits

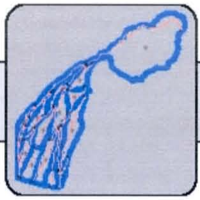
Separate on-piedmont within-fan subbasin

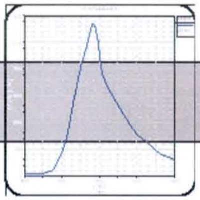
Sun Valley Parkway



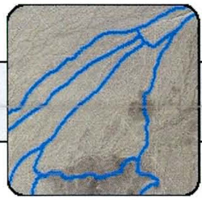
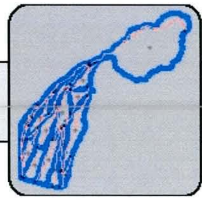
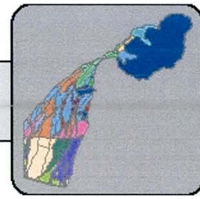
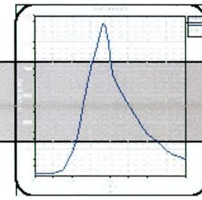
Multiple active areas & inactive splits



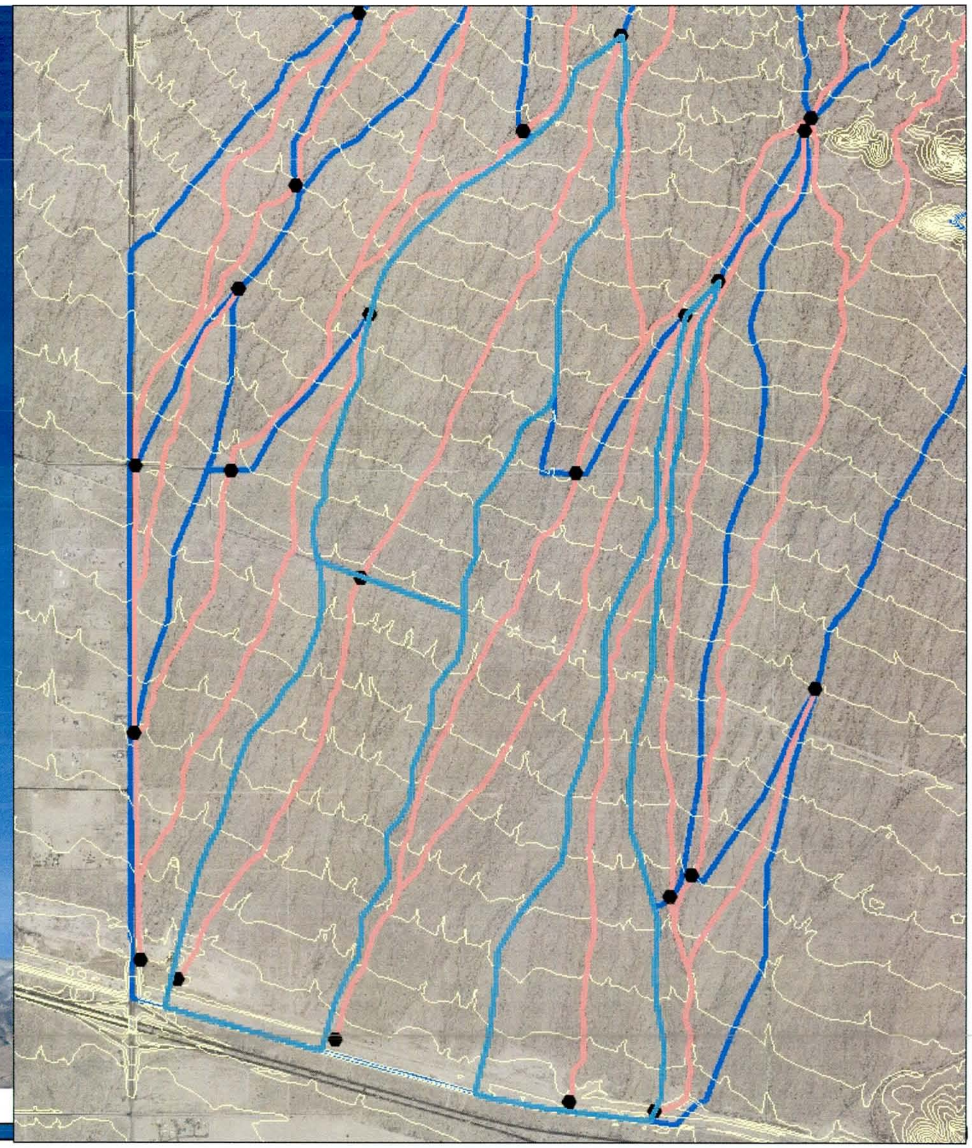



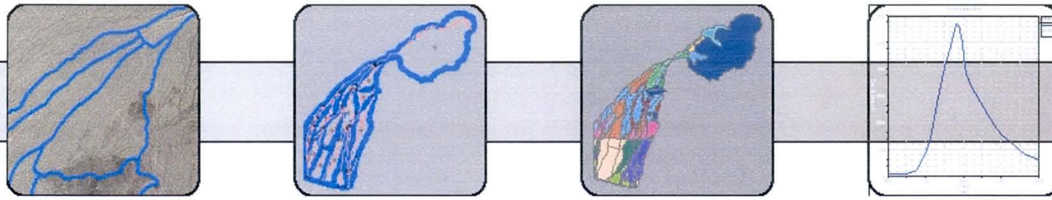


Lateral limits

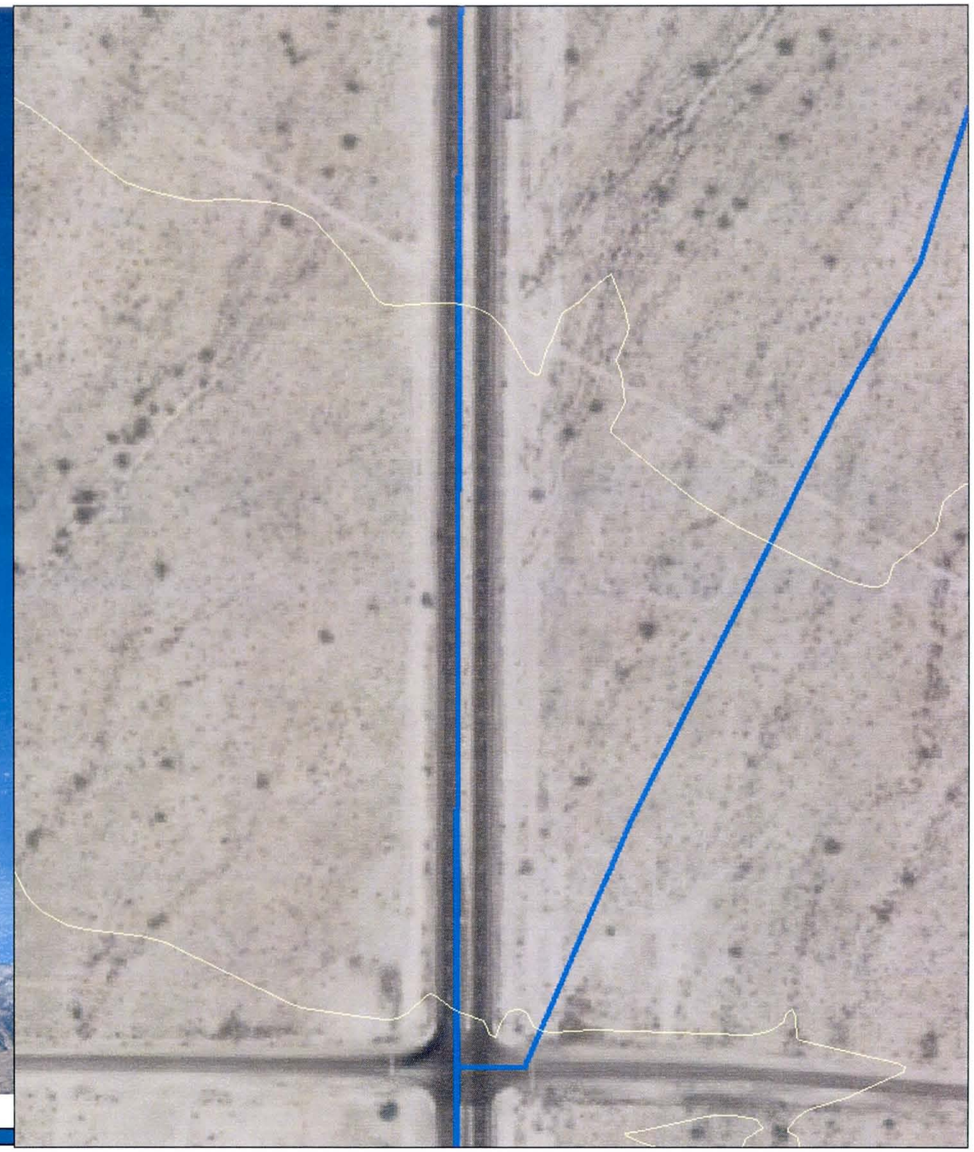






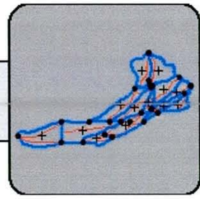
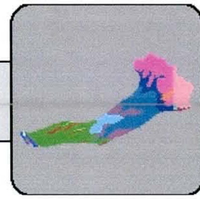
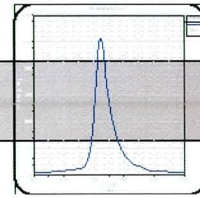
Separate on-piedmont subbasins



Sun Valley Parkway Channel



Rainbow Valley Fan 12

Summary of Key Data

Drainage Area to Apex = 1.09 sq.mi.

Drainage Area on piedmont = 7.0 sq.mi.

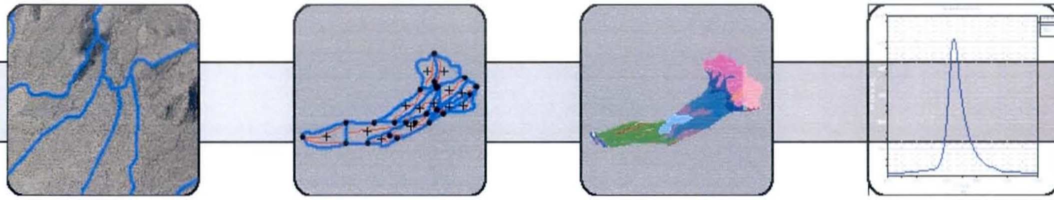
Fan Slope = 0.018

Above Apex Point Rainfall = 3.355 in

Piedmont Point Rainfall = 3.223 in

Apex Q100 = 1,020 cfs

2-way split at apex – 80/80 assumed



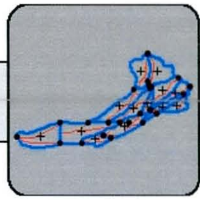
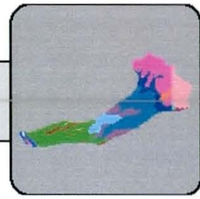
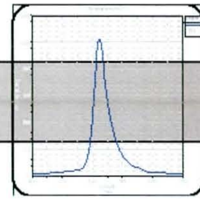
Rainbow Valley Fan 12

Special Elements

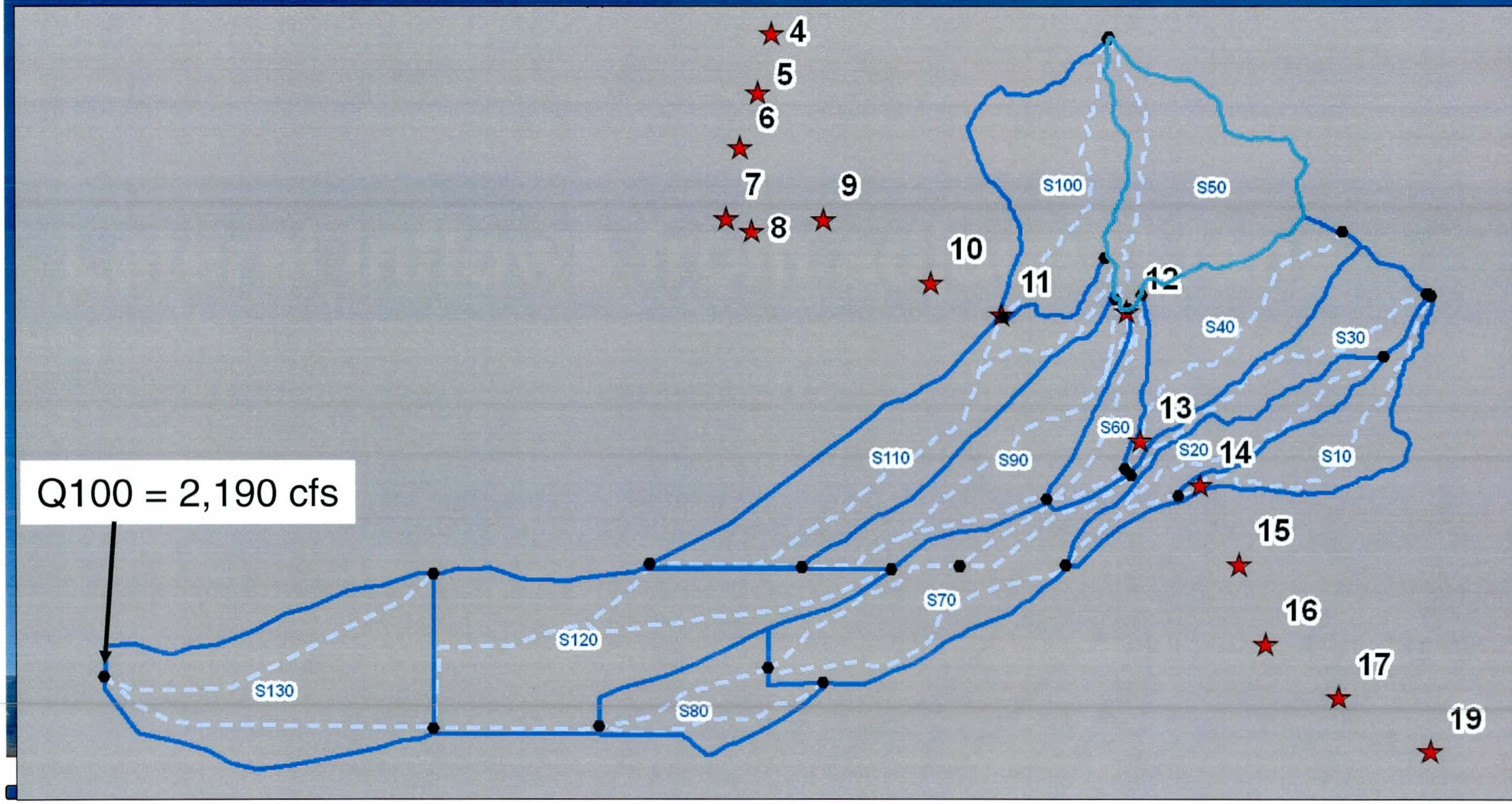
Numerous lateral inflows from other active fans

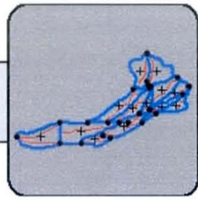
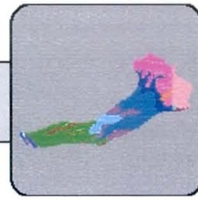
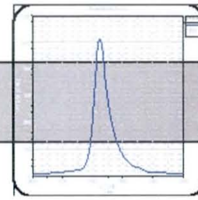
Influence of dirt roads, agricultural features, etc.

Diffuse character of flow and lack of channels on-piedmont

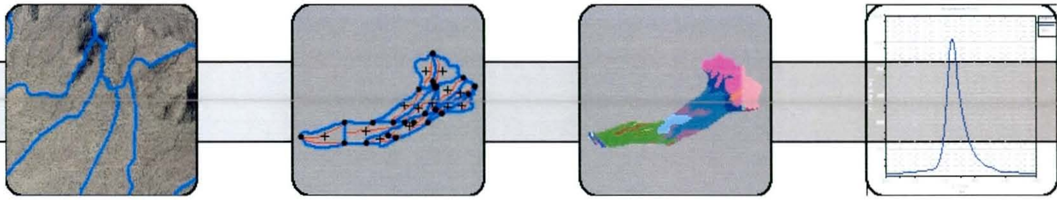





Lateral inflows from adjacent fans

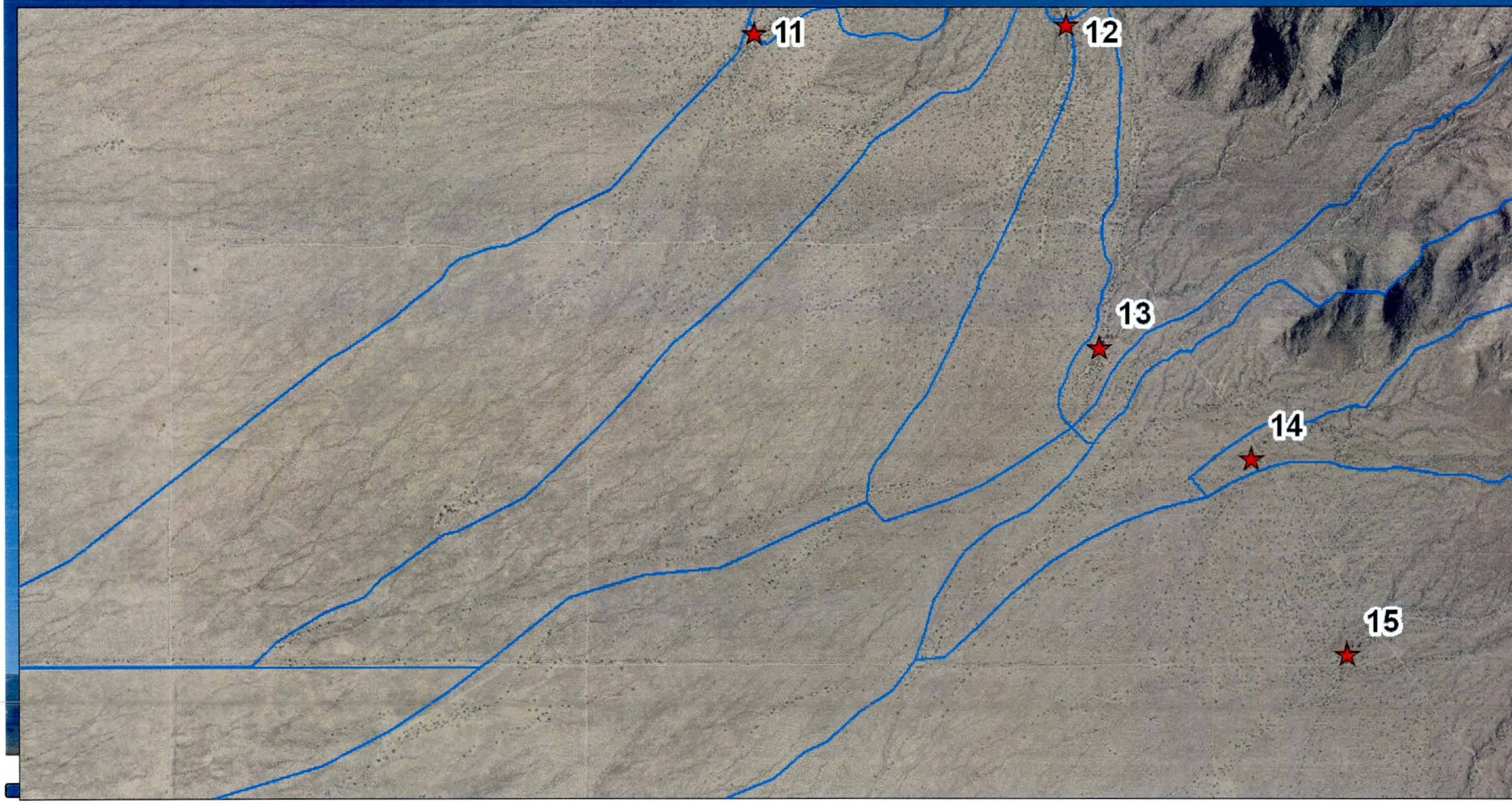


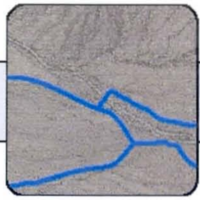
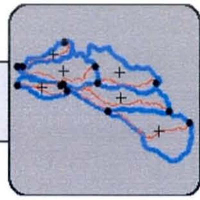
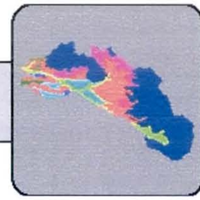
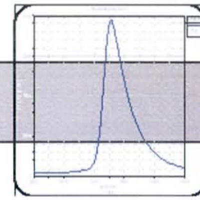





Influence of dirt roads, etc.



Diffuse character & lack of channels



Rainbow Valley Fan 1

Summary of Key Data

Drainage Area to Apex = 7.17 sq.mi.

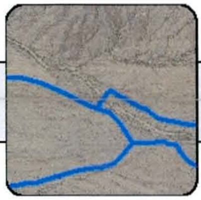
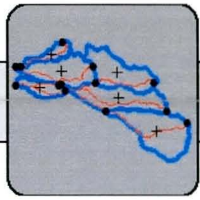
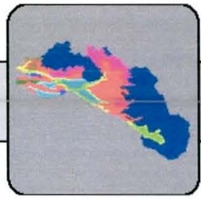
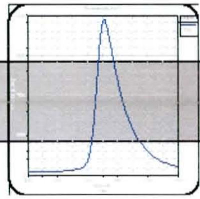
Piedmont Drainage Area = ?

Fan Slope = 0.01

Point Rainfall = 3.417 in

Apex Q100 = 3,900 cfs

No real active area at 100-yr?

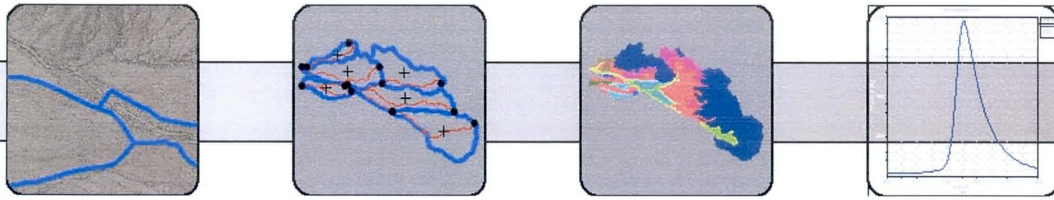





Rainbow Valley Fan 1

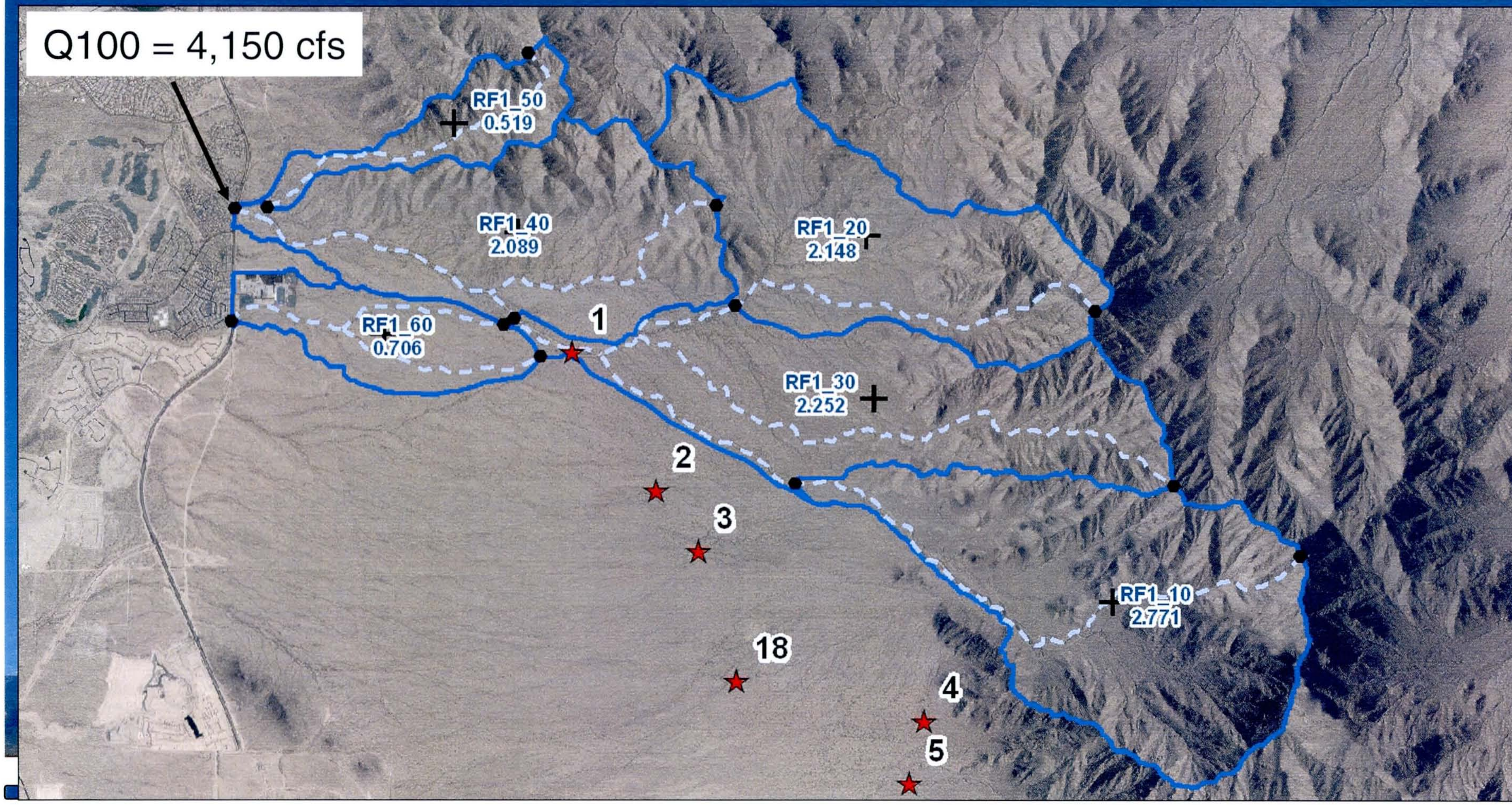
Special Elements

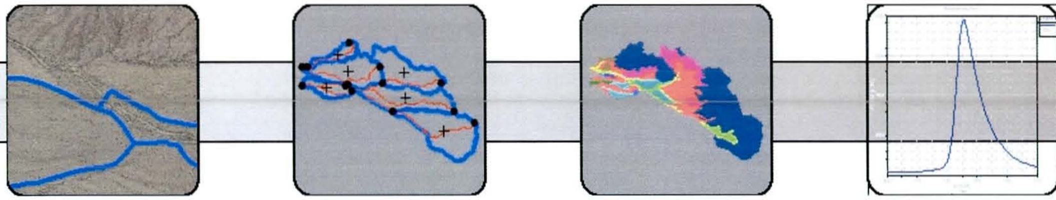
Multiple mountain watersheds upstream of apex

No real active area at 100-yr?

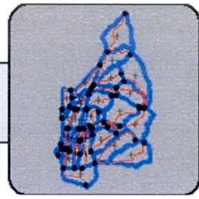
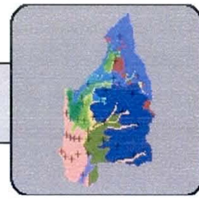
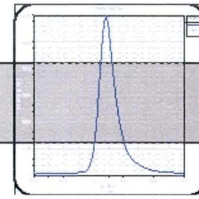


Multiple upstream mountain subbasins





100-year containment?

Reata Pass Fan

Summary of Key Data

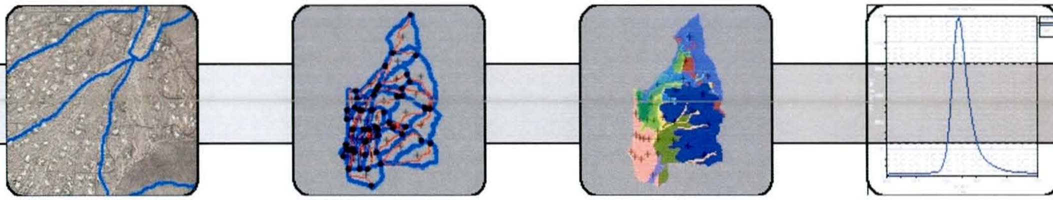
Drainage Area to Apex = 8.06 sq.mi.

Fan Slope = 0.035

Total Watershed Point Rainfall = 4.713 in

Apex Q100 = 11,900 cfs

3-way split at apex – 40 W / 80 middle / 60 SE



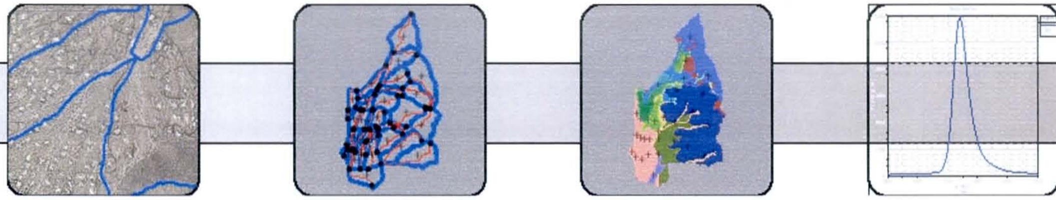
Reata Pass Fan

Special Elements

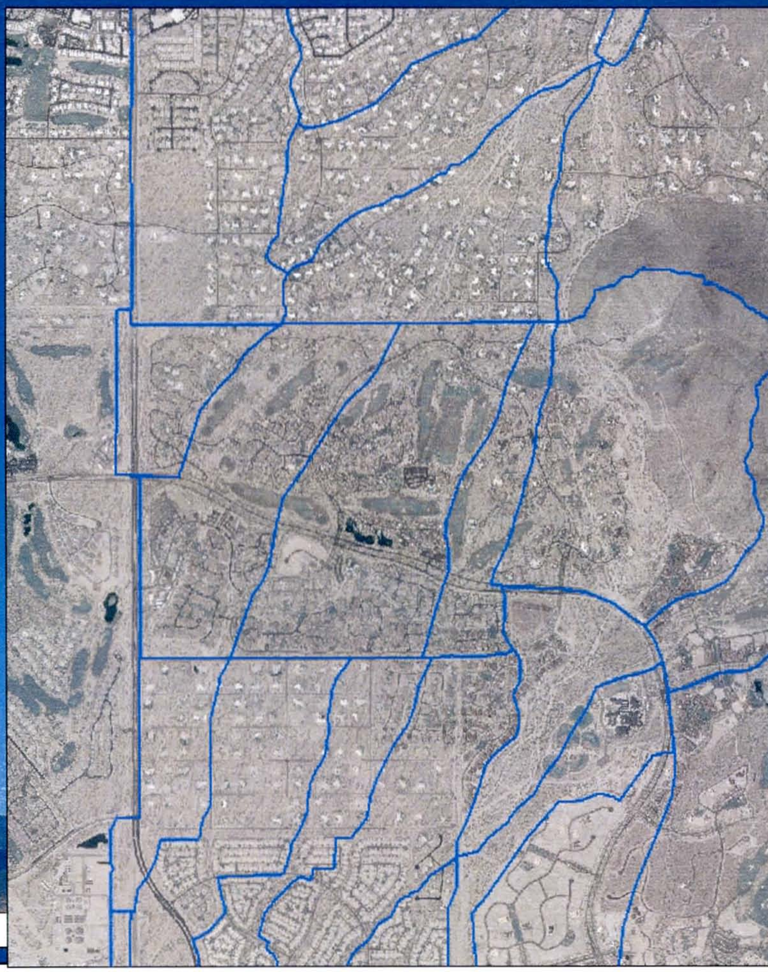
Highly urbanized watershed

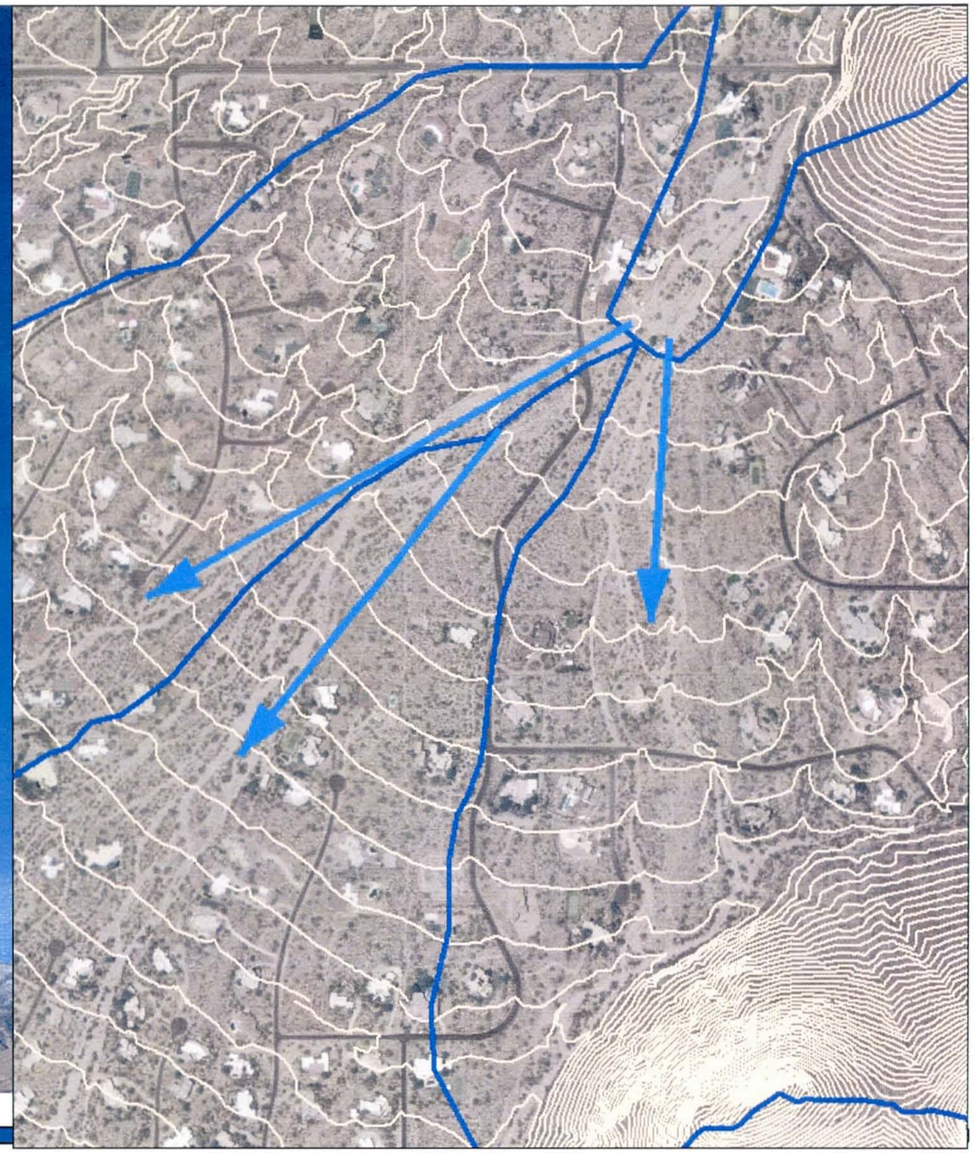
Influence of complex manmade features on-piedmont

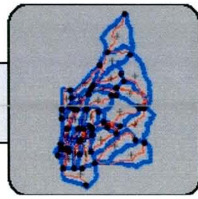
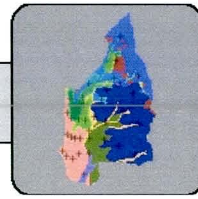
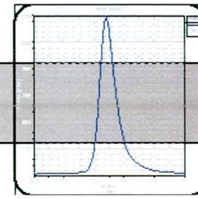
Pace of development



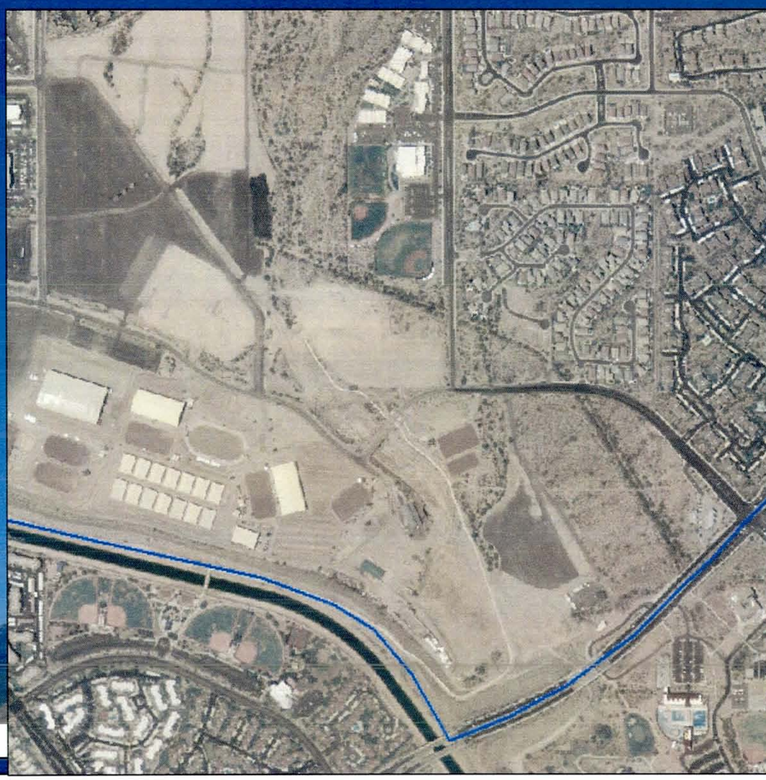
Urbanization

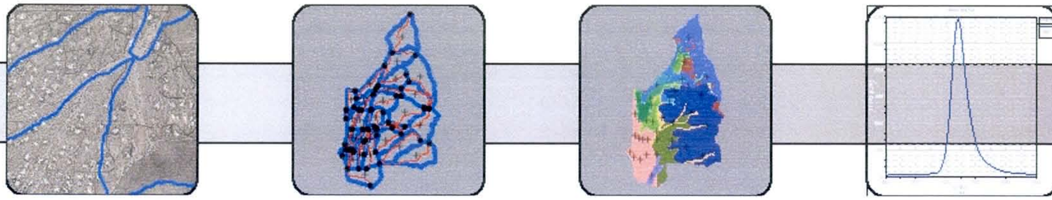




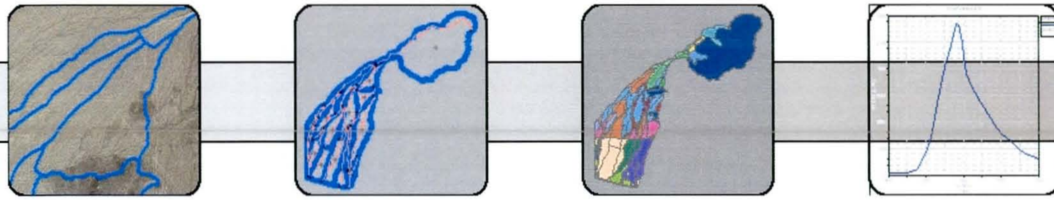





Influence of manmade features



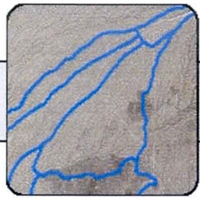
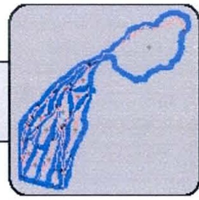
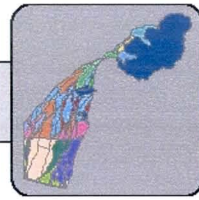
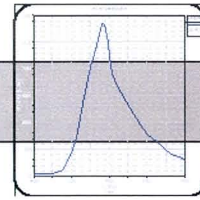



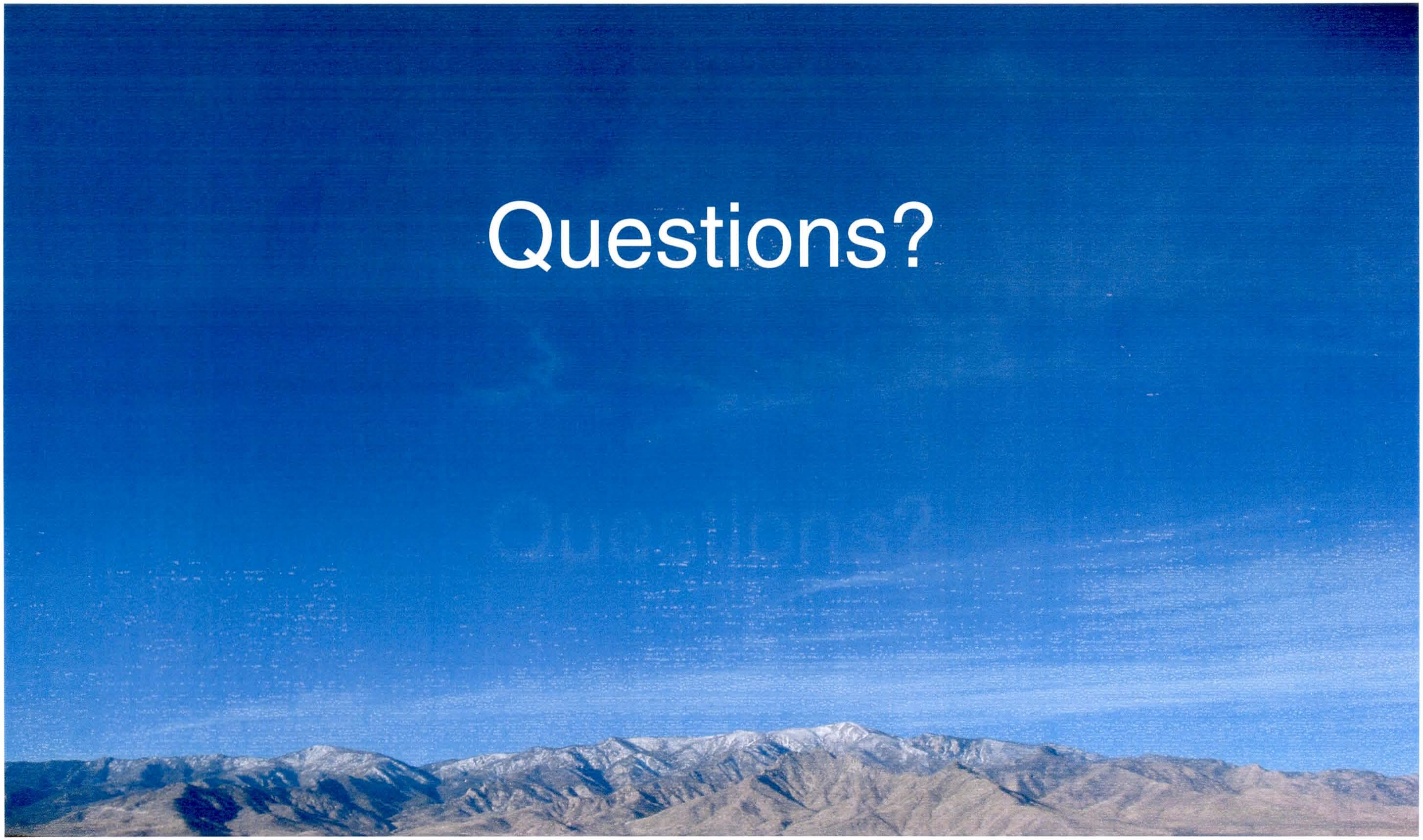
Pace of development



Other Observations

- HEC-1 for FLO-2D vs. just for HEC-1
- New DDMSW works slick
- Utility of geomorph especially Stage 2 info (active vs. inactive)
- Need for compromises


Questions?

Appendix F:
FLO-2D and Sedimentation Engineering Report

Alluvial Fan
FLO2D Modeling &
Sedimentation Evaluation

Tasks 2.4 & 2.5, Contract FCD2008C007

Report prepared by:

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8400 South Kyrene Road, Suite 201
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480.752.2124

Report prepared for:

Flood Control District of Maricopa County
2801 West Durango Road
Phoenix, AZ 85009
602.506.1501

Contract #FCD2008C007
Work Assignment #1, Task 2.5

Registered Professional Engineer (Civil)
CERTIFICATE NO.
26846
JONATHAN E.
FULLER
Date Signed 7-22-2010
ARIZONA, U. S. A.
Expires 03/31/2011

Executive Summary

Aspects of alluvial fan hydraulics and sedimentation were investigated to support refinements of the District's PFHAM methodology. Modeling was performed using FLO-2D, a two-dimensional flood routing and sediment transport model. The modeling evaluation found that FLO2D performed the hydrologic, hydraulic, and sediment transport calculations adequately, and that the model is the best available for the purposes of quantifying flood hazards on active alluvial fans in Maricopa County. Other significant conclusions of the evaluation included the following:

- Frequent floods, such as the 2- to 10-year events, induce channel changes which may not be significant on a single event basis, but may have important cumulative impacts, particularly when large, rare floods occur. However, long-term cumulative sediment impacts are difficult to simulate using any available modeling tool, including FLO-2D.
- The impact of the assumed (or computed) sediment supply was not found to be significant if the sediment inflow point was placed sufficiently upstream of the area of concern. Clear-water inflow and sediment laden inflow models resulted in nearly identical results for the areas downstream of the fan apex.
- Three methods of predicting channel avulsion using FLO-2D were identified: (1) loss of channel capacity was simulated by creating artificial channel blockages, (2) large (Q500 or PMP) discharges were used to overtop existing channels and track overbank flow paths, and (3) depth-velocity plots were compared to existing channel locations to identify potential avulsive flow paths.
- A slope-walk tool was developed to help predict potential avulsive flow paths. The tool identifies alternative steepest slope flow directions, some of which are outside the existing channel network.
- Modeling results reinforce the importance of accurate, detailed topography and appropriate grid size when performing FLO-2D modeling on alluvial fans.
- The range of sediment transport functions available in FLO-2D was evaluated. The results indicate a high sensitivity of the hazard zone delineation. The Zeller-Fullerton appears to predict the most reasonable depiction, but more investigations and calibrations are recommended.
- Wash load fraction of the sediment supply was found to have no significant widespread impact on fan processes.

Table of Contents

1 INTRODUCTION

1.1 OBJECTIVES

The objective of the sedimentation evaluation is to determine and quantify how sedimentation influences flood hazards on alluvial fan landforms in Maricopa County. This information is to be used to refine the Integrated Alluvial Fan Hazard Assessment Methodology.

1.2 SCOPE

The scope of services for this evaluation is described in Tasks 2.4 and 2.5 of Contract FCD 2008-C007, which lists the following:

> *(Task 2.4) The CONSULTANT will prepare FLO-2D models for the alluvial fan areas downstream of the apexes for three of the alluvial fan study sites. The FLO-2D models will be used to generate hydraulic parameters for use in preparation of the flood hazard classification matrix, sedimentation analyses, and the Integrated Alluvial Fan Flood Hazard Assessment Methodology.*
>
> *(Task 2.5) The objective of the sediment yield evaluation is to determine and quantify how the potential for sediment delivery, transport, and deposition across the alluvial fan surface can be quantified, and how such processes influence flood hazards on alluvial fan landforms in Maricopa County. This information is to be used to refine the Integrated Alluvial Fan Hazard Assessment Methodology.*
>
> *The recommended methodology shall be applied to up to three of the alluvial fan sites selected for evaluation in Task 2.4.*

The goals of this sedimentation evaluation included the following:

- To identify processes/phenomena that influence fan sedimentation,
- To identify procedure to quantify sediment impacts on flood hazards,
- To aid in prediction of changes in flow-pattern due to sedimentation, and
- To recommend methods for addressing sedimentation concerns.

2 BACKGROUND

Alluvial fan flooding is characterized by flow containment in a well incised channel until it reaches the hydrographic apex. Downstream of the apex, the fan channel loses flow containment, resulting in increased sheet- and overbank flooding, as well as a greater possibility of flow path uncertainty and avulsions. One of the major causes of the flow path uncertainty and avulsion is sedimentation on the alluvial fan surface. Deposition can be expected in a widespread fashion across the alluvial fan surface, although some moderately well defined channels may still be observed along the main flow corridors.

Sedimentation on the fan surface is caused by several factors such as the following:

- High sediment yield from steep watersheds above the apices
- Gradual change in the topographic slope between the mountainous sediment supply area, the fan apex, and the fan area downstream of the apex
- Loss of flow containment leading to reduction of flow depths and velocities, and transition of channelized flow to sheet-flooding conditions
- Reduced velocities and slope lead to reduction in sediment transport capacity resulting in deposition

Note that while net aggradation occurs on active alluvial fans, significant flow is still conveyed within defined channels downstream of the apex, leading to the possibility of local and general scour within those corridors.

The sedimentation characteristics of alluvial fans were evaluated using the sediment transport capabilities in the FLO-2D model. The impacts due to wash load were evaluated using the District's standard MUSLE sediment yield approach. The sediment transport analyses performed for the four selected fan sites are presented below.

3 FLO-2D MODELING

FLO-2D modeling was performed to identify the processes and phenomena that influence sedimentation and to quantify likely sedimentation characteristics. FLO-2D modeling was also used to evaluate procedures that predict the possible changes in the flow pattern due to sedimentation. FLO-2D's sediment transport component makes use of several well-known transport equations to model the bed-material load component of the sediment transport. The sediment transport models uses the input files developed for the water-only FLO-2D runs, with additional input data that describe the sedimentation-related parameters.

FLO-2D uses conservation of volume, for both water and sediment, to approximate two-dimensional routing of a rainfall runoff hydrograph over a system of square grid elements. The limits of inundation are primarily controlled by topography and resistance to flow (Manning's n-value). The FLO-2D models included the following components: the grid system, an inflow hydrograph, rainfall, rainfall and runoff losses, channel flow routing parameters, and sediment data.

One of the goals of this evaluation was to identify and quantify the sedimentation impacts that can occur under the influence of a range of hydrological and geomorphological conditions. A sensitivity-based approach was adopted to analyze the impact of various key parameters that influence piedmont sedimentation. A summary of the procedures adopted, and a discussion on the results obtained, are presented in the following sections.

3.1 TOPOGRAPHY AND GRID SYSTEM

The FLO-2D grid system was generally comprised of 50 feet by 50 feet grids encompassing the project study areas. Grid element elevations (project area topography) were computed from a project TIN that was generated using the topographic data obtained from the District and the City of Scottsdale. For the sediment transport modeling, the model computational domain was reduced to cover a smaller area located near the hydrographic apexes of the Rainbow Valley and Reata fans. This reduction was done to reduce model run times, since the sediment transport component in FLO-2D takes significantly longer to complete compared to a water-only model runs. The initial roughness value (Manning's n-values) for grid elements was input as 0.045. This initial value was based on interpretation of aerial photography and engineering judgment. Roughness values were then modified by FLO-2D to improve computational analysis. However, the FLO-2D modifications were kept in check by setting the limiting Froude Number value to 0.95, which ensured subcritical flow within each grid element.

Inflow grid elements were located slightly upstream of the hydrologic apices of the fans. To prevent ponding, the outflow grid elements were located along the downstream boundary of the grid system for all fans other than White Tanks Fan 36. For White Tanks Fan 36, the outflow elements were not set at the downstream end due to the presence of the Buckeye FRS where the lack of outflow elements would allow ponding along the FRS.

The impact of topographic map accuracy (scale) and the grid-system resolution (grid size) on FLO-2D modeling results were investigated by considering White Tank Fan 36. The area near the fan apex was modeled as water-only case using the 10-ft District-wide topography, as well as 2-ft topography provided by the District. In addition, grid sizes of 25 feet and 50 feet were modeled. The results clearly indicated that better topography and smaller grid size lead to more refined results, as well as finer identification and depiction of detailed flow paths. The results also indicated that use of a smaller grid and the less-accurate 10-foot topography only marginal improved the results, highlighting the fact that the gains from the use of reduced grid sizes are limited by the topographic data quality. While this modeling effort is not strictly sediment transport related, the results are still applicable to any FLO-2D modeling, including sediment transport components.

3.2 Flow Events And Inflow Hydrographs

Inflow hydrographs were computed from 24-hour HEC-1 models. Hydrographs at apices were input at a location slightly upstream of the HEC-1 concentration point locations by dividing the flows over several grid elements. This approach is applied to aid in the numerical aspects of the FLO-2D modeling.

The impact of sedimentation can vary significantly over the range of possible flood events. These impacts were studied by modeling a range of recurrence intervals : 2, 10, 50, 100, 500 and PMP (Probable Maximum Precipitation). The 2-, 10-, 50- and 100-year recurrence intervals were modeled with sediment transport, while the 500-year and PMP modeling simulations were water-only runs.

One of the purposes of the modeling of 500-year and PMP events was to analyze the impact of flooding due to deposition that may occur in the main flow paths. The motivation behind this effort was to study the impact of deposition which can be expected to result in elevated water surface elevations in the existing major flow paths. The idea is to artificially elevate the flood water surface elevations by increasing the discharge, leading to flows leaving the main flow paths, thus aiding in the identification of new flow paths that flood-event may take under this scenario. Even though these model simulations are strictly water-only runs, the purpose is to investigate the impacts of sedimentation on flooding patterns. The model simulation results showed a more widespread inundation in the alluvial fan surface along with a wider two-dimensional representation of the flow directions. While the 500-year model results showed some increase in the flooding extent compared to 100-year runs, the PMP runs showed a more significant widespread inundation that may happen during a catastrophic flood event.

3.3 Rainfall

In addition to the inflow hydrographs discussed above, runoff on the fan surface below the hydrographic apex was generated for a 24-hour rainfall event, which was modeled as a storm covering the entire computational domain (FLO-2D grid system). Rainfall characteristics were based on the 24-hour point precipitation values and distributions obtained from NOAA Atlas 2 to be consistent with the watershed hydrologic models. Depth-area reduction factors for the 24-hour duration storms were input based on Table 2.2 of the FCDMC Hydrology Manual. The rainfall was included in all model runs except the simulations done to estimate wash load distributions. The details of the wash load runs are presented Section 4 of this report.

3.4 Runoff Losses (Infiltration)

Runoff losses for each grid element were modeled using the soils and land-use coverages provided by the District. Estimates of the wash load deposition were obtained using the assumption that the infiltration of water on the fan surface leads to deposition of the wash load on the fan surface. Additional details on wash load estimation are presented in Section 4.

3.5 Sediment Gradations

The sediment transport analyses were performed using sediment data obtained from locations throughout Maricopa County. These samples were collected as part of various other District projects from different locations in Maricopa County. A model-sensitivity based approach is used to predict the impact of sediment gradation on the sedimentation characteristics. Three characteristic sediment gradation curves were developed for this purpose, with two curves enveloping the lower and higher extremes of the sediment data and a third one representing the approximate average. These three sets have a D50 of 0.3mm (Fine), 2mm (Average) and 20mm (Coarse), respectively. All the raw gradation data, as well as the three curves used in the analysis are presented in the Appendix.

Sediment data from the NRCS soils database were also obtained for locations near the fan apices for comparison with the ranges of sediment sizes modeled. The countywide sample set compares well with the ranges presented in the NRCS database with the possible exception of a small deviation in the very fine sediment sizes, which would be transported as wash load and would not likely affect bed-material load computations.

The modeling results indicate that finer sediment increases the potential for significant sedimentation (both scour and deposition) compared to the coarser sediment model results. While the main flow path corridors remain mostly unchanged, portions of the corridors show wider areas of higher flow depths and velocities compared to coarse sediment models. The hazard plots generated by FLO-2D also indicates a wider area of impact.

3.6 SEDIMENT INFLOW

The water flow inflows were input into the model using hydrographs obtained from the HEC1 models. The sediment inflow at these inflow locations were estimated using the following process:

- Normal depth was assumed and Manning's equation was applied at a cross-section upstream of the apex to generate the required hydraulic data.
- A range of flows were considered to encompass the entire range of discharges in the inflow hydrograph.
- The Zeller-Fullerton sediment transport equation was used to compute sediment transport capacity for the range of flow, using the hydraulic data obtained from the Manning's rating.
- A power curve fit using Microsoft Excel software was used to determine coefficients ASED and BSED (see FLO-2D data input manual) needed for the FLO-2D input file.
- The ASED coefficient was set at zero for the clear water inflow (zero sediment supply) simulations.

The impact of clear water inflow was investigated by comparing the model results with sediment inflows for the Reata Fan. The clear water inflow tends to result in a scour near the inflow location, continuing downstream some distance. Since the inflow location is set at a location upstream of the hydrographic apex, the impact of clear water significantly diminished before the flows reached the apex and the area of concern, i.e., the fan surface. These results indicate that use of clear water inflows is a feasible alternative as long as the impacts are restricted to an area outside the actual area of interest.

3.7 SEDIMENT TRANSPORT EQUATIONS

The FLO-2D sediment transport modeling was performed using the Zeller-Fullerton equation for the base condition models as the Zeller-Fullerton equation is known to predict reasonable results for a range of hydraulic and sediment conditions common in Arizona. Additional equations were used to analyze the impact of the transport function on the sediment transport modeling results, using the Reata fan model. The transport functions used included: (1) Yang, (2) Engelund-Hanson and, (3) MPM-Woo. These equations were selected based on descriptions of their applicability range. FLO-2D modeling was performed with these four equations using clear water inflow. Clear water inflow was used to aid in an easier comparison process. The transport equation sensitivity analysis indicated a significant influence of the sediment transport equation used on the modeling results. While the major flow paths are still present at the end of the simulation, the preference of the flow to use a particular flow path varied significantly with the equations. The results indicate that the appropriateness of sediment transport equation needs to be investigated further in the future. The analysis of the results indicates that the results obtained using Zeller-Fullerton equation presents a more realistic depiction of the flow and sediment transport characteristics.

Of the sediment transport equations available for use within FLO-2D, the Larsen, Tofalleti and Kennedy equations are intended for streams with low transport rates, and thus are not recommended for use in alluvial fan models. The Zeller-Fullerton and Yang equations are anticipated to provide good results for steep slopes and give mid-range sediment transport results. The MPM-Woo equation was developed for use in arroyos (typically found in New Mexico) and is recommended for steep slopes. Ackers-White and Engelund-Hanson equations are expected to predict higher sediment transport rates than the Zeller-Fullerton and Yang equations. Another equation, MPM-SMRT reportedly performs well for high concentration events that typically occur under dam Break or breach type situations. However, the use of this equation is not recommended for alluvial fans.

3.8 Impact of Sedimentation Near Apex

Sedimentation that occurs in the active area near the fan apex can significantly alter the downstream flow characteristics. There are two types of processes that can occur that alter the main flow path: 1) Loss of channel capacity due to deposition within the channel and 2) Redirection of flow into a new path due lateral migration or failure of banks. While these two phenomena can be caused by sedimentation, they are highly complex in nature and therefore are difficult to reliably predict, even using state-of-the-art modeling techniques. However, the impact of such occurrence can be estimated by making some adjustments to the modeling parameters. The water-only FLO-2D simulations, considered as part of Task 2.4, addressed the following two scenarios which has direct relation to alluvial fan sedimentation:

1) The main channel downstream of the apex was artificially filled to mimic loss of channel capacity. This scenario was analyzed using White Tank Fan 36 water-only model. The purpose of this scenario is to demonstrate the ability of FLO-2D modeling to identify any possible new flow paths that result from sedimentation that can occur within the main channel. A candidate site for sediment accumulation was chosen based on geomorphological evidence of an existing alternate path visible in the aerial photography. The grid cells at this location were artificially elevated to block the flow in the channel. Results indicate that this blockage diverted the flow in the direction of the alternate path demonstrating the ability of FLO-2D to model such behavior at certain candidate locations.

2) For some fans, there is considerable uncertainty in flow paths within the active alluvial fan areas near the apex, in part resulting from near-apex sedimentation. Therefore, the possibility of avulsions that can alter the flow direction exists within the active fan area. These possible changes in flow directions were identified based on aerial photography and topography and virtual levees were input into the FLO-2D models to force the model to redirect the flows in different directions. In essence, this emulates avulsive behavior within the active area. The results indicate that this process could be used as a deterministic mechanism to quantify the impacts of possible avulsive behavior within the active area.

4 WASH LOAD

4.1 OVERVIEW

The wash load component of sediment transport was estimated using the MUSLE sediment yield procedure as outlined in the ADWR manual (Appendix B of the *Design Manual for Engineering Analysis of Fluvial Systems* (ADWR, 1985). The MUSLE method was developed by the Natural Resources Conservation Service (NRCS). Using this methodology, sediment yield can be estimated on either an average annual or event-based basis. Computations of average annual sediment yield take into account sediment yields from all possible runoff events and, using probability-based weighting for each of those events, arrive at a value for the average annual yield. Therefore, if large events have not occurred for some time in the basin then the average annual sediment yield may over-predict the actual sediment yield observed by direct measurements, since it is taking into account sediment yields from events that have not occurred. Conversely, average annual sediment yields are much less than yields for large single events. Event-based sediment yield is generated by runoff events of specific frequencies, such as the 2- or 100-year flood.

4.2 SEDIMENT YIELD INPUT PARAMETERS

4.2.1 Storm Runoff

The MUSLE equation used to compute storm runoff energy factor uses coefficients α and β. The Arizona Department of Water Resources (ADWR, 1985) recommends values for α and β of 95[1] and 0.56, respectively. The peak discharge volumes for the 100-year 24-hour and 6-hour events were obtained from the HEC-1 model results and the maximum of the two values was used in the sediment yield calculations. The Q2, Q5, Q10, Q25, and Q50

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[1] ADWR manual recommends use of 95 for alpha. The applicability of 285 used in the AMAFCA Manual based on "limited testing" in watersheds near Albuquerque to watersheds in New River is not very clear (the AMAFCA Manual also reports an alpha of 95 as the "most commonly used value" – see p. 2-11). We note that Renard and Stone (1981) reported an alpha value of 11.8 for watersheds in Southern Arizona, and other authors have reported that 11.8 is the most commonly used value of alpha. There are no sediment data for the study area watersheds from which to derived basin-specific parameters. Therefore, JEF used the default value recommended by ADWR Manual due to lack of other clear recommendation.

were determined by applying discharge-ratios to the peak flows for all the subbasins. These discharge ratios were based on the Hydrology Design Manual of the Flood Control District of Maricopa County (FCDMC, 2003).

4.2.2 Soil Erodibility Factor (K)

The soil erodibility factor (K) for each soil was obtained from the NRCS soils database for the local NRCS soil surveys covering the study areas. The soil survey described the composition of each map unit as a percentage of each soil series. The map unit K was based on an area-weighted average of the soil series percentages. Further, several map units covered each sub-basin. Thus, the subbasin K is a weighted average of the weighted map unit K-values occurring in the basin.

4.2.3 Slope Length and Gradient Factor

The slope length and slope angle calculations were performed using the GIS based procedure presented in Hickey, 2000. The calculations were performed on a rectangular point grid overlapping the subbasin area. The procedure can be briefly described by the following steps:

- Obtain elevation data in a grid format.
- Eliminate sinks in the elevation data.
- Determine flow directions at each grid point using maximum downhill slope to adjacent grid point.
- Identify high points as grid points with no net inflow (this was done using the flow directions at the adjacent grid points).
- Estimate a non-cumulative slope length at each grid point which is the slope length contributed by the cell area of the particular grid point.
- Track the flow path in the downstream direction from a high point using the flow directions. The tracking stops when the flow path reaches a pour point or the slope break is greater than 50%.
- Determine the slope length using the flow path and summing the non-cumulative slope lengths.

The elevation data were obtained from the topographic mapping using ArcGIS TIN. The elevation data on the rectangular grid required some smoothing to eliminate sinks which disrupt accurate computation of the slope lengths. The elimination of the sinks was performed using the algorithm provided in Planchon and Darboux (2001). Using the "adjusted" elevation data and the procedure outlined above, the slope length and slope angle calculations were performed for all the points that fall inside the subbasin area. Using these values, average values of the slope length and slope angle were obtained for all the subbasins. These values were then used in the slope-length equation presented in ADWR manual.

4.2.4 Cover and Management Practice

Values for the canopy, mulch and root factors were estimated using the percent vegetation for varying land uses within the study area, field observation, and engineering judgment. The percent vegetation cover was divided into percent canopy and percent mulch. Canopy cover includes leaves and branches that do not directly touch the ground. Mulch cover includes plants that are low to the ground such as grasses, as well as litter and in some cases rock (i.e. xeriscaped lawns). For desert and open areas it was assumed that 80% of the vegetation cover was in the form of canopy and 20% in the form of mulch based on field observations. It was assumed that residential areas would have slightly higher proportions of mulch due to the increased probability of grass and rock lawns. Thus 66.7% and 33.3% percent of the vegetation cover was assigned to canopy and mulch respectively. For industrial, commercial, and park area it was assumed that mulch would be more prominent than canopy cover. Thus 33.3% and 66.7% percent of the vegetation cover was assigned to canopy and mulch respectively. For the root factor it was assumed that rooting percentages would equal vegetation cover percentages. Figures B.2., B.3., and B.4. in Appendix B of the *Design Manual for Engineering Analysis of Fluvial Systems* (ADWR, 1985) were used to assign factor values. The results are presented in Table 4.1.

Table 4.1 Land use vegetation cover and associated MUSLE C factors

Land Use	% Veg. Cover	% Canopy	Canopy Factor C_I	% Mulch	Mulch Factor C_{II}	% Rooting	Root Factor C_{III}	C Factor
Sonoran Desert	25	20	0.85	5	0.9	25	0.42	0.32
Open	10	8	0.95	2	1	10	0.44	0.42
Very Low Density Residential	30	20	0.85	10	0.76	30	0.4	0.26
Low Density Residential	50	33	0.78	17	0.63	50	0.37	0.18
Medium Density Residential	50	33	0.78	17	0.63	50	0.2	0.1
Multi-Family Residential	50	33	0.78	17	0.63	50	0.2	0.1
Industrial	60	20	0.85	40	0.39	60	0.17	0.06
Commercial	75	25	0.82	30	0.31	75	0.12	0.03
Park	90	30	0.78	60	0.25	90	0.1	0.02

Many of the subbasins are characterized by multiple land use divisions that comprise a percentage of the total subbasin area. These percentages were used to develop a weighted average C factor.

4.2.5 Erosion Control Practice Factor (P)

The erosion control practice factor this factor accounts for conservation practices such as contouring and terracing. In desert rangeland and open space areas it can be reasonably assumed that no such activities have taken place, and the factor can be assigned a value of 1.0.

The MUSLE computations were performed for all subbasins using weighted average values of parameters for each subbasin. In order to account for impervious surfaces in developed regions, the "RTIMP" values from the FCDMC Hydrology Design Manual was used to reduce the soil occurring in areas that can be classified as Medium Density Residential, Multi-Family Residential and Commercial.

4.2.6 Wash load Deposition Results

The sediment yield procedure, presented in the previous sections, provides estimates for the wash load derived from the upper-watershed. The wash load is then carried by the flows across the fan and are deposited on the fan surface if runoff infiltrates into the soil. Based on guidance from the District's Engineering Group, the following simplifying assumptions were made to determine the wash load deposition rate:

- Wash load is carried without deposition by the flow in areas of high velocity and/or depth even though there may be water infiltration occurring in these regions. Based on this reasoning, no wash load deposition was permitted in the high hazard areas which represent areas with high velocities and/or depth.
- Rainfall related infiltration may occur over the watershed. However, the wash load from the upper watershed is not carried by flows generated by rainfall on the fan surface. Therefore, for the purpose of wash load deposition, the flows resulting from the rainfall were eliminated by modeling the flows from the apices without the inclusion of rainfall on the fan surface. This was performed by turning off the rainfall option within FLO-2D.
- Using the above two assumptions, FLO-2D models runs were made to simulate the flows from the apices and infiltration distributions were obtained. These infiltration distributions were then used to determine wash load distributions incorporating two assumptions: 1) FLO-2D model does not include rainfall and 2) the infiltration values in the high hazard areas were not considered to contribute to the wash load deposition.
- Using this approach, wash load distributions were obtained for the 2-, 10-, 50- and 100-year events by using FLO-2D model simulations results (without on-fan rainfall). The wash load distributions were then probability-weighted using the sediment yield results from the MUSLE procedure to provide average annual wash load deposition depths. The probability weighting procedure is similar to the procedure presented in the ADWR manual with the exception that the 25 year events were not included in the weighting procedure.

The procedure described above was selected after initial modeling iterations using similar procedures to determine the wash load deposition. Guidance from the District's

Engineering Group was used to modify the procedure to reflect a more realistic depiction of wash load deposition process. While the initial computations were performed for all the four sites, the final modified procedure was implemented for the Reata Fan, which was deemed have the most severe conditions in terms of sediment deposition on the fan surface. The wash load results are presented in the Appendix. The wash load deposition depths estimates show that the average annual depths are less that 0.01 ft for most of the fan surface, with slightly larger values in areas adjacent to the significant wash corridors. Because the results are probability weighted, the smaller events also contribute significantly, as their probability weights are larger than that of the more rare larger events.

5 CHANNEL AVULSION DUE TO SEDIMENTATION

Sedimentation occurring along the main channel corridors on an alluvial fan can result in new channel formation. This is fundamentally an avulsive mechanism. The ability of FLO-2D to predict and simulate such behavior is limited in nature due to the correlation of the results with the topography used in the modeling. Drastic and sudden changes in the ground elevations are hard to model using the cell-averaged numerical methodology adopted by FLO-2D. The channel piracy mechanism is strongly correlated to the topographic contours. The piracy mechanism is more likely to occur in locations where there is adequate topographic relief (i.e., positive slope) in a direction oriented away from the main channel corridor. In such locations, if the water were to get to locations outside the existing bank confinements, the flows can be carried along totally new flow paths. The mechanism described here is related to avulsion mechanism which has been addressed in greater detail in the Task 2.8 Report.

To address the channel piracy caused by in-channel sediment deposition, a flow-direction tracking tool called the Slope-Walk Method was developed. The tool uses either velocity data or steepest slope values on the fan surface grid. For the purpose of the analysis, the FLO-2D grid was re-used as input to the tool. Potential locations of piracy were identified along the main channel corridor using aerial photography, topographic contours and the local geomorphology. Once these locations were identified as the possible starting points of the piracy mechanism, the tool is applied, beginning at grid cell locations near the starting points. The tool uses an iterative process by starting from each starting grid cell locations and tracks the path downstream by following: 1) steepest slope and 2) velocity vector direction. The steepest slope is estimated using the elevations at the cell locations within the entire grid. The velocity vector direction is obtained from the PMP FLO-2D model run results. The PMP model run was used because this provided velocity direction in locations where flow would not get to under a smaller flood event (i.e., greater depths of inundation). The PMP model results, thus, provided a more comprehensive distribution of velocity directions on the fan surface. Using the directions from steepest slope and velocity distributions, the potential flow paths were tracked from one grid cell to another cell in the downstream direction. These flow paths were then drawn pictorially on top of aerial photography to visualize the potential avulsive paths. Some paths revealed the tendency for the flows to merge back into the main channel corridor downstream of the potential breakout points, while other paths showed potential channel piracy flow alignments that differ significantly from the existing channel network.

The Slope-Walk tool provides a quick method of analyzing the potential flow paths and their impacts. For example, if the path merges back into the main channel, the concern from the flood hazard point of view may be minimal compared to a situation where a completely new channel path is developed. The impact of hazard can be different depending on the land use over which the new channel can form. The tool provides a way to quickly identify such locations and may trigger a need for additional more sophisticated analysis. The tool also has potential benefits for assessing the potential for channel mitigation. For example, upon identification of such locations, additional bank protection efforts could be under taken to prevent the avulsion. Computationally, the tool is quite simple, but could be developed further to provide more enhanced benefits.

6 SUMMARY & CONCLUSIONS

As part of this study, various aspects of alluvial fan hydraulics and sedimentation were investigated. Most of the modeling was performed with FLO-2D. Wash load aspects were investigated using the District's sediment yield approach. The modeling results were analyzed in detail by performing simulations for various scenarios and making comparisons between the scenarios. Some of the scenarios analyzed are: 1) Impact of flow events, 2) Sediment inflow sensitivity, 3) Channel aggradation 4) Impact of sediment transport equations 5) Impact of grid-size and topography 6) Possible alternate flow paths during high-flow events and 7) Impact of wash load deposition. A summary of findings of these scenario analysis are presented here.

The results from the series of flow events indicated that smaller event impacts were restricted geographically, with flows confined to the main channel corridors identified on the aerials. As anticipated, the area of inundation is more widespread for the larger events. The water-only simulations of 500-year and PMP showed the presence of possible alternate flow-paths and give a better depiction of the flow-direction in areas which may see flows less frequently. Smaller events, such as 2-year flood, resulted in significant bed changes at some locations which could result in more significant cumulative changes due to repeated occurrence of such events over the long-term. The availability and changes in sediment characteristics caused by long-term sedimentation projected over long time durations is difficult to predict using current run-time limitations of FLO-2D. As computers get faster in the future and FLO-2D algorithm is improved, it is more likely that a two-dimensional modeling based approach can be used to predict long-term behaviors such as the 100-year rather than smaller duration.

The impact of available sediment supply at locations upstream of the apex was investigated by comparing the clear-water inflow simulations with equilibrium sediment inflow simulations. The results indicated that overall, the active portions of the fans downstream of the apex are not affected by the sediment inflow rate. The impact is restricted to area immediately below the sediment inflow location. Therefore, the inflow locations were intentionally located further upstream of the apex so that such impacts diminish as the flow approaches the apex and the area of interest on the fan surface. The hazard delineations obtained from either approach were very similar, leading to the conclusion that sediment inflow impacts are minimal and can be addressed by shifting the inflow location further upstream from the areas of interest.

One of the major goals of this evaluation was to attempt to model avulsive channel behavior. Two possible mechanisms have been identified as causing many avulsions on alluvial fans: 1) Loss of channel capacity and 2) Channel piracy leading to alternate flow paths. The results sediment transport modeling using FLO-2D of various flow events showed that the ability of FLO-2D to predict the development of avulsions is somewhat limited. Therefore, alternate approaches were used to investigate the impacts of avulsions, as described in the Task 2.8 Report. The channel aggradation simulation was performed by artificially clogging the channel immediately downstream of the White Tank Fan 36 apex. This revealed the presence of possible breakouts and demonstrated the ability of FLO-2D to predict the breakouts that may occur when the modeling the efforts are focused on a location and the loss of channel capacity is artificially induced. The channel piracy mechanism where the channel takes new flow paths was harder to simulate. The results from larger flow events such as the PMP simulations provide a map of possible flow directions on areas which encounter infrequent flows. Using the results from such a simulation, a flow path tracking tool was developed. This tool uses the dominant flow directions to track the flow path from upstream to downstream. Candidate locations were identified using the aerial photography and topographic contours and a map of possible flow paths were obtained. While some flow paths indicated the redirection of the possible new flow path back into the main streampath, several flow paths were identified depicting possible new flow paths that can result from avulsive conditions. A simpler tool, the slope-walk method, was also developed, which uses the slope distribution rather than FLO-2D results. For this tool, the dominant steepest slope is used to represent the predominant flow-direction instead of the FLO-2D results. This tool, which is simpler in nature because topography is the only input, promises to be a quick and easy way of evaluating possible avulsive channel alignments on a particular alluvial. The results from these tools may be used to perform preliminary evaluations, with the results driving the need for more intensive and thorough investigations.

One of the conclusions from the water-only simulations performed as part of Task 2.4 is the emphasis that is needed in procurement of accurate, detailed topography and the use of a grid size scaled to the surface detail available in the topographic mapping. The results demonstrated that better topography and smaller grid size leads to better results. The results of the Task 2.5 evaluation indicate that these conclusions are equally applicable to sediment transport simulations.

Sensitivity to various sediment transport equations was investigated by testing different sediment transport equations in the Reata fan models Various sensitivity-type simulations were performed using Zeller-Fullerton, Yang, MPM-Woo and Engelund-Hanson equations. The results indicate a high sensitivity of the hazard zones to the transport equation used. While Zeller-Fullerton appears to predict the most reasonable depiction, it is clear that more investigations and calibrations need to be conducted to get a reliable direction on the appropriateness of the sediment transport equations.

As noted above, there is no known data set from which to calibrate or directly evaluate the sediment modeling results. Therefore, we relied on the following to determine the "most realistic, physically-possible" result: (1) Standard of Practice – for other types of sediment transport analyses, the District has recommended using the MPM and/or Zeller-Fullerton equations. The ADWR Manual uses the Zeller-Fullerton equation. (2) Engineering Judgment – lacking data for calibration or verification, the engineer must rely on experience and judgment to select the best results. (3) Continued Study – as noted in the report, we recommend that the District continue to explore sediment transport modeling options for alluvial fans, and to work with Dr. Jim O'Brien to test, modify, and improve the modeling capabilities of the FLO2D software

Wash load estimates were performed using the sediment yield approach as outlined in the ADWR manual. The wash load results show no significant widespread impact during the short-term and even a somewhat long-term duration such as a 100-year period.

In summary, extensive two-dimensional analyses of sediment transport modeling and related transport characteristics have been presented. The results demonstrate the state-of-the-art that is practical at the present moment. In order to enhance the effectiveness of the two-dimensional sediment transport models, further calibration of sedimentation results to measurements is needed. Presently, there is lack of data to verify the adequacy of the models to predict reliable results from a qualitative as well as a quantitative point of view. The collection of such data may be difficult and expensive. While this task analyses the various sediment transport aspects, the overall recommendations from the analyses presented here will be performed as part of Task 2.9.

7 REFERENCES

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Exhibits

For exhibits and supporting documentation please use the DVD.

Appendix G:
Dating Techniques for Piedmont Landforms in Maricopa County

Dating Techniques for Piedmont Landforms in Maricopa County

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Executive Summary

This dating technique assessment demonstrates how landform surface age estimates can be used in the evaluation of alluvial fan flood hazards in Maricopa County, Arizona. Detailed geomorphic mapping of alluvial fan surfaces combined with surface age estimates reveal the degree of flood hazards by identifying the most recently active active flooding areas. Geomorphic mapping and application of relative dating methods (surface morphology, degree of soil and desert pavement development, vegetation type and density, carbonate content and structure) should be performed prior to applying any numerical dating techniques. However, by themselves, relative dating techniques do not provide direct age estimates for Holocene surfaces. OSL and AMS radiocarbon dating methods are the most applicable numerical dating methods for dating alluvial fan sediments on fan landforms in Maricopa County. Cosmogenic nuclide dating and varnish microlamination correlation are the most favorable methods for estimating surface ages. Varnish microlamination (VML) is a correlative method and should be evaluated further in Maricopa County. The types of dating techniques and their resolution and age ranges are shown in Table E-1.

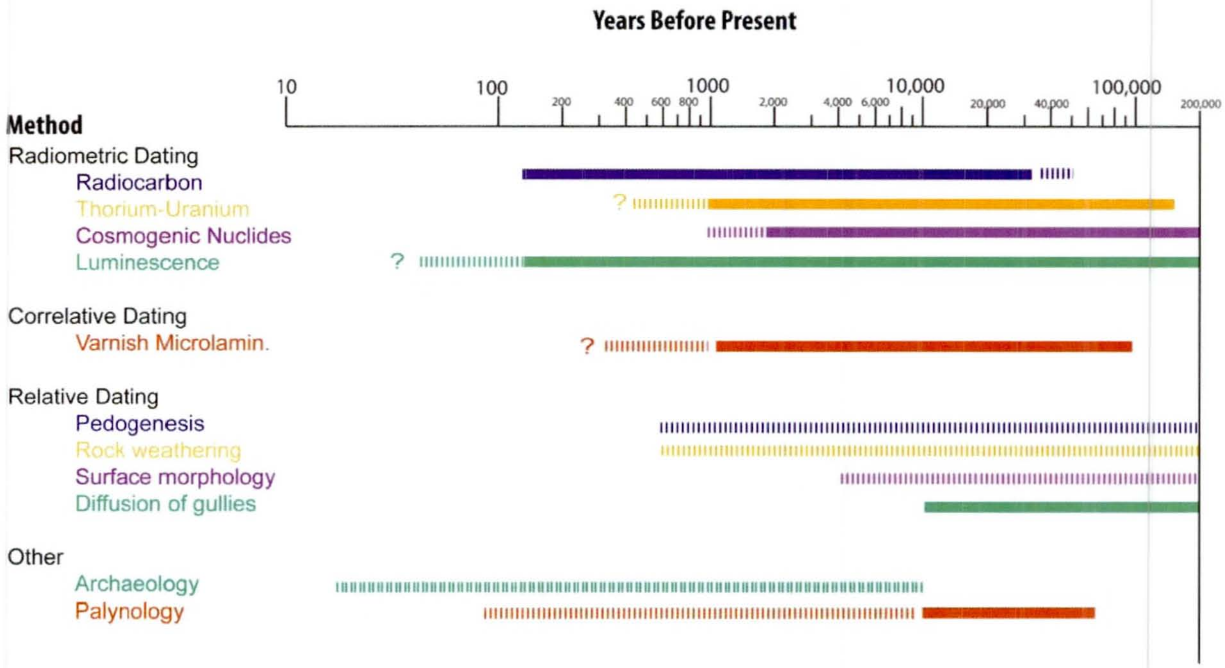

Table E-1. Dating techniques and age-resolution available for use on alluvial fans in Maricopa County.

This study recommends that a combination of relative and numerical methods be applied to most accurately determine surface age on alluvial fans in Maricopa County. It is further recommended that a regional chronology be constructed so that more cost-effective relative dating techniques can be used to determine correlative ages.

Table of Contents

Introduction

The objective of this dating technique assessment is to demonstrate how surface age informs on piedmont landform flood hazards, and outline how surface age estimates can be used in the evaluation of alluvial fan flood hazards in Maricopa County, Arizona. This report describes the types of absolute and relative dating techniques applicable to Holocene-aged landforms in Maricopa County, the limitations of specific dating techniques, and how surficial dating has been applied in previous alluvial fan flood hazard assessments.

Types of Dating Methods

Surficial dating methods can be categorized into the following three types:

- Relative dating methods
- Numerical dating methods
- Correlative dating methods.

Relative Dating Methods. Geomorphic surfaces can be dated using a relative order of age by evaluating the degree or intensity of weathering features observed on a particular surface and comparing them to those observed on other surfaces. The physical characteristics of a landform provide clues as to its age, as well as its depositional history, existing level of stability, and future flood potential. If a portion of the landform becomes isolated from its original watershed and watercourse, it ceases to receive new deposits and its surface will begin to develop specific physical characteristics indicative of its age. These physical characteristics include soil profile development, an integrated tributary drainage network, rock varnish, desert pavement, topographic relief, rounding of surface margins, color, and distinctive vegetative suites. Relative dating provides a first-order approximation of the age range of surfaces, and is often used to estimate ages of alluvial landforms in the southwest.

Numerical Dating Methods. Numerical dating methods are rooted in radiometric dating techniques, such as radiocarbon and cosmogenic nuclide dating, but also include other measurable techniques such as Optically Stimulated Luminescence (OSL). Numerical dating methods usually provide specific age estimates from measuring the physical properties of fan constituents, including organic material, sand grains, or gravel.

Correlative Dating Methods. Correlative dating methods are sometimes referred to as age-equivalence dating, and involve correlating physical attributes of a surface or deposit with similar physical attributes that have been constrained with numerical dating methods, such as the correlation of desert varnish microstratigraphy from one region to another.

Dating Holocene Alluvial Fan Landforms

Alluvial fans are complex and dynamic geomorphic systems that alternate between deposition and erosion both spatially and temporally. Numerical age estimates of deposits and their associated alluvial surfaces, in conjunction with geomorphic mapping of alluvial fan deposits, could provide a detailed record of shifting depositional patterns on alluvial fans over the past few hundreds to tens of thousands of years. This information could then be used to identify active and potentially active alluvial fan areas, and could potentially be used to assess the frequency and character of major channel pattern avulsions and associated areas of deposition.

Several features of an alluvial fan landform may be datable. However, selection of datable material must be done judiciously and within the geomorphic context of the alluvial fan as a system. Datable features may include fan surfaces, lobes of deposits, and deposits from channel avulsions. Numerous dating methods have been tested on geologically young deposits in various parts of the world. Only a few of these methods are applicable to alluvial fans in arid environments such as that of Maricopa County, and only the most applicable methods are discussed in this report.

The "Dating Techniques" section of this work discusses the subtleties of dating alluvial fan deposits and associated alluvial surfaces in arid environments, describe numerical and relative dating techniques applicable to Holocene alluvial fans and their limitations, and discuss how dating techniques have been applied to other alluvial fan systems.

Limitations of Dating

Deciding which dating method is appropriate depends on site specific conditions and what it is that you actually want to date. For example, if you wanted to know the age of a particular fan surface, you could use surface dating methods, such as cosmogenic nuclide dating, or varnish microlamination dating. One might also find dateable material in the deposit beneath the surface that would provide constraints on the estimated age of the surface. Because of the unavoidable uncertainties in any dating method, using multiple methods is always advisable.

There are several inherent geologic processes to consider: flooding, scouring and sedimentation. Flooding, scouring and sedimentation occur when a part of a fan is the locus of floodwater and sediment flux. The water and sediment flux may shift abruptly to another part of the fan, resulting in the abandonment of part of the fan. Equally, and perhaps more likely, however, is that some water and sediment may continue to enter the "abandoned" part of the fan in large floods, perhaps only in topographically low areas. Even if parts of fans are completely isolated from flood flow, local processes of erosion and deposition will continue to alter the original fan surface, albeit at a much slower rate. Alluvial fans are typically composed of nested channel deposits that can be derived from different flooding events even though they are part of the same alluvial fan. In some situations these nested deposits might be very similar in age, but in other situations they might differ in age by thousands of years. This would result in different age estimates for those sediments. It is important to note that the dating of a surface or deposit does not include the dating of subsequent floods over that surface. That is, the mere presence of surface age does not necessarily preclude potential future flooding. For example, geologically old surfaces may not have enough relief between them and surrounding channels to confine water and sediment. These older surfaces may experience aggradation, flooding and erosion.

Dating of specific floods on a particular surface is difficult unless special conditions exist, such as the burial of a historic artifact of known age. Dating past avulsion events can be done if sediment from the initial event still exists, or a correlation can be made from abandoned surfaces related to the initial avulsion event. Detailed geomorphic mapping could elucidate the relative chronology of deposits so that deposits from subsequent flow along an avulsion channel can be distinguished from deposits from the initial avulsion event.

It should be noted that estimating the age of a landform from numerical dating methods may not provide greater resolution than can be determined with relative dating techniques, and determining a numerical age of a Holocene surface may not necessarily improve hazard assessments. Errors associated with each numerical dating method and imperfect conditions, such as re-transported organic material, could lead to incorrect ages, even when care is taken in sample selection.

Dating Techniques Applicable to Alluvial Fans in Maricopa County

Potential dating methods were narrowed down to those may be useful in the age determination of Holocene alluvial fans in semi-arid environments like those found in Maricopa County (Figure 1). Not all of these methods have been applied to fans within Maricopa County. However, they may prove useful in the future, since they have been used in other arid environments to date alluvial fan systems. The methods most applicable to Maricopa County include the following, which are described in the following paragraphs:

1. Optically Stimulated Luminescence (Numerical)
2. Radiocarbon (Numerical)
3. Cosmogenic Nuclides (Numerical)
4. Thorium-Uranium (Numerical)
5. Varnish Micro-Lamination (Correlative)
6. Pedogenesis (Relative)
7. Rock weathering (Relative)
8. Surface Morphology (Relative)
9. Gully diffusion (Relative/Correlative)
10. Palynology (Correlative)
11. Archaeology (Correlative)

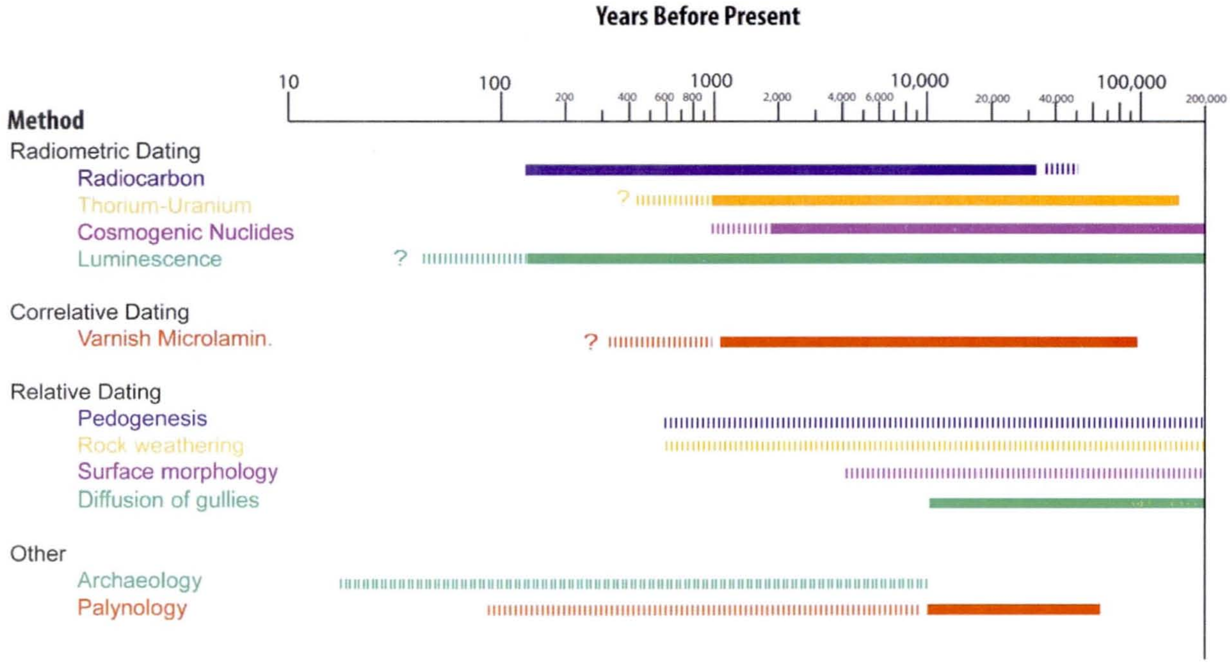

Figure 1: Numerical and relative dating methods that are appropriate to use in arid, alluvial fan environments; Age ranges possible per each method type is shown with corresponding color bars; age scale is logarithmic and in Years Before Present (YBP).

A number of numerical dating techniques have been applied to Quaternary sediments, soils, lavas and ice, such as electron spin resonance, paleomagnetism, amino-acid diagenesis, potassium-argon/argon-argon dating. However, only a few are applicable to alluvial fans in arid environments such as that of Maricopa County. Notable Quaternary dating methods that are not applicable to dating Holocene alluvial fan sediments include electron spin resonance, paleomagnetism, amino-acid racemisation, and Argon-Argon dating. Electron spin resonance (ESR) is often used to date bone and tooth enamel found in sediment greater than 40,000 years old, although some success has been made in dating quartz-rich sediment. ESR dating requires a full re-zeroing of the electron clock, which is problematic for geologically young sediments, such as those deposited in the Holocene. Paleomagnetism as a dating technique generally relies on periodic reversals of the earth's magnetic field that are recorded in magnetic minerals in volcanic rocks and sediments. The most recent magnetic reversal occurred about 780,000 years ago, so this technique only works for sediments that are hundreds of thousands to millions of years old. Amino-acid racemisation measures chemical changes in organisms following their death. This technique is limited to mollusks and animals with skeletal carbonate matrices, and thus is not useful in alluvial fan settings. Potassium-argon and argon-argon dating methods are generally limited to igneous rocks. Even with the exclusion of the above mentioned dating methods, there are still several Quaternary dating methods that are applicable to dating Holocene alluvial fan deposits in arid environments like that found in Maricopa County.

A combination of applicable techniques listed above would result in better age constraints. A combination of at least two field or relative dating methods should always be combined with one or more numerical methods. This will ensure that the numerical dates obtained would be in the correct context of the geomorphic system, and provides an independent check that the numerical value is not erroneous. For example, a suspicious radiocarbon age could actually be much older than the sediment in which the sample was taken since most radiocarbon samples found in alluvial fan sediments are detrital in nature, (not *in situ*). If the soil appears geomorphically young, and the surface morphology indicates a relatively young fan surface, but the radiocarbon age suggests a much older age, then that radiocarbon age should be excluded from the age estimate.

Optically Stimulated Luminescence (OSL)

Description. OSL dating works on the principle that sediments containing sources of naturally occurring radioactive isotopes, such as uranium, thorium, or potassium-40 are subject to low levels of radiation (Walker, 2005). Mineral grains exposed to radiation in the soils become ionized and release electrons that consequently become trapped in defects in the mineral grains. When sediment samples with these mineral grains are heated up, the electrons are released and can be counted to quantify how long the sediment has been exposed to the low level radiation, ideally after deposition. The amount of released electrons is proportional to the amount of time the sediment has been buried (Figure 2). This process of heating and measuring the amount of electrons that are released is called Thermoluminescence (TL). The sediment can also be exposed to a beam of light to release electrons in a process called Optically Stimulated Luminescence (OSL). OSL dating has essentially replaced TL dating in the dating of sediment (Walker, 2005), so this section will focus on OSL dating only.

The sample age is determined when the amount of radiation in the grains (dose equivalent) is measured and divided by the amount of radiation dose per unit of time absorbed by the mineral of interest since the zeroing of the luminescence clock by exposure to sunlight (dose rate). Because thermally stable traps cannot be pre-selected in OSL samples, sample aliquots are heated after exposure to laboratory radiation, but before final measurement. This "pre-heating" method empties all of the unstable traps that were filled with laboratory radiation, but it also leads to the transfer of some electrons, which will result in an erroneous error if not accounted for (Aitken, 1998; Huntley, 1985; Huntley et al, 1993b). The pre-heating error can be accounted for by constructing a dose-response curve from aliquots that have been given various lab doses and then given a long bleach (Walker, 2007; Huntley et al., 1993b). The dose equivalent is proportional to the point where two dose-response curves intersect over the dose axis. The environmental dose rate must account for the radiation absorbed by a mineral grain from itself and from surrounding minerals. Concentrations of uranium, thorium, potassium-40 for example, in the sample and its surrounding must be measured and converted to known formulae for this step. Cosmic rays, organic matter and water can infiltrate the sample and its surroundings and also must be accounted for in the dose rate.

OSL dating has been used to date Holocene sediments derived from fluvial, eolian, and alluvial systems. Dating of individual grains (single-grain OSL) of quartz has yielded late Holocene ages for alluvial sands in the Cuyama Valley near the central coast of California. Several samples from alluvial fans and fluvial terrace deposits were dated using OSL, radiocarbon methods and cosmogenic nuclides. Sand and silt deposited in a known flood event in 1998 were dated using the single-grain OSL method and yielded an age of 10 years (DeLong and Arnold, 2006). The U.S. Geological Survey's Luminescence Geochronology Laboratory successfully dated sands from alluvial fans located in the northeastern Mojave Desert (Mahan et al., 2007). They reevaluated geomorphic surfaces that had been previously dated with accelerator mass spectrometry (AMS) radiocarbon methods so that they could refine their OSL dating methodology and evaluate the applicability of dating alluvial fans. They refined Holocene and Pleistocene dates from multiple deposits from Valjean Valley, Silurian Lake Playa, Red Pass and California Valley using OSL and found that the dates were in agreement with previous AMS dating and mapping results.

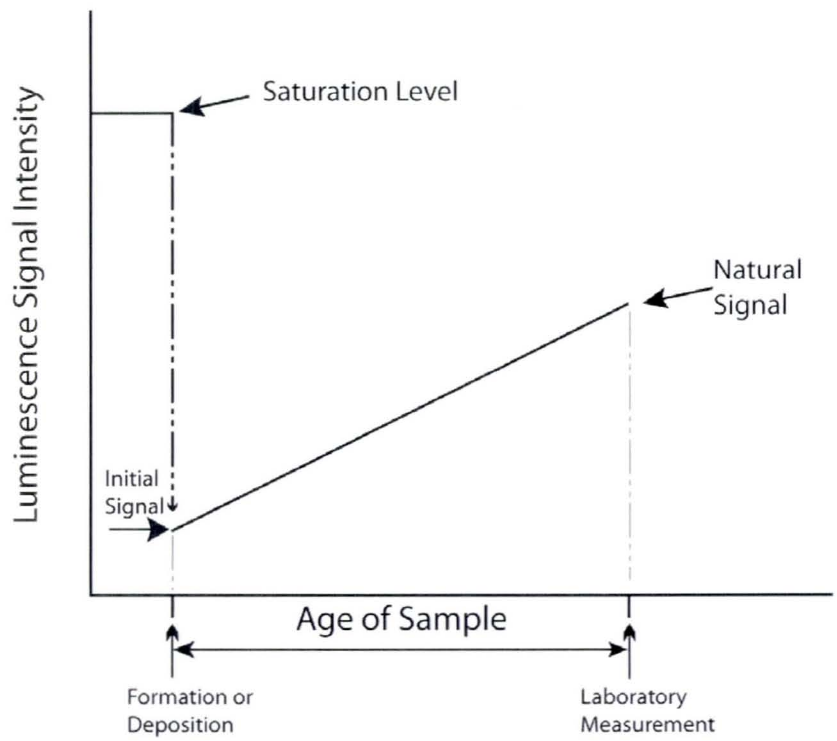

Figure 2: Schematic plot representing luminescence dating principles as applied to sediment; The "Initial Signal" represents the bleaching or erasing of low level radiation by exposure to light during erosion, transport or deposition; the "Natural Signal" represents the buildup of radiation after the sediment has been buried; modified from Walker, 2005 and Aitken, 1998).

Sampling Techniques. OSL sampling protocols have been determined by the U.S. Geological Survey, and by individual laboratories that perform OSL analysis, such as the laboratory at Utah State University. This section gives a generalized description of sampling protocols, but specific protocols set forth by the laboratory that will process the samples should supersede this description. OSL samples should be targeted around sandy deposits, preferably deposits that contain bedding structures, such as laminae, cross-bedding or grading. Eolian deposits are especially preferred since they are quartz-rich and have had adequate exposure to sunlight. Fire can reset the luminescence clock and if sediments are suspected to have experienced a fire, they cannot be sampled for OSL dating. OSL sampling requires one tube sample, one bulk sample and one moisture sample per each lens or bed of silty sand or sand layer to be dated. The exposure is cleaned off by removing about 8 inches to a foot deep of sediment. An inch diameter and 8 inch long aluminum (or thick pvc) tube is driven perpendicularly into the exposure after it has been cleaned off. A moisture sample should be collected using a small cylinder that has an air-tight cap, such as a film canister. The aluminum or pvc tube should be capped on the exposed end to prevent light from entering into the tube. To prevent mixing of sediment when the tube is driven into the exposure, the Utah State OSL Laboratory suggests adding a 1 inch thick disk of Styrofoam to the tube at the open end prior to driving the tube into the exposure. For the bulk sample, the sediment around the tube should be collected in a 1 quart Ziplock-type plastic bag. Collection of the bulk sample will also aid in the removal of the tube sample. Upon removing the tube sample from the exposure, the tube should be pulled out gently and tipped upward on the open end. Once the tube is removed, it should be quickly capped and taped to prevent exposure to light. The precise location of the sample should be noted, along with the depth from the surface and orientation of the exposure with respect to north. It is strongly recommended that prior to OSL sampling, a working relationship be developed with the laboratory operators and scientists because most academic laboratories, like the Utah State OSL Laboratory, do not do outside contract work.

Limitations. OSL dating requires that the radiation clock in the grains has been completely reset by adequate exposure to sunlight prior to deposition and that they are not exposed to intermittent sunlight after deposition. For example, if sediment was removed from another landform and then transported rapidly and deposited after a storm, it may not have received adequate sunlight to zero the luminescence clock (residual OSL). Moreover, if the sediment had been densely burrowed by roots and animals, it may receive intermittent sunlight. Deposition in alluvial fan settings may mix grains with differing amounts of residual OSL, resulting in different age estimates. The rate of bleaching or zeroing is less rapid for quartz than say for feldspar minerals, thus quartz samples may have more residual OSL than feldspar and give different ages. Young sediments in particular, are thought to be problematic because of the rate of bleaching associated with them (Aitken, 1998; Walker, 2007); however, very young sediments were dated in the recent study by DeLong and Arnold (2006). Although the bleaching rate is controlled by site conditions, such as fire, transport history, and grain types, the results from the DeLong and

Arnold (2006) study suggest that bleaching may occur during grain transport within an individual flood event.

Radiocarbon Dating of Organic Material

Description. The radiocarbon dating method was first developed in the 1950's (Libby, 1952) and has been applied to a wide variety of geological and archaeological studies. Organic material and charcoal found in alluvial fan sediments have been dated over the last several decades with meaningful results. Dating organic debris or charcoal in deposits dates those deposits, and would generally provide a maximum age constraint for the overlying alluvial surface.

The radiocarbon dating method relies on the principle that terrestrial organisms bind up carbon isotopes from the atmosphere until they die. After death, the carbon isotopes decay at a known rate and can be analyzed to obtain the time since death of the organism. The isotope of carbon, ^{14}C is not stable and decays to a stable form of nitrogen via the release of a beta particle. ^{14}C becomes part of the global carbon cycle when it interacts with the atmosphere and forms $^{14}CO_2$ which is used in plant photosynthesis and ingested by animals when they eat plant tissue. Once an animal or plant dies, the organism no longer replenishes itself with ^{14}C and the ^{14}C begins to decay. The half-life of a ^{14}C atom has been determined and is 5730 years. By comparing how much ^{14}C remains to a modern standard amount, the age of death of the organism can be estimated. Accelerator Mass Spectrometry (AMS) techniques are now commonly applied by dating laboratories and can be used to date 1/10 of a milligram of material. AMS dating measures the amount of ^{14}C directly by accelerating the sample atoms as ions to high energies with a particle accelerator and then detecting the amount of particles in a nuclear particle detector.

In a depositional setting, such as an alluvial fan, the organic material usually has been transported by water and is often referred to as "detrital". The length of time between death and transport and final deposition can vary, resulting in varying reliability of the age estimate. For example, if a desert tree dies and parts of it are entrained in a flood, it may be deposited relatively quickly with respect to the time since its death. If that same part of a tree is transported and re-deposited several times, it may not yield a meaningful age for the deposits it ends up in. Radiocarbon dating of situ dead trees may also provide constraints on the age of alluvial fan deposits (Pearthree et al, 2000).

Sampling Techniques. In order for radiocarbon dates to effectively date alluvial fan deposits and surfaces, the stratigraphic or geomorphic position of the sample must be documented. Radiocarbon dating plant debris or charcoal in alluvial fan sediments requires that the sample be taken at a particular stratigraphic interval. In other words, the sample must be taken from an identifiable sedimentary or pedogenic unit. Alluvial fan sediments can contain decaying plant debris or pieces of charcoal. If such material is identifiable with the naked eye, it is likely large enough for AMS radiocarbon dating. The sample should be collected with tweezers and wrapped in foil, taped and bagged with a label. Bulk sediments can be selected and dated. One-gallon air-tight plastic bags, like Ziplock Freezer bags can be used to collect bulk samples. Organic material can be separated from the bulk sediments via floatation and can be identified by an AMS laboratory or palynologist for selection of datable plant debris. The bulk age will represent the age obtained by combining the small fraction of floated plant debris and will not represent the date on a specific piece of organic material. Bulk sample dates may provide an idea of the age of the sediments, but can also have so much detrital plant material that the date is rendered unreliable.

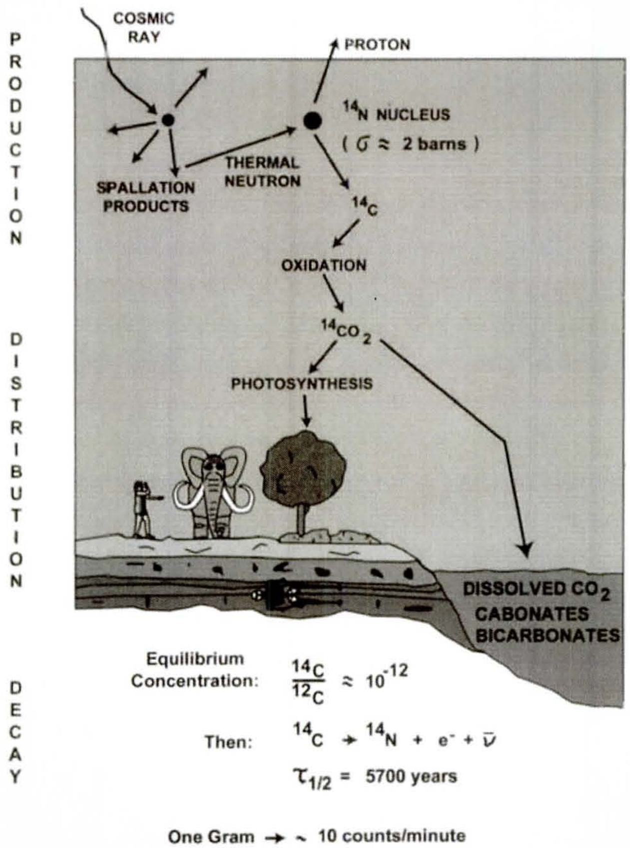

Figure 3: Schematic of the production of carbon-14 in the upper atmosphere, distribution to plants via photosynthesis, distribution to animals via ingesting plant material, and decay after death of plants and animals. Schematic taken from the University of Arizona's AMS Laboratory website (http://www.physics.arizona.edu/ams/education/theory.htm).

Limitations. Finding datable organic debris and charcoal in arid alluvial fan settings is rare. In addition to its rarity, the detrital effect described above could yield ages that are much older than the sediments from which the sample was collected, and younger organic material can be introduced into sediment by burrowing and root growth. Bulk samples can be collected and floated by laboratories to determine if any organic material is present, but this step is an additional cost to the actual AMS radiocarbon dating of the sample and bulk age estimates may have larger detrital error effects. Given the uncertainties with bulk sampling, they may still provide the basis of dating young soils and sediments in alluvial fan systems when other dating methods are not available. For example, radiocarbon ages obtained from bulk samples taken from an alluvial fan near the base of the Ajo Mountains in southern Arizona (Liu et al., 1996) yielded reasonable ages that were in stratigraphic order. The radiocarbon ages were compared to cosmogenic ^{36}Cl accumulation ages, and although the radiocarbon ages were younger than the cosmogenic ages by several thousand years, they provided a meaningful age estimate of the sediments from which they were collected (Liu et al., 1996).

Cosmogenic Nuclide Dating of Surface Exposure

Description. Cosmogenic dating is based on measuring the amount of nuclides generated by cosmic radiation that has accumulated on the upper few feet below the earth's surface. The production of nuclides in the subsurface exponentially decreases with increasing depth beneath the surface. The Earth's surface is bombarded with high energy neutrons that form when cosmic rays entering the atmosphere collide with nuclei. The collision of neutrons (and muons) and nuclei within certain atoms in minerals leads to the creation of new nuclides. The new nuclides progressively accumulate in exposed and near-surface rocks over time and can therefore provide an age of the surface exposures once their concentrations have been determined. The accumulation of cosmogenic nuclides is a function of the time of rock exposure to cosmic radiation, rock chemical composition and the intensity of cosmic radiation, which is dependent on the geomagnetic latitude, altitude, and mass shielding depth. Surface ages can be estimated with ^{3}He, ^{14}C, ^{10}Be, ^{26}Al and ^{36}Cl (see Table 1 for age ranges per nuclide). ^{14}C, ^{10}Be, and ^{26}Al nuclides are measured from pure quartz samples, ^{3}He typically is measured from olivine crystals, and ^{36}Cl is measured from whole rock samples.

Because clasts undergo cycles of erosion, transport and deposition, the amount of cosmogenic nuclides builds up prior to the final event of deposition. This residual concentration of cosmogenic nuclides is referred to as inheritance and must be accounted for in the age determination of an alluvial surface. Repka et al. (1997) collected 30 clasts and amalgamated their ^{10}Be and ^{26}Al concentrations so that they could calculate the average inheritance of these nuclides. The average inheritance from these clasts corresponded to an error of 30 to 40 Ka, which would have resulted in erroneously older terrace ages. Depth profiles can also be used to indicate how much movement clasts may have experienced since deposition. Disturbed clasts may have more exposure to cosmogenic nuclides, even after burial and some surface clasts may have been buried and exhumed as erosion of the surface took place. Dating a surface clast that has been buried and then exhumed would result in an erroneously young age. Judicious selection of samples and depth profiles is paramount to estimating the age of any surface.

Nuclide	Target Nuclides	Half-life (yrs)	Approx. Useful dating range (yrs before present)	Materials commonly dated
Helium-3	Uranium-235 Uranium-238 thorium-232	12	1,000 to several million	olivine
Beryllium-10	Oxygen-16, Silicon-28, Beryllium-7, Beryllium-9, Boron-10, Carbon-13	1.6 million	< 5 million	quartz, olivine, magnetite, plagioclase
Carbon-14 (not the same as C-14 formed from N-14)	Oxygen-16, Oxygen-17, Silicon-28, Nitrogen-14, Boron-11	5,730	< 20,000	quartz
Aluminum-26	Silicon-28, Sodium-23	705,000	< 5 million	quartz
Chlorine-36	Calcium-40, Potassium-39, Chlorine-35	301,000	< 1 million	potassium-feldspar, plagioclase, calcite, chlorite, fluid inclusions in quartz

Table 1: Cosmogenic nuclides commonly used in surface exposure dating and their age ranges.

Robinson et al., (2000) applied the cosmogenic dating method to three Quaternary deposits on the western piedmont of the White Tank Mountains, in Maricopa County. Using relative dating techniques they estimated the ages of the surface to be O > 1,000,000 yrs, M = 10 – 1,000,000 and Y < 10,000 years old. They sampled for ^{10}Be, ^{26}Al, and ^{36}Cl cosmogenic nuclides on all three surfaces and completed two depth profiles up to 8.8 meters deep. The results of their study were inconclusive and warranted more sampling for inheritance estimations. To date, this has been the only cosmogenic nuclide dating study performed in Maricopa County and surrounding vicinities. Although only one study has been completed in Maricopa County, cosmogenic nuclide dating could be developed into a viable dating tool once inheritance estimates and sampling protocols are developed.

Sampling Techniques. Not all alluvial surfaces can be dated with cosmogenic dating methods. A datable surface should not exhibit erosional features, such as dissection and the clasts on the surface must not have been disturbed or exhumed. Once a surface has been selected for dating, boulders exposed on top of the surface are collected. The upper few centimeters of the boulder's surface will be targeted for age estimation in the laboratory. Samples should be taken from horizontal or near horizontal surfaces. To estimate the amount of inherit cosmogenic nuclides present on a surface, measurements must be made on several clasts per depth of the surface. As mentioned above, a depth profile must be excavated and several clast samples (up to 50) should be collected from the profile so that the amount of inheritance can be calculated from the amalgamated sample concentrations. The depth of the profile would depend on the thickness of a clast-rich deposit, but generally would be a few feet.

Limitations. Several factors can inhibit the use of cosmogenic dating of alluvial fans. In particular, young deposits have been known to have problematic and complex inheritance histories. Reworking of gravel from older landforms in the vicinity of young alluvial fan is likely, and this would contribute clasts from landforms with different exposure histories. The influence of inheritance on the estimated age diminishes with the age of a fan (Gosse et al., 2005). If enough samples were collected and yielded stratigraphically good dates, and those dates were corroborated with other techniques, such as OSL and relative dating of pedogenic components of the landform, then a chronology of fan development and associated features could determined.

Th230/U Disequilibrium Dating of Pedogenic Carbonates

Description. Uranium radioactively decays to several isotopes over time. In a closed system, if a mineral is left undisturbed for several million years, the activity of each daughter isotope will come to be equal to that of the parent uranium isotope. In most cases, the mineral is disturbed and daughter isotopes escape and a break in the decay chain will result in disequilibrium. When a break in the decay chain occurs, the nuclides above and below the isotope in the chain are in disequilibrium and they strive to reach equilibrium by forming more daughter products. The formation of pedogenic carbonate represents an example of a system in disequilibrium. Uranium is quite soluble and its daughter product thorium is not, so it is reasonable to assume that all the thorium in a sample is the product of uranium decay disequilibrium. The age of the carbonate can be determined by measuring the extent to which the decay product 230^{Th} has grown back in the carbonate matrix.

Ku et al. (1979) used the disequilibrium relationships among Th230, U234, and U238 to date pedogenic carbonates that formed in the arid and semi-arid climate of Vidal Valley, in southeastern California. They leached carbonate rinds from several clasts found on Pleistocene geomorphic surfaces and corrected for contamination by separating the carbonate matrix from the silicate component with chemical separation techniques. Their results indicated that dating pedogenic carbonates was a viable dating method for Pleistocene surfaces and was in stratigraphic agreement with relative dating techniques. Sharp et al. (2003) dated pedogenic carbonate rinds in the Wind River Basin of northwestern Wyoming with Th230/U thermal-ionization mass spectrometry (TIMS). They targeted microscopic rind laminations from carbonate rinds found in Pleistocene glacio-fluvial terraces. In addition to the dates they obtained for the terraces they determined that the lag time between alluvial deposition and the formation of carbonate rinds was about 2000 to 5000 years. The Th230/Udating of Holocene carbonate rinds using TIMS may prove useful for surfaces that are greater than 5000 years old.

Sampling Techniques. Several pebbles must be collected from the same soil horizon with a deposit, and all of the samples should exhibit similar rind thickness and general appearance. When sampling pebbles for carbonate rind dating, it is recommended to avoid pebbles with truncated laminations since they were likely the result of erosion of carbonate during transport of the pebble with accretion resuming upon repeated deposition (Ku, et al., 1979). Another type of pebble coating or rind to avoid is one in which salt splitting has allowed young carbonate to be precipitated between the pebble and the oldest carbonate layer (Ku et al., 1979). Sharp (2003) collected 35 to 70 pebble-sized clasts at each sampling locality. The pebbles were cut, polished, examined and photographed at 5 to 20X magnifications to select the microscopic sample point on the carbonate rind. Under the microscope, pristine rind material was selected by finding sample areas in each rind that were dense, translucent, reddish brown, and characterized by sub-millimeter-scale laminae lying sub-parallel to the clast-rind boundary (Sharp, 2003).

Limitations. Th230/U disequilibrium dating of pedogenic carbonates has been used to successfully date Pleistocene alluvial deposits, but dating younger Holocene deposits has not been done largely because of the lag time in deposition of the sediments and the formation of carbonate rinds on clasts. This method may prove useful in the future to date early Holocene deposits if work to refine the method progresses. Some researchers are wary of using pedogenic carbonates to date any deposit since the formation of pedogenic carbonate on clasts is not a truly closed system. The formation of the carbonate is posited to occur from the clast surface, outward, away from the clast. Some research suggests that there is microscopic pore space between the clast and the forming rind and that water and other microscopic particles can infiltrate the rind, thus resulting in erroneously young age determinations. The two studies cited in the section above were successful in dating alluvial deposits and surfaces with this method and their results were consistent with other dating methods.

Varnish Microlamination Dating of Surface Rock Varnish

Description. Rock varnish is a slowly accreting dark coating on subaerially exposed rock surfaces in arid to semiarid deserts (Liu and Broecker, 2007) and forms as microlaminations. Varnish microlamination dating (VML) is a correlative age dating method first used by Dorn (1988) to study the chronostratigraphy of alluvial fan deposits in Death Valley. Liu (2003), Liu and Broecker (2000 and 2007), and Liu and Dorn (1996) have improved VML dating methods by correlating varnish microlaminations from deserts found all over the world. The VML method assumes that the formation of varnish microlaminations is largely influenced by regional climatic variations, and that climatic signals have been recorded in varnish as microlaminations of varying color and composition (Liu and Dorn, 1996; Liu et al., 2000). Varnish microlaminations are composed of about 30% manganese and iron oxides and up to 70% clay minerals and several trace and rare earth elements (Liu, www.vmldatinglab.com).

Liu and Broecker (2007) studied hundreds of rock varnish samples from late Pleistocene and Holocene alluvial fan surfaces and other geomorphic features in the western United States. Their analysis resulted in a replicable microlamination sequence that consisted of 12 evenly spaced dark layers intercalated with 13 orange/yellow layers (Figure 4) (Liu and Broecker, 2007). They interpret the dark layers as having formed during relatively wet climatic periods. Several of the Holocene geomorphic features had been previously dated with other methods, such as AMS radiocarbon, so that they could calibrate the ages of their assigned layering units (Figure 4).

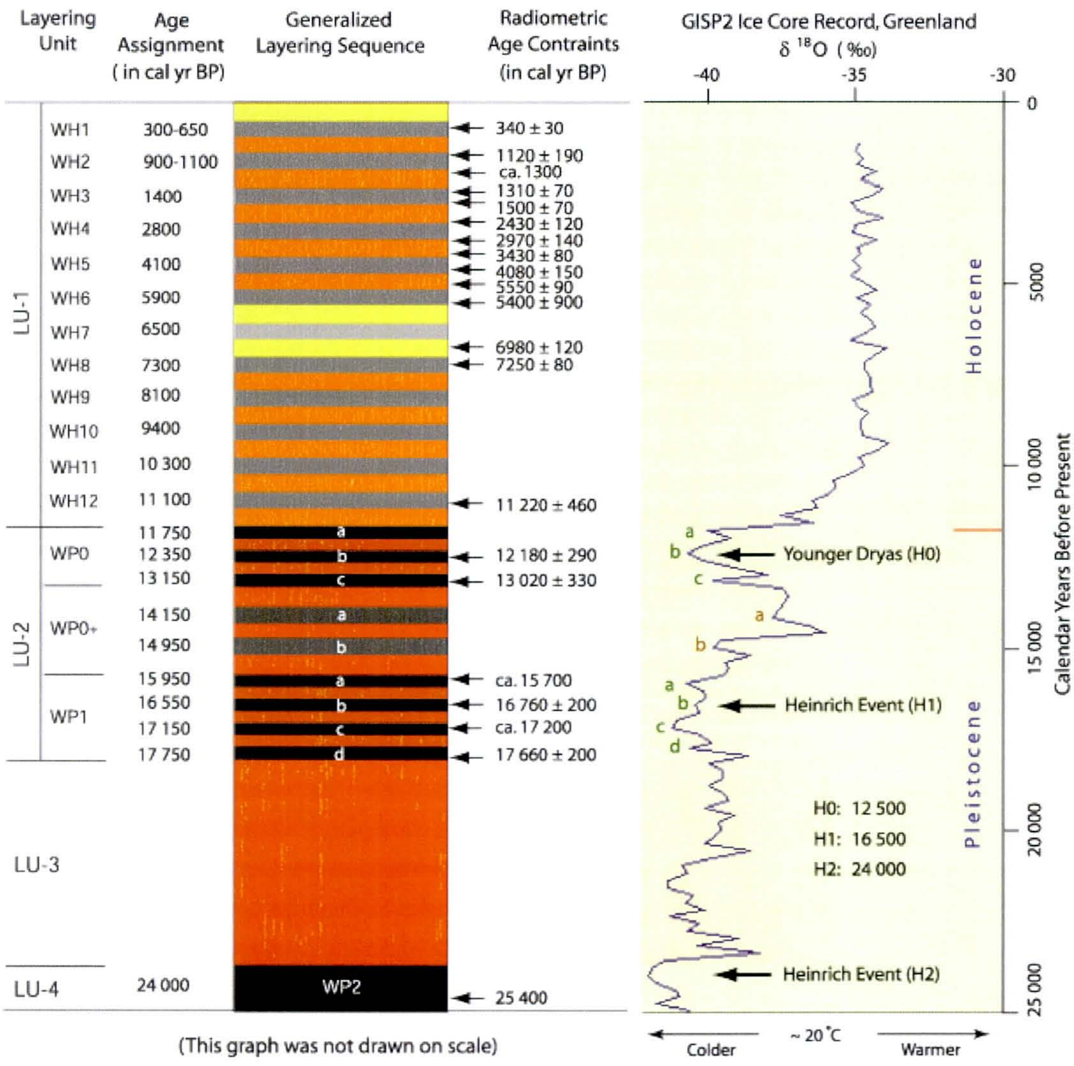

Figure 4: Late Pleistocene and Holocene varnish microstratigraphy and associated layer units, age assignments and comparison with Pleistocene varnish and the GISP2 Ice Core Record (Liu, www.vmldatinglab.com); WH = wet event in Holocene, WP = wet event in Pleistocene, LU = layering unit.

Sampling Techniques. Samples collected from alluvial surfaces for VML dating should be taken from exposed rock surfaces. Two types of varnish may form, one on rocks exposed at the surface of a landform and the other beneath the rocks (Liu and Dorn, 1996). Exposed varnishes are the only varnishes that display consistent microlamination sequences (Liu and Dorn, 1996). Liu and Dorn suggest that scientists be trained in sample collection methods by the VML Laboratory employees and then samples can be shipped to their lab so that they can make ultra thin sections of the samples for correlation.

Limitations. The major drawbacks of using VML dating on Maricopa County fans are that: (1) it is a relatively new method and has only been applied to 2 sites in Arizona, and one them is an otherwise undated alluvial fan near the McDowell Mountains; (2) Holocene varnish microstratigraphy would need to be further calibrated in southern Arizona; and (3) sampling protocols need to be performed by someone specializing in VML dating. The first and second issues could be addressed with more investigations in Arizona and the use of other dating techniques to assess and calibrate VML dating. For example, if the global climate has changed from a wet to dry to wet as recorded by deep sea sediments in the North Atlantic Ocean, would that cycle of wet to dry to wet be recorded in rock varnish in Arizona's deserts? Would the local climate actually have a different signal in response to global climate changes? In addition to problems with direct global correlation, the development of varnish microlaminations may occur at different rates and would be time transgressive, therefore rendering calibrated ages from different sites invalid. We suggest, after researching its apparent usefulness in dating other arid landforms, that VML dating be applied to dating fans in Maricopa County. The method could be applied as experimental, and if deemed useful, it could develop into a viable technique for dating Holocene alluvial fan surfaces throughout Maricopa County.

Pedogenesis and Surface Morphology

Description. The degree of soil development can be used as a relative measure of the amount of pedogenic change that has occurred in the parent material. Soils chronosequences can be developed for soils that have developed in a particular region in which all of the factors of soil formation, except time are reasonably constant. Contrasts between different soil profiles in terms of carbonate content and form, particle size variations, depth of soil development, strength of material, clay content and films, and color can change as a function of time. These properties can vary for soils of the same age, however, because of local variations in aspect, erosion, lithology of clasts, movement of ground and surface water and biological activity. Some researchers have developed soil development indices (Birkeland, 1999; Harden and Taylor, 1983; Berry, 1994) to quantify soil ages based on pedogenic features, but because pedogenic features can vary so greatly on the same aged surface, the use of these indices as rough numerical soil age estimates can be problematic.

In a semi-arid environment like that of the White Tank Piedmont, the degree of soil development is proportional to surface age. As the surface ages, a soil profile develops, and its structure, color and content changes. Clay and calcium carbonate accumulate in the soil from eolian sources and chemical weathering of the parent material, forming distinct soil horizons. The degree of soil profile development, particularly in the clay and carbonate horizons, can be used as a proxy for surface age. The soil surface also tends to become reddish in color with time due to oxidation of iron (rubification) as well as accumulation and weathering of clay. Young, active surfaces lack soil profile development, and on active alluvial fans consist of stream bed alluvium.

Geomorphic surfaces may also develop an accumulation of pebbles and cobbles at the surface as they age. These gravel coverings are known as desert pavement, which form as a byproduct of windblown silt and clay accumulation in the soil column. Repeated wetting by precipitation causes the fine-grained materials to swell, lifting the larger gravels to the surface. Repeated surface drying creates cracks into which more fine windblown material may accumulate. Over thousands of years these processes form a mantle of closely packed gravels that resembles asphalt pavement (Dohrenwend, 1987; Vanden Dolder, 1992). The pebbles and cobbles that form the pavement surface, if they contain sufficient ferromagnesian minerals, will develop a dark black patina on their tops and an orange coating underneath that is known as desert varnish.

Landform surfaces free from new deposition will also begin to erode due to direct rainfall and the ensuing runoff on the surface. As the surface erodes, new tributary channel networks develop which become more incised and integrated with time. The channels gradually deepen and widen, creating a greater degree of relief between the channel bottoms and the ridges which separate them. The degree of relief can be directly observed in the field or on aerial photographs, but can also be detected by the examining the crenulation (curviness) of topographic map contours.

The degree of relief of an apparently inactive landform relative to adjacent active, young surfaces is also an important characteristic. Because active alluvial fans are aggrading landforms, it follows that some older surfaces may gradually become buried by sediment deposition derived from the adjacent younger active alluvial fan. Therefore, where there is little topographic difference between younger and older surfaces, the investigator must take care to evaluate the rate of, and potential for, long-term aggradation of the fan. Typically, the rate of fan aggradation is greatest near the hydrographic apex, with lower accumulation rates as the distance from the apex increases and/or the active fan widens.

AZGS surficial geology mapping differentiate surfaces based on the types of geomorphic characteristics discussed above. Therefore, the map data also provide information about surface age, stability, and flood potential. Young surfaces with little soil development are likely to continue to experience flood inundation, sediment deposition, and channel movement. Older surfaces are unlikely to experience such processes. Older surfaces with cemented soils and entrenched channels also tend to be more stable because their soils are more resistant due to the cohesion provided by clay, carbonate, and pavement, as well as due to containment of flow within defined, vegetation-lined channels. That is, the likelihood of the channel changing its location over time is greatly diminished. Conversely, areas with non-cohesive, coarse soil materials and little lateral relief are more susceptible to lateral changes in channel position.

Even with local variations in pedogenic features, their use as relative age indicators is practical and often the only way to constrain the age of a soil and its surface, which can provide the basis for evaluating dates generated by chronometric or numerical techniques. Geomorphic mapping of alluvial fan surfaces is based on several factors, such as degree of preservation of bar and swale topography, desert pavement development, general rind thicknesses, reddening of underlying soils and bottoms of surface clasts, vegetation types and density, degree of carbonate development, plasticity of soil, and presence of B-horizons. The use of pedogenic features to estimate the age of soils and their surfaces is helpful in determining what deposits are youngest to oldest in a given area, and a numerical *range* can be assigned to those deposits. For example, if an alluvial fan surface in Maricopa County has been mapped as a "Qo" surface, its associated soil probably contains laminar carbonate layers and chunks of thick carbonate rinds, and the surface is likely > 1,000,000 years old. Fan deposits that have very weakly to weakly developed soils with minimal carbonate and clay accumulation can be estimated to be middle to late Holocene aged.

Young alluvial fan deposits have rough surfaces that are composed of bar and swale topography and as the fan surface ages, it becomes smoother and eventually armored with desert pavement. With further aging of the alluvial fan surface, it can become dissected, with rounding of its edges and dissecting channels. Hsu and Pelletier (2004) applied linear hillslope diffusion to cross-sectional gully profiles taken from Quaternary alluvial fan surfaces at the base of the Ajo Mountains in southern Arizona. They focused on pre-dated fan surfaces with ages of approximately 10 ka to 1.2 Ma and found that their method produced ages with 30 to 50% accuracy. They cautioned that their method should not be used to correlate and relatively date alluvial fan surfaces (Hsu and Pelletier, 2004) until the method has become more refined.

Limitations. Relative dating methods such as the use of pedogenic features to characterize soils do not provide specific numerical age values, but rather broad age ranges. The variation in pedogenic features as mentioned above vary from region to region, although there usually are consistent cross-correlating features. For example, if a soil is thought to be late Pleistocene in age and it contains reddened soils in one locality, but not another, then other features can be used to constrain the age estimate, such as the degree of carbonate buildup. Topography and vegetation have been shown to be as important as time in explaining soil genesis, and can control the distribution and types of soil features in a given region (Walker, 2005). Even with the largely unconstrained nature of relative dating methods such as pedogenesis and surface morphology, these methods should be used as a first order approximation of age because they are useful in distinguishing between Holocene and Pleistocene surfaces. These methods are cost effective and should be used to isolate areas that may need more labor and cost intensive methods to determine their ages.

Rock Surface Weathering

Description. Physical and chemical weathering processes begin to alter geomorphic surfaces and their sediments right after they are deposited. Boulders exposed on geomorphic surfaces develop weathering rinds, rock varnish (discussed previously), and can disintegrate over time. Weathering rind thickness is usually indicative of the time the boulder has been exposed and subjected to physical and chemical weathering processes. Relative ages between surfaces can be estimated by measuring weathering rind variations on similar lithologic samples. Knuepfer (1994) suggests that surface weathering rind variation dating in the western United States is best suited for application to shorter time intervals, such as the Holocene, whereas subsurface rinds may be utilized for longer time intervals. This is due in part to the decrease in chemical weathering rates over time. Early stages of weathering rind growth follow a power-law increase and growth slows down as the buildup of weathering residues impedes the movement of water into the rock. Weathering rinds should be measured on homogeneous, fine-grained lithologies, such as basalts and limestones, to ensure that the rates of rind formation are consistent from sample to sample (Knuepfer, 1994). In addition, sample selection should be limited to clasts that do not have rinds that were developed prior to transport to their current locations. Comparison of rinds on tens of samples of the same lithology on the same surface may elucidate which rocks have inherited rinds. Transport of rocks as bedload in floods tends to rejuvenate rock surfaces due to rind removal by abrasion and other processes (Knuepfer, 1994).

The rock surface weathering features described above is relatively inexpensive and could provide correlative age constraints, especially if they are calibrated by using one or more of the numerical methods described above. In other words, surfaces with the same climate and rock types that have been dated with OSL or even cosmogenic nuclides could be analyzed for rind thicknesses, and degree of weathering. A chronology and associated rind thicknesses per general rock type and degree of weathering could be applied to other surfaces that have not been dated with numerical dating techniques.

Limitations. To date, a comprehensive study to calibrate surface ages in the Southwest based on rind thicknesses and degree of weathering has not be completed. Calibration of these methods would require hundreds of measurements of rinds and degree of weathering on multiple surfaces and their associated geomorphic surfaces would need to be dated with independent numerical methods. The variability in rind thickness or weathering would likely be high as both of those surface weathering processes are controlled by lithology, local climate, altitude, aspect, biological activity and the movement of water in the soil column. Few lithologies lend themselves to consistent rind production. Weathering rind measurements would need to be focused on fine-grained, homogeneous lithologies, such as basalts.

Palynology

Description. The introduction of exotic plants and animals after the arrival of European settlers to the Americas resulted in the deposition of exotic plant debris, fungus, and exotic pollen grains that can provide age estimates of the sediments and soils in which they were deposited. For example, *Salsola*, commonly referred to as tumbleweed was introduced to the United States in 1871 with a shipment of flax seed to South Dakota. After approximately 10 years, tumbleweed had been distributed across the western U.S. and its pollen deposited in sediments and soils. Cattle grazing in the western United States began with the arrival of European settlers. This led to the introduction of *Sporomiella,* a dung fungus associated with livestock that has been observed in sediments and soils in the southwest. The presence of this spore in soils and sediments can also be used to infer their young ages (Burney et al., 2003; Young et al., 2002; Davis, 1990). An alluvial fan displaced by the San Andreas fault in central California was dated by the identification of historic pollen types from tumbleweed and eucalyptus (Young et al., 2002). Pollen grains from tumbleweed and eucalyptus, and the *Sporomiella* fungus were identified in silts collected in the upper ¾ of a meter of the excavation and these types were not found in samples taken at much deeper depths, thus suggesting the silts were deposited during historic time (Young et al., 2002). In addition to the identification of historic grains, pollen horizons were constructed based on the concentration of pollen and the type of sediment the sample was taken from. Fine-grained, laminated silts contained several pollen species, while coarse grained sands did not contain any pollen (Young et al., 2002). This is due in part, to the movement of pollen out of the sands after deposition. Construction of pollen horizons in a sedimentological context is important to constrain the possibility of movement of pollen.

Sampling Techniques. Collecting samples for concentration and identification of pollen types can be done by extracting soil or sediments from an exposure or by coring. Exposures need to be scraped and cleaned prior to sampling and approximately 300 grams should be collected per sample. Samples should be floated for identification of plant debris. Concentration of pollen is done with a series of acid washes (HCl and HF) and centrifuging. Concentration and identification of pollen, spores and plant debris can be done with specialty laboratories such as Paleo Research Laboratory in Colorado.

Limitations. The identification of historic pollen grains, spores or other plant debris must be performed by trained palynologists. This endeavor, including acid washing is time consuming and costly. In addition, historic index taxa may not be present in samples, and if they are, movement in the soil column must be considered. As mentioned in the above example, some sediment may be completely void of pollen grains, even after careful collection, preparation and identification procedures have been followed. Ages obtained from identifying historic spores or pollen grains are only bound by the introduction of historic plants and livestock and cannot be used to resolve ages younger than 1900 A.D.

Archaeology

Description and Limitations. Although the use of archaeology to help constrain the ages of alluvial fan deposits is limited, it can provide valuable age constraints for some fan sediments. The identification of potsherds, stone tools, farming remnants, fire pits and other artifacts has been used in the past to infer the sediment and surface ages. If artifacts are found within the soil or sediment column of an alluvial fan, they could provide age estimates of the sediments and surfaces overlying them.

Recommendations

Relative, numerical and correlative dating methods can be used to date Holocene alluvial fans in the southwest, including Maricopa County. However, accurately estimating the ages and establishing a chronology of alluvial fan development in Maricopa County will require a multi-method approach. Relative dating methods are an important first step, and are used to generate a contextual geomorphic interpretation as well as detailed maps that define the physical framework of the alluvial fan system. The relative dating results provides a basis for evaluating what type of material and surface to sample and what dating methods would be most useful. Generally, numerical dating methods should always be coupled with relative age indicators. If numerical ages are obtained from alluvial fan sediments and surfaces like those found in Rainbow Valley or Tiger Wash, then indirect dating techniques like VML, weathering rind thickness measurements, surface roughness and degree of soil formation can be calibrated from those same sediments and surfaces. When relative dating methods have been calibrated at several sites within Maricopa County, a regional chronology of fan and surface development can be constructed that would apply throughout Maricopa County. The process of constructing a regional chronology could take several years to complete, and would require the involvement of several types of dating and surficial geology experts. Once completed, it would provide useful guidelines in the PFHAM for dating and delineating young alluvial fan surfaces.

There are several relative dating methods that can be used to generate landform base maps, and provide estimates of surfaces ages. There are two to three numerical and correlative methods that can be used refine surface and sediment ages. Below is a list of those methods and their general limitations:

- Geomorphic mapping and application of relative dating methods (surface morphology, degree of soil and desert pavement development, vegetation type and density, carbonate content and structure) should be performed prior to applying any numerical dating techniques. Relative dating techniques do not provide direct ages and may not be useful in resolving ages of Holocene surfaces. In addition, most of these relative age indicators have not been calibrated for fans and sediments/soils in Maricopa County and surrounding regions.

- OSL and AMS radiocarbon dating methods are the most applicable numerical dating methods in dating alluvial fan sediments. OSL dating has not previously been applied to alluvial fans in Maricopa County, and the method would need to be refined for this region. AMS radiocarbon dating is problematic because of the nature of detrital organic input and the low production of organic debris.

- Cosmogenic nuclide dating and varnish microlamination correlation are the most favorable methods for estimating surface ages. Cosmogenic nuclide dating of relatively young alluvial surfaces is limited by problems associated with inheritance, but may prove useful once inheritance values are estimated with repeated use. Varnish microlamination (VML) is a correlative method and should be evaluated further in Maricopa County. This technique is not widely in use and must be performed by one or two specialists.

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Appendix H:

Methods for Evaluating Alluvial Fan Flood Hazards From Debris Flows in Maricopa County, Arizona

Methods for Evaluating Alluvial Fan Flood Hazards From Debris Flows in Maricopa County, Arizona

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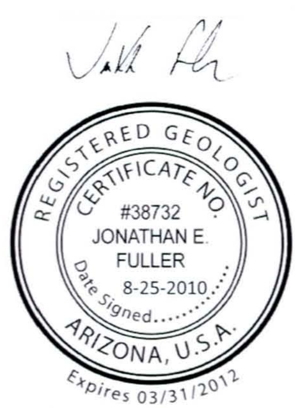

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Contract #FCD2008C007
Work Assignment #1, Task 2.7

Executive Summary

This study evaluated methods to quantify the risk of debris-flow initiation and runout potential to impact alluvial fan flooding hazards in Maricopa County. Debris flows are unsteady, non-uniform, very poorly sorted sediment slurries that are generated when hillslope soils become saturated and fail. While there is some evidence that debris flows have occurred in Maricopa County on very steep slopes of mountainous watersheds, there are no documented cases of historic debris flows impacting flood hazards on mid-piedmont alluvial fans. Based on known general characteristics of debris-flow behavior, as well as on the specific climatic and geologic conditions in Maricopa County, the expected recurrence interval for debris flows in Maricopa County probably exceeds 1,000 years. Furthermore, because of the regional physiography and watershed characteristics, it is likely that future debris flows will have low volumes because of limited sediment supplies, will travel only short distances from their point of initiation due to their coarse sediment composition and low clay content, and that most will not reach the active areas of alluvial fans, particularly the fans that are located away from the mountain front.

To assess potential debris flow impacts on alluvial fan flooding, a combined approach of geologic reconnaissance and mapping, with a two-phase application of the LAHARZ debris-flow runout hazard model is recommended. Geologic reconnaissance will confirm the presence or absence of relatively young debris-flow deposits, and provide details of the basin and piedmont conditions which will be useful for calculating and evaluating potential debris-flow volumes. Geologic mapping will provide data regarding minimum number of deposits, relative ages, and travel distances of past debris flows. Debris-flow runout models will provide hazard information regarding potential travel distances, and the volumes required to reach those distances.

Table of Contents

Introduction

Debris flows are significant geologic hazards worldwide (Larsen, 2008). Historical occurrences (<150 years) of debris flows have been documented in all three physiographic provinces in Arizona (Figure 1), including the Grand Canyon, isolated peaks on the Colorado Plateau (Melis and others, 1995; Griffiths and others, 1996; Webb and others, 2008a), the Mogollon Rim, the Mazatzal Mountains in the Transition Zone (Pearthree and Youberg, 2004; Jenkins, 2007; Youberg, 2008), and numerous mountain ranges within the Basin and Range Province of central and southern Arizona (Wohl and Pearthree, 1991; Webb and others, 2008b; Youberg and others, 2008). Pleistocene and Holocene debris-flow deposits provide ample geologic evidence of debris-flow activity in most of Arizona's mountain ranges. Extensive, large caliber debris-flow deposits on alluvial fans across central and southern Arizona record periods of aggradation during the wetter climates of the Pleistocene and early Holocene (older than about 8,000 years), and attest to the primary importance of debris flows in constructing fans during that time. Geologic mapping of debris-flow deposits on fans along the front range of the Santa Catalina Mountains show that mid-Holocene to modern debris-flow deposits are smaller and more limited in extent than Pleistocene to early Holocene deposits (Youberg and others, 2008).

The objective of this debris flow assessment is to determine and quantify how debris flow potential influences alluvial fan flood hazards in Maricopa County. The purpose of this report is to evaluate methodologies to assess the potential for debris flows to impact alluvial fan flooding in Maricopa County. The report evaluates and recommends methods for determining potential debris flow occurrence and run-out onto the alluvial fan flood hazard areas. Other debris-flow hazard issues such as expected magnitude, frequency, or direct impacts on developments located at the base of steep slopes (Péwé, 1978) are not directly addressed in this report.

Debris Flows – Definitions, Descriptions & Rheology[1]

Definition

Debris flows are unsteady, non-uniform, very poorly sorted sediment slurries (Costa and Williams, 1984; Iverson, 2003) that are generated when hillslope soils become saturated and fail. As pore pressures in saturated soils increase and shear strengths decrease, a critical point of failure occurs resulting in a rapidly mobilized soil mass that transforms into a viscous slurry through liquefaction or dilatancy (Costa, 1984; Iverson and others, 1997).

Descriptions

A review of debris-flow literature reveals considerable variability and contradictory usage of descriptive terms due to the inconsistent appearance of debris-flows. In general, flood flows are classified as water floods, hyperconcentrated flows, and debris flows based on sediment concentration and flow rheology (Pierson and Costa, 1987; Pierson, 2005). Debris flows are sediment-rich slurries at one end of a continuum with floods (water flows) at the other end, and hyperconcentrated flows in the middle. Flood flows typically contain less than 40% sediment by volume and are turbulent Newtonian flows (Pierson and Costa, 1987). Clay, silt and sometimes sand are transported as suspended sediment in floods while

[1] Rheology. The study of the flow, behavior and deformation of materials.

gravel is generally transported as bedload. Hyperconcentrated flows have around 40-60% sediment by volume and have sufficient interaction between grains to keep sediment in suspension as long as flow velocities are maintained (Pierson, 2005). Thus deposits from both flood and hyperconcentrated flows exhibit some degree of sorting by grain size (Pierson, 2005).

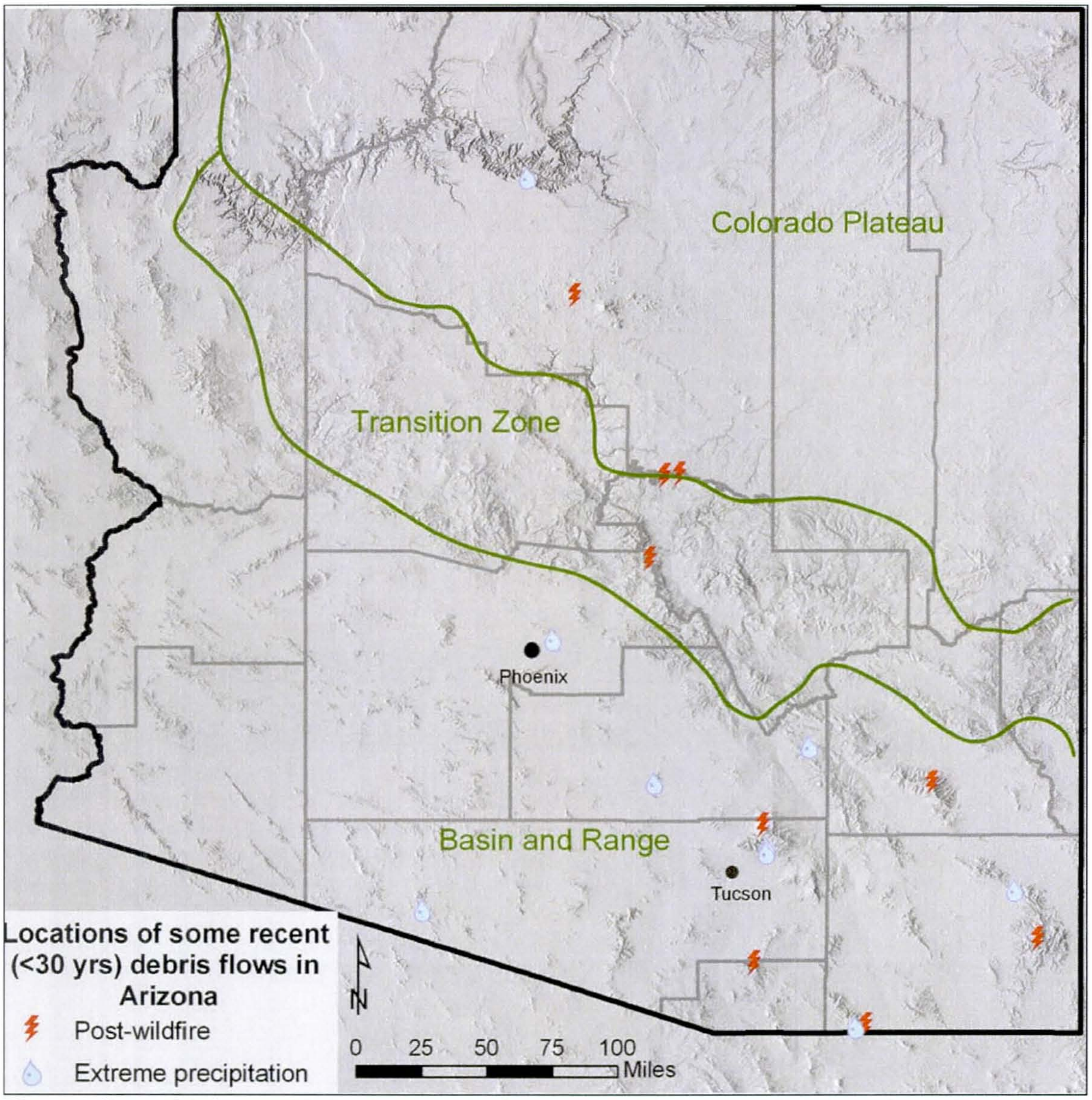

Figure 1. State of Arizona with the three geophysical provinces (green), and locations of some known recent (<30 yrs) debris flows. Red symbols indicate those debris flows that were fire-related. Blue symbols are those that occurred due to extreme precipitation.

Debris flows differ from flood flows and hyperconcentrated flows both in the amount of sediment they contain, more than 60% by volume (Pierson and Costa, 1987), and in flow behavior. Debris flows are grain-fluid mixtures that have unsteady flow characteristics due to fluctuating states between the fluid and solid phases. The fluid matrix phase of a debris flow is composed of clay, silt, and sand in suspension and is driven by high pore pressure. The solid-particle phase is composed of coarse clasts that interact by frictional and gravitational forces. The solid and fluid phases maintain flow by transferring momentum both within and between each phase simultaneously (Iverson, 1997). This interaction within and between phases is what distinguishes debris flows from other flows and prevents particles from settling, even at low velocities, resulting in deposits that exhibit minimal sorting (Iverson and Vallance, 2001; Pierson, 2005).

Rheology

Debris-flow behavior varies depending on grain size and the dominance of the solid and fluid phases. Behavior in a single debris flow can transform from a viscous plug to a very fluid flow through time and space as composition, pore pressures and grain-to-grain interactions evolve (Iverson, 2003). Fluid-flows are dominated by the matrix phase, and are typically composed of fine-grained clay, silt and sand, or ash if volcanic related. Fluid flows behave as a single-phase flow exhibiting Bingham-type flow behavior (Parsons and others, 2001), and tend to have thinner deposits and longer runout distances (Iverson, 2003). Granular-flows have a wider range of material sizes and behave more as a two-phased, non-Newtonian flow with a fluid matrix and a solid-particle phase (Iverson, 1997; Iverson, 2003). These flows can have very little silt and clay in the matrix resulting in shorter runout distances and thicker deposits (Iverson, 2003). Recent debris flows in the Santa Catalina Mountains near Tucson appeared to be granular-flows based on the presence of abundant coarse clasts in their deposits and lack of clay in the matrix (Webb and others, 2008b). Coarse deposits from other historical debris flows in Arizona (Péwé, 1978; Wohl and Pearthree, 1991; Webb and others, 2000) were also most likely deposited by granular flows. In Maricopa County, debris flows are expected to be granular, with coarse clasts and low clay content, resulting in shorter runout distances.

There are three distinct zones in which different debris-flow processes occur - initiation, transportation and deposition (Hungr, 2005). Initiation zones are located on steep upper hillslopes and are most often identified by distinct head scarps of slope failures where debris flows are generated (Figures 2 and 3). Generally, the term landslide-induced debris flow is used to describe a shallow translational failure of thin soil over an impervious surface, such as bedrock, that liquefies and transforms into a debris flow (Iverson and others, 1997; Santi and others, 2008). Debris flows can also be initiated in channels when channel bed sediments are mobilized by runoff (Costa, 1984). Although the initiation mechanisms are not well understood, runoff-induced debris flows typically occur after wildfire when relatively high-frequency storm events can generate very high runoff volumes due to the removal of vegetation and other fire-induced changes (Wohl and Pearthree, 1991; Cannon, 2001; Moody and Martin, 2001; Moody and others, 2008; Santi and others, 2008). Changes due to wildfire include decreased interception and surface roughness due to consumption of plant and duff material, decreased infiltration due to surface sealing and fire-induced water repellency, which leads to increased runoff and flow velocities. Probable initiation mechanisms for runoff-induced debris flows include channel bank collapse, channel bed failures, or the temporary emplacement and failure of dams.

Once initiated, debris flows travel downslope via existing channels through the transportation zone (Figures 2 and 3), changing character in time and space. Debris flows commonly move in surges led by a coarse-boulder front (head), followed by a liquefied slurry (body), and a more watery tail, which is commonly a hyperconcentrated flow (Hungr, 2005). As debris flows move downslope, longitudinal sorting of coarse clasts results in the deposition of lateral levees , either in the transportation or deposition zones, which act to confine the flow (Figure 4) (Hungr, 2005). Although levees may be deposited along the channel in the transportation zone, they are most obvious in areas with less lateral topographic

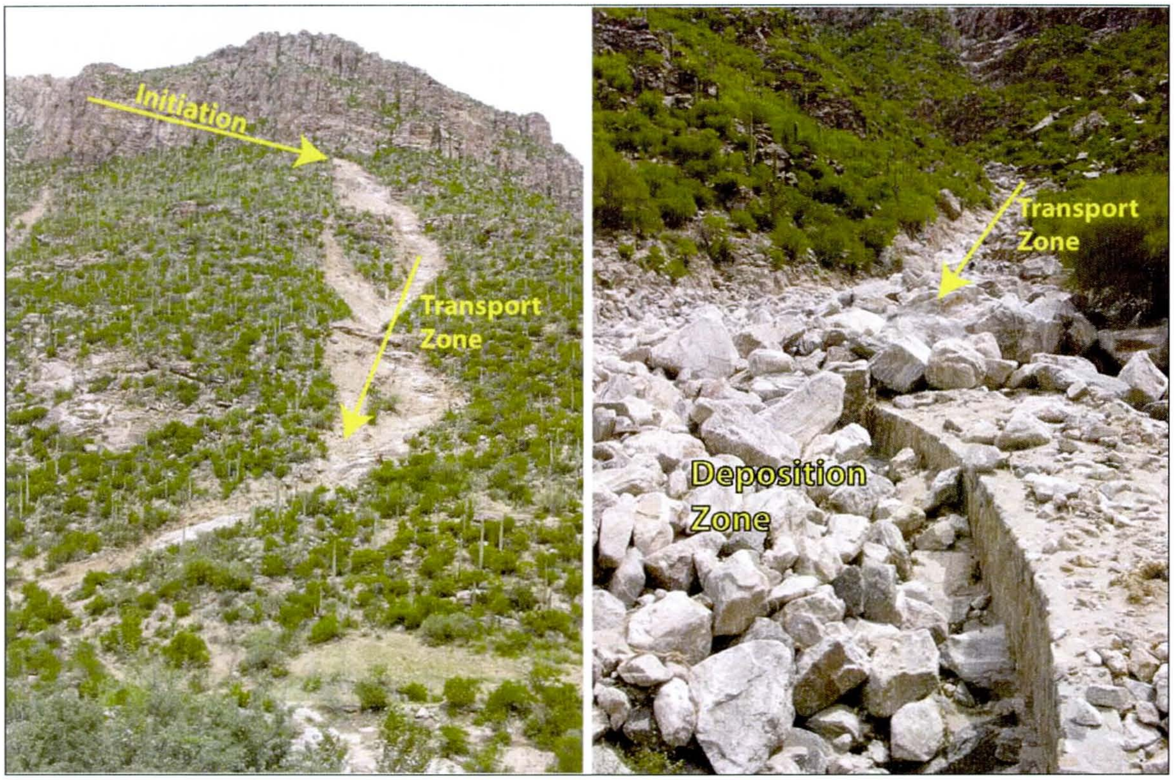

Figure 2. Examples of initiation, transport and deposition zones from Sabino Canyon, Santa Catalina Mountains, Tucson (modified from Youberg and others, 2008). These debris flows are on very steep slopes in the watershed above the alluvial fan apex.

Figure 3. Example of a landslide scarp at the top of an initiation zone (left) and transportation zone in a debris-flow channel (right). Blue arrows indicate flow direction.

confinement. Debris-flow volumes can change significantly during downslope movement as scouring or deposition occurs (Iverson and Vallance, 2001). Debris-flow deposition occurs in areas where lateral confinement decreases and/or channel slope decreases.[2] Depositional areas are often alluvial fans located at the mouths of drainages (Figure 4).

Figure 4. Examples of debris-flow levees (yellow arrows). Recent (2006) debris-flow levee along a channel in the Huachuca Mountains (left photo) and late Pleistocene debris-flow levees near the apex of an alluvial fan in the Santa Catalina Mountains (right photo). Blue arrows indicate channel flow direction.

Factors That Affect Debris Flow Initiation, Transport and Deposition

Numerous factors influence the initiation, transportation and deposition of debris flows. Initiation occurs when hillslope soils become saturated, pore pressures increase and shear strengths decrease to the critical point of failure (Costa, 1984; Iverson and others, 1997). Some factors that increase the likelihood of initiation include steeper slopes, exposed bedrock, which increases runoff and flow velocity, high antecedent moisture conditions, and prolonged or intense rainfall (Giraud, 2005).Disturbances such as wildfires decrease vegetation cover resulting in decreased interception, and infiltration, and increase runoff, increasing the likelihood of initiation. In areas where trees are killed by fires, root strength also decreases with time leading to an increase in the likelihood of slope failure (Gerber and Roering, 2003).

Basin relief and channel gradient influence debris-flow transportation and deposition, but the most important factors are debris-flow volume and composition. Debris-flow composition determines the behavior of the flow. Finer-grained, fluid flows travel farther and have thinner deposits, while coarser-grained granular flows do not travel as far and have thicker deposits (Iverson, 2003). Debris-flow volume is determined both by the magnitude of the hydroclimatic event and by the amount of sediment available for transport. In supply-limited basins, such as those in Maricopa County, sediment is stored over time as loose colluvium on hillslopes, in colluvial wedges at the base of hillslopes, and in channels (Jakob, 2005). With an appropriate triggering rainfall, sediment is released through hillslope failures, colluvial wedge and channel bank collapses, and channel bed failures and/or scouring (Giraud, 2005; Jakob, 2005). The amount and nature of material released from storage will be a key factor in debris-flow runout.

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[2] While there are some reported slope thresholds for deposition, they vary by environment and do not appear to be consistent. There are no known reported thresholds for Arizona.

Historical Debris Flows in Arizona

Historical records from relatively populous areas during the past 150 years reveal some debris flows in the mountains surrounding Tucson (Webb and others, 2008b), and small but damaging debris flows in Phoenix area during the 1970's (Péwé, 1978). Documented historical debris flows, however, are typically limited to steep watersheds in mountainous terrain and sparsely populated areas. Over the past 30 years, Arizona saw an increase in fire-related debris flows as the size and severity of wildfires increased (Wohl and Pearthree, 1991; Pearthree and Youberg, 2004; Schaffner and Reed, 2005). Numerous debris flows have also been generated from low-frequency, high-magnitude storms, such as dissipating tropical storms (Griffiths and others, 1996; Webb and others, 2008b) as shown in Figure 1. No evidence or records of any documented historical debris flows in Maricopa County exiting mountain fronts or flowing onto active alluvial fans was identified during the course of this study.

While the record of historical debris-flow deposits demonstrates that debris flows can occur in Arizona, the frequency of debris flows in this desert region may be an order of magnitude less than in humid areas (Webb and others, 2008b). The occurrence of debris flows are a culmination of several factors, including a triggering hydroclimatic event, a watershed with sufficient material available for entrainment, and slopes steep enough to initiate and maintain flow movement. Debris flows are less frequent in supply-limited basins, such as those found in Arizona, where coarse material accumulates in channels over relatively long time periods (Jakob, 2005). Sediment recharge rates are dependent on sediment production and erosion rates (weathering and delivery), which are functions of lithology, climate, and basin morphology. Channels in supply-limited basins tend to be filled with coarse material and have high hydraulic conductivity, which require large amounts of precipitation and runoff to trigger a debris flow. Thus, not only is the triggering hydroclimatic threshold higher in supply-limited basins, but long time periods may be required to accumulate sufficient sediment for transport (Jakob, 2005). Once a debris flow occurs in a supply-limited basin, another debris flow cannot occur until sufficient time has passed to build up enough material for another event. If an extreme rainfall occurs before the sediment supply is available, the resulting flow may be a water flood or hyperconcentrated flow. Based on geologic mapping of debris-flow deposits observed at the base of the Santa Catalina Mountains, their recurrence intervals were estimated to be on the order of 1,000 years (Youberg and others, 2008). The frequency of debris flows in Maricopa County may be as low or lower (i.e., less frequent) due to generally drier conditions, lower elevations, sparser vegetation and shallower soils compared to the Santa Catalina Mountain area.

Prior to 2006, the trend of decreasing size and extent of debris-flow deposits from the late Pleistocene to late Holocene, along with the dearth of historical debris flows, suggested that debris flows did not represent a significant geologic hazard in Arizona (Webb and others, 2008b). That view was challenged when an unusual weather pattern in late July, 2006, resulted in approximately 1,000 hillslope failures in four mountain ranges across southeastern Arizona (Pearthree and Youberg, 2006b; Magirl and others, 2007; Webb and others, 2008b) as shown in Figure 1. Although much of the Santa Catalina mountain range had burned in 2003, nearly all of the hillslope failures initiated in areas that either had not burned or had been subject to low-severity burns (Webb and others, 2008b). Most of these hillslope failures transformed into debris flows that traveled only short distances well within the mountain front, although some coalesced into larger debris flows and traveled surprisingly far (Webb and others, 2008b). Debris flows damaged or destroyed infrastructure in Coronado National Memorial (Huachuca Mountains) and in Sabino Canyon (Santa Catalina Mountains). Debris flows exited or nearly exited the mouths of five canyons along the front range of the Santa Catalina Mountains (Figure 5), and caused significant alluvial fan flooding at the mouth of Soldier Canyon (Webb and others, 2008b).

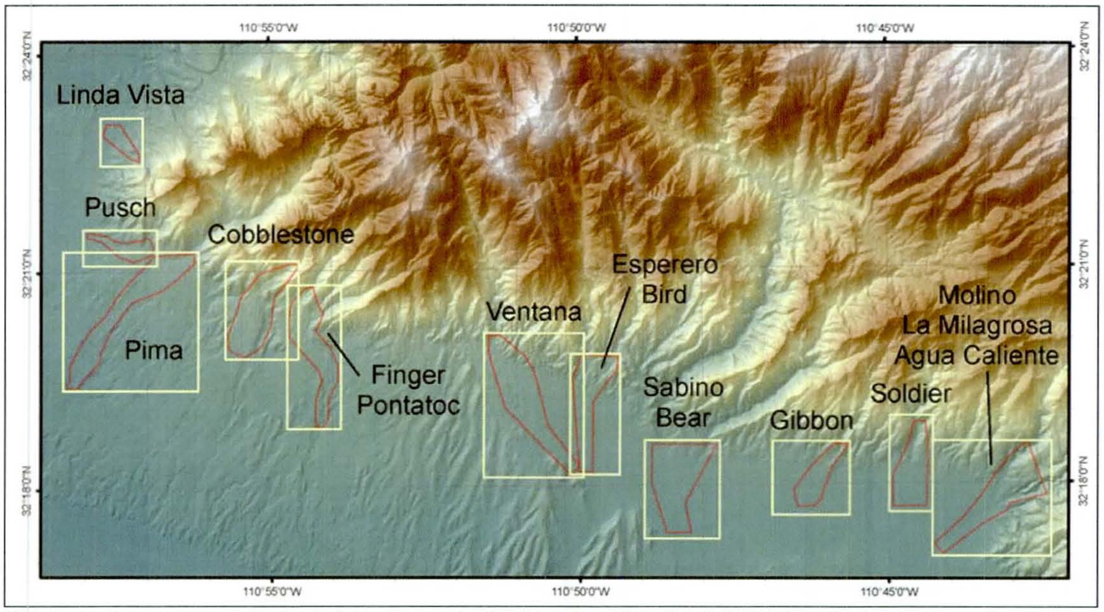

Figure 5. Alluvial fans included in the geologic mapping of paleodebris-flow deposits along the Santa Catalina front range. Debris flows exited the mountain front in Soldier and Gibbon Canyons, and almost exited the mountain front in Bear, Sabino and Bird Canyons. (Youberg and others, 2008).

The events in Soldier Canyon from the July 2006 storms illustrates the most likely (albeit highly infrequent) impacts of debris flows on alluvial fan flooding expected for the developed areas around the base of low desert mountains in Maricopa County. In Soldier Canyon, Webb and others (2008b) documented 56 hillslope failures within the watershed. These hillslope failures coalesced into debris flows and travelled down canyon onto the Soldier Canyon alluvial fan (Figure 5). Pre- and post-event orthophotographs from 2005 and 2007 show significant channel widening and sediment deposition occurred during the 2006 debris flows and floods (Figure 6). It is important to note that the active fan surface at the mouth of Soldier Canyon is adjacent to the mountain front, unlike most of the alluvial fans in Maricopa County. Sediment from at least two debris-flow pulses reached the Mt Lemmon Short Road crossing near the fan apex, plugging the bridge and channel. The recessional flood was then forced to spread out across the fan head (Figure 7) which caused extensive damage to infrastructure and one house (Youberg and others, 2008).

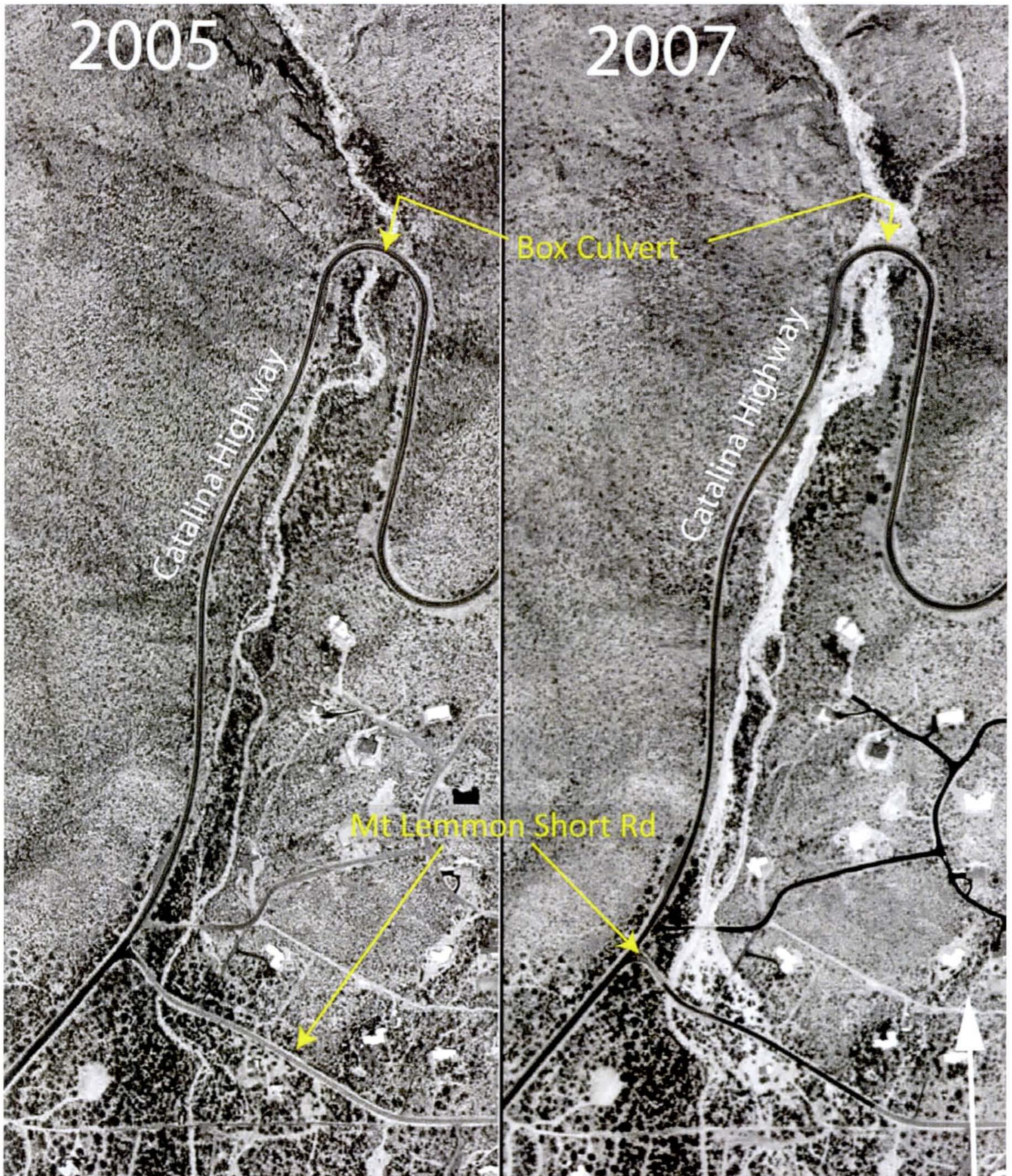

Figure 6. Comparison of Soldier Wash channel between 2005 (left) and 2007 (right). Debris flows and floods significantly widened the channel; older, abandoned channels were re-occupied. (Modified from Youberg and others, 2008).

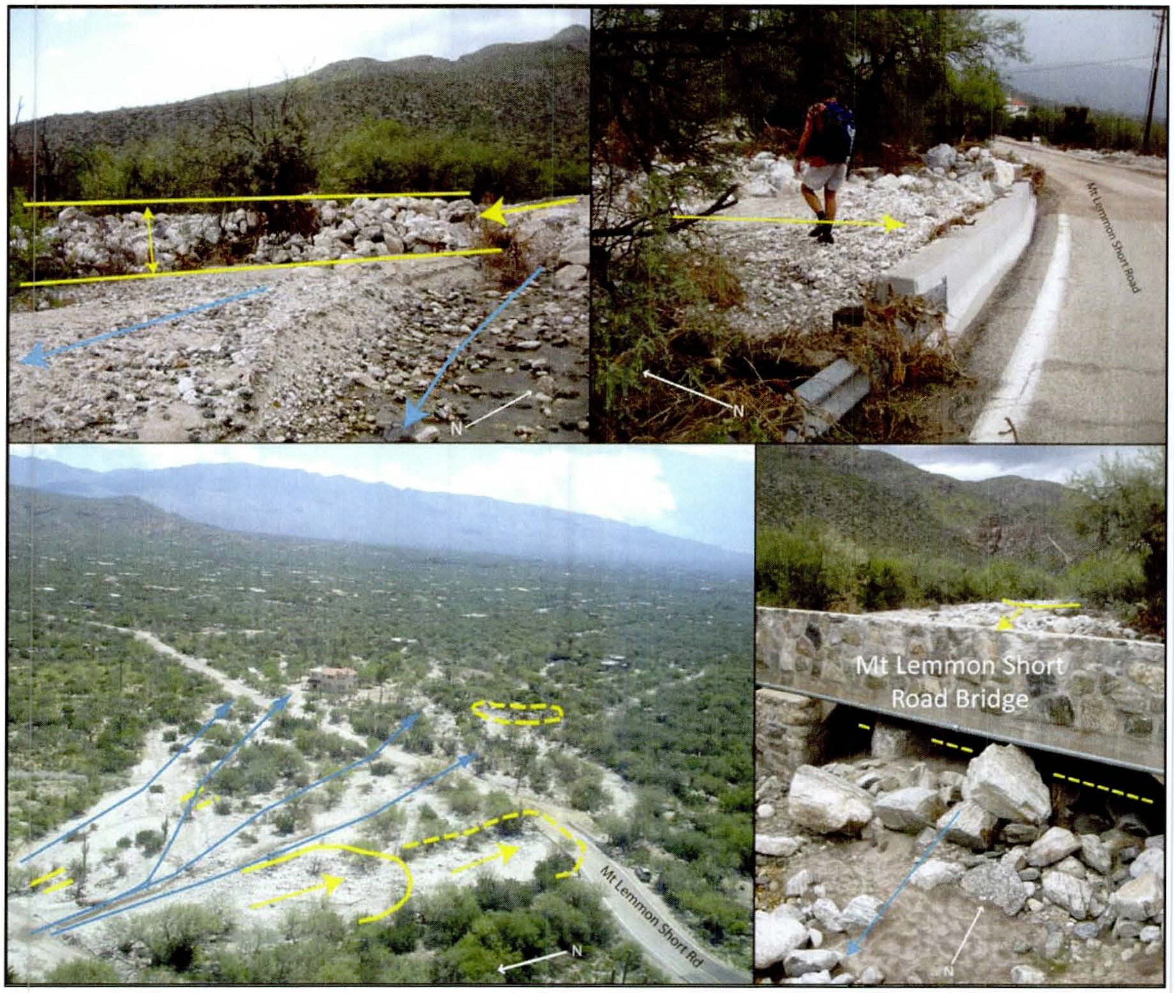

Figure 7. Soldier Canyon fan – impacts from 2006 debris-flows. Upper left: boulder snout of debris flow upstream of the Mount Lemmon Short Road. The debris-flow deposit was deposited after, and on top of, an earlier pulse that likely plugged the bridge (Photo: P.G. Griffiths, Sept. 12, 2006). Upper right: Mt Lemmon Short Road bridge plugged by debris-flow deposits (Photo: C. S. Magirl, 9-12-06). Lower left: aerial view of debris-flow deposits (yellow lines) and recessional flood flow (blue lines) (Photo: P.G. Griffiths, 9-3-06). Lower right: view upstream of the plugged Mt Lemmon Short Road bridge (Photo: P.G. Griffiths, 9-12-06).

Debris Flow Generation in Arizona

Historical hydrological conditions that have generated debris flows in central and southern Arizona are quite varied. Debris flows have been documented following short-duration, high-intensity summer convective storms, long-duration, less-intense, regional winter frontal systems, and widespread and intense late summer to early fall dissipating tropical storms (Webb and Betancourt, 1992; Griffiths and others, 1996). In the lower desert regions of Arizona, similar to conditions in Maricopa County, debris flows have been documented from these different storm types. For example, numerous debris flows occurred in the Picacho Mountains during the incursion of tropical moisture from Tropical Storm Octave in 1983, and in 2008 debris flows occurred in the Ajo Mountains following an intense summer convective storm. Debris flows have also occurred following wildfires from high-frequency, low-magnitude monsoonal storms (Wohl and Pearthree, 1991; Pearthree and Youberg, 2004). Following the 2004 Willow Fire near Sunflower, a 5- to 10-year frequency monsoonal storm generated debris flows in every burned drainage along State Route 87 at the Gila-Maricopa County line (Pearthree and Youberg, 2006a). Debris flows have also been generated from more rare and extreme storms, such as the 2006 debris flows in southern Arizona (Magirl and others, 2007). Griffiths and others (2009) analyzed radar and rain gage data from the Santa Catalina Mountains to estimate return intervals for this series of July 2006 storms. Estimated return intervals for individual daily storms were less than two years, while return intervals for average 2-day storms were greater than 50 years, and greater than 200 -500 years for the 4-day storm with return intervals up to greater than 1,000 years in some areas (Griffiths and others, 2009). These findings show that high antecedent soil moisture conditions prior to debris-flow initiation was a critical factor for the 2006 event (Griffiths and others, 1996; Webb and others, 2008b). Youberg and others (2008) concluded that debris-flow frequency in individual canyons in the Santa Catalina Mountains are on the order of a thousand years, somewhat longer than the most extreme return intervals estimated for the storms of 2006. The low desert mountains of Maricopa County is likely to have even lower return intervals than the higher mountain ranges in southern Arizona due to the lower elevations, slow sediment recharge rates, and low annual rainfall.

The mountains and associated alluvial fans in the developed, low desert areas of Maricopa County, have characteristics that make them less like to have debris flows that would impact alluvial fan flooding, compared to more mountainous areas of the county or the state. The low desert mountains, in general, have moderate relief, but channel gradients near the mountain fronts tend to be low, making it more difficult for debris flows to travel down channel and reach the piedmont, much less the mid-piedmont alluvial fan apexes. In addition, the hot and dry climatic conditions result in low sediment production and shallow hillslope soils, limiting available sediment. Wildfires are unlikely in this environment as the desert vegetation is typically too sparse, except in the wettest years (e.g. 2005), to carry fire. Therefore, hydrologic changes due to fire and the increased likelihood of post-fire debris flows do not typically apply to the low desert mountains of Maricopa County. Another factor influencing the likelihood of debris flows to impact alluvial fan flooding is the location of the active fan surface to the mountain front. If the active fan surface is adjacent to the mountain front then it is more likely debris flows could impact alluvial fan flooding. Many alluvial fans at the base of the low desert mountains in Maricopa County have active fan surfaces removed from the mountain front. Typically, these fans are fed by incised, low gradient, feeder channels. The distance from the mountain front and the low gradient channels make it very unlikely that debris flows will impact alluvial fan flooding in Maricopa County.

Methods for Modeling Debris-Flow Hazards

This section provides a discussion of debris-flow hazard assessment models that could be used to quantify how debris flows influence alluvial fan flood hazards in Maricopa County. In addition, some examples of debris-flow hazard assessments are presented. A comprehensive review of all available models is not presented. Rather, the models most useful for assessing potential debris-flow occurrence and runout capability in Maricopa County are reviewed. The challenge in identifying appropriate methods lies in the fact that most methods and models have been developed in wetter climates, where model testing and calibration is easier due to the higher frequency of occurrence of debris flows. Data used to test and calibrate models includes LiDAR-derived topography, extensive soils information, existing landslide inventories, detail maps of previous debris flows, and measured debris-flow parameters such as matrix composition, basal friction, flow depth and flow velocity. In the absence of these detailed data, results from debris-flow hazard models will, at best, be a preliminary assessment.

Importance of Geologic Reconnaissance Prior to Modeling
The Flood Control District of Maricopa County (FCDMC) wants to assess potential hazards associated with the impacts of debris flows on alluvial fan flooding. In order to model these hazards, it must first be determined that the basin of interest is a debris-flow producing basin, and that debris flows have actually run out onto the associated alluvial fan. This requires geologic reconnaissance to evaluate whether young debris flow deposits exist in the basin of interest, and geologic mapping to determine the downstream extent of deposits. Then, models assessing the likelihood of debris-flow occurrence (initiation) and runout capability can be used to assess the potential hazard. Initiation models provide information about slope stability in basins of concern. If no evidence of historical (i.e., less than 100 years) or geologically recent (i.e., less than 10,000 years) is found, then there is no need to apply the detailed debris flow modeling techniques described below. A method that incorporates results from geologic mapping and debris-flow modeling will provide the most robust means of assessing these geologic hazards. In addition, the data collected during the geologic reconnaissance can be used to help verify and/or calibrate the modeling results, as described below.

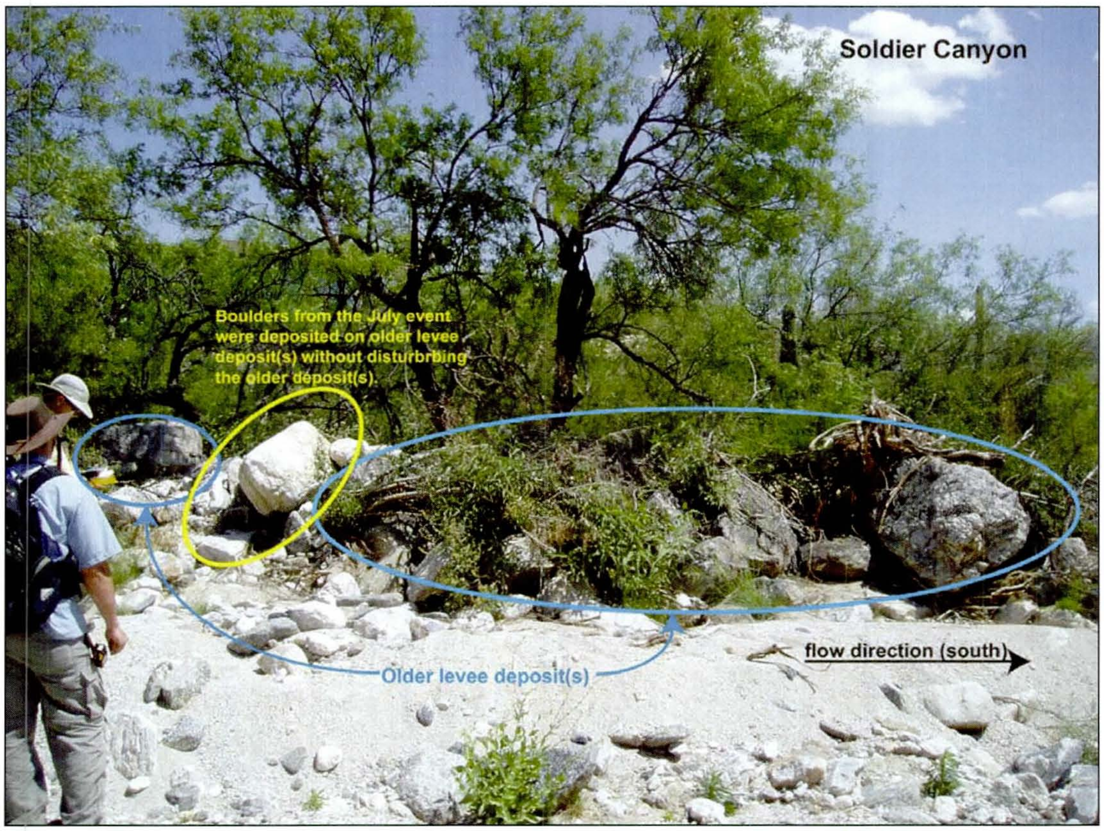

Figure 8. Examples of multiple debris-flow deposits of different ages. The fresh 2006 deposits are clearly visible now, but will be less so over time. (Modified from Youberg and others, 2008)

Recognizing Debris-Flow Prone Basins and Fans

Many factors determine whether or not debris flows can occur in a drainage basin, and how far they will travel. While models can provide information to assess the likelihood of debris-flow occurrence and runout, verification that there is physical evidence of young debris flows is a key component of any hazard assessment. Geologic reconnaissance involves field investigations to determine if deposits characteristic of debris flows are present. Key characteristics indicative of debris flows are large caliber sediment, linear arrangement of boulders along channels (levees), and bulbous, coarse boulder aggregations where debris flows stopped or changed direction (snouts). Geologic reconnaissance also includes a review of previous geologic and geotechnical reports, aerial photographs, soils data, and other historic information (e.g. newspaper articles) that may shed light on past debris flows. If young debris flow deposits exist along a channel, mapping them will provide information regarding past debris-flow travel distances, relative ages of deposits, and a minimum number of past debris-flow events (Figure 8) (Youberg and others, 2008). Although geologic data generally will not provide a complete census of individual debris flows, information regarding ages, extent and number of debris-flow deposits can provide valuable information regarding trends in debris-flow travel distance, volumes, and clast sizes.

Debris Flow Model Classification

Models have been developed to assess debris-flow behavior (Iverson and Denlinger, 2001), to estimate debris-flow erosion (Stock and Dietrich, 2006), and to predict debris-flow hazards (O'Brien and others, 1993; Wilford and others, 2004; Cannon and Gartner, 2005). There are two general classes of debris-flow models:

- Initiation models
- Runout models

Initiation models evaluate slope stability conditions to identify areas of potential slope failure and assess the likelihood of debris-flow occurrence. Runout models evaluate potential travel distance from the initiation point to the debris-flow deposition zone, which in some cases may be on alluvial fans. While initiation and runout models can provide hazard information regarding likelihood of occurrence or potential runout distances, they will not provide any information with respect to frequency-magnitude relationships. Actual occurrences and expected volumes are not predicted by these models. These models address debris flows generated from extreme precipitation, rapid snow melt, or as a result of disturbance due wildfires. Selection of a particular model depends on project goals, available data, and funding.

Debris flow models can be further classified as physically based or empirical. Physically-based models are rooted in classic physics, and incorporate mass, energy, and/or momentum conservation laws (Wilcock and others, 2003). These models can be very detailed, data intensive and expensive. Some of the more rigorous models may be best suited for post debris-flow assessments. Other physically-based models use generalized parameters and simplifying assumptions (Rickenmann, 2005). These models can provide good results but require input parameters that are difficult to estimate, such as travel velocity and friction coefficients. The models also require extensive field calibration (Fannin and Wise, 2001). Empirical models are based on field observations, measurements, and statistical relationships, and should only be used in the areas and conditions under which they were developed, or be re-calibrated using local data (Fannin and Wise, 2001).

Initiation Models

Initiation models assess slope stability conditions to identify areas of potential slope failure. Most of these models employ the same equation, but calculate the parameters and results differently. The most common models are used in a grid-based geographic information system (GIS), which partitions topography into regularly celled digital elevation models (DEMs) and allows for rapid spatial analysis of large areas. Models that use GIS can incorporate diverse factors including topography, geology, soils, hydrology, and vegetation to evaluate slope stability and potential debris-flow initiation. Most models evaluate slope stability using the infinite slope form of the Mohr-Coulomb failure law;

$$\tau = c' + (\sigma - \mu) \tan \varphi \qquad (1)$$

where τ is the shear stress, c' is effective cohesion, σ is normal stress, μ is pore pressure, and tan Φ is the internal friction angle of the soil. The left side of this equation represents shear stress, or the driving forces, while the right side represents shear strength, or resisting forces. For slope stability analysis this equation if often rearranged to calculate the factor of safety (FS) for each DEM cell by finding the ratio of resisting forces to driving forces:

$$FS = \frac{C_r + C_s + \cos^2 \alpha [\gamma_s (D - D_w) + (\gamma_s - \gamma_w) D_w] \tan \varphi}{\sin \alpha \cos \alpha (\gamma_s D)} \qquad (2)$$

where C_r and C_s are root strength and soil cohesion, D is the vertical depth of the soil and D_w is the vertical depth of the saturated zone, γ is the unit weight of water (w) and soil (s), and α is the slope. Slopes are considered stable when FS>1 and unstable when FS<1.

There are four commonly-used debris flow initiation models that incorporate the infinite slope equation (1) in the factor of safety form (2). All of the models are physically-based and can be used in any environment, including Maricopa County. The following models are discussed in more detail below:

- SHALSTAB
- SINMAP
- LISA
- TRM

SHALSTAB. SHALSTAB (Montgomery and Dietrich, 1994) is a steady-state model that couples a hydrologic model with gridded topographic data (Dietrich and Montgomery, 1998). SHALSTAB calculates a topographic index based on contributing area per unit contour length, which is assumed to be equal to the cell resolution of the DEM. The FS equation is re-arranged to calculate a critical rainfall rate at which the slope will fail. SHALSTAB attempts to be as parameter-free as possible and requires only a single value for each input parameter. The default version of SHALSTAB requires input describing the soil bulk density and internal friction angle (Table 1). A newer version of SHALSTAB also allows input for effective cohesion (soil + root strength) and soil depth (Witt and others, 2007; Harp and others, 2008). From these parameters SHALSTAB calculates transmissivity and effective rainfall to determine a critical steady-state rainfall rate for slope instability (Montgomery and Dietrich, 1994). Cells are then classified as unconditionally stable, stable, unstable, and unconditionally unstable. Unconditionally stable slopes are slopes that won't fail even at full saturation, and sometimes includes rock outcrops. Unconditionally unstable slopes often have internal friction angles, Φ, less than slope angles, α, and can fail with less saturation. SHALSTAB assumes steady-state hydrologic conditions, uniform soil depth, constant saturated hydraulic conductivity, subsurface flow parallel to surface topography, and neglects friction along the sides of the failure plane (Montgomery and Dietrich, 1994). Data requirements for SHALSTAB are DEMs and single values for selected soil parameters. Benefits of the SHALSTAB model are that it can be applied across diverse environments, it is less costly to parameterize, and different sites can be directly compared. However, some studies have found that the model can fail to produce results that match on-the-ground conditions (Dietrich and Montgomery, 1998). However, a failed model can indicate that physical processes other than those being modeled are influencing slope failures, which also is valuable information.

SINMAP. SINMAP (Pack and others, 2005) is a steady-state model that follows in the footsteps of SHALSTAB, but differs in a few key ways. SINMAP uses the same FS equation (2) and makes the same assumptions as SHALSTAB: steady-state hydrologic conditions, uniform soil depth, constant saturated hydraulic conductivity, subsurface flow parallel to surface topography, and neglects friction along the sides of the failure plane. SINMAP allows the user to provide a range of values for input parameters which are then distributed using a uniform probability distribution function (Table 1). Parameters input by the SINMAP user include rainfall rate, transmissivity, cohesion, internal friction angle, and soil depth. SINMAP calculates a FS for each cell and assigns a stability index (SI) based on the FS. If $FS \geq 1$, the slopes are stable. If $FS < 1$, a stability index (SI) is calculated based on the probability of failure for the best and worst conditions for the range of soil parameters described by the uniform probability functions (Pack and others, 2005). Data requirements for SINMAP include DEMs, ranges for selected soil parameters, and rainfall rates (Table 1). An advantage of SINMAP is that a study area can be broken into homogeneous regions to reflect different localized conditions.

LISA. The Level I Stability Analysis model (LISA) developed by the US Forest Service (Hammond and others, 1992) is similar to SINMAP. LISA uses the same FS equation (2) as SINMAP, but also includes a tree surcharge factor (Table 1). LISA uses probability distribution functions defined by the user to describe all soil parameters and the rainfall distribution. The factor of safety is calculated for up to 1000 different combinations of site conditions using a Monte Carlo simulation. These distributions are shown as histograms (Hammond and others, 1992), and a failure probability is then calculated for the different combinations (Morrissey and others, 2001). Like SINMAP, LISA can divide the study region into different subareas to reflect local soils and geologic conditions. LISA model assumptions are the same as SHALSTAB and SINMAP. Data requirements include DEMs and a range of values for all soil parameter and rainfall distribution.

TRM. Iverson's (2000) transient response model (TRM), also uses the factor of safety approach with the infinite slope equation, but uses the Richard's equation (Jury and others, 1991) to calculate pore pressure response to transient rainfall of individual storms (Iverson, 2000). Pore pressures are calculated for vertical flow to find where in the soil column instability occurs. The model assumes that rainfall influences subsurface flow by modifying water table heights, subsurface flow is parallel to the surface, slopes are initially wet, and the catchment area is much greater than the depth of the landslide (Iverson, 2000). The benefit of the TRM model is that it evaluates slope stability in terms of spatial and temporal changes to pore pressure (Morrissey and others, 2001). Results from this model may be used to create hazard maps, although such maps are not automatically generated.

Table 1. Methods to model debris-flow initiation.				
Model	**Model parameters**	**User-provided data**	**Results/Products**	**Comment**
SHALSTAB	Soil bulk density, ρ_s Internal friction angle, Φ Effective precipitation, q Transmissivity, T In the newer version: Effective cohesion, c	Single values for: Soil bulk density, ρs Internal friction angle, Φ New version: Effective cohesion, c Soil depth, d	Creates a GIS-based hazard map from a calculated critical steady-state rainfall for slope stability. Cells are classified for slope stability as Unconditionally Stable, Stable, Unstable, Unconditionally Unstable	Requires verification with existing data
SINMAP	Steady-state recharge rate,R/T Effective cohesion, c Internal friction angle, Φ	Range of values for each region: Rainfall rate, R Transmissivity, T (=Kd) Hydraulic Conductivity, K Soil depth, d Soil bulk density, ρ_s Internal friction angle, Φ Effective cohesion, c	Creates a GIS-based hazard map from calculated factors of safety and a slope stability index (SI)	Requires verification with existing landslide data
Level 1 Stability Analysis, LISA	Steady-state Soil depth, moist (d_m) & saturated (d_s) Soil bulk density, moist (ρ_m) & saturated (ρ_s) Root and soil cohesion, C_r & C_s Tree surcharge, q_o Internal friction angle, Φ	Each parameter assigned constant value or user-defined probability distribution function: Soil depth, moist (d_m) & saturated (d_s) Soil bulk density, moist (ρ_m) & saturated (ρ_s) Cohesion, root (C_r) & soil (C_s) Tree surcharge, q_o Internal friction angle, Φ	FS is calculated for up to 1000 different combination of site conditions using a Monte Carlo simulation. Probability of failure then calculated.	Can generate hazard maps based on probability of failure for different regions.
Iverson's transient response model (TRM)	Pore pressure head, P; in the vertical direction, Z Time, t	Catchment area, A Landslide thickness, H Hydraulic diffusivity, D_o Rainfall duration, T Initial steady state water table depth, d Infiltration rate (equal to rainfall rate), I Hydraulic conductivity, k Friction angle, soil (□) and slope (α) Soil cohesion, c Soil bulk density, ρ_s	Factor of safety is calculated by balancing gravitational stresses, basal frictional stress, and pore pressure.	Evaluates timing and location of landslides using pore pressure and an FS approach.

Discussion. Several comparisons have been made for some of these models. Morrissey and others (2001) compared results from SINMAP, LISA, and TRM for slope stability using data from Madison County, Virginia, where over 600 debris flows were triggered during a June 27, 1995, rainstorm. All three models produced similar soil and hydrologic property results (Morrissey and others, 2001). Only SINMAP provided a hazard potential map that could be directly compared to a previously existing landslide hazard map. However, SINMAP over-predicted the hazards due to some inherent assumptions in the model, such as uniform soil depth and landslide thickness (Morrissey and others, 2001). The authors found that while LISA and SINMAP calculated failure probabilities by similar methods. LISA was preferred over SINMAP because all soil parameters and rainfall rates could be described by probability distribution functions which they felt caught the heterogeneous soil conditions better and increased the accuracy of prediction (Morrissey and others, 2001). The overall preferred model was Iverson's TRM because slope stability was analyzed according to spatial and temporal changes in pore pressure in response to individual storms (Morrissey and others, 2001).

Witt and others (2007) compared SINMAP and SHALSTAB to determine which model to use for their debris-flow hazard mapping in North Carolina. They found both methods made similar predictions, but chose SINMAP for its factor of safety classifications of slope stability, as they felt planners, engineers and the public would better understand the model results (R. Wooten, written communication, 2009).

Meisina and others (2007) compared SINMAP and SHALSTAB for shallow colluvial landslides in Italy. They found SHALSTAB worked well for the study area with non-extreme events but overall preferred SINMAP due to its flexibility in determining soil and rainfall values. Note that all of these studies had landslide inventories and data from recent extreme events to which to calibrate their models. All of the authors noted how important calibration data sets were for extracting realistic model results.

Runout Models

Runout models evaluate the potential travel distance of debris flows away from the initiation and transport zone into the deposition zone. Several factors influence runout distances, including flow composition and rheology, flow volume, channel slope, channel angles, loss of confinement, and obstructions, as shown in Table 2 (Benda and Cundy, 1990; Fannin and Wise, 2001; Rickenmann, 2005). Some runout models predict total travel distance while others predict runout distance, which is the length traveled just in the deposition zone (Rickenmann, 2005). Runout prediction models can be dynamic or empirical. Dynamic models are physically based and typically require parameters such as flow velocity and friction coefficients, which can be very difficult to determine. Sometimes these parameters are selected using simplifying assumptions, calibration, and/or back calculation (Fannin and Wise, 2001). Many dynamic debris-flow runout models are based on avalanche runout models (Rickenmann, 2005). Empirical models predict runout distances based on a set of statistical relationships developed from observed data, without considering the physics or mechanics controlling the flow and deposition (Fannin and Wise, 2001). The main limitation of empirical models is that they should only be applied for the conditions under which they were developed, or re-calibrated for local conditions. If used properly, empirical models provide very practical methods for hazard assessments.

Models have also been developed to estimate runout length in the depositional zone. Although hazards from a debris flow occur all along the flow path, runout within the deposition zone will have greater impact on alluvial fan flooding. In addition, long runout distances may be required to extend beyond the mountain front and reach the apexes of mid-piedmont alluvial fans. Some methods for modeling runout distance in the deposition zone include:

- LAHARZ
- FLO-2D

Both LAHARZ and FLO-2D were developed with data from outside Arizona. However, LAHARZ has been calibrated and used to model runout distances in southeastern Arizona. FLO-2D was initially based on work done in Colorado but has been applied to numerous settings throughout the western US (Fuller, 2008; 2009) and the world (Hübl and Steinwendtner, 2001; Garcia and others, 2003; Sosio and others, 2007; Armento and others, 2008). FLO-2D is a dynamic model and LAHARZ is an empirical model. Other available dynamic models either require detailed data from historical debris flows, such as debris-flow basal friction, flow velocity and flow thickness,[3] or were developed for experimental and research purposes (for example Iverson and Denlinger, 2001). While any chosen empirical model will require calibration for use in Maricopa County, the models described below are most appropriate for the types of data available.

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Table 2.
Influence of debris-flow and environmental parameters on debris-flow runout distances

Parameter	Influence on runout distances	Likely conditions in Maricopa County
Flow composition and rheology	Granular flows with low clay content and coarse clasts have thicker deposits and shorter runout distances as opposed to fluid flows with high clay content.	Granular flows
Flow volume	Determined by available sediment supply. Function of lithology, current climatic conditions and time since last debris flow.	Flow volume is likely to be low for most watersheds, particularly those in metropolitan Phoenix.
Channel slope	Higher channel angles (~>10°) facilitate flows, while low angles (~<4°) facilitates deposition.	Alluvial fans beyond the mountain front have low slope angles, thus deposition will be above or close to the mountain front.
Channel angles	Steep channel angles (~>70°) facilitate deposition.	Site specific; influenced by factors listed above.
Confinement	Confinement facilitates flow, loss of confinement typically results in deposition.	On alluvial fans, incised channels will facilitate flow. Non-incised surfaces will facilitate deposition.
Obstructions	Obstructions can include vegetation, buildings and infrastructure (culverts or bridges). Obstructions facilitate deposition of flow.	On developed active alluvial fans, bridges and culverts will be cause for concern.

LAHARZ. LAHARZ (Schilling and Iverson, 1997; Iverson and others, 1998; Griswold and Iverson, 2008) is an empirical area-volume model. It is a GIS-based runout prediction model originally developed for volcanic-related debris flows (lahars) and recently revised to predict runout distances for non-volcanic debris flows and rock avalanches (Griswold and Iverson, 2008). It uses an empirical approach based on observations that the debris-flow inundation area (units - L^2) is proportional to flow volume (units - L^3) raised to the 2/3 power (Schilling and Iverson, 1997). This model assumes the total planimetric area, B,

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[3] It is unlikely that such data exist for debris flows in Arizona.

and maximum valley cross-section area, A, inundated by a passing flow is a function of flow volume, V, and topography (Griswold and Iverson, 2008). The LAHARZ equations are:

$$A = c_1 V^{2/3} \quad (3)$$
$$B = c_2 V^{2/3} \quad (4)$$

where c_1 and c_2 are coefficients determined by empirical data. The model calculates planimetric area based on user-defined volumes. Then, for each thalweg stream cell, LAHARZ calculates A and fills the valley cross-sectional area using topography until A is satisfied (Figure 9). It is important to understand that LAHARZ is modeling inundation of the largest passing snout, which is typically higher in elevation than the subsequent debris-flow deposits. The cells that form the lateral extent of A at the top of the cross-section is then applied as an increment to the total planimetric inundation area, B, and the model moves to the next downstream cell. These steps continue until B has been satisfied. The extent of B then defines the hazard zone for the given debris-flow volume.

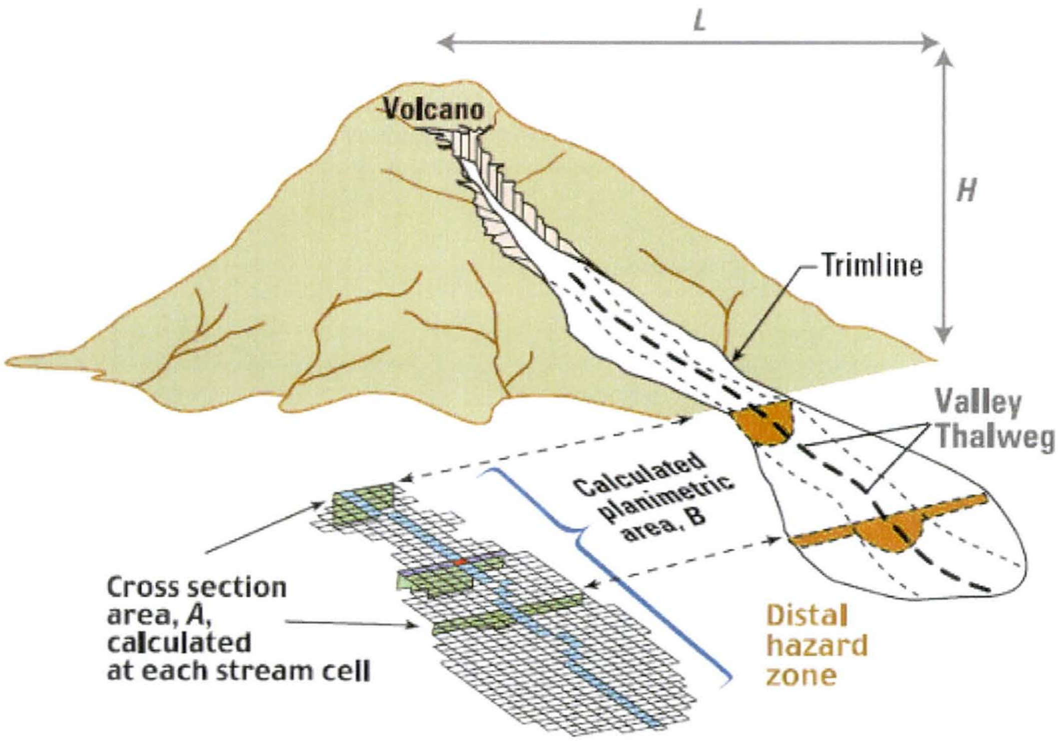

Figure 9. Diagram showing the relationship between maximum cross-sectional area, A, and total planimetric area, B. For lahars the beginning of deposition is calculated using an energy cone using a ratio of vertical decent, H, to lateral runout distance, L. For alluvial fans, the fan apex, or the fan intersection with the feeder channel will be the beginning of deposition. (Figure from Griswold and Iverson, 2008, used with permission.)

LAHARZ can calculate debris-flow hazard zones in two ways. One way is to use the "lahar" function to delineate hazard zones on the alluvial fan. The other way uses the "debris flow" function to model debris-flow travel distances within the basin to determine the likelihood of debris flows reaching an alluvial fan. The first method is based on modeling lahars. The point of beginning deposition is found using an energy cone, which is the ratio of vertical decent, H, to lateral runout distance, L (Iverson and others, 1998). To model inundation on alluvial fans, instead of using an energy cone, the fan apex or the intersection of the feeder channel with the active fan surface is selected as the point of beginning deposition. LAHARZ then calculates inundation hazard zones for user-defined volumes.

The second method uses the debris-flow function which begins deposition below potential initiation points based on a grid developed from user-defined criteria. These criteria may include parameters such as contributing area, slope, and channel gradient. For example, the user can create a grid by defining a minimum upstream contributing area, minimum slope of the contributing area, and channel gradient at which deposition begins. This grid defines the start of deposition and LAHARZ then models debris-flow travel distances downstream for a given set of flow volumes. This second method is useful for determining if debris flows that originate in a basin can travel the distance necessary to exit the mountain front and impact an alluvial fan.

Data requirements for the LAHARZ model include detailed topographic information of the deposition zone in the form of a DEM, the point where deposition begins, and a series of selected volumes to model (Table 3). Volumes are used in an iterative process to calculate potential inundation limits (Iverson and others, 1998; Griswold and Iverson, 2008). A potential problem with this model is selecting realistic debris-flow volumes. This model does provide flexibility for evaluating debris-flow travel distances and inundation. LAHARZ was tested in southern Arizona using local data to model the 2006 Santa Catalina Mountains debris flows with reasonable success (Webb and others, 2008b). The model could be further refined for locations in Maricopa County using additional modeling of historical debris flows.

FLO-2D. FLO-2D is a continuum based dynamic model that assumes Bingham or viscoplastic fluid flow. It is a grid-based, volume conservation, two-dimensional flow routing model developed to model floods and mudflows (fluid-flows) over unconfined surfaces such as alluvial fans (O'Brien and others, 1993). FLO-2D uses a full dynamic-wave momentum equation and a finite-difference routing scheme (O'Brien and others, 1993). It requires either determination of friction parameters, or needs to be calibrated to previous flow events prior to use for prediction of runout lengths (Rickenmann, 2005). Total friction is determined from three terms: yield strength, viscosity, and collision-turbulent friction. The collision-turbulent friction term dominates the faster, channelized flow whereas yield strength dominates flow stoppage (Rickenmann, 2005). FLO-2D data input requirements include detailed topography, flow roughness variables, rainfall, runoff and infiltration rates, and data regarding obstructions such as buildings and infrastructure (Table 3) (O'Brien and others, 1993; Hübl and Steinwendtner, 2001).

FLO-2D has been used to model distributary flow and alluvial fan flooding in Maricopa County and elsewhere in Arizona (JE Fuller, 2008; 2009). The model has a sediment concentration component that is used to calculate yield stresses, viscosity, and granular dispersive stresses for simulating debris-flow behavior and runout. Results from the FLO-2D model have been compared to other model results and actual flows in several studies. FLO-2D was found to model floods well, and was able to identify hazard zones relatively well for single-phased flows (Garcia and others, 2003; Armento and others, 2008). FLO-2D did not perform as well when modeling debris-flow behavior and runout distances for two-phased, coarse-grained granular flows (Sosio and others, 2007) similar to those more likely to occur in Maricopa County.

Sosio and others (2007) reconstruct debris-flow runout from the November 2002 Rossiga debris flow in the central Italian Alps to test FLO-2D's assumption that modeling that the fine-grained matrix and pore-pressure dominates flow behavior and runout distances, and that frictional and collisional effects from coarse clasts are negligible. They used laboratory tests and field data to find the grain-size distribution and rheologic properties of the flow. Based on samples from two different surge deposits, the debris flow contained 5-15% clay and had a coarse fraction with up to 50% larger than 0.5-meter clasts (Sosio and others, 2007). These researchers tested FLO-2D by using rheologic data from the Rossiga debris flow and the FLO-2D code to model runout distances. They then compared modeled distances with actual distances. They found that FLO-2D was not able to accurately predict the extent of the granular debris flow, and that FLO-2D over-predicted the runout length due to the assumption of a smaller yield strength found in fluid flows (Sosio and others, 2007).

Other Models. Other variations on travel distance models include empirical equations based on travel angle and volume (Corominas, 1996; Rickenmann, 2005; Prochaska and others, 2008), volume-balanced approaches that model entrainment and deposition throughout the debris-flow zone (Cannon, 1993; Fannin and Wise, 2001), and mass point dynamic models based on the Voellmy two-parameter snow avalanche model using turbulence and friction components to model travel distance. These models were developed with data from Europe and California, require parameters that difficult to ascertain, and require re-calibration with data from field-documented debris flows in the region of interest. Therefore, these other models are not recommended for application in Maricopa County.

Table 3.
Methods to model debris-flow runout.

Model	Model parameters	User-provided data	Results/Products	Comment
LAHARZ	Cross-sectional area, A Planimetric area, B	GIS (GRID), topography (DEM), location of start of deposition zone, potential flow volumes.	GIS-based maps show potential extent of inundation for a series of volumes	Tested on some 2006 debris flows with coefficients derived from local data.
FLO-2D	Friction parameters: yield strength, viscosity, and collision-turbulent friction, or calibration from other events.	topography (DEM), flow roughness variables, rainfall, runoff and infiltration rates, infrastructure and obstruction data	Flow distribution hazard maps.	Modified Bingham flow with a friction parameter to account for channel roughness and turbulence.

Reconnaissance-Level Assessment of Debris Flow Potential

Several studies have developed methods to evaluate the influence of basin morphometric parameters on debris-flow initiation (Montgomery and Dietrich, 1994; Griffiths and others, 1996), transport and erosion (Wilford and others, 2004; Stock and Dietrich, 2006), and deposition zones (Benda and Cundy, 1990). Basin morphometric parameters include basin contributing area, relief, hillslope processes, geology, and climate (Tucker and Bras, 1998). Basins with higher relief and thus higher-gradient streams have greater capacity to adjust to changes in sediment supply and can transport larger clasts than smaller or low-relief basins (Montgomery and Buffington, 1997). Unfortunately, most methods using basin and channel morphometry to assess debris-flow hazards were developed in areas with different climates from Arizona. For example, Wilford and others (2004) used morphometrics to discriminate basins prone to debris-flow from flood-flow in western Canada. They found that watershed length, in combination with the Melton Ratio, a measure of basin ruggedness, was the best potential indicator of debris-flow prone basins (Wilford and others, 2004). Benda and Cundy (1990) used channel gradient and angle to determine debris-flow deposition zones in debris-flow producing basins of the Pacific Northwest. These researchers found channels gradients less the 3.5° and channel angles greater than 70° produced debris-flow deposition (Benda and Cundy, 1990). Griffiths and others (1996) found drainage-basin area, channel gradient, and river corridor aspect to be significant variables in determining debris-flow frequency in Grand Canyon. They postulate that this relationship is ties to storm tracks moving through the Grand Canyon (Griffiths and others, 1996).

Youberg and others (2008) derived morphometric data for debris-flow producing canyons in the Santa Catalina Mountains near Tucson, and found basin morphometric data useful for assessing the influence of basin size and channel gradient on debris-flow conveyance and potential deposition zones along the front range. Their analysis indicated that larger canyons with lower channel gradients (<10%) had tributary debris flows that terminated in the main channel at the base of the hillslopes. In contrast, smaller, steeper basins had debris flows that exited or nearly exited the mountain front (Youberg and others, 2008). These studies provide some intriguing ideas for identifying debris-flow prone basins and potential deposition zones that might be applicable in Maricopa County, but would require a database of debris flow measurements from which to calibrate predictive morphometric characteristics. To date, no such database exists.

Examples of Debris-Flow Assessments

The following examples illustrate how some assessment methods have been used to evaluate debris-flow hazards.

- The Oregon Department of Geology and Mineral Industries produced 1:100,000-scale debris flow hazard maps using three models (Hofmeister and others, 2002). A GIS-analysis of slope steepness was conducted as a proxy for initiation (model #1). Debris flows were then routed through the transport zone using rules-based routing on channel gradients and topographic confinement (model #2). LAHARZ was then used to model for runout and deposition (Hofmeister and others, 2002). Oregon already had a landslide inventory completed with which to compare the model results. They also did extensive field checking, and model calibration and validation prior to finalizing their assessment.

- The North Carolina Geological Survey conducted a pilot study to develop a method for assessing landslide hazards in Macon County. This work was in response to numerous landslides generated from intense precipitation during Hurricanes Frances and Ivan (Wooten and others, 2007; Wooten and others, 2008). As part of the pilot study, they compared SINMAP and SHALSTAB. Model requirements included the ability to deal with complex terrain, geology and soils, interface with a GIS, and be easily understood by the policy makers and community while standing up to scientific scrutiny (Witt and others, 2007). SINMAP was chosen because of its factor-of-safety approach. LiDAR data, an existing landslide inventory, and intensive field mapping were used to develop the methodology, test the models and create hazard maps.

- Gomes and others (2008) used SHALSTAB, in conjunction with a deposition prediction model based on channel gradient and channel angle (Benda and Cundy, 1990), to model debris-flow hazard zones in Brazil. They used an iterative GIS approach to the model deposition zones, and compared model results to mapped debris flows that occurred during intense summer rainfall in 1996. Results matched well to actual data (Gomes and others, 2008).

These few examples show how combining different models can be an effective approach to assessing debris-flow hazards, if field observations or historical records of past debris flows are available.

Debris Flow Impacts on Alluvial Fans in Maricopa County

There is ample evidence that debris flows have occurred in Maricopa County in the past. For example, (Péwé, 1978) describes minor debris flows that occurred in steep mountainous areas located within the City of Phoenix during the mid-1970's. There are, however, no documented cases of historical debris flows traveling onto active, mid-piedmont alluvial fans that affecting flooding or flood hazards. This was also true in Pima County until 2006, when debris flows traveled onto the Soldier Canyon alluvial fan and impacted some roadway infrastructure and altered ground elevations in the floodplain. Based on known characteristics of debris-flow behavior in general, and the specific climatic and geologic conditions in Maricopa County, debris flows are expected to have low-frequencies and long recurrence intervals (> 1000 years; Webb and others, 2008b; Youberg and others, 2008). Modern debris flows probably will have low volumes, because of the limited sediment supply in the watershed, and short travel (runout) distances due to coarse composition and low clay content. Therefore, most debris flows are highly unlikely to reach the active areas of alluvial fans, particularly those fans that are located away from the mountain front. While the occurrence of debris flows is relatively rare, the impacts from those that do travel to alluvial fans could be significant. Models, in conjunction with geologic reconnaissance and mapping provide a method with which to evaluate debris-flow potential to impact fan flooding, as described below.

Recommendation Debris Flow Modeling Approach

This study evaluated methods to quantify the risk of debris-flow initiation and runout potential to impact alluvial fan flooding hazards in Maricopa County. Based on the District's goal of assessing debris-flow potential to impact alluvial fan flooding, the following steps are recommended:

- Initial Assessment of Alluvial Fan
- Geologic Reconnaissance
- Debris-Flow Runout Hazard Modeling

The first step in the recommended approach is to select a fan of interest and determine if the alluvial fan is adjacent to or distant from the mountain front. If the alluvial fan is distant from the mountain front, it is highly unlikely debris flows will impact alluvial fan flooding and there is no need to proceed with further assessment of debris flow impacts. If the alluvial fan is adjacent to the mountain front, then the next step is a geologic reconnaissance to determine if debris flows have occurred in the basin of interest, and if any debris flow deposits are found on the fan.

Geologic reconnaissance of the watershed and alluvial fan, especially near the fan apex, will confirm the presence or absence of debris-flow deposits, and provide details of the basin and piedmont conditions that will be useful for calculating and evaluating potential debris-flow volumes. Geologic mapping will provide data regarding minimum number of deposits, relative ages, and travel distances of past debris flows. If debris-flow deposits are not found in the watershed or on the alluvial fan, it is not a debris-flow producing basin and no further debris flow hazard evaluation is warranted. If debris-flow deposits are in found in the basin and/or on the fan then the deposits should be geologically mapped. Detailed field mapping of young debris flow deposits at and below canyon mouths can provide real data to help constrain estimates of debris flow volumes and runout distances using the procedures outlined in Youberg and others (2008). This field-mapping step is critical to realistically assess the potential impacts of debris flows on alluvial fan flooding under modern climate conditions. If debris-flow deposits are found on the alluvial fan then additional modeling will be required to assess the potential impacts to alluvial fan flooding hazards.

The next step is to model various debris-flow volumes using LAHARZ as shown in Chart 1. The first phase of the recommended LAHARZ methodology uses the lahar function, where deposition zone begins at the apex of the active fan area. Various flow volumes should be modeled, in ½ order of magnitude increments, to estimate potential volumes required to emplace debris-flow deposits at the farthest distance the youngest deposits (late Holocene to modern) were mapped. Debris-flow maps will provide the basis for determining potential deposition zones and modeling flow volumes. Results from LAHARZ can also then be used to identify potential hazard zones on alluvial fans.

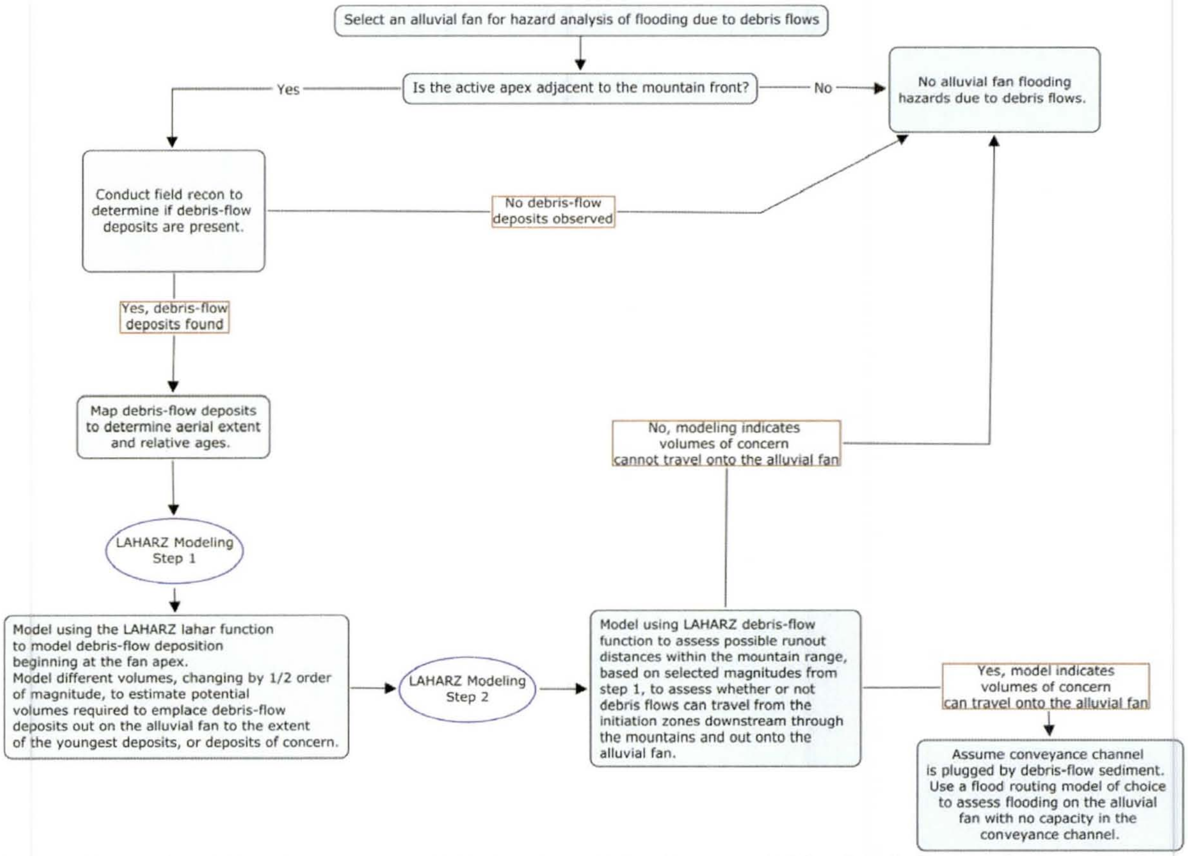

Chart 1. Flow chart showing recommended steps to evaluate the potential for debris flows to impact alluvial fan flooding.

Once potential volumes have been estimated, a geologic analysis of material available is required. For example, if the model indicates 100,000 cubic yards of material are required to emplace debris-flow deposits on the fan, then that volume can be compared to the average depths of hillslope soils, as well as to the material volume stored in upstream channels. The sediment production rate should also be compared to the required volume to determine if the basin can produce enough material to reach the modeled volumes. If sufficient sediment material is available, then the second phase of LAHARZ modeling should be conducted using the debris flow function.

The purpose of the second phase of LAHARZ modeling is to determine if debris flows produced in the basin can actually travel to the alluvial fan. Deposition zones for this phase will be based on field- and GIS-derived data, such as minimum contributing area and slopes, channel gradients, and soils data if available. The second phase of modeling will take several iterations, as the modeler will need to consider the effects of coalescing debris flows. If the modeling indicates that debris flows cannot reach the alluvial fan, then it is unlikely that debris flows will impact alluvial fan flooding. If the modeling indicates that debris flows can reach the fan, then the assumption that the conveyance channel can become blocked with sediment should be made, at which point more traditional distributary alluvial fan flooding models (e.g., FLO-2D) can be applied. The greatest impact debris flows may have on flooding is to block existing channels with sediment, forcing the following floods onto other areas on alluvial fans.

Model Testing, Validation and Calibration

Application of debris-flow runout models like LAHARZ will provide hazard information regarding potential travel distances, as well as the volumes required to reach those distances. It should be noted that these methods will not provide any information to quantify frequency-magnitude relationships or the actual risk of debris-flow occurrence or expected volumes. Initiation modeling to evaluate the likelihood of debris-flow occurrence would require significant resources in terms of time commitments to set up and run the models, and collect field data with which to calibrate the models. In addition, these models need debris flow inventories for calibrating model results. Because no such inventory currently exists for Maricopa County, one would have to be developed by qualified personnel. Without such an inventory, initiation modeling is not recommended.

Model results from LAHARZ should be locally validated and calibrated with debris-flow data from Maricopa County. LAHARZ has been calibrated using the limited data set from southeast Arizona to model the 2006 debris flows in the Santa Catalina Mountains with reasonable success. It may be possible to test LAHARZ in Maricopa County on alluvial fans with young debris-flow deposits by making generalized assumptions regarding location of debris-flow initiation, and volume estimates. The 2006 southern Arizona debris flows may act as a proxy for initiation locations and volumes. If results from these tests are satisfactory, LAHARZ can be considered ready to use in Maricopa County. Otherwise, additional calibration LAHARZ coefficients will have to be developed from newer debris flows as they occur, or other modern debris flows in Arizona that have not yet been studied in detail.

Conclusions

This study evaluated methods to quantify the risk of debris-flow initiation and runout potential to impact alluvial fan flooding hazards in Maricopa County. While there is some evidence that debris flows have occurred in Maricopa County on very steep slopes of mountainous watersheds, there are no documented cases of historic debris flows impacting flood hazards on mid-piedmont alluvial fans. Based on known general characteristics of debris-flow behavior, as well as on the specific climatic and geologic conditions in Maricopa County, the expected recurrence interval for debris flows in Maricopa County probably exceeds 1,000 years. Furthermore, because of the regional physiography and watershed characteristics, it is likely that future debris flows will have low volumes because of limited sediment supplies, will travel only short distances from their point of initiation due to their coarse sediment composition and low clay content, and that most will not reach the active areas of alluvial fans, particularly the fans that are located away from the mountain front.

To assess potential debris flow impacts on alluvial fan flooding, a combined approach of geologic reconnaissance and mapping, with a two-phase application of the LAHARZ debris-flow runout hazard model is recommended. Geologic reconnaissance will confirm the presence or absence of relatively young debris-flow deposits, and provide details of the basin and piedmont conditions which will be useful for calculating and evaluating potential debris-flow volumes. Geologic mapping will provide data regarding minimum number of deposits, relative ages, and travel distances of past debris flows. Debris-flow runout models will provide hazard information regarding potential travel distances, and the volumes required to reach those distances.

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Appendix I:

Evaluation of Avulsion Potential on Alluvial Fans in Maricopa County

Evaluation of Avulsion Potential on Active Alluvial Fans in Maricopa County

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Executive Summary

An avulsion is the process by which flow is diverted out of an established channel into a new course on the adjacent floodplain. The occurrence of avulsions is what makes an alluvial fan "active." Avulsions give the alluvial fan the ability to distribute water and sediment over the surface of the landform, which results in the radial "fan" shape. Avulsions influence flood hazards on an alluvial fan landform by changing the location, concentration and severity of flooding on the fan surface.

Avulsions have been observed on several alluvial fans in Maricopa County, including some of the four fan evaluation sites selected for the PFHAM study. The avulsion history of the four PFHAM fan evaluation sites and Tiger Wash are documented and described. It is likely that there are other examples of major avulsions in Maricopa County, but no comprehensive evaluation of avulsion frequency or occurrences has been made. Historical records clearly indicate that avulsions do occur on the types of alluvial fans found in Maricopa County. The cursory data summarized above indicate that it is likely that avulsions are relatively rare events, and that they are often associated with the occurrence of large floods. However, further documentation of the avulsion history of local alluvial fans is warranted to better assess the recurrence interval and frequency of avulsions. Almost all of the known causative factors for avulsions exist on alluvial fans in Maricopa County, and thus it is likely that avulsions will continue to occur in the future.

Review of the literature regarding alluvial fan avulsions identified the following three primary gaps in the knowledge base required to develop a robust methodology for quantifying alluvial fan flood hazards in Maricopa County:

- Avulsion Frequency. To resolve this knowledge gap, the District should conduct a study of avulsion frequency on active alluvial fans in Maricopa County.
- Modeling Methodology. To address the lack of a universally accepted methodology for evaluating avulsion potential, the District should adopt the recommended methodology presented in this report as a first step. Subsequent steps include testing the methodology on alluvial fans in Maricopa County, and vetting the methodology with FEMA.
- Engineering Design Standards. The District should include engineering and design guidelines for development on active alluvial fans in the updated PFHAM.

Based on the results of the analyses and information summarized above, the recommended procedure for evaluating the potential for avulsions on active alluvial fans in Maricopa County consists of the following steps:

- Step One: Historical Analysis. The most reliable means of determining if an alluvial fan is subject to avulsions is to identify evidence of historically recent avulsions.
- Step Two: Geomorphic Analysis. An evaluation of the surficial geology of the alluvial fan should be conducted that includes field observations, surficial mapping of active and inactive surfaces, and assessment of debris flow potential.
- Step Three: FLO-2D Modeling. FLO-2D models of the fan surface from the hydrographic apex to the downstream limit of the active alluvial fan should be prepared.

- Step Four: Sediment Modeling. The sediment yield at the hydrographic apex should be computed and used to estimate potential deposition along the fanhead channel. Until such time as the available methodologies are improved, detailed sediment transport modeling of the alluvial fan downstream of the hydrographic apex is not recommended as part of the recommended avulsion prediction methodology.
- Step Five: Floodplain Delineation. The potential for future avulsions should be considered when delineating an active alluvial fan floodplain.

Table of Contents

1. Introduction

1.1. Objectives

The objective of the avulsion potential evaluation is to determine and quantify how channel avulsions influence flood hazards on alluvial fan landforms in Maricopa County. This information is to be used to refine the Integrated Alluvial Fan Hazard Assessment Methodology that may be used in future revisions of the Flood Control District of Maricopa County's (District) Piedmont Flood Hazard Assessment Manual (PFHAM).

1.2. Scope

The scope of services for this analysis is described in Task 2.8 of Contract FCD 2008-C007, which lists the following tasks:

- The objective of the avulsion potential evaluation is to determine and quantify how channel avulsions influence flood hazards on alluvial fan landforms in Maricopa County. This information is to be used to refine the Integrated Alluvial Fan Hazard Assessment Methodology.
- The CONSULTANT shall evaluate and recommend methods appropriate for determining avulsion potential and occurrence in Maricopa County.
- The recommended methodology(ies) shall be applied to up to three of the alluvial fan sites selected for evaluation in Task 2.4.
- The CONSULTANT shall prepare a technical memorandum summarizing the results of the assessment.

1.3. Importance of Avulsions to Alluvial Fan Flood Hazard Assessment

The occurrence of avulsions is what makes an alluvial fan "active." Avulsions give the alluvial fan the ability to distribute water and sediment over the surface of the landform, which results in the radial "fan" shape. Avulsions influence flood hazards on an alluvial fan landform by changing the location, concentration and severity of flooding on the fan surface. That is, an area not previously inundated by flooding (or inundated only by shallow flow) may in a subsequent flood become the locus of flood inundation, sediment deposition, and/or erosion. If an alluvial fan has no risk of avulsion, flood hazard delineation and mitigation become much simpler engineering problems, consisting only of modeling two-dimensional flow and/or normal riverine hydraulic and sedimentation issues.

The occurrence of major avulsions in an alluvial fan drainage system introduces the following complications into an engineering analysis of the flood hazard:

- Uncertain and changing flow path locations, during and between floods
- Continually changing channel and overbank flow path topography
- Inundation and/or sedimentation hazards in previously unflooded areas
- Uncertain and changing flow rate distribution for areas downstream of avulsions
- Uncertain and changing watershed boundaries for areas downstream of avulsions
- Aggrading, net depositional land surfaces and channels with diminishing capacity

- Unsteady, rapidly-varied flow conditions
- High rates of infiltration and flow attenuation across the fan surface

Most importantly, there is lack of appropriate engineering standards for evaluation of flood hazards or design of flood mitigation measures on alluvial fans with avulsion potential. Despite the importance of avulsions to the assessment of flood hazards on alluvial fans, the causes and frequency of avulsions have not been extensively studied (Slingerland & Smith, 2004).

2. Background

2.1. Definition of Avulsion

An avulsion is the process by which flow is diverted out of an established channel into a new course on the adjacent floodplain (Slingerland & Smith, 2004). Avulsions divert flow from one channel into another, leading to a total or partial abandonment of the previous channel (Field, 2001; Bryant et. al., 1995), or may involve simple flow path shifts in a braided or sheet flooding system (Slingerland & Smith, 2004). An example from Maricopa County of avulsive channel change that occurred on the Tiger Wash alluvial fan during the 1997 Hurricane Nora flood is shown in Figure 1. Avulsions are commonly associated with alluvial fan flooding, but are also known to occur on riverine systems and river deltas (Slingerland & Smith, 2004).

2.2. Classification of Avulsions

Several investigators (Slingerland & Smith, 2004; Field, 2001; Bryant et. al., 1995) have classified types of avulsions and avulsive processes, as shown in Table 1. In nature, the classifications given in Table 1 exist as a continuum, with no distinct boundaries between end members, and an infinite number of possible combinations of characteristics on any given stream system.

Table 1. Avulsion Terminology & Classification Continuum

End Member ←	**→ End Member**
Major Avulsion Occurs near the apex Divert > 50% of flow from the parent channel	**Minor Avulsion** Doesn't meet the major avulsion criteria
Full Avulsion All of flow diverted Parent channel abandoned	**Partial Avulsion** Part of flow diverted Parent and avulsive channel coexist
Nodal Avulsion Recurring at fixed point, e.g., a fan apex	**Random Avulsion** Occurs anywhere along an active channel system
Local Avulsion Avulsive channel rejoins parent downstream	**Regional Avulsion** Large scale event Affects all system downstream of origin
Abrupt Avulsion Full avulsion occurs in single event	**Gradual Avulsion** Avulsion completed over decades or more
Anastamosing Avulsions return to parent downstream	**Distributary** Avulsions don't return to parent channel

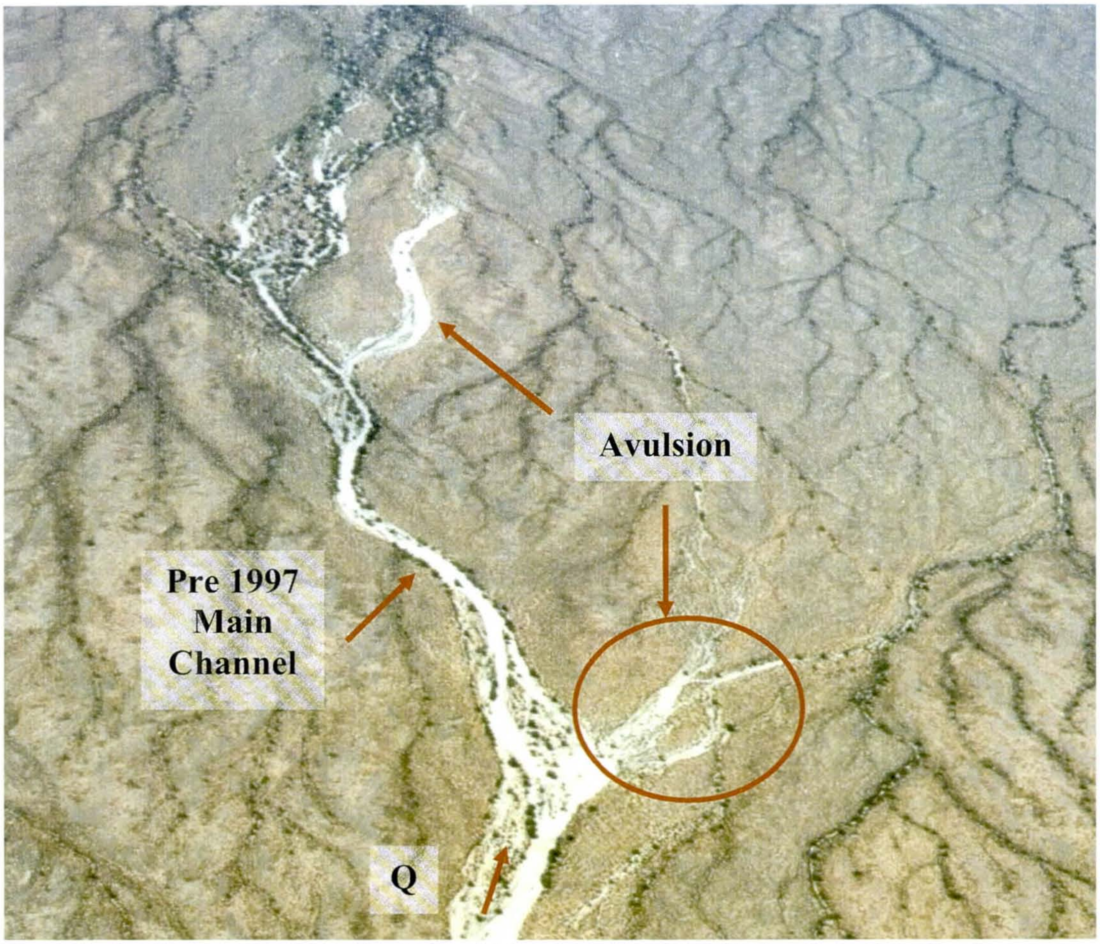

Figure 1. ***Avulsions on the Tiger Wash alluvial fan caused by the 1997 Hurricane Nora flood.***

2.3. Other Terminology

Other terms commonly used in discussions of avulsions include the following:

- Avulsion Belt. The entire area of the floodplain affected by avulsions, in which avulsion have occurred in the past.
- Parent Channel. The channel or flow path which existed prior to the avulsive event is called the parent channel. In some cases, the term may apply primarily to the channel reach upstream of the avulsion initiation point.

2.4. Occurrences of Avulsions in Maricopa County

Avulsions have been observed on several alluvial fans in Maricopa County, including some of the four fan evaluation sites selected for the PFHAM study. It is likely that there are other examples of major avulsions in Maricopa County, but no comprehensive evaluation of avulsion frequency or occurrences has been made. The avulsion history of Tiger Wash and the four PFHAM fan evaluation sites are described below.

2.4.1. Tiger Wash

The 1997 avulsions on the Tiger Wash alluvial fan are some of the better documented avulsions in the literature (Figure 1). The Tiger Wash fan was evaluated in some detail as part of the District's *Alluvial Fan Data Collection and Monitoring Study* (CH2M HILL, 1992), which was completed prior to the 1997 Hurricane Nora flood. After the 1997 flood, the following publications thoroughly evaluated and documented the flood hydrology, avulsive channel change, and sediment deposition on the fan surface:

- JE Fuller/Hydrology & Geomorphology, Inc., 2000, *Approximate Floodplain Delineation Study for Portions of Tiger Wash Piedmont, Technical Data Notebook*, Report to the Flood Control District of Maricopa County, Contract FCD 98-48.
- Pearthree, P.A., Klawon, J.E., and Lehman, T.W., 2004, *Geomorphology and Hydrology of an Alluvial Fan Flood on Tiger Wash, Maricopa and La Paz Counties, West-Central Arizona*, Arizona Geological Survey Open-File Report 04-02, 40 p.
- Pelletier, J.D., Mayer, L, Pearthree, P.A., House, P.K., Demsey, K.A., Klawon, J.E., and Vincent, K.R., 2005, An integrated approach to flood hazard assessment on alluvial fans using numerical modeling, field mapping, and remote sensing, *Geological Society of America Bulletin*, Vol. 117, no. 9/10, p. 1167-1180.

Rather than reiterate the information contained in the reports listed above, some of which is discussed in more detail elsewhere in this report, several of the key conclusions regarding the occurrence of avulsions at the Tiger Wash Site are enumerated below:

- More channel change occurred on the Tiger Wash fan during one day of flooding in 1997 than in the previous 18,000 days since 1953 (Pearthree et. al., 2004).
- Several moderate-sized floods occurred prior to and after the 1997 event which left no evidence of new avulsions (Pearthree et. al., 2004).
- Based in part on geologic and photographic information collected at Tiger Wash, Field (1994) estimated the recurrence interval of avulsions on alluvial fans in central Arizona at 50 to 650 years.
- Even during the extreme 1997 event, most flood water generally followed the pre-flood channel network (Pearthree et. al., 2004).
- Flood depths greater than 0.6 feet were capable of scouring new channels, but flow depths less than 0.3 foot were not (Pearthree et. al., 2004).
- Streamflow (fluvial) fans have less frequent avulsions than debris flow fans (Pelletier et. al., 2005).
- In the arid west, "rapid" channel change on active alluvial fans occurs on a decadal time scale (Pelletier et. al., 2005).
- Stratigraphic evidence of recent pre-historical (ca. 600 yrs BP) channel avulsions were observed in trench soil profiles, and was corroborated by vegetative evidence (CH2M HILL, 1992).
- Prior to the 1997 flood, of the five Arizona alluvial fans evaluated by Field (1994), the Tiger Wash site had been the most stable (Pearthree et. al., 2004).
- Several types of avulsions were described (Figure 2): (1) two major avulsions that formed long, wide new channels and captured significant percentages of the flood hydrograph (Figure 2B), (2) minor avulsions that scoured small channels on the margins of otherwise

active areas (Figure 2D), (3) changes in flow distribution between well-established, semi-permanent distributary flow branches (Figure 2A), and (4) changes in flow distribution in sheet flooding areas (Pearthree et. al., 2004).

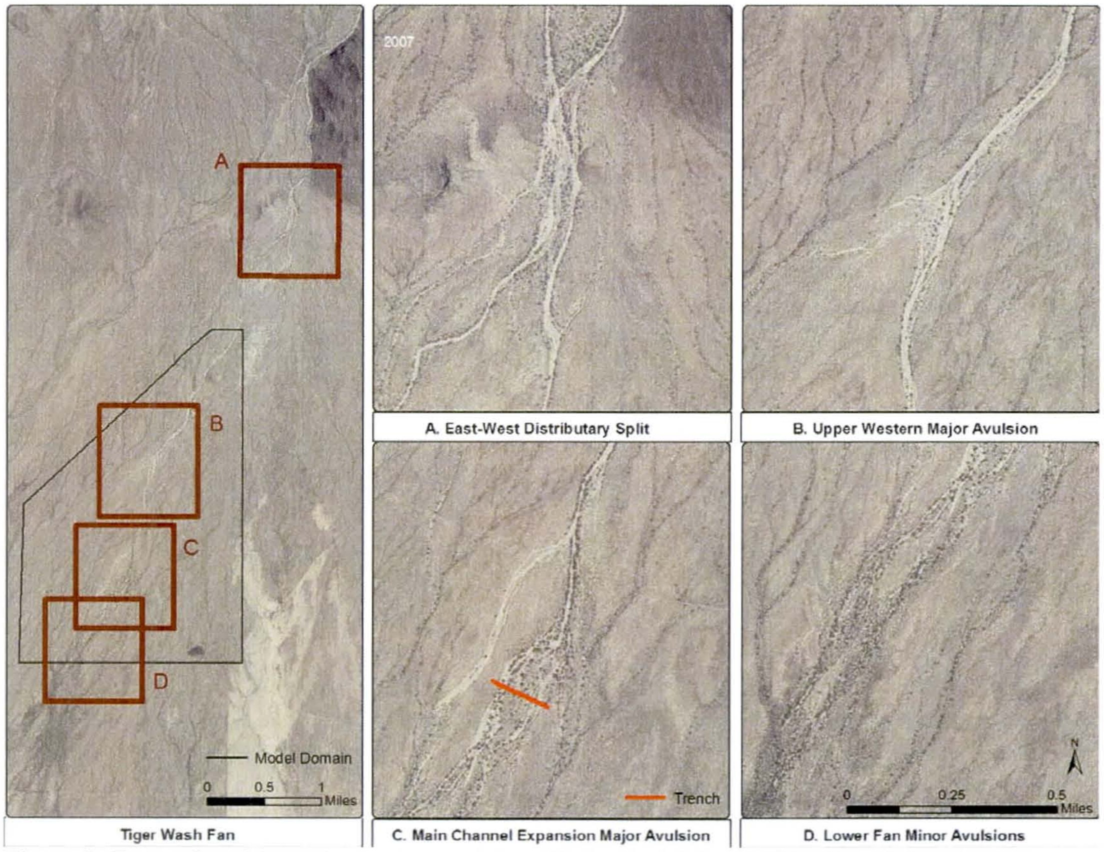

Figure 2. ***Types of avulsions observed on the Tiger Wash alluvial fan in 1997. Trench location in red.***

2.4.2. White Tank Fan 36

The history of avulsions on White Tank Fan 36 has been documented in a number of technical publications and scientific studies, including the following:

- CH2M HILL, 1992, *Alluvial Fan Data Collection and Monitoring Study, Appendix A,* Report to the Flood Control District of Maricopa County.
- Field, J.J., 1994, *Surficial Processes, Channel Change, and Geological Methods of Flood-Hazard Assessment on Fluvially-Dominated Alluvial Fans in Arizona*, Ph.D. Dissertation, Department of Geosciences, University of Arizona, 258 p.
- JE Fuller/Hydrology & Geomorphology, Inc., 2001, *Approximate Floodplain Delineation Study for White Tank Fan (Site 36), Technical Data Notebook*, Report to the Flood Control District of Maricopa County, Contract FCD 99-02.
- Field, John, 2001, "Channel Avulsion on Alluvial Fans in Southern Arizona," *Geomorphology*, Vol. 37, p. 93-104.

Major disruptions of the fan surface of White Tank Fan 36 are thought to have occurred during the August 1951 monsoonal storm which dropped over five inches of rain at Buckeye in a four day period (JE Fuller, 2001). The channel and surficial changes observed near the apex of the fan were different in character than "typical" channel avulsions. In the 1951 flood, a very broad area downstream of the apex, nearly 2,000 feet wide and one mile long, experienced significant changes that included scour and/or deposition of alluvium, removal (or burial) of overbank and channel vegetation, in addition to new channel formation, the more classic behavior of fan avulsions (Figure 3). Aerial photographs bracketing the 1951 event also record a number of minor, local avulsions along some of the small channels that comprise the on-fan drainage network in the lower portion of the fan (Figure 4). These lower fan avulsions consist primarily of relocation of some of the fine-textured distributary branches, probably due to excessive overbank flow that escaped the defined channels, as well as sheet flooding which scoured out new flow paths. Subsequent aerial photographs document that the pre-flood channels were abandoned, filled with sediment, lost their bank vegetation and virtually disappeared. These abandoned channels would be nearly undetectable on recent aerials or in the field if pre-flood aerials or subsurface stratigraphic data were not available. Hydraulic analyses by JE Fuller (2001) indicate that the avulsive channels could have been formed by overbank flows of 1.0 foot depth or less, with velocities in the range 2.5 to 4.0 feet per second.

Interpretation of the soil stratigraphy exposed in test trenches (CH2M HILL, 1992) identified that net aggradation of about three feet occurred over the past 600 years. Despite this level of aggradation, no abandoned channel paths were identified within the recent geologic time period exposed in the trench alignment, even though the trenches were excavated in the area strongly impacted by the 1951 flood. The lack of major channel relocations (classic avulsions[1]) in the area of the trench is probably attributed to very high infiltration rates in the coarse soil materials, and very rapid expansion from the single channel at the apex to highly distributary and sheet flooding conditions immediately downstream of the apex (i.e., no extended linear well-defined major channels exist on the fan surface downstream of the hydrographic apex).

[1] The 1951 "avulsive" behavior consisted of excessive erosion and deposition, rather than relocation of well-defined single channels.

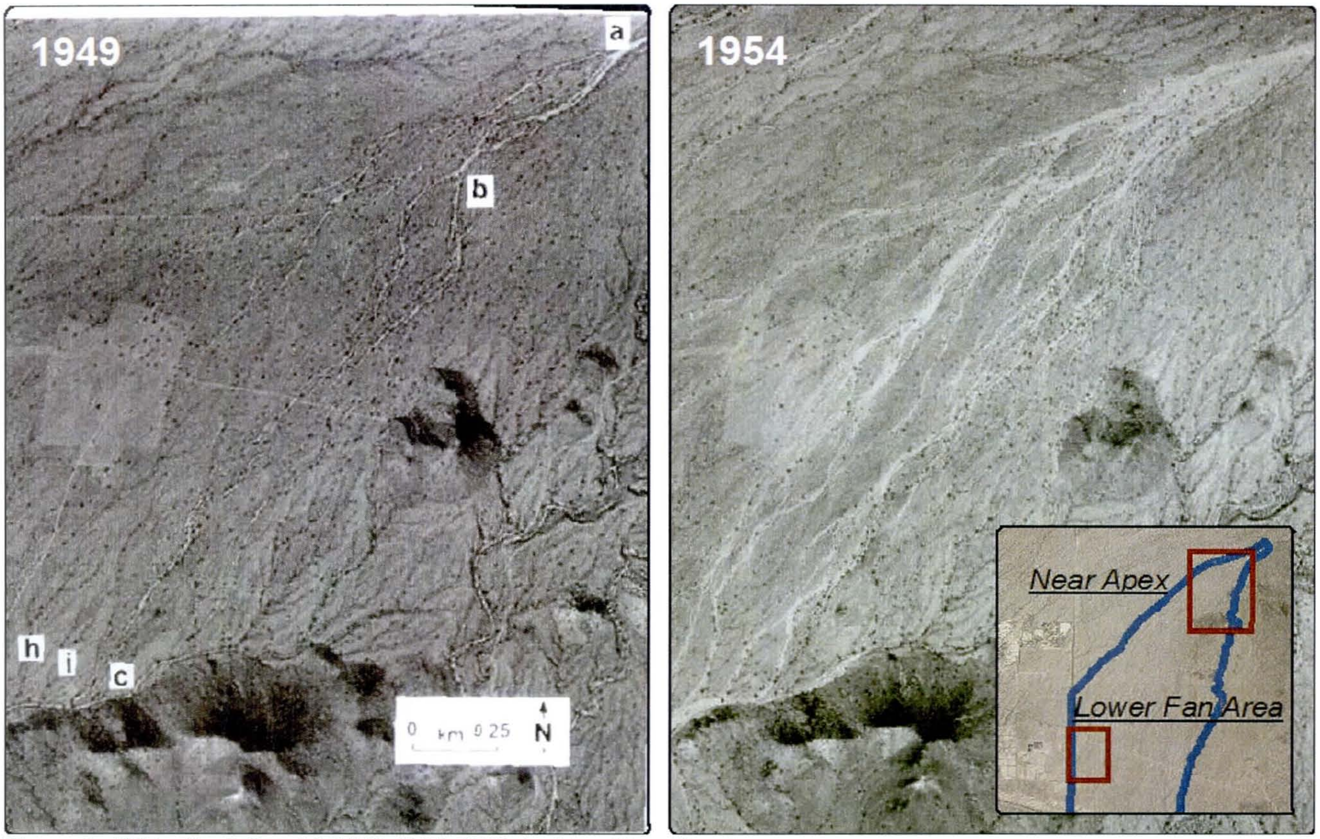

Figure 3. *White Tank Fan 36, 1949-1954, 1951 Avulsion Near Fan Apex.*

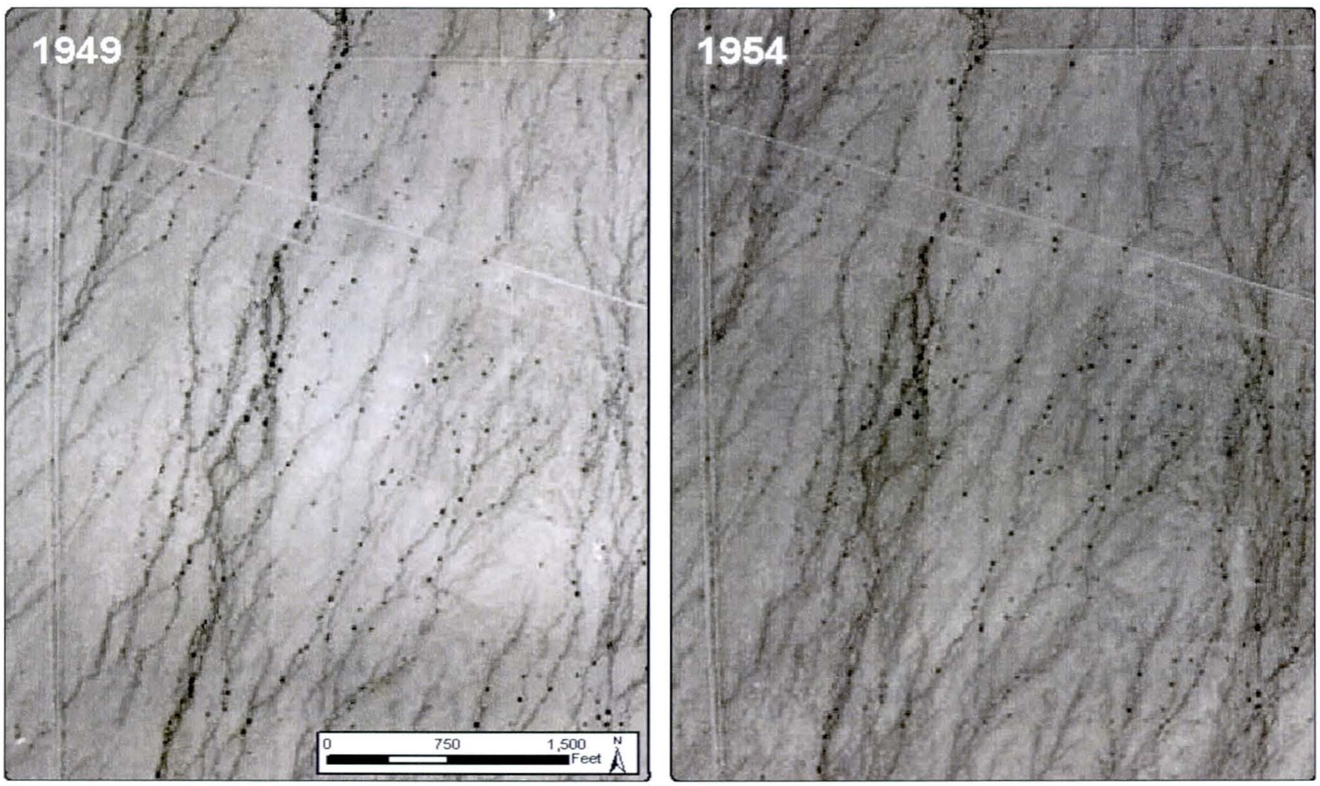

Figure 4. White Tank Fan 36, 1949-1954, Avulsions in Lower Fan Area.

2.4.3. Reata Pass Alluvial Fan

There have been no known major avulsions on the Reata Pass alluvial fan during the 47 year period of record. A comparison of the oldest and most recent aerial photographs is shown in Figure 5 (see also Section 5 of the Task 2.4 Historical Fan Report). The lack of historical avulsions on the Reata Pass alluvial fan is probably due to two factors. First, there have been no large floods in the period of record. Second, development has obscured and altered the fan surface, and possibly has neutralized some of the potential avulsion mechanisms. If the latter factor is true, it implies that avulsive processes may be hindered or even prevented by development, which in turn indicates that avulsion hazards on low-sloping, fluvially-dominated alluvial fans in Maricopa County may not be severe. If the former factor is the real reason avulsions have not occurred, then a significant number of homes may currently be at risk of future flood damage.

Figure 5. ***Reata Pass Alluvial Fan, 1962-2009.***

2.4.4. Rainbow Valley Fan 1

There has been no systematic evaluation of historical avulsions at the Rainbow Valley Fan 1 site, and such an analysis is beyond the scope for this study. Simple comparison of 1937 and 2009 aerial photographs (Figure 6) reveals no evidence of any avulsions during the 72 year period of record. The lack of fan avulsions is most likely due to the degree of flow containment along the main flow path that limits the frequency and duration of overbank flooding, although lack of large floods may also be a contributing factor.

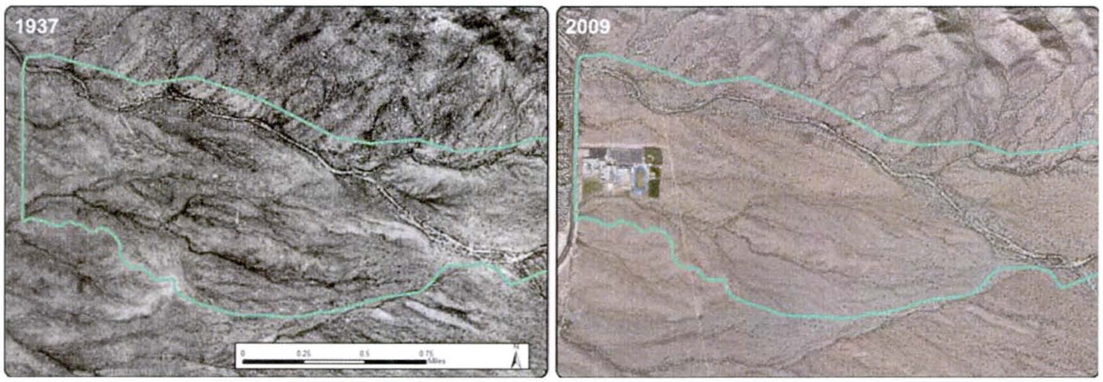

Figure 6. Rainbow Valley Fan 1, 1937-2009

2.4.5. Rainbow Valley Fan 12

There has been no systematic evaluation of historical avulsions at the Rainbow Valley Fan 12 site, and such an analysis is beyond the scope for this study. However, simple comparison of 1937 and 2009 aerial photographs (Figure 7) reveals both apical and lower fan minor avulsions have occurred during the 72 year period of record. The low resolution of the 1937 photographs precludes very detailed description of the avulsions, although this interpretation is consistent with conclusions drawn from trench soil stratigraphy, as reported by CH2M HILL (1992). The CH2M HILL trench profile indicated that while the main channel location had been stable during recent geologic time, several "smaller tributary or distributary abandoned channels that did not correlate with active channels [on the surface] were visible." It was also noted that about three feet of net aggradation had occurred over the past 600-1,000 years at the trench location. The lack of major channel avulsions on this fan is probably attributed to the rapid transition to sheet flooding conditions, very high infiltration rates, and low flood water volume during flows.

Figure 7. ***Rainbow Valley Fan 12, 1937-2009.***

2.4.6. Summary

Historical records clearly indicate that avulsions do occur on the types of alluvial fans found in Maricopa County. The cursory data summarized above indicate that it is likely that avulsions are relatively rare events, and that they are often associated with the occurrence of large floods. However, further documentation of the avulsion history of local alluvial fans is warranted to better assess the recurrence interval and frequency of avulsions.

3. Avulsion Mechanisms

3.1. Past Studies of Avulsions

The topic of avulsive channel change on alluvial fans is not well represented in the scientific literature. The majority of the limited avulsion references found in an extensive literature search are directed at riverine avulsions. Most of the remainder of avulsion literature either assume a priori the existence of avulsions because the landform is an active alluvial fan, or lack any detailed analysis of avulsion mechanisms, processes, or recurrence interval. The few studies that specifically focus on alluvial fan avulsions can be classified as follows:

- Field based observations. These studies include after-the-fact descriptions of avulsions, some with hypotheses or speculation as to the cause(s) of the avulsive channel change. Field (1996, 2001), examined avulsions in central and southern Arizona, including two sites in Maricopa County, and is the most relevant of the field-based studies. As noted by Field (2001), field-based observations of alluvial fan avulsions have been recorded around the globe in a wide variety of environmental conditions.
- Physical modeling. Some interesting physical model studies of alluvial fan processes have been completed. Although the physical modeling studies were primarily oriented at alluvial fan behavior in general, they make relevant observations about avulsions as an essential element of fan development and evolution. The most relevant of these studies include Hooke (1965; 1967), Schumm et. al. (1987), Bryant et. al. (1995), and Parker et. al. (1998a, 1998b).
- Mathematical modeling. Very limited mathematical modeling of avulsions has been completed. Dawdy (1978) developed a statistical procedure that was intended to account for the effects of channel avulsions on alluvial fan flood hazards. Although the Dawdy procedure was the first model adopted by FEMA for alluvial fan floodplain delineations, the methodology has been highly criticized (Fuller, 1990; NRC, 1996; French and Miller, in press) and is rarely applied today. Other similar formulations (Magura & Wood, 1980; DMA, 1985; Flippin and French, 1994; Heggen and Anderson, 1995) exist, but rely on the tenuous assumption of random channel movement. Parker et. al. (1998) formulated a mathematical model to describe alluvial fan behavior that shows some promise, but as yet has not gained acceptance outside its initial application, and is probably not applicable to the low-sloped, ephemeral, fluvially-dominated alluvial fan systems found in Maricopa County. Finally, several new modeling procedures were applied for the PFHAM study, as summarized in Section 4 of this report.

In addition to the three types of alluvial fan avulsion investigations listed above, there is a growing body of literature focused on riverine avulsions (c.f., Slingerland and Smith, 1994) in which most authors recognize at least some level of similarity between riverine and alluvial fan avulsive processes. While there may be much that is applicable to alluvial fan avulsions, the following differences between arid-region alluvial fans and perennial riverine systems are noted:

- Fan channels typically lack an alluvial ridge (a.k.a., natural levee) along the channel bank, a feature which is integral in the riverine avulsive process. Because of the lack of an alluvial ridge, the critical slope ratio threshold for riverine avulsions is rarely achieved on alluvial fans, and discharge and sediment deposition are more important causes of avulsions.
- Fans have higher excess sediment supply rates than rivers, increasing the role of sediment supply in causing avulsions.
- Fans in the arid west usually have higher flood ratios (Q100:Q2) than rivers, making the least frequent floods more important in causing avulsions.
- Fans have short, lower volume flood hydrographs, decreasing the amount of geomorphic work that can occur in any given flood, and increasing the amount of time needed to complete an avulsive cycle.
- Flow attenuation over the fan surface can absorb an entire flood hydrograph on many fans in the arid west, which induces sediment deposition and decreases the likelihood of avulsions in the downstream direction.
- Fan planform (shape) is expanding, not linear, resulting in extensive flow attenuation in the downfan direction.
- Fan sediments typically are coarser than riverine sediments, increasing the rate of infiltration and flow attenuation, both in the channel and on the floodplain.
- Fan slopes typically are steeper, increasing flow velocities and stream power (i.e., more erosive) and altering slope ratio characteristics.
- Fan surfaces typically have less organic matter and vegetative cover than rivers, resulting in fewer obstructions on the floodplain and higher floodplain velocities.
- Flood flow over fan surfaces is typically unconnected to ground water.

Because of these differences, methodologies derived from studies of riverine erosion are only partially applicable to alluvial fans, and should be applied with caution to the arid-region alluvial fans in Maricopa County.

3.2. Types of Avulsions

All alluvial fan avulsions occur as the result of flow leaving a defined parent channel and entering a floodplain. Slingerland and Smith (2004) classified avulsions into the following types:

- Avulsion by Annexation. For this type of avulsion, an existing floodplain channel is appropriated or reoccupied when overbank flow leaves the parent channel and flows across the floodplain. Avulsion by annexation is sometimes called "second-order avulsions," in contrast to "first order avulsions" which involve channel shifts to entirely new parts of the floodplain (Nanson and Knighton, 1996). If the annexed channels are too small for volume of flow they are usually widened and/or deepened by erosion to contain the discharge. Avulsion by annexation is favored where floodplain aggradation rates are low, sediment supply is low, and some level of channel formation is present on the floodplain.

- Avulsion by Incision. For this type of avulsion, new channels are scoured into the floodplain surface. Flow across the floodplain seeks low ground where a channel is scoured and/or floodplain flow re-enters a pre-existing channel at some point downstream of the avulsion, and knickpoint erosion works headward creating a new channel. In some cases, the parent channel fills by aggradation after the avulsion occurs, particularly if the parent channel is perched above the surrounding floodplain. Incision avulsions are favored in quick draining floodplains that have steep slopes, sparse vegetation, little lateral relief, erosive soil materials, and/or no significant floodplain obstructions, all of which are conditions that exist on most active alluvial fans in Maricopa County.
- Avulsion by Progradation. Avulsions by progradation occur where there is extensive sediment deposition on multi-channeled distributive networks such as anastomosing streams. They typically occur where the avulsive flow is slow moving, and on flat floodplains with dense vegetation or extensive ponding. Sediment deposition on floodplain progrades from parent channel exit point further out onto floodplain as avulsion continues.

All of the avulsion types listed above can be grouped as "overflow" avulsions. Based on extensive field reconnaissance and analysis of historical aerial photographs of alluvial fans in central and southern Arizona, Field (2001) recognized an additional type of avulsion caused by stream piracy. Piracy avulsions have elements of avulsions by annexation, in that an existing floodplain channel is involved, as well as annexation by incision, in that they tend to occur on steep, fast draining floodplain surfaces and new channels can be scoured into the fan surface. For piracy avulsions, headwater erosion from an on-fan drainageway intercepts the parent channel, creating a flow bifurcation. If the pirate channel is steeper than the parent channel, it may divert a high percentage of the runoff, eventually leading to abandonment of the parent channel downstream of the bifurcation. It is likely that headward erosion is not the only process involved, and that overflow from the parent channel also contributes to, or accelerates, the avulsion process. The 1997 Tiger Wash alluvial fan avulsions (Pearthree et. al., 2004) were formed by annexation of the incipient on-fan drainage network, but also included elements of avulsion by incision and progradation. It is likely that combinations of avulsive mechanisms operate in any given historical avulsion.

FEMA (2003) guidelines identify an additional type of avulsion that occurs on alluvial fans. Changes in flow distribution within sheet flooding areas are considered by FEMA to be avulsive (a.k.a., active alluvial fan flooding) because the overall area of inundation changes between floods. FEMA's inclusion of sheet flooding as avulsive behavior differs somewhat from traditional definitions of avulsions in most of the literature, although the historical channel changes observed in the distal mid-fan region of White Tank Fan 36 (See Section 2.4.2) corroborate their interpretation in that avulsions have been documented in areas that FLO-2D modeling indicates are subject only to shallow flooding. FEMA's inclusion of changes in flow distribution as avulsive, without necessarily any accompanying channel change, is not inconsistent with the literature, though most literature sources focus on physical changes in channel location.

3.3. Factors That Cause Avulsions

While there is much yet to be understood about avulsion prediction, avulsion frequency, and avulsion mechanics, there is general consensus about many of the factors that are conducive to forming avulsions (Table 2). Because of the number of variables that affect the occurrence of avulsions, accurate prediction of their occurrence may always elude modelers. Similarly, any given avulsion may be caused to some degree by a large number of variables.

Other important considerations in assessing the cause of alluvial fan avulsions include the following:

- Aggradation is a necessary condition for riverine avulsions (Slingerland & Smith, 2004). Most avulsions occur on aggrading landforms or channels.
- Overbank flooding is necessary condition (Slingerland & Smith, 2004) for avulsions. Therefore, avulsions tend to occur during large floods (Wells & Dorr, 1987; Field, 2001; Pearthree, 2004). However, not all large floods cause avulsions (Pearthree et. al., 1992; Whipple et. al., 1998; Field, 2004), even if conducive set-up conditions exist (Tornqvist & Bridge, 2002).
- It is important to distinguish between the set-up conditions (those conducive to avulsion) and the triggering event (e.g., a flood, debris blockage, or bank failure).
- The radial topographic pattern is evidence that avulsions have occurred (Beaty 1963). Avulsions on alluvial fans will tend to be directed toward topographically lower areas, i.e., slopes steeper than the parent channel, in areas that haven't received recent sediment deposition (Hooke 1967).

Table 2. Physical Variables Which Affect Alluvial Fan Avulsions	
Factor	**Comments**
Fan Physiography	
• Fan Slope	Steeper fans experience more frequent avulsions (P)
• Floodplain morphology	Size and configuration of invaded flood basin (SS)
• Floodplain vegetative cover	Affects conveyance & resistance (SS, M)
• Erosion resistance	Less cohesive floodplain soils more prone to avulsion (SS)
• Presence of existing channels	Overbank flows exploit on-fan flow paths (SS, F)
• Wide, unobstructed floodplain	Open conveyance more conducive to avulsions (SS)
• Drainage area	Large drainage area generates higher peaks and volumes (P)
• Radial contour pattern	Low radius contours indicate greater avulsive potential (B)
Discharge	
• Size and duration of avulsion	Large, long overbank flows form more complete avulsions (SS)
• Flood magnitude	Large peaks after proper set-up condition (SS, F)
• Frequency	Floods are of limited duration, avulsions at finite rate (SS)
• Flood ratio	High flood ratio watersheds prone to high overbank floods (P)
• Flood volume	High flood volume capable of more geomorphic work (P)
• Flood sequence	Sequence of floods important for set-up conditions (F)
• Overbank flooding	Overbank flooding is a necessary condition (SS)
Channel Pattern	
• Outside of bends	Avulsions more likely on outside of bends (SS, F)
• Sheet flooding	Avulsions likely in sheet flooding areas (F)
• Splays	Avulsion likely in braided channel splays (F)
• Near channel tributaries	Piracy more likely when channels close to parent (F)
Sediment Transport	
• Sediment partitioning	Between parent and avulsion affects closure rate (SS)
• Suspended sediment	Initial overflow high in water column, is sediment deprived (F)
• Bed material load	Occurs on channel bottom, deep avulsions only (SS)
• Small floods aggrade	Results in set-up conditions, loss of capacity (F)
• Total supply	More sediment supply, more frequent avulsions (SS)
• Debris flow potential	Avulsions common on debris flow fans (SS)
• Aggradation	Aggradation is a necessary condition (SS)
Breach Geometry	
• Avulsion vs. parent bed elevation	Sediment distribution affected, rate of completion (SS, F)
Slope	
• Downstream vs. cross slope	If slope ratio > 5 avulsion will occur (SS, T)
Channel Conditions	
• Low bank height; channel depth	Low bank height causes overbank flow (F, SS)
• Aggrading	Main channel aggradation lowers capacity (SS)
• Debris blockage	Lowers capacity (SS, F)
• Bed elevation vs. overbank	Overbank flow need for avulsion (SS)
• Bank vegetation	Increases channel stability, leads to aggradation (SS, S)
• Height of alluvial ridge	Inversely related, higher ridge when overtopped avulses (SS)
• Bank stability	Directly related (M, S)
Allogenic Factors	
• Change in sediment supply	Increased sediment supply increases avulsion risk (S)
• Change in water supply	Increased water supply increases avulsion risk (S)
• Change in base level	Initiates regional aggradation or degradation (S)
References: SS = Slingerland & Smith, 2004 F = Field, 1994; 2001 S = Southamer, 2007 M = McCarthy et. al., 1992 P = Pearthree et. al, 2004 M = Mohrig, 2000	

3.4. Avulsion Processes

The following investigators have developed conceptual models that describe the avulsion process on alluvial fans.

- Field's Five Stage Development Model
- Bryant's Three Phase Development Model
- Schumm's Cyclical Incision Model
- Parker/Whipple Model

These models are briefly described below.

3.4.1. Field's Five Stage Development Model

Based on field work, review of aerial photography, interpretation of stratigraphic profiles exposed in soil trenches, post-flood reconnaissance and mapping in central and southern Arizona, Field (1994, 2001) identified five key stages in development of alluvial fan avulsions (Figure 8). Each of the five stages is characterized by unique channel morphologies:

- Stage 1: On-Fan Channels. In this stage, a distributary channel branch conveys flow from the fan apex (and above) onto the active fan surface. These on-fan channels cover only a small portion of the fan surface. Because of rainfall directly on the fan surface, small dendritic channel networks form in the areas not directly drained by the active distributary (main) channel.[2] These weakly defined channels are considered an incipient drainage network.
- Stage 2: New Channel. During large floods that overtop the parent channel, portions of the on-fan channels that approach the main drainage concentrate overbank flow and are captured. Alternatively, headward erosion of the incipient drainage network may capture the parent channel.
- Stage 3: New Channel Widened. During the flood, the captured flow expands the width of the now-connected avulsive channel, increasing its capacity to divert flow from the parent channel. The channel width adjusts toward a regime width associated with the maximum captured flow rate.
- Stage 4: Aggrading Channel. After the avulsive event, small floods tend to infill the captured channel with sediment and vegetation, decreasing its width and capacity. The infilled channel is more prone to overtop and cause bedload-limited (erosive) sheet flooding, which if concentrated in the on-fan channel network, may initiate headward erosion and additional avulsive captures.
- Stage 5: Abandoned Channel. Depending on the relative bed elevations of the parent and avulsive channel, the flood sequence, and their alignments, one of the channels may be completely filled and abandoned as a low flow conveyance corridor.

In Field's model, large floods are the most effective agents of change, although the sequence of events leading up to an avulsive flood may be important for setting up

[2] Note: Field tends to describe the surfaces outside the main through-channel on a fan as "inactive," but assigns a different meaning than that used in the PFHAM and FEMA Appendix G.

conditions conducive to avulsion. Field developed his model from observations on alluvial fans in and near Maricopa County, including the White Tank Fan 36 and Tiger Wash alluvial fans. Therefore, his model should be directly relevant to fan processes in Maricopa County. Field's model is analogous to Slingerland and Smith's (2004) category of avulsion by annexation, which is thought to be more common on floodplains with low aggradation rates (low sediment supply), a consistent finding with observations of alluvial fans in Maricopa County made for this study.

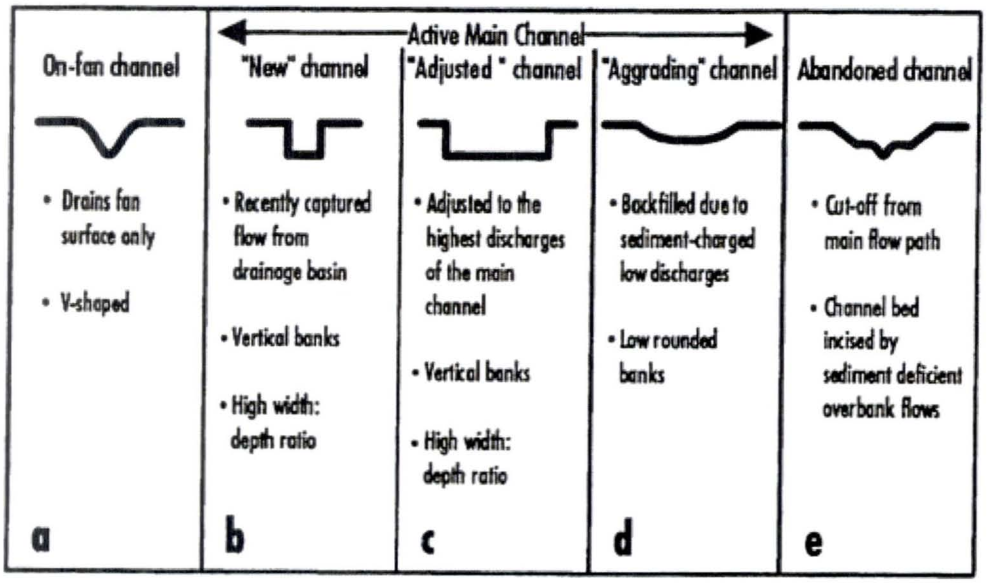

Figure 8. *Field's five-stages of alluvial fan avulsions.*

3.4.2. Bryant's Three Stage Development Model

Bryant et. al. (1995) used laboratory experiments to theorize that fans typically develop in the following three phases:

- Phase 1: Initial Conditions. More than 50% of the fan surface is covered by sheet flooding, with no defined channels and avulsions. Sediment deposition occurs by sheet flooding processes.
- Phase 2: Fan Growth. As the alluvial fan grows, distinct channels develop, but they are unstable and bifurcate. Sediment deposits form as crevasse splays off the main channel, with less than 50% of flow exiting the parent channel.
- Phase 3: Maturity. In this phase, a single channel is solely responsible for fan deposition. Apical avulsions relocate this channel to other parts of the fan, which then delivers sediment to new parts of the fan surface. A secondary sediment supply comes from the crevasse splays.

In Bryant's model, non-avulsive systems never reach Phase 3, and distribute most of their sediment supply via secondary channels and sheet flooding. While the frequency of channel avulsions is not well documented in Maricopa County, several researchers (Field, 2001; Pearthree et. al., 2004) have hypothesized that avulsions are at least infrequent, making it likely that much of the sediment delivery on fans in Maricopa County is accomplished through sheet flooding and secondary channels, rather than by direct avulsion.

3.4.3. Schumm's Cyclical Incision Model

Based primarily on laboratory physical models, with some field verification from alluvial fans in the northern Rocky Mountains, Schumm et. al. (1987) described alluvial fan evolutionary processes that included repeated cycles of channel filling, avulsions and scour. The Schumm model focuses on avulsions along fanhead trenches, which are the defined channels that originate upstream of an alluvial fan apex and continue to the point where the channel pattern becomes distributary. Schumm noted the following two basic patterns in fan sedimentation:

- Deposition at Fan Perimeter. Deposition along the distal margins of an alluvial fan is associated with periods of channelization at the apex and midfan. When defined channels exist in the mid-fan area, they tend to push sediment across the fan surface to the toe, with additional sediment contributed by bank erosion along the channel. Fanhead channel trenches fill slowly, generally filling near the fan toe first, and then progressing up toward the apex. Sediment deposition in the toe area was found to be mostly uniform with time.
- Deposition at Fan Apex and Midfan. When the fanhead trench has been fully backfilled (or prior to its development), deposition on the alluvial fan is widespread and dispersed, but is concentrated near the apex, increasing the fan slope near the apex. Eventually, the apical slope increase causes a fanhead trench to be incised. Deposition in the near-apex zone was found to be highly variable (episodic) with time. The midfan area, which is primarily a transport zone, was generally not subject to either extreme deposition or erosion rates.

Schumm also noted the following modeling results with respect to avulsion processes on an alluvial fan:

- The cycle of fanhead entrenchment, fill, and avulsion to a new location repeats often, regardless of whether a constant or variable discharge was applied to the experimental fan.
- Geomorphic channel changes on the fan are "extreme and dramatically episodic" with very short time periods separating fan deposition from fanhead trenching.
- Fan entrenchment and deposition did not correlate well with fluctuations in sediment yield, particularly at the apex. Specifically,

  > *"Fluctuations in both the location and rate of deposition over the fan surface persisted during period of relatively constant sediment yield. Therefore, it did not appear that the events occurring on the fan were directly controlled by sediment delivery. Similarly, minor fluctuations of sediment yield did not correlate well with periods of fanhead aggradation or incision. Thus, while downfan patterns of alluvial fan sedimentation were controlled by events at the apex, events at the apex were not uniquely controlled by events in the drainage basin."*

- Avulsions tended to occur in the steeper portions of the fan, but there is a transition zone in which the flow path curves from the direction suggested by momentum (straight from upstream) toward the direction of the steepest slope, i.e., the influence of topography increases in the downfan direction. The most stable channel location (fanhead trench) is along the axis of the fan. If the main channel is located off-axis, it will tend to migrate by lateral erosion toward the axis.

- Episodic (variable discharge) fans were very similar in evolution and process to constant discharge fans, except that less lateral migration of trench channels occurred on the episodic fans. Big floods on episodic fans were not the primary agents of change.
- Sites of active deposition are rapidly abandoned, probably because aggradation tends to direct flow away from topographically rising areas.
- On fan as a whole, it was found that: (1) there was a 2% chance of erosion at any given point, (2) if erosion did occur, there was 76% chance of deposition at the point in the following time period, and (3) 63% of sample points experienced "no substantial change" over course of experiment (12,418 measurements) cumulatively during all flow periods.36% experienced deposition.
- Two kinds of fanhead trenches were observed:
    - Shallow, short-term features subject to frequent overflow that were formed by active fluvial processes.
    - Deep, permanent features that were not overtopped, and were formed in geologically stable settings. The deep, permanent channels were formed by changes in geologic processes, such as tectonism or climate change.

Due to potential model scaling issues, Parker (1999) questions whether the physical modeling results like those of Schumm are directly applicable to real-world fans. Certainly, some of Schumm's observations are contrary to observations of real-world fans in central Arizona. For example, Field (1994) concluded that large floods were a primary cause of alluvial fan avulsions and that avulsions are rare. In fact, Schumm's experimental fans were much steeper and wetter than alluvial fans in Maricopa County. Certainly, the rate of avulsive channel change observed in the experimental fans far exceeds not only the rate of channel change observed on alluvial fan in Maricopa County, but also the frequency of avulsions. Experimental fans in the laboratory typically have near continuous avulsions. Alluvial fans in Maricopa County appear to experience avulsions on at least decadal or century time scales.

However, there are several conclusions drawn from Schumm's work that are relevant to avulsions on alluvial fans in Maricopa County. The apparent independence of avulsion frequency from sediment supply rate on fluvial fans is probably applicable, particularly given the relatively low sediment yields for the low desert mountain watersheds in Maricopa County. Schumm's finding regarding the low probability of erosion or deposition at any given point on the fan, even on the highly active experimental fans, probably indicates that most active fan surfaces in Maricopa County have a high probability of no significant change during any given year. Finally, Schumm's observation that deep, stable fanhead trenches are relatively permanent features formed and removed by geologic processes that operate outside normal engineering time scales is directly relevant to assessment of alluvial fan flood hazards in Maricopa County.

3.4.4. Parker/Whipple Model

Parker et. al. (1998) and Whipple et. al. (1998) used experimental studies and observations of alluvial fans composed of mining by-products and talus to develop theories of fan formation, evolution, and behavior. While their mathematical model assumes the occurrence of avulsion, they do not explicitly model formative mechanisms for avulsions. Some of their findings, however, are relevant to alluvial fans in Maricopa County. In particular, they found that the process of sheet flooding is unstable over the long term. In their physical model studies, sheet flooding areas always transitioned to channels after a short flow distance, regardless of what part of the fan was considered. After sheet flow in the physical models became concentrated into channels, the channels tended to extend up fan via headward erosion. Incised channels formed in this manner had high rates of sediment transport delivered to depositional lobes ("splays"), which also tended to migrate up fan, filling and obliterating the previously incised channels.[3] No evidence of up fan migration of splays during the period of historical record was identified for any of the fan sites considered for this study. This cyclical process occurred at all fan scales and in all parts of the fan. Parker's model is also discussed in more detail in Section 4.4.2 of this report.

3.5. Avulsion Frequency

There have been few published studies of avulsion frequency, and fewer still that are applicable to alluvial fans in Maricopa County. The following statements summarize the current understanding regarding avulsion frequency:

- Field (1994) estimated a 50 to 650 year return period for avulsions at five active alluvial fan sites in central and southern Arizona. His estimates were based on interpretation of historical and recent aerial photographs, post-flood inundation mapping, interpretation of soil trench profiles, and limited radiocarbon dating of organic material from two sites.
- Kesel and Lowe (1987) estimated an avulsion recurrence interval of several hundred years for humid region alluvial fans, based on radiocarbon dates.
- Parker et. al. (1998), Whipple et. al. (1998), Schumm et. al. (1987), and Hooke (1967) found that avulsions occurred rapidly and continuously in physical modeling studies of alluvial fans.
- Pelletier et. al. (2005) noted that rapid avulsions occur on a decadal time scale, with a lower frequency on fluvial fans compared to debris flow fans.
- Pearthree et. al, (1992) found that 13 of 19 off-channel soil pits on the Tortolita piedmont near Tucson, Arizona had channel deposits that could be at least tentatively interpreted as evidence of past avulsions.
- DMA (1985), in their verification analysis of FEMA's FAN model (Dawdy, 1978), determined that avulsions occurred on 18 sites in California and Nevada. However, inspection of their records as part of this study indicates that as few as

[3] The described process mimics Bull's (1997) discontinuous ephemeral stream model.

two of the 18 sites had solid evidence of avulsions. DMA further reported that the avulsion coefficient of 1.5 in FEMA's FAN model means that a major avulsion occurs in every other 100-year event.

- Slingerland & Smith (2004) report avulsion frequency ranges from 28 years on the Kosi River in India to 1400 years on the Mississippi River, but that rates may be less in glacial outwash streams and more on non-aggrading rivers.

3.5.1. Prediction of Avulsion Frequency

The following models have been developed to predict avulsion frequency on riverine systems:

- Jerolmack & Mohrig (2007)
- Tornqvist (2004)
- Slingerland and Smith (2004)

Jerolmack and Mohrig (2007), in a study of riverine avulsions, developed the following equations to predict avulsion frequency:

$$T_c = B/V_c \qquad \text{Equation 1}$$
$$T_a = h/V_a \qquad \text{Equation 2}$$
$$f(a) = V_a N / h \qquad \text{Equation 3}$$
$$M = T_a / T_c = (h V_c) / (B V_a), \qquad \text{Equation 4}$$
$$E = S ((g h B^4)^{0.5}) / Q \qquad \text{Equation 5}$$

where:

T_c = time for a channel to migrate a distance equal to its width
B = total channel width
V_c = bank erosion rate.
T_a = time for channel to aggrade amount equal to its depth (h) above the distal floodplain. T_a is an avulsion time scale
V_a = aggradation rate near the channel.
$f(a)$ = avulsion frequency of the stream channel
N = number of active channels
M = Mobility number
  $M >> 1$, very rare avulsions
  $M << 1$, frequent avulsions
E = Parker's stability criterion
  $E << 1$, single channel
  $E > 1$, braided
S = water slope
Q = channel forming discharge

It is possible that Jerolmack and Mohrig's methodology could be applied or modified to predict avulsion frequency on alluvial fans in Maricopa County. However, it may be difficult to collect the data required to populate their equations (migration times, lateral erosion rates, aggradation rates) without a regional data collection effort, analysis of regional avulsion frequency, and extensive geologic data collection at the site of interest. Interestingly, Jerolmack and Mohrig also found that the type of triggering event is not important for determining the avulsion frequency. In addition, they found that to generate avulsions, the aggradation rate should be high and the lateral movement rate low.

Tornqvist (2004) found that the probability of avulsion could be estimated using the following equation:

$$P(a) = (Q_f/Q_a)^{eQ} * (k_s\, S_{cv} / S_{dv})^{eS} \qquad \text{Equation 6}$$

where:

- Q_f = maximum flood peak in any year
- Q_a = threshold discharge that causes an avulsion
- S_{cv} = local cross valley slope at edge of channel belt
- S_{dv} = local down valley slope near the edge of the channel belt
- k_s = avulsion coefficient, added to reflect required slope ratio, Eqn. 5
- eQ = avulsion discharge exponent
- eS = avulsion slope exponent

For Tornqvist's methodology, Equation 6 is computed at each time step and at each cross section, and then is compared to random number between zero and one. If P(a) is greater than the random number, avulsion occurs. Note that this model is more probabilistic than deterministic. If the ratio of the terms to right in the equation is close to one, the probability of an avulsion increases. The probability of an avulsion increases with the slope ratio and discharge, both of which are intuitively obvious and are supported by numerous field studies. It may be possible to apply this equation to alluvial fans in Maricopa County, although it would require a significant amount of data from which to calibrate the various parameters. Currently, none of these regional or site-specific data sets exist.

Slingerland and Smith (2004) found that the time rate of the avulsion sequence is dependent on the following factors:

- Parent channel initial depth. A deeper channel requires more time to aggrade to the point of overtopping, or a large recurrence interval flood.
- Flood magnitude. The larger the flood, the higher the avulsion potential.
- Flood sequence. Large floods tend to flush and reset system. Small floods, or extended periods of low flows, tend to aggrade the main channel and set-up conditions conducive to avulsions.
- Proximity of on-fan channels. Nearby avulsive flow conduits increase the probability of forming complete avulsions.
- The ability of bifurcated channels to change their capacities. The stability of the bifurcated channels is a function of:
    - Shield parameter (fluid shear stress: weight of grains/area)

- Friction coefficient
- Median grain size
- Aspect ratio (1/2 width: depth)
- Water slopes in split channel segments relative to the parent channel
- Bed elevation differences of parent and new channels at the bifurcation point

- Slope ratio. For suspended load streams (D50<0.4 mm), if the branch slope is greater than five times the slope of the parent channel (or another branch), it will tend to capture all of the flow and abandon the flatter branch. However, such drastic slope differentials are rare on alluvial fans in Arizona.
- For bedload streams with large Shields parameter, water discharge is proportional to the inverse slope ratio.

3.5.2. Avulsion Frequency for Alluvial Fans in Maricopa County

The recurrence interval of avulsions on alluvial fans in Maricopa County is not well known. It is known that avulsions do occur on alluvial fans in Maricopa County, as documented by several historical accounts summarized in Section 2.4 of this report. Almost all of the causative factors for avulsions listed in Table 2 exist on alluvial fans in Maricopa County, and thus it is likely that avulsions will continue to occur in the future. It is also likely that avulsions are relatively rare events, as suggested by Pearthree et. al. (2004), and may have less than a one percent chance of occurrence in any given year (Field, 1994; 2001). Given the importance of the avulsion process to quantifying flood hazards on alluvial fans (See Section 1.3 of this report), it is strongly recommended that a systematic evaluation of avulsion frequency on Maricopa County alluvial fans be performed.

4. Methods to Predict Avulsions

Historically, the methodologies used to predict avulsion hazards on alluvial fans can be grouped into the following four basic categories:

- Evaluation of Past Behavior
- Evaluation of Field Evidence
- Physical Models
- Mathematical Modeling

Each of these basic categories is discussed below. In addition, the methodologies used to predict channel avulsions in this study are summarized.

4.1. Evaluation of Past Behavior

4.1.1. Comparison of Historical Aerial Photographs

The most reliable way to determine whether a risk of avulsion exists on an alluvial fan is to document evidence of recent historical avulsions. For most of the United States, and all of Maricopa County, it is relatively easy to find historical aerial photographs that date back to at least the 1950's, and in many cases to the late 1930's.[4] The channel position, geometry, and characteristics identified on historical aerials can be compared to that shown on recent aerials, and the occurrence and nature of avulsions readily determined. Photographic comparisons can either be done over the entire period of record (i.e., oldest to most recent aerial), or can be done using coverage that pre- and post-dates a significant flood. Examples of this type of photographic comparison are shown in Figure 3 to Figure 7. The aerial photography comparison methodology is robust, cost-effective, and easy to apply, although it is somewhat dependent on the quality of the aerial coverage and the availability of photography near the dates of known floods. In some cases, photographic evidence of an avulsion can become faint or disappear completely over longer time periods, making it possible to miss some types of avulsions if too long a gap between photograph dates is used. In addition, if only the oldest and most recent aerials are used and are assumed to represent the entire history of channel movement during the period of record, the occurrence of multiple avulsions during that time period might be missed.

4.1.2. Interpretation of Soil Stratigraphy

The occurrence of past avulsions can also be identified by examining soil stratigraphy exposed in trenches excavated across a fan surface. Experienced soil scientists and geomorphologists can readily identify stratigraphic features in the soil profile that yield information about the following:

- Former channel deposits that are now below current overbank areas, indicating that the current channels have avulsed away from their former location.
- Overbank deposits below current channels, indicating that the current channels have avulsed into areas that formerly were overbank floodplains.

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[4] In rare cases, channel position comparisons can be made using historical topographic mapping, which may extend the period of record beyond the inception of aerial photography (circa 1930).

- Multiple, stacked sequences of channel and floodplain deposits indicating repetitive avulsion or migration of channels across the fan surface.
- No change in past channel and overbank deposits, indicating a lack of significant avulsions or channel migration.
- Buried soil profiles or surficial features, indicating progressive long-term aggradation of the fan surface, which in turn implies high potential for future channel avulsions.

If datable material is found in the soil profile, then a chronology of channel change can be pieced together to estimate the frequency of avulsions (or duration of stability). Dating the soil profile can be done using archaeological or historical artifacts, organic material that can be carbon dated, trees with measurable tree rings, pollen samples, or soil development principles. Datable material can also be used to estimate the rate of fan aggradation. On alluvial fans, high rates of aggradation generally correlate to frequent avulsions. Evaluation of soil trenches can be labor-intensive, and may require permits and right-of-entry that can be difficult to obtain. It also requires experience in soil profile interpretation, a skill set that is moderately uncommon. In addition, on large alluvial fans, it may be difficult to sample a representative portion of the fan surface, necessitating extensive extrapolation between trench locations. However, in some cases, investigators may opportunistically take advantage of utility trenching or other construction projects to obtain subsurface soil data.

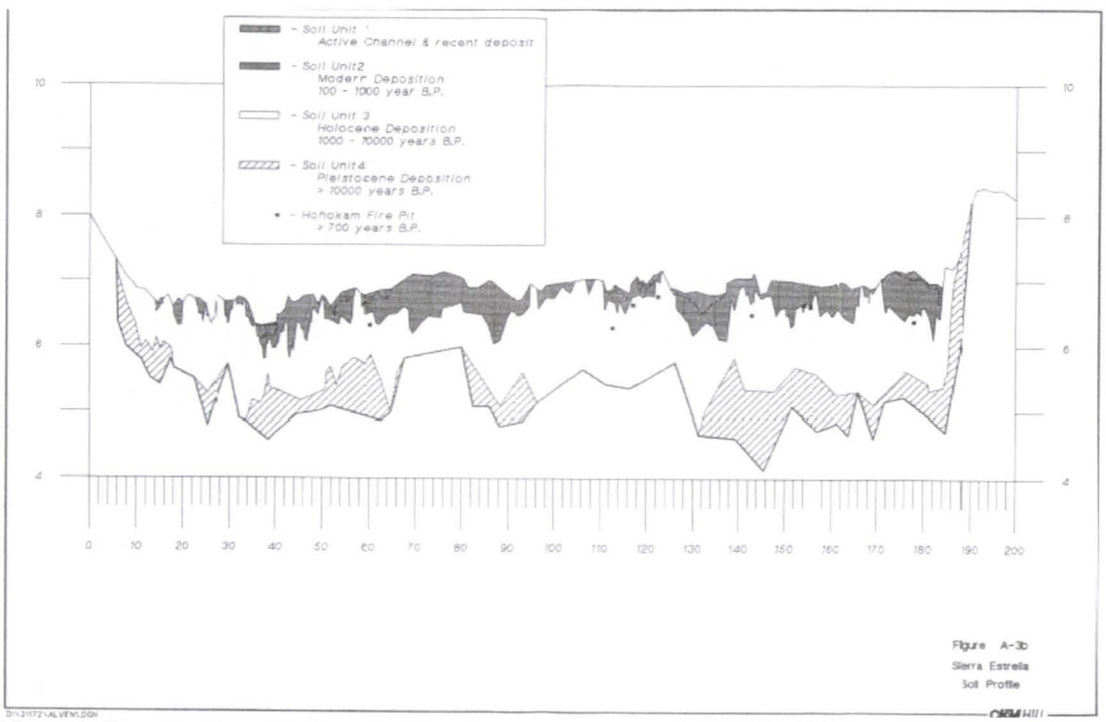

Figure 9. Trench soil profile from Rainbow Valley Fan 12 (CH2M HILL, 1992)

4.1.3. Other Methods

In rare cases, usually if historical avulsions impacted private buildings or public infrastructure, there may be written descriptions, news accounts, or photographic records of past avulsions, which represent a third possible source of information about the past behavior of an alluvial fan.

4.2. Evaluation of Field & Map Evidence

The potential for alluvial fan avulsions can also be assessed by observation of existing site conditions in the field. Some portion of the work can be completed in the office through the use of topographic maps and aerial photographs. Types of field evidence that indicate avulsion potential are described below. These types of evidence may be used as indications of past or future avulsion, although any one type of evidence generally should not be considered definitive evidence by itself. These types of indicators are most diagnostic when a suite of indicative characteristics are present at a field site.

4.2.1. Channel Pattern

Beaty (1963) reported that the mere presence of a distributary channel pattern is evidence of past avulsions, although Hjalmarson and Kemna's (1992) study of distributary flow areas in Arizona identified other potential causes for channel bifurcations on piedmont surfaces. Historical evidence from the alluvial fans evaluated for this study indicates that the presence of distributary channels on active alluvial fans (as opposed to other types of piedmont surfaces) is at least correlative with past channel avulsions, if not causally related. Other channel pattern evidence of avulsions includes the following:

- Perched, active channels elevated above the surrounding floodplain surface. These types of channels are sometimes difficult to identify in the field, but are readily identified in hydraulic models where more conveyance is available at lower elevations in the overbanks than above the sandy channel bed.
- Abandoned or perched channels disconnected from the active channel network. These types of channels can be identified as abandoned by the types of vegetation on the channel bed, the lack of fresh deposition or erosion, filling by fine-grained (overbank) sediments, or complete infilling of the channel leaving only linear remnants of bank vegetation.
- Underfit channels. These types of channels were formed by expansion in response to large flood flows which no longer are conveyed along that flow path, and can be identified by inset channel features, offset cut banks separated from the currently active channel, and irregular channel geometry.
- Channels with no or poor bank vegetative cover, in stark contrast to channel conditions elsewhere on the fan. These channel types typically indicate very recent formation (avulsion) or expansion, and often have very fresh, vertical cut banks.
- Relict buried channels, sometimes identified by alignments of dead trees only found along channel banks elsewhere on the alluvial fan. In some cases, relict infilled channels can be identified only by trenching and stratigraphic description of the soil profile.

- Erosive lineations in the floodplain apparently caused by overbank flows leaving the active channel network at a discrete point. These features may be more easily identified in aerial photographs than in the field, particularly if some time has passed since the causative event.
- Discontinuous ephemeral stream pattern (repeating chute and splay channel form). Rapid transition from a single, well-defined channel to a highly distributary channel pattern is evidence of net sediment deposition which can result in widely varying flow distributions between floods.
- Aggrading channels. Field evidence of aggrading channels includes low or downstream-decreasing bank heights (in contrast to bank heights elsewhere on the channel system), highly braided channels, and bed elevations that are higher mid-channel than at the margins.

4.2.2. Surface Age

The distribution of geologically young surfaces on the alluvial fan may be evidence of the potential for avulsions. If the youngest surfaces are arrayed in a radial pattern extending outward from the fan apex (i.e., a "fan" shape), the surface was formed by channel avulsions of some type. It would not be possible to form a fan-shaped young surface by stable riverine processes. Riverine floodplains tend to be distributed in a linear pattern roughly parallel to the channel, and contained between higher, older terraces that converge in the downstream direction.

The relative age of the surfaces is also indicative of the avulsion potential. Alluvial fans that are subject to very frequent avulsions will have the widest distribution of the youngest surfaces, with little distinction in surface age between the active channels and the floodplain. Less avulsive alluvial fans will tend to have slightly older surfaces and a greater distinction in age between the active channel and the adjacent floodplains.

On active alluvial fans with potential avulsions, "islands" of older surfaces are often inset within the broader areas of younger surfaces. On the most active, avulsive alluvial fans there is usually little or no topographic relief between the younger and (inset) older surfaces. In other cases, the younger surfaces are perched topographically above the older surfaces, making the older surface areas vulnerable to inundation during an avulsion.

Types of field evidence used to estimate surface age are well documented in the District's PFHAM Manual, as well as in the Task 2.6 Dating Methods report prepared for the PFHAM study. Therefore, no detailed description of these indicators is provided in this report. Age indicators include such features as desert varnish, desert pavement, surface color, vegetative characteristics, topographic expression, channel pattern development, and soil profile development.

4.2.3. Stratigraphy (Smith et al, 1989).

The occurrence of avulsions on an aggrading landform creates a unique stratigraphic footprint, as described by Smith et. al. (1989). Where deeper stratigraphic information is available, it can be interpreted to estimate the frequency of avulsion as well as the overall rate of avulsion (Smith et. al., 1989; Tornqvist, 2004). However, no such stratigraphic data sets exist for alluvial fans in Maricopa County. If deep aggregate mines are sited on alluvial fans in the future, it may be possible to obtain such data by inspection of the exposed cut slopes in the mines. The near-surface stratigraphy is also useful for interpreting the more recent history of avulsions, as described in Section 4.1.2 above. Finally, the burial of older surfaces along the margins of the young, active area may indicate a type of avulsion that also leaves a distinct stratigraphic pattern, as varnished pavement surfaces with soil development are covered by younger alluvium.

4.2.4. Topography and Map Analysis

The topography of an alluvial fan can also be used to indicate the potential for avulsions. First, the radial contour pattern is not only one of the key identifying characteristics of the alluvial fan landform, the degree of contour bending is directly proportional to the risk of an avulsion leaving and remaining separated from the parent channel. The greater the degree of contour bending (i.e., lower radius of curvature), the more likely it is that any flooding that overtops the main channel banks will not return to the channel, but will instead find a new path to the toe of the alluvial fan. Second, areas of recent deposition (i.e., young surfaces) tend to be perched topographically above areas that have not received sediment deposition (i.e., older surfaces). Where such topographic inversions exist, they are likely sites for future avulsion since flood water tends to seek out the steepest flow paths. Third, potential flow paths outside the existing channel network can sometimes be identified as continuous low areas by inspecting topographic maps, as described in Section 4.5.7 below. Fourth, lack of topographic relief between the active channel network and the fan floodplain surfaces provides an opportunity for overbank flows that could cause avulsions. Finally, development of an on-fan drainage network provides topographic features that could collect and concentrate overbank flooding and provide sufficient energy for an avulsive channel to form.

4.3. Physical models

Physical model studies of alluvial fans (Hooke, 1967; Schumm et. al., 1987; Parker et. al., 1998) have made significant contributions to understanding alluvial fan processes, including the role of avulsions in alluvial fan evolution. Some of the more important findings relating to avulsions include the following:

- Avulsions can occur anywhere between the apex and the toe.
- Avulsions along fanhead trenches occur as cyclical cut and fill processes.
- The occurrence of avulsions is directly related to discharge, but is only weakly correlated to sediment supply.

However, these physical model studies have not directly improved our ability to predict the occurrence or frequency of avulsions on specific, real-world alluvial fans. Constructing a physical model of a specific alluvial fan field site would be cost-prohibitive in most cases, and is probably physically impossible. In general, the physical model studies report observations of avulsion, but do not explicitly evaluate the cause of avulsions. Whipple et. al. (1998) warn that scaling effects in the model study make it difficult to apply the results to fans outside the laboratory.

4.4. Mathematical & Computer Modeling

There have been several attempts to formulate mathematical descriptions of alluvial fan avulsion processes, none of which are particularly useful for predicting avulsions on alluvial fans in Maricopa County. These models include the following:

- FEMA FAN Model
- Parker Model
- Riverine Avulsion Models
- Fixed Bed Hydrologic & Hydraulic Models

4.4.1. FEMA FAN Model

The FEMA FAN model (FEMA, 2003) was one of the earliest attempts to generate a mathematical model of alluvial fans flood hazards that incorporated potential avulsions. The probabilistic model is based on a mathematical formulation developed by Dawdy (1978), as well as a number of key assumptions about the behavior of alluvial fans. The FAN model has been extensively criticized in the literature (Fuller, 1990; French, 1992; NRC, 1996) and is prohibited from use by at least one Arizona agency (ADWR, 1995). Some of the key reasons it should not be applied in Maricopa County for flood hazard assessments include the following:

- Discharge. The predicted flow depths are based on the assumption that the full apex discharge is not attenuated or supplemented by tributary or on-fan flow sources as the flood traverses the alluvial fan landform. The results of this study, as well as post-flood field observations, indicate that significant flow attenuation occurs during transmission of the flood hydrograph across the fan surface, particularly in Maricopa County where flood volumes tend to be small relative to the fan area.
- Random Flow Path. The FAN model assumes that flow is no more likely to follow an existing flow path than to create an entirely new flow path. Historical flood accounts (Pearthree et. al., 1992; Field, 1994; Pearthree et.al., 2004) and extensive modeling done for the PFHAM study clearly demonstrate that floods are far more likely to follow the existing channel network than create new channels. The net effect of this erroneous assumption is to significantly underestimate flood hazards along the existing channel network and significantly overestimate flood hazards outside the existing channels.
- Channel Geometry. The FAN model results are derived from an unsubstantiated channel width-depth relationship that was shown to be erroneous on all of the alluvial fans examined by CH2M HILL (1992). Past research by District staff indicates that original developments of the width-depth relationship have repudiated it as used by FEMA (Tram, 2010). The FAN model assumed that flow is channelized, either in a single channel or in multiple channels, from the fan apex to the toe, and does not account for flood hazards related to sheet flooding or overbank conditions, which are known to be important components of flood conveyance on Maricopa County alluvial fans.
- Topography. The flood hazards predicted by the FAN model do not account for topographic variation (high ground, low ground) across a radial profile of the fan

surface, resulting in inaccurate predictions of flow depths, velocities, and inundation areas.
- Inundation Area. The FAN model assumes that all of the active area across a radial contour is inundated, particularly near the hydrographic apex. FLO-2D modeling performed for this study, as well as FEMA guidance documents (FEMA, 2003) indicate that not all of the Holocene surface is part of the regulatory floodplain.
- Design Data. The flood depths and velocities generated by the FAN model are not suitable for use in hydraulic design of structures.

For these reasons, it is recommended that the District definitively preclude use of the FAN model for flood hazard assessments in Maricopa County.

4.4.2. Parker Model

Parker et. al. (1998; Parker, 1999; Whipple et. al., 1998) formulated mathematical descriptions of alluvial fan behavior. While the Parker formulations are intriguing, and probably could be adapted for alluvial fans in Maricopa County if sufficient data were available for calibration, they are probably not applicable as currently formulated. The Parker model was developed for steeper fans with much higher sediment inflows and aggradation rates. Furthermore, the models assume the occurrence of avulsions, rather than explicitly modeling them, making their utility for predicting avulsions somewhat limited. Future development and enhancement of the Parker models is worth monitoring for possible future application to alluvial fans in central Arizona.

4.4.3. Riverine Avulsion Models

Some of the more recent mathematical formulations of avulsion risk and behavior on river channels were summarized in Section 3.5.1 above. While these formulations appear promising, they have not yet been evaluated specifically for use on alluvial fans, nor are there currently enough data for alluvial fans in Maricopa County from which such an evaluation could be performed.

4.4.4. Fixed Bed Hydrologic & Hydraulic Models

The processes of alluvial fan avulsions occur over time frames that generally exceed a single flood hydrograph. In addition, alluvial fan avulsions inherently involve changes in bed and floodplain elevations, as well as changing channel boundaries on aggrading landforms. Therefore, fixed bed models are not capable of directly generating a realistic process-based simulation of an alluvial fan avulsion. For this reason, FEMA (2003) specifically precludes[5] use of such models for floodplain delineation and hazard assessment on active alluvial fans, at least without consideration of flow uncertainty and site geomorphology. Nevertheless, because of the limited number of alternatives, the following uses of fixed-bed hydrologic and hydraulic models may have a place in assessment of avulsion hazards on alluvial fans:

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[5] FEMA, Appendix G, Table G-1; Section G.2.3.4

- Hydrology: HEC-1. This study has demonstrated that HEC-1 (or any similar lumped-parameter unit hydrograph based rainfall-runoff-routing models) does not adequately model the hydrology of floods downstream of the alluvial fan apex. HEC-1 may be useful for generating flood hydrographs in tributary drainage areas upstream of the fan apex or model flow distributions between stable bifurcating channels. On alluvial fans, however, HEC-1 performs poorly in developing and routing the flood hydrograph across broad, shallow floodplains and poorly defined distributary flow networks, and accounting for re-infiltration on permeable alluvial surfaces.
- Hydrology: FLO-2D. While FLO-2D cannot explicitly predict or simulate avulsion, a method of accounting for flow path uncertainty on peak discharges at concentration points downstream of the alluvial fan apex was developed for this study, as described in Section 4.5.4 below. The recommended methodology uses multiple model runs and virtual levee scenarios to represent the range of possible discharge variations resulting from avulsions in the most active part of the alluvial fan. FLO-2D offers an additional advantage in that it simultaneously computes the hydrology and hydraulics of flow.
- Hydraulic models. Although fixed bed hydraulic models cannot directly simulate an alluvial fan avulsion because avulsions inherently involve bed elevation changes, it is possible to generate hydraulic data from fixed bed models that can be used to identify conditions conducive to avulsive channel processes. Based on the results of the PFHAM study summarized in the Task 2.4-2.5 Report (JEF, 2010), the following model characteristics were found to be important for predicting hydraulic variables related to alluvial fan avulsions:
    - Volume accounting. Because of the extensive attenuation that occurs on alluvial fans in Maricopa County, unsteady, volume-accounting models (e.g., FLO-2D) are preferred over steady state models (e.g., HEC-RAS).
    - Two-dimensional flow. Flow over an alluvial fan surface is inherently a two dimensional problem. The most successful simulations will be capable of simulating two-dimensional flow. In most cases, use of one-dimensional models requires unacceptable simplification of the input data.
    - Variable flow depths. The best hydraulic models for alluvial fans are capable of simulating temporally variable conditions ranging from dry surfaces to shallow overland flow to deep channelized flow.
    - Sediment transport. Hydraulic models that compute estimates of scour, deposition, and sediment transport are preferred over water-only models. It is expected that alluvial fan surfaces will be net aggradational over the long term, but that significant amounts of scour may occur locally during single events that will affect water surface elevations and local hydraulic conditions.
    - Flexible output. To understand and predict conditions conducive to avulsion, it is necessary to use a model capable of generating hydraulic variables over a spatially extensive area, at differing time periods, and for both net (model end) and intermediate time periods.

While there are other two-dimensional models available, the FLO-2D model was found to have all of the components and capabilities needed for analysis of alluvial fans in Maricopa County. FLO-2D is a physically-based model, combines rainfall and runoff modeling, provides hydrologic and hydraulic data everywhere within the model domain (not just at selected concentration points), is familiar to and frequently used by District staff, and has been accepted by FEMA for use in hydrologic and hydraulic modeling studies, including alluvial fan floodplain studies, as well as by other local, state, and federal agencies. The model is fully compatible with GIS-based data sets and technology. The model is capable of simulating infiltration, storage, sediment transport, and flood control structures. It is relatively inexpensive, well-documented, and has a large number of users in Maricopa County. Furthermore, the US Army Corps of Engineers (2000), in a study of alluvial fans in California, concluded that FLO-2D was the best available model for floodplain analysis. Use of other two-dimensional models is, of course, not precluded or discouraged if they meet the minimum criteria outlined above.

4.5. PFHAM Study Avulsion Modeling

A number of methodologies to predict avulsions on active alluvial fans were explored as part of this study, including the following:

- FLO-2D 100-Year Models
- FLO-2D Mega-Flood Models
- FLO-2D Depth-Velocity Zones
- FLO-2D Hazard Classification
- FLO-2D Virtual Levee Scenarios
- FLO-2D Sediment Transport Models
- FLO-2D Channel Blockage Models
- Topographic Analysis: Avulsive Flow Path Models

The methodologies described below attempt to identify two types of avulsive characteristics: (1) non-channelized portions of an active fan surface in which formation of an avulsion is likely, or (2) portions of the existing channel network that are ripe for being abandoned by avulsive processes. The results of these analyses were verified by comparing their predictions to conditions observed in the field and on aerial photographs, as well as by comparing their results to channel changes observed during known avulsive floods on White Tanks Fan 36 and the Tiger Wash alluvial fan. Note that sensitivity tests described in the PFHAM final report (JEF, 2010) indicate that FLO-2D results are affected by the grid size used and topographic mapping accuracy.

4.5.1. FLO-2D 100-Year Models

The FLO-2D model routes a flood hydrograph across a fan surface according to the topographic data and other input parameters coded into the model. The computed distribution of flood water and flow depths on an active fan surface are dictated by the existing channel pattern only to the extent that the existing channels reflect topography and other model input parameters. On many active alluvial fans, the "active" channels, as defined by a sandy bed and bank vegetation, are perched topographically above the surrounding terrain. In other places the channels have aggraded to the point where they no longer have the capacity to convey the volume of flow delivered by upstream reaches. In such situations, FLO-2D distributes runoff to topographically lower areas in the floodplain, thus enabling potential avulsive flow corridors to be identified from plots of flow depths on the fan surface relative to the existing channel locations. The accuracy of FLO-2D modeling is affected by grid size and the accuracy of the topographic data.

The location of potential avulsive flow paths can be readily identified by careful inspection of plots of FLO-2D modeling results relative to the existing channel network visible on recent aerial photographs. In most cases, FLO-2D predicts that most flood water will be conveyed via the existing channel network, which is consistent with observations of historical alluvial fan flooding in Arizona (Pearthree et. al., 1992; Field 1994; Section 2.4). In some cases, FLO-2D shows concentrations of flood water outside the existing channel network. Based on field observations published by Pearthree et. al. (1994; 2004), a 100-year 0.3 foot flow depth[6] was used as the lower depth threshold for potential avulsive flow. Potential avulsive flow paths identified using the 100-year FLO-2D models for each of the four alluvial fan analysis sites are shown in Figure 10 to Figure 13.

[6] The FLO-2D maximum depth value for each grid cell was used.

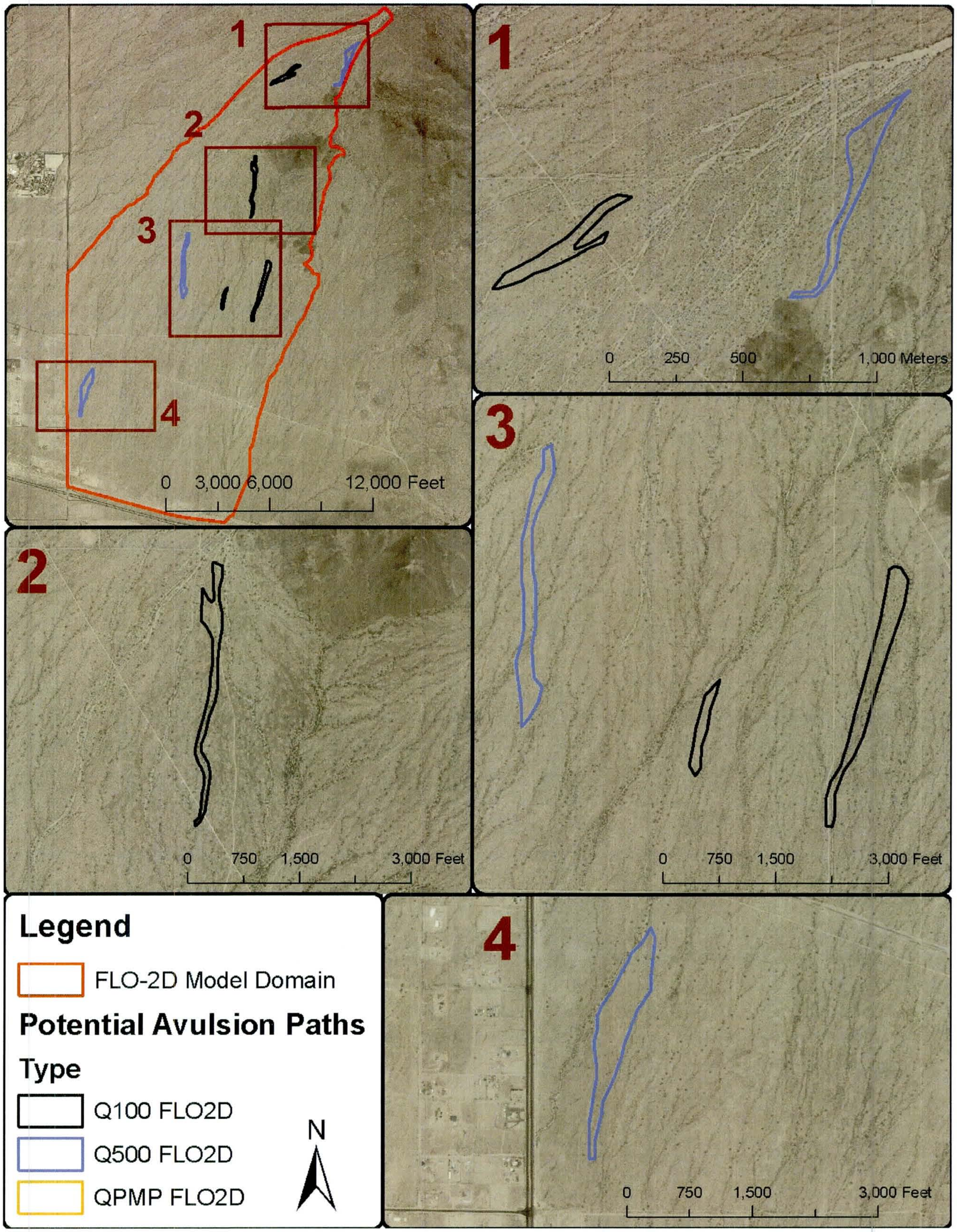


Figure 10. Potential avulsion locations identified from 100-year FLO-2D modeling results for the White Tank Fan 36 site. Black and blue lines indicate avulsions identified from 100- and 500-year results, respectively.

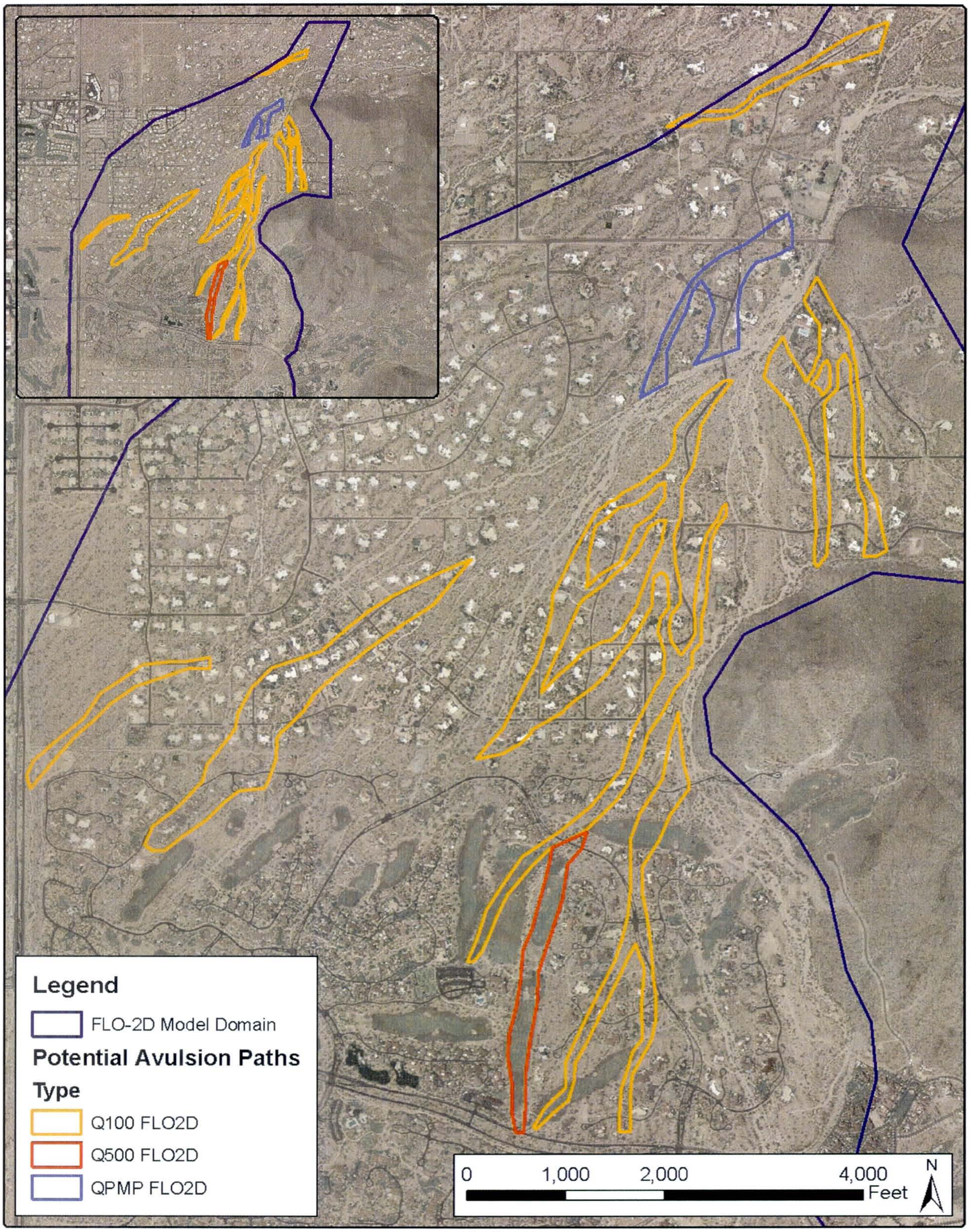


Figure 11. Potential avulsion locations identified from 100-year FLO-2D modeling results for the Reata Pass Fan site. Yellow, blue and red lines indicate avulsions identified from 100-year-, 500-year and PMP results, respectively.

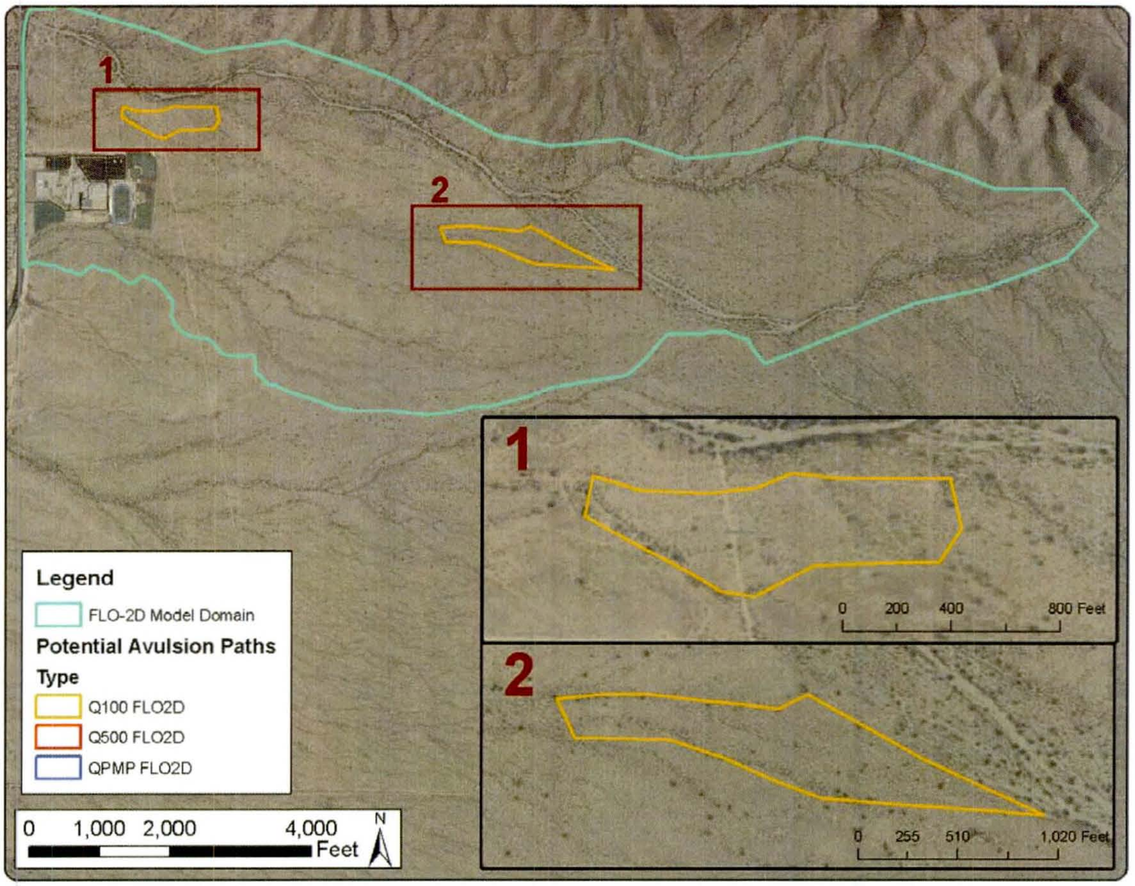


Figure 12. Potential avulsion locations identified from 100-year FLO-2D modeling results for the Rainbow Valley Fan 1 site. Yellow lines indicate avulsions identified from 100-year results.

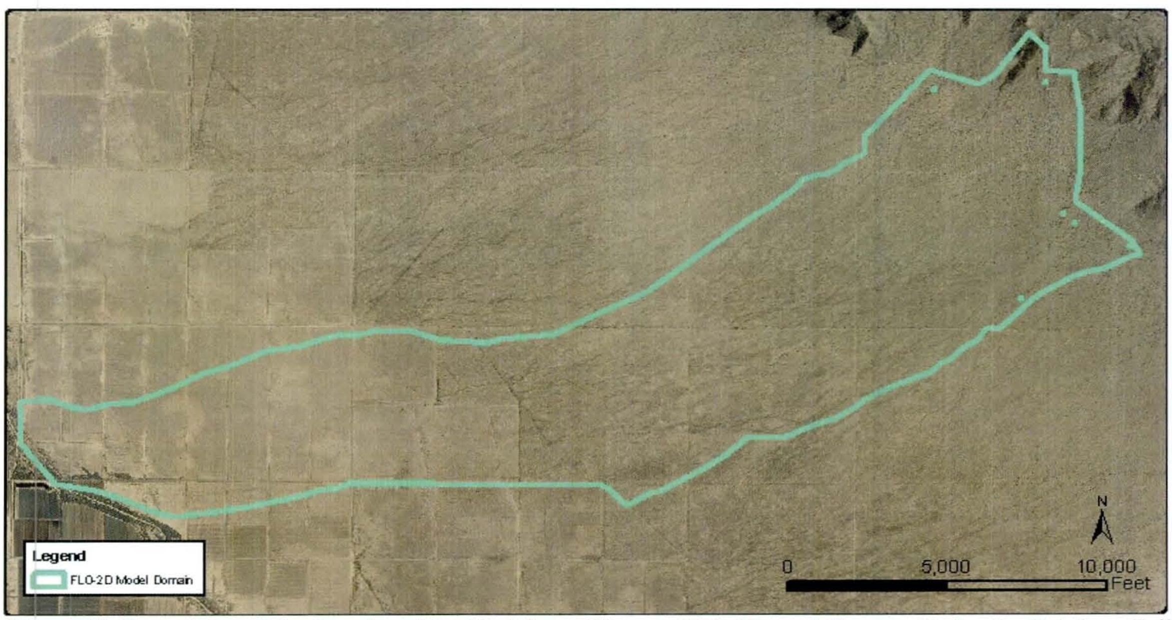


Figure 13. Potential avulsion locations identified from 100-year FLO-2D modeling results for the Rainbow Valley Fan 12 site (NO Avulsions identified).

The following summarize the findings from the modeling illustrated in *Figure 10* to *Figure 13*:

- White Tanks Fan 36
  - Four potential avulsion corridors were identified from the 100-year base model results, with three additional corridors identified for the 500-year event.
  - Only one of the potential avulsion corridors (Q500) was located within 4,000 feet of the hydrographic apex of the alluvial fan. The majority of the potential avulsions were located in the mid- to distal-fan areas. One reason that few potential avulsion corridors were identified near the hydrographic apex is that this portion of the WTF 36 site is covered by a dense distributary channel network, i.e., there are relatively few non-channelized areas in the most active portion of the fan.
  - The potential avulsion corridor located nearest the hydrographic apex is not indicated by crenulations in the 10-foot topography, and thus may represent a more classic type of avulsion (single channel cut into undisturbed floodplain). Note that flows well in excess of the 100-year event, or significant aggradation of the main channel, would be required to exploit this avulsion corridor.
  - One more prominent potential avulsion corridor is located below the secondary apex downstream of the large inselberg on the WTF 36 site. This avulsion follows an incised on-fan flow path, and would likely occur due to piracy.
  - Overall, FLO-2D modeling indicates that most flooding on the fan surface will be conveyed along the existing channel network, especially in mid- to distal fan areas.
- Reata Pass Fan
  - There are numerous interconnected potential avulsive flow paths that are depicted by the 100-, 500-, and PMP FLO-2D modeling results.
  - The presence of a dense network of distributary channels in the western arm of the RPF site precludes identification of avulsive flow paths in that area, i.e., there are relatively few non-channelized areas in that portion of the fan.
  - There is a potential avulsive flow path located above what has been traditionally called the hydrographic apex. If the FLO-2D modeling is correct, then the location of the hydrographic apex should be moved upstream, since the hydrographic apex is identified at the point where the fanhead channel loses capacity. This potential breakout is not readily apparent in the topography or aerial photography, and warrants more detailed investigation in the future.
  - There are several prominent potential avulsive flow paths that bisect the "island" of geologically older soils located downstream of the hydrographic apex. Flow through this area may reflect a different mechanism more associated with traditional stream piracy, since the surrounding fan surfaces may be more stable than the younger alluvial surfaces elsewhere on the alluvial fan landform.

- Potential avulsions were only mapped to Thompson Peak Parkway, and are probably only reliably mapped to the upstream limit of the DC Ranch subdivision, because of the impact of development on flow paths below those points.
- Note that the FLO-2D models of the RPF site were built without accounting for blockage by the numerous homes constructed within the active fan area. Therefore, the FLO-2D models show the natural, not post-development topography and potential flow paths.
- Tendency for high flow to inundate surfaces untouched by small floods.

- Rainbow Valley Fan 1
  - Two potential avulsive flow paths were identified from the 100-year FLO-2D base model. Neither of these flow corridors is located at the hydrographic apex.
  - FLO-2D does not predict that runoff enters the overflow corridor located at the apex until flow exceeds the 500-year event.
- Rainbow Valley Fan 12
  - The existing drainage network on the RVF 12 site is so fine-textured and the transition to sheet flooding conditions so rapid that most flow paths located more than 1,000 feet from the hydrographic apexes are too small to reliably identify, making comparison with FLO-2D corridors difficult.
  - No avulsive flow corridors were identified using either the FLO-2D 100-year base model or 500-year results.

4.5.2. FLO-2D Mega-Flood Models (Q500 & QPMP)

There is some indication in the literature that avulsions on active alluvial fans in Maricopa County are rare (Field, 1994; 2001; Pelletier et. al., 2005; Section 3.5), with recurrence intervals that may exceed the 100-year event. Furthermore, it is likely that large flood volumes are required to perform the geomorphic work necessary to fully form major avulsions. Therefore, FLO-2D modeling results for the 500-year (Q500) and a flood generated from the probable maximum precipitation (QPMP) were compared to the existing channel positions shown on recent aerials to determine if potential avulsive flow paths other than those identified for the 100-year event could be recognized.[7] These so-called "mega-floods" provided greater peaks and volumes needed to inundate a greater percentage of the alluvial fan surface. Conversely, if no avulsive flow paths were identified in the mega-floods, then it is more likely that the alluvial fan is not avulsive.

A description of the 500-year and PMP results was provided in Section 4.5.1 above. Some trends of these results are discussed below:

- Most of the 500-year potential avulsive flow paths overlie the 100-year flow paths, although the 500-year flow paths tend to be wider and deeper and convey more discharge than the corresponding 100-year flow paths.

[7] Use of the mega-flood hydrographs also addresses potential concern regarding possible over-estimation of loss rates in the 100-year event.

- For the PMP FLO-2D results, the predicted flow nearly inundates the entire Holocene surface, making identification of individual flow paths somewhat subjective.
- Some of the PMP potential flow paths are not significantly deeper than the 100- or 500-year predicted flow depths, indicating that if additional flow is directed at some flow corridors, they simply overflow and the additional flow is shifted to other parts of the floodplain.
- On the WTF 36 site, the FLO-2D PMP model predicts greater flow depths on the southeast side of active alluvial fan surface immediately downstream of the hydrographic apex, possibly indicating a preference for avulsions to occur on that side of the alluvial fan.

An analysis of FLO-2D results was conducted to determine if the 500-year or PMP modeling results could be used as simpler alternative to the virtual levee scenario methodology. However, the analysis indicated that the results of the mega-flood models and virtual levee scenario models were not equivalent hydrologically or hydraulically, and that there was no known relationship between recurrence interval and avulsion potential. Even if the District's regulatory interest is limited to the 100-year event, evaluation of the mega-flood FLO-2D model results was useful because the larger discharges accentuated trends that may not have been as evident in the results from the 100-year or more frequent events.

4.5.3. FLO-2D Velocity Zones (water-only models)

For an overbank flow to be avulsive, it must have sufficient energy to erode the floodplain surface and form a new channel. The magnitude of energy required to erode a natural surface is a function of the surface composition, cohesiveness, and ground cover. Data describing the composition, cohesiveness and cover for the alluvial fan surfaces at the four fan evaluation sites are available from the NRCS Soil Survey Maps, and can be verified by field observations. Like most alluvial fan surfaces in Maricopa County, all of the four evaluation sites are underlain by relatively non-cohesive sandy, sandy loam, and loamy sand soils, with sparse desert scrub vegetative cover. A variety of investigators have developed relationships between flow velocity and surface erodibility (BUREC, 1974; Neill, 1975; USACE, 1970; 1995), all of which suggest that the alluvial fan surfaces at the four evaluation sites could be eroded wherever flow velocities exceed two feet per second. Floodplain velocities are readily obtained from the FLO-2D results and are plotted in Figure 14 to Figure 17.

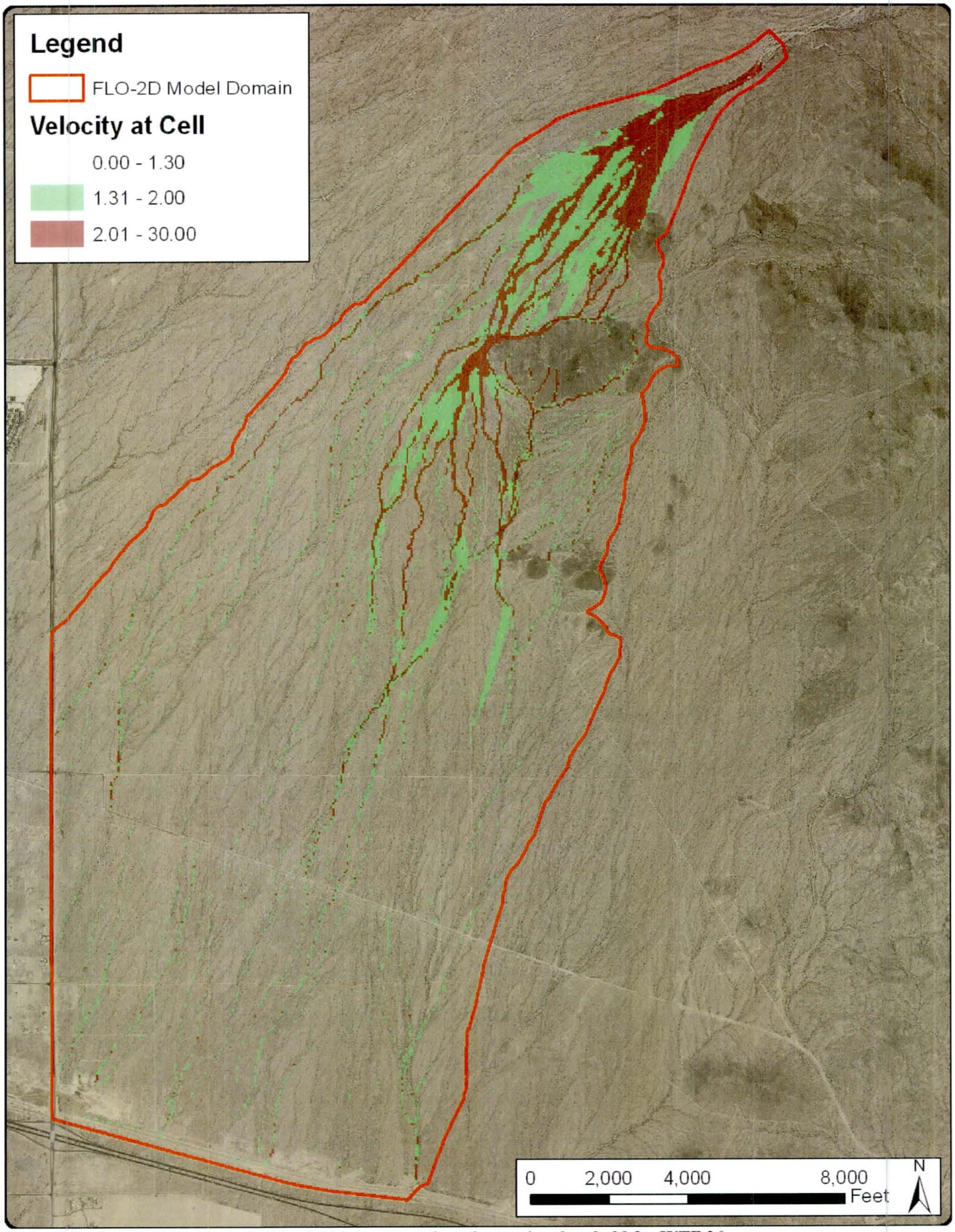


Figure 14. Plot of 100-year FLO-2D velocities greater than the erosive threshold for WTF 36.

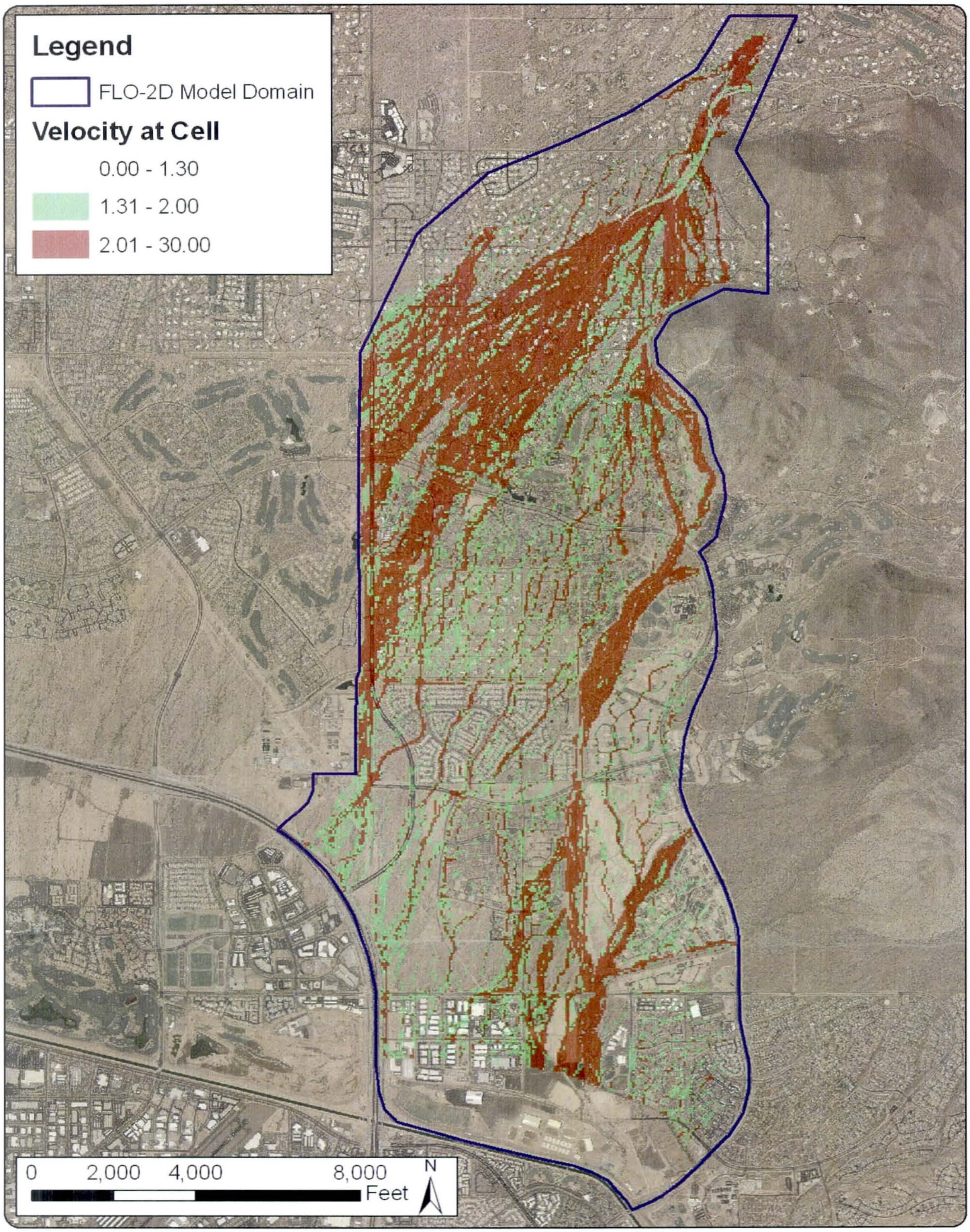


Figure 15. Plot of 100-year FLO-2D velocities greater than the erosive threshold for RPF.

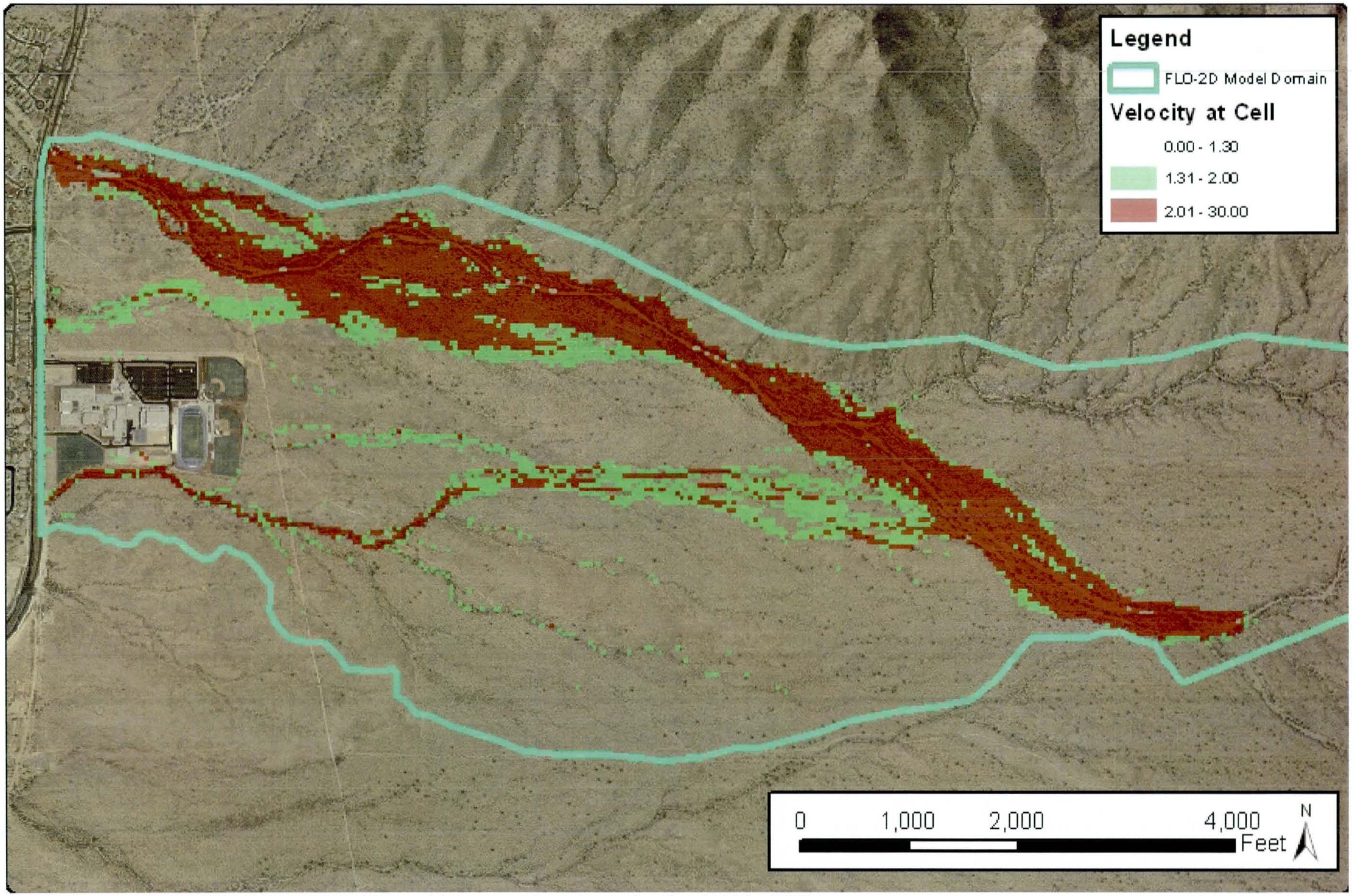


Figure 16. Plot of 100-year FLO-2D velocities greater than the erosive threshold for RVF 1.

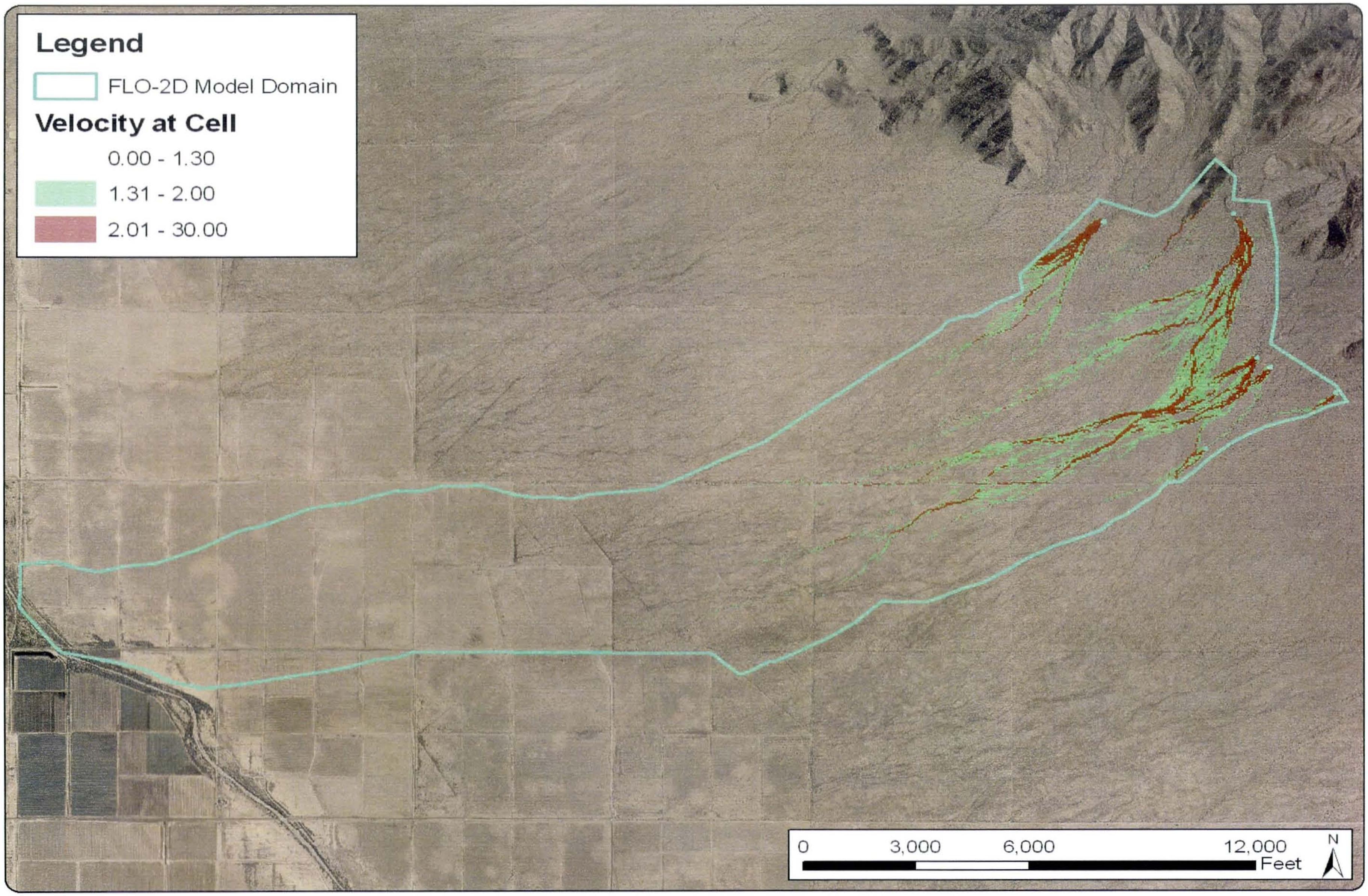


Figure 17. Plot of 100-year FLO-2D velocities greater than the erosive threshold for RVF 12.

Evaluation of the FLO-2D velocity threshold plots in Figure 14 to Figure 17 yielded the following conclusions:

- Any of the colored areas in Figure 14 to Figure 17 could be subject to surface erosion during a 100-year event. These potential erosive velocity zones tend to be very broadly distributed near the hydrographic apexes, but are generally limited to the existing channel network in the mid- and distal fan areas.
- The velocity zone method identified erosive corridors along all of the potential avulsive corridors identified using the base and mega-flood FLO-2D results described above.
- Some of the potential avulsive corridors identified using the base and mega-flood FLO-2D results were shown by the velocity method to have non-erosive velocities.
- The velocity threshold method revealed significant differences in the erosion (and avulsion) potential between the more avulsive WTF 36-RPF sites and the more passive, sheet flooding dominated RVF 12 site.
- On the RPF site, there are numerous homes located in erosive velocity - potential avulsion zones.

Note that the velocity data shown in Figure 14 to Figure 17 are average velocities for each FLO-2D grid cell. Therefore, a 60% downward adjustment of the threshold velocity was made to depict a more accurate maximum channel velocity within each individual grid, as is shown as a separate color in Figure 14 to Figure 17. In addition, the results shown are for the water-only base models and do not reflect inundation of surfaces or alternate distribution of flow that might result from upstream avulsions or sedimentation processes. Further evaluation of this methodology could include composite results from multiple models, or consideration of stream power or shear as a determinative variable. Argett and Wilson (2009) have noted that surfaces may be assumed to be avulsive if the computed overbank stream power or shear equals the values computed for the existing channels.

4.5.4. BUREC Hazard Classification Zones

The Bureau of Reclamation (BUREC) ACER Technical Memorandum No. 11 includes a series of charts that purport to depict flow hazards downstream of dams. These charts relate flow depth and velocity to hazards to buildings on foundations, mobile homes, motor vehicles, adult pedestrians, and children. Engineering judgment and field observations indicate that if the flow depth and velocity were sufficient to knock over a small child, it would also be likely to transport the fine- to medium-grained sediment (i.e., erosion) found in the loamy sand soils on most active alluvial fans in Maricopa County. Therefore, the BUREC (1988, Figure 6) hazards to children chart was selected to identify erosive (and thus potentially avulsive) areas on the four alluvial fan evaluation sites. The BUREC charts subdivide flood hazards into "high" and "low" categories, with an intermediate "judgment" zone between them, as shown in Figure 18. The boundaries of the BUREC hazard zones on the Tech Memo No. 11 figures were approximated using a polynomial function, and the resulting equations were applied to the FLO-2D output for each grid cell in the 100-year base model results for each alluvial fan evaluation site. The corresponding hazard zones were then determined for each cell from the function results (e.g. above or below the lines), and were plotted using ArcGIS. The results for each site are shown in Figure 19 to Figure 22.

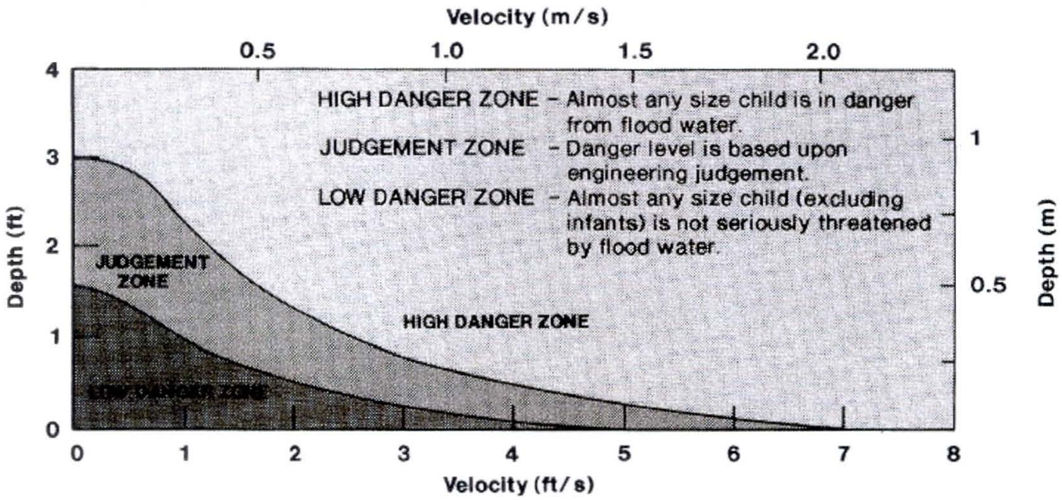
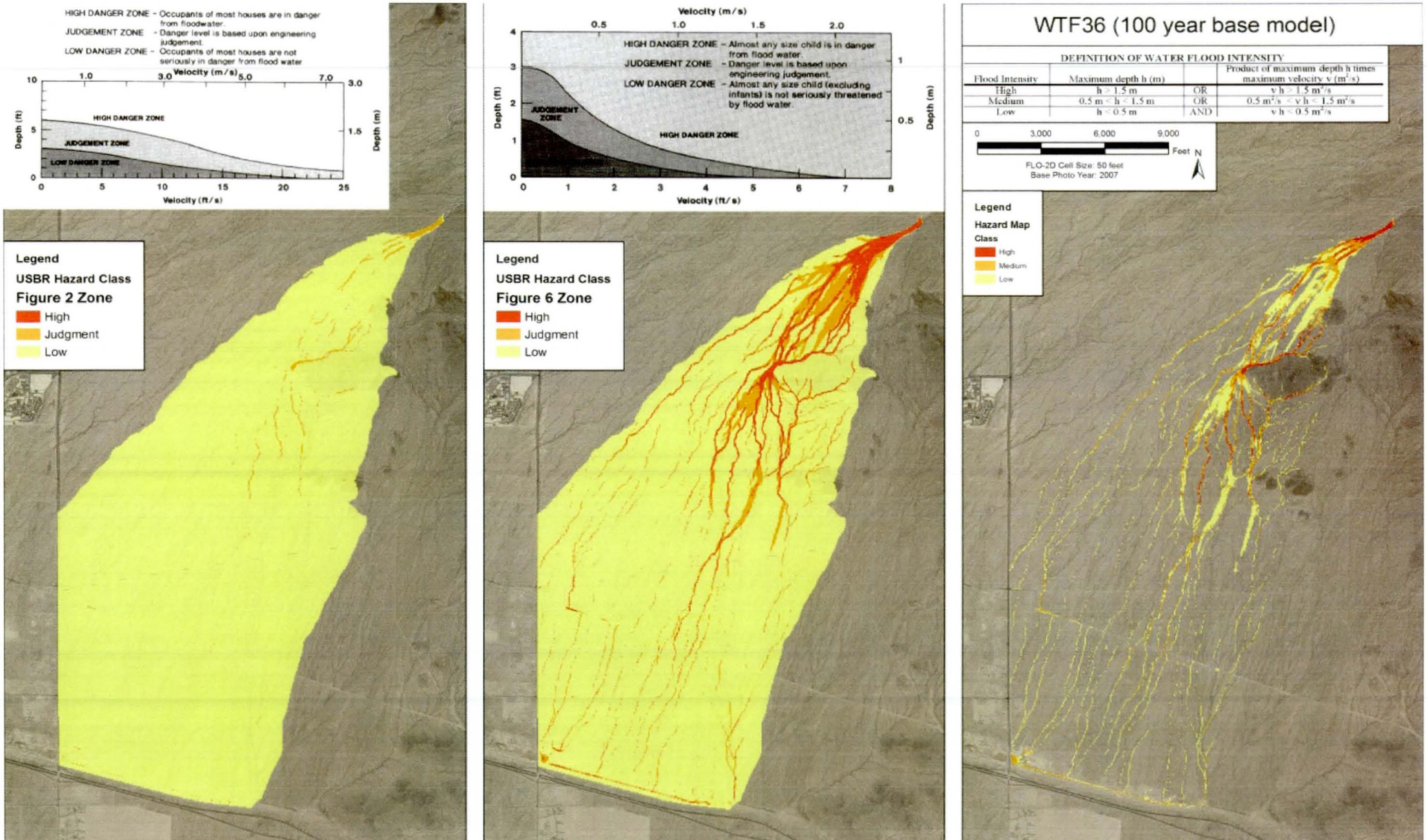


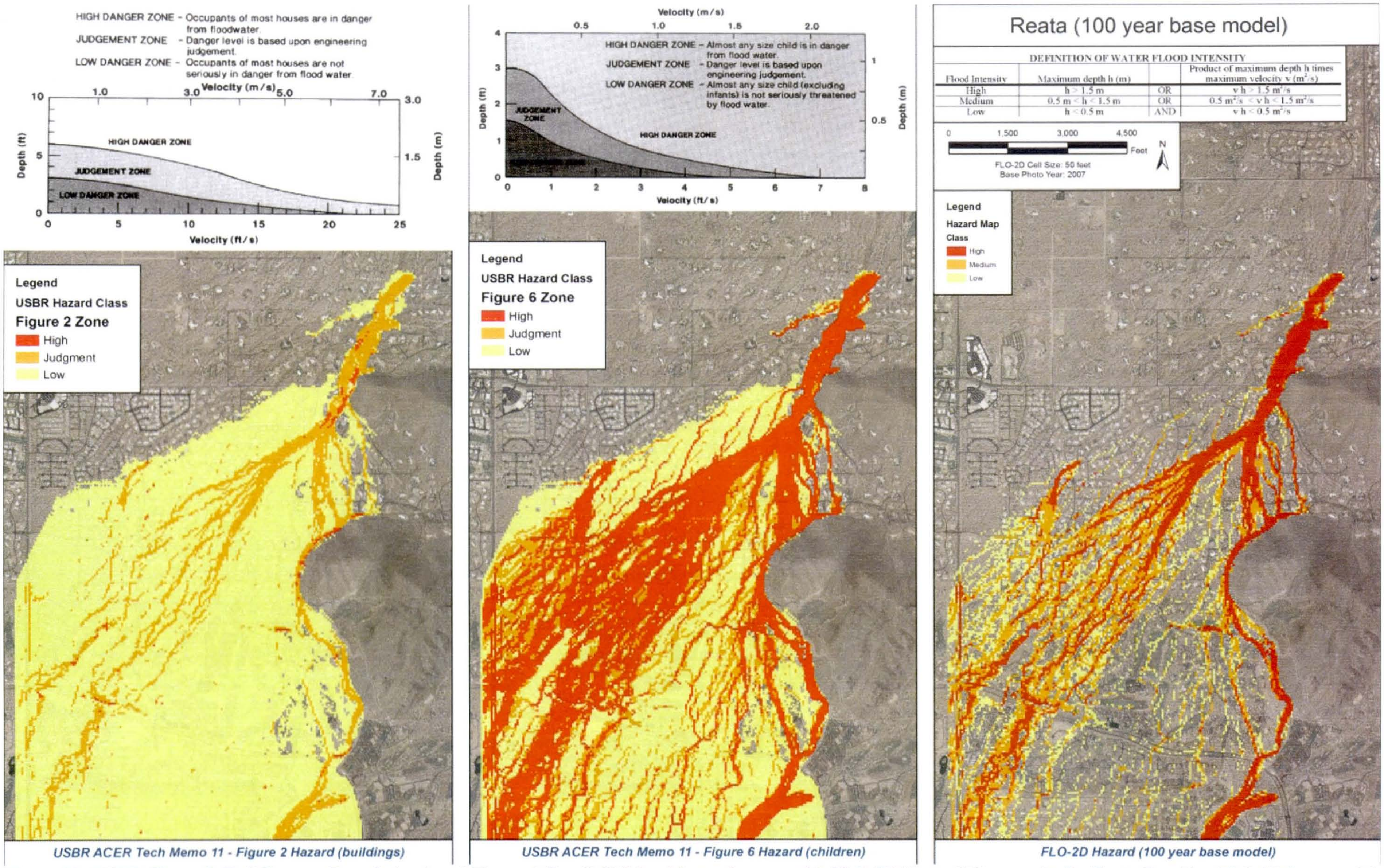
Figure 6. – Depth–velocity flood danger level relationship for children.

Figure 18. USBR ACER Tech Memo No. 11 Figur



USBR ACER Tech Memo 11 - Figure 2 Hazard (buildings) | *USBR ACER Tech Memo 11 - Figure 6 Hazard (children)* | *FLO-2D Hazard (100 year base model)*

Figure 19. USBR Figure 2 (Buildings on Foundations) and Figure 6 (Small Children) hazard zones, with FLO-2D Hazard Map results for White Tanks Fan 36 FLO-2D base model.



USBR ACER Tech Memo 11 - Figure 2 Hazard (buildings) | USBR ACER Tech Memo 11 - Figure 6 Hazard (children) | FLO-2D Hazard (100 year base model)

Figure 20. USBR Figure 2 (Buildings on Foundations) and Figure 6 (Small Children) hazard zones, with FLO-2D Hazard Map results for Reata Pass Fan FLO-2D base model

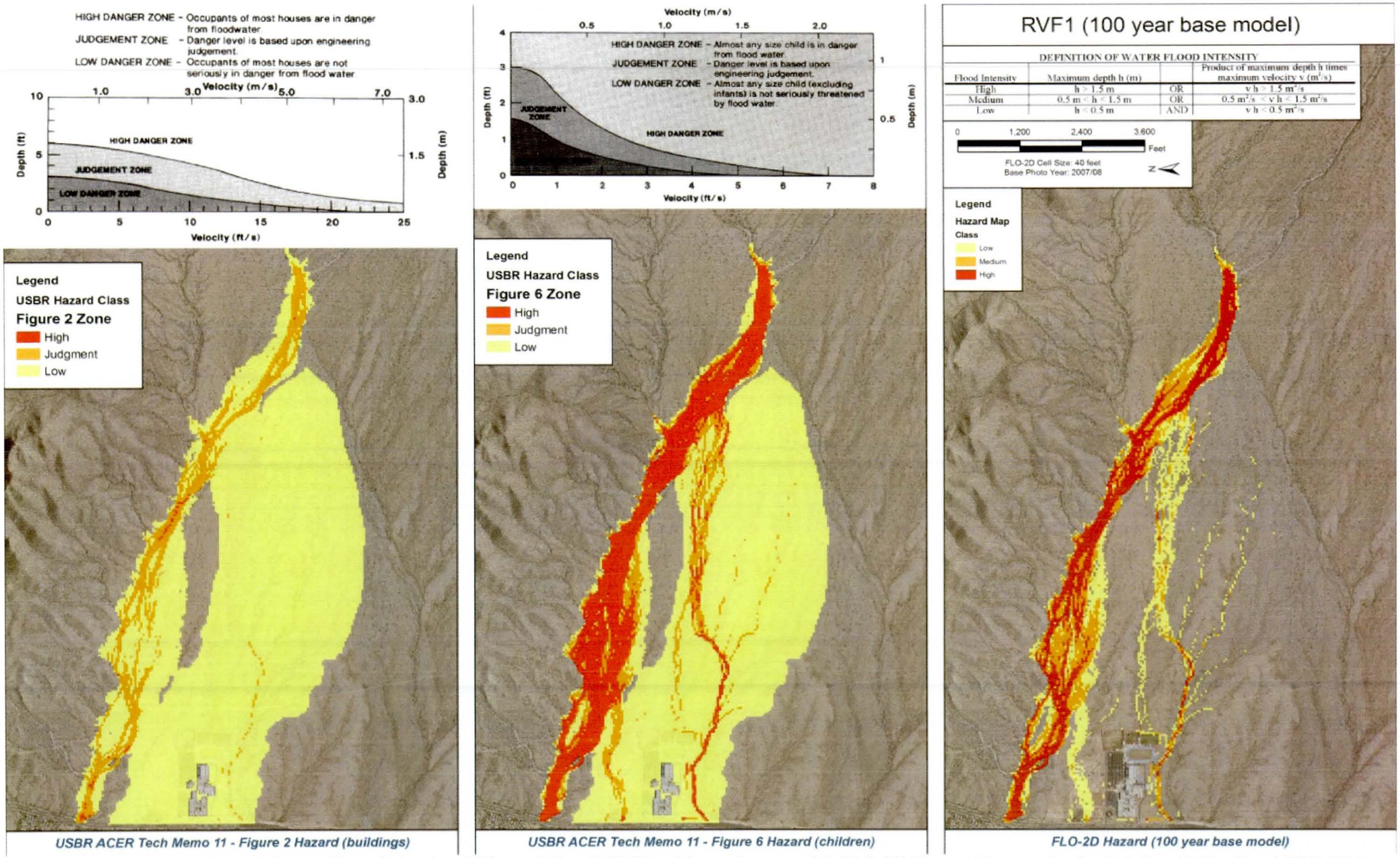
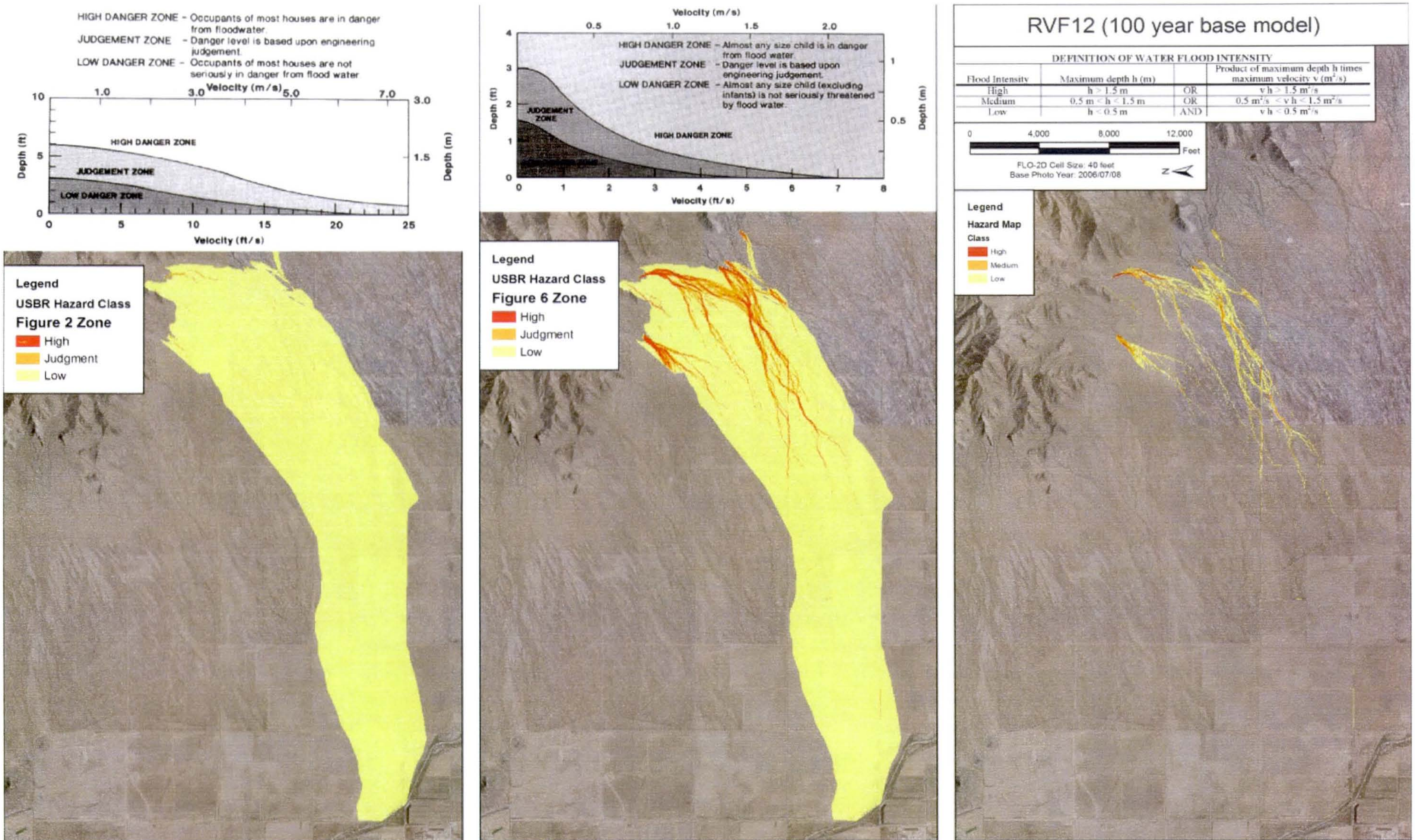


Figure 21. USBR Figure 2 (Buildings on Foundations) and Figure 6 (Small Children) hazard zones, with FLO-2D Hazard Map results for Rainbow Valley Fan 1 FLO-2D base model



USBR ACER Tech Memo 11 - Figure 2 Hazard (buildings)

USBR ACER Tech Memo 11 - Figure 6 Hazard (children)

FLO-2D Hazard (100 year base model)

Figure 22. USBR Figure 2 (Buildings on Foundations) and Figure 6 (Small Children) hazard zones, with FLO-2D Hazard Map results for Rainbow Valley Fan 12 FLO-2D base model.

The results of using the BUREC hazard classification charts yielded the following conclusions:

- This methodology of identifying potential avulsion corridors is similar to those summarized above, except that the BUREC method integrates both flow depth and velocity, and it assigns risk to pre-defined categories.
- Like the other avulsion identification methods used, there is a substantial difference in avulsion hazard between the WTF 36-RPF sites (high risk) and the RVF 12 site (low risk).
- The BUREC data indicate that the RPF site has the highest risk of avulsive conditions, probably due to the large 100-year discharge and steep fan slope.

Use of this method to identify potential avulsive flow corridors could be improved by integrating the results of multiple flow scenarios (frequency and virtual levee), and by overlaying the results on aerial photographs to identify zones that do not correspond to the existing channel network.

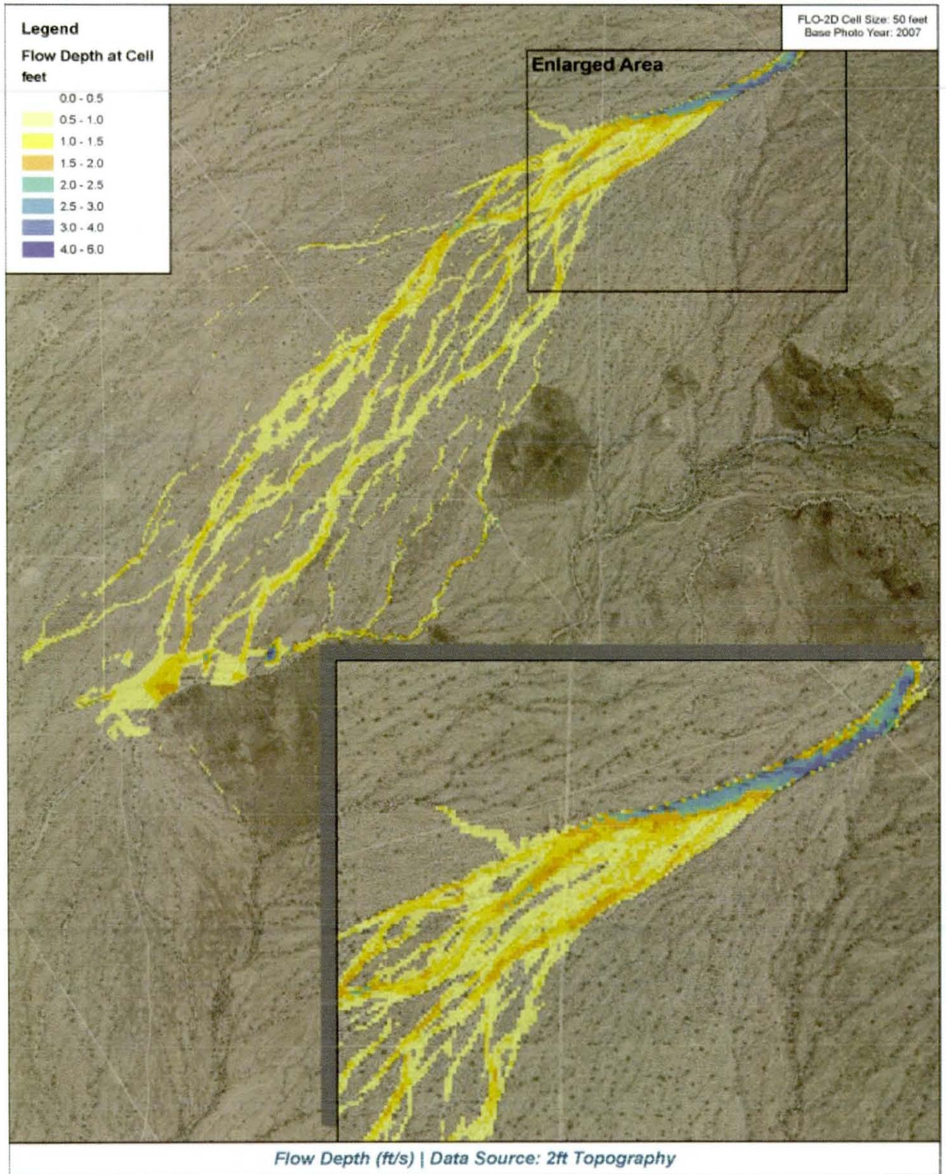
4.5.5. FLO-2D Channel Blockage Model

Attempts to simulate an alluvial fan avulsion using FLO-2D were made for the WTF 36 site. Because the occurrence of avulsions are related to loss of channel capacity and flow outside the existing channel network, the FLO-2D topographic data input file was manipulated to create a channel blockage that would force channel flow into the floodplain. Blockages were created at three places on the WTF 36 site.

The first blockage (Figure 23) was located on a gradual channel bend immediately downstream of the hydrographic apex, and consisted of a 600-foot long wedge of (simulated) sediment that completely filled the main channel to the elevation of the surrounding floodplain. The objective of the first blockage was to try to force flow onto an early Holocene surface which had a moderately well developed on-fan drainage network that drained away from the rest of the active alluvial fan. In this case, the obstruction did force a portion of the 100-year hydrograph onto the floodplain along a flow path that did not return to the active alluvial fan area. However, even with the main channel entirely blocked and filled, most of the 100-year flood hydrograph continued along the without-obstruction existing flow paths on the active alluvial fan surface.

The second blockage (Figure 24) was located in the most active part of the alluvial fan, at a bend in a well-defined channel, near what appeared to be either a developing or abandoned avulsive flow corridor. In this case, the FLO-2D modeling indicated that runoff simply bypassed the obstruction and continued along the pre-obstruction flow path with minimal changes in flow characteristics downstream. The second blockage was located well within the distributary channel network of the active fan, but in a reach where the individual flow paths were nearly parallel, rather than radiating outward. Lacking alternative flow paths that trended away from the parent channel, flow simply continued downstream parallel to the drainage pattern until it was recaptured by existing channels.

The third blockage (Figure 25), was located further downstream than the first and second blockages, in a reach of expanding distributary channels. This blockage consisted of an obstruction of infinite height oriented perpendicular to the primary flow direction, intended to prevent flow from moving directly downstream (i.e., the obstruction could not be overtopped). The FLO-2D modeling results show that flow mounded up along the upstream side of the obstruction until it could flow around it laterally, and then continued along the nearest existing distributary braids.



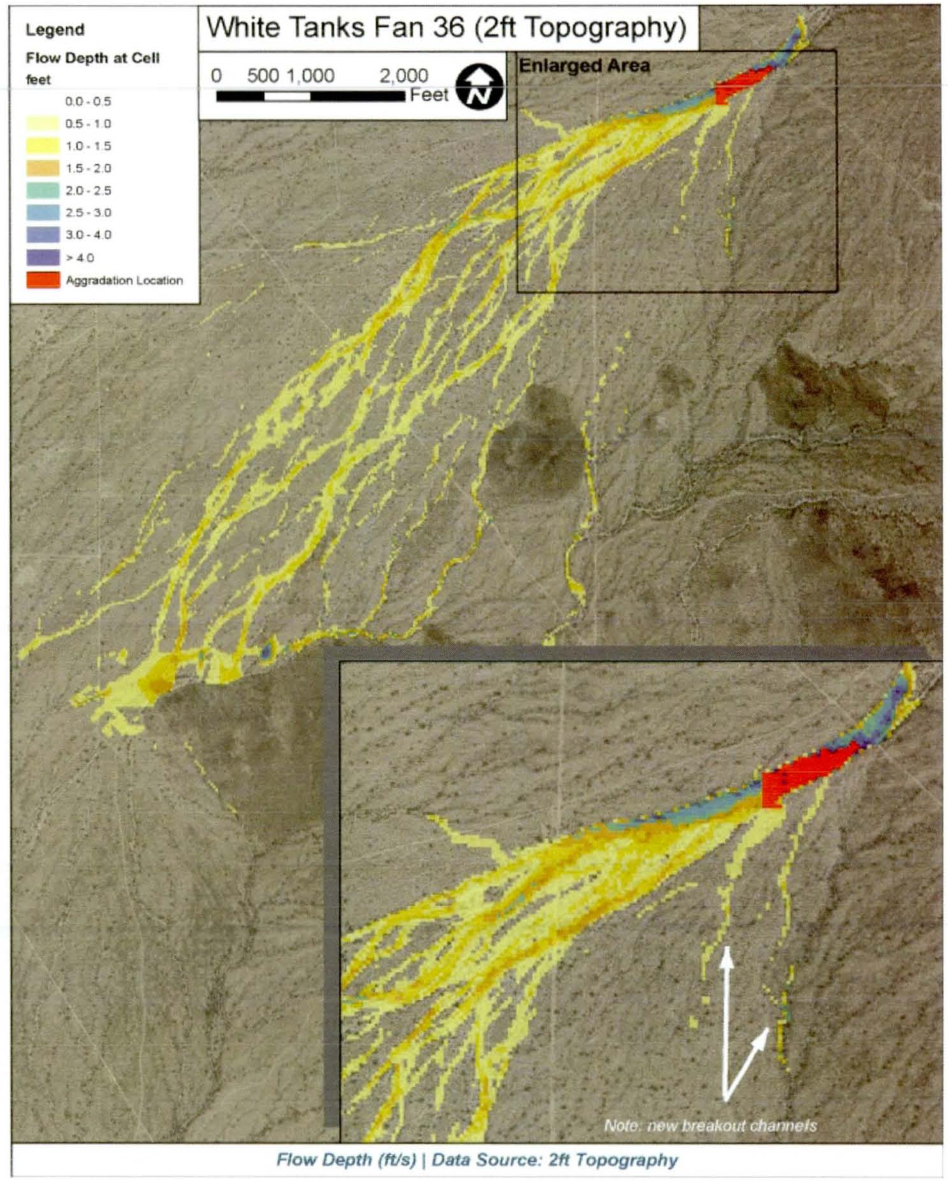


Figure 23. Channel blockage scenario #1 (apex area) for White Tanks Fan 36.

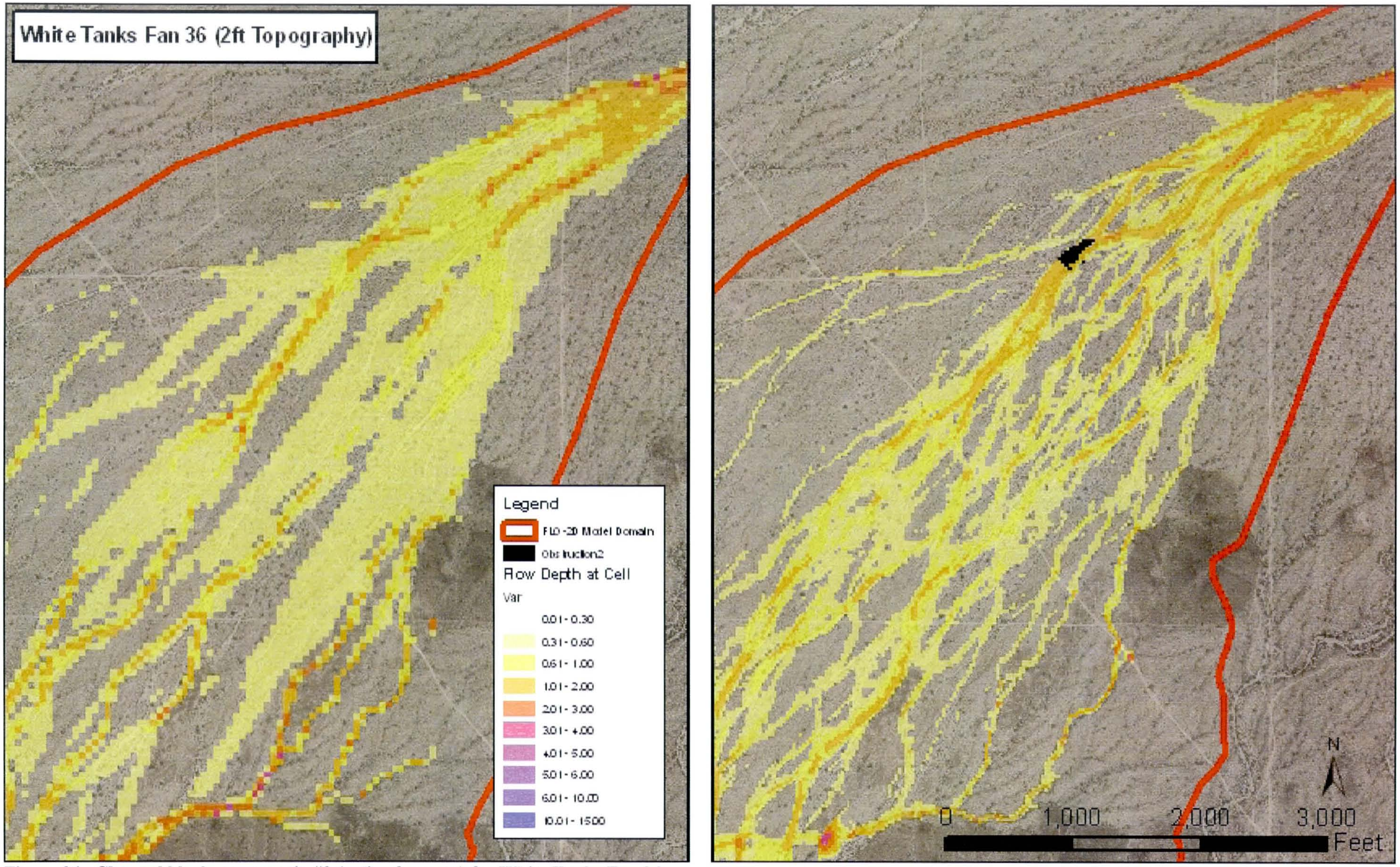


Figure 24. Channel blockage scenario #2 (active fan area) for White Tanks Fan 36.

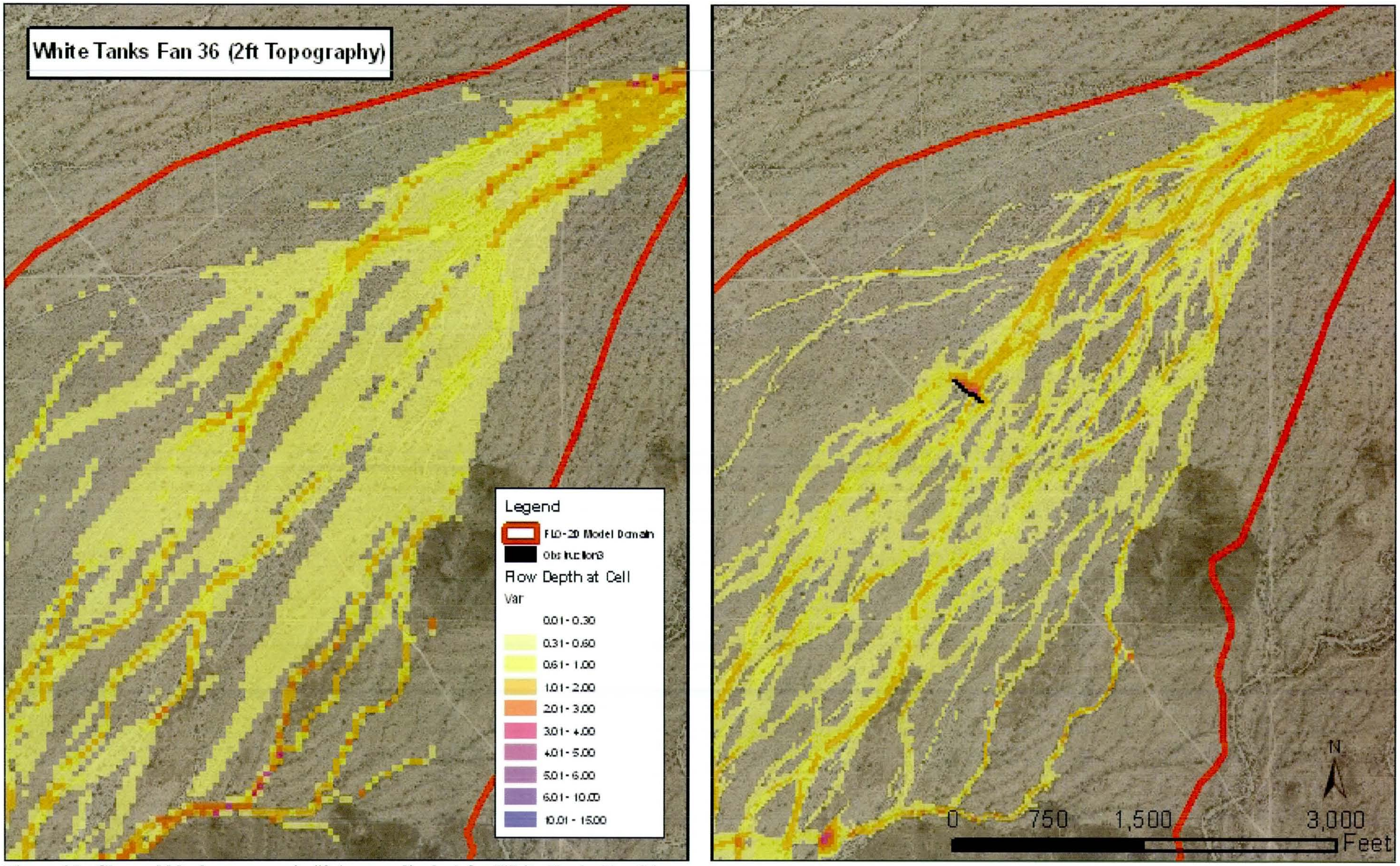


Figure 25. Channel blockage scenario #3 (perpendicular) for White Tanks Fan 36.

Based on the results of the scenarios described above, the channel blockage methodology is considered a useful technique for examining the possible impacts of channel obstructions at specific, well-defined locations. The methodology would be somewhat labor intensive if a modeler were to attempt to apply it regionally over a large active alluvial fan, since many model iterations would be required to consider every possible avulsion location. It may also be tentatively concluded from the modeling performed for the WTF 36 site that major avulsions are only likely where the flow diverted from the parent channel is diverted along flow paths that drain away from the pre-avulsive channel network. Channel obstructions due to debris blockage or sediment deposition within the lateral limits of the active distributary portion of the alluvial fan are unlikely to result in major avulsions.

4.5.6. FLO-2D Sediment Models

Two attempts to simulate long-term behavior leading to avulsions on active alluvial fans were made using FLO-2D. The first attempt consisted of probability-weighting the results of 2-, 10-, 50- and 100-year models and projecting the average annual result over a long planning period. Unfortunately, this approach resulted in predictions of unrealistically excessive scour and deposition in some locations (e.g., greater than 25 feet). Future use of this methodology may be possible if subroutines are developed to cull out unrealistic results through an area-weighting or local averaging procedure. The second attempt consisted of running a series of flood hydrographs back-to-back in the model. However, since the FLO-2D model processing time is already slowed considerably by inclusion of sediment transport modeling, the addition of even longer duration flows caused the model to slow to the point where it was no longer practical. As computers get faster in the future and the FLO-2D algorithm is improved, it is more likely that a two-dimensional modeling based approach can be used to predict long-term behaviors in addition to single event models. For the PFHAM study, the attempts to model surficial changes leading to alluvial fan avulsions using FLO-2D, were found to be unsuccessful and were abandoned in favor of the other methodologies discussed in this report.

Some of the FLO-2D sedimentation modeling results, summarized in other PFHAM study documents, which pertain to alluvial fan avulsion processes include the following:

- Differences From Water-Only FLO-2D Models. There were some differences in the predicted flow depths, velocities, and flood hazard zones between water-only and sediment transport FLO-2D models. The differences were generally most pronounced in the highly active areas immediately downstream of the hydrographic apexes, and were less significant elsewhere on the fan surfaces.
- Small Flood Trends. Since small floods tended to be completed absorbed by infiltration and attenuation, the entire sediment load from these events will be deposited on the inundated portion of the fan surface. Such deposition will tend to reduce channel capacity, induce overbank flooding, and result in overall aggradation, creating conditions potentially conducive to avulsions in subsequent floods.

- Scale of Analysis. FLO-2D sediment model results appear more reasonable when viewed as a large-scale composite of fan behavior, rather than on a single-grid basis.

4.5.7. Topographic Analysis: Avulsive Flow Path Tool

For a fully-developed channel avulsion to occur, flow leaving the parent channel must become and remain hydraulically separated from the parent channel for some measurable distance. In the case where the fan surface elevations and slope are not drastically altered during a flood, the only way a hydraulically separate flow path can exist is if the local ground slope and topography convey flow away from the parent channel. On an idealized alluvial fan with perfectly smooth radial contours, any flow escaping the parent channel would not return since the steepest flow path would be perpendicular to the contours. On many real-world alluvial fans, especially the low-sloping fans in Maricopa County, on-fan incipient drainage networks, distributary channels, and other topographic features tend to capture overbank flows and return them to the parent channel network. Nevertheless, given that avulsions are known to occur on alluvial fans in Maricopa County, it was assumed that some avulsive flow paths must exist on local alluvial fans that would direct runoff away from the parent channel network.

An avulsive flow path tool was developed to identify potential overbank flow paths that could serve as avulsive flow corridors. Two variations of the avulsive flow path tool were developed. The more complex version of the tool uses FLO-2D velocity data over the fan surface grid to identify probable flow paths. A computationally similar, but simpler version uses just topographic data, eliminating the need for running the FLO-2D model. For the purpose of this analysis, the FLO-2D modeling grid was used in both model variations as an input to the avulsive flow path tool. Potential locations of flow bifurcations (initiation points for avulsions), such as significant bends in the main parent channel or reaches of limited or diminishing conveyance capacity, were identified using aerial photography, topographic mapping, and field observations. These identified bifurcation points served as the starting point for the avulsive flow path tool computations. The avulsive flow path tool then uses an iterative process, and moves in the downstream direction following the steepest ground slope or largest velocity vector direction obtained from the topographic mapping or previous FLO-2D modeling results. The steepest slope in the eight directions between adjacent grids was estimated using the cell elevations in the FLO-2D topographic data file. The velocity vector direction was obtained from the PMP FLO-2D model run results. The PMP FLO-2D run was used because it provided velocities at the greatest number of cells, i.e., more cells are inundated by the PMP discharge than for smaller floods. Using the directions from steepest slope and velocity distributions, the potential flow paths were tracked from one grid cell to another cell in the downstream direction. These flow paths were then drawn pictorially on top of aerial photography to visualize the potential avulsive paths, as shown in Figure 26.

Once the avulsive flow path model results were overlain on a recent aerial photograph and compared to the existing network of defined channels on the alluvial fan surface, the avulsive flow path model flow paths could be grouped in the following categories:

- Flow along existing defined channels (non-avulsive)
- Flow paths that immediately re-joined existing channel (non-avulsive)
- Flow paths that do not overlie existing channels or rejoin the existing channel network (avulsive)

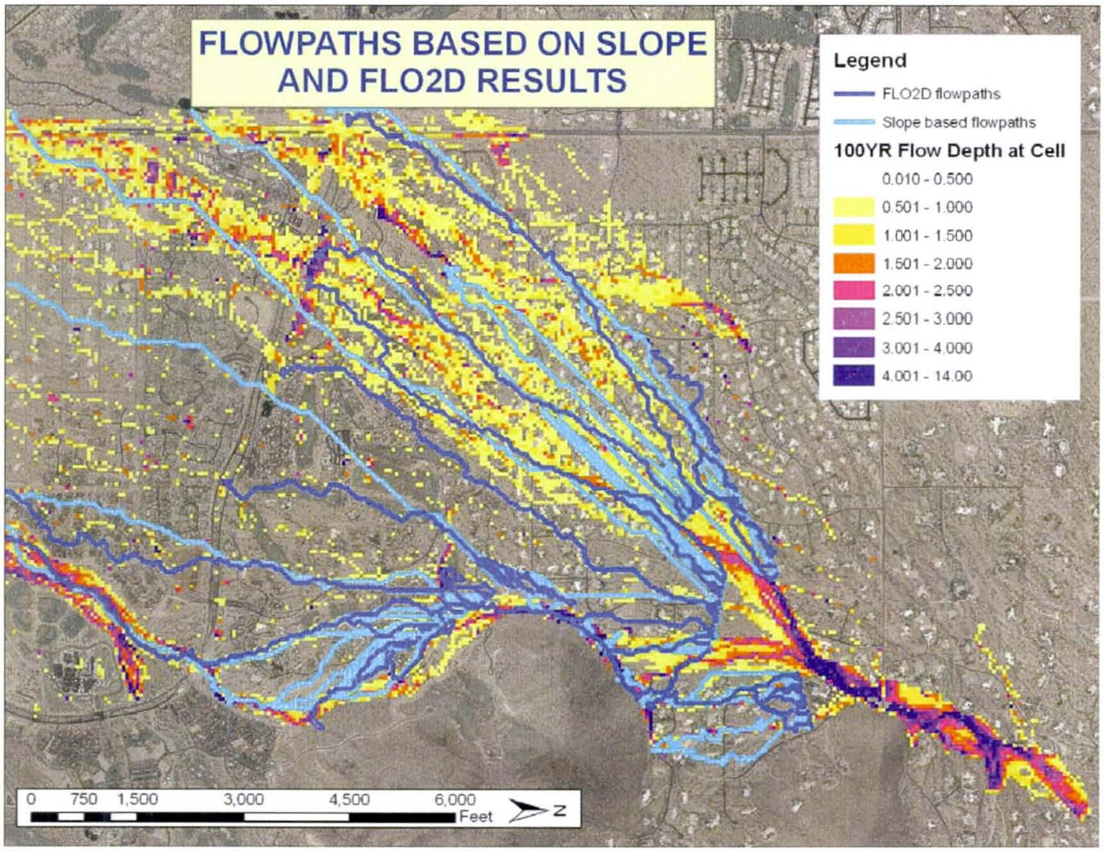


Figure 26. Avulsive flow path tool results for the Reata Pass Fan

The avulsive flow path tool was applied to the Reata Pass Fan (Figure 26). Several key potential avulsive flow paths were identified by the avulsive flow path tool as shown in Figure 27. If flow leaves the parent channel at the possible bifurcation points, and sufficient flow volume leaves the main channel, formation of a new channel is possible along the identified alignment.

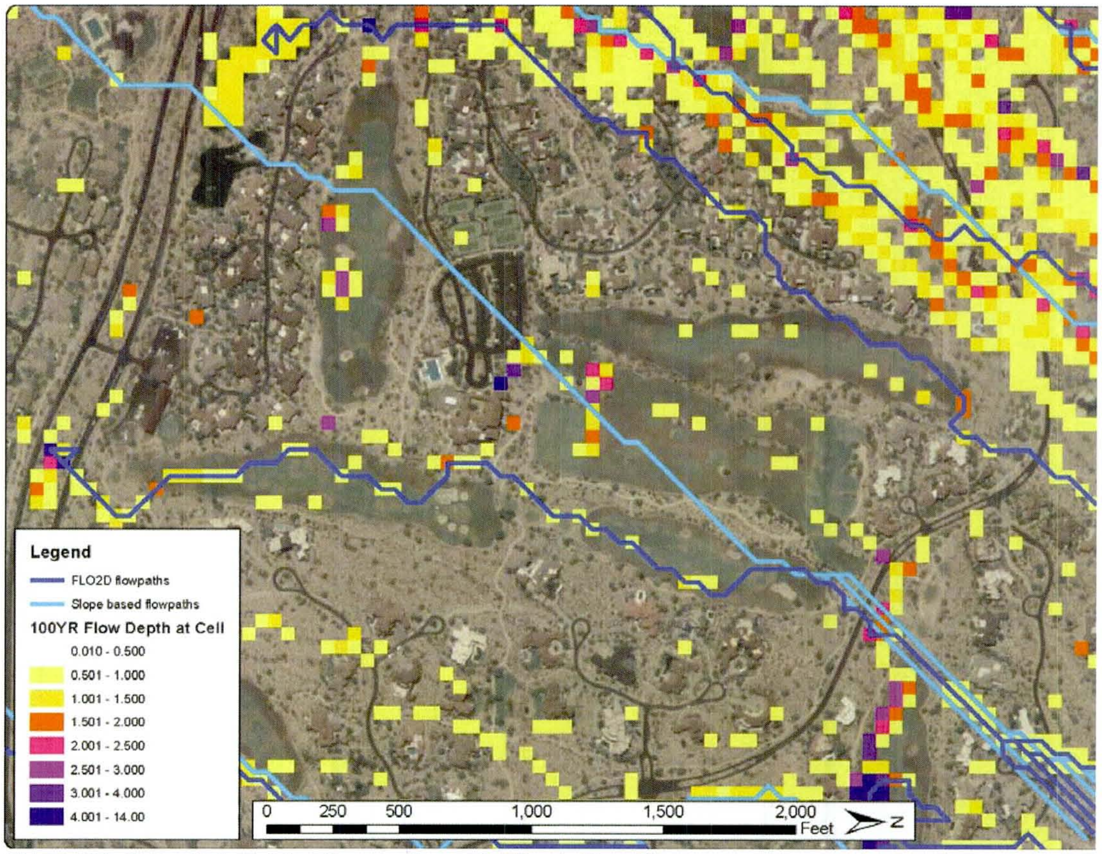


Figure 27. Potential avulsive flow paths on the Reata Pass Fan.

The avulsive flow path tool provides a quick method of analyzing the potential avulsive flow paths and their impacts. For example, if the avulsive flow path model flow path quickly merges back to the parent channel, the risk of avulsion is probably low and would not significantly impact the overall flow distribution on the fan surface. The degree of avulsion hazard may differ depending on the land use, development density, location of flood control structures, discharge peak, volume and duration, soils, and vegetative cover along the potentially avulsive flow path. The avulsive flow path tool may be most applicable as a quick way to identify possible avulsion locations, or as a trigger for additional more sophisticated analyses of the avulsion potential.

4.5.8. Verification: Hindcast of White Tank Fan 36 1951 Flood Avulsions

Large floods occurred at the WTF 36 site in 1951 (JEF, 1999). There is good correlation between the inundation areas visible on the 1953 aerials and the FLO-2D base model results (Figure 28), indicating that the overall topography of the WTF 36 site has probably not changed significantly since the 1951 flood. However, there are a number of differences between the 1951 and FLO-2D base model inundation areas. First, there are several readily identified channels visible on the 1953 aerials that are not shown as flooded in either the 100- or 500-year FLO-2D results. These channels have either aggraded since they were exploited in the 1951 flood, or other parts of the fan surface have changed sufficiently to re-direct flow away from them.[8] Second, some avulsive flow corridors along the northern margin of the active fan area near the hydrographic apex identified from the FLO-2D modeling results do not appear to have been inundated during the 1951 flood. These potential avulsion corridors picked up by the FLO-2D model either did not exist as topographic lows in 1951 or changes in ground elevations near the apex since 1951 now direct flow towards them. Third, avulsions in the distal portion of WTF 36 occurred in areas shown by FLO-2D modeling to have extremely low flow depths and velocities. Finally, it is known that the 1951 event flooded portions of the Town of Buckeye and was one of the reasons for construction of the Buckeye FRS#1. However, the FLO-2D base models indicate that relatively little flow reaches the Buckeye FRS. Therefore, either the 1951 event was larger than a 100-year event, other sources contributed to the flooding in Buckeye, and/or the FLO-2D model is over-estimating losses on the fan surface. Given the results of the multiple channel modeling, it is likely that at least part of the difference is due to over-estimated losses in the FLO-2D base models.

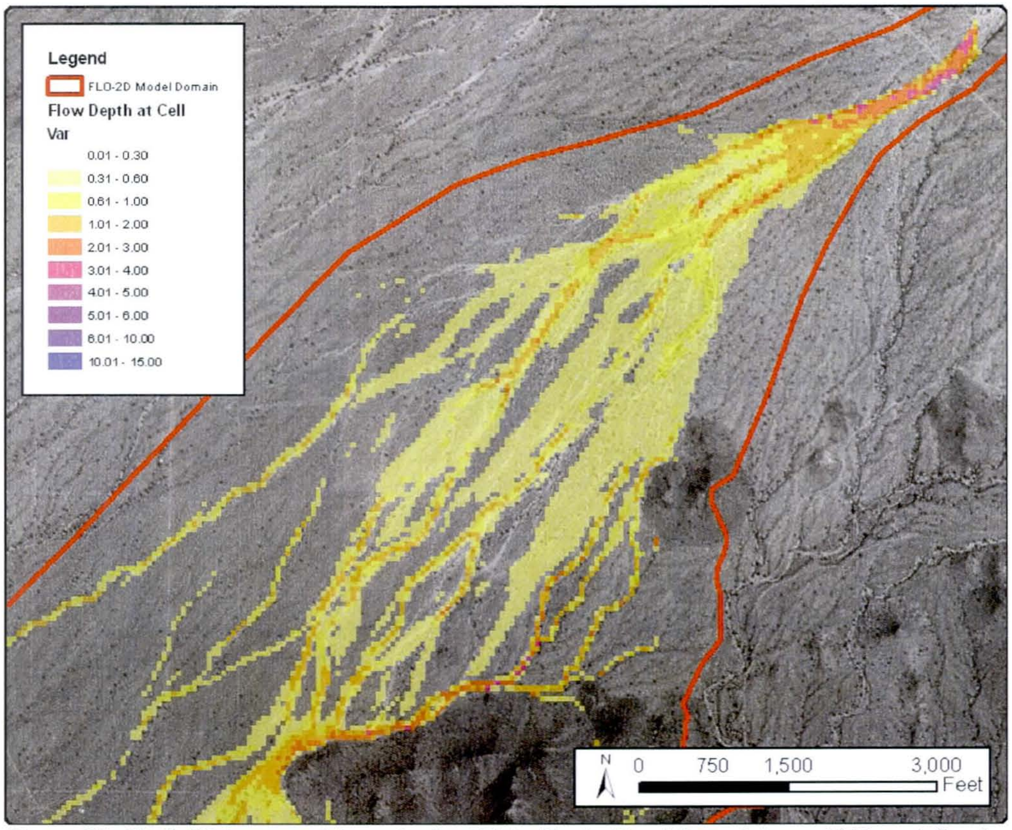


Figure 28. FLO-2D base model results for White Tanks Fan 36 overlain on 1953 post-flood aerial.

4.5.9. Verification: Hindcast of Tiger Wash 1997 Flood Avulsions

The 1997 Hurricane Nora flood on Tiger Wash resulted in at least two major channel avulsions as well as inundation of significant portions of the alluvial fan surface. To

[8] Topographic map accuracy or model grid cell size may also be factors.

attempt to hindcast the occurrence and locations of the 1997 avulsions, FLO-2D models were also prepared using pre-1997 topographic mapping and the 1997 flood hydrograph estimated by Pearthree et. al. (2004), a 100-year inflow hydrograph, a 500-year inflow hydrograph, and a hydrograph based on PMP rainfall. As shown in Figure 29, the FLO-2D results do not clearly predict the location of the 1997 avulsions. For the estimated 1997 hydrograph, the FLO-2D results indicate that the areas where avulsions occurred were inundated by flows less than 0.3 feet deep. Even for a mega-flood discharge like the PMP event, the FLO-2D results did not predict highly erosive flow depths and velocities along the avulsion alignments. Unfortunately, the poor quality[9] of the only available pre-1997 topographic mapping makes it impossible to draw firm conclusions about the ability of FLO-2D to predict alluvial fan avulsions.

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[9] The only available pre-1997 topography was a USGS 10 meter DEM from circa 1951.

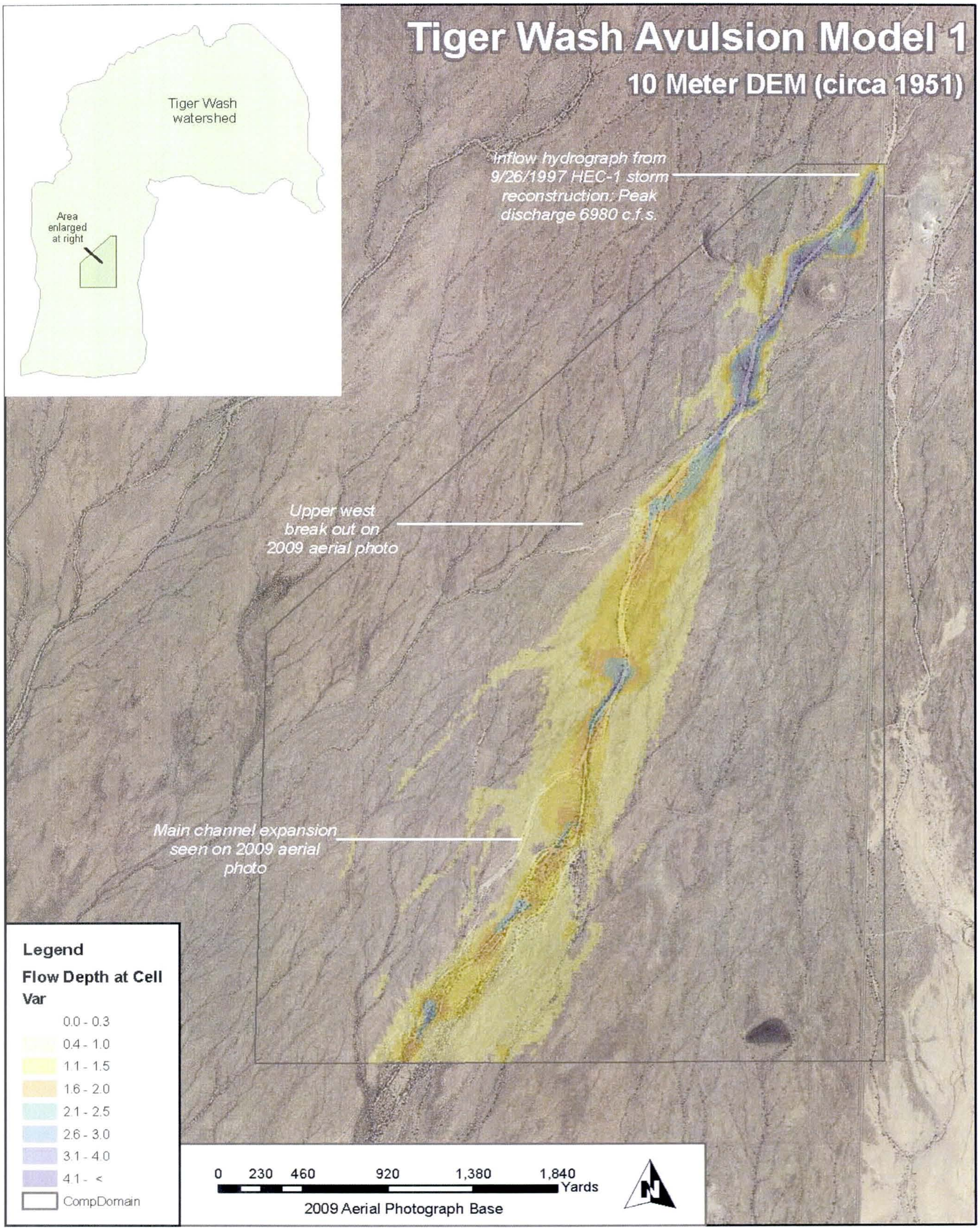

Figure 29. FLO-2D base model results for Tiger Wash Fan overlain on 2007-post-flood aerial.

4.5.10. FLO-2D Virtual Levee Scenarios

The "virtual levee scenario" methodology was originally developed to evaluate the hydrologic impacts of avulsions on concentration points below the apex of an active alluvial fan (JEF, 2009). The virtual levee scenario methodology is described in detail in the final report for the PFHAM study (JEF, 2010). It is important to note that the virtual levee scenario methodology does not explicitly model the mechanics of an alluvial fan avulsion. Instead, it assumes that an avulsion can occur within a user-identified part of the active alluvial fan, that the avulsion will redirect runoff across that portion of fan surface in a manner that only partially reflects the pre-flood topography, and that flow will be conveyed over the non-avulsive part of the fan surface as directed by the surface characteristics and topography. The portion of the active alluvial fan that is subject to potential avulsions is identified by a composite method of FLO-2D modeling, geomorphic landform interpretation, and other techniques described elsewhere in the PFHAM report documentation.

While the virtual levee scenario methodology does not itself predict the occurrence or character of alluvial fan avulsions, plots of FLO-2D modeling results achieved by applying the virtual levee scenario methodology elucidate the possible changes in flow depth and other hydraulic variables (velocity, stream power, etc.) downstream of an avulsion on an active alluvial fan, as shown in
Figure 30 to Figure 33. These results indicate that while changes in upstream flow paths (i.e., avulsions) could create changes in flow hydraulics that could also produce minor avulsions in the mid- and lower portions of an active fan, in most cases avulsions near the fan's hydrographic apex have little impact on the predicted flow depths, velocities, and areas of inundation in the mid- to distal-portions of the active alluvial fan. A historically documented example of a minor mid-fan avulsion on the White Tank Fan 36 site was discussed in Section 2.4.2 and shown in Figure 4.

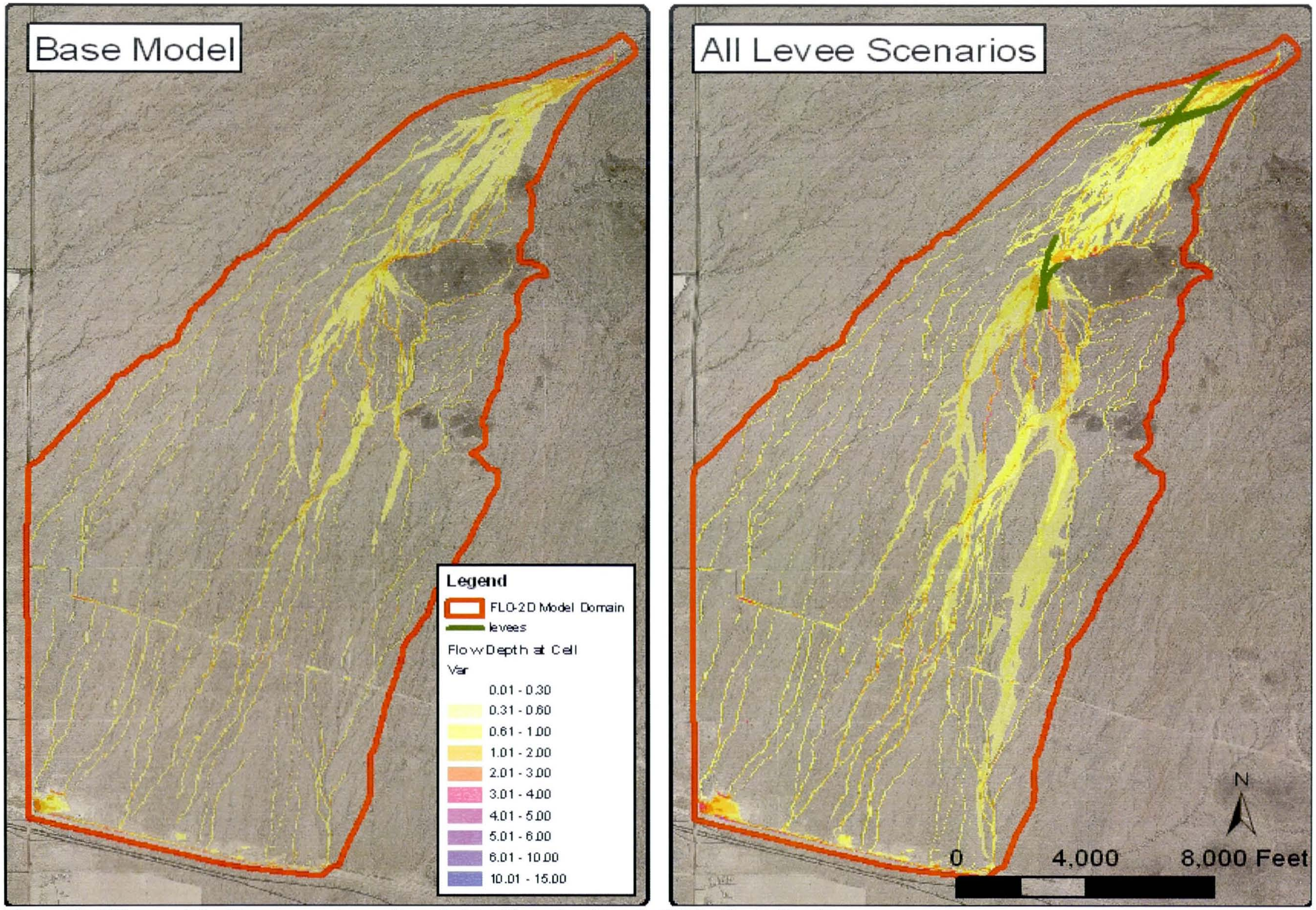

Figure 30. 100-year virtual levee scenario results and virtual levee locations for White Tanks Fan 36

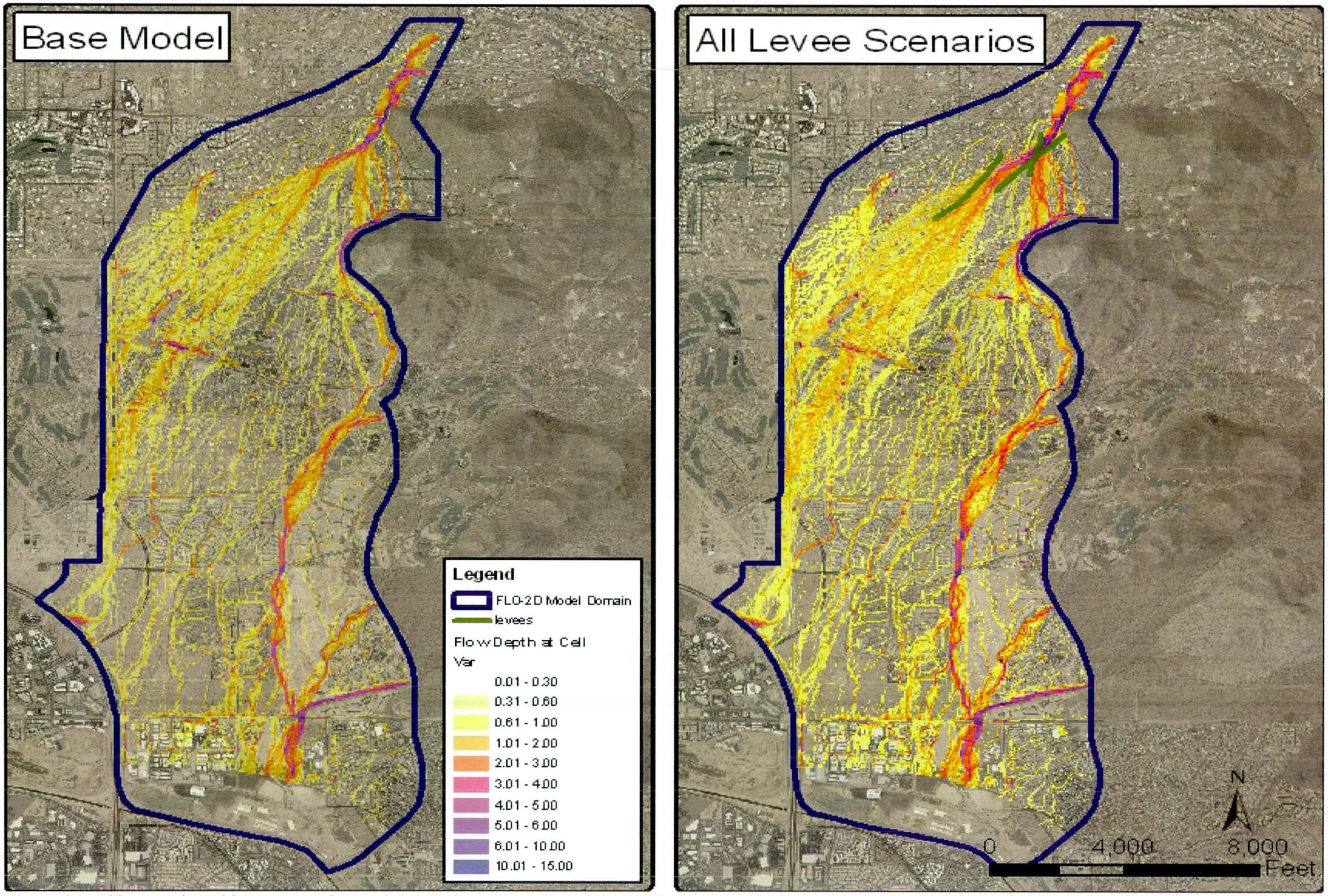

Figure 31. 100-year virtual levee scenario results and virtual levee locations for Reata Pass Fan.

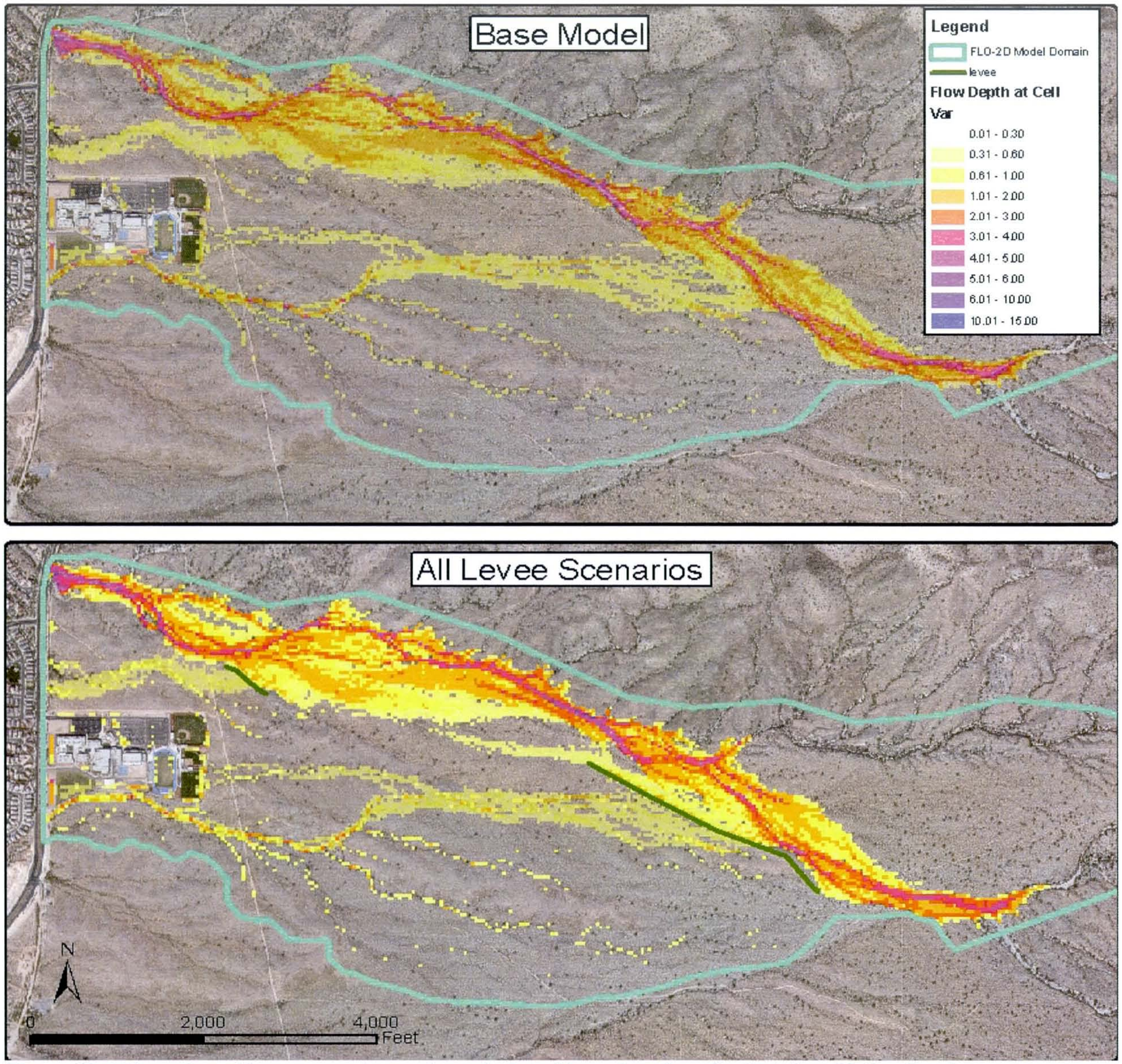

Figure 32. 100-yr virtual levee scenario results and virtual levee locations for Rainbow Valley Fan 1.

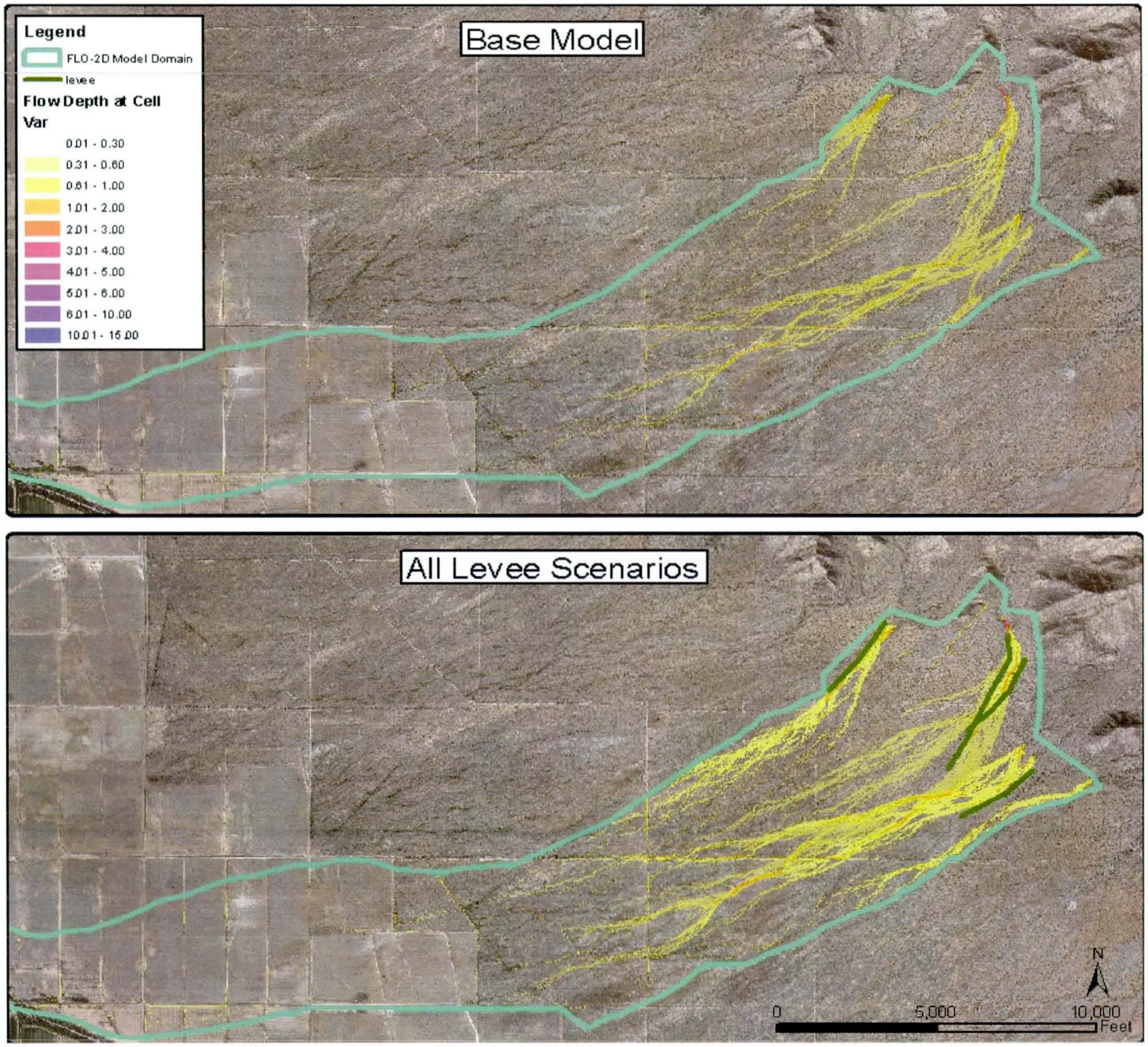

Figure 33. 100-yr virtual levee scenario results and virtual levee locations for Rainbow Valley Fan 12.

4.5.11. Other Potential Methodologies

It is likely that new techniques for identifying and modeling alluvial fan avulsions will be developed in the future. Some of the more promising techniques include those being developed by Parker et. al. (1998), application of riverine avulsion equations (c.f., Tornqvist, 2004), or physical modeling. FLO-2D evaluation of higher frequency floods, such as a 10-year event, using the techniques outlined above also might be useful for identifying the most likely avulsion locations.

4.6. Knowledge Gaps

Review of the literature regarding alluvial fan avulsions identified the following three primary gaps in the knowledge base required to develop a robust methodology for quantifying alluvial fan flood hazards in Maricopa County:

- Avulsion Frequency. As indicated below, there are several lines of evidence that suggest that avulsion on fans in Maricopa County are rare (Field, 1994). Physical model studies which indicate avulsions are common events (Schumm et. al., 1987) may be misleading due to model scaling issues (Whipple et. al, 1998). However, to date there has been no definitive analysis of avulsion frequency or recurrence interval, in Maricopa County or elsewhere.

  Recommendation: The District should conduct a study of avulsion frequency on active alluvial fans in Maricopa County.

- Modeling Methodology. Identifying past channel avulsions is a rather simple task of observation and documentation. The causative factors leading to avulsions are relatively well known. Several authors have speculated that they may be able to predict likely locations of some avulsions (Field, 2001), but there is currently no accepted method for quantifying such predictions.

  Recommendation: The District should adopt the recommended approach presented Section 5 below as a first step toward developing a standard methodology for predicting avulsion potential. Recommended subsequent steps include testing the methodology on alluvial fans in Maricopa County, and vetting the methodology with FEMA reviewers and other communities with alluvial fan flooding concerns.

- Engineering Design Standards. Short of designing structures for the full apex discharge and hydraulic conditions, or the "virtual levee" methodology recently developed and applied to Fans 1-2 in Maricopa County (Fuller, 2009), the standard of practice for design of structures on alluvial fans has not yet been defined.

  Recommendation: The District should include engineering and design guidelines for development on active alluvial fans in the updated PFHAM.

5. Recommended Methodology

Based on the results of the analyses and information summarized above, the recommended procedure for evaluating the potential for avulsions on active alluvial fans in Maricopa County consists of the following steps:

- Step One: Historical Analysis. The most reliable means of determining if an alluvial fan is subject to avulsions is to identify evidence of historically recent avulsions. Documentation of past avulsions can be completed by comparing channel locations and conditions on historical and recent (or pre- and post-flood) aerial photographs. In addition to the presence of historical avulsion, the extent, location on the fan surface, and type of avulsions should be described and related to the flood history.

- Step Two: Geomorphic Analysis. An evaluation of the surficial geology of the alluvial fan should be conducted that includes field observations, surficial mapping of active and inactive surfaces, and assessment of debris flow potential. If possible, the geomorphic analysis should include interpretation of stratigraphic data from subsurface soil profiles to estimate fan aggradation rates and occurrence of channel sediments outside the existing channel corridors. If the potential exists for debris flows to impact that active fan surface, then a detailed debris flow analysis should conducted using the procedures outlined elsewhere in the PFHAM report documentation, prior to proceeding to Step Three.

- Step Three: FLO-2D Modeling. FLO-2D models of the fan surface from the hydrographic apex to the downstream limit of the active alluvial fan should be prepared. At minimum, FLO-2D models for the 100-year base condition and a 500-year "mega-flood" should be prepared. Potentially avulsive flow corridors can be identified by overlaying 100- and 500-year FLO-2D flow depths and velocities, and hazard classification zones over a recent aerial photograph and identifying disparities from the existing channel network. Avulsions should be expected within the high hazard classification zones. For specific sites where concerns about avulsion exist, channel blockage FLO-2D models can be prepared to estimate overflow frequency and behavior. Finally, FLO-2D modeling results should be used to prepare a avulsive flow path model analysis to identify potential avulsive flow paths.

- Step Four: Sediment Modeling. The sediment yield at the hydrographic apex should be computed and used to estimate potential deposition along the fanhead channel. The sediment yield values should be used to help identify the location of the hydrographic apex as the point where flow is no longer contained in a single channel, and where alluvial fan flooding begins. At some point in the future, improvements in sediment transport modeling tools for alluvial fans may progress to the point such modeling will improve our ability to predict alluvial fan avulsions. Until such time, detailed sediment transport modeling of the alluvial fan downstream of the hydrographic apex is not recommended as part of the recommended avulsion prediction methodology.

- Step Five: Floodplain Delineation. The potential for future avulsions should be considered when delineating an active alluvial fan floodplain. To this end, the virtual levee scenario method results should be incorporated into the predicted inundation limits.

6. Conclusions

The objective of the avulsion potential evaluation was to determine and quantify how channel avulsions influence flood hazards on alluvial fan landforms in Maricopa County. This information is to be used to refine the Integrated Alluvial Fan Hazard Assessment Methodology that may be used in future revisions of the District PFHAM methodology. The following conclusions can be made from the evaluation summarized in this report:

- Avulsions Occur on Alluvial Fans in Maricopa County. The occurrence of past alluvial fan avulsions is well documented in the literature, by past District studies, and by aerial photographs.

- Avulsion Frequency. The frequency of avulsions on alluvial fans in Maricopa County is not well known, although it is likely that avulsions are relatively rare events. A systematic study of avulsion frequency is strongly recommended.

- Avulsions Affect Flood Hazards on Alluvial Fans. When avulsions occur, they change the distribution of flood peaks and volumes downstream, lead to extensive erosion of the fan surface, and redistribute areas of sediment deposition. Consideration of avulsion impacts should be included in any revisions of the District's PFHAM methodology.

- Methodology. There is no broadly accepted technique for identifying and predicting the location or nature of future avulsions. A five-step methodology for use on alluvial fans in Maricopa County has been proposed as part of this study.

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Appendix J:
Blue Ribbon Panel Review Summary

PFHAM Blue Ribbon Panel Meeting Summary

Overview

The scope of services for FCD2008C007, Work Assignment #1 authorized formation of an independent panel to review the study recommendations. The independent panel was called a "Blue Ribbon Panel." The scope language is cited below:

> *1.6.1 <u>Independent Panel Review Meeting</u>. - The CONSULTANT shall develop an invitee list, invite, host and conduct a meeting to critically review the draft finding and recommendations of this study. The independent panel review meeting shall replace one of the bi-monthly progress meetings. The independent panel review meeting shall be ½ day in duration (4 hrs). The CONSULTANT will provide a neutral facilitator for this meeting.*

The Blue Ribbon Panel meeting was held at the Flood Control District of Maricopa County on June 2-3, 2010. The meeting was facilitated by District staff. The Blue Ribbon Panel consisted of experts from a variety of disciplines associated with alluvial fan flood hazard assessment. Information on the panel members is provided in Table 1.

The Blue Ribbon Panel meeting format consisted of the following elements:

- Day One (June 2, 11:00-5:00 pm)
  - Introductions & overview (District)
  - Presentation of Study Findings (Fuller)
  - Presentation of Seed Questions (Fuller)
  - Open Discussion of Seed Questions (Facilitated by District)
  - Optional Evening Discussion Session
- Day Two (June 3, 8:00-5:00 pm)
  - Open Discussion – Day One Follow-Up (Facilitated by District)
  - Small Group Discussions of Seed Questions (Panel Members)
  - Presentation of Small Group Findings to Panel Members
  - Presentation of Recommendations to District Staff
  - District Question and Answer Period

This meeting summary consists of the following elements:

- Summary of Panel Member Information (Table 1)
- Summary of Panel's Key Findings (Table 2)
- Summary of Panel's Concerns (Table 3)
- Recommendations for Additional Study (Table 4)
- Attachments:
  - List of Seed Questions Considered by Blue Ribbon Panel
  - Seed Question Response Forms (Findings)
  - Meeting Notes by Individuals
  - Written Comments by Blue Ribbon Panel Members

Table 1. Blue Ribbon Panel Member Information					
Name	**Affiliation**	**Discipline**	**Expertise**	**Home Area**	**Role**
Bill Bull, PhD	University of Arizona Dept of Geosciences, Retired	Geologist	Alluvial fans Tectonics & Climate	Tucson, AZ	Attended Panel
Bob Mussetter, PhD, PE	Tetratech, Inc Principal	Engineer	Sedimentation Hydraulics	Ft. Collins, CO	Attended Panel
Doug Hamilton, PE	Exponent, Inc. Engineer	Engineer	Hydraulics NRC Panel Member	Los Angeles, CA	Attended Panel
Dusty Williams, PE	Riverside Co. Flood Control Chief Engineer	Engineer	Flood Control AFTF Member	Riverside, CA	Attended Panel
Ed Curtis, PE	FEMA Region 9 Engineer	Engineer	FEMA Policy	Arizona-Nevada	Attended Panel
Jeremy Lancaster, RG	California Geological Survey Geologist	Geologist	California geology AFTF Member	Los Angeles, CA	Attended Panel
Joe Kuechenmeister, PE	Michael Baker, Inc (FEMA review)	Engineer	FEMA Policy Floodplain delineation	Denver, CO	Attended Panel
Kyle House, PhD	University of Nevada Reno Nevada Bureau Geology	Geologist	Alluvial fan mapping Mega-floods	Reno, NV	Attended Panel
Phil Pearthree, PhD	Arizona Geological Survey Research Geologist	Geologist	Arizona geology Arizona natural hazards	Tucson, AZ	Attended Panel
Ricardo Pineda, PE	CA Dept Water Resources Chief, Floodplain Management	Engineer	Floodplain management AFTF Member	Sacramento, CA	Attended Panel
Richard French, PhD, PE	University Texas – San Antonio Professor	Engineer	Hydraulics Sedimentation Alluvial fan flooding	San Antonio, TX	Attended Panel
Roger Hooke, PhD	University of Maine Orono	Geologist	Alluvial fans Physical modeling	Deer Isle, ME	Attended Panel
Vic Baker, PhD	University of Arizona	Geologist/ Hydrologist	Flooding Geomorphology NRC Panel Member	Tucson, AZ	Attended Panel
Gary Parker, PhD, PE	University Illinois @ Urbana	Engineer	Hydraulics Physical modeling	Urbana, IL	Did not participate
Mark Schmeeckle, PhD	Arizona State University	Geography	Sedimentation Modeling	Phoenix, AZ	Report review only
Ramon Arrowsmith, PhD	Arizona State University	Geologist	Tectonics Geomorphology	Phoenix, AZ	Report review only
Ron Dorn, PhD	Arizona State University	Geography	Debris flow Dating	Phoenix, AZ	Report review only

Table 2. Summary of Blue Ribbon Panel Key Findings			
	Finding	**Documentation**	**JEF Response / Action**
	Key to documentation codes: Response G1/Q1 – See meeting notes, Group 1, Question 1 (See Attachments) Response AQ7 – See meeting notes, Additional Question 7 (See Attachments) JEF Day 1, #46 – See JEF meeting notes, point #46 (See Attachments)		
1	The methodology as proposed in the draft report is reasonable, defensible, and scientifically sound.	Response G1/Q1 Response G1/Q10 Response G5/Q3 Response AQ7 JEF Day 1, #46,50	No response required.
2	The proposed methodology may have applicability to similar fan areas elsewhere in the semi-arid west, but it should be adopted specifically for Maricopa County and sent to FEMA as a test-case delineation (with documentation) for review and approval.	Response AQ2 Response AQ3	No response required.
3	The 100-year flood should be used as the basis of engineering design and floodplain delineation on alluvial fans in Maricopa County.	Response G4/Q1 Response G5/Q1 JEF Day 1, #47	No response required.
4	Two-dimensional modeling is strongly recommended for alluvial fan flood hazard assessment.	Response G1/Q7	No response required.
5	Flow attenuation is a key process on alluvial fans in Maricopa County and should be accounted for the methodology.	JEF Day 1, #52 JEF Day 2, #7-13,16	No response required.
6	The virtual levee scenario is an important and necessary component of the proposed methodology.	Response G1/Q5 Response G1/Q6 Response AQ8 JEF Day 1, #8, 36	No response required.
7	The proposed hazard assessment methodology (BUREC Figure 6, FLO2D depth-velocity, frequency-weighted) is acceptable. Depth-velocity are the best variables for assessing the hazard level, if uncertainty is addressed through the virtual levee scenario method.	Response G1/Q9	No response required.
8	Avulsions are a key process for alluvial fan flooding hazards. Avulsion methodology should distinguish between major avulsions, minor avulsion and simple lateral channel erosion. Recent occurrence of avulsions may preclude formation of new avulsions in near term.	Response G3/Q2 JEF Day 1, #19	No response required.
9	The avulsion risk assessment methodology is acceptable	JEF Day 1, #24	No response required.
10	Slope-walk method is a useful tool	JEF Day 1, #9	No response required.
11	"Active alluvial fan flooding" refers to an ultrahazardous flooding condition characterized by very high velocities and flow depths, active transport of boulder-sized sediment, high avulsion potential, rapid aggradation, and debris flow potential. New terminology, such as "piedmont active flooding," may be needed to address uncertain flow path flooding on active alluvial fans that is not ultra-hazardous.	Response G2/Q1 Response G3/Q2 JEF Day 2, #5, 13, 26	Revise methodology to include new terminology
12	There is no known physical characteristic that could serve as the minimum threshold of concern to identify alluvial fan landforms or the potential for alluvial fan flooding. Hazards can be quantified based on the flow depths and velocities predicted by the proposed methodology	Response G1/Q2 Response G2/Q1	No response required.
13	There is no need to quantify the Stage 1 delineation process.	Response G1/Q3	No response required.

Table 2. Summary of Blue Ribbon Panel Key Findings			
	Finding	**Documentation**	**JEF Response / Action**
14	Some quantification of flood hazards is needed in the Stage 2 delineation process. Flow depth and velocity estimates are needed to identify "active alluvial fan flooding" as defined by FEMA.	Response G1/Q4	No response required.
15	Alluvial fans in Maricopa County are not unique. They are typical of alluvial fans formed near tectonically inactive mountain ranges in semi-arid climates.	Response G3/Q1 JEF Day 1, #14	No response required.
16	Areas on active fans outside the 100-year floodplain should be designated as having some hazard potential, but should not be mapped as part of the FEMA floodplain	Response G5/Q1 Response AQ1 JEF Day 1, #11	Consider adding an additional, advisory flood zone.
17	Development in low hazard areas on alluvial fans is acceptable as long as it is adequately regulated for impacts to adjacent areas. High hazard areas should be regulated with higher restrictions. Policies to prevent loss of attenuation (downstream impacts) should be developed.	Response G4/Q3 Response G4/Q4	No response required.
18	There are significant problems with the Dawdy Method (FAN model).	JEF Day 1, #15, 35, 38	No response required.
19	FEMA's current plans to revise the NFIP provides a rare two-year window of opportunity for also revising the FEMA Appendix G methodology to incorporate the recommendations of the PFHAM study.	JEF Day 2, #21	Add as recommendation of study.
20	There is a need for high quality topographic mapping when performing floodplain delineations.	Review comment by Burke Lokey	

Table 3. Summary of Blue Ribbon Panel Key Concerns			
	Concern	**Documentation**	**JEF Response / Action**
1	"Point-in-time" modeling may not adequately characterize long-term fan behavior and flood risks. Fan processes evolve dynamically over time. We do not have the ability to reliably predict how those processes will change the landscape or impact other functions such as flow attenuation over time. Therefore, a composite methodology is needed.	JEF Day 1, #2,3,4 Review comment by Burke Lokey.	Flood hazards associated with long-term behavior are addressed through geomorphic evaluation, virtual levee scenario method, avulsion assessment, and sedimentation modeling. Like any floodplain delineation, periodic updates may be required after major floods or development changes.
2	Need clarification of mechanics of virtual levee scenario methodology – length of levees, orientation, number of scenarios, approach at secondary apexes, etc.	JEF Notes	Clarification and additional explanation of the virtual levee methodology will be provided in the updated PFHAM manual.

Table 4. Blue Ribbon Panel Recommendations for Additional Study			
	Recommendation	**Documentation**	**Response**
	Key to documentation codes: Response G1/Q1 – See meeting notes, Group 1, Question 1 (See Attachments) Response AQ7 – See meeting notes, Additional Question 7 (See Attachments) JEF Day 1, #46 – See JEF meeting notes, point #46 (See Attachments)		
1	Need to determine avulsion frequency for fans in Maricopa County	G1/Q5 G3/Q2 JEF Day 2, #6	Additional study was proposed and scoped. The District has elected not to fund the additional study.
2	Infiltration parameters need verification	AQ9 JEF Day 1, #52	The District is currently undergoing an infiltration parameter analysis under separate contract.
3	If and when large floods occur on alluvial fans in Maricopa County, they should be thoroughly documented & studied, and compared with proposed methodology.	JEF Day 1, #30	This will be added as a recommendation of the study.
4	Provide documentation on how "risk" is quantified by the proposed methodology. This documentation will be important for FEMA approval.	JEF Day 1, #32,39	This will be added as a recommendation of the study.
5	The methodology should be submitted to FEMA for review & approval. Characterize the methodology in RiskMAP language. The best way to submit to FEMA is with an example delineation using the methodology together with a document summarizing the method (e.g., the final report).	JEF Day 1, #43 JEF Day 2, #21	This will be added as a recommendation of the study.
6	Clarify which sediment transport function produces best results	G1/Q8	This will be added as a recommendation of the study.
7	Explore definition of hazard level for no-build zones and/or floodways. No-build zones could be based on hazard classification as well as the "ultrahazardous" areas. Could also incorporate zoning overlays.	G3/Q4 G3/Q5	This will be added as a recommendation of the study.

Attachments:

- List of Seed Questions Considered by Blue Ribbon Panel
- Seed Question Response Forms (Findings)
- Meeting Notes by Individuals
- Written Comments by Blue Ribbon Panel Members

Attachment #1:
Seed Questions for Blue Ribbon Panel

Question Group #1: Methodology

1. Is proposed methodology reasonable? How would you improve the proposed methodology?
2. Is there a minimum threshold of concern (slope, drainage area, etc.) for alluvial fan flooding? Is there a maximum threshold at which our methodology should not be applied (e.g., slope)?
3. How could the Stage 1 delineation process be quantified or use engineering methodologies to replace or supplement geomorphic methods?
4. Are "detailed" methods for identifying active or inactive alluvial fans needed at the Stage 2 level?
5. Is the virtual levee scenario methodology a reasonable and viable method for assessing the potential impact of avulsions on the hydrology and hydraulics of alluvial fan flooding?
6. Should the District use the virtual levee or the mega-flood methodology to address flow path uncertainty?
7. What modeling tool would be most appropriate for an alluvial fan in Maricopa County?
8. What sediment transport function would be most appropriate for an alluvial fan in Maricopa County?
9. How would you differentiate between a high hazard fan and a low hazard fan?
10. What is the best way to use the proposed method – to delineate flooding or to delineate "no build" zones?

Question Group #2: Landform Identification

1. How can we distinguish between alluvial plains and active alluvial fans? How is the flood hazard different on each of these landform classifications?
2. Many alluvial fans in Maricopa County are geologically old features. Is most of what has been called alluvial fans in Maricopa County actually alluvial plains or alluvial slopes? Is 2% or 1% a reasonable slope threshold that distinguishes between alluvial plains and alluvial fans? Are we over-estimating the flooding hazard for areas away from mountain front?
3. Most of active alluvial fans delineated in Maricopa County are located away from the mountain front. They represent depositional areas where the fanhead channels lose their capacity and start to split into small braids. Typically, the active fan areas are located on mild slopes which may not have enough energy to cause avulsions. Should we be concerned about avulsions and flood hazards in these types of areas? Should we even call them alluvial fans?

Question Group #3: Alluvial Fan Characteristics in Maricopa County

1. Are alluvial fans in Maricopa County different from fans in other parts of the Southwest? Are they more or less hazardous? Are they not hazardous? According to NRC Report "Alluvial Fan Flooding," an alluvial fan flooding hazard occurs in an environment where the combination of sediment availability, slope and topography creates an ultra-hazardous condition. Given the low slopes

and low availability of sediment in Maricopa County, what do you think about the alluvial fan flooding hazards in Maricopa County?

2. What is the risk of avulsions on active fans in Maricopa County?
3. Should the PFHAM Manual use the same landform and flooding definitions as FEMA or should they be revised to reflect the differences in Maricopa County fans from alluvial fans in other parts of the Country?

Question Group #4: Floodplain Management on Alluvial Fans

1. Should the 100-year flood be used as the basis of analysis and design, or should a larger event be used? If so, on what basis?
2. What depth should define shallow flooding? (should this be shallow sheet flooding?) In this report it is defined as less than 0.3 feet (3.6 in).
3. Should we allow development on low hazard fans?
4. Is a no build zone needed on active alluvial fans in Maricopa County?
5. Is there a need for a floodway zone on active alluvial fans?

Question Group #5: Application of Geomorphology

1. In general, Maricopa County uses the 100-year flood as the basis of engineering design and floodplain management. The geomorphology-based approach to alluvial fan is not tied to any specific return period flood. The current FEMA geomorphology-based method is based on a geologic time scale which is much larger than engineering design time scale. The use of geomorphology by FEMA for the current alluvial fan method already assumes that the alluvial fan return period is more than the typical 100-year event for floodplain delineation. Since this project is focused on adding engineering criteria to current FEMA geomorphology-based method, it is essential to make a decision on return period for floodplain delineation on alluvial fans. What return interval to consider for flood hazard and floodplain delineation on alluvial fans?
2. What is the risk of overtopping the fanhead trench above the hydrographic apex on fans in Maricopa County due to debris flow, sediment deposition, or extreme flooding? How would such risk affect the Stage 1-2-3 delineations?
3. Is the District under-estimating the flooding hazard for alluvial fan landform areas located at the mountain front? Is geomorphic-based analysis enough to justify whether we should allow development next to the incised fanhead channels where they leave the mountain front (above the hydrographic apex of active fans)? What is the accuracy and uncertainty of geomorphic analyses of flooding hazard near the mountain front?
4. There is great uncertainty in determining the location of the hydrographic apex. What is the best way to assess the uncertainty in locating a hydrographic apex?

Additional Questions from Blue Ribbon Panel Discussion on Day 1

1. Should all of the active alluvial fan be considered some kind of flood hazard area, regardless of modeling results?
2. Is this methodology intended for just Maricopa County, or is it intended for other areas?
3. How should we approach getting FEMA approval of the methodology?
4. Is lateral migration a type of avulsion?
5. Are break outs avulsions?
6. How can there be avulsions on erosional surfaces?
7. Does the proposed methodology adequately quantify the flood risk?
8. How can we model the effects of multiple, sequential floods on fan behavior?
9. What is our confidence level in the infiltration parameters used in FLO2D models?
10. If it is not ultrahazardous, is it alluvial fan flooding? What does ultrahazardous mean?
11. Should avulsion frequency be evaluated in more detail?

Attachment #2:
Seed Question Response Forms (Findings)

Blue Panel Review Recommendation

Project: Alluvial Fan Methodology Refinement
Group 1
Topic G1/Q1

Original Concept

Is proposed methodology reasonable?

Proposed Concept

Yes. Reasonable Method. Should be dependant on availability of high-level topo. Second part of question will be answer in the response to the following questions.

Advantages:

- Reasonable method compared to other methods.
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Disadvantages:

- Need to have high-level of mapping.
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Discussion

Good topographic mapping is required.

Blue Panel Review Recommendation

Project: Alluvial Fan Methodology Refinement

Group 1

Topic G1/Q2

Original Concept

Is there a minimum threshold of concern (slope, drainage area, etc.) for alluvial fan flooding? Is there a maximum threshold at which our methodology should not be applied (e.g., slope)?

Proposed Concept

No minimum threshold - need to quantify hazard based on velocity, depth, uncertainty, and sediment. Second part: no.

Advantages:

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Disadvantages:

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Discussion

Probably maximum threshold where modeling breaks down - outside of maricopa county. Group 2 came to same comclusion regarding slope. Is slope and feature tied together? No, just slope doesn't define the fan. Slope is not a useful parameter for landform definition. With enough data you might be able to define some kind of slope threshold, but such data does not currently exist. Low slope does not mean low risk. Some active fans in San Joaquin Valley (2m/3km) are actively aggrading but the land slope is imperceptible. Might be possible to textural analysis with high-density LIDAR data, but it would still require a competent geomorphologist to interpret the results. The process would far simpler to do by simple visual inspection. Slope alone is not diagnostic. Landform identification is an intrinsically subjective process, which is not a bad thing.

Blue Panel Review Recommendation

Project: Alluvial Fan Methodology Refinement

Group 1

Topic G1/Q3

Original Concept

How could the Stage 1 delineation process be quantified or use engineering methodologies to replace or supplement geomorphic methods?

Proposed Concept

Quantification is unnecessary at Stage 1.

Advantages:

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Disadvantages:

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Discussion

Reconnessance level to see if the fans even exist at all.

Blue Panel Review Recommendation

Project: Alluvial Fan Methodology Refinement

Group 1

Topic G1/Q4

Original Concept

Are "detailed" methods for identifying active or inactive alluvial fans needed at the Stage 2 level?

Proposed Concept

It is a case by case issue. Not a cookbook, has to include geomorphic method too. Both components should be used for stage 2: geomorphic and computational component.

Advantages:

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Disadvantages:

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Discussion

Group 2 conclusion: Cannot define alluvial fan flooding unless velocities and depths defined. Suggest depth and velocity criteria. First phase of detail. One concern: at this stage we determine if it is inactive or active. Are more detailed points necessary at this stage to determine whether the fan is active or inactive? Recommend that in stage 2 there is an application of the FLO2D model. Evaluate in the field reasonableness of the model.

Blue Panel Review Recommendation

Project: Alluvial Fan Methodology Refinement
Group 1
Topic G1/Q5

Original Concept

Is the virtual levee scenario methodology a reasonable and viable method for assessing the potential impact of avulsions on the hydrology and hydraulics of alluvial fan flooding?

Proposed Concept

Yes. The VLS is an attempt to determine flow path uncertainty if it might exist on an alluvial fan. Recommendations under discussion is answer to Q1.

Advantages:

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Disadvantages:

- If look at historically, no guarantees that the sediment is going to be similar to the past.
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Discussion

Important to define where likely areas are and what the tools are to identify. Look at sediment transport that comes into this as well as geomorphic model. Sediment transport would be historic look or numerical analysis. Figure methodology to identify relative risk, map the avulsion areas; identify potential avulsion areas. Might need multiple scenarios. Needs to have more data. Avulsion frequency should be studied in more detail. Could quantify sediment. Start process at apex and repeat for worst case scenarios downstream. Where an avulsion might occur might be dependant on the sequence of events leading up to it. Limit on number of iterations with actual data of recurrance of avulsions. Also need to add guidance on how to apply VLS where there are secondary apexes on fan.

Blue Panel Review Recommendation

Project: Alluvial Fan Methodology Refinement

Group 1

Topic G1/Q6

Original Concept

Should the District use the virtual levee or the mega-flood methodology to address flow path uncertainty?

Proposed Concept

No, these are two completely different processes - the group strongly prefers the virtual levee method.

Advantages:

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Disadvantages:

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Discussion

Blue Panel Review Recommendation

Project: Alluvial Fan Methodology Refinement

Group 1

Topic G1/Q7

Original Concept

What modeling tool would be most appropriate for an alluvial fan in Maricopa County?

Proposed Concept

Two dimensional model is appropriate for that area. Use composite of different models, especially in areas of highest uncertainty.

Advantages:

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Disadvantages:

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Discussion

Blue Panel Review Recommendation

Project: Alluvial Fan Methodology Refinement
Group 1
Topic G1/Q8

Original Concept

What sediment transport function would be most appropriate for an alluvial fan in Maricopa County?

Proposed Concept

Depends on grain size distribution and hydraulic conditions. It is a case by case issue.

Advantages:

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Disadvantages:

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Discussion

The Zeller-Fullerton equation should provide reasonable results. The Yang and MPM-Woo are not recommended for most situations in Maricopa County.

Blue Panel Review Recommendation

Project: Alluvial Fan Methodology Refinement

Group 1

Topic G1/Q9

Original Concept

How would you differentiate between a high hazard fan and a low hazard fan?

Proposed Concept

Based on velocity, depth, uncertainty. Concept of the USBR ACER curve being used is good. Follow Stage 1,2,3 processes and qualitatively make the assessment.

Advantages:

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Disadvantages:

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Discussion

Blue Panel Review Recommendation

Project: Alluvial Fan Methodology Refinement
Group 1
Topic G1/Q10

Original Concept

What is the best way to use the proposed method – to delineate flooding or to delineate "no build" zones?

Proposed Concept

Both. Use multiple simulations to determine highest hazard and assign administrative floodway on it. Apply the method for both hazard determination and floodway/floodplain delineation.

Advantages:

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Disadvantages:

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Discussion

Blue Panel Review Recommendation

Project: Alluvial Fan Methodology Refinement
Group 2
Topic G2/Q1Landform Identification

Original Concept

How should we distinguish between alluvial plains and active alluvial fans? Is slope a reasonable threshold for hazard?

Proposed Concept

1. Stage 1: Identify landforms (geomorphic process). Use new terminology (e.g., piedmont inundation area)
2. Stage 2: 2D Model to determine depth and velocities. Includes a certain number of avulsion scenarios. Field check model results.
3. Stage 3: 100-year floodplain designation: Use a tiered hazard threshold: The "active alluvial fan" will be designated as the ultrahazardous zone that meets FEMA's definition for an alluvial fan. The remaining areas of the geologic "active alluvial fan" will be categorized as inundation areas and then ranked by risk (high, medium, low) based on proposed criteria. A property owner could elevate on fill in the areas outside of the delineated (FEMA-defined) active alluvial fan.

Advantages:

- Compatible with FEMA stages/framework
- Identifies areas of inundation on fan landform that are not active alluvial fan flooding.
- This approach runs the model in Stage 2 to allow earlier definition of active vs. inactive flooding portion:
- Introduces new terminology in Stage 1.
- Can efficiently delineate landforms/areas of concern in Stage 1.

Disadvantages:

- Need experienced professionals to perform modeling and geomorphic analysis
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Discussion

• Stage 3 is the regulatory model run, after active/inactive flooding areas are identified in Stage 2
• In some areas of Maricopa County, the flooding hazard is over-estimated with current methodology. Slope may not be an adequate indicator of alluvial fan flooding hazard areas. Recommend depth and velocity as a threshold to identify active alluvial fan flooding.

Blue Panel Review Recommendation

Project: Alluvial Fan Methodology Refinement
Group 2
Topic G3/Q1 Alluvial Fan Characteristics

Original Concept

1.) Are alluvial fans in Maricopa County different from fans in other parts of the Southwest? 2.) Should the PFHAM Manual use the same landforms and flooding definitions as FEMA?

Proposed Concept

1.) Alluvial fans in Maricopa County are typical of fans in tectonically inactive areas. 2.) No. In Stage 1 (identification of landforms) the geomorphic evaluation should identify "piedmont inundation areas." In Stage 2 and 3, the "active alluvial fan" will be delineated per FEMA definition. The remaining areas on the geologic "active" alluvial fan should be identified by new terms indicative of the relative hazard (that is not per se an alluvial fan flooding hazard). The term for these areas should indicate activity (this is not an "inactive" alluvial fan), but should indicate a flooding type that does not rise to the level of the FEMA definition of an alluvial fan.

Advantages:

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Disadvantages:

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Discussion

Blue Panel Review Recommendation

Project: Alluvial Fan Methodology Refinement
Group 2
Topic G3/Q2 Avulsions

Original Concept

1.) Should we be concerned with avulsions? Should they be evaluated in greater detail?
2.) Is lateral migration a type of avulsion?
3.) Are break-outs avulsions?
4.) How can there be avulsions on erosional surfaces?

Proposed Concept

1.) Yes. More study is needed to determine the probability and extent of avulsions in Maricopa County.
2.) No. It is an unstable channel. There are issues with the FEMA definition that can confuse this issue.
3.) An avulsion is a shift in a channel. A breakout could lead to an avulsion only if the whole system switches to the new pathway/channel and the original channel is abandoned.
4.) No surface is totally erosional. A surface is erosional in geologic time. In an engineering timescale, you can have temporary sediment/debris storage or deposition that can cause an avulsion.

Advantages:

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Disadvantages:

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Discussion

Blue Panel Review Recommendation

Project: Alluvial Fan Methodology Refinement
Group: 3
Topic : G4/Q1

Original Concept

Keep 100 yr flood: Should the 100-year flood be used as the basis of analysis and design, or should a larger event be used? If so, on what basis?

Proposed Concept

Develop maps using 100 year flood and consider imposing more conservative regulations wihtin the local ordinance whether that means increasing Qs or introducing a factor of saftey

Advantages:

- Results are more locally controlled
- takes into account more extreme event (such as avulsions)
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-
-

Disadvantages:

- If we start regulating outside of FEMA it might be overstepping boundries
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Discussion

Maps should try to "accurately" represent the 100 year flood and then use other policies to make more conservative

Blue Panel Review Recommendation

Project: Alluvial Fan Methodology Refinement

Group 1

Topic: G4/Q2

Original Concept

Shallow flooding be defined as 0.3 ft: What depth should define shallow flooding? (should this be shallow sheet flooding?) In this report it is defined as less than 0.3 feet (3.6 in).

Proposed Concept

Seems a little arbitrary, but there is no reason to question 0.3 ft, assuming JEF, Inc. had justification for choosing that value.

Advantages:

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Disadvantages:

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Discussion

No reason to question 0.3 ft, but what was the thought behind it? Depth may be moot, since hazard is regulated and equals depth x velocity.

Blue Panel Review Recommendation

Project: Alluvial Fan Methodology Refinement
Group 1
Topic: G4/Q3

Original Concept

Should development be allowed on low hazard fans?

Proposed Concept

Development should be allowed as long as it is not mapped as an active fan on FEMA maps, density controls are in place, and low hazard is in compliance with question 1 (defined by good engineering and science)

Advantages:

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Disadvantages:

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Discussion

What is low hazard fan? Density of development and flow paths should be regulated.

Blue Panel Review Recommendation

Project: Alluvial Fan Methodology Refinement
Group: 3
Topic : G4/Q4

Original Concept

Should there be a no-build zone on active alluvial fans?: Is a no build zone needed on active alluvial fans in Maricopa County?

Proposed Concept

Yes; alluvial fan functions such as attenuation and infiltration should be maintained so designate these zones &/or regulations (or policies) based on the goals/functions that should be maintained.

Suggestions

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Disadvantages:

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Discussion

Explore No-build Zones, which would be the easist to implement from a regulatory perspective but difficult from a property rights perspective. Other options for implementation could be to re-zone areas as open space through the general land use plans. Density transfers could also be used. Breaking areas into sub-areas and determining the amount of open space within each sub area that should be preserved in order to meet goals of NAI, infiltration, attenuation, etc. The amount of area to preserve could be determined by modeling build-out scenarios and the effects of them (i.e., determining that "tipping" point. Have areas where they are to be kept in a naturalistic form, minimize amount of intervention. Maintain flow through areas.

Blue Panel Review Recommendation

Project: Alluvial Fan Methodology Refinement
Group: 3
Topic : G4/Q5

Original Concept

Is there a need for a floodway zone on active alluvial fans?

Proposed Concept

Deliniating a floodway could be problematic in an alluvial fan area; however, floodways should be deliniated for riverine and entrenched areas within the alluvial fan.

Advantages:

- Results are more locally controlled
- Takes into account more extreme events we can't predict
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Disadvantages:

- Property rights are affected
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Discussion

Relates back to question number 4. Develop floodplane maps, but also develop other flood hazard zones... How do you define a true floodway in an alluvial fan. Administrative floodways can be used, allows for a no-build zone.

Blue Panel Review Recommendation

Project: Alluvial Fan Methodology Refinement
Group: 3
Topic : G5/Q1

Original Concept

Return Interval: In general, Maricopa County uses the 100-year flood as the basis of engineering design and floodplain management. The geomorphology-based approach to alluvial fan is not tied to any specific return period flood. The current FEMA geomorphology-based method is based on a geologic time scale which is much larger than engineering design time scale. The use of geomorphology by FEMA for the current alluvial fan method already assumes that the alluvial fan return period is more than the typical 100-year event for floodplain delineation. Since this project is focused on adding engineering criteria to current FEMA geomorphology-based method, it is essential to make a decision on return period for floodplain delineation on alluvial fans. What return interval to consider for flood hazard and floodplain delineation on alluvial fans?

Proposed Concept

Delineate the floodplain for the FEMA maps using the 1% chance flood but also delineate other hazard areas outside the "100-yr" floodplain that have other hazardous characteristics.

Advantages:

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Disadvantages:

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Discussion

Use FLO-2D for modelling alluvial fans and then compare results with the geomorphic analysis; refine results based on the geomorphic/FLO-2D comparison. .....Don't call them alluvial fans if they are not.....Use higher discharges to help inform the "subjective" decisions (e.g., avulsion potential/location)......Use ALL available information. Use of geologic information such as mapping Holocene surfaces does NOT imply that a 10,000-year event is being modeled. Geologic information is used to inform on engineering time scale processes.

Blue Panel Review Recommendation

Project: Alluvial Fan Methodology Refinement
Group: 3
Topic : G5/Q2

Original Concept

Overtopping Risk: What is the risk of overtopping the fanhead trench above the hydrographic apex on fans in Maricopa County due to debris flow, sediment deposition, or extreme flooding? How would such risk affect the Stage 1-2-3 delineations?

Proposed Concept

Based on information we received, the risk from debris flows is low but there could be issues with sediment deposition.

Advantages:

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Disadvantages:

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Discussion

Sediment deposition: during low discharges, sediment can deposit at the fanhead; sediment can redistribute during higher flow events. Theoretically an avulsion can occur from either the low or high discharge.... Can't answer this question without more information on the nature of the trenches (eg. don't know how deep these fan heads are)....Why did the fanhead trench develope in the first place? Depending on the geomorphic reason why the fanhead is entrenched can determine the risk....To manage the sediment deposition risk you could expand the active fan area....Maybe the flow will return into the channel but it depends on the slope.....Extreme flooding you could answer this question using HEC-1 to determine how much discharge it takes to fill the channel. In Maricopa County, debris flow occurance seems to be 1000 years, needs to be more data.

Blue Panel Review Recommendation

Project: Alluvial Fan Methodology Refinement
Group: 3
Topic : G5/Q3

Original Concept

Underestimating the flooding hazard? Is the District under-estimating the flooding hazard for alluvial fan landform areas located at the mountain front? Is geomorphic-based analysis enough to justify whether we should allow development next to the incised fanhead channels where they leave the mountain front (above the hydrographic apex of active fans)? What is the accuracy and uncertainty of geomorphic analyses of flooding hazard near the mountain front?

Proposed Concept

No...Geomorphic based analysis can justify no development...The uncertainty with the geomorphic analysis can be addressed using an experienced geomorphologist

Advantages:

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Disadvantages:

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Discussion

Development should be appropriately regulated near incised fanhead channels where erosion can be an issue

Blue Panel Review Recommendation

Project: Alluvial Fan Methodology Refinement
Group: 3
Topic : G5/Q4

Original Concept

Assessing the uncertainty in determing the location of the hydrographic apex: There is great uncertainty in determining the location of the hydrographic apex. What is the best way to assess the uncertainty in locating a hydrographic apex?

Proposed Concept

Define where it is first. One way is to define it is where the flows split into more than one channel (split can change the location). The apex location is discharge-dependent, but can be defined based on the surficial geology. A channel capacity definition must account for potential sediment deposition.

Advantages:

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Disadvantages:

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Discussion

Models don't define avulsions well...Hire smart people with good judgement. Combining FLO2D modeling with geomorphology should come up with the hydrographic apex. It is the head of the active fan. Officially the point where the flow path uncertainty begins. If overtopping occurs upstream, then the apex should be moved upstream. Run a HEC type model on fanhead trench and look for the point where the width/depth ratio reduces to a point of the Parker models. Q: If 100yr flow is used and it breaks out above the apex what happens? Is a bulking factor should be used to mult. the peak in order to identify the hydrographic apex upstream? Modelling simplifies reality. Should be modelled as cascading sequence of channels. FLO2D utilizing present topography and don't know topography after flood, maybe use HEC type model. Bulking factor may be good addition. When storm hits, lots of sediment available. Early stages of flood may be time when avulsions are most likely and a factor to account for that might be good approach. Bulking factor shouldn't be bigger than 1.2 unless in debris flow. Deposition in early stages of flood is concern and will be

Blue Panel Review Recommendation

Project: Alluvial Fan Methodology Refinement
Group 1
Topic AQ1

Original Concept

Should all of the active alluvial fan be considered some kind of flood hazard area, regardless of modeling results?

Proposed Concept

If defined as active alluvial fan, it should be considered as flood hazard area.

Advantages:

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Disadvantages:

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Discussion

The term active can be active alluvial fan flooding. Possibly need another term such as active piedmont flooding. Difference between active alluvial fans in Maricopa County vs. other parts of the country? Generally lower hazard in Maricopa County.

Blue Panel Review Recommendation

Project: Alluvial Fan Methodology Refinement
Group 1
Topic AQ2

Original Concept

Is this methodology intended for just Maricopa County, or is it intended for other areas?

Proposed Concept

Better to make is just for Maricopa County because of the fan situation. Making a better case to FEMA as they do allow concepts based on regional basis rather than the national basis.

Advantages:
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Disadvantages:
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Discussion

Blue Panel Review Recommendation

Project: Alluvial Fan Methodology Refinement
Group 1
Topic AQ3

Original Concept

How should we approach getting FEMA approval of the methodology?

Proposed Concept

Just apply for Maricopa County. Works better to submit the study as MT2 with the methodology for FEMA approval.

Advantages:

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Disadvantages:

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Discussion

Finalize draft with cover memo asking for comments. Improvement to risk analysis, may raise interest for FEMA.

Blue Panel Review Recommendation

Project: Alluvial Fan Methodology Refinement

Group 1

Topic AQ7

Original Concept

Does the proposed methodology adequately quanitfy the flood risk?

Proposed Concept

Yes, the methodology quantifies flood risk.

Advantages:

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Disadvantages:

- If an area of alluvial fan flooding, it does not address it properly because flow is attenuating.
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Discussion

Blue Panel Review Recommendation

Project: Alluvial Fan Methodology Refinement

Group 1

Topic AQ8

Original Concept

How can we model the effects of multiple, sequential floods on fan behavior?

Proposed Concept

Virtual levee process is doing this.

Advantages:

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Disadvantages:

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Discussion

Don't know what sequence of flooding is going to be, hard to determine sequence of events. Use levee approach on coalescing fans? This is discussing virtual levees on same fan. No large coalescing fans in Maricopa.

Blue Panel Review Recommendation

Project: Alluvial Fan Methodology Refinement

Group 1

Topic AQ9

Original Concept

What is our confidence level in the infiltration parameters used in FLO2D models?

Proposed Concept

There is a confidence level as long as the parameters are defensible. Should conduct sensitive analysis to determine how large of an effect infiltration has on the result.

Advantages:

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Disadvantages:

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Discussion

Attachment #3:
Meeting Notes by Individuals

Blue Ribbon Panel Meeting Notes

Meeting notes received from the following individuals are provided in this document:

- District facilitator notes (sticky pads used in panel meeting)
- Jon Fuller/ JEF
- Bethany Fye/ JEF
- Teresa Pinto/FCDMC
- Kathryn Gross/FCDMC

These notes are provided in an "as-is" condition. No attempt to improve the grammar or spelling of the original note-taker has been made.

Jon Fuller's Meeting Notes

Day 1: General Comments (includes Day 1 sticky pad notes)

1. Can we merge Group 2 & 3 questions?
2. We have a concern about fixed bed, single event modeling results because they represent a point in time. Alluvial fan flood hazards are due to changing flow distribution and changing topography that aren't captured by a point in time approach.
3. "Active" area should include the future floodprone areas not just point in time
4. The idea of quantifying the flood hazard is questionable.
5. The methodology should include redelineation after significant events or changes.
6. In sheet flooding areas, development will concentrate flow and create new hazards unlike pre-development conditions.
7. Models are good and useful (quantifying hazards).
8. Virtual levee scenario method is a good approach to address uncertainty. There may be some potential problems with the method, but it is the best we can do.
9. The slope walk method is a good approach too.
10. Remember that VLS and slope walk are both based on point in time, existing topography, and may still need updates after big floods.
11. All of the active area should be a flood hazard area.
12. More information is better than less. The more information about the hazards we can develop, the better our risk assessment will be.
13. Are you expecting FEMA approval of the methodology?
14. Fan in Maricopa County are not that different than fans elsewhere.
15. Dawdy method is not good.
16. There are erosional and depositional landforms. Pediments are erosional and experience lateral planation and migration (avulsion) due to erosional processes.
17. We do not have FEMA-type alluvial fans in Maricopa County. Fans in Maricopa County are formed by bursts of deposition from climatic change or are channel fans following a discontinuous ephemeral stream model process.
18. For each fan site, we should assess:
    a. What type of fan
    b. Is it a pediment
    c. How long has the landform persisted in the landscape
    d. Create a unique hazard modeling approach for each unique fan type
19. Avulsion is the key question. Uniform deposition over long time periods (1ft/1000 yrs) – this occurs by lateral movement and avulsion and creates alluvial fans. If an avulsion has occurred in recent past, the fan may not be subject to near term future avlusions. Fans without avulsions are more likely to experience near-term future avulsions (they're due). Need to distinguish gradations in avulsion: (1) major – drastic redirection of flow, (2) minor – simple overflow, (3) lateral erosion of channel.
20. Is lateral migration a type of avulsion?
21. How do we reconcile geologic time frames with regulatory issues (100-yr)

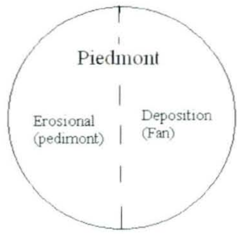
22. When considered managing rare events, we need to consider more than frequency. The severity and consequence of the hazard should be considered. The greater the consequence, the greater the recurrence interval used.
23. Avulsion results from deposition that creates differential changes in slope on the fan surface. This really only happens with tectonic uplift, which can create real avulsions. Avulsions can occur as erosional process too.
24. Fan avulsions shown in study indicate that avulsions followed on-fan drainage, and therefore could be predicted. The avulsion methodology developed uses available information reasonably and is acceptable.
25. Fans (landforms) in Maricopa County are dominantly erosional.
26. Pediments are excluded from the PFHAM recommended methodology. Pediments are not well understood.
27. How can there be avulsions on erosional surfaces?
28. Alluvial fan vs. pediment is not important to FEMA.
29. Don't set process in stone – needs to be flexible and have continual re-evaluation.
30. We probably haven't seen a design event yet. If we do, District should study it like mad and learn as much as possible.
31. FEMA never adopted the recommended NRC definition of alluvial fan flooding.
32. Does the proposed methodology adequately quantify the flood risk?
33. If there is erosion in one place, there must be deposition in another place.
34. Risk is the quantification of uncertainty.
35. Is JEF saying Dawdy works? No.
36. The PMP or mega-flood approach is not an acceptable way to model long-term behavior. We should use a series of floods in conjunction with the virtual levee scenario.
37. We should not use the term "mega-flood" since that has a specific definition (Q>1,000,000 cms) and earth has not seen one of those.
38. Dawdy method is only ok if you have zero information about the fan. Proposed methodology is an immense improvement over Dawdy.
39. FEMA will need to know how we addressed uncertainty and quantified the risk.
40. Sediment does not move instantaneously with water flow.
41. The threshold of sediment movement should be much less than 2 ft/sec for fine grained sediments on fans.
42. How can we model the effects of multiple, sequential floods on fan behavior?
43. Getting FEMA to change is hard. Since MapMOD, FEMA is more willing to put more information on FIRM panels. The information in the methodology could easily be added to the FIRM. The methodology complements RiskMAP goals too.
44. We could use higher standard than FEMA.
45. Should we be using a shorter storm duration, say 2 hr? Don't 2 hr events cause biggest floods?
46. Methodology is better than before and is more realistic.
47. We recommend using multiple Q100 events in sequence rather than a single PMP event.
48. Many landforms in Maricopa County are stable, with incised channels at the head of the fan.
49. The hydrographic apexes are located away from the mountain front.

50. Methodology is on the right track with respect to FEMA acceptance.
51. Why doesn't the District use HEC-HMS, rather than HEC-1?
52. Flow attenuation is a key process. Attenuation includes storage and infiltration. What is our confidence level in the infiltration parameters used in FLO2D models?
53. How do we define hazard?
54. Did we consider using other 2d models?
55. Consider the Heisenberg principle.

Day 2: Opening Comments

1. Can we identify stability thresholds for fans?
2. Are we concerned with only undeveloped fans?
3. Under what conditions are fans erosional?
4. Would prolonged El Nino result in fans crossing a threshold?
5. Ultrahazardous means debris flows, avlusions, floods carrying boulders, floods that can kill you.
6. We don't know much about avulsion frequency – that should be studied more.
7. (Refer to handout) G4,Q1- For the 100 yr peak; if area is mapped as alluvial fan flooding refers to NFIP Part 65.13. Items "c1" leads to Q100 apex (1%). Attenuation or reduction of water downfan makes the Q less than Qapex… For c2 measures will accommodate peak and volume per paragraph c1. FEMA has interpreted this to mean full apex (peak) Q. This might be a problem for FEMA to use smaller than full apex Q in the active alluvial fan flooding area.
8. How does this language apply? We know Q is less over fan… peak should also be less
9. This is true in reality, but regulations do not match reality.
10. We don't have ultra hazard. Tectonically active fans can raise squash.
11. Does this mean we have to use full apex peak Q? Ed Curtis says "yes."
12. Ed Raleigh: This is why we're concerned about alluvial fans around WTF extending for 7 miles until they reach axial stream. However, slope is less than 1% and there cannot be full apex Q at 1% slope- can't carve out channel. What area do we need to call for FEMA. Don't call it an alluvial fan (from FEMA perspective).
13. FEMA regulations only apply to "alluvial fan flooding".
14. Definition was an issue for NRC. The hazardous process is the problem; not the landform.
15. How to get around FEMA- There are no depositional fans in Maricopa County (they are pediments). Stop calling these alluvial fans.
16. Disagree with previous comment. Yes, we have fan behavior, fans don't have Q100 apex at toe, and it is alluvial fan flooding. Flood Control District should define "high hazard" and identify them.
17. There are no single channel fans in Maricopa County. Alluvial fans are a restricted area in Maricopa County. ID these areas instead of continuing for miles.
18. Stream behavior is typical of pediments and is not long term behavior (geologically).
19. Hurricane Kathleen in Coachella Valley in 1976 got attention from FEMA. Led to fan delineation process by Dawdy and regulations in 1989. Ever since we've been trying to clarify the intent.

20. If scientific data indicates that these are not technically alluvial fans, then Maricopa County should communicate that to FEMA
21. FEMA is bound by regulations. Arid West is pursuing a change in guidelines. FEMA is looking at revising NFIP? These could be a component of this. FEMA is challenged daily on the interpretation of their regulations. There must be technical justification to reduce Q and has to be reviewed by HQ.



22. We mainly focus on active fans, and when we say its active we trigger regulations to deal with high hazard.
23. It comes back to discontinuous ephemeral streams and channel fans.
24. We have to use Q100 at apex and ignore what a geomorphologist would call a fan. Inconsistent with common definition of alluvial fan… If only the upper fan is active does that solve the problem? That's confining and illogical.
25. What is Maricopa County's purpose? Is it to remove insurance or safeguard development? If mapped by FEMA then just insurance and the county can develop its own standards.
26. Ed Raleigh: We just want realistic delineation. We're afraid of connotation- 100% of apex. Therefore, be realistic about what we call active.
27. FEMA is only insurance, not management. If you don't care if they pay insurance who cares?
28. Ed Raleigh: The bottom line is that we want development regulations.
29. If you permit and allow development in fan, you're in violation of regulations.
30. We've never found the toe of a fan. We've never done anything but geomorph
31. How to define "toe". We have alluvial fan-like landforms, not fans.
32. Alluvial fan vs. alluvial plain- is that in report?
33. Depends on if FEMA map exists with alluvial fan delineation. Changing FEMA maps is hard.
34. Regardless of whether there is FIRM map, alluvial flooding if velocity and depth are low.
35. Appendix G is guidelines, not regulations. Curtis agrees, but Hamilton says FEMA stands behind guidelines.
36. Discontinuous ephemeral streams is issue. FEMA.

Seed Question Responses

1. Group #1, Question1: Proposed methodology
    a. Group finds the method reasonable likes the quantifying aspects.
    b. They comment need topo.
2. Group #1, Question 2: Minimum threshold of concern, e.g., slope?
    a. No. Slope is not a useful parameter.

   b. No. From FEMA's perspective, no. With enough data, you may be able to define a slope threshold, but such data do not exist at this time for Maricopa County.
   c. No. Low slope does not mean low risk. Ponding at low slope could be significant. Example of low slope fans in San Joaquin Valley in California (S=2m/3km) – these fans are actively aggrading but the slope is imperceptible.
   d. I don't know what the threshold would be.
   e. No. Not applicable for defining alluvial fan landforms.
   f. For landform identification, you could do textural analysis using high-density LIDAR data to identify fans, but would still require competent geomorphologist to interpret the results correctly, and would be more laborious than simple visual inspection. Why would you go through the effort to do it?
   g. Could also use slope mapping or texture mapping procedures, but slope alone is not diagnostic.
   h. No. Quantification is not needed at Stage 1.
   i. No. There are no absolute distinctions between landforms. It is an intrinsically subjective process. You need a competent geomorphologist. Subjectivity is not bad, it is based on experience and data.
   j. No. Don't use slope to define landform hazards.
   k. FCD feedback: Is there a minimal slope to define a fan? Answer: No.
3. Group #1, Question 3: Delineation process quantified
   a. Why would you, don't worry about it. Use quantification at stage 3.
   b. It is unnecessary at Stage 1
4. Group #1, Question 4: Detailed methods needed at stage 2?
   a. This is a case by case decision.
   b. There is no cookbook way and wouldn't be definitive.
   c. Need to run model to get depth and velocity to figure out if active.
   d. FCD feedback: If it is "active vs inactive" is the big question? If its considered active, is all of it active flooding is that a coarse grid Flo 2D? We are concerned that a coarse grid model might not be active enough.
      i. BRP response: you might need to constrain coarse FLO2D with virtual levee scenario results.
5. Group #1, Question 5. VLS method reasonable?
   a. Yes. More information is better than less information. But since it is a fixed bed model, it needs updating after significant events or development.
   b. Yes. Generally a good approach. May need more model runs. Need better definition of the mechanics of how to apply it – number of scenarios, etc.
   c. Yes. Needs more information to assure confidence in results. Also, guidance on topographic map accuracy requirements.
   d. FEMA mapping is usually based on existing conditions only. Consideration of future, different conditions might be problematic, but since the method more clearly defines the area of risk, that is an improvement.
   e. Yes, it is an improvement over existing methods.
   f. Yes, I think it's great.

g. Channel fans in Maricopa County. Apexes migrate upstream (in geologic time).
h. Set up conditions important

6. Group #1, Question 6: Virtual Levee or Mega-Flood?
    a. Virtual levee scenario is strongly preferred.
7. Group #1, Question 7: Most appropriate modeling tool?
    a. 2-d modeling is the best for modeling fans in Maricopa County.
    b. Might have to use FAN some places.
8. Group #1, Question 8: Most appropriate sediment transport function
    a. Zeller-Fullerton ok, but decide case by case. ZF tends to predict low so some question remains as to why its considered better in report.
    b. MPM-Woo: Probably not (it is intended where there is a high concentration of fines)
9. Group #1, Question 9. High vs. low hazard.
    a. From geologic perspective, high defined by caliber of sediment and debris moved, frequency of avulsion, density of active channels.
    b. Also, is stream close to equilibrium condition or not, it area tectonically active, and is there rapid deposition?
    c. There can be high hazard areas on portions, but not all, of fan.
    d. At what stage is the high vs. low question being asked? Is this a Stage 1 screening question or a Stage 3 definition question? If Stage 1, then a simple geomorphic assessment can answer that. If Stage 3, then the proposed methodology can answer that.
10. Group #1, Question 10: Best way to use the method
    a. Both delineate flooding and delineate "no build" zones.
11. Additional comments
    a. Q1 – Yes, some kind of hazard. The term active leads to regulations on active alluvial fan flooding.
    b. Q2 – Maricopa County
    c. Q3 – skipped
    d. Q7 – If active alluvial fan flooding, then no.
    e. Q8 – Virtual levee scenario. But if you don't know flood sequence, it's hard to do.
    f. Q9 – Yes, it is defensible
12. Group #2, Question 1-2:Alluvial fans vs. alluvial plains
    a. Proposed new procedure- see excel files
    b. Use depth/velocity in fan surface
    c. Avulsions never really totally abandon parent channels
    d. Be aware of legal definition of avulsion (from boundary work, riverine)
    e. FDC feedback:
        ii. Is it a good check if engineering and geomorphic results are the same?
            1. BRP Answer: We have same kinds in fans in Pima County
        iii. Is new terminology needed in stage 1? See discussion.
        iv. How much would we need to elevate? See discussion
        v. Do we regulate outside of FIRM? You can

vi. Active does not equal flood plain. True. But active implies some hazard.

13. Group #4, Question 1: 100 year flood?
    a. Keep the Q100
    b. Make the maps represent the Q100
    c. Add explicit safety factor if you wish to be more conservative.
    d. FCD Feedback: Riverside County uses overlays in ordinances.
14. Group #4, Question 2: Define shallow flooding
    a. If the FCD is ok with .3 we're ok. Hazard = depth x velocity
15. Group #4, Question 3: Develop on low hazard?
    a. Yes if not a FEMA active fan.
    b. Beware of loss of attenuation due to development
    c. Regulate development density
16. Group #4, Question 4-5: No build zone and floodway zone
    a. Yes, need no build zone and floodway zone on active alluvial fans
    b. Will have to take the departments heat and politics
    c. AFACA/SCAFCA- product time concept
17. Group #5, Question 1: Return period
    a. Q100
18. Group #5, Question 2: Risk of overtopping the fanhead trench
    b. Sediment deposition is the issue. Assess potential for that.
    c. Depends on why the fanhead is cited
19. Group #5, Question 3: Flood hazard at mountain front
    d. No to all questions
20. Group #5, Question 4: Best way to asses hydrographic apex location uncertainty
    e. Location/containment of Flo 2D split
    f. At the widening point (2x upstream width)
    g. Location is Q dependent plus geomorphic surficial
    h. Submit a delineation to approach FEMA
    i. FCD Feedback:
        vii. Use HEC-RAS for hydrographic apex. What if break out occurs way upstream?
        viii. Is bulking or safety factor needed for Flo 2D to move it upstream to capture uncertainty?
            1. Treat them as channel fans
            2. If channel fan overtops, move the apex upstream
        ix. What about bulking factor?
            1. B.F. greater than 1.2 is not justified.
        x. We could estimate sediment deposit, then run HEC-RAS on top of that.
        xi. What is the difference between channel fans and alluvial fans? Is the proposed method applicable to either?
            1. Dawdy active- ultrahazard
            2. Pulses of deposition- example is climate (1.5 m thick)
            3. Channel fans are typical of arid regions.
            4. Channel fans cannot transport all sediment

5. Channel fans apex migrates upstream

21. Additional, Question 1: All active alluvial fans be considered flood hazard?
    j. Yes, should be identified as some kind of hazard
    k. The term "active" leads to active alluvial fan flooding
    l. FCD feedback: Is there a difference between fans in Maricopa County and elsewhere? They decide what is high hazard, right?
22. Additional, Question 2 Intended just for Maricopa County or other areas?
    m. Only Maricopa County
23. Additional, Question 7: Proposed methodology adequately quantify the flood risk?
    n. Yes it does.
    o. If active alluvial fan flooding then no
24. Additional, Question 8: Model multiple, sequential floods?
    p. Using virtual levee scenario
    q. RH- you don't know/load sequence
    r. Hard to do
    s. FCD Feedback: No large coalescing fans in Maricopa County
25. Confidence level in the infiltration parameters?
    t. They are defensible

Bethany's Notes

Day 1
Notes for Blue Ribbon Panel Presentation:
Refinement of Methodology: Alluvial Fan Identification & Mitigation Methods
June 2, 2010
Flood Control District of Maricopa County

Introductions

Scope: refine current PFHAM manual and make recommendations for update. This group provides critical review to the study.

Presentation by Jon Fuller
Comments (slide, p. 12):

- It is necessary to document damages to alluvial fans (Ricardo)
- Recommendation: local agencies need to do what they can to document damages after flood event. (Ricardo)

Comments (slide, p.22)

- Recommended using FLO2D below the apex (Jon Fuller)

Comments (slide, p. 22 – video)

- Summarize storm?
- 100yr, 24hr rainfall (Jon Fuller)
- What size watershed?
- 5.7 square miles, 28 (Jon Fuller)
- Rainfall over apex and on the fan
- Infiltration is turned on (Jon Fuller)
- Attenuation – temporary storage of the peak flow of water of unoccupied areas and then re-enters the stream. Makes peak flow reduce as you go downstream. On the fan water is branching out. Is it the same thing as attenuation? Or is it a different term? (Jim)
- No, there are differences in how the flow volume is moving down the fan; but the water is being stored and moving slowly downward (Jon Fuller).
- But the infiltration is not coming back to the stream
- Less than a third of a foot is not shown on video (Jon Fuller).
- Concept of numerical attenuation: found anything that numerically indicated attenuation? (Jim)
- Volume is conserved, not a numerical error. (Jon Fuller)
- Not an error, a phenomenon (Doug)
- Is MCFDC attempting to communicate the flood risk to the property/future property owner? Growing area of importance is making the public aware. (Ricardo)
- Yes, color coding allows people to understand (Jon Fuller)
- Is there velocities going over the mountain top?
- The rainfall creates sheetflow there. (Jon Fuller)

- What is the quality of the topo?
- 2 ft for Reata, 10ft for WTF 36, then had 1-2ft topo (Jon Fuller)

Comments (slide, p. 29 - video)

- Are channel banks steep (vertical) or sloping?
- They are steeply sloping. (Jon Fuller)

Comments (slide, p. 30)

- What is going on?
- This is what might go on. It considers topography in more detail (Jon Fuller)

Comments (slide, p. 31)

- What size is the material?
- At apex, sands and fine gravels. Overbanks, sands and fines. 2 ft used b/c of Maricopa County standards. Also depth dependant. (Jon Fuller)

Comments (slide, p. 38)

- The worst case would be in a 2hr rainfall instead of 24hr. (Bill)
- Maricopa County uses 6hr or 24hr storm (Jon)
- In monsoons, isn't 1-2hrs the norm? (Bill)
- B/c the volume is less, less extreme volumes with that (Jon)
- Good point for open discussion (Afshin)
- Good point, I have been researching a wash that an 1.75 hr storm overwhelmed the system more than the 6 or 24hr storm. It is a model. (Tom)

Comments (slide, p. 39)

- How do they define a small child? If the flow depth is 3ft, then the child could be 4 to 5 feet high.
- It's the standard put out be the federal government (Jon Fuller)

Comments (slide, p. 42)

- Example of alluvial fans that went down a long way, does it at some point turn into an alluvial plain?
- Yes and that is something that we can discuss (Jon Fuller)
- Do you consider it a fan all the way down? What's the point?
- The point is to identify areas that are subject to alluvial fan flooding. (Jon Fuller)
- How will it be affected by urbanization, climate change? Good discussion point. (Bill)

Comments (slide, p. 45)

- Is it the FEMA floodplain?

End of Presentation

Seed Questions

Focus Areas:

- Generated from review comments and comments that are recurring themes that have come up in discussion.
- Categories: methodology, landform identification, alluvial fan characteristics in Maricopa County, floodplain management, applications of geomorphology
- (Bill) Would it be possible to merge groups 2 and 3?
- There are no objections to combining groups 2 and 3.

- (Kyle) The modeling is a point in time characterization; active fans go under avulsions and redistributes the flow. Have concerns about how useful the hazard is for the fan. Fans are dynamic and change from flood to flood. Concerned that there is not enough flexibility to account for that. Some of the models depicted clearly the alluvial fan from a geologic standpoint. The model could be inaccurate after a flood and a re-analysis would be necessary after a flood.
- (Vick Baker) Critical question: sheet flow – relatively shallow, lower velocity. It is defined as active then becomes a hazard. Sheet flow can't happen if there is an object in the way. If there are no objects like construction, then the sheet flow won't be hazardous b/c nothing is there. Key is alluvial fan flooding b/c it will trigger regulatory response. Having a precise definition is unreal. The hazard must involve the vulnerability and the risk. Understanding must feedback into the regulation. Context must be local. Definitions need to allow for change.
- (Bob) Can map areas that appear to be a hazard, but to regulate it, it must be quantified. The model is a point in time, but it is the time now. The virtual levee idea allows analysis for other possibilities. The slope-walk and virtual levee procedure takes it beyond point in time.
- (Kyle House) The virtual levee and slope-walk concept are also dependant on the present geometry. The prediction of the future is still controlled by the present geometry. It represents an attempt to broaden a timeframe, but future changes are very dependant on geometry. If you consistently remodel, then you would have a quantification of what is out on the ground now in the active alluvial fan.
- (Bob) If the whole area has equal probability of flooding, then the whole thing would be a hazard.
- (Kyle House) Principle problems w/ Dawdy method was not differentiating active vs. inactive.
- (Doug) After reviewing the report, represents scientific and engineering work: it is better to have more info and use it. Looking at historical floods helps. Integrated approach of overlaying techniques gives you more confidence. This helps to understand where the flood hazards are. Is this document going to be a document for Maricopa County exclusively or try to expand it to other counties/states/FEMA?
- (Greg) There will be an applicability section that states that this is applicable to alluvial fans typical to Maricopa County. These fans avulse less and have less sediment. This report is geared to Maricopa County. There might be other things that other jurisdictions might want to look at. If they have similar fans they could take things from this document.
- (Bill Bull) The piedmont, slopes, fans here in Maricopa are very similar to most. Each alluvial fan area has distinct characteristics. There is erosional vs. depositions. Erosional surface can have different types of fans. Pg. 12 – there is an old alluvial fans, but it can change within 10,000 years. There are many, many different scenarios. Each channel fan tends to migrate upstream and must be considered. This is practical for use outside of MC. For each study site, identify the type of fan, how long they will persist and how different types of fans should be managed and modeled.

- (Roger Hooke) Back to Kyle's point. Key problem: question of avulsion. A layer of sediment develops on the fan that is uniform. Occurs b/c the flow is in the same place a one time and leaves other parts lower. An avulsion occurs and starts building up a lower area. If avulsion is known to have occurred, then that is a fan that is subject to avulsion – which is not always the case. The fans that have not recently experienced avulsion could be most likely to avulse. There are different sizes of avulsions. The most concerning are those that direct the flow to a different place on the toe entirely. Can we reconcile the length of time for design vs. the change that can happen over millennia? Is lateral migration an avulsion?
- (Bill Bull) Lateral migration is deposition shifts to a stream that if flowing. In order for long term deposition to occur, there must be space. Avulsion in an erosional sense is more of a concern because there isn't space for other types of avulsions.
- (Vic Baker) The 100yr flood designation will be different if there are avulsions. If you can anticipate the avulsions, then you have a more realistic was to quantify the risk. You do know something and have the topography of a predominantly erosional landscape. The report takes advantage of the information available and assesses it. Limitation is that it will change as development changes. There has to be a follow-up when original conditions change.
- (Bill Bull) Depositional and erosional landforms are very different. Maricopa County is predominantly erosional.
- (Roger Hooke) This report is not going to deal with pediments at this point. Maybe it will be necessary to discuss in the future. The lateral migration of the stream on pediments could be responsible for their development. If erosional, how does avulsion occur? The overflow on a surface can erode. If there is erosion in one place, there is deposition somewhere else, most likely in enclosed basins.
- (Bill Bull) Key point: In the middle (valley) there will be deposition
- (Vic Baker) FEMA cares about the consequence of the definition only. They are interested in probability, not time. Alluvial fan flooding to them only refers to regulatory concerns, not actual process or geomorphic beginnings. We have to develop a methodology that is applicable. You have to learn from reality as you proceed. Part of risk assessment is re-evaluation as you see an extreme event.
- (Doug) Definition of alluvial fan flooding from FEMA in 1989. It would be applied to a series of parallel steams. NRC 1996 has revised definition of alluvial fan flooding for FEMA. FEMA now has Appendix G. This would be simpler if FEMA adopted a new definition.
- (Ed Curtis) The methodology represented starts with a point in time and attempts to predict future flows. It tries to quantify uncertainty. Is there a way to quantify how well its doing to quantify the uncertainty? Is there something about the MC fans (geology) that makes this a more regional risk assessment? What level of confidence can you give FEMA that the risk/flow path uncertainty is adequately addressed?
- (Jon Fuller) Are we quantifying the risk? Answer: we are certainly quantifying the hydraulics better, but there isn't a tool to predict flow path uncertainty. There are many fans that are different throughout the country. In MC, fans have low slope. There are both high hazard and low hazard area. The greatest uncertainty/avulsion

is by the apex. These don't really affect the area downstream, they always seem to be low hazard. There is not a perfect tool to quantify hazards in high parts, but there are tools to allow FEMA to make rates.

- (Bob M) Follow up question: Is the Dawdy method ok?
- (Jon Fuller) The lower ends of the fans have lower hazards, but the Dawdy method is not ok.
- (Phil) There are existing drainages on the lower half of the fan, and these are higher hazards than other parts. However, these drainages do not change as much.
- (Bob M) The flows are more predictable on the lower half of the fan. There is less sediment
- (Phil) Question about using PMP: suggest doing multiple 100yr flood instead of using the PMP. That was the change over mult. events can be seen.
- (Vic Baker) Dawdy method: has total ignorance of where channels are and is based on probability. When the information is there, the Dawdy method has problems.
- (Afshin) Are we looking at lower frequency, lower duration for this methodology? Example 1 or 2 hr storms
- (Bob M) We need to think about the time scale. Can use really long time scale processes to look at how they behave, but need to confine it to an engineering time scale. The geologic processes don't really fit into an engineering time scale. What is the risk for the engineering time scale?
- (Roger Hooke) The fan heads would become entrenched over time, as observed by Rich. Hydrographic apexes are many times some distance from the mountain front and the area above may not be of concern.
- (Ricardo) With FEMA, everything is moving toward a GIS based system. A lot of this information is good and provides greater description of risks and hazards. Point: we are moving in the right direction and has methodologies that merit consideration for implementation. My recent experience with FEMA is that they what their minimum to be followed, but the county can always do more. The process is moving in the right direction and GIS tools should be used.
- (French) Are breakouts avulsions? Why HEC1, not HMS? Flow attenuation is key composed of storage and infiltration. What is confidence with infiltration? Have you tried another 2d model? Modeling is snapshot in time. Can a long term plan that is coherent be developed? What about developing fans? What about variability?
- (Ricardo) FEMA is launching a new program called RiskMAP. Want to develop maps that don't just show 100yr floodplain, but also include risk and have community assess risk and plan for that risk. A lot of the MC method is compatible/complimentary with FEMA's goals for RiskMAP. Every year large flood events are seen.

Group Discussion: Group 1, Methodology

- Number 2,3,5,9 are priority questions.
- Q2: Is there a minimum threshold of concern below which methodology should not be applied?

- (Phil) Difficult to generalize. Drainage area – is there a minimum size? These are not applicable to alluvial fan flooding.
- (Ricardo) Does delineation include flood hazard area
- (Jon) Is there a slope at which the flooding is not of concern b/c it is not steep enough? Or is there a different threshold due to area, etc.?
- (Vic Baker) Ultra hazardous conditions exist. There is an empirical answer. In this area, can we develop data where we can argue that alluvial fan flooding occurs? At this point we can't answer it but it can be done. We would need our own empirical data. For egr purposes, it would be an adjustifyable approach.
- (Bill Bull) Low slope can be identifies w/ ponding vs. erosional capabilities. Low slope can be damaging as well. Debris flows and avulsion will happen by apex. You can set thresholds but low slope is not associated with lower risk.
- (Roger Hooke) Ultra-hazardous – clarification on term. One way: that is the only type of situation with which we need to be concerned. Other way: used as an upper limit of hazardous conditions. Which definitions are we dealing with?
- (Doug Hamilton) Ultra-hazardous needs other components. Example: water carrying debris or water eroding your house. Ultra-hazardous conditions has more components than just hazardous. It is a hazard with an additional hazard, not just an upper range to hazard.
- (Kyle House) Is this a question about a threshold no longer making it an alluvial fan or no longer making it dangerous?
- (Phil) Is is an attempt to define a point where the fan changes to an alluvial plain?
- (Jon) This question encompasses all of these.

- Q3: Discussion.
    - (Kyle House) 1. Why would you want to do that if you can find a competent geomorphologist? 2. Collect LIDAR data and use surface texture analysis.
    - GIS analysis and delineating fans based on slope: need to do slope/roughness mapping. Relates to Q2, is there a min threshold. Do you have radial topo contours? If yes you are prob. On a fan.
    - (Bob M) 1. What is the purpose of stage one? Not to delineate the hazard, just to identify the landform.
    - (Bill Bull) Some of the cone shaped landforms in MC are only pediments
    - (Phil) Stage one is reconnaissance, why would you want to make it quantitative?
    - (Jon) The topic has come up in team meetings and the idea is to eliminate subjectivity in identifying the fans vs. the plains.
    - (Vic Baker) There seems to be an assumption that there is an absolute distinction. The concern is that the next steps eventually leads to regulation. The regulatory thing involves actual processes and these processes can happen on both an alluvial fan and a pediment. We are getting caught up in a precise distinction. There isn't an absolute way to

  - do this. When landforms are identified, it is intrinsically subjective, which isn't always bad. Detective example. Someone experienced can identify the landform in stage one. This definition will trigger many consequences.
  - (Bill Bull) Don't limit fans to slopes. Example: San Joaquin Valley where there are low slopes, but are rapidly accumulating.
- Q5: Discussion
  - (Joe) It is a reasonable method, b/c it uses as much info as possible to define the risks. Anytime there is more info to make it more accurate, it is an improvement. The virtual levee scenario and a currant snapshot is better than what is currently being used. If this is viable, there should be something regulated that it there is a lot of change, then it needs to be re-evaluated to have an accurate representation to the updated situation.
  - (Bob M) In the mechanics of it: Is the virtual levee enough to adequately quantify the hazard, or should more types of model runs/scenarios be done?
  - (Ed) There could be variations in the topography that would reflect the results. When have you run enough scenarios? How many do you before it is enough?
  - (Joe) The flood hazard on the map for FEMA must be based on current conditions. There will be an element of elevated risk on an alluvial fan. The base level of condition is going to be a situation of elevated risk on a fan. This is a good way to capture that. The whole fan needs to have a base level of risk, then the higher risk areas can be shown.
  - (Phil) Slope-walk scenarios: how would these work with virtual levees?
- Q9: Discussion high hazard vs. low hazard fan
  - (Kyle House) From geological perpective: caliber of debris/sediment, density of active channel environments, evidence of lack of stability, evidence for avulsions
  - (Bill Bull) Whether the stream at the site is close to equilibrium. Not steady state, but short term erosion. The hazardous is rapid deposition, tectonic activity, not in MC.
  - (Joe) Quantifying high hazard vs. low hazard. No matter what type of characteristics there will be higher vs. lower hazard areas. Look at the individual fans, not fans as a whole. Beneficial to quantify the hazard based on the individual fan, not define hazard levels as a whole.
  - (Vic Baker) In question, unclear that this is necessary in the early part of the methodology. Could be better in latter part of methodology. Do it after methodology and define some criteria that makes it high hazard. Unclear in question if you want early criteria or later criteria to determine hazard level.
  - (Jon Fuller) Question intended as screening
  - (Vic Baker) This could be a sorting criteria which determines which fans are more of a risk. Geomorphic process then needs to be involved.
  - (Bob M) The question can be asked at any stage, it is different depending on the stage.

- (Phil P) In stage 2, asking which areas are high hazard, not if the fan is high hazard.
-

Group 2:

- Q1: Discussion alluvial plains vs. fans
  - (Kyle House) Tansition between two is gradational. Look at rate of change slope, not necessarily just a slope. Also sedimentological phenomenon. Geologic criteria can be used and will be a little bit arbitrary. Change in contour pattern as well from radial. Not going to be simple.
  - (Doug Hamilton) In certain places once you go far away from alluvial fans, the countour lines become parallel and then there are arroyos, incised channels. In the active wash in an incised alluvial fan it is extremely dangerous. It is also extremely dangerous on an alluvial plain. In this case we don't have alluvial fan flooding, but can identify where the most hazardous areas are. In a plain there is a great deal of certainty as to where the water will go.
  - (Phil P) Downstream sheet flooding becomes more important than channels. The alluvial plain areas can be seen by modern photos, not very quantitative. Avulsions are not likely to occur in plain environments.
  - (Bill Bull) Is there a decrease in hazard as you go downslope?
  - (Phil) Cannot make that generalization, it would be case by case.

Group 4

- Q1: Discussion
  - (Doug Hamilton) Should we use 200yr, 500yr flood? One study used 100yr flood and added a factor (high as 2 or 3) to account for various conditions. This methodology was adopted in 1930 and is standard. But for alluvial fans, the hazard is more than just flowing water and applying a factor is one way to compensate.
  - (Vic Baker) Is this the right question? Are we interested in risk? Risk is not just probability, and the 100yr flood is a probability factor. This is not just mapping inundation. We should be mapping risk not the 100yr flood. It is quantifiable. Risk where we include some measure of high velocities, sediment, etc.
  - (Roger Hooke) The 100yr flood is a means of getting at risk. The 100yr flood is used to determine velocity vs. depth. Then risk is assigned. The question is what means do we use to get at risk? Part of that involves the small child scenario, part involves the size of flood, etc.
  - (Ricardo) Should you provide protection and regulate beyond the 100yr flood? In Central Valley, CA: there are higher standards than the 100yr flood and the 200yr flood is taken into account. It depends on what is being protected housing versus school or high density of housing. Should local community require higher amount of protection to be in place?
  - (Kyle House) Some channels on an alluvial fan will be more risky for a lower flood. Geologically, these can be delineated easily. It is harder to assess risk.

- (Phil P) Is there a standard for the factors? No one knows how frequently significant avulsions happen.
- (Roger Hooke) One consideration: estimate of the 100 year floods are base on the last 40-50 years. Things are changing in ways that are likely to make larger floods more frequent. Being conservative is good and a factor might provide some extra safety.
- (Bill Bull) Global climate change. 2 factors: urbanization on streamflow creating impervious surface, and is global climate change changing enough to affect AZ? There will be an impact in AZ. Possibly more rainfall? Stronger monsoon storms? Major event in 2006 in Sabino Canyon that generate debris flows is an example.

Last Comments

- (Debbi) Tomorrow: groups.

Day 2

Where is it reasonable to define the slope of the fan?
Want to stay within FEMA regulations
Does this method restrict the hazard on the fan?
Want recommendations on how to proceed.

(Phil) Did Jon's presentation attempt to define alluvial fan vs. alluvial plain?
(Ricardo) Appendix G is guidelines, not regulations. It is more flexible than a regulation and can be varied a little bit.
(Bill Bull) All three types of fans are lumped into one category in FEMA. Discontinuous ephemeral streams are common to MC
(Jon Fuller) Chapter 3 deals with alluvial fans vs. alluvial plains. There is a fair amount of overlap between the characteristics. Alluvial plains can occur on alluvial fans and can make for confusion in stage 1. Regardless of what the definition is in stage 1, if there is flooding, it should be active. NRC the standard of alluvial fan flooding is different than FEMA guidelines.
(Bill Bull) Goals of groups
(Debbi) Based on question sheet – these are the groups.

Group 1

- Near the apex there is a lot of sensitivity and uncertainty.
- Appendix G- there is 8 different examples using composite methods. If it overtops, it will probably steepen and become dangerous.
- It is hard to set a clear boundary on where things change? Does it have something to do with slope.
- It is hard to get everyone to agree on where the change from fan to plain occurs.
- One methodology needs to be followed.

- To what extent was Appendix G used for the draft report? We made the draft to be as compatible as possible with FEMA, however there are some areas that do not quite fit.
- Goal: recommendation on whether or not the draft is good.
- End product is one final recommendation
- First three questions: this method is reasonable. FLO2D is a good way. Minimum threshold is irrelevant and the hazard should be looked at. There is no minimum. Find a way to get hazard out of quantification. Start out and do rigid boundary FLO2D model and get hazard. Then think about uncertainty. Virtual levee idea is right way to go, but can be refined. Work harder to find where high risk areas are. That should determine the scenarios.
- Overall, as a group, is this a better methodology?
    - Yes
    - It is unsafe to assume that this methodology is better to use than other methodologies. It is more realistic and uses more information.
    - For an active fan, it says use the fan model not hydraulics on an active fan.
    - Table G-1, you have to use the fan if its active. But hydraulic models have been used in conjunction.
    - Effective FEMA maps are in place using 2d modeling
- If the big area cannot be defined, then look more closely to see which areas don't have a chance of getting flooded (stage 2).
- Stage 1 – you declare fan landform, then find an area that cannot be flooded. Do you have the flexibility to eliminate parts of that fan from being hazardous? Yes. How do I prove that its not active?
- If proven that the fan is inactive, then that is ok.
- Are we on the right track or should we go a completely different direction? Then the next question is what would you do to improve it?
    - The basic approach is fine. We need to think our way though suggestions to improve it.
- FLO2D shows the flooding hazard.
- Virtual Levees are to try to figure out the hydrologic impacts of avulsion (Q). There was conformity of flow depths at the bottom regardless of the levee. Where to put levees? Goal is to produce differences in end members.
- Another area is historical locations
- Refining virtual levees: is there more that can be done. Is it arbitrary or look at landform and historical evidence, do an initial assessment, find apex and work way down fan. Can look at areas further down but use lower discharge b/c the flow of the whole mountain is not necessarily there.
- We suggest that you use max discharge from the upstream portion location out of various scenarios.
- The flow isn't in one single channel.
- Flo2d: attenuation: the hydrograph peak is going to be different for each stream path. Do you add the peaks of the hydrograph or based on time so that the peaks don't line up?
- Flo2d takes all of that into account and will combine it in the appropriate timing.

- How did you determine where water would go?
- Apply engineering judgment by looking at channel patterns. That is also one of the differences between FLO2D and HEC-1. FLO2D you do not have to tell it.
- Check cross sections down the fan? Yes.
- There is an infiltration component in FLO2D.
- Major consideration in flooding is infiltration and the conditions.
- Looking at no infiltration on fan, the peaks still had no attenuation.
- There is a suspicion that the model is over accounting for losses.
- FLO2D is assuming there is infinite amount of infiltration. Need to define level of infiltration. Already counting the pre-wetting.
- At some point, you can't model for every storm. The 100yr storm needs to be taken into account.
- Are we always held to the 100yr storm or is there another condition that would also create a 1 percent chance?
- The 100yr storm is usually used unless proven otherwise.
- What it 2 200yr storm occurs 2 hours apart?
- Can be modeled with flo2d.
- FEMA's 100yr flood in some cases is not the best way to measure the fan
- The method is a means to help you be reasonable
- The methodology should be pursued: agreed.
- Dependant on high quality topo. Needs to be a least 2ft contour
- It is reasonable if you have topo to support it.
- The methodology needs to address uncertain flow paths. In order to do this there are virtual levees, slope walk, and blockage.
- Number of methods that show whether there is a potential for avulsion.
- Does the proposed methodology adequately assess risk?
- Q 2,3,7, and possibly 8. 3 and 7 most important.
- Determining the hazard is important, finding a threshold based on slope is not necessarily important.
- How to define hazard (based on depth, velocity, uncertainty. Have repeatable, quantifyable method)
- Line dividing flow path uncertainty vs minimal flow path uncertainty.
- Virtual levees may define that
- Looking at modeling results, specific characteristics vs thresholds.
- A geomorphic component is necessary, can't just be based on a model.

Q2:

- Idea of applying specific criteria I don't agree with.
- The depth, velocity, uncertainty, sediment is what the hazard relies on.
- If there is still flow path uncertainty, we have to use more of a fan method.
- Where does the uncertainty become small enough?
- Agreed it's not necessary.

Q3:

- At stage one its unnecessary

- Its is a reconnaissance level, figure out first if you need to apply the methods

Q4: Detailed Studies

- To identify if its active vs. inactive, there needs to be a detailed analysis
- Quantification is different than the geomorphic
- Yes.
- One approach three broad boxes: high hazard, very low/not hazard, in between. The in between stage is where detailed studies come in.
- Yes, helps allow for focus on where detailed studies need to be.
- Needs to have geomorphic and computational component in stage two

Q5: Virtual Levee

- Yes, it is an attempt to account for flow path uncertainty if it might exist on part of an alluvial fan.
- Specific recommendations for approval.
  - Formalize how to use techniques
  - Define where likely areas are for avulsion
  - Partially geomorphic, but also has a sediment transport component
  - Look at historical evidence of past avulsions, areas of high probability of sediment transport, and virtual levees
  - Want to first map areas on the fan and avulsion areas, then set up virtual levees.
  - Mark on map avulsions areas.
  - The avulsion incision process is not modeled by FLO2D. Blocking a channel is more realistic

Q6: Should a safety factor be applied?

- No, these are two completely different processes.
- May be places where bulking flows is applicable
- Thinking about floods that inundate the entire fan's surface.
- Virtual levee is preferred over applying a safety factor or larger flood.

Q7: FLO2D vs. HEC-1

- Some 2d models are a lot better
- 2D models are the appropriate tool
- If significant area of flow path uncertainty, the fan model may still need to be used for that from the apex down to some point. Below that, a 2d model can be appropriate for FEMA. In areas that have enough high hazard and uncertainty.

Q8:

- Dependant on grain size distribution and hydraulic conditions. Case by case.
- Different equations are applicable in different scenarios
- In general not one cookbook process

Q9:

- Based on velocity, depth, uncertainty, stuff in the water
- The concept of the curve is the right way to go.
- The concept of the curve can help with delineation
- Need in depth analysis to determine high hazard.
- Can't assess hazard level with solely a simple model
- Need to find high hazard area within each fan

Q10:

- MC: cannot put structures in the floodway
- In MC, the Dawdy method would not be used
- Administrative floodway based on degree of hazard. Floodway would cover the highest degree of floodway.
- Proposed method: mult. simulation.
- Don't feel comfortable with overstated Q

From sheet Q2: Methodology only for MC

- To be recognized by FEMA, better to keep it just to MC. Report geared toward MC
- Better case to just keep it with FEMA

From sheet Q3: How should we approach getting FEMA approval of methodology?

- Confine to MC
- Start the process.
- Seems like the methodology is in right direction. Have historical documents, peer review, etc.
- Take it through MT2 process with methodology for approval

From sheet Q7:

- Seems like it
- Good general idea
- If its an are a of an alluvial fan flooding, then it is not adequately addressed
- It quanitifies it, but hard to know that its adequate
- The methodology quantifies flood risk.

From sheet Q8:

- Do mult. sequential floods alter the flow?
- If it does, it needs to be remodeled.
- Big floods need to be photographed
- Depends if the topography changes, and if so, new data needs to be gathered
- The virtual levee process is for this purpose
- What is it that causes flowpath uncertainty?
- Erosion is not addressed

From sheet Q9: What is confidence level of infiltration values from FLO2D?

- If values are defensible, it seems to be a reasonable analysis
- Conducting a sensitivity analysis to determine
- If fan area is accurately defined.
- Active alluvial fan is associated with high risk.

Q1: Is the proposed methodology reasonable?

- Needs to be dependant on quality of topo
- Method is reasonable

Alluvial Fan Blue Ribbon Panel – June 2cnd Meeting Notes from T. Pinto

- Is one of the goals of this project to improve communicating the risk to the public?
- Debris flow – not an issue in M. Cty
- What is the perseverance of these land forms?
- How will they be affected by urbanization and/or climate change?
- 2-hour storm vs. 6-hour or 24-hour storms – 2-hour storms generate less extreme volumes and peaks but could be more intense and damaging; also, depths and velocities could be higher.
- How useful is it to have a model for areas that are dynamic?
- Kyle House suggested having a system in place to monitor changes after floods that change the geometry of the fan; also recognized that the floodplain should be re-mapped. But how do you do this if development is already being permitted (and may not be in a SFHA today) but yet the area is always changing?
- Hazard definition – problem defining sheet flow as a hazard; FEMA wants a precise definition of a hazard but it's a moving target.
- Bob M. – can map areas with geomorphic processes as a hazard but to regulate it, we need to quantify it. Jon's approach with the rigid/virtual levee helps cover more than a single point in time; slope walk approach accounts for a few of these issues as well.
- What happens to existing geometry with dramatic events?
- The rigid levee approach (and the other methods used by Jon) represents a scenario of events but accounts for one event and not a series of events; i.e., perhaps an iterative modeling process would accomplish this.
- Bob M – if we implement an iterative modeling approach, the alluvial fan will cover a large area and the results would be similar to the Dowdy (sp?) approach (which didn't distinguish between active and inactive fans).
- Doug H. – better to have more info and use it; Jon did a good job in identifying the hazard in where it is today. Will document be expanded to be used in areas outside of Maricopa County? Greg answered that the report will have an "application area" section but that it's geared toward M. Cty.
- Bill B. – he thought this approach has a lot of applicability to other areas; categorized in meaningful ways; different fans will respond differently and on different time scales; mentioned the perseverance effect; M. Cty has tectonically stable mountains.

- If avulsion has occurred, then that does not necessarily mean that it will be avulsive again; maybe the fans that have not avulved (sp?) are more prone to avulsion?

- Degrees of avulsion – should the small and large degrees of avulsion be characterized the same?

- Time scale of avulsions – what do we define? 100-yr period vs. geological?

- We don't have uplifting mountain fronts in M. Cty.

- Methodology can designate a probable risk.

- Depositional and erosional hazards are different. Depositional – not much in M. Cty.

- Roger H. – Pediments are poorly understood but don't need to address at this time; how does avulsion occur if pediments are erosional since avulsion is depositional?

- Consequences of definition – FEMA doesn't care if it's pediments vs. alluvial fan

- Methodology - must decrease human risk and compromise with…..?? ; must be flexible;

- If an extreme event occurs, then we need to study it "like mad".

- Ed Curtis – Deterministic vs. Probabilistic approach; are we quantifying the risk? Jon said yes with respect to hydraulic characteristics but it's difficult to quantify the flow path uncertainty.

- FEMA should recognize that there are different levels of risk on the fan; the apex has the greatest risk of avulsion and uncertainty but with the "levee method", it doesn't really affect the hazard downstream so in a sense it can be quantified.

- Risk is a quantification of uncertainty not vice versa.

- Phil P. – suggested using multiple 100-yr floods with changes to topo to help quantify the hazard verses the PMF

- Mega flood – has never happened in history (is this true?)

- Dowdy method – it states huge risk and requires significant flood protection verses a neighbor building in a wash that supposedly has a lower risk; violates common sense; Jon's approach is much better.

- Higher frequency storms & the 2-hr 100-yr storm need to be evaluated.

- Time scale – use long term to define/explain why it looks the way it does but use engineering time scale for FEMA/regulatory.
- Hydrograph apex distance – need to consider
- Dr. French's questions/comments:
  - Are breakouts avulsions? Why HEC1 and not HMS?
  - Flow attenuation consists of 2 things, storage and infiltration. How confident are with the infiltration values we use?
- Tipping points – are there tipping points from development?
- FEMA Risk Map program – similar to this process.
- Is a minimum threshold of concern? Phil P. said no.
- Can we develop data in this area (e.g., slopes, etc.) and correlate the data with risk?
- Can set thresholds but flat slopes dot necessarily mean that there's no hazard; i.e., the hazard could be different, such as ponding.
- Ultra Hazardous – additional component than being inundated with water; ultra-hazardous could be defined as a hazard that would kill a person.
- Stage 1 – someone asked if this stage should include numerical methods/equations to quantify some parameters.
  - Kyle and Bob M. both responded by asking why would you need to do this since it's a stage 1 assessment and recon level, so what's the point. All you need is a competent geomorphologist.
  - Vic Baker stated that if a process/method is intrinsically subjective does not mean it's flawed (I liked this comment).
- Fans should not be defined using slopes because in CA there are areas with flat slopes but still have high levels of deposition.
- District question: If the topo changes due to development or floods, then does the fan have to be restudied?
  - Bob M. said yes; using the virtual levee and completing multiple runs; determining how many model runs is sufficient is the question.
  - Joe K. said the base level of risk can be established initially.

- Ed Curtis said it depended on the accuracy of the topo.

- District question: should we differentiate between high verses low hazard fans?
  - Bill B. said we don't have high hazard fans here.
  - Joe K. said that we should evaluate each individual fan and quantify low vs. high hazard areas within the fan because each fan has an area of high risk.
  - Someone asked if this is the right question, i.e., is it in the right section (i.e., in stage 1). Jon clarified the question by stating that this was intended to be used as a screening method.

- District question – Group 2, question 1(alluvial plains vs. alluvial fans):
  - Kyle said the transition can be gradational; rate of slope change could be a threshold; geologic criteria could be used but it could be arbitrary.
  - Doug H. said incised channels can exist on both features so that an active wash on an all. fan or plain are very dangerous.
  - Phil P. said to distinguish the two you could look at modern orthoplots; he stated that avulsions are not likely to occur in the alluvial plains unless there is a perturbation.

- District question in Group 4, Q 1 – 100-yr flood or larger?:
  - Doug H. said they ask the same thing in CA; they ended up using the 100-yr flood and multiplied the results by a factor of 2 or 3 to account for debris, fire in watershed, etc., which ends up being similar to a 2000-yr flood extent.
  - Dick (?) asked if this was the right question or are we really interested in risk? Risk = probability of occurrence plus the consequence; he suggested we should be mapping risk instead of the 100-yr flood.
  - Ricardo – FEMA and the Corps are asking this same question; urban flood protection should be higher than 100-yr flood but it also depends on what you are trying to protect.
  - Kyle – stated that some channels in alluvial fans may have similar flow characteristics and hazards for the more frequent events.
  - Phil P – Does the District add a bulking/safety factor? Suggested we should for alluvial fans.

- Roger H. – 100-yr floods are based on a short history and these "100-yr" floods could become more frequent due to climate change, etc., so safety factor should be considered.

- Bill B. – Postulated that we do need to worry about climate change and discussed diatom research in Canada that verified that climate change is occurring. He also stated that the July 30 2006 event in Sabino Canyon was an 8000-yr flood (I don't know if I captured the flood frequency correctly).

Blue Ribbon Panel Notes – taken by Kathryn Gross

Questions/Comments during the Method Summary Presentation

House

Concerned about sensitivity. We are modeling a point in time but active fans change over time. The fan itself is a testament the channels do change or it would not look like a fan. Concerned about when re-analysis after an event would place a presently "safe" home into the floodplain due to changes.

Baker

A critical question is sheetflow. Shallow low velocity flows and is defined as active

Vulnerability – hazard requires development. Anything placed in sheetflow will concentrate the flow. "Idealized" points in time.

Original 1996 Question "FEMA wanted a precise definition" - reality is fans are a moving target, process – continually evaluating what is occurring. Context needs to be able to be defined locally

Mussetter

We can map areas geomorphically in order to get into a framework but for regulation and mitigation we need the engineering

Virtual levee is a means to get beyond single point in time

House

Commenting on virtual levee and slope walk – concerned since it still relies on the current geomorphic configuration. Recommended iterative model process changing the topo

Mussetter

Following up on House above – if it was all equally possible than Dawdy should be applied but

Hamilton

Flood Insurance/Regulatory Framework. Reviewing the report: it represents a lot of scientific research. If we have information on the fan then we should use it.

The method presents a number of different ways to understand the hazard today – still out on whether it will apply 20 to 30 years from now (need for re-study of areas in future)

Greg Jones – Question: Is this geared for outside MC/ applicable to MC

Bull

MC is not an isolated entity

This will work where similar fans are found – Non-tectonic basin and range fans

Each fan can be classified

Plains/coalescing fans

Pediment discussion – erosional landform

What we have is small fans diverging dropping sediment, braided channels

Potential for channel fans

Do not have Dawdy type of fans

How long do we expect the fan type to persist? Landform perseverance

<u>Hooke</u>

Key problems here.

Uniform deposition - layer of sed comparatively uniform

Occurs when flow being in one place and building it up leaving other portions lower

Avulsion will concentrate flows into other areas

If avulsion is known to occur than fan is subject to avulsion

Fans that have not experienced avulsion are primed and others are relatively stable since the avulsion has already occurred

Avulsions: total redirection, small shift, lateral migration of the channel

Ones of the most concern are the ones that redirect flow to different portions of the fan

Millennia versus design

Avulsions are not frequent but drastic

<u>Bull</u>

Depositional shifts can promote shifting of flow. In order for long term deposition (to occur?) you need to create space for the deposition, typically done by mountain uplift (KAG note – accommodation space in lit)

<u>Baker</u>

Agree with Bull on process

100 year flood designation – but you could switch

This method provides a way of accounting for ....

You know something – know topo.. on predominantly erosional surface

System and surface (development) will change

<u>Bull</u>

Term introduced: Erosional Piedmonts

<u>Hooke</u>

According to report do not need to worry about pediments

How do you get an avulsion on an eroding surface (avulsion needs sediment deposition)

Closed basins should be depositional environments

If you are eroding you must be depositing somewhere

<u>Baker</u>

If we trace term of definition of alluvial fan..

All FEMA wants to know is probabilistic numbers not process

<u>Baker</u>

Mountain fronts are inactive brings a different behavior to our fans

Defining hazard look to definition

Develop a methodology that minimizes public risk to the hazard

Compromise – do not set it completely in stone. Learn from reality as you proceed

Part of risk assessment is re-evaluation of the situation

<u>Hamilton</u>

Definition of alluvial fan flooding

Discussion on the definition "there is no definition"

Challenges of a nationwide program

<u>Bull</u>

You are studying "piedmonts, not fans"

Curtis

Agree with house point in time with method but attempt to handle flow uncertainty

Deterministic approach of uncertainty

Using info to develop a flood map – is there a difference, is there something about MC fans that can be used, what level of confidence can you provide?

Jon Fuller Question: Are we quantifying risk? Certainly quantifying the hydraulics better, flow path uncertainty is uncertain- any suggestions. MC fans are different results in how the uncertainty is handled

Hamilton

Should the above question be reversed?

Mussetter

Intrigued by result – upstream does not necessarily influence downstream

Pearthree

Suggest we consider multiple 100 year floods with changes to topo (?)

A mega flood?

Baker

There is a definition of mega flood (1 million cms) do not use mega flood

Dawdy method assumes no info but we do have information. Jon's method is an improvement

"does not violate common sense"

Mussetter

We need to think about time scale

FEMA context should confine to engineering time scale

Actual process is much longer timescale what is the risk of getting that significant event

Hooke

Stability of the landscape

Rich described landscape evolution – basically amounts to mountains wearing down from fans, fans would become entrenched

Implication – one may not need to worry about above apex

Ricardo

Dealing with FEMA for years regarding changing policies

Very difficult to get FEMA to change

Everything moving to GIS

Moving in right direction.....

FEMA wants to follow their requirements and locals can be more restrictive

Methodology – 2, 3, 5, 9

Is there a minimum threshold – slope, Q, Watershed Area?

Pearthree

not applicable, not seeing a point to doing this...

Pineada

Threshold for determination? Or FEMA? Is there a slope below which an alluvial fan floodway would not be a concern?

Baker

Alluvial Fan flooding defined by abrupt deposition/ultra hazardous...

No abstract answer, could develop an empirical answer based on MC fans if develop the data

Bull

Is there a concern – low slopes could have their own problems

MC fans are low hazard

Not fond of automatic low slope criteria – different kind of risk

Hooke

Clarification of ultra hazardous

(1) One way we need to be concerned
(2) Upper limit of hazardous conditions – this needs to be clarified in the report

Hamilton

Idea was river floods....

Ultra hazardous – water eroding foundation/house filling with sediment that was the original idea

How Can Stage 1 be Quantified

<u>House</u>

Why would you want to do that?

One approach might be to collect LIDAR surface texture analysis, scour analysis

<u>Lancaster</u>

GIS analysis- slope mapping, roughness, look for basic info: radial contours

<u>Mussetter</u>

What is the purpose, the stage is to determine the landform

<u>Bull</u>

Pediments, not more than 1 foot of sediment – cone shaped…

<u>Pearthree</u>

Could potential contour convexity be used?

Anything below a minimum slope is not a fan..

<u>Baker</u>

Process is backward

Processes can be associated with fans and pediments

Caught up in precise definition

When landforms identified by geomorphologists: long process, intrinsically subjective but that does not mean it is not objective

"geomorphologists are familiar with an immense amount of stuff"

<u>Bull</u>

Steep sloping piedmonts can have fans

Large fans on low slopes and high accumulating fans

Not good to use slope only as a defining character

Is the Virtual levee method viable?

Kuchenmeister

Appears to be a reasonable method, agrees it is an improvement

Given that it is fixed topo then restudy would be necessary for development impacts to be documented

Mussetter

Good approach – question about mechanics

Assumes flow forced to one side or the other, is that enough? Recommend greater suite of XX (can't read my notes)

Curtis

Concerns regarding accuracy of topo being used for modeling – need good scale topo

When you have run enough scenarios

Kuchenmeister

FEMA current policy future condition cannot be shown on FIRM (kag note- App G discusses that future flow paths should be accounted for)

Pearthree

How would slope walk tie into the use? Would slope walk assist in identifying where levees would be placed? Jon answered "Yes"

How to differentiate high and low hazard

House

Caliber of debris and sediment, recent channels, density of number of channels

Lack of stability

Bull

Whether the stream is close to equilibrium

Hazardous – rapid deposition – tectonic mountain front

Kuchenmeister

Would like quantification on the specific fan hazard areas

Each one will have an area of high risk

Baker

Typical reaction – Are we asking the right question

Do we want to say this at beginning or end of the method?

Objective criteria and at end determine where fall in the criteria

Mussetter

You can ask questions at any stage then can quantify and refine

Pearthree

Answering through the Stages which area are high hazard

How can we distinguish between alluvial fans and alluvial plains?

House

Know it when you see it or when you are on it

Not at specific slope threshold

Rate of slope change might be consistently applied

Sedimentological phenomenon, channel dynamics change

Local standard

Change in nature of contour pattern

Hamilton

In certain places when you get away from fans contours are parallel

Certainty of where flooding is to go

Pearthree

Lower parts of fans

Sheetflooding becomes important

Channels smaller distributary channels have minor overbank flooding (?)

Overbank flooding is major

Bull

Clarification – map decrease in hazard as you go down slope?

May not be able to make that claim

Group 1 Report

1. Is method reasonable?
   - Yes, there are challenges and you need good quality topo data

2. Is there a minimum threshold?
   - Slope and D/A are not appropriate way to do it
   - Use depth and velocity to focus on hazard
   - Amir question to group – is there a slope that can be defined as not alluvial fan? Answer from group: slope in of itself does not define a fan

3. Can Stage 1 delineation be quantified?
   - Reconnaissance process – why would you want to add to it?

4. Are detailed methods needed at Stage 2?
   - Discriminate between active and inactive
   - Some modeling is already suggested and that seems reasonable
   - Tom question to group- should Stage 2 be tightened up with more data? Answer: defer to another group who may present the answer

5. Is virtual levee viable?
   - In general, yes. Hazard depth velocities
   - Does quantify uncertainty; helpful to constrain iterations/runs
   - avulsion frequency.....
   - may need to go a little further when the method is applied – refine

6. Should we use virtual levees or mega flood
   - Cranking up the flows does not answer the question
   - Virtual levees handled the uncertainty

7. Modeling tools?
   - Two-dimensional is the way to go

8. Sediment Transport functions?
   - Depends on grain size and hydraulic conditions

9. High hazard low hazard fans?
    - Look at your data to distinguish the differences

10. What is the best way to use method or determine no build zones?
    - Active fan – stuck with Dawdy (kag comment – no we are not..) but still can use local designations and floodways

11. Should all active fans be considered hazard areas?
    - Based on current definition

12. Is the method intended for MC?
    - Yes, but if method work then it theoretically could apply elsewhere with similar fans
    - From FEMA perspective, keep it local

13. FEMA approval?
    - Go through MT-2 process

14. Does it adequately define adequate flood risk?
    - Define "adequately"
    - If it helps you manage and fits FEMAs criteria then yes

15. Multiple sequences of fan behavior?
    - Try modeling

16. What is your confidence level?
    - Proof is model giving reasonable results
    - Sensitivity analysis – what is the range that can be used to assist answer

17. Coalescing fans?

Group Two Report

1. How should we distinguish between alluvial fans and alluvial plains?
    - Stage 1 landforms – new terminology
        i. Landform and process go together
        ii. Avoid active alluvial fan
        iii. Do want to use active for inundation
    - Stage 2
        i. 2D determine depth and velocities, avulsion scenarios

ii. Probably need avulsion frequency

- Stage 3 – 100 year event
    i. Tag different zones – active fan flooding, inundations (low, med, high)
- Compare with framework – objective criteria
- Burke question: Check with geomorphology; Baker answer: Yes it allows for consistency
- Ed question: Could you talk about adding more terminology in Stage 1 – Erosional piedmont, depositional piedmont, active mountain front
    i. Answer: Piedmonts have a variety of aspects. Suggest piedmont flooding- can work on the term.
    ii. Term that does not raise the flag on active fan flooding
    iii. Type of flooding that can occur in a variety of situations
    iv. But can look into terms

2. Are MC fans different
    - Typical of other fans in tectonically inactive areas
    - Are at one end of the extreme

3. Avulsions – Should we be concerned with avulsions?
    - Yes, they do occur. Frequency should be further investigated. But levee method does account for it

4. Is lateral migration a type of avulsion?
    - No

Group 3 Report

1. Should 100 year flood be used?
    - Yes and no
    - Protecting development/ FEMA requirement
    - Use 100 year but if want to go further recommend velocity heads as a safety factor
    - Or FEMA plus a foot (KAG comment- this is already our requirement for our floodplains)

2. What depth should define shallow flooding?
    - .3 feet - .5 feet would be "better sounding"
    - Shallow flow – depth and velocity

3. Should development be allowed on alluvial fans
    - A reasonable amount of development and fan function could occur
    - No build zones/floodways
    - Need to have open space and flow through areas – wildlife

4. Should a longer return interval be used for the model?

- Start out defining 100-year – FEMA
- Then use all available techniques to see where there might be areas that might be subject to flooding

5. What is the risk of overtopping a fan-head trench?
    - No debris flow here
    - Understand why the fans are trenched at the head – climate, tectonics, normal evolution
    - How would risk affect stages
    - Is it under estimating the hazard at trench location? Depends on the type of fan head trench, no most likely not underestimating. Might have a chance for lateral migration.

6. There is great uncertainty in identifying the hydrographic apex
    - Define apex as the point where the 100 year flow first divides into multiple channels, FLO-2D utilizes existing topo/topo may change. Lots of uncertainty
    - Although arbitrary, suggest when width is twice the width of the fan head channel
    - Run a HEC-type model and look for width and depth. Reference: Parker models for when braiding will occur
    - Bing Question: hydrographic apex is when it loses capacity, what if flows are lost above the actual point of deposition
        i. Hooke – if channel is overtopping upstream, depends on purpose of definition of hydrographic apex, FLO-2D on present topography

7. Bulking factors
    - Mussetter – numbers might seem unrealistic. Bulking factor should be less than 1.2
    - Maybe should not call it a bulking factor
    - deposition can occur at different stages of storm event
    - CA bulking factor used in areas prone to fire and debris flows – 2.0

8. How do we get approval from FEMA
    - Use the methodology on a new or existing delineated fan
    - Apply method and submit based on results along with method documentation
    - Submit through MT-2 office then it will go two ways – local reviewer and blessing at regional level

<u>Attachment #4:</u>
Written Comments by Blue Ribbon Panel Members

Panel Member Notes:

Comments received via email	
Panel Member	**Feedback**
Phil Pearthree	I was glad to participate, and enjoyed interacting with all of the panel members.
Dusty Williams	Anything I might have contributed was more than off-set by what I learned. Thanks for inviting me – I really enjoyed it.
Roger Hooke	Thanks for including me on the Blue Ribbon Panel. The discussion was quite interesting and I learned a lot. Attached is a pdf of a paper I published with one of my students in 1979. You may be interested in the section on "Low areas on fans." I mentioned this a couple of times during the meeting, but did not find an appropriate time to bring it up in detail. It might be possible for you to fit 'ideal' surfaces to your fans, as we did (see Table VI), and in that way identify areas that we 'low' and thus likely candidates for future flooding. Rohrer and I did not use the term 'avulsion' in the paper, but the diversions we were studying in this part of the paper were essentially avulsions.
Vic Baker	Yes, it was an interesting meeting, Jon. You seem to have moved a long way on getting to the appropriate way for handling this issue. It was great to see all the progress since 1996.
Jeremy Lancaster	It was a good experience overall, but I was a little disappointed for not articulating a few additional things that I wanted to add. However, it was a limited amount of time in the big group and most the people were much more experienced than myself so I was deferring to them.
Ricardo Pineda	Thanks to you and Maricopa County for the invitation. I enjoyed it and felt Jeremy and I made some positive contributions. I made it through 2 of the chapters of your report last night and will continue until complete. I noticed in the report that Pima County has additional flood zones beyond the fema floodplains in the SFHA. I think MCFCD should consider something like this similar to Riverside County and Pima County. The California Central Valley Flood Protection Board (formerly Reclamation Board) also has additional floodplains that go beyond the FEMA regulatory floodplains (they are called designated floodways). I suggest MCFCD update their cooperating technical partners agreement with FEMA to reflect the work MCFCD is doing on flood mapping and to lay out a clear path on how the work products will be integrated into
Doug Hamilton	It was a great experience be with all of you. I'm impressed at the group you assembled. Let me know if you need anything.
Dick French	Obviously would have loved to be there but... hope

Comments received via email	
Panel Member	**Feedback**
	my comments prove helpful. I really enjoyed participating.
Bill Bull	Really seems like the grand get-together turned out superbly well. The Maricopa folks seemed both attentive and enthused. Your procedure, results, and presentation came across as being flawless. Choice of wording should help the District — we don't have "FEMA fans", instead flooding occurs on "channel fans" in Maricopa County. Your 2D modeling was a big step forward, using a single hydrographic apex. Might fit the Maricopa field situation better to have a cascading sequence of hydrographic apices to simulate the actual piedmont situation of many channel fans.
Bob Mussetter	Glad I could help. I think you've done a good job with a tough problem, and I felt like the meeting went very well. Hopefully, you and the District go what you needed to finish this up.
Ramon Arrowsmith	It is an impressive, thorough, and up-to-date statement of the problem of alluvial fan hazards and methods for their mitigation. I commend you for its production and the District for its leadership in these topics. This document will guide decision making for the county and I am certain could be of use across the southwestern US and beyond. It also properly identifies numerous targets for more research and discussion.

Dick French Comments – Received via email during panel meetings

6/2/2010 2:36 pm	Are breakouts avulsions? Why HEC-1 not HMS? "FLOW ATTENUATION IS KEY" composed of two parts 1. Storage 2 infiltration. How confident are we with infiltration method and parameters? LOW HAZARD FLOODPLAIN How do you define hazard? FLO-2D Have you tried another 2-d model? DISCUSSION Kyle and Vic? Generally agree with comments. Modeling is a snapshot in time And then we have the Heisenberg principle – anything we do on the fan causes change. Therefore, unless we develop the whole fan at once, there is a dynamic situation which must be continuously addressed. Can a long term plan that is coherent be developed? Are we concerned with undeveloped fans or one undergoing development throughout some period of time. VARIABILITY Things are stable under current conditions; climate, lan use, etc.. Are there tipping points we need to consider? Under current conditions are some fans erosional and some depositional? What small changes could change this? Would prolonged periods of El Nino cross a threshold? AVULSION COMMENT Prolonged stability may lead to increased odds of instability. A system may be erosional one place but it is depositional somewhere else. ENGINEERING TIME A modeling approach is fine what about variability?
6/2/2010 4:40 pm	SEDIMENT TRANSPORT Need to be very careful – how goes FLO-2D work numerically. Can FLO-D be used easily for continuous simulation? Bill Bull? What is the cumulative effect of a lots of low frequency event. DEVELOPMENT STYLE On a developing fan do we develop from bottom up, top down, or start in the middle and go both ways? Would make a big difference. THRESHOLD First problem what is "ultrahazardous?" Are we protecting property, life, or both? If we have sheet flooding elevating on fill might be ok, but what about traveling on streets with dip crossings. So distributary flow systems could be hazardous. I could see a situation where slopes were low, infiltration were high then the flow disappears – back to infiltration. Minimum threshold yes but a result of many factors finding the factors is the key. 100-yr Seems to me it should be based on what is at risk. But where do we stop? I have done 10,000 yr flood – a regulatory requirement. 100-yr is more legal than engineering. Remember "acts of god" as a legal defense? 100-yrflood based on correlation between precip and runoff. Does a correlation exist do we know it.
6/4/2010 7:21 am	1.2 SCOPE This was the source of many of my comments; that is, identifying and mitigating hazard. What has been done helps in both areas but I see problems in joining them as ideally they should be. Joining them is a policy rather than technical issue. Related question how will these new approaches affect history – again a policy issue. I went through some of the issues when dam stability issue with the district a number of years ago. I do not know if the issue was resolved. Could you ask one of the district people to get in touch with me about HEC -1 vs HEC-HMS it's a teaching issue.
6/4/2010 7:21 am	**Sheet Flooding, p. 6:** An excellent job of attempting to define "sheet flooding" but there are still issues that should be considered such as, "(8) highly unpredictable flow … and/or debris loads." This seems to contradict the concept. "unconfined flow" While I know what is meant, all flow must be confined! Sheet flooding general occurs over topography where the longitudinal slope is slight and the horizontal topographic variation very slight. So the flow is confined micro-topography in the transverse direction. "flow depths" I am not sure that a flow several feet deep could be termed sheet flooding – I believe this is why FEMA objected to the term throughout the 80's and 90's.

	I have a suggestion. Can we add to definition the concept of tractive force? I think of sheet flooding occurring and leaving no trace it occurred. That means the tractive force must be slight. Should emphasize infiltration and abstraction losses-they are generally huge. Both MacArthur and Heggen developed sheet flooding approaches I will see if I can find references, but they were not significant works. **p. 7** "(1) structure inundation …. (7) hydrodynamic forces" These hazards do not seem consistent with sheetflow. **Section 2.3.2.3 HEC-1 vs FLO-2, p 27:** A well written section. Just two suggestions which are aimed at clarifying for readers with minimal experience. 1. The report indicates FLO-2D produces superior results compared with HEC-1. While the report suggests this superiority is not quantifiable I would suggest this be emphasized. It should equally be emphasized the FLO-2D results fit the anecdotal evidence and the behavioral expectations of the engineering and geosciences communities. 2. You should discuss the data densities used in the FLO-2D modeling. Superior results have a cost, and the required data may not be available. You might address by noting the discussion in following sections; e,g, p38. **Section 2.4.2.4 "While the Zeller-Fullerton …. Most reasonable results."** Basis of statement? **Section 2.4.2.5 long term:** This has been done on 1-D basis with interesting results. **Section 2.4.2.6:** So sediment "bulking" is not important. I am not surprised others will be. What about depths in Table 10? **p. 71:** What is LAHARZ? Reference? **Figure 54:** Would benefit from "on-figure" labels. **p. 75, "Most importantly…..:** Statement is not entirely accurate. Would suggest "Most importantly, ther is a lack *of cost effective* …

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Jon Fuller
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Dear Jon,

I am sorry that I could not attend the meeting of the Flood Control District Blue Ribbon Panel. Nevertheless, I have reviewed the report entitled "Refinement of Methodology: Alluvial Fan Hazard Identification & Mitigation Methods " prepared by you and your colleagues at JE Fuller/Hydrology & Geomorphology, Inc. for the Flood Control District of Maricopa County. It is an impressive, thorough, and up-to-date statement of the problem of alluvial fan hazards and methods for their mitigation. I commend you for its production and the District for its leadership in these topics. This document will guide decision making for the county and I am certain could be of use across the southwestern US and beyond. It also properly identifies numerous targets for more research and discussion.

I fundamentally agree with the approach advocated: "The overall recommendation of the PFHAM study is for a methodology that integrates engineering and geomorphic techniques to achieve a more robust, comprehensive analysis of flood hazards on active alluvial fans." I strongly argue that the geomorphic approach provides valuable information about materials, processes, history, and rates and its value should not be underestimated.

I have provided a number of comments on the following pages. Some of my comments are more editorial in nature and are aimed at helping to clarify the expression in the report, as well as a manifestation of my reading activity. I also reviewed the "seed questions document. Many of my answers to those questions are embedded in my comments of the main document.

Thank you and the District for the opportunity to be involved in this project.

Sincerely,

Ramón Arrowsmith

J Ramón Arrowsmith
Professor of Geology
Arizona State University

General comments

1) Audience: One thing that never really becomes clear is the target audience for this document. Explicitly, it is the management and technical staff at the District as well as the "Blue Ribbon" team. But implicitly it is many other people with various interests in the problem. On one hand, you could say this is a non issue because there are multiple layers in the activity and knowledge of alluvial fan hazards, and so different audiences are addressed by different products, but on the other hand, It might be worth reviewing somewhere early two points: a) Who is reading this report?, and b) Who is doing alluvial fan hazard identification and mitigation? For this second question, it thus helps justify the writing style and content, as well as the technical requirements associated with these activities. (Note that this comment manifests to some degree my naivete with respect to the practice. But, it is part of what the reviewers should be pointing out I suppose.)
2) Title: "Refinement of Methodology: Alluvial Fan Hazard Identification & Mitigation Methods"; maybe should also include something about "flooding" or "inundation" just to make absolutely clear the topic? For example, earth fissures are also another hazard across many alluvial fans because of their typical geological setting, yet they are not covered here.
3) Figure captions: perhaps this is pedantic on my part, but most of the figure captions are inadequate. They are often too short and don't adequately document want the point of the figure is, nor what the main components of the figures are. I guess you have to make a decision again about the audience and expected longevity of this document, but it would be good to help readers turning to a section and seeing a figure to know what they are looking at.
4) Exhaustive basic characterization of the entire county? What I find slightly awkward is the rather appropriate general and scientific approach versus the finite (though large) set of alluvial fans in the County. From a management standpoint, where does the basic characterization and infrastructural support that applies broadly and evenly across the region end (FCDMC) and the local, site-specific (probably consultant) study begin? I am sure this is a constant challenge on the mind of the District's managers; but is there a place to provide guidance of this type in this document?
5) A point made in section 2.2.4 might be worth further analysis. That is, how much of the infrastructure built for flood mitigation has yet to be tested by substantial flows? Another way to say this and maybe a plot to make would be a histogram of numbers of features tested by what return frequency flood? My assertion (needs to be tested) here is that the great majority of the infrastructure is fairly young due to rapid urbanization and has not been tested; so we don't have a good sense of the degree to which it is over or under engineered in practice. This point is also brought up in the 2.2.5 summary, but it could be highlighted and analyzed a bit further in my opinion.
6) Not much mention is made with respect to the necessary characteristics of the underlying topographic models of the alluvial fans under consideration. The topographic data and grid size issues are brought up in the sections on Flo2D modeling but this is an area where more commentary about topographic data quality and the source of the data is appropriate. As you may know, I am very impressed by the power of LiDAR-based topography and think that in many cases, it can deliver high quality alternatives to the photogrammetric topography data that the District typically employs. I had a meeting in 2009 with a number of District staff to talk about this issue. They have had bad experiences with LiDAR data, but the data quality was poor compared to what you might be able to acquire. Have a look at this link https://arrowsmith.blog.asu.edu/2009/07/24/analysis-of-lidar-data-covering-luke-wash-area-west-of-phoenix-notes-on-processing-and-comparison-with-usgs-dems and report: http://lidar.asu.edu/KnowledgeBase/Notes_on_Luke_Wash_Lidar_Survey.pdf.

7) There are many cases in the main text of the report where I would like more documentation or elaboration or citation (see below). I think that the reference to the appendices is fine, but pulling a little more up to the main text will make it more readable and provide a more balanced and appropriate level of documentation of the research activities and justification for conclusions.
8) The issue of the Tiger Wash avulsions remains a critical predictive unknown. While these events are probably rare, they represent potentially catastrophic failures of planning if they cannot be properly anticipated. Continued analysis of this problem is a good idea.

Specific comments tied to the report

Section 1.5—I was not totally happy with the clarity of language used here in this first, brief set of definitions. I would like to see three things: a) more context—an alluvial fan is part of the set of landforms developed in the low gradient portion of the terrestrial, fluvial dominated margins of the low relief basins of the region; etc. b) more quantification about the size, shape and setting of the fans; and c) an acknowledgement that to call something an alluvial fan is to make a morphogenetic interpretation. That is different from but related to the geologic, surface process, or morphologic name of the feature and its context.

The definition of active and identification of it as the focus is reasonable.

Section 2.1.1.—Would be nice to spell out the acronyms the first time they are identified (CLOMR, etc.).

2.1.2—Fan characteristics literature review. While these geometric characteristics are relevant and somewhat interesting, I think that additional effort to characterize geologic relationships for example might have been helpful. For example, does the watershed's rock type have any influence on the fan behavior in terms of grain size delivered? Or, in an alluvial fan complex or bajada, how much (area) is the active portion and what controls this degree of localization of flow?

2.1.3—It might be nice to introduce this section with another sentence or so that reminds the reader that there are a range of flow behaviors on alluvial fans, but one of particular interest for various reasons includes sheet flooding.

2.1.3--Bullet list missing word: "Flood hazards unique TO sheet flooding areas"

2.1.3--Definition(s) of Sheet Flooding and Defining Characteristics of Sheet Flooding; I think the defining characteristics is much clearer than the definitions. In some senses, the sheet flooding is not defined by high discharge and high precipitation rate, but rather the geometry and characteristics of the flow.

Hydrologic and Hydraulic Modeling Tools Specifically for Sheet Flooding Areas—The latter portion of this paragraph is a bit too terse and unclear to anyone not directly familiar with the details of modeling. I think it is worth saying a bit better that the two dimensional component to which you are referring is in the horizontal plane and the hydrograph attenuation is largely due to infiltration loss of flood volume. The latter is important process-wise because of the additional physics or empiricism required to account for infiltration and its spatial and temporal variation.

2.2.—Figure 2—This figure leaves a bit to be a desired. It would be nice to use an opportunity like this to introduce the overall physiography and geology of the greater Phoenix area. I think the shaded relief could be a bit darker and elaborate in the caption.

2.2.1.—I like these historic vignettes. Figure 3 could use a bit more annotation so that it is clearer where the features are to which you refer including the fan head, the dam, and the concrete-lined channel.

2.2.2. and elsewhere—no apostrophe for years "1930s"?

2.2.2.—Indicate location of Guadalupe FRS on Figure 4. Also, the two airphoto comparison would be more effective if the coverage between the two were exactly the same extent and I think they may not be?

2.2.4.—Annotate airphotos to point out flood mitigation structures.

2.3—Typo: "For" should be "Four"

2.3.—Show locations of fan study sites on figure 2 or other overview location map?

2.3.1. and Table 1—add a little more geology and geomorphologic description?

Figure 8—consider slightly better annotation and elaborate in caption. Indicate location on Figure 7.

2.3.1.2—Reata Pass Alluvial Fan description is nice. Figure cation for 9 could have elaboration.

2.3.1.4—Line 3 figure references need a comma and re order (Figures 7 and 11)"

Figure 11—Are those slope perpendicular lineaments in the Figure 11 caption earth fissures?

2.3.2.1. HEC-1 Modeling—I like the detail in this section with respect to the difficulties in applying HEC-1 approaches to this environment. It is probably sufficient as it is, but a few graphics to illustrate these points would be nice.

2.3.2.2. FLO-2D Modeling—What does "…flow normalized…" mean?
"aerial" should be "areal" in this paragraph?

2.3.2.3. Comparison of HEC-1 and FLO-2D Hydrologic Modeling--Peak discharges—Is it really rainfall losses or infiltration losses? Could be a semantic issue, but the process difference is important in that any near surface evapotranspiration; wind, vegetation, and microtopographic effects on local precipitation distributions is really challenging, whereas loss of the flow to the surface over which it flows is somewhat easier to parameterize.

Figures 12-15—The captions are too short; the explanation is incomplete: what is the yellow to red coloring? Calculated water depths?

Re-infiltration—Why call it re-infiltration? It is infiltration. Seems like an over complication of the language.

Flow peak attenuation—This is pretty important. The second paragraph generally captures the point that the attenuation occurs largely because of both infiltration losses as well as the distributary flow geometry and transition to sheet flood which also has increased drag due to the resulting shallow depths. Low flow velocities increase the relative amounts of infiltration and thus there is a positive feedback between the two processes.

Advantages of FLO-2D modeling—Maybe explicitly mention the requirements for high resolution topographic data (~1 m pixels for the DEMs)?

Development impacts—Important paragraph. There could be more elaboration about the direct effects of development.

Flow path uncertainty—I realize there is a lot of information in the appendices about the virtual levee approach, but another sentence or two here in the main text would be helpful to further explain how the method works and how it is a modification of the prior methods.

2.3.3.1. 100-Year Base Model—would be nice to have all of these locations on Figure 2?

2.3.3.1. 100-Year Base Model—Conclusions presented are important and interesting.

Figures 16-22—These results are compelling in the apparent natural complexity that they capture. I would like to see a bit more elaboration in the captions and a table that provides the main parameters and assumptions used in the models (I realize this is in the appendix, but it might be nice to have a summary here). Furthermore, some narrative about how the hazard is calculated and the thought process behind it is appropriate beyond the simple tabulation provided on the figures.

Figure 16—Why is the one bedrock hill yellow in the middle panel (non zero velocity)? Does not quite make sense.

2.3.3.2. Multiple Frequency Models—PMP needs more documentation/elaboration/citation. Is it spatially uniform and just scaled?

Figures 23-26—These captions are not acceptable. They are too short and don't point out the key features; and in particular don't say what magnitudes of precipitation are being modeled in each case.

2.3.3.3. Model Sensitivity Runs—Multiple channels—It is appropriate to add one or two more sentences that better explain exactly what Flo2D is doing when the multiple channel option is selected.

2.3.3.3. Grid size issues: "It is noted that smaller grid sizes can significantly increase the model run times for large alluvial fans, and that selection of the appropriate grid size requires experience, engineering judgment, and knowledge of site conditions." You might be glossing over a fairly critical point. I think that 25 foot pixels (~8 m) is still a fairly coarse representation of landforms which are controlled by features more at the meter scale. Increasingly, and if the District were to view LiDAR more favorably, higher resolution DEM data (at closer to the few foot/1 m scale) will be available. I don't think that computational run time delays are necessarily a reason not to do the modeling at the appropriate scale. You do address this point to some extent.

2.3.3.3. Model Sensitivity Runs--No Infiltration and On-Fan Rainfall—conclusion that attenuation is dominated by on fan storage is interesting.

Figures 27-30—I like this parameter space exploration.

2.3.3.4. Encroachment Impact Models—needs more explanation: What exactly was done in the Flo2D modeling to build upon the earlier related models? I like this idea, but what was done? Did you put some sort of virtual development into the fan with roads and sidewalks and engineered channels?

White Tanks and Tiger Wash hindcasting—These are very important tests and qualitative characterizations of important events. The District should continue to support further studies of these events and be ready to support study of major events as they happen in the future. The issue of the Tiger Wash avulsions remains a critical predictive unknown. I think that those pre 1997 DEMs probably leave a lot to be desired and their analysis is not going to be that helpful. Would it be worth doing some photogrammetry with pre 1997 aerial photography to produce some finer DEMs? We have had success making 5 m and finer DEMs with historic aerial photography.

2.3.3.6. Avulsion Simulation Models—I realize that a lot of this is in the appendix, but a little bit more on what was done to modify the DEMs, and also more annotation of figures 37 and 38 would be helpful.

USBR Flood Danger Level Charts. This seemed clever and interesting.

FLO-2D Mapper Hazard Classification. I would like to see a bit more commentary here, rather than just referring to the figures and tables. One thing that is definitely clear is where the probabilities come from for the calculation (are they propogated from FLO2D annual flood series?).

2.3.5. Fan Site Evaluation Conclusions; Flow Attenuation.—I certainly agree in principle that attenuation occurs and so the full apex discharge is something like the maximum. However, the language is pretty strong there and I think we don't know so much about the effects of context on the behavior of the hydrograph. In otherwords, the same flow at the end of a wet winter season or storm sequence might have a lot less attenuation than one early in the sequence. Or, you might argue that significant precipitation on a fan surface and local sourcing of runoff could counteract the attenuation effects. I think it would be worth clarifying or testing these issues.

2.4.1. Sediment Yield Analysis—how well calibrated is this approach? Is the District actively gathering data about sediment yield from the numerous impoundments and other local basins (upstream side of CAP canal, etc.) that would help to calibrate based on local conditions? There is reference to trenching and geologic work, but I would argue that there is more data out there.

Page 59—Define at least parenthetically the underlying assumptions and equations of the Zeller-Fullerton transport function.

2.4.2.2. Sediment Gradation—This needs a bit more commentary relative to the results shown in figure 48. In addition, it is worth talking a bit more about what is known with respect to the sediment size distributions at different positions along the fans in the District and how it might vary with local geologic context.

Figure 48 caption and explanations are inadequate. Explanations say flow depth, except on right where it says 100 year sed depth, and then the caption says flow depths. Confusing.

2.4.2.4. Sediment Transport Functions—might be worth having a table that explains just a bit more what these functions are and how they vary.

Figure 49 could use a nice caption that would talk a bit more about what it is that causes not only the different depths, but also the different flow paths.

2.4.2.5. Series of Events—It seems like there is a lot of literature out there; some written by members of the panel on the longer term evolution of alluvial fans. It might be worth citing some of it.

Table 10—What were the sediment rule and parameters used?

Figure 50 could use a nice caption.

Figure 51—This is somewhat confusing because some of the plots are actual hazard and some are hazard difference, yet they seem to use the same explanation and the same color scheme?

2.5 Holocene dating section—probably should say Quaternary given the age of landforms in the region. I realize that you do define Holocene, but it might be worth expanding the discussion a bit. Probably the real action in terms of landform development is the transition from the late Pleistocene (Last Glacial Maximum at 18ish ka) into the Holocene.

I do agree that an extensive dating effort (going beyond the Holocene) to develop a regional chronosequence of landscape history and landform age would be very helpful to the district and would be useable broadly. However, it would be fairly costly in terms of actual analyses and effort.

2.6. Debris Flow Potential Assessment—One thing missing here is more characterization of the upland geomorphology from topographic metrics (see Stock and Dietrich for example). If a landscape is generating a lot of debris flows, it might be evident in a changed slope-area relationship higher in the watershed.

2.6. Debris Flow Potential Assessment—One other point is that it is probably true that most of the watersheds of the County are not capable of regularly generating debris flows. But, significant anthropogenic alteration of uplands by grading might significantly change the sediment configuration and make it possible to generate debris flows.

Figure 54—Provide annotation to delineate avulsion and related features.

Table 12 is a nice summary.

Page 78—This is a reasonable approach to assessing avulsion.

Page 79—I agree with the concern about the gaps in understanding of avulsion processes.

Table 13—Alluvial Fan definition. I would say it is a landform comprised of deposits and reworked deposits modified by subsequent erosion, soil formation, and anthropogenic activity.

Inactive alluvial fan flooding: you can use riverine approaches in distal conditions, but in the proximal setting, hazards like debris flows and rockfalls are really the issue.

Page 82—There is time of both 100 years and 1000 years which is a bit confusing.

Page 83—The recommendations sound reasonable. Given that there is a lot of GIS data out there, you could try to provide some quantification in the sense taking currently agreed upon alluvial fans and computing some topographic metrics (slope, etc.), which might guide delineation so you can get away from qualitative terminology.

Page 84—I agree with the move toward an integrated classification. Too much time can be wasted splitting uncertain hairs.

3.2. Recommended Design Frequency—100 years is fine. The trick is that the 100 year behavior might need to be updated. 100 years makes a lot of sense. The reason you want to put the 500 year in there in places is because the 100 years is probably not quite right and is really reflecting a shorter return frequency. I would attack it on that end.

Page 87--hydrologic modeling recommendations—I agree with these and I think it is worth stressing the need for investigators to run lots of models to explore how the behavior of the model changes with different input parameters and local geometry, in order to built confidence with respect to the dominant controls in the particular area of interest.

Page 88—With respect to HEC-RAS, this site (towards the bottom) has a nice tutorial and thoughts by Noah Finnegan (UC Santa Cruz) about using HEC-RAS on high resolution topography: http://www.opentopography.org/index.php/resources/short_courses/lidar2_2010/

3.3.7. Limitations of the Geomorphic (Only) Approach—I certainly agree with these limitations. With respect to expertise, it might be worth encouraging the District to strengthen its partnership with the universities in the region for training and cultivation of geomorphic programs. This is a chicken and egg kind of thing: if the programs know that there is a move to promote the use of geomorphological analysis, we can build up student numbers. But if the District thinks there will be a lack of expertise, then they might be pushed away from the approach.

Table 18—Do you want to talk about some minimum mappable unit or size? There could be all kinds of problems trying to push this to fine details.

Table 19—Sounds reasonable overall. Do you want to mention something about data integration using GIS?

3.6. Recommended Design Guidelines—I would recommend that a steady effort to assess the performance of these kinds of features in the County and analogous places in the SW US should continue and the results be used to refine design.

Page 101—Pediments. I agree that it is worth moving this out of the consideration officially. However, more research should be done on the flow behavior of fans on pediments. Along with probably having some different infiltration behaviors, they may promote different avulsion characteristics, and they are often steeper. These old maps we made with the Phoenix 1:250k digital geology show some good pediments (low slope settings, but underlain by granite):
http://www.geoinformaticsnetwork.org/swgeonet/Data/phxgeo_lithtime.htm

FEMA Coordination.—I think that coordination here is a place where the District can show leadership and also pre emptively clarify a range of issues on policy, methods, and nomenclature that will save problems moving forward.

Jon Fuller, PE, RG
Principal
JE Fuller/Hydrology & Geomorphology, Inc.
8400 S. Kyrene Rd., Suite 201
Tempe, AZ 95284

Subject: Additional Comments from FCDMC Blue Ribbon Panel Meeting for Methodology Refinement to PFHAM.

Dear Mr. Fuller:

Based on my participation in the Flood Control District of Maricopa County (FCDMC) Blue Ribbon Panel and your request for additional comments, I have reviewed my notes from the subject meeting and am providing the attached comments. In addition to the meeting notes, I reviewed the following report:

> **Refinement of Methodology: Alluvial Fan Hazard Identification & Mitigation Methods, FCD 2008C007, Assignment No. 1 – Final Report;** received 5-25-2010; Prepared by: JE Fuller/Hydrology & Geomorphology, Inc., 8400 S. Kyrene Rd., Ste. 201, Tempe, AZ 85284

INTRODUCTION

The following comments are based on my participation in the FCDMC Blue Ribbon Panel conducted June 2nd and 3rd of 2010, at the district office in Phoenix Arizona. While as a participant in the panel meeting I was serving as a representative of the State of California, these comments are formulated based on my participation in the panel and my review of the referenced document. Given that senior California Geological Survey (CGS) staff were not in attendance, and the referenced document has not been reviewed by CGS management, comments contained herein should not be considered an official position of the California Geological Survey. However, these comments are based on my professional experience, care, and judgment as a registered Professional Geologist in the State of California, and I have signed in this regard.

Summary of Maricopa County Alluvial Fans

Maricopa County piedmont alluvial fans are commonly narrow as opposed to broad when comparing their longitudinal distance to their lateral margin width. Fan-heads are commonly embayed into mountain fronts where modern washes are incised and through flowing around older alluvium, branching and joining. Zones of whole flow-path migration commonly appear enclosed (confined) within older piedmont geomorphic surfaces, including older Holocene-age and relict alluvial fan surfaces. These older geomorphic surfaces appear to be grossly stable (on an engineering timescale) and commonly dissected with dendritic drainage patterns. Within the areas of historic and most recent deposition and erosion, enclosed fan areas with apparent branching and joining drainage patterns contain intervening "islands" of older fan-deposits that are mappable in their areal distribution.

Are Maricopa County Alluvial Fans Different Than in Other Regions

Alluvial fans in California are both similar and different than those in Maricopa County, based on their geographic location (See geomorphic provinces in CGS, 2002). These differences reflect the presence of, among others, range bounding faults, erodible bedrock within the upland drainage basin, colluvial swales, organic litter, vegetation and the fire/flood sequence. William Bull presented a concise description of alluvial fans based on the fan forming processes (Presented at FCDMC Blue Ribbon Panel, See Attached), including the terminology: Tectonic Alluvial Fan, Climatic Alluvial Fan, and Channel Fan. Based on his definitions, Maricopa County piedmont areas include depositional alluvial fans that occurred in response to past climate change, termed Climate Alluvial Fans. The processes that formed these alluvial fans are no longer occurring today, but as Dr. Bull warned, global climate change may alter processes once again. The term Channel Fan was used by Dr. Bull to describe the current net erosional processes involved in creating piedmont alluvial fans in Maricopa County. This description appears reasonable, as it described the landform as being dominated by erosion (channelized), but that local deposition also occurs, causing the formation of fan apices.

Many areas in California, including, the Mojave Desert, Colorado Desert, Basin and Range, Sierra Nevada, and Transverse Ranges geomorphic provinces, contain Climate Fans. A few of these provinces also contain channel fans, as described by Dr. Bull. However, another type of alluvial fan, the Tectonic Alluvial Fan, is present in California, but does not appear to be present in Maricopa County. To most geologists this is obvious; Maricopa County does not contain active mountain range bounding faults. Hence the term <u>Tectonic Alluvial Fan</u> implies the active uplift of the mountain range, increasing relief, and creating space for deposition on the piedmont. Of particular importance in describing these depositional systems, are the processes involved. Debris flow fans are commonly found along tectonically active range fronts. This is not only because active faulting generates higher relief between the mountains and valleys, but can also be due to the influence of faulting on rock masses in the form of fractures that serve to reduce erosion resistance, and thus increase sediment yields. In some areas of California piedmont areas are occupied by one landform, a single, or series of, debris flow fans. Debris flow recurrence on Tectonic Alluvial Fans in California can be on the order of decades to hundreds of years, depending on the occurrence of random extreme rainfall events, and the propensity for the fire-flood sequence within the upland drainage basin.

GENERAL COMMENTS

Debris Flow Methodology

A. The debris flow methodology outlined in the methodology update document appears reasonable. From the limited review of the AZGS debris flow paper, LAHARZ, and documentation of the predominantly erosion resistant bedrock that underlie the upland drainage basins, debris flow recurrence may be outside the range of engineering time scales. However, it appears that additional work is needed in order to assign debris flow recurrence to specific areas within the district.
B. It may be reasonable to assign bulking factors to account for the potential of rapid aggradation in channels due to debris flows or hyperconcentrated flows near the fan apices. However, many of the southern California counties use debris basin cleanout records to assist in calibrating bulking factors on a local basis.
C. Using a bulking factor of 20% (per comments made by Bob Mussetter on June 3rd) may be reasonable for floods derived from erosion of fine-grained sources because fine-grained material tends to control the viscosity of flow (Costa, 1988). However, fine-grained sources appear to be mostly absent, so one may want to explore the possibility of a higher bulking factor due to the likelihood that the lack of fines will allow higher sediment concentrations below the viscosity threshold (and resistance to shear) at which the flow will act as a Bingham fluid (As in hyperconcentrated flows). If hyperconcentrated flows are roughly 20-60% water by volume, then perhaps some research and testing will allow the district to determine a modal coarse-grained sediment concentration that may occur during a streamflow flooding event below the hyperconcentrated flow threshold when there is an absence of fines. Perhaps a greater bulking factor than 20% is possible.
D. LAHARZ and slope investigations – If debris and sediment sources are located near enough to the fan apex to contribute to blockage and subsequent flow redirection, then it may be useful to have the methods remain broad, possibly including with slope inspections, the use of surficial slope stability analyses on slopes that meet a slope, bedrock, soil, colluvium thickness criteria.

Avulsion

A. Refining the Definition – While there may be some advantages to refining the definition of avulsion, this appears to be one of the modes of flow path uncertainty on Maricopa County piedmonts; either in the form of breakouts that form new channels where the old channel is abandoned, or remains occupied, or as channel capture due to headward erosion of tributary channels on older surfaces into active channels. The process of avulsion, whether by capture, breakout, and whether the original channel remains occupied or abandoned appears to be a moot point because regardless of the cause, avulsions are one of the primary reasons why Maricopa County alluvial fans fit the definition of alluvial fan flooding.
B. Avulsion frequency - It would be useful to start developing regional frequencies because it appears that avulsions occur, and being that your piedmont areas are grossly erosional it may be reasonable to use avulsion frequencies coupled with geomorphic interpretations to constrain how many times one may want to run the virtual levee analysis. This way the modeler does not arbitrarily run the virtual levee analysis to the degree that exceeds the recurrence of avulsions in a region.
C. Debris Flow Effects – The discussion on Page 78 (final paragraph) of the update manual regarding the potential for debris flows affecting channel avulsions appears reasonable.

SPECIFIC COMMENTS

Recommended PFHAM Refinements

A. Page 100, 4th Bullet: Countywide Delineation of Stage 1. This recommended delineation is not only useful for the FCDMC drainage master plan, it may also be used by planning departments as the impetus to require communication with flood control for new projects.
B. Page 101, 4th Bullet: Countywide Delineation of Stage 2. This would be useful as indicated above, but may be used as the impetus to require detailed regulatory floodplain (Stage 3) analyses where developments are proposed.

SUMMARY

In summary, Maricopa County alluvial fans are different than other regions. They appear to be more channelized in form, having narrow active portions in relation to their longitudinal extent. They are not tectonic fans, and the debris flow hazard appears to be minimal in comparison to fans dominated by debris flow hazards in other regions of the southwest. Maricopa County alluvial fans do not appear to be less hazardous than piedmont areas occupied solely by a single active alluvial fan (or active coalescing fans), they are just not as laterally extensive in their active portions.

I thank you for requesting my involvement in the Flood Control District of Maricopa County - Blue Ribbon Panel, and look forward to any future correspondence.

Sincerely,

Jeremy Lancaster, PG, CEG
863 Washington Street
El Segundo, CA 90245

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References Cited:

California Geological Survey, Note 36, 2002
http://www.consrv.ca.gov/cgs/information/publications/cgs_notes/note_36/Documents/note_36.pdf

Costa, J.E., 1988, Rheologic, geomorphic and sedimentologic differentiation of water floods, hydperconcentrated flows, and debris flows, in Baker, V.R., Kochel, R.C., and Patton, P.C., eds., Flood Geomorphology, Wiley, New York, p. 113-122.

Piedmont flooding potential depends on type of alluvial fan and on how far removed streamflow is from threshold or equilibrium conditions. Future Maricopa flood hazards will also be a function of urbanization and global climate change.

BACKGROUND TERMS

Piedmont — A plain sloping down from a mountain front that may be coalescing alluvial fans or a pediment. Different piedmont landforms behave differently when it comes to assessing potential for flood hazards.

Tectonic alluvial fan — Thick, 100 m to > 1 km of alluvium, accumulating rapidly as water-laid and/or debris flow deposits just downstream from an active fault or fold. Tectonic uplift rate determines rates of fan deposition and channel incision upstream from the fan apex by creating vertical space for these processes. Normal faulting favors thicker fans than thrust faulting.

Perseverance timespan can be longer than a million years, during which large flow events are concentrated in medial fan areas, but can shoot off to the fan edges. The entire depositional area remains a major flood hazard zone.

Climatic alluvial fan — Created by a pulse of deposition strong enough to partially or completely backfill a fanhead trench and create a single-age surface whose apex may be where the stream emerges from the mountains. Climatic fans look like tectonic fans but have two important differences; 1) although areally extensive, the single-age deposits are thin, being only 1 to 5 m thick; 2) the source canyon upstream from the fan apex has a fill terrace created at the same time as the fan.

Perseverance timespan is only ~ 10 ky but deposition may occur at intervals of 50 or 100 ky in response to major global climate changes. The transition from Pleistocene to Holocene climates in the southwest deserts created climatic fans that are now entrenched.

Channel fan — Small alluvial fans that migrate upstream in fluvial systems where, locally, annual stream power is insufficient to entrain and transport a large sandy-to-silty sediment load. Local deposition of bedload creates a fan apex, spreading streamflows. This self-enhancing feedback promotes further decreases in stream power as flow infiltrates into the fan. Continued loss of entrained sediment causes stream behavior to switch back to downcutting, as shown by headcuts into the toe of the fan. Concurrent fan apex deposition and fan toe headcutting promote upstream migration of channel fans.

Perseverance timespan is only decades or a century. Channel fans are sensitive to climate change and human alteration of either sediment or stream discharge. Channel fans respond quickly to changes in sediment or stream discharge caused by humans or climate change.

Pediment — An erosional surface downslope from remnants of former mountains that is beveled across both bedrock and previously deposited tectonic fans. Beveling by piedmont streams requires avulsion events where flood flows shift to an adjacent strip of the piedmont. Channel-fan deposition determines avulsion locations.

Appendix K:
Project Meeting Notes

<u>Meeting #1 Agenda</u>: March 17, 2009 3:30 pm @ District

2008C007 – Task #1: Alluvial Fan Hazard Identification & Mitigation Methods

Attendance					
District		**District**		**Consultant/Others**	
	Greg Jones		Burke Lokey		Jon Fuller
	Kathryn Gross		Amir Motamedi		David Meyer
	Bing Zhao		Felicia Terry		Hari Sundaraghavan
	Tom Loomis		Kelli Sertich		Ted Lehman
	Ed Raleigh		Stacey Lapp		Mike Kellogg
	Don Rerick		Tim Murphy		Bob Mussetter (phone)
	Doug Williams		Apu Borah		Stan Schumm (phone)
	Joe Tram				Mike Harvey (phone)

<u>Agenda Items:</u>

1. Introductory Remarks (GLJ)
2. Bi-Monthly Meetings
    a. Set Regular Bi-Monthly Meeting Date & Time (Task 1.6.1)
    b. Enable Telephone Participation (MEI)
    c. Bi-Monthly Discussion Topics (Handout)
3. Literature Search Revision & Review
    a. District Comments from previous task (2007C051)
    b. Review by MEI due 60 days from NTP
4. Flood Hazard Classification Matrix (Task 1.6.3; Task 2.9.2)
    a. Schedule Matrix Brainstorming Meeting
    b. Matrix due 30 days from NTP
    c. Seed Ideas (Handout)
5. Historical Analysis (Task 2.3)
    a. Draft List of Sites (Handout)
    b. District Suggestions
    c. Analysis due 60 days from NTP
    d. Select Sites by March 24

<u>Meeting #2 Minutes</u>: April 7, 2009 2:30 pm @ District

2008C007 – Task #1: Alluvial Fan Hazard Identification & Mitigation Methods

Attendance					
District		**District**		**Consultant/Others**	
X	Greg Jones	X	Burke Lokey	X	Jon Fuller
X	Kathryn Gross	X	Amir Motamedi		David Meyer
X	Bing Zhao		Felicia Terry		Hari Sundaraghavan
X	Tom Loomis		Kelli Sertich	x	Ted Lehman
x	Ed Raleigh	X	Stacey Lapp	x	Mike Kellogg
	Don Rerick		Tim Murphy	x	Bob Mussetter (phone)
	Doug Williams	X	Apu Borah		Stan Schumm (phone)
x	Joe Tram			x	Mike Harvey (phone)

<u>Agenda Items:</u>

1. Introductory Remarks (GLJ)
2. Literature Search Summary.
    a. JEF summarized the literature search for each of the topic areas:
        i. Existing Delineation Methodologies (Mike Kellogg)
        ii. FEMA LOMR/CLOMR Methodologies (Jon Fuller)
        iii. NRC Committee Interviews (Jon Fuller)
        iv. Debris Flow Hazard & Risk (Ted Lehman)
        v. Channel Avulsion Frequency (Jon Fuller)
        vi. Mitigation Measures (Jon Fuller)
        vii. Hazard Quantification Methods (Ted Lehman)
    b. JEF provided copies of a DVD with the literature search, summaries, literature and responses to previous District review comments from FCD2007C051.
    c. Discussion questions were addressed and topics were discussed for each area.
3. Other Actions
    a. JEF will include alluvial case histories as part of future bi-monthly meetings

<u>Meeting #4 Agenda</u>: May 19, 2009 10:00 am @ District

2008C007 – Task #1: Alluvial Fan Hazard Identification & Mitigation Methods

Attendance					
District		**District**		**Consultant/Others**	
	Greg Jones		Burke Lokey		Jon Fuller
	Kathryn Gross		Amir Motamedi		David Meyer
	Bing Zhao		Felicia Terry		Hari Sundaraghavan
	Tom Loomis		Kelli Sertich		Ted Lehman
	Ed Raleigh		Stacey Lapp		Mike Kellogg
	Don Rerick		Tim Murphy		Bob Mussetter (phone)
	Doug Williams		Apu Borah		Stan Schumm (phone)
	Joe Tram				Mike Harvey (phone)

<u>Agenda Items:</u>

1. Introductory Remarks (GLJ)
    a. Project Status Issues
    b. Literature Search Review (Mussetter)
    c. Bi-Monthly Meeting Agenda Revisions
2. Historical Site #1: Ahwatukee Alluvial Fan Summary
    a. Powerpoint Presentation
    b. Discussion
3. FEMA Fan Review Example
    a. Tortolita Piedmont Alluvial Fan
    b. Powerpoint Presentation
4. Flood Hazard Classification Matrix (Task 1.6.3; Task 2.9.2)
    a. Variable List
    b. Draft Matrix
    c. Discussion
5. Action Items

<u>Meeting #5 Agenda</u>: June 2, 2009 10:00 am @ District
2008C007 – Task #1: Alluvial Fan Hazard Identification & Mitigation Methods

Attendance					
District		**District**		**Consultant/Others**	
	Greg Jones		Burke Lokey		Jon Fuller
	Kathryn Gross		Amir Motamedi		David Meyer
	Bing Zhao		Felicia Terry		Hari Sundaraghavan
	Tom Loomis		Kelli Sertich		Ted Lehman
	Ed Raleigh		Stacey Lapp		Mike Kellogg
	Don Rerick		Tim Murphy		Bob Mussetter (phone)
	Doug Williams		Apu Borah		Stan Schumm (phone)
	Joe Tram				Mike Harvey (phone)

<u>Agenda Items:</u>

1. Introductory Remarks (GLJ)
    a. Project Overview
    b. Status Issues
2. Presentation on Fan 1-2 Floodplain Delineation Methodology (JEF)
3. Historical Site #1: Ahwatukee Alluvial Fan Summary Recap
    a. Powerpoint Presentation
    b. Discussion
4. Historical Site #2: Pima Canyon / South Mountain Fan, Scottsdale
    a. Powerpoint Presentation
    b. Discussion
5. Historical Site #3: Reata Pass Fan, Scottsdale
    a. Powerpoint Presentation
    b. Discussion
6. Historical Site #4: Lost Dog Fan, Scottsdale
    a. Powerpoint Presentation
    b. Discussion
7. FEMA Fan Review Sites – Deferred to next meeting
    a. Fontana Wash Trib, Yuma, AZ
    b. Lancaster, CA Site (alluvial plain)
8. Action Items

<u>Meeting #5 Agenda</u>: June 16, 2009 10:00 am @ District
2008C007 – Task #1: Alluvial Fan Hazard Identification & Mitigation Methods

Attendance					
District		**District**		**Consultant/Others**	
	Greg Jones		Burke Lokey		Jon Fuller
	Kathryn Gross		Amir Motamedi		David Meyer
	Bing Zhao		Felicia Terry		Hari Sundaraghavan
	Tom Loomis		Kelli Sertich		Ted Lehman
	Ed Raleigh		Stacey Lapp		Mike Kellogg
	Don Rerick		Tim Murphy		Bob Mussetter (phone)
	Doug Williams		Apu Borah		Stan Schumm (phone)
	Joe Tram				Mike Harvey (phone)

<u>Agenda Items:</u>

1. Introductory Remarks (GLJ)
   a. Project Overview
   b. Status Issues
2. Literature Search Peer Review (MEI)
   a. Mike Harvey – via telephone
3. Historical Site #1: Ahwatukee Alluvial Fan Summary Recap
   a. Powerpoint Presentation
   b. Discussion
4. Historical Site #2: Pima Canyon / South Mountain Fan, Scottsdale
   a. Powerpoint Presentation
   b. Discussion
5. Historical Site #3: Reata Pass Fan, Scottsdale
   a. Powerpoint Presentation
   b. Discussion
6. Historical Site #4: Lost Dog Fan, Scottsdale
   a. Powerpoint Presentation
   b. Discussion
7. FEMA Fan Review Sites – Deferred to next meeting
   a. Fontana Wash Trib, Yuma, AZ
   b. Lancaster, CA Site (alluvial plain)
8. Action Items

`Meeting #6 Agenda: August 11, 2009 10:00 am @ District
2008C007 – Task #1: Alluvial Fan Hazard Identification & Mitigation Methods

Attendance					
District		**District**		**Consultant/Others**	
	Greg Jones		Burke Lokey		Jon Fuller
	Kathryn Gross		Amir Motamedi		David Meyer
	Bing Zhao		Felicia Terry		Hari Sundaraghavan
	Tom Loomis		Kelli Sertich		Ted Lehman
	Ed Raleigh		Stacey Lapp		Mike Kellogg
	Don Rerick		Tim Murphy		Bob Mussetter (phone)
	Doug Williams		Apu Borah		Stan Schumm (phone)
					Mike Harvey (phone)

Agenda Items:

1. Introductory Remarks (GLJ)
    a. Project Overview
    b. Status Issues
2. PFHAM Alluvial Fan Evaluation Sites: HEC1 Modeling Results
    a. PowerPoint
    b. Q&A
3. PFHAM Alluvial Fan Evaluation Sites: FLO2D Modeling Results
    a. PowerPoint
    b. Q&A
4. Next Meeting: August 18, 2009
    a. Discussion Items
5. Action Items

`Meeting #7 Agenda: August 18, 2009 10:00 am @ District

2008C007 – Task #1: Alluvial Fan Hazard Identification & Mitigation Methods

Attendance					
District		**District**		**Consultant/Others**	
	Greg Jones		Burke Lokey		Jon Fuller
	Kathryn Gross		Amir Motamedi		David Meyer
	Bing Zhao		Felicia Terry		Hari Sundaraghavan
	Tom Loomis		Kelli Sertich		Ted Lehman
	Ed Raleigh		Stacey Lapp		Mike Kellogg
	Don Rerick		Tim Murphy		Bob Mussetter (phone)
	Doug Williams		Apu Borah		Stan Schumm (phone)
					Mike Harvey (phone)

Agenda Items:

1. Intro
    a. Discussion Objective – "So What?"
        i. What do we do with the HEC1 & FLO2D results?
        ii. What gaps remain?
        iii. How do we focus our efforts for the remaining tasks / time?
2. Current Gaps in Progress
    a. Sediment transport element
        i. Assume that depth-velocity results not significantly different
    b. Debris Flow & Dating Methods
        i. Not critical path
    c. Avulsions
        i. In Progress
        ii. Examples
            1. White Tank Fan 36 apex area
            2. White Tank lower piedmont
    d. Schedule: preliminary answers by mid-October
    e. Legal questions…what can FCD regulate?
3. Q&A on Last Week's Presentation
    a. Handout: 4 FLO2D maximum depth model results.
4. Major Discussion Questions
    a. Is FLO2D an adequate tool to quantify the flood hazards on fans?
        i. Should we stop using HEC-1 below the apex?
        ii. Re-Infiltration & attenuation issues?
    b. Hazard classification methods.
        i. What are our objectives & needs?
        ii. What is basis of standard?
    c. Floodplain Management & Regulation
        i. What is minimum flow depth to regulate?
        ii. Or is it minimum depth-velocity?

d. What do we do with parts of fan landform that are geomorphically young (and are indistinguishable from FLO2D inundated areas) but FLO2D shows as non-inundated? Or very shallow inundation?
    i. Near apex (sides of fan)
    ii. Near mid-fan
    iii. Near toe
e. Floodplain zones
    i. High hazard
    ii. Shallow sheet flow
    iii. Through-flow corridors
f. What about "islands?"
g. Have we adequately accounted for flow path uncertainty?
    i. FLO2D approach is okay for estimating discharge (with uncertainty), but does it adequately model hazard in area near apex?
h. How does our approach address needs of different types of development?
    i. Master planned communities – intense engineering design
    ii. Single lot (ma & pa trailers)
i. FEMA needs
j. Maricopa Co. P&D needs

5. Technical Questions
    a. Grid sizes in FLO2D
        i. Whole fan focus
        ii. Single site focus
    b. Modeling avulsions
        i. Establishing a procedure
    c. Additional modeling scenarios needed / desired?
        i. Development impact
6. Next Meeting: September 1, 2009
    a. Discussion Items
7. Action Items

`Meeting #9 Agenda: November 17, 2009 10:00 am @ District
2008C007 – Task #1: Alluvial Fan Hazard Identification & Mitigation Methods

Attendance					
District		**District**		**Consultant/Others**	
	Greg Jones		Burke Lokey		Jon Fuller
	Kathryn Gross		Amir Motamedi		David Meyer
	Bing Zhao		Felicia Terry		Hari Raghavan
	Tom Loomis		Kelli Sertich		Ted Lehman
	Ed Raleigh		Stacey Lapp		Mike Kellogg
	Don Rerick		Tim Murphy		Bob Mussetter (phone)
	Doug Williams		Apu Borah		Stan Schumm (phone)
					Mike Harvey (phone)

Agenda Items:

1. Intro
    a. Project Status Update
        i. Task 1.7: Site Visits: DONE
        ii. Task 2.1: Literature Search: DONE
            1. Literature Fan Site Data: DONE (FCD2007C051)
            2. Sheet Flow Reports: Draft (FCD2007C051)
        iii. Task 2.2: Data Collection: Perpetual
        iv. Task 2.3: Historical Fan Sites: DONE
        v. Task 2.4: Alluvial Fan Sites: On-Going (Scoped activities done)
        vi. Task 2.5: Sedimentation: On-Going (Scoped activities done)
        vii. Task 2.6: Dating Techniques: Draft (December 1)
        viii. Task 2.7: Debris Flow Methods: Draft (December 1)
        ix. Task 2.8: Avulsion Potential: On-Going (December 15)
        x. Task 2.9: Integrated Method: On-Going (Jan-Feb)
        xi. Task 2.10: Final Report: Future
2. Task 2.4 Summary
3. Presentation of Additional FLO2D Modeling Results
    a. Sedimentation Models
    b. Q500 Models
    c. PMP Models
    d. Channel Blockage Models (WTF36)
    e. Mapping / Grid Cell Size Models (WTF36)
    f. Historical Flood Comparison (WTF36)
    g. FEMA Map Comparison (Reata)
    h. Future Modeling Ideas
4. Next Meeting: December 1, 2009
    a. Discussion Items: Dating & Debris Flow Methods
5. Review of Meeting Action Items

`Meeting #12 Agenda: December 1, 2009 10:00 am @ District
2008C007 – Task #1: Alluvial Fan Hazard Identification & Mitigation Methods

Attendance					
District		**District**		**Consultant/Others**	
	Greg Jones		Burke Lokey		Jon Fuller
	Kathryn Gross		Amir Motamedi		David Meyer
	Bing Zhao		Felicia Terry		Hari Raghavan
	Tom Loomis		Kelli Sertich		Ted Lehman
	Ed Raleigh		Stacey Lapp		Mike Kellogg
	Don Rerick		Tim Murphy		Bob Mussetter (phone)
	Doug Williams		Apu Borah		Stan Schumm (phone)
					Mike Harvey (phone)

Agenda Items:

1. Intro (Greg)
   a. Project Status (Greg)
2. Task 2.6: Dating Techniques: (Dr. Jeri Young, AZ Geological Survey)
3. Task 2.7: Debris Flow Methods: (Dr. Phil Pearthree & Ann Youberg, AZGS)
4. Next Meeting: December 15, 2009
   a. Discussion Items:
      i. Avulsion Mechanisms (Fuller)
      ii. FLO2D Verification (Loomis)
   b. Eliminate Jan 5, 2010 meeting.
5. Review of Previous Meeting Action Items
   a. FLO2D file submittal: DONE
   b. FLO2D sedimentation modeling tasks (see meeting notes): IN PROGRESS
   c. Slope-Flow Path models: IN PROGRESS
   d. Historical Fan Site Report Revisions: DONE

<u>Meeting #13 Agenda</u>: December 15, 2009 10:00 am @ District
2008C007 – Task #1: Alluvial Fan Hazard Identification & Mitigation Methods

Attendance					
District		**District**		**Consultant/Others**	
	Greg Jones		Burke Lokey		Jon Fuller
	Kathryn Gross		Amir Motamedi		David Meyer
	Bing Zhao		Felicia Terry		Hari Raghavan
	Tom Loomis		Kelli Sertich		Ted Lehman
	Ed Raleigh		Stacey Lapp		Mike Kellogg
	Don Rerick		Tim Murphy		Bob Mussetter (phone)
	Doug Williams		Apu Borah		Stan Schumm (phone)
			Ken DeRoulac		Mike Harvey (phone)

<u>Agenda Items:</u>

1. Intro (Greg)
    a. Project Status (Greg)

2. Q&A on Task 2.6 Report: Dating Techniques: (Dr. Jeri Young, AZGS)

3. Q&A on Task 2.7 Report : Debris Flow Methods: (Dr. Phil Pearthree, AZGS)

4. FLO2D Loss Rate Verification Analysis – Tom Loomis

5. Sheet Flooding Literature Search Results - Fuller

6. Avulsions - Fuller
    a. Tiger Wash 1997 Event
    b. Avulsion Basics

7. Next Meeting: January 5, 2010
    a. Discussion Items:
        i. Avulsions, Part II (Fuller)

Meeting #13 Agenda: January 5, 2010 10:00 am @ District
2008C007 – Task #1: Alluvial Fan Hazard Identification & Mitigation Methods

Attendance					
District		**District**		**Consultant/Others**	
	Greg Jones		Burke Lokey		Jon Fuller
	Kathryn Gross		Amir Motamedi		David Meyer
	Bing Zhao		Felicia Terry		Hari Raghavan
	Tom Loomis		Kelli Sertich		Ted Lehman
	Ed Raleigh		Stacey Lapp		Mike Kellogg
	Don Rerick		Tim Murphy		Bob Mussetter (phone)
	Doug Williams		Apu Borah		Stan Schumm (phone)
			Ken DeRoulac		Mike Harvey (phone)

Agenda Items:

1. Intro (Greg)
    a. Project Status (Greg)

2. Q&A on Task 2.6 Report: Dating Techniques: (Dr. Jeri Young, AZGS)

3. Q&A on Task 2.7 Report : Debris Flow Methods: (Dr. Phil Pearthree, AZGS)

4. FLO2D Loss Rate Verification Analysis – Tom Loomis

5. Sheet Flooding Literature Search Results - Fuller

6. Avulsions - Fuller
    a. Tiger Wash 1997 Event
    b. Avulsion Basics

7. Next Meetings:
    a. January 19, 2010 Discussion Items:
        i. FLO2D Loss Rate Verification, Part II (Loomis)
        ii. Avulsions, Part II (Fuller)
    b. February 2, 2010
        i. Sediment Modeling Results (Raghavan)
    c. February 16, 2010
        i. Avulsions, Part III (Fuller)

<u>Meeting #14 Agenda</u>: January 19, 2010 10:00 am @ District
2008C007 – Task #1: Alluvial Fan Hazard Identification & Mitigation Methods

Attendance					
District		**District**		**Consultant/Others**	
	Greg Jones		Burke Lokey		Jon Fuller
	Kathryn Gross		Amir Motamedi		David Meyer
	Bing Zhao		Felicia Terry		Hari Raghavan
	Tom Loomis		Kelli Sertich		Ted Lehman
	Ed Raleigh		Stacey Lapp		Mike Kellogg
	Don Rerick		Tim Murphy		Bob Mussetter (phone)
	Doug Williams		Apu Borah		Stan Schumm (phone)
			Ken DeRoulac		Mike Harvey (phone)

<u>Agenda Items:</u>

1. Intro (Greg)
   a. Project Status (Greg)
   b. Comments on Debris Flow & Dating Comments Provided. Response pending.
   c. Comments on Sheet Flooding Report due.

2. Encroachment Analysis – Fuller
   a. White Tank 36
   b. Rainbow Valley 12

3. Avulsions - Fuller
   a. Tiger Wash 1997 Event (postponed until Feb mtg)
   b. Avulsion Basics

4. Next Meetings:
   a. February 2, 2010
      i. Sediment Modeling Results (Raghavan)
      ii. Tiger Wash Avulsions
   b. February 16, 2010
      i. Avulsions, Part III (Fuller)
      ii. FLO2D loss rates (Loomis)

Meeting #15 Agenda: February 2, 2010 10:00 am @ District

2008C007 – Task #1: Alluvial Fan Hazard Identification & Mitigation Methods

Attendance					
District		**District**		**Consultant/Others**	
	Greg Jones		Burke Lokey		Jon Fuller
	Kathryn Gross		Amir Motamedi		David Meyer
	Bing Zhao		Felicia Terry		Hari Raghavan
	Tom Loomis		Kelli Sertich		Ted Lehman
	Ed Raleigh		Stacey Lapp		Mike Kellogg
	Don Rerick		Tim Murphy		Bob Mussetter (phone)
	Doug Williams		Apu Borah		Stan Schumm (phone)
	Jen Pokorski		Ken DeRoulac		Mike Harvey (phone)

Agenda Items:

1. Intro (Greg)
    a. Project Status (Greg)
    b. Moment honoring groundhogs
    c. Comments on Debris Flow & Dating Comments due.
    d. Comments on Sheet Flooding Report due.

2. Integration of 2008C007 into PFHAM Revisions (Greg)

3. Sediment Modeling Results (Raghavan)
    a. Sediment Yield
    b. FLO2D Modeling

4. Next Meetings
    a. February 16, 2010
        i. Tiger Wash Avulsions
        ii. Avulsions, Part III (Fuller)
        iii. FLO2D loss rates (Loomis)

Meeting #16 Agenda: February 16, 2010 10:00 am @ District
2008C007 – Task #1: Alluvial Fan Hazard Identification & Mitigation Methods

Attendance					
District		**District**		**Consultant/Others**	
	Greg Jones		Burke Lokey		Jon Fuller
	Kathryn Gross		Amir Motamedi		David Meyer
	Bing Zhao		Felicia Terry		Hari Raghavan
	Tom Loomis		Kelli Sertich		Ted Lehman
	Ed Raleigh		Stacey Lapp		Mike Kellogg
	Don Rerick		Tim Murphy		Bob Mussetter (phone)
	Doug Williams		Apu Borah		Stan Schumm (phone)
	Jen Pokorski		Ken DeRoulac		Mike Harvey (phone)

Agenda Items:

1. Intro (Greg)
    a. Project Status (Greg)
    b. Debris Flow & Dating Reports revised & submitted
    c. Sheet Flooding Report revised & submitted
    d. FLO2D loss rates – RE-POSTPONED
    e. Report on discussion with O'Brien
    f. Hari's 2-2-06 action item update

2. Tiger Wash Avulsions – Flood of 1997 (Phil Pearthree, AZGS)
    a. 1997 event
    b. Update from January 2010 flows

3. Avulsions, Part III (Fuller)
    a. FLO2D Modeling
    b. Recommendations

4. Next Meetings
    a. March 2, 2010
        i. Integrated Method Discussion

<u>Meeting #17 Agenda</u>: March 2, **2010** **10:00 am @ District**

2008C007 – Task #1: Alluvial Fan Hazard Identification & Mitigation Methods

Attendance					
District		**District**		**Consultant/Others**	
	Greg Jones		Burke Lokey		Jon Fuller
	Kathryn Gross		Amir Motamedi		David Meyer
	Bing Zhao		Felicia Terry		Hari Raghavan
	Tom Loomis		Kelli Sertich		Ted Lehman
	Ed Raleigh		Stacey Lapp		Mike Kellogg
	Don Rerick		Tim Murphy		Bob Mussetter (phone)
	Doug Williams		Apu Borah		Stan Schumm (phone)
	Jen Pokorski		Ken DeRoulac		Mike Harvey (phone)

<u>Agenda Items:</u>

1. Intro (Greg)
    a. Project Status (Greg)

2. Fan 7-12 Modeling Report

3. FLO2D – Multiple Channel Option Results

4. Avulsions, Part II (Fuller)
    a. Recommended Methodology

5. Next Meetings
    a. Integrated Methodology Presentation - March 23, 8:30-11:00 AM
    b. Internal District Meeting – March 17, 3:00-4:30 PM

Meeting #18 Agenda: March 23, **2010**   **8:30 am @ District**

2008C007 – Task #1: Alluvial Fan Hazard Identification & Mitigation Methods

Attendance					
District		**District**		**Consultant/Others**	
	Greg Jones		Burke Lokey		Jon Fuller
	Kathryn Gross		Amir Motamedi		David Meyer
	Bing Zhao		Felicia Terry		Hari Raghavan
	Tom Loomis		Kelli Sertich		Ted Lehman
	Ed Raleigh		Stacey Lapp		Mike Kellogg
	Don Rerick		Tim Murphy		Bob Mussetter (phone)
	Doug Williams		Apu Borah		Stan Schumm (phone)
	Jen Pokorski		Ken DeRoulac		Mike Harvey (phone)

Agenda Items:

1. Intro (Greg)
    a. Project Status (Greg)
    b. Presentation Format (Greg)

2. Presentation of Draft Integrated Methodology

3. Discussion

4. Next Meeting:
    a. Regular Team Meetings: April 6 & 20, 10:00-12:00 AM

<u>Meeting #19 Agenda</u>: April 6, **2010** **10:00 am @ District**

2008C007 – Task #1: Alluvial Fan Hazard Identification & Mitigation Methods

Attendance					
District		**District**		**Consultant/Others**	
	Greg Jones		Burke Lokey		Jon Fuller
	Kathryn Gross		Amir Motamedi		David Meyer
	Bing Zhao		Felicia Terry		Hari Raghavan
	Tom Loomis		Kelli Sertich		Ted Lehman
	Ed Raleigh		Stacey Lapp		Mike Kellogg
	Don Rerick		Tim Murphy		Bob Mussetter (phone)
	Doug Williams		Apu Borah		Stan Schumm (phone)
	Jen Pokorski		Ken DeRoulac		Mike Harvey (phone)

<u>Agenda Items:</u>

1. Intro (Greg)
    a. Project Status (Greg)
    b. Discussion Overview (Greg)
    c. Project Schedule – Complete by June 30, 2010

2. Potential Discussion Topics: Response to Draft Integrated Methodology
    a. Virtual levee methodology vs. mega-flood
    b. Minimum engineering threshold criteria (lower limit of concern)
    c. Identifying active alluvial fans vs. stable distributary areas
    d. Design discharges for stable distributary areas
    e. Need for regulatory outlet (throughflow channel – apex to toe)
    f. Modeling avulsion hazards
    g. Sediment bulking
    h. Regulation of high hazard zone – no build zones.

3. Next Meeting:
    a. April 20, 10:00 am -12:00 pm

<u>Meeting #20 Agenda</u>: April 20, 2010 10:00 am @ District
2008C007 – Task #1: Alluvial Fan Hazard Identification & Mitigation Methods

Attendance					
District		**District**		**Consultant/Others**	
	Greg Jones		Burke Lokey		Jon Fuller
	Kathryn Gross		Amir Motamedi		David Meyer
	Bing Zhao		Felicia Terry		Hari Raghavan
	Tom Loomis		Kelli Sertich		Ted Lehman
	Ed Raleigh		Stacey Lapp		Mike Kellogg
	Don Rerick		Tim Murphy		Bob Mussetter (phone)
	Doug Williams		Apu Borah		Stan Schumm (phone)
	Jen Pokorski		Ken DeRoulac		Mike Harvey (phone)

<u>Agenda Items:</u>

1. Intro (Greg)
    a. Project Status (Greg)
    b. Project Schedule – 60 day extension requested by District PM (August 2010)

2. Potential Discussion Topics: Response to Draft Integrated Methodology
    a. Hazard classification
        i. BUREC, Figure 2, Figure 6
        ii. Frequency weighted method
    b. Tiger Wash Fan FLO2D
        i. Q500
        ii. QPMP
    c. Pile-up of flow against virtual levees
    d. Virtual levee methodology vs. mega-flood
    e. Floodways on alluvial fans – no build zones?

3. Still in Progress
    a. Attenuation along virtual levees
    b. Avulsion report – darn close to done though
    c. Distinguishing active alluvial fans from stable distributary areas

4. Next Meeting:
    a. May 4 Meeting – post-pone due to FMA Fan class…May 11?
    b. May 18 Meeting – ASPFM…May 25?
    c. Blue Ribbon Panel – June 2-3

Meeting #21 Agenda: May 25, 2010 10:00 am @ District

2008C007 – Task #1: Alluvial Fan Hazard Identification & Mitigation Methods

Attendance					
District		**District**		**Consultant/Others**	
	Greg Jones		Burke Lokey		Jon Fuller
	Kathryn Gross		Amir Motamedi		David Meyer
	Bing Zhao		Felicia Terry		Hari Raghavan
	Tom Loomis		Kelli Sertich		Ted Lehman
	Ed Raleigh		Stacey Lapp		Mike Kellogg
	Don Rerick		Tim Murphy		Bob Mussetter (phone)
	Doug Williams		Apu Borah		Stan Schumm (phone)
	Jen Pokorski		Ken DeRoulac		Mike Harvey (phone)

Agenda Items:

1. Intro (Greg)
   a. Project Status (Greg)
   b. ASFPM Report
      i. Arid Regions White Paper
      ii. Fan 1-2 Methodology Presentation

2. Comment Resolution Discussion
   a. JEF, Inc response to District comments on
      i. Task 2.4-2.5 Report
      ii. Draft methodology presentation (4-20)
   b. District comments on:
      i. Avulsion report
      ii. Draft final report

3. Next Meeting:
   a. Blue Ribbon Panel – June 2-3

<u>Meeting #22 Agenda</u>: June 22, 2010 10:00 am @ District
2008C007 – Task #1: Alluvial Fan Hazard Identification & Mitigation Methods

Attendance					
District		**District**		**Consultant/Others**	
	Greg Jones		Burke Lokey		Jon Fuller
	Kathryn Gross		Amir Motamedi		David Meyer
	Bing Zhao		Felicia Terry		Hari Raghavan
	Tom Loomis		Kelli Sertich		Ted Lehman
	Ed Raleigh		Stacey Lapp		Mike Kellogg
	Don Rerick		Tim Murphy		Bob Mussetter (phone)
	Doug Williams		Apu Borah		Stan Schumm (phone)
	Jen Pokorski		Ken DeRoulac		Mike Harvey (phone)

<u>Agenda Items:</u>

1. Intro (Greg)
    a. Project Status (Greg)

2. Blue Ribbon Panel Follow-Up Discussion
    a. Meeting summary report
    b. District staff comments

3. Comment Resolution Discussion (Continued from 5/25/10)
    a. JEF, Inc response to District comments on
        i. Task 2.4-2.5 Report
        ii. Draft methodology presentation (4-20)
    b. District comments on:
        i. Avulsion report
        ii. Draft final report

4. Next Meetings & Project Completion Schedule:
    a. June 25 (Fri) – District comments on Blue Ribbon Panel Report
    b. July 6 – 10 a.m. Comment resolution
    c. July 6 – District IPR
    d. July 8 – District comments on draft PFHAM methodology
    e. July 20 – 10 a.m. Comment resolution
    f. July 22 – Revised PFHAM Study Report Due
    g. August 3 – 10 a.m. Comment resolution (if needed)
    h. August 10 – District comments on revised PFHAM Report due
    i. August 24 – Final PFHAM Report due
    j. September 7 – Lesson learned meeting

<u>Meeting #23 Agenda</u>: July 20, 2010 10:00 am @ District

2008C007 – Task #1: Alluvial Fan Hazard Identification & Mitigation Methods

Attendance					
District		**District**		**Consultant/Others**	
	Greg Jones		Burke Lokey		Jon Fuller
	Kathryn Gross		Amir Motamedi		David Meyer
	Bing Zhao		Felicia Terry		Hari Raghavan
	Tom Loomis		Kelli Sertich		Ted Lehman
	Ed Raleigh		Stacey Lapp		Mike Kellogg
	Don Rerick		Tim Murphy		Bob Mussetter (phone)
	Doug Williams		Apu Borah		Stan Schumm (phone)
	Jen Pokorski		Ken DeRoulac		Mike Harvey (phone)

<u>Agenda Items:</u>

1. Intro (Greg)
   a. Project Status (Greg)

2. Next Meetings & Project Completion Schedule:
   a. July 20 – Team meeting
   b. July 22 – Revised PFHAM Study Report Due
   c. August 3 – 10 a.m. Comment resolution (if needed)
   d. August 10 – District comments on revised PFHAM Report due
   e. August 24 – Final PFHAM Report due
   f. September 7 – Lesson learned meeting

<u>Meeting #1 Minutes</u>: March 17, 2009 3:30 pm @ District

2008C007 – Task #1: Alluvial Fan Hazard Identification & Mitigation Methods

Attendance					
District		**District**		**Consultant/Others**	
X	Greg Jones	X	Burke Lokey	X	Jon Fuller
X	Kathryn Gross	X	Amir Motamedi	X	David Meyer
X	Bing Zhao	X	Felicia Terry		Hari Sundaraghavan
X	Tom Loomis		Kelli Sertich		Ted Lehman
	Ed Raleigh	X	Stacey Lapp		Mike Kellogg
	Don Rerick		Tim Murphy		Bob Mussetter (phone)
	Doug Williams	X	Apu Borah		Stan Schumm (phone)
	Joe Tram				Mike Harvey (phone)

<u>Agenda Items:</u>

1. Introductory Remarks (GLJ)
    - This was the first bi-monthly meeting.
    - Contact Issues: JEF needs prior authorization & written permission from GLJ before working on any out-of-scope item.
    - It is ok to speak with member of the project team directly, but GLJ and JEF must be CC-ed on all email communication.
    - Invoicing will be monthly.
    - ACTION ITEM: JEF will send a sample invoice to GLJ for review. Done 3-18

2. Bi-Monthly Meetings
    a. Set Regular Bi-Monthly Meeting Date & Time (Task 1.6.1)
    - Bi-Monthly meetings will be the 1st and 3rd Tuesdays of month. 10am-12. (2 hrs)
    - Next meeting is April 7.

    b. Enable Telephone Participation (MEI)
    - ACTION ITEM:GLJ will have phone set up for MEI for next meeting
    - ACTION ITEM: JEF will remind GLJ before next meeting

    c. Bi-Monthly Discussion Topics (Handout)
    - ACTION ITEM: JEF will email the list of topics to group. Done 3-18
    - ACTION ITEM: Group will comment on topic priority and whether any topics should be added or withdrawn. Group will respond with comments about topics by March 20.
    - Topic for next meeting will be the 2007C051 Literature Review.

3. Literature Search Revision & Review
    a. District Comments from previous task (2007C051)
    - ACTION ITEM: JEF will check with Kathryn to assure that JEF has received all previous FCDMC literature review comments. JEF will check whether he has Tom Loomis' comments. Done 3-19-09
    - Literature Review Search Results will be the topic for the next bi-monthly meeting.

    b. Review by MEI due 60 days from NTP

- ACTION ITEM: JEF will address previous FCD comments, and send to MEI for QC check per scope.

4. Flood Hazard Classification Matrix (Task 1.6.3; Task 2.9.2)
    - Discussion: The matrix is important to do up front
    - Discussion: Matrix is a quantification of flood hazard
    - Discussion: Matrix will add up to one number. Each factor in the matrix must be weighted; one could apply filters to some criteria- much like a decision tree.
    - Discussion: Difference between flood risk and flood hazard. It was agreed that this is an important question to be considered at the Brainstorming meeting on 4/21.
    - Discussion: It must be kept in mind that purpose of matrix is to assist in delineations and floodplain regulation.
    - ACTION ITEM: JEF will email out the Matrix seed idea handout to group. JEF needs comments back from District by 3/30 on what should be included in the matrix along with what relative weight should be for particular items. Done 3-18-09.
    - Follow up discussion questions:
        - What defines a hazard? Is it anything built? Habitable?
        - Is there only a hazard if a structure is involved? (Does the structure have to be insurable?)
        - Can hazard be removed by fill?

    a. Schedule Matrix Brainstorming Meeting
        - Matrix Brainstorming Meeting will be April 21st from 10am – 2pm (4 hours), with lunch included.

    b. Matrix due 30 days from NTP
        - It was noted that the Matrix was already late given the 2/13 NTP, but the matrix cannot be finalized until after the Brainstorming meeting on the April 21st.

    c. Seed Ideas (Handout)
        - ACTION ITEM: Group will provide input to JEF by 3/30 on seed ideas.

5. Historical Analysis (Task 2.3)
    a. Draft List of Sites (Handout)
        - Group reviewed JEF handout of developed historic fan site possibilities. It was agree that the first site (Ahwatukee, South Mountain Area T1S R3E Sec 24) and the last site, (Reata Pass Wash, McDowell Mts, T04N R05E Sec 17) were two that JEF could start on.
        - ACTION ITEM: JEF will continue search for other developed fans. Places to look for fans are: Phoenix Preserve, Camelback Mountain, Usery Mountain area, east Mesa, Mummy Mountain. Fans that were brought up by name included: Lost Dog, Rawhide, Guadalupe FRS Fan, and Harquahala Fan (Saddleback Mtn, USACE Report Example).
        - ACTION ITEM: JEF will compute watershed area for each potential fan to assist in the decision making and create a small database to assist in site selection.

    b. District Suggestions
        - Discussion: Should we check drainage reports before deciding to study an area? Agreed: no- because the lack of drainage problems might indicated effective mitigation measures. Also the comment was made that one of the four fans could have a small watershed.

c. Analysis due 60 days from NTP
d. Select Sites by March 24

6. Areas for Detailed Evaluation, Including FLO2D Analysis
   - H3 Fan from district (model complete) will be included
   - Discussion: 2D Study Location- A big issue is adequate topographic mapping. Two foot mapping is preferred. If 10 foot mapping is used- make sure not to use the break lines.
   - Discussion: Rio Verde Fan or not a Fan?
   - Discussion: Fan areas to look at include: McDowells, White Tanks, Tiger Wash, White Tank Fan 1-2, Rainbow Valley, H3 & South Mountain Park.
   - ACTION ITEM: JEF will bring a list of site candidates to the April 7 meeting.
   - JEF can prepare a polygon shapefile for areas of interest and send it to GLJ to provide info on what topographic coverages are available.

DATE: April 28, 2009

TO: Greg Jones, P.E./FCDMC

FROM: Jon Fuller, P.E.

RE: Flood Hazard Matrix Brainstorming Meeting
April 21, 2009 Meeting Notes

CC: File

MEETING ATTENDEES

Amir Motamedi	FCDMC
Apu Borah	FCDMC
Bob Mussetter	MEI
Burke Lokey	FCDMC
Debbie Shortal	FCDMC
Ed Raleigh	FCDMC
Felicia Terry	FCDMC
Greg Jones	FCDMC
Hari Sundararaghavan	JE Fuller
Joe Tram	FCDMC
Jon Fuller	JE Fuller
Kathryn Gross	FCDMC
Mike Harvey	MEI
Mike Kellogg	JE Fuller
Stacey Lapp	FCDMC
Tim Murphy	FCDMC

PROJECT VISION

1. Provide administrative guidance to define the term "alluvial fan".
2. Develop criteria by which areas of active and inactive alluvial fans can be identified and defined.
3. Develop criteria by which hazards on alluvial fans are quantified and characterized.
4. Indicate distinguishing characteristics for identification, and methods of delineation, on piedmont landforms including alluvial plains and relict incised fans.
5. Identify parameters to locate the toe of fans, beginning and ending of alluvial plains and other piedmont landforms listed in PFHAM.
6. Recommend procedures for modeling hydrologic and hydraulic processes on piedmont surfaces that reflect an appropriate level of flow continuity for flood hazard identification purposes. This work shall include sheet flow, coalescing fans, and incised fans.
7. Recommend mitigation measures appropriate for the identified hazards.
8. Use the results of the project as an opportunity to provide guidance/influence for FEMA alluvial fan floodplain delineation methodologies.

The overall objective of the Brainstorming Meeting was to set the foundation for the development of a flood hazard classification matrix. Before the matrix can be developed, it was important that each meeting participant's perceptions of the success of the PFHAM be discussed. There needed to be a consensus on a few fundamental principles before the matrix could be developed.

Fundamental Consensus

The following concepts were discussed and were met with eventual consensus with each meeting participant:

1. Alluvial fan landforms are present in Maricopa County.
2. Most alluvial fan landforms in Maricopa County are characterized by low slopes (<2%).
3. The alluvial fan landform extends from the topographic break (apex) to the axial stream.
4. Alluvial plains are found on alluvial fans landforms and floodplain landforms. Alluvial plains are not a separate landform.
5. Alluvial fans in Maricopa County contain high hazard areas, generally located near the fan apex.
6. Areas subject to sheetflooding are generally considered low hazard.

The group discussed several ideas on what defines a hazard. Specifically, how hazards can be classified. The following ideas on what constitutes a hazard were presented:

1. If the process results in erosion or flow inundation.
2. Damage to property.
3. Threat to life.
4. Qualify a hazard based on how difficult it is to mitigate. The more difficult/expensive it is to mitigate, the higher the hazard.
5. High Hazard
    a. No built areas.
    b. Very difficult to mitigate.
    c. Regional solutions are required.
6. Low Hazard
    a. Single-lot solutions are possible.

As part of the discussion on how to begin to identify different flood hazards on alluvial fans, the group discussed ideas on how to differentiate alluvial fan landforms from non-alluvial fan landforms on a piedmont. The following were presented as non-alluvial fan characteristics:

1. Channels are laterally stable.
2. Channels do not have silty-sand overbanks.
3. Area not located at the base of a mountain or hill – e.g. located far distant from the apex.
4. Channels are parallel, not in a radial pattern.
5. Topographic contours are not in a radial pattern.
6. The top of the watershed.
7. Channels have flow path certainty.
8. Tributary/dendritic channel pattern.
9. Not composed of alluvium.
10. < 3% slopes.

11. Doesn't fit the NRC criteria for an alluvial fan landform.

The following ideas were presented on how the hazard identification matrix tool will be used:

1. To identify hazards and delineate alluvial fans.
2. It will form a decision tree.
3. Used to distinguish between an alluvial fan landform and other piedmont landforms.
    a. Fan or non-fan?
    b. Where does the fan landform start and stop on the piedmont?
4. A guide for master planning.
5. A guide for regulation and development.
6. Used as a guide to differentiate the difference between "scary" fans and "non-scary" fans.
7. Used to define floodplain/hazard zones.
8. Used to define conveyance areas/zones.

The following ideas were presented on the necessary characteristics and requirements for the hazard matrix:

1. Simple, concise, implementable, and understandable.
2. Usable by the "journeyman" engineer and regulators.
3. Unambiguous guidance for regulation.
4. Contains specific criteria for defining hazards.
5. Supports responsible and appropriate regulation.
6. Provides mitigation guidance.
7. Dynamic – able to reflect changes over time (e.g. increased development density over time).
8. Has quantitative measures that are reliable, repeatable, and address uncertainty.
9. Is technically supportable.
10. Quantifiable tools for the different types of flooding hazards.

The group discussed at length how to define "low hazard" flooding on an alluvial fan landform. The discussion included specific characteristics that could be used. Those characteristics include:

1. Velocity $\leq$ 3 feet/second; Depth $\leq$ 1 foot/second.
2. Velocity $\leq$ 2 feet/second; Depth $\leq$ 2 foot/second.
3. Low velocity, low depth, low probability of flooding.
4. Low sediment transport potential.
5. Above the apex and flow within stable channels.
6. Below the alluvial fan toe or sheet flood area.
7. Low probability of channel concentration and/or channel avulsion.
8. No risk of debris flow or mud flow.
9. Small drainage area.
10. Low slopes.
11. Fan areas distant from the mountain front and/or hydraulic apex.
12. Consider using a low hazard definition dependant on land use.

13. Minor man-made structures (e.g. roads, canals, agricultural development) that interrupt alluvial fan processes indicate low hazard potential. Fan processes that overwhelm such structures indicate a higher hazard potential.

No specific group discussion on how to define a "moderate" hazard occurred during the meeting. However the following was presented during the "low hazard" discussion and was proposed as a "moderate hazard" definition:

1. Area between the fan apex and the toe of the fan with flow rate uncertainty and the potential of flow to concentrate.

The following concepts were brought-up during the meeting, however due to time constraints were not fully addressed. It is recommended that some or all of these concepts be discussed in follow-up meetings:

1. Define hazard areas vs. conveyance corridors. Conveyance corridors are seen as important features that should be preserved. Can conveyance corridors and hazard areas be coincident?
2. What do we call hazard areas? Are "low", "medium", and "high" still appropriate? Is there other nomenclature that would be more appropriate?
3. Should we consider not mapping "low" hazard areas as floodplains? Could they be appropriately regulated using existing drainage regulations?
4. Develop mitigation actions for different hazard classifications.
5. Can we use terminology other than alluvial fan? Does this terminology carry certain preconceptions that are no longer valid?
6. Should the hazard matrix tool go beyond Maricopa County? Should it be formatted for a "global" audience?

Meeting #3 Minutes: May 5, 2009 10:00 am @ District

2008C007 – Task #1: Alluvial Fan Hazard Identification & Mitigation Methods

Attendance					
District		**District**		**Consultant/Others**	
X	Greg Jones	X	Burke Lokey	X	Jon Fuller
X	Kathryn Gross	X	Amir Motamedi		David Meyer
X	Bing Zhao	x	Felicia Terry		Hari Sundaraghavan
X	Tom Loomis		Kelli Sertich		Ted Lehman
x	Ed Raleigh	X	Stacey Lapp	x	Mike Kellogg
	Don Rerick		Tim Murphy		Bob Mussetter (phone)
	Doug Williams	X	Apu Borah		Stan Schumm (phone)
x	Joe Tram				Mike Harvey (phone)

Agenda Items:

1. Introductory Remarks (GLJ)
   a. The four historical sites have been selected. JEF will begin presenting findings at the May 19th meeting for the Ahwatukee and Pima Canyon sites.
   b. The four fan evaluation sites have been selected: Reata Pass Fan, White Tank Fan 36, Rainbow Valley Fan 1, Rainbow Valley Fan Monitoring Site
2. History of Alluvial Fan Floodplain Management.
   a. JEF summarized some of the key milestones in FEMA & District alluvial fan floodplain delineation:
      i. 1970's. Rancho Mirage Flood in Coachella Valley, CA
      ii. 1978. Publication of Dawdy Method and adoption of probabilistic method by FEMA (FEMA FAN Model)
      iii. 1980's. Application of FAN model throughout arid west
      iv. 1986-1990. Fan delineation appeals and lawsuits by Pima & Maricopa Counties.
      v. 1996. Publication of NRC Report "Alluvial Fan Flooding"
      vi. 2002. Revision of FEMA Guidelines to NRC Three-Stage process
      vii. 1998. Publication of original draft of PFHAM by District (Win Hjalmarson & Joe Tram as primary authors)
      viii. 1998-2008. Application of PFHAM to fans in Maricopa County.
   b. JEF discussed some of the key differences between the PFHAM, the NRC Report and FEMA guidelines.
   c. JEF reiterated the need for quantification of alluvial fan flood hazards to improve floodplain delineations and provide technical information to enable sound management and regulation of fan areas.
3. General Discussion. Topics brought up by District staff included:
   a. Alluvial plains and alluvial fans
   b. Alluvial fan longitudinal profiles
   c. Pima County sheet flow maps
   d. Bruce Rhoads (ASU Geography) classification system
   e. Channel patterns on fans

f. Differences between Maricopa County & California fans
g. Debris flow hazards
h. Floodplain delineation vs. drainage regulation on fans
i. Need for flow continuity corridors
j. Need to move past definition to the flood hazard classification matrix

4. Other Actions
    a. JEF will include alluvial case histories as part of future bi-monthly meetings
        i. Lancaster Fan Site
        ii. Tortolita Fan Sites
    b. AZGS staff will be assisting with the Debris Flow & Dating subtasks.
    c. Greg & Kathryn will explore funding an intern to provide documentation of fan characteristics described in the literature.

<u>Meeting #3 Minutes</u>: May 19, 2009 10:00 am @ District

2008C007 – Task #1: Alluvial Fan Hazard Identification & Mitigation Methods

Attendance					
District		**District**		**Consultant/Others**	
X	Greg Jones	X	Burke Lokey	X	Jon Fuller
X	Kathryn Gross	X	Amir Motamedi	X	David Meyer
X	Bing Zhao	X	Felicia Terry	X	Hari Sundaraghavan
X	Tom Loomis		Kelli Sertich		Ted Lehman
X	Ed Raleigh	X	Stacey Lapp		Mike Kellogg
X	Don Rerick		Tim Murphy		Bob Mussetter (phone)
	Doug Williams	X	Apu Borah		Stan Schumm (phone)
	Joe Tram	X	John South		Mike Harvey (phone)

<u>Agenda Items:</u>

1. Introductory Remarks (GLJ)
   a. Project Status Issues
      i. MEI's literature search review should be completed this week & will be submitted prior to the next team meeting.
      ii. JEF will make revisions to the bi-monthly meeting schedule.
      iii. The data collection effort has experienced delays in getting site information from the District and other agencies.
      iv. Stakeholders from the Cities of Phoenix and Scottsdale will be invited to future bi-monthly meetings.
2. Historical Site #1 Summary (Ahwatukee)
   a. Summary: For nearly 20 years, the engineered channel has conveyed flow from the (former) apex to the fan toe without overtopping, but has required repair of the concrete channel, and regular removal of sediment. At least one flood near the design capacity of the channel.
   b. District staff requested that additional site data be added to the report, including channel and fan slope. The exact type of data will be determined by the District in a separate meeting.
   c. JEF reiterated their commitment to the concept of and need for quantifying flood hazards on alluvial fans to provide engineering data needed for effective floodplain management.
3. FEMA Fan Review Example: Wild Burro Canyon, Tortolita Piedmont, Pima County
   a. Major portions of the alluvial fan landform downstream have been mapped by the AZGS, the Town of Marana, Pima County as an active alluvial fan. The project site is located above the hydrographic apex in a reach with two "channel fans."
   b. The group discussed whether the site was subject to alluvial fan flooding and whether HEC-RAS was the appropriate tool for mapping the floodplain.
4. Flood Hazard Classification Matrix
   a. JEF presented a list of variables that could be used to quantify alluvial fan flood hazards and requested feedback from the group.

b. JEF presented a draft "straw man" version of a matrix for consideration by the group.
c. The group provided feedback on both items. The importance of fan slope was discussed by the group.

5. Actions Items
   a. Kathryn will work with Hari to try to obtain more detailed topographic mapping for the White Tank Fan 36 site.
   b. JEF will attempt to set up Webex capabilities for future meetings to help facilitate participation by MEI.
   c. FCDMC will identify what types of additional data should be added to the historical summaries.
   d. JEF will provide shapefiles for the historical fan sites and digital copies of the Powerpoint presentations.
   e. FCDMC will convene a small group to discuss the fan identification matrix "triage" concept.

<u>Meeting #3 Minutes</u>: June 2, 2009 10:00 am @ District
2008C007 – Task #1: Alluvial Fan Hazard Identification & Mitigation Methods

Attendance					
District		**District**		**Consultant/Others**	
X	Greg Jones	X	Burke Lokey	X	Jon Fuller
X	Kathryn Gross	X	Amir Motamedi	X	David Meyer
	Bing Zhao	X	Felicia Terry	X	Hari Sundaraghavan
X	Tom Loomis		Kelli Sertich		Ted Lehman
X	Ed Raleigh	X	Stacey Lapp		Mike Kellogg
	Don Rerick		Tim Murphy		Bob Mussetter (phone)
	Doug Williams	X	Apu Borah		Stan Schumm (phone)
	Joe Tram		John South		Mike Harvey (phone)
				X	Manny Patel (ASLD)
				X	Ashley Couch (Scottsdale)

<u>Agenda Items:</u>

1. Introductory Remarks (GLJ)
    a. Project Overview by Greg
    b. Stakeholders from the Cities of Phoenix and Scottsdale, and ASLD are invited to future bi-monthly meetings as appropriate given the agenda.
2. White Tank Fan 1-2 Presentation
    a. Jon & Hari presented a summary of the methodology used to re-map the floodplain using a composite approach that combined FLO2D and geomorphic techniques.
    b. Questions/Comments:
        i. Suggest evaluating FLO2D results to see if there is a defined threshold of depth – velocity that could be used to define the downstream limit of the AFHH zone.
        ii. Suggest evaluating other recurrence intervals besides the Q100. Discussed looking at Q500 and Q2-Q10.
        iii. Need criteria for selection of FLO2D grid size. Small grids will reduce amount of attenuation simulated.
        iv. Suggest plotting depth-velocity products as GIS layer.
        v. Consider using AO zones for mapping of low hazard and sheet flow areas on fan surface.
        vi. Reconsider designation of AFUFD zone as floodway zone.
        vii. More detailed (smaller grids) may be useful in AFHH zone near apex to provide better resolution.
3. Research Topic
    a. Ashley suggested developing a new model using research grant funds, potentially in conjunction with BYU & UA PhD candidates.
4. Actions Items
    a. Next Meeting Topics

i. Historical Summaries, three remaining sites
ii. Literature Review by MEI

Meeting #3 Minutes: **June 16, 2009** **10:00 am @ District**

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2008C007 – Task #1: Alluvial Fan Hazard Identification & Mitigation Methods

Attendance					
District		**District**		**Consultant/Others**	
X	Greg Jones	X	Felicia Terry	X	Jon Fuller
X	Kathryn Gross		Kelli Sertich	X	David Meyer
	Bing Zhao	X	Stacey Lapp	X	Hari Sundaraghavan
X	Tom Loomis		Tim Murphy		Ted Lehman
X	Ed Raleigh	X	Apu Borah		Mike Kellogg
	Don Rerick			X	Bob Mussetter (phone)
	Doug Williams				Stan Schumm (phone)
X	John South			X	Mike Harvey (phone)
X	Burke Lokey	X	Mike Nabor (ASLD)	X	Manny Patel (ASLD)
X	Amir Motamedi	X	Tom Dixon (Buckeye)	X	Ashley Couch (Scottsdale)

Agenda Items:

1. Introductory Remarks (GLJ)
    a. Welcome.
2. Literature Search Peer Review Results (Mike Harvey offered the following summary of their findings:
    a. JE Fuller Hydrology and Geomorphology, Inc. (JEF) were tasked with reviewing the geologic, geomorphic and engineering literature that dealt with various aspects of alluvial fan morphology, process, risk assessment, mitigation measures and hazard quantification methods. The results of the JEF review were reported in seven technical memoranda. External review of these memoranda by Mussetter Engineering, Inc. (MEI) was conducted as part of the Scope of Work (Section 2.1.1). The following are the conclusions developed from the MEI review.
    b. JEF has conducted a thorough and extensive review of the available literature and reports that deal with the seven identified research topics. Additional literature was identified by the MEI review and has been added for completeness. However, the absence of this material did not adversely influence the JEF review and reporting.
    c. No additional research topics were identified as a result of the MEI review.
    d. Based on the geologic, tectonic and climatic conditions in Maricopa County it is highly unlikely that debris flows are an integral part of the local alluvial fan dynamics. Given the entrenched nature of the fans where the hydrographic apex is located a considerable distance down-fan from the mountain front (topographic apex), it is highly unlikely that a debris flow, if one was to be generated, would reach the hydrographic apex, and thus influence avulsive processes in the unconfined midfan region. The absence of debris flows on the Maricopa County alluvial fans in no way diminishes the fact that these are alluvial fans.

e. Because of the importance of local aggradation in determining avulsion potential in the mid-fan region downstream of the hydrographic apex, emphasis should be placed on more accurately quantifying sediment delivery from the contributing watersheds and channels. The role of event sequencing should be incorporated into assessment of avulsion risk.
f. Identification of the boundary between alluvial fans and alluvial plains might be possible with high resolution topographic data (e.g. LiDAR). If cross-feature topographic convexities are not present, it is likely that sheetflooding will be the predominant process.
g. In response to a District question, MEI stated that they did not believe additional literature search on the topic of sheet flooding would identify much of interest to the PFHAM group.

3. Historical Site Review. Dave Meyer presented summaries for the following sites:
    a. Pima Wash (Phoenix South Mountain, City of Phoenix)
    b. Reata Pass Wash (McDowell Mountains, City of Scottsdale)
        i. Ashley Couch indicated that the Legacy drop structure failed because the rock size was too small.
        ii. Ashley Couch suggested investigating the 9/9/06 storm, which Gordon Wark of Wood/Patel called a 50-year event at DC Ranch.
        iii. Ashley Couch stated that analysis of smaller (more frequent) rainfall events is key both to understanding and predicting the behaviout of floods on these landforms, as well as to designing appropriate mitigation structures.

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4. Actions Items
    a. The July 7th meeting is cancelled. The next meeting will held on July 21st.
    b. JEF to meet with Greg Jones re. invoice format and project schedule.
    c. Next Meeting Topics
        i. Historical Summary – Lost Dog Wash
        ii. Preliminary Hydrology Results for 4 Assessment Sites
        iii. Preliminary FLO2D Modeling Results for Assessment Sites
        iv. FEMA Review Case Histories

Meeting #6 Minutes: August 11, 2009 10:00 am @ District

2008C007 – Task #1: Alluvial Fan Hazard Identification & Mitigation Methods

Attendance					
District		**District**		**Consultant/Others**	
X	Greg Jones		Felicia Terry	X	Jon Fuller
X	Kathryn Gross		Kelli Sertich		David Meyer
X	Bing Zhao	X	Stacey Lapp	X	Hari Sundaraghavan
X	Tom Loomis		Tim Murphy	X	Ted Lehman
X	Ed Raleigh	X	Apu Borah		Mike Kellogg
	Don Rerick	X	Valerie Swick		Bob Mussetter (phone)
X	Doug Williams	X	Diana Stewart		Stan Schumm (phone)
	John South				Mike Harvey (phone)
X	Burke Lokey		Mike Nabor (ASLD)		Manny Patel (ASLD)
X	Amir Motamedi		Tom Dixon (Buckeye)		Ashley Couch (Scottsdale)

Agenda Items:

1. Introductory Remarks (GLJ)
   a. Project is currently on schedule.
2. PFHAM Alluvial Fan Evaluation Sites: HEC1 Modeling Results
   a. Ted presented the methodology & results for the HEC1 modeling of the four fan sites. Key comments:
      i. Questions were raised about the method of (over)estimating splits to account for flow path uncertainty vs. estimating split distributions based on fixed-bed modeling (no over-accounting) for a single event.
   b. A digital copy of the PowerPoint presentation was provided to the District.
3. PFHAM Alluvial Fan Evaluation Sites: FLO2D Modeling Results
   a. Ted presented preliminary findings & results of FLO2D modeling of the four fan sites. Key comments:
      i. A key finding was that the existing (pre-development) condition FLO2D discharge estimates were much lower than the HEC1-based discharge estimates, especially as the distance from the apex increased.
      ii. A likely consequence of the discharge estimate disparity (FLO2D v. HEC1) is that the impacts of development on the fan are probably much greater than has been previously considered based solely on HEC1 modeling (e.g., in previous and on-going ADMP's).
      iii. There was some discussion of JEF's method of using Gaussian averaging to estimate grid cell elevation.
      iv. There was some question about whether JEF had conducted sensitivity runs for various modeling parameters (Answer: not explicitly, though somewhat through trial & error and peer review).
      v. There were question on how the ARF (FLO2D) was computed (Answer: using land use coverages).

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vi. There were questions about the technical basis of the hazard classification (Answer: used FLO2D default, which is based on publications from outside the USA. Additional background will be research at later date).

vii. There were questions about reporting the minimum depth in plots (0.2-0.5).

viii. There were questions on WT Fan 36 about possible implications of results to SVADMP corridor design.

ix. There were questions on what is the appropriate FLO2D cross section for obtaining discharge estimates for comparison to HEC-1 results.

x. It was pointed out the depth and velocities reported by FLO2D are averages over a grid cell, which may be different than the actual maximum in that cell.

xi. There was a question as to whether the apex peaks would be less (losses greater) if the entire watershed were modeled with FLO2D.

xii. There was suggestion to put a cross section in the FLO2D model at the downstream limit and use that output to compare to HEC1 results.

b. A digital copy of the PowerPoint presentation was provided to the District.

4. Next Meeting: August 18, 2009
   a. Discussion Items – ideas were presented on the last slide of the FLO2D presentation.
5. Action Items:
   a. Hari will contact Bing regarding a meeting to brainstorm sediment transport methodologies (Task 2.5)
   b. Ted will provide HEC-1 and FLO2D files to the District. No formal model review is requested at this time.
   c. Jon is preparing a scope of services for additional literature search on sheet flooding.

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<#>Because of the importance of local aggradation in determining avulsion potential in the mid-fan region downstream of the hydrographic apex, emphasis should be placed on more accurately quantifying sediment delivery from the contributing watersheds and channels. The role of event sequen ... [1]

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Introductory Remarks (GLJ)

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Ashley Couch stated that analysis of smaller (more frequent) rainfall events is key both to understanding and predicting the behaviout of floods on these landforms, as well as to designing appropriate mitigation structures.

Actions Items

The July 7th meeting is cancelled. The next meeting will held on July 21st.

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Next Meeting Topics

- Historical Summary – Lost Dog Wash
- Preliminary Hydrology Results for 4 Assessment Sites
- Preliminary FLO2D Modeling Results for Assessment Sites
- FEMA Review Case Histories

<u>Meeting Minutes</u>: **August 17, 2009** **11:00 am @ District**

2008C007 – Task #1: Alluvial Fan Hazard Identification & Mitigation Methods

Attendance: Bing Zhao, Apu Borah, Greg Jones, Hari Sundararaghavan

Agenda:

- Short-term vs Long-term event
- Sediment Yield
- Fan Surface Sedimentation
- Sediment Samples
- Debris

Short-term vs Long-term event

Bing Zhao recommended that the focus will be on 24 hour event with consideration to higher event (250, 500 year/SPF) from debris flow potential point of view. Post sediment water surface elevations are to be investigated. At critical cross-sections, sediment transport rates must be investigated. Greg Jones recommended that 10-year event can be considered for single fan to identify sedimentation pattern and potential impact of such an event.

Sediment Yield

Bing Zhao recommended that District's MUSLE methodology should be adopted to determine the wash load. Bing Zhao mentioned that a ratio based approach could be used as a backup to analyzing a range of events.

Fan Surface Sedimentation

FLO-2D would be used to model the sedimentation on the fan surface. Greg Jones recommended that the FLO-2D model for a single fan is adopted at first to identify sedimentation pattern. Bing Zhao recommended the use of Zeller Fullerton equation to model the bed material load. Hari Sundararaghavan mentioned that the wash load could deposit on the fan surface if flow does not leave the fan. Bing Zhao recommended that an approach based on minimum/allowable velocity to investigate the deposition of the wash load on the fan surface.

Sediment Samples

Hari Sundararaghavan mentioned that sediment sample may exist for White Tank fan 36. He also mentioned that URS may be collecting sediment samples for the Rainbow Valley ADMP and no sediment sample exists for the Reatta area. Bing Zhao mentioned that, at minimum, one sample at the apex and one sample on the fan surface is needed. Greg Jones mentioned that Jon Fuller needs to contact him with regards to sediment sample collection. Bing Zhao mentioned that the NRCS soils data could be used as a last resort.

Debris

Greg Jones and Bing Zhao mentioned that JE Fuller needs to document the reasoning if debris flow is not considered. Bing Zhao mentioned that larger events should be looked at for possible trigger for debris flow.

Other issues discussed

Bing Zhao will provide JE Fuller a beta version of DDMSW and another tool for information purposes only.
Bing Zhao and Hari Sundararaghavan will discuss sediment specific weight and sediment inflow estimates offline.
Greg Jones mentioned that H3 Fan should be used as the fifth fan.

Meeting #7 Minutes: August 18, 2009 10:00 am @ District
2008C007 – Task #1: Alluvial Fan Hazard Identification & Mitigation Methods

Attendance					
District		**District**		**Consultant/Others**	
X	Greg Jones	X	Felicia Terry	X	Jon Fuller
X	Kathryn Gross		Kelli Sertich		David Meyer
X	Bing Zhao	X	Stacey Lapp	X	Hari Sundaraghavan
X	Tom Loomis		Tim Murphy	X	Ted Lehman
X	Ed Raleigh	X	Apu Borah		Mike Kellogg
X	Don Rerick	X	Valerie Swick		Bob Mussetter (phone)
X	Doug Williams	X	Ken DeRoulac		Stan Schumm (phone)
	John South				Mike Harvey (phone)
X	Burke Lokey		Mike Nabor (ASLD)		Manny Patel (ASLD)
X	Amir Motamedi		Tom Dixon (Buckeye)		Ashley Couch (Scottsdale)

Agenda Items:

1. Introductory Remarks (GLJ). The objective of today's meeting was to discuss the results of the HEC1 and FLO2D modeling presented at the 8-11-09 meeting.
2. Discussion Items
   a. JEF presented animations of three avulsions on White Tank Fan 36. The avulsive channel change at the apex was from the 1951 flood. The avulsions in the lower piedmont were for unknown events that occurred between 1954 and 1999.
      i. Ed Raleigh questioned whether the avulsions similar to those shown on the lower piedmont could also occur on non-fan landforms. JEF responded that avulsions can occur in riverine systems.
      ii. Ed Raleigh suggested that the District may have information regarding similar types of channel changes in the Groom Ranch area (south of US60 near Wittmann) from a lawsuit several years ago.
   b. Burke Lokey asked why the FLO2D results were so different between the Reata Pass Fan (which showed high hazard zones across the entire landform) and the three other sites. The following reasons were suggested:
      i. Scale. The peak discharge and volume is much larger on the Reata Pass Fan. The large discharge is directly related to the large watershed area.
      ii. Velocity. As a consequence of the higher fan slope and higher discharge, the flow velocities are higher over a greater portion of the fan.
      iii. Losses. Attenuation and infiltration may be less on the Reata Pass fan because there is coverage by sandy soils and higher clay content.
      iv. Topography. In addition to the higher slope, there is greater lateral relief, resulting from (or due to) a higher degree of channel formation (less sheet flow).

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v. Flow Sources. There are several large tributary drainage areas that outlet onto the fan below the apex that create secondary apexes as well as additional water volume.

vi. It was suggested that there may be some index of flow volume-slope vs. flow area that could indicate a threshold size where the level of hazard warrants concern. It was suggested that the JEF team derive such a relationship. (Post-meeting notes: (1) such an analysis is not currently scoped, (2) four data points may be insufficient to accurately define an index.)

c. Bing Zhao asked whether the upcoming sediment modeling tasks would use all of the same FLO2D modeling scenarios presented last week. Greg Jones noted that the sediment modeling tasks were discussed at a meeting on Monday and the sediment modeling would be done for one site first (Rainbow Fan 12) and then a decision would be made how to proceed for additional modeling. The second modeling site would likely be Reata Pass.

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d. Tom Loomis directed JEF to contact Bob Herz @ MCDOT (602.506.2818) for additional information (help! about what? Groom Creek?).

e. Stacey Lapp asked what investigation had been done to document why the FLO2D and HEC1 results were so different. A variety of opinions were suggested ranging from unit hydrographs to time of concentration to loss accounting. The following action items were proposed:

i. Tom Loomis will have his intern develop HEC1 and FLO2D models to specifically compare how the Green-Ampt loss parameters are applied in each model.

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ii. JEF will investigate and document reasons for the modeling results differences.

iii. It was agreed that this was a high priority action item.

f. Valerie Swick stated that the level of effort was much higher for FLO2D modeling than HEC1 and that if the PFHAM is revised some guidance as to when the increased effort was justified should be included. Others questioned whether the level of effort really was increased for FLO2D given the availability of the digital data sets needed.

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g. It was agreed by consensus that FLO2D is an adequate tool to quantify alluvial fan flooding hazards, with the following clarifications:

i. Ed Raleigh stated that the District was not tied specifically to FLO2D and that other 2d models are probably acceptable.

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ii. Kathryn Gross stated that she was concerned that FLO2D was under-estimating the flow volume leaving the fans, based on the lack of ponding indicated in the FRS at the base of Fan 36, as well as the narrow inundation limits at the toe of the fan. She suggested that we may have some data for verification (or disproof) of the FLO2D results if we investigate why the FRS were built, whether they have been filled, etc. Greg Jones indicated that some of these records are available from the Buckeye ADMP, and that the FRS were built by the NRCS to protect I-10, as well as the RID and BID canals that had been damaged in the 1972-73 floods.

iii. Ed Raleigh suggested that FLO2D may not be appropriate for steeper fans (steeper than those in Maricopa County) and fans subject to debris flows. If the PFHAM is revised, it should be clearly stated that the recommended methodology is just for fans in our area, and that the methods may not apply to other regions.
iv. JEF stated that other modeling tools (HY8, HEC-RAS, etc) may be needed in addition to FLO2D for constructed elements on fans (culverts, complex channels, etc).
v. Tom Loomis reminded the group that FLO2D shows average depths within grid cells, so the accuracy of the depth & velocities is a function of the grid size and the topographic detail. It is likely that the FLO2D velocities are less than maximum velocities in channels, particularly channels that are smaller than the grid size.

h. JEF asked for feedback on hazard classification methods.
i. Bing Zhao requested that JEF identify the technical criteria that were the bases for the default FLO2D classification be researched and identified. These criteria then might be adapted and applied to Maricopa County. JEF stated that they had looked for the documentation during the literature search, but had not been able to find published records beyond those collected, and that perhaps a District intern who is a registered student at ASU might have better success through international library loans.
ii. Greg Jones noted some information on other methods was part of the literature search.
iii. Ed Raleigh suggested that this was a high priority research item.
iv. Tom Loomis suggested that slope, discharge/grid, flow path uncertainty, and sediment supply were other variables that could be part of the hazard classification.

i. JEF noted that the team will need to decide how to address geomorphically young surfaces that are shown as not inundated by hydraulically modeling (Item #4d in agenda).
i. Tom Loomis, Ken DeRoulac and Felicia Terry concurred that this situation occurs, notably in the Rio Verde area.
ii. Ed Raleigh suggested that such young geomorphic surfaces may be the remnants of a pre-historical but recent large (> Q100) event.
iii. Ed Raleigh expressed concerns that "geomorphically young" is a subjective concept and that application of geomorphology is inherently subjective (i.e., non-repeatable).
iv. JEF suggested that the upcoming site visits include stops where this condition exists so that the team can see first hand.

j. JEF asked for feedback on additional modeling scenarios.
i. Bing Zhao suggested that models be run with different antecedent moisture conditions, and that the results be compared to the previous FLO2D models.
ii. Kathryn Gross suggested that the rill erosion option in FLO2D be investigated to see if avulsion by piracy was predicted.

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iii. Bing Zhao suggested that recurrence intervals greater than Q100 be modeled to see if avulsion are predicted for very large floods. He made reference to a paper by Leopold that suggested that fans in Maricopa County are dormant (inactive) up to the 500-year event.
iv. Stacey Lapp suggested that if the 500-year models predict different flow paths, then Q100 discharges could be directed down the Q500 flow paths as a means of addressing flow path uncertainty.
v. Ed Raleigh requested that the team document accounts of alluvial fan flood damages, and document the similarities and differences of those fans to fans in Maricopa County.
vi. Felicia Terry requested that the White Tank Fan 36 FLO2D results be compared to the avulsion animations, as well as to the flow corridors.

3. Next Meeting: September 1, 2009
   a. Discussion Items
      i. Fan damage flood accounts
      ii. Lost Dog Fan historical accounts
4. Action Items:
   a. Note: these action item are not currently scoped and will require action by the District's and JEF project managers.
   b. HEC1 vs. FLO2D. Tom Loomis will do additional modeling to investigate loss rate differences. JEF will investigate other differences (note: this action item is not currently scoped and will require action by District).
   c. FRS background – verification data for White Tank Fan 36 outflow (note: this action is not currently scoped and will require action by District).
   d. Hazard classification bases.
   e. Flood damage accounts.
   f. Q500 FLO2D models
   g. Rill erosion models.
   h. White Tank Fan 36 FRS historical data.

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In response to a District question, MEI stated that they did not believe additional literature search on the topic of sheet flooding would identify much of interest to the PFHAM group.

Historical Site Review. Dave Meyer presented summaries for the following sites:

Pima Wash (Phoenix South Mountain, City of Phoenix)

Reata Pass Wash (McDowell Mountains, City of Scottsdale)

Ashley Couch indicated that the Legacy drop structure failed because the rock size was too small.

Ashley Couch suggested investigating the 9/9/06 storm, which Gordon Wark of Wood/Patel called a 50-year event at DC Ranch.

Ashley Couch stated that analysis of smaller (more frequent) rainfall events is key both to understanding and predicting the behaviout of floods on these landforms, as well as to designing appropriate mitigation structures.

Actions Items

- The July 7th meeting is cancelled. The next meeting will held on July 21st.
- JEF to meet with Greg Jones re. invoice format and project schedule.
- Next Meeting Topics
  - Historical Summary – Lost Dog Wash
  - Preliminary Hydrology Results for 4 Assessment Sites
  - Preliminary FLO2D Modeling Results for Assessment Sites
  - FEMA Review Case Histories

Meeting #8 Minutes: September 1, 2009 10:00 am @ District

2008C007 – Task #1: Alluvial Fan Hazard Identification & Mitigation Methods

Attendance					
District		**District**		**Consultant/Others**	
X	Greg Jones		Felicia Terry	X	Jon Fuller
X	Kathryn Gross		Kelli Sertich	X	David Meyer
X	Bing Zhao	X	Stacey Lapp	X	Hari Sundaraghavan
X	Tom Loomis		Tim Murphy		Ted Lehman
X	Ed Raleigh	X	Apu Borah		Mike Kellogg
	Don Rerick	X	Valerie Swick		Bob Mussetter (phone)
	Doug Williams		Ken DeRoulac		Stan Schumm (phone)
	John South				Mike Harvey (phone)
X	Burke Lokey		Mike Nabor (ASLD)	X	Manny Patel (ASLD)
	Amir Motamedi	X	Tom Dixon (Buckeye)	X	Ashley Couch (Scottsdale)

Agenda Items:

1. Lost Dog Fan Historical Account. Dave Meyer presented the results of the Lost Dog Fan historical study.
2. Review of FLO2D Modeling. Jon Fuller presented a brief overview of the FLO2D results for the four analysis sites using the animations, for the benefit of the stakeholders attending.
3. Next Meeting: September 15, 2009
   a. Discussion Items
      i. FCDMC HEC-1 v. FLO2D model comparison & infiltration analysis.
      ii. JEF Q500 FLO2D models
4. Action Items:
   a. Field trip to west side fan sites on October 6. Greg to get headcount & vehicle roster.
   b. FCD staff to provide review comments on:
      i. Literature search (final)
      ii. Supplemental literature fan GIS
      iii. Fan historical sites report
   c. Stakeholders comments on historical report due 9/15.

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In response to a District question, MEI stated that they did not believe additional literature search on the topic of sheet flooding would identify much of interest to the PFHAM group.

Historical Site Review. Dave Meyer presented summaries for the following sites:

Pima Wash (Phoenix South Mountain, City of Phoenix)

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Ashley Couch indicated that the Legacy drop structure failed because the rock size was too small.

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Actions Items

- The July 7th meeting is cancelled. The next meeting will held on July 21st.
- JEF to meet with Greg Jones re. invoice format and project schedule.
- Next Meeting Topics
  - Historical Summary – Lost Dog Wash
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Meeting #9 Minutes: September 15, 2009 10:00 am @ District

2008C007 – Task #1: Alluvial Fan Hazard Identification & Mitigation Methods

Attendance					
District		**District**		**Consultant/Others**	
X	Greg Jones	X	Felicia Terry	X	Jon Fuller
X	Kathryn Gross		Kelli Sertich		David Meyer
X	Bing Zhao	X	Stacey Lapp	X	Hari Sundaraghavan
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X	Burke Lokey		Mike Nabor (ASLD)		Manny Patel (ASLD)
X	Amir Motamedi		Tom Dixon (Buckeye)		Ashley Couch (Scottsdale)

Agenda Items:

1. FLO2D Modeling. Hari presented Q500 results for the four fan sites. Few new flow paths were observed, but flows were generally deeper with higher velocities than the Q100 runs.
    a. Hari noted that DDMSW could be upgraded to include Q500 (hydrology).
    b. Greg requested that the results be compared to the effective delineations and historical aerials for WTFan 36.
2. Sediment Modeling. Hari reported on preliminary results and modeling issues, and the steps JEF has been using to resolve the modeling problems.
    a. Hari noted that sediment data is needed for Rainbow Fan 12. Burke stated that there is a meeting scheduled for 9/15/09 @ 1 pm with URS to address the sediment sampling.
    b. Bing suggested that Hari send non-performing models to Jim O'Brien for review.
3. FEMA CLOMRs. Jon reviewed sites in CA, NV & AZ where CLOMRs have been submitted on alluvial fans.
4. Action Items:
    a. Field trip to west side fan sites on October 6. Greg to get headcount & vehicle roster. Tentative meeting time 8:30 am. All day trip.
    b. Field trip to east side fan sites on October 20. Same schedule.
    c. FCD staff to provide review comments on:
        i. Literature search (final)
        ii. Supplemental literature fan GIS
        iii. Fan historical sites report (due yesterday)
    d. Stakeholders comments on historical report due 9/15.
    e. Jon & Greg to meet to discuss upcoming meeting agendas.

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Reata Pass Wash (McDowell Mountains, City of Scottsdale)

Ashley Couch indicated that the Legacy drop structure failed because the rock size was too small.

Ashley Couch suggested investigating the 9/9/06 storm, which Gordon Wark of Wood/Patel called a 50-year event at DC Ranch.

Ashley Couch stated that analysis of smaller (more frequent) rainfall events is key both to understanding and predicting the behaviout of floods on these landforms, as well as to designing appropriate mitigation structures.

Actions Items

The July 7th meeting is cancelled. The next meeting will held on July 21st.

JEF to meet with Greg Jones re. invoice format and project schedule.

Next Meeting Topics

- Historical Summary – Lost Dog Wash
- Preliminary Hydrology Results for 4 Assessment Sites
- Preliminary FLO2D Modeling Results for Assessment Sites
- FEMA Review Case Histories

`Meeting #9 Agenda: November 17, 2009 10:00 am @ District
2008C007 – Task #1: Alluvial Fan Hazard Identification & Mitigation Methods

Attendance					
District		**District**		**Consultant/Others**	
X	Greg Jones	X	Burke Lokey	X	Jon Fuller
X	Kathryn Gross		Amir Motamedi		David Meyer
X	Bing Zhao	X	Felicia Terry	X	Hari Raghavan
	Tom Loomis		Kelli Sertich	X	Ted Lehman
X	Ed Raleigh	X	Stacey Lapp	X	Mike Kellogg
	Don Rerick		Tim Murphy		Bob Mussetter (phone)
	Doug Williams	X	Apu Borah		Stan Schumm (phone)
X	Ken DeRoulac				Mike Harvey (phone)

Agenda Items:

1. Intro
   a. Project Status Update – Greg reviewed the status of each task per the agenda
      i. Kathryn is checking to see if all comments have been addressed and a comment response memo was provided. This applies to FCD2007C051 Task 4.
      ii. The draft Sheet Flow Literature search was submitted at today's meeting as a paper copy and on DVD.
      iii. Greg provided District comments on the Historical Fan report.
2. Presentation of Additional FLO2D Modeling Results
   a. Sedimentation Models
      i. JEF will compare NRCS soils data to the sediment distribution curves (fine-average-coarse) used in the FLO2D modeling.
      ii. JEF will prepare a plot comparing the FLO2D maximum scour depths.
      iii. JEF will prepare a clear-water (no sediment supply) run for one fan to test the sensitivity of the FLO2D sediment model.
      iv. JEF will consider testing alternative transport functions for one fan.
      v. JEF will determine whether total sediment mass balance and sediment outflow can be evaluated from FLO2D results.
      vi. JEF will determined if Scottsdale's sediment maintenance GIS can be used to verify some of the FLO2D sedimentation modeling results.
      vii. JEF will ask Jim O'Brien to consult / brainstorm on the FLO2D sedimentation modeling results & methodologies. Greg suggested that Tom Loomis be invited to participate if these discussions occur.
   b. Q500 Models
   c. PMP Models
   d. Channel Blockage Models (WTF36)
   e. Mapping / Grid Cell Size Models (WTF36)
      i. JEF will determine if peak flow rates changed at the downstream end of the model (and key points) due to the different topographic input (resolution & grid size) for the WTF36 example.

f. Historical Flood Comparison (WTF36)
g. FEMA Map Comparison (Reata)
h. Slope – Flow Path Modeling
   i. Bing suggested using depth & velocity in determining where wash load might deposit.
   ii. Ted suggested eliminating the on-fan precipitation component for the wash load deposition analysis.

3. Next Meeting: December 1, 2009
   a. Discussion Items: Dating & Debris Flow Methods
   b. Tom Loomis will present his conclusions for FLO2D loss rate evaluation
   c. December 15 meeting will address Avulsions & Sheet Flow Literature search results.
   d. January/February meetings will focus on developing final guidelines & recommendations.
4. Review of Meeting Action Items
   a. Bing requested copies of FLO2D files. Ted will facilitate this request.

`Meeting #12 Notes: December 1, 2009 10:00 am @ District
2008C007 – Task #1: Alluvial Fan Hazard Identification & Mitigation Methods

Attendance					
District		District		Consultant/Others	
X	Greg Jones	X	Burke Lokey	X	Jon Fuller
X	Kathryn Gross	X	Amir Motamedi		David Meyer
X	Bing Zhao	X	Felicia Terry	X	Hari Raghavan
	Tom Loomis		Kelli Sertich		Ted Lehman
X	Ed Raleigh	X	Stacey Lapp		Mike Kellogg
	Don Rerick		Tim Murphy		Bob Mussetter (phone)
	Doug Williams		Apu Borah		Stan Schumm (phone)
X	Ken DeRoulac				Mike Harvey (phone)

Agenda Items:

1. Intro (Greg)
2. Task 2.6: Dating Techniques: (Dr. Jeri Young, AZ Geological Survey)
    a. The draft Task 2.6 report was submitted last week.
    b. District comments on the report are due 12/15/09.
    c. A copy of the PowerPoint presentation was provided to Greg.
    d. Key points:
        i. Numerical, relative and correlative dating methods are available for use in Maricopa County. These methods could be used to provide age resolution within the Holocene from 10-10,000 years.
        ii. Basic geomorphic/geologic mapping is recommended prior to application of any dating technique.
        iii. Dating techniques would be improved and facilitated by development of a regional chronology for Maricopa County.
3. Task 2.7: Debris Flow Methods: (Dr. Phil Pearthree & Ann Youberg, AZGS)
    a. The draft Task 2.7 report was submitted last week.
    b. District comments on the report are due 12/15/09.
    c. A copy of the PowerPoint presentation was provided to Greg.
    d. Key points:
        i. Debris flows do occur in Maricopa County, but have recurrence intervals that probably exceed 1,000 years, and tend to occur in steep watersheds rather than on fans located distant from the mountain front.
        ii. Initiation and runout models are available that would be appropriate for use in Maricopa County, but require local calibration.
        iii. Field assessment, including geomorphic mapping, is strongly recommended prior to further analysis of debris flow potential at any given fan site.
4. Next Meeting: December 15, 2009
    a. Discussion Items:
        i. Q&A Session on debris flow report/presentation (AZGS to participate via webex & phone)

        ii. FLO2D Verification (Loomis)
        iii. Avulsion Mechanisms - Part I (Fuller)
    b. Jan 5, 2010 meeting: Avulsion mechanisms Part II
5. Action Items
    a. Investigate whether flood insurance covers debris flow damage (District)
    b. Review Task 2.6 and 2.7 reports (District)

Meeting #13 Notes: January 5, 2010 **10:00 am @ District**

2008C007 – Task #1: Alluvial Fan Hazard Identification & Mitigation Methods

Attendance					
District		**District**		**Consultant/Others**	
	Greg Jones	X	Burke Lokey	X	Jon Fuller
X	Kathryn Gross	X	Amir Motamedi	X	David Meyer
X	Bing Zhao	X	Felicia Terry	X	Hari Raghavan
X	Tom Loomis		Kelli Sertich	X	Ted Lehman
X	Ed Raleigh	X	Stacey Lapp		Mike Kellogg
X	Don Rerick		Tim Murphy		Bob Mussetter (phone)
	Doug Williams	X	Apu Borah		Stan Schumm (phone)
X	Ken DeRoulac	X	Jen Pokorski		Mike Harvey (phone)
X	Tim Phillips				

Agenda Items:

1. Project Status (Kathryn)
    a. Review comments on the Debris Flow & Dating reports were due 12/15/09. Any outstanding comments should be provided immediately.
2. Q&A on Task 2.6: Dating Techniques: (Dr. Jeri Young, AZ Geological Survey)
    a. Key points:
        i. Numerical, relative and correlative dating methods are available for use in Maricopa County. These methods could be used to provide age resolution within the Holocene from 10-10,000 years.
        ii. Basic geomorphic/geologic mapping is recommended prior to application of any dating technique.
        iii. Dating techniques would be improved and facilitated by development of a regional chronology for Maricopa County.
3. Q&A on Task 2.7: Debris Flow Methods: (Ann Youberg, AZGS)
    a. Key points:
        i. Debris flows do occur in Maricopa County, but have recurrence intervals that probably exceed 1,000 years, and tend to occur in steep watersheds rather than on fans located distant from the mountain front.
        ii. Initiation and runout models are available that would be appropriate for use in Maricopa County, but require local calibration.
        iii. Field assessment, including geomorphic mapping, is strongly recommended prior to further analysis of debris flow potential at any given fan site.
        iv. Mapping of mountain front (steep) debris flow fans may be warranted and should be considered as a separate category of alluvial fan flooding if the PFHAM is revised.
4. FLO2D Loss Rate Verification Analysis (Tom Loomis)
    a. Key Points

    i. Rainfall infiltration losses – hand calculations verify HEC-1 loss rates, FLO2D loss rates appear to the 2-4% less than HEC-1. FCD is checking the FLO2D source code to attempt to identify the cause of the discrepancy.
    ii. Continuous infiltration (re-infiltration) – work in progress, probably ready for presentation at next meeting.
    iii. Rainbow Wash. FLO2D appears to predict losses more accurately than HEC1 relative to measured flow data.

5. Sheet Flooding Literature Search
    a. The results of the sheet flow literature search were presented.
    b. Key issues:
        i. A definition of sheet flooding was proposed.
        ii. Flow characteristics for sheet flooding areas were summarized.
        iii. No specialized tools for sheet flooding on fans were identified.
        iv. Floodplain management requirements from other jurisdictions were summarized.
6. Next Meeting: January 19, 2010
    a. January 19, 2010 Discussion Items:
        i. FLO2D Loss Rate Verification, Part II (Loomis)
        ii. Avulsions, Part I (Fuller)
    b. February 2, 2010
        i. Sediment Modeling Results (Raghavan)
    c. February 16, 2010
        i. Avulsions, Part II (Fuller)
7. Action Items
    a. Review Task 2.6 and 2.7 reports (District)
    b. Review Sheet flooding literature summary

Meeting #14 Notes: January 19, 2010 **10:00 am @ District**
2008C007 – Task #1: Alluvial Fan Hazard Identification & Mitigation Methods

Attendance					
District		**District**		**Consultant/Others**	
X	Greg Jones	X	Burke Lokey	X	Jon Fuller
X	Kathryn Gross	X	Amir Motamedi		David Meyer
X	Bing Zhao	X	Felicia Terry	X	Hari Raghavan
X	Tom Loomis		Kelli Sertich	X	Ted Lehman
X	Ed Raleigh	X	Stacey Lapp		Mike Kellogg
	Don Rerick		Tim Murphy		Bob Mussetter (phone)
	Doug Williams	X	Apu Borah		Stan Schumm (phone)
X	Ken DeRoulac	X	Jen Pokorski		Mike Harvey (phone)

Agenda Items:

1. Project Status (Greg)
   a. Debris Flow/ Dating Reports. Bing's group will be providing additional comments asap. Greg had previously delivered District comments.
   b. Sheet Flooding Report. District comments are due February 2nd. The report will be posted on the P: drive by Greg.
   c. Methodology Update. Greg will present information and recommendations on integration of the findings at the next team meeting.
2. Encroachment Analysis. JEF presented FLO2D modeling for the WTF 36 and RVF 12 sites that demonstrates the impacts of development in the most active portion of the fans near the apex. If the upper fan area is unavailable for storage and attenuation, flood peaks, depths and hazards are increased downstream.
3. Avulsion Hazards. JEF presented an overview of avulsion impacts on alluvial fan flooding hazards. A copy of the PowerPoint presentation was provided to the District. Key discussion points:
   a. The team will be "plowing new ground" when it comes to developing methodologies for evaluating avulsion potential, as well as for development/ engineering guidelines.
   b. If avulsion occurrence is related to sequence of floods/sedimentation, then modeling of a single event may not effectively quantify the hazard.
   c. Regardless of the method selected, there is likely to be some uncertainty regarding prediction of avulsions.
   d. It may be helpful to identify hazard factors that lead to avulsions or that increase avulsion potential.
   e. It is important to be cognizant of management and engineering design implications of any delineation methodology.
   f. There is a need to quantify the frequency of avulsion on fans in Maricopa County. A potential scope of services to do that was outlined & presented.
4. Future Meetings:
   a. February 2, 2010
      i. Greg: PFHAM - integration of results

        ii. Sediment Modeling Results (Raghavan)
    b. February 16, 2010
        i. FLO2D Loss Rate Verification, Part II (Loomis)
        ii. Avulsions, Part II (Fuller) – includes Tiger Wash 1997 avulsions
5. Action Items
    a. Review Task 2.6 and 2.7 reports (District)
    b. Review Sheet flooding literature summary

<u>Meeting #15 Minutes</u>: February 2, 2010 10:00 am @ District

2008C007 – Task #1: Alluvial Fan Hazard Identification & Mitigation Methods

Attendance					
District		**District**		**Consultant/Others**	
X	Greg Jones	X	Burke Lokey	X	Jon Fuller
X	Kathryn Gross	X	Amir Motamedi		David Meyer
	Bing Zhao	X	Felicia Terry	X	Hari Raghavan
	Tom Loomis		Kelli Sertich		Ted Lehman
X	Ed Raleigh	X	Stacey Lapp		Mike Kellogg
	Don Rerick		Tim Murphy		Bob Mussetter (phone)
	Doug Williams	X	Apu Borah		Stan Schumm (phone)
	Jen Pokorski	X	Ken DeRoulac		Mike Harvey (phone)

<u>Agenda Items:</u>

1. Integration of 2008C007 into PFHAM Revisions (Greg)
    a. Greg expects to present our recommended methodology to the Blue Ribbon Panel at the end of March or in mid-April.
    b. Greg asked the group: "Is FLO2D the best hydrology & hydraulic tool for engineering analyses of alluvial fans in Maricopa County – are we on the right track?" The group consensus was yes, with the following comments:
        i. Ken: we should evaluate the results that indicate flow doesn't leave the fan surface (attenuation).
        ii. Amir: two dimensional modeling is appropriate, but we will need to continue to refine the modeling approach and application.
        iii. Amir/Kathryn: we need to address whether we can mandate use of a proprietary model. Burke suggested that improved results may justify the learning curve for 2d modeling. Ed noted that FCDMC may be leading the way, and we may be pushing the envelop.
        iv. Ed noted that whatever we develop, we should be sure to specify the limitation and applicability beyond Maricopa County so as to not mislead other jurisdictions.

2. Sediment Modeling Results (Hari)
    a. Hari presented an overview of the sedimentation modeling results.
    b. A copy of the presentation was provided to the District.
    c. Hari will make an individual presentation of the result to Bing, who was unable to attend today due to a scheduling conflict.
    d. Hari will investigate whether FLO2D assumes an infinite supply of sediment at the inflow point, and will compare the predicted net deposition volume to reasonable estimates of sediment yield from the watershed.
    e. Hari will investigate why the Zeller-Fullerton results are significantly different from the other transport functions considered (it's an outlier).
    f. Hari will verify the run time differences between the 25-ft and 50-ft grid models.

3. Next Meetings
    a. February 16, 2010
        i. Tiger Wash Avulsions
        ii. Avulsions, Part III (Fuller)
        iii. FLO2D loss rates (Loomis)
4. Action Items
    a. Comments on Debris Flow & Dating Comments needed
    b. Comments on Sheet Flooding Report needed

Meeting #16 Minutes: **February 16, 2010** **10:00 am @ District**
2008C007 – Task #1: Alluvial Fan Hazard Identification & Mitigation Methods

Attendance					
District		**District**		**Consultant/Others**	
	Greg Jones	X	Burke Lokey	X	Jon Fuller
X	Kathryn Gross	X	Amir Motamedi		David Meyer
X	Bing Zhao		Felicia Terry	X	Hari Raghavan
	Tom Loomis		Kelli Sertich		Ted Lehman
X	Ed Raleigh	X	Stacey Lapp		Mike Kellogg
	Don Rerick		Tim Murphy		Bob Mussetter (phone)
	Doug Williams		Apu Borah		Stan Schumm (phone)
	Jen Pokorski	X	Ken DeRoulac		Mike Harvey (phone)

Agenda Items:

1. Kathryn presided over the meeting in Greg's absence
   a. The Debris Flow & Dating Reports have been revised & submitted
   b. The Sheet Flooding Report was revised & submitted
   c. FLO2D loss rates – RE-POSTPONED until TBD
   d. FLO2D Discussion with Jim O'Brien. Overall, Jim concurs with the FLO2D modeling methodologies we have developed and applied. Jim offered some suggestions on how to interpret model results, suggested that the multiple channel routine be used to decrease excessive attenuation (if it exists), indicated that FLO2D cannot explicitly predict long-term avulsive fan behavior)
   e. Previous action items:
      i. Hari has coordinated with Bing re. an individual presentation of the sediment modeling results.
      ii. Hari reported that the previous version had a bug that did not properly apply the sediment reservoir limit.
      iii. Hari will include a discussion on the Zeller-Fullerton equation results in the Sediment Report.

2. Tiger Wash Avulsions – Flood of 1997 (Phil Pearthree, AZGS)
   a. A detailed account of the 1997 avulsions was presented, including presumed causes for each type of avulsion observed.

3. Avulsions, Part III (Fuller) – discussion deferred due to time constraint.

4. Next Meetings
   a. March 2, 2010
      i. Integrated Method Discussion

<u>Meeting #17 Minutes</u>: March 2, 2010 **10:00 am @ District**
2008C007 – Task #1: Alluvial Fan Hazard Identification & Mitigation Methods

Attendance					
District		**District**		**Consultant/Others**	
X	Greg Jones	X	Burke Lokey	X	Jon Fuller
X	Kathryn Gross	X	Amir Motamedi	X	David Meyer
X	Bing Zhao	X	Felicia Terry	X	Hari Raghavan
X	Tom Loomis		Kelli Sertich		Ted Lehman
X	Ed Raleigh	X	Stacey Lapp		Mike Kellogg
	Don Rerick		Tim Murphy		Bob Mussetter (phone)
	Doug Williams	X	Apu Borah		Stan Schumm (phone)
	Jen Pokorski	X	Ken DeRoulac		Mike Harvey (phone)

<u>Discussion Items:</u>

1. Intro & Project Status.
    a. Greg summarized the status. We're working towards a presentation of the integrated method later this month. Jon will be scheduling the blue ribbon panel of experts after the initial presentation of the integrated methodology to the District.

2. Fan 7-12 Modeling Report
    a. Dave presented the results of FLO2D modeling (virtual levee scenarios, sediment modeling, hazard zones) for another site on the White Tank Piedmont. Results were similar to previous modeling efforts in many respects, although it is noted that significant flow depths occurred on a larger portion of the landform surface (relative to previous FLO2D results for other fans) than we initially anticipated given the watershed size.
    b. The conclusions were:
        i. A large portion of the piedmont is characterized by widespread shallow flooding
        ii. FLO-2D results suggest piedmont flood hazard is not extensive as geomorphic delineation suggests.
        iii. The Fan 12 floodplain appears to be independent of Fan 7 and 8.
        iv. Running multiple FLO-2D levee scenarios appears to be a reasonable approach to modeling unpredictable flow paths on alluvial fans.
        v. Aggregating multiple scenarios together to calculate maximum values reasonable to view risk associated with uncertain flow paths.
        vi. FLO-2D maximum depth results show divergence from original stage III delineations, and could be used to modify delineations in those areas.
        vii. The 2007 floodplain where individual structures have been identified includes some buildings and excludes others shown within the worst case inundation areas from the FLO-2D model scenarios.

viii. Consideration of appropriate map scale should be considered if mapping 'islands' based on the FLO-2D results.
ix. Corridors emanating from the downstream limits of sheetflooding should be considered for some kind of corridor designation. Apparent longitudinal discontinuities may require some interpolated connection along these corridors.
x. A combination approach of the geomorphic mapping and FLO-2D models can produce a better, more defensible presentation of the 100-year flood hazards for Fan 7, 8, &12.

c. The modeling of avulsion impacts on flood hazards is reasonably accomplished using the virtual levee procedure. However, some additional guidance is needed to assure that the "worst case" scenario is identified and captured. Both the number and alignment of virtual levees may be an issue.
d. A report summarizing the investigation was submitted to Kathryn (Contract FCD2007C051)

3. FLO2D – Multiple Channel Option Results
    a. Dave presented preliminary results of using the multiple channel option in FLO2D on WTF 36. Our draft conclusions are:
        i. There are significant differences between the multiple channel and base condition results.
        ii. In general, these differences include more extensive "inundation."
        iii. The multiple channel option eliminates some large-cell depth averaging that results in very shallow predicted depths.
        iv. The multiple channel option eliminates the shallow n value used in the base model and uses a global n value of 0.04 for the channels modeled. Therefore, the comparison is not quite apples to apples. Additional runs with Base Model N=0.04 are needed to complete the comparison.
        v. Regardless of the approach, there are still very shallow depths predicted for the distal fan area.
        vi. Additional investigation of this option is warranted.

4. The results of the WTF7-12 and multiple channel runs illustrate that FLO2D is an evolving technology, making it unlikely that a "cookbook" approach can be developed for assessment of alluvial fan flood hazards. It is likely the outcome of the PFHAM study will be a state-of-the-art, defensible methodology, which combines engineering and geomorphic approaches. However, it is important to note that individual expertise and considerable judgment cannot be eliminated as key elements in the process. Both will be required to generate meaningful results.

5. Avulsions, Part II (Fuller)
    a. Jon briefly presented the recommended methodology for assessing the potential for avulsions on alluvial fans in Maricopa County.

6. FLO2D vs. HEC1 Loss Rate Evaluation

a. Tom & crew have concluded that FLO2D is performing its calculations correctly as compared with hand-calculations for a controlled sample area. There are some differences in how loss rates are computed. District staff have recommended further study.
b. A more complete summary of Tom's conclusions regarding the differences between the two models is forthcoming.

7. Next Meetings
   a. Integrated Methodology Presentation - March 23, 8:30-11:00 AM
   b. Internal District Meeting – March 17, 3:00-4:30 PM – to discuss the big lessons learned from the PFHAM exercises completed thus far.

Meeting #18 Minutes: March 23, **2010** **8:30 am @ District**
2008C007 – Task #1: Alluvial Fan Hazard Identification & Mitigation Methods

Attendance					
District		**District**		**Consultant/Others**	
X	Greg Jones	X	Burke Lokey	X	Jon Fuller
X	Kathryn Gross	X	Amir Motamedi	X	David Meyer
X	Bing Zhao	X	Felicia Terry	X	Hari Raghavan
X	Tom Loomis		Kelli Sertich		Ted Lehman
X	Ed Raleigh	X	Stacey Lapp		Mike Kellogg
X	Don Rerick		Tim Murphy		Bob Mussetter (phone)
	Doug Williams	X	Apu Borah		Stan Schumm (phone)
X	Jen Pokorski	X	Ken DeRoulac		Mike Harvey (phone)

Agenda Items:

1. Intro (Greg)
    a. Project Status (Greg)
    b. Presentation Format (Greg)

2. Presentation of Draft Integrated Methodology (Jon Fuller)
    a. Jon presented the Draft Integrated methodology
    b. Key Points
        i. Reviewed major advancements, and identified current knowledge gaps.
        ii. Presented recommended methodology to consist of three stages
            1. Stage I- Identify alluvial fan landforms
            2. Stage II - Identify active vs. inactive areas on fan landforms
            3. Stage III – two methods for active alluvial fans
                a. Approximate method: current PFHAM geomorphology method.
                b. Detailed method: numeric and quantified. Scaled level of effort.

3. Discussion topics brought up by the District staff included.
    a. Discussion on whether wash load was negligible. (Tom) Jon thought was load was too little volume to be significant
    b. Ed brought up the wording that debris flows were negligible on "most" fans, implying that there are some fans with debris flow hazard in Maricopa county. Consider revised wording.
    c. (Ed) What defines a slope break? Response: Initial literature pointed to slope break between mountain front and piedmont. Stream profiles have little if no actual break in slope at apex. More of a lateral break in slope, an expansion or loss of confinement that defines that slope break.
    d. (Tom) What goes into a manning's rating? Response: It is the same as a normal depth rating

e. Ed, in response to Stage III approximate method, mentioned that two other variables that are easy to calculate are slope on fan and distance from apex.
f. Tom commented that during the Stage III methods the land-use will be critical to this approach. What is the consequence of delineation of this zone if we lose all attenuation due to development in this area? Jon added that we may be able to incorporate the potential attenuation loss into the definition of the lower (downfan) limit of the regulatory floodplain, either as an actual depth or as justification for using a threshold depth less than 1 ft.
g. (Tom) What was the basis for the 1.5% slope criteria? Response: It is slightly more than most riverine flow. Tom suggested that the slope, discharge and drainage area categories be justified based on the four evaluation sites (plus H3 & WTF7-12)
h. Discussion on >30 sq. miles. Response: It is based on judgment, but with some precedence in several State Standards.
i. Tom commented on correlation between FLO-2D and HEC-1, we may be forced to use two models, though would prefer not to. This is discussion to come back to.
j. Ed asked if infiltration and losses incorporated into FLO-2D. Response: Yes. Ed mentioned that in the future the door will be open to testing other two-dimensional models.
k. Tom wanted to discuss why 0.6ft was chosen as the upper limit, followed by comment that grid size has a huge impact in the flow depth.
l. There was discussion that there is no moderate zone. Only low and high, just as in FEMA there is only F/P and F/W to in the middle.
m. Bing asked if we compared FLO2D hazard classification with Bureau of Reclamation paper. Bing suggested we could try the Bureau's classifications for Reata.
n. Tom recommended that the high/low flood hazard zones be shown on some example watersheds.
o. Ed noted that if the high hazard zone is equal to floodway then it could be onerous because of lots of current F/W regulations and hoops to jump though. More discussion is needed on this topic. Perhaps the F/W regulations might be changed for portions of alluvial fan floodplains.
p. General comment that FLO-2D works well for large areas. Could use HEC-RAS or finer grid FLO-2D model for sight specific criteria.
q. Ken asked if the District should delineate debris flow potential. Response: (Jon) Not sure who would regulate that but would be easy enough to create a slope map for County, and compare it to soils.
r. Tom asked if we should be bulking flo-2d flows in general. Response: (Jon) No. Tom would like more discussion on that point.
s. Jon recommended that the District needs a methodology for handling flow splits between stable distributary areas.
t. Greg asked about scenario where a developer constructs a total fan solution. Do you still delineate fan zones? Response: In that case don't delineate zones just to take them off your map. More discussion is needed on this point.

u. Discussion on whether there is a lower limit to the peak discharge. Is a fan too small to map? Response: Use the current County lower discharge threshold (50 cfs). It would have a small floodplain.
v. Bing brought up Schumm's paper in regards to how active fans are in Maricopa County and questioned the definition of "active alluvial fan." Response: The federal definition is recommended, since it is identical to the County definition. There are active fans in Maricopa County, although most of the alluvial fan landforms are composed mostly of inactive surfaces.
w. Amir asked to clarify whether you could skip from Stage I directly to Stage III. Jon clarified that Stage II will give you different tools to select from for inactive parts of fan landforms, as well as identify criteria by which to apply the virtual levee technique.
x. Tom inquired to see why you can't build a FLO-2D model and let it tell you whether an area is active or inactive? Response: There is a long-term behavior component to the active/inactive delineation that is not modeled well by FLO2D.
y. Ed thought the issue might be more about confined/un-confined flow rather than active/in-active.
z. Greg noted that the presentation will be on the P:drive for review.
aa. Jon would like to know what aspects of the Draft integrated methodology people would like to discuss further.

4. Next Meeting:
   a. Regular Team Meetings: April 6 & 20, 10:00-12:00 AM

5. Action Items
   a. JEF:
      i. Finish Avulsion Report (Task 2.8)
      ii. Finish FLO2D Modeling Report (Task 2.4)
      iii. Submit Sediment Modeling Report (Task 2.5)
      iv. Hazard Classification
         1. Plot BUREC hazard classification zones for sample fans
         2. Compare to FLO2D zones
         3. Compare to depth = 0.3 ft, 0.6 ft thresholds
   b. FCDMC:
      i. Identify areas of recommended methodology for detailed discussion at April team meetings

<u>Meeting #19 Minutes</u>: April 6, 2010 10:00 am @ District
2008C007 – Task #1: Alluvial Fan Hazard Identification & Mitigation Methods

Attendance					
District		**District**		**Consultant/Others**	
X	Greg Jones		Burke Lokey	X	Jon Fuller
X	Kathryn Gross	X	Amir Motamedi	X	David Meyer
X	Bing Zhao	X	Felicia Terry	X	Hari Raghavan
	Tom Loomis		Kelli Sertich	X	Ted Lehman
X	Ed Raleigh	X	Stacey Lapp		Mike Kellogg
	Don Rerick		Tim Murphy		Bob Mussetter (phone)
	Doug Williams	X	Apu Borah		Stan Schumm (phone)
	Jen Pokorski	X	Ken DeRoulac		Mike Harvey (phone)

<u>Agenda Items:</u>

1. Intro (Greg)
   a. Project Schedule – Complete by June 30, 2010. A draft report is due at the beginning of May, with the Blue Ribbon Panel review on June 2-3.

2. Virtual levee methodology vs. mega-flood
   a. There was a long discussion of the merits of the virtual levee methodology as opposed to a more simplistic approach based on using a mega-flood (Q500 or greater).
   b. Some of the concerns regarding the virtual levee method include: 1) subjectivity in selecting the levee alignment, length, & width, 2) complexity of method, 3) how to treat model depths resulting from flow "piling up" against levees. Some of the concerns raised over the mega-flood approach include: 1) does it address flow path uncertainty, 2) can the mega-flood discharge be used for regulatory purposes (> Q100), 3) what size flood is appropriate and will that size flood be appropriate for every fan.
   c. JEF Action items:
      i. Compare levee run FLO2D results with base models to determine how much "piling up" occurs.
      ii. Develop guidance for determining levee length, alignment, width, etc to minimize subjectivity. Guidance will likely include an iterative approach using initial and final FLO2D runs.
      iii. Compare Q500 & QPMP FLO2D results (depth, velocity, Q) to levee scenario results to see how they differ.
      iv. Write up pros/cons of virtual levee and mega-flood approaches.
      v. Identify amount of attenuation occurring between apex and end of virtual levee.
      vi. Run Q500 on Tiger Wash fan
3. Minimum engineering threshold criteria (lower limit of concern)
   a. The discussion of a minimum threshold of concern was truncated by discussion of other topics. The County uses 50 cfs for drainage regulations.

The State Standard (2-96) recommends 500 cfs or 0.25 mi2. The question of whether there is a slope so flat that no hazard exists was posed. Bing suggested that slopes less than 1.5% were resulted in no significant hazard. It was suggested that the methodology exclude high slope fans (e.g., 8%).

4. Identifying active alluvial fans vs. stable distributary areas
    a. JEF Action item: Provide guidance on how to distinguish active fans from stable distributary areas and include as recommendation for the PFHAM revision.
5. Modeling avulsion hazards
    a. No single available tool adequately simulates avulsions. A composite method is required.
6. Regulation of high hazard zone – no build zones.
    a. Amir questioned whether even "high" hazards on alluvial fans would warrant a no-build zone, if depths were less than three feet.
7. Next Meeting:
    a. April 20, 10:00 am -12:00 pm. Greg will present a flow diagram outlining the methodology process.

<u>Meeting #20 Minutes</u>: April 20, 2010 10:00 am @ District
2008C007 – Task #1: Alluvial Fan Hazard Identification & Mitigation Methods

Attendance					
District		**District**		**Consultant/Others**	
X	Greg Jones		Burke Lokey	X	Jon Fuller
X	Kathryn Gross	X	Amir Motamedi		David Meyer
X	Bing Zhao	X	Felicia Terry		Hari Raghavan
X	Tom Loomis	X	Tim Phillips	X	Ted Lehman
X	Ed Raleigh	X	Stacey Lapp		Mike Kellogg
X	Don Rerick		Tim Murphy		Bob Mussetter (phone)
X	Doug Williams	X	Apu Borah		Stan Schumm (phone)
X	Jen Pokorski	X	Ken DeRoulac		Mike Harvey (phone)

<u>Discussion Items:</u>

1. Introduction
    a. Greg reviewed the project status. Greg has requested a 60 day extension to August 13, 2010 to allow time to incorporate comments from the Blue Ribbon Panel. Greg suggested that we use the Blue Ribbon Panel as a sounding board for some of the remaining issues for which there is no consensus on approach.
    b. Greg proposed that the District fund additional work to evaluate the frequency of avulsions. Ed & Bing said they would get back to Greg on that.

2. Potential Discussion Topics: Response to Draft Integrated Methodology
    a. Hazard classification. Ted presented application of the BUREC, Figure 2 & Figure 6 hazard classifications relative to FLO2D base model results for each of the four evaluation sites. The consensus was to use the BUREC Figure 6 (small children) with the frequency method to be coded into FLO2D under O'Brien's on-call contract. Bing noted that the MS Excel regression equation function may have problems, and suggested that the equation be checked.
    b. Tiger Wash Fan FLO2D. Ted presented Q500 and QPMP results for Tiger Wash. There was some indication of flow near the 1997 avulsion sites, but no definitive results, possibly due to the low quality of the only available topography. The Q500 did not accurately predict the 1997 avulsion locations.
    c. Pile-up of flow against virtual levees. Jon presented comparisons of Q100 FLO2D depths with virtual levee scenario FLO2D depths (differences). There is some pile-up against the levees, but it is not extreme and is readily identifiable.
    d. Virtual levee methodology vs. mega-flood. Jon summarized pro's and con's of each method, and showed comparisons of the FLO2D results for both approaches. There was good correlation on most of Reata Pass, slightly less so on Rainbow Valley 1, but poor correlation on Rainbow Valley 12 and White Tank 36. There was no consensus on the virtual levee or mega-flood methods.

e. Floodways on alluvial fans – no build zones. Jon led a discussion of floodway zones on active alluvial fans. There was a good discussion, but no final decision. There was consensus that any fan floodway policy should be consistent with riverine policies, but that it might be different from riverine no-build zones.
f. Bing proposed that the team consider the potential for avulsions to occur upstream of the apex, analogous to the fanhead trench cyclical filling observed in some laboratory models.
g. The final report will be submitted in early May and will require quick review turnaround to get the revised report to the Blue Ribbon Panel.

3. Next Meeting:
   a. May 4 Meeting – postpone due to FMA Fan class to May 11
   b. May 18 Meeting – postpone due to ASPFM to May 25?
   c. Blue Ribbon Panel – June 2-3

Meeting #21 Notes: May 25, 2010 10:00 am @ District
2008C007 – Task #1: Alluvial Fan Hazard Identification & Mitigation Methods

Attendance					
District		**District**		**Consultant/Others**	
X	Greg Jones	x	Burke Lokey	X	Jon Fuller
	Kathryn Gross		Amir Motamedi		David Meyer
X	Bing Zhao	X	Felicia Terry		Hari Raghavan
X	Tom Loomis		Kelli Sertich		Ted Lehman
X	Ed Raleigh	X	Stacey Lapp		Mike Kellogg
	Don Rerick		Tim Murphy		Bob Mussetter (phone)
	Doug Williams	X	Apu Borah		Stan Schumm (phone)
x	Jen Pokorski	X	Ken DeRoulac		Mike Harvey (phone)

Agenda Items:

1. Comment Resolution Discussion
   a. JEF, Inc response to District comments on
      i. Task 2.4-2.5 Report. Greg provided copies of JEF, Inc responses to District review comments. The team discussed and satisfactorily addressed the comments up to #6 of the 2nd group of comments from the EARM group, at which point the discussion moved to the Blue Ribbon panel due to time constraints. The discussion also incorporated comments from individuals on the draft final report. The remaining comments will be addressed at a future meeting.

   b. Blue Ribbon Panel – June 2-3. Greg presented an overview of the Blue Ribbon panel meeting, which will be facilitated by Debbie Shortall & Afshin Ahouraiyan.

<u>Meeting #22 Minutes</u>: June 22, 2010 10:00 am @ District
2008C007 – Task #1: Alluvial Fan Hazard Identification & Mitigation Methods

Attendance					
District		**District**		**Consultant/Others**	
X	Greg Jones	X	Burke Lokey	X	Jon Fuller
	Kathryn Gross	X	Amir Motamedi		David Meyer
X	Bing Zhao		Felicia Terry	X	Hari Raghavan
X	Tom Loomis		Kelli Sertich		Ted Lehman
X	Ed Raleigh	X	Stacey Lapp		Mike Kellogg
	Don Rerick		Tim Murphy		Bob Mussetter (phone)
	Doug Williams	X	Apu Borah		Stan Schumm (phone)
	Jen Pokorski		Ken DeRoulac		Mike Harvey (phone)

<u>Agenda Items:</u>

1. Introduction: Greg gave a brief update on the project status & reviewed the few remaining upcoming deliverable & review milestones.

2. Comment Resolution Discussion (Continued from 5/25/10)
   a. The team discussed JEF, Inc responses to District comments #7, 10, 14 & 16.
      i. Q7) FLO2D is part of the Stage 2 methodology, though a coarse grid model is not recommended. A preliminary FLO2D model with normal grid sizes (but minimal coding) will be used to help identify active / inactive surfaces. A discussion of the term "active" ensued. "Active alluvial fan flooding" will be used to refer to the ultrahazardous flooding conditions described by FEMA as regulated in NFIP Part 65.13. This term will be quantified using the BUREC Figure 2 (damage to structures), FLO2D results for fans with debris flow potential, documented avulsions, very high velocities and boulder transport. For portions of alluvial fans subject to uncertain flow paths, the procedures described in the draft report as endorsed by the Blue Ribbon Panel will be used.
      ii. Q10) Better guidance on the virtual levee scenario method will be provided in the final report, and will be based on the procedures used in the fan site evaluations. Refinement of the guidance can occur at some future date if needed.
      iii. Q14) Better guidance on identifying the hydrographic apex will be provided in the final report, and will include sediment impacts, both a single event (Q100) and a series of events, as well as hydraulic ratings of channel capacity.
      iv. Q16) The 100-year event will be used for design in conjunction with the virtual levee scenario methodology.
   b. The remainder of the previous review comments were considered but not discussed. Greg will provide a digital version of the JEF, Inc. response memo to District staff by June 24th, so that the District can respond to JEF's

responses by July 2nd. The responses will be finalized at the July 6th team meeting.

   c. District comments on the Avulsion Report & Draft Final Report. Greg will provide a consolidated list of review comments to JEF by June 25th. JEF will provide written responses to these comments prior to the July 6th meeting. Remaining issues will be discussed at the July 6th meeting.

3. Blue Ribbon Panel Follow-Up Discussion
   a. JEF's meeting summary report was delivered on June 15th and distributed to District staff. District comments are due to Greg by June 25th.
   b. A brief discussion of the Blue Ribbon Panel meeting was held. There was consensus that the Blue Ribbon Panel review was valuable and that the Panel had endorsed the proposed methodology.

4. Next Meetings & Project Completion Schedule:
   a. June 25 (Fri) – District comments on Blue Ribbon Panel Report
   b. July 6 – 10 a.m. Comment resolution
   c. July 6 – District IPR
   d. July 8 – District comments on draft PFHAM methodology
   e. July 20 – 10 a.m. Comment resolution
   f. July 22 – Revised PFHAM Study Report Due
   g. August 3 – 10 a.m. Comment resolution (if needed)
   h. August 10 – District comments on revised PFHAM Report due
   i. August 24 – Final PFHAM Report due
   j. September 7 – Lesson learned meeting

<u>Meeting #23 Minutes</u>: July 20, 2010 10:00 am @ District

2008C007 – Task #1: Alluvial Fan Hazard Identification & Mitigation Methods

Attendance					
District		**District**		**Consultant/Others**	
X	Greg Jones		Burke Lokey	X	Jon Fuller
X	Kathryn Gross	X	Amir Motamedi		David Meyer
	Bing Zhao	X	Felicia Terry		Hari Raghavan
X	Tom Loomis		Kelli Sertich		Ted Lehman
X	Ed Raleigh	X	Stacey Lapp		Mike Kellogg
	Don Rerick		Tim Murphy		Bob Mussetter (phone)
	Doug Williams	X	Apu Borah		Stan Schumm (phone)
	Jen Pokorski		Ken DeRoulac		Mike Harvey (phone)

<u>Agenda Items:</u>

1. Introduction. Greg Jones reviewed the upcoming schedule.
    a. July 22 – Revised PFHAM Study Report Due
        i. JEF to submit one paper copy & one pdf copy.
        ii. Report to be distributed (by District) to Stakeholders
        iii. DVD of supporting documentation will be provide asap but may be submitted on Monday (26^{th})
    b. August 3
        i. Comment resolution changed to possible stakeholder presentation. District to arrange meeting.
    c. August 10 – District comments on revised PFHAM Report due
    d. August 17 – Comment resolution meeting
    e. August 24 – Final PFHAM Report due
    f. September 7 – Lesson learned meeting
2. IPR Summary. Greg summarized the results of the District IPR:
    a. Blue Ribbon Panel recommendations are to be followed (BRP summary document to be added to draft final report)
    b. Greg will prepare a white paper on decision making process for District management.
    c. JEF to include BRP recommendations regarding terminology.
3. Other discussion:
    a. Greg asked if there were any issues to be discussed: no response.
    b. Greg asked if we are headed in the right direction: Ed said yes.

Appendix L:
Scope of Services, FCD2008C007, Work Assignment #1

Scope of Work
Refinement of Methodology:
Alluvial Fan Hazard Identification & Mitigation Methods
Work Assignment No. 1, Contract No. 2008C007

1 GENERAL

1.1 PROJECT DESCRIPTION

1.1.1 Vision: The study outlined by this scope of services will develop policy, guidelines and recommendations for regulation(s) that identify, classify and address flood hazards on alluvial fan landforms in Maricopa County, Arizona.

1.1.2 Purpose: This scope of work is for professional engineering services necessary to refine the District's current PFHAM methodology and identify engineering procedures to determine flood hazards on alluvial fan landforms, recommend hazard mitigation measures, further refine the landform designations and make recommendations for updating the PFHAM.

1.1.3 The final report shall provide clear guidance on the following:

1.1.3.1 Provide administrative guidance to define the term "alluvial fan."

1.1.3.2 Develop criteria by which areas of active and inactive alluvial fans can be identified and defined.

1.1.3.3 Develop criteria by which hazards on alluvial fans are quantified and characterized.

1.1.3.4 Indicate distinguishing characteristics for identification, and methods of delineation, on piedmont landforms including alluvial plains and relict incised fans.

1.1.3.5 Identify parameters to locate the toe of fans, beginning and ending of alluvial plains and other piedmont landforms listed in PFHAM.

1.1.3.6 Recommend procedures for modeling hydrologic and hydraulic processes on piedmont surfaces that reflect an appropriate level of flow continuity for flood hazard identification purposes. This work shall include sheet flow, coalescing fans, and incised fans.

1.1.3.7 Recommend mitigation measures appropriate for the identified hazards.

1.2 GENERAL REQUIREMENTS

1.2.1 The CONSULTANT shall comply with the requirements of the Flood Control District of Maricopa County's Consultant Guidelines Dated December 1, 2003 (CONSULTANT GUIDELINES) for the items of work referenced under this Scope of Work.

1.2.2 The CONSULTANT shall appoint a Project Manager who shall be knowledgeable of the progress and have responsible charge of the progress of each phase of the project.

1.2.3 The Project Manager shall be the same person listed in the CONSULTANT's Technical Proposal for this scope of work, unless otherwise approved by the

DISTRICT. The DISTRICT may request replacement of the Project Manager if it becomes apparent that this would be in the best interest of the project.

1.2.4 The Project Manager shall be the point of contact for the DISTRICT.

1.2.5 The DISTRICT may terminate this Work Assignment if the Project Manager is not available or if the CONSULTANT is unable to provide a replacement Project Manager acceptable to the DISTRICT.

1.3 LOCATION

1.3.1 The area of concern is all of Maricopa County.

1.4 PARTICIPANTS

1.4.1 Coordination with the following organizations is expected for information and input into the study, as well as floodplain management staff from the Cities of Phoenix, Buckeye, Goodyear, Avondale, Scottsdale and Paradise Valley:

Flood Control District (DISTRICT), Greg Jones (602) 506-5537
State Land Department, Manish Patel, 602-364-1596
FEMA, Craig Kennedy 202.646.1643

1.5 SCHEDULE

1.5.1 The CONSULTANT is expected to complete the Study within 360 calendar days from issue of the notice to proceed. The milestones shall be as follows in days from notice to proceed:

1.5.1.1 <u>Notice to Proceed - Day 1</u>
1.5.1.2 <u>Draft Flood Hazard Assessment Matrix – Day 30</u>
1.5.1.3 <u>Revised Literature Search & Subconsultant Review – Day 60</u>
1.5.1.4 <u>Field Visit - Day 60</u>
1.5.1.5 <u>Historical Analysis – Day 60</u>
1.5.1.6 <u>Alluvial Fan Site Hydrologic Modeling - Day 90</u>
1.5.1.7 <u>Dating Methodology – Day 90</u>
1.5.1.8 <u>Avulsion Assessment – Day 90</u>
1.5.1.9 <u>Debris Flow Assessment – Day 120</u>
1.5.1.10 <u>Alluvial Fan Site FLO-2D Modeling – Day 180</u>
1.5.1.11 <u>Alluvial Fan Site Normal Depth Modeling – Day 180</u>
1.5.1.12 <u>Sedimentation Analysis – Day 210</u>
1.5.1.13 <u>Flood Hazard Analysis and Design Guidelines – Day 210</u>
1.5.1.14 <u>Draft Summary Report – Day 240</u>
1.5.1.15 <u>Independent Panel Review – Day 270</u>
1.5.1.16 <u>Final Comment Resolution Meeting – Day 330</u>
1.5.1.17 <u>Final Report – Day 360</u>

1.6 MEETINGS

1.6.1 The CONSULTANT shall develop agendas and sign-in sheet, and take meeting minutes at all meetings. Meeting notes shall be included in the final report as an appendix.

1.6.2 <u>Bi-Monthly Progress Meetings</u>. - The CONSULTANT shall attend bi-monthly progress meetings. At these meeting the CONSULTANT shall brief the DISTRICT on the CONSULTANT's progress and a specific Piedmont topic as approved by the DISTRICT's Project Manager to expand the knowledge base of the project team and to identify any areas that may required further investigation or require policy decisions by the DISTRICT. Meetings shall last no longer than two (2) hours in duration. Up to 24 bi-monthly meetings shall be held.

1.6.3 Brainstorm Meeting, Matrix Development. – The CONSULTANT shall conduct a facilitated meeting to brainstorm an initial flood hazard classification matrix. The brainstorming meeting shall replace one of the bi-monthly progress meetings. The brainstorming meeting shall be ½ day in duration (4 hrs). The CONSULTANT will provide a neutral facilitator for this meeting.

1.6.4 Independent Panel Review Meeting. - The CONSULTANT shall develop an invitee list, invite, host and conduct a meeting to critically review the draft finding and recommendations of this study. The independent panel review meeting shall replace one of the bi-monthly progress meetings. The independent panel review meeting shall be ½ day in duration (4 hrs). The CONSULTANT will provide a neutral facilitator for this meeting.

1.6.5 Stakeholder Meeting. – The CONSULTANT shall develop an invitee list, invite, host and conduct a meeting to present the findings and recommendations of this study. The stakeholder meeting shall be two (2) hours in duration, and shall replace replace one of the bi-monthly progress meetings.

1.6.6 Final Comment Meeting. - The CONSULTANT shall attend a meeting where all final comments and the resolution to the comments are discussed and consensus achieved for incorporation into the Final Report. The final comment meeting shall replace one of the bi-monthly progress meetings

1.7 SITE VISITS

1.7.1 The CONSULTANT shall make a minimum of one (1) site visit to each alluvial fan being studied to become familiar with existing conditions.

1.7.2 The CONSULTANT shall document observations made during site visits in the Final Report.

1.7.3 The CONSULTANT shall coordinate with DISTRICT staff for site visits.

2 TASKS

2.1 LITERATURE SEARCH

2.1.1 The CONSULTANT shall develop an executive summary of the findings from the original literature search (FCD2007C051, Assignment #1).

2.1.2 The CONSULTANT shall respond to, and the DISTRICT will provide, review comments previously prepared for FCD2007C051, Assignment #1. The CONSULTANT will make appropriate revisions in the literature search deliverable prior to initiating Task 2.1.3.

2.1.3 The CONSULTANT shall provide the revised literature search and executive summary to an independent SUB-CONSULTANT to review for completeness and recommendations for any additions or search activities.

The results of this review shall be documented and submitted to the DISTRICT for approval. Documentation of the SUB-CONSULTANT review shall be included in the final report appendix.

2.1.4 The CONSULTANT shall perform additional literature search as directed and approved by the DISTRICT's Project Manager.

2.2 DATA COLLECTION

2.1.1 The CONSULTANT shall collect, review and document the reports pertinent to the project from the DISTRICT and other sources. Data/reports to be collected will include materials relevant to the project such as: flooding reports, previous hydrology/hydraulics studies and computer models completed within the study area; existing topographic mapping; as-built plans for existing drainage structures; FEMA Flood Hazard Boundary Maps and any Letters of Map Amendment and/or Revisions, sub-division drainage reports, site plans and future drainage improvement plans and other pertinent information. The CONSULTANT shall provide a list summarizing the collected data in the Summary Report.

2.1.2 The following is a list of data the DISTRICT will provide at no cost to the CONSULTANT:

- GIS data that may include parcel data, land use, hydrologic modeling data sets, floodplain delineations, or other information identified by the CONSULTANT.
- Existing digital topographic mapping for alluvial fan study sites
- Digital aerial photography, both recent & historical
- Existing hydrologic models for alluvial fan study sites
- Available reports and documents requested by the CONSULTANT

2.1.3 The CONSULTANT shall conduct limited research for other potential sources for collection of historical photography if such historical photography is not available from the DISTRICT.

2.1.4 The CONSULTANT shall provide a list of key data collected as part of the final report.

2.3 HISTORICAL DEVELOPMENT ON ALLUVIAL FAN LANDFORMS

2.3.1 The CONSULTANT shall assess the successes, failures, and/or drainage problems associated with historic development on alluvial fan landforms in Maricopa County. The primary objective of the analyses will be to assess the nature of flood hazards and damages associated with development on alluvial fans in Maricopa County.

2.3.2 The CONSULTANT shall review historical and recent aerial photographs, in conjunction with NRCS soils maps and topographic mapping, to identify up to four (4) areas of urbanization on distributary flow areas that may have been active alluvial fans prior to development. The four areas should include, if possible, areas of dense urbanization and single lot development, developments with major structural drainage measures and developments that lack significant drainage measures, and areas draining large watersheds. Study sites will be selected to cover the longest time period possible and/or the occurrence of large floods. The CONSULTANT shall propose the recommended study areas for approval by the DISTRICT prior to detailed site analysis.

2.3.3 The CONSULTANT shall classify the probable pre-development landform type at each selected study site using the PFHAM Stage 1 categories. The classification shall be done for informational purposes with a minimal documentation requirement.

2.3.4 The CONSULTANT shall briefly document the changes in landform characteristics due to development using aerial photography and construction plans, if available. In addition, the CONSULTANT shall interview maintenance staff, long-term residents, local floodplain managers, or homeowner associations to find anecdotal or systemic information regarding the performance of drainage structures, maintenance problems, and flood damages.

2.3.5 The CONSULTANT shall conduct a site visit to each study site to document existing conditions along the drainage system, including upstream and downstream channel reaches.

2.3.6 The CONSULTANT shall document the effectiveness of the structural or non-structural flood mitigation measures (or lack thereof) at each study site based on the information collected in Tasks 2.3.3 and 2.3.4.

2.3.7 The CONSULTANT shall prepare a technical memorandum summarizing the findings with a recommendation on how to apply the findings to the Integrated Alluvial Fan Hazard Assessment Methodology.

2.4 ALLUVIAL FAN FLOOD HAZARD SITE EVALUATIONS

2.4.1 The CONSULTANT shall evaluate flood hazards on four (4) alluvial fan landforms located in Maricopa County. The primary objective of the flood hazard site evaluations is to determine and quantify the flood hazards on a range of alluvial fan and alluvial plain landforms. This information will be used to refine the Integrated Alluvial Fan Hazard Assessment Methodology.

2.4.2 The CONSULTANT shall identify four (4) study sites that include potential alluvial fan landforms. If possible, the study sites will include a range of alluvial fan landform types and characteristics that reflect the range of landforms in Maricopa County, including landform slope (steep/flat), watershed size (small/large), development (natural/urbanized), and flow type (channelized/distributary/sheet flow). At least one of the sites shall have coalescing fans and unconfined sheet flow. Sites with existing, recent, approved hydrologic modeling and detailed topographic mapping are preferred. The CONSULTANT will submit a recommended list of study sites for approval by the District's Project Manager prior to proceeding with the remainder of this task.

2.4.3 Hydrologic Modeling

2.4.3.1 For each study site, the CONSULTANT shall review an existing hydrologic model provided by the DISTRICT (if one is available), to determine if the model is appropriate for site analysis. If no acceptable hydrologic model is currently available, the CONSULTANT will develop new 100-year HEC-1 modeling for the site using DISTRICT guidelines for no more than three (3) sites. The HEC-1 model shall cover the entire area subject to alluvial fan flooding, including tributary watersheds, as well as sheet and distributary flow areas downstream of the alluvial fan flooding area. A downstream limit of study may be defined where the model may be truncated. If hydrologic data for other recurrence interval events are required, hydrographs will be generated by applying the ratios published in the DISTRICT's Hydrology Design Manual (Table 6.1) to the 100-year modeling results.

2.4.3.2 The CONSULTANT shall use the inflow hydrograph(s) from the existing HEC-1 model at the hydrographic apex(es) and tributary inflow points for the study sites. The CONSULTANT may use FLO-2D to model runoff (both routing and on-fan runoff) on the portions of the alluvial fan downstream of the apex(es).

2.4.3.3 The CONSULTANT shall recommend criteria to establish the design frequency discharge to be used in the hydraulic models.

2.4.3.4 Based on the results of Task 2.4, the CONSULTANT shall recommend specific hydrologic methods for estimating flood hydrographs and peak discharges at concentration points downstream of the fan apex, in sheet flow areas, and on coalescing fans.

2.4.4 FLO-2D Modeling

2.4.4.1 The CONSULTANT will prepare FLO-2D models for the alluvial fan areas downstream of the apexes for three of the alluvial fan study sites. The CONSULTANT will also consider the results of FLO2D modeling provided by the DISTRICT for other alluvial fans in Maricopa County (e.g., Heiroglyphic Fan #3 or White Tank Fans 1-2) previously prepared by others. The FLO-2D models will be used to generate hydraulic parameters for use in preparation of the flood hazard classification matrix, sedimentation analyses, and the Integrated Alluvial Fan Flood Hazard Assessment Methodology.

2.4.4.2 The CONSULTANT will recommend for approval an appropriate grid size by balancing the accuracy of the results, the computational speed and the grid-independence of the results. A small initial area will be chosen to perform tests. Once an adequate grid size has been established, a new grid will be chosen that covers the entire area of study. For the selection of grid size, a rule of thumb is a grid size such that $Q_{peak}/A_{surf} < 1.0$ cfs/ft^2, where Q_{peak} is the peak discharge inflow to one grid element, and A_{surf} is the surface area of one grid element. However, this criterion may allow a large grid size which may miss the detailed terrain information. In all model runs, the total running time shall be documented. The downstream boundary for the FLO-2D domain shall extend 500 feet beyond the area of consideration to ensure that the boundary does not affect the results.

2.4.4.3 The CONSULTANT will develop the rainfall/land use/soil parameters for the fan area as part of the FLO-2D modeling. The preliminary GIS soil and land use shape files and associated hydraulic parameter tables may be obtained from FCDMC.

2.4.4.4 The CONSULTANT will use the FLO-2D model to compute the peak discharge and flow hydrograph volume at key downstream concentration points.

2.4.4.5 The CONSULTANT will prepare plots of FLO-2D results for the following parameters: (1) maximum flow depth, (2) maximum flow velocity, and (3) maximum bed change (degradation or aggradation) by using FLO-2D. These plots will be generated for the 2-, 10-, and 100-year events.

2.4.4.6 The CONSULTANT will provide an exhibit that shows the high-danger-zone, low-danger-zone, and judgment-zone for Children, Adults, Mobile Homes and regular houses per Bureau of Reclamation (1988) based on FLO-2D results.

2.4.4.7 The CONSULTANT will prepare additional FLO-2D modeling scenarios required to effective evaluate alluvial fan flood hazards as authorized in writing by the DISTRICT Project Manager.

2.4.5 Normal Depth Modeling

2.4.5.1 The objectives of this task are to compare the results of basic hydraulic modeling approaches to the results of more complex FLO-2D modeling described above, and to develop simplified methods of providing engineering assessments of alluvial fan flood hazards.

2.4.5.2 The CONSULTANT shall perform normal depth modeling of the alluvial fan surfaces and main channels using a Manning's rating program or HEC-RAS, per the guidelines in the DISTRICT's Hydraulics Manual.

2.4.6 The CONSULTANT shall document the results of the engineering analyses for each of the five alluvial fan study sites in a technical memorandum, which shall include written recommendations on how to apply the findings to the Integrated Alluvial Fan Hazard Assessment Methodology.

2.5 SEDIMENTATION EVALUATION

2.5.1 The objective of the sediment yield evaluation is to determine and quantify how the potential for sediment delivery, transport, and deposition across the alluvial fan surface can be quantified, and how such processes influence flood hazards on alluvial fan landforms in Maricopa County. This information is to be used to refine the Integrated Alluvial Fan Hazard Assessment Methodology.

2.5.2 The DISTRICT's sediment yield methodology described in Chapter 11 of the draft Drainage Design Manual for Maricopa County: Hydraulics will be used for sediment yield delivery to the alluvial fan apex for each of the five sites selected in Task 2.4. Wherever possible, the modeling guidelines described in Chapter 11 of the draft *Drainage Design Manual* *for Maricopa County: Hydraulics* will be used for the alluvial fan sedimentation task.

2.5.3 The CONSULTANT shall investigate sediment yield, transport and deposition modeling techniques and make written recommendations for review and approval by the DISTRICT's Project Manager for incorporating into the Integrated Alluvial Fan Hazard Assessment Methodology.

2.5.4 The recommended methodology(ies) shall be applied to up to three of the alluvial fan sites selected for evaluation in Task 2.4.

2.5.5 The CONSULTANT shall prepare a technical memorandum summarizing the results of the assessment, and recommending methods for quantifying sedimentation processes on alluvial fans.

2.6 DATING TECHNIQUES

2.6.1 The objective of the dating technique assessment is to demonstrate how surface age informs on piedmont landform flood hazards, and outline how this type of information is to be used in the Integrated Alluvial Fan Hazard Assessment Methodology.

2.6.2 The CONSULTANT shall prepare a technical memorandum describing types of Holocene absolute and relative dating techniques applicable for landforms in Maricopa County. The memorandum will describe how surficial dating techniques should be applied to alluvial fan flood hazard assessment. The memorandum will also include a discussion of the limitations of specific dating techniques as well as the more general limitations of dating with respect to flood hazard assessment. The memorandum will also discuss examples of how surficial dating techniques have been applied to previous alluvial fan flood hazard assessments.

2.7 DEBRIS FLOW POTENTIAL ASSESSMENT

2.7.1 The objective of the debris flow potential assessment is to determine and quantify how debris flow potential influences alluvial fan flood hazards in Maricopa County. This information is to be used to refine the Integrated Alluvial Fan Hazard Assessment Methodology.

2.7.2 The CONSULTANT shall evaluate and recommend methods appropriate for determining the potential for debris flow occurrence and run-out capability in Maricopa County. The potential for debris flow run-out onto the alluvial fan flood hazard areas, as well as downstream of the mountain front, in Maricopa County shall be considered.

2.7.3 The recommended methodology(ies) shall be applied to up to three of the alluvial fan sites selected for evaluation in Task 2.4.

2.7.4 The CONSULTANT shall prepare a technical memorandum summarizing the results of the assessment.

2.8 AVULSION POTENTIAL EVALUATION

2.8.1 The objective of the avulsion potential evaluation is to determine and quantify how channel avulsions influence flood hazards on alluvial fan landforms in Maricopa County. This information is to be used to refine the Integrated Alluvial Fan Hazard Assessment Methodology.

2.8.2 The CONSULTANT shall evaluate and recommend methods appropriate for determining the avulsion potential and occurrence in Maricopa County.

2.8.3 The recommended methodology(ies) shall be applied to up to three of the alluvial fan sites selected for evaluation in Task 2.4.

2.8.4 Task deleted.

2.8.5 The CONSULTANT shall prepare a technical memorandum summarizing the results of the assessment.

2.9 INTEGRATED ALLUVIAL FAN HAZARD ASSESSMENT METHODOLOGY

2.9.1 The CONSULTANT shall identify criteria that quantify the degree of flood hazard on alluvial fan and alluvial plain landforms. The criteria will include physics-based engineering parameters such as stream power, shear stress, flow velocity, flow depth, sediment transport capacity, debris flow potential, and flood frequency. The CONSULTANT shall use the flood hazard classification matrix to develop integrated flood hazard assessment guidelines for alluvial fans in Maricopa County.

2.9.2 Flood Hazard Classification Matrix.

2.9.2.1 The CONSULTANT shall develop a draft flood hazard classification matrix based on engineering parameters for discussion purposes at the "Brainstorm Meeting - Matrix Development." The flood hazard classification matrix is intended to distinguish the degree of alluvial fan flood hazards using both physics/engineering- and geomorphic-based criteria. The flood hazard classification matrix shall be used to guide the hydraulic/hydrologic modeling conducted for the site investigation tasks.

2.9.2.2 The flood hazard classification matrix shall be a working document and shall be modified to reflect the results of the analyses and data collected for this study. The final matrix shall be submitted in the final report.

2.9.2.3 Depending on the results of the study, the flood hazard classification matrix may be used to recommend updates and refined definitions of key terms or concepts used in the PFHAM, including alluvial fan, active/inactive, stable/unstable.

2.9.2.4 Depending on the results of the study, the flood hazard classification matrix may be used to recommend updates and refinements to the DISTRICT's piedmont floodplain delineation zones (AFHH, AAFF, etc).

2.9.3 Flood Hazard Analysis and Design Guidelines

2.9.3.1 The CONSULTANT shall develop a matrix (or list) of engineering tools and methodologies to be used to assess the type and degree of hazards identified in the flood hazard classification matrix. The design guidelines matrix shall be submitted as part of the final report for review and approval.

2.9.3.2 The CONSULTANT shall develop a decision tree that maps the engineering, investigation, and analyses required for flood hazard assessment and mitigation on alluvial fans. The decision tree shall be based on the results of the flood hazard classification matrix and will be used as design guidelines for alluvial fans in Maricopa County.

2.10 FINAL REPORT

2.10.1 The CONSULTANT shall submit a report for review and approval that documents the following:

- 2.10.1.1 Clear administrative guidance based upon technical definitions of what is an Alluvial Fan to be used for regulators.
- 2.10.1.2 Appropriate design frequency(ies) for alluvial fans
- 2.10.1.3 Appropriate design frequency(ies) for distributary flood hazard areas.
- 2.10.1.4 Recommendations for revision of the Piedmont manual.
- 2.10.1.5 Required engineering analysis on piedmont land forms.
  - 2.10.1.5.1 Hydrology
  - 2.10.1.5.2 Hydraulics
  - 2.10.1.5.3 Structural mitigation
- 2.10.1.6 Flood Hazard Classification Matrix
- 2.10.1.7 Flood Hazard Analysis and Design Guidelines
- 2.10.1.8 Appendixes of all analysis and investigations required by this scope of work.

2.11 PROJECT DELIVERABLES

2.11.1 Draft Deliverables. The CONSULTANT shall provide three (3) hard copies of the draft final report for review by the District, plus a CD containing any electronic data generated by the CONSULTANT that is needed for District review and a PDF version of the draft final report. The DISTRICT will make any additional copies needed for review by its staff or outside agencies and stakeholders:

- 2.11.1.1 Literature Search executive summary.
- 2.11.1.2 Response to previous DISTRICT literature search comments.
- 2.11.1.3 Subconsultant review of literature search
- 2.11.1.4 Technical memorandum – historical development on alluvial fans
- 2.11.1.5 Technical memorandum – alluvial fan flood hazard site evaluations
- 2.11.1.6 Technical memorandum – sedimentation evaluation
- 2.11.1.7 Technical memorandum – dating techniques
- 2.11.1.8 Technical memorandum – debris flow potential assessment
- 2.11.1.9 Technical memorandum – avulsion potential evaluation
- 2.11.1.10 Draft flood hazard classification matrix
- 2.11.1.11 Flood hazard design guidelines and decision tree
- 2.11.1.12 Final report

2.11.2 Final Deliverables.

2.11.2.1 The CONSULTANT shall provide a copy of all collected data and reports, except the data collected directly from the DISTRICT. Copies of the data will be provided in the format in which it was collected, or in digital format, at the discretion of the CONSULTANT.

2.11.2.2 The CONSULTANT shall also provide 1 hard copy of the Final Report

2.11.2.3 The CONSULTANT shall provide 1 CD of the Final Report in PDF format.

2.11.2.4 The CONSULTANT shall provide 1 CD of the Final Report in the original format.

2.11.2.5 The CONSULTANT shall provide 1 CD containing of all exhibits in their original formats in which they were created and in a tif or jpg format.

2.11.2.6 The CONSULTANT shall provide a DVD with copies of all electronic files, computer program input/output files, and computations generated by the CONSULTANT for this project.

2.11.3 Deliverables and Reports Content. The Reports and data DVD's shall contain the following:

2.11.3.1 Executive Summary, findings and recommendations, and a section that clearly documents the data collection, parameters; and exhibits showing the study area, cross sections and location, areas of danger zones, and flows and flow locations.

2.11.3.2 All models shall include input and output files and GIS representations of the 2D modeling output results. The format, structure and content of the GIS database tables shall be agreed to with the District's Project Manager prior to report production.

2.11.3.3 Data collected and/or developed shall be in the original format except as noted other wise.

Appendix M:
Study Participants

Flood Control District of Maricopa County

District Project Manager: Gregory L. Jones, PE

Alluvial Fan Task Force Members:

- Kathryn Gross, CFM
- Bing Zhao, PhD, PE
- Ed Raleigh, PE
- Tom Loomis, PE
- Amir Motamedi, PE
- Burke Lokey, PE
- Felicia Terry, PE
- Stacey Lapp, CFM
- Apu Borah, PhD, PE
- Don Rerick, PE
- Tim Murphy, PE
- Doug Williams, AICP
- Jen Pokorski, AICP
- Ken DeRoulac, PE

Agency Coordination

- City of Phoenix (Hasan Mushtaq, PhD, PE)
- City of Scottsdale (Ashley Couch, PE)
- Arizona State Land Department (Manny Patel, PE)

Consultant Team

Project Manager: Jonathan E. Fuller, PE, RG, PH, CFM, D.WRE

JE Fuller/ Hydrology & Geomorphology, Inc. Team Members

- Hari Raghavan, PhD, PE
- Ted Lehman, PE
- Mike Kellogg, RG
- Dave Meyer, GIT, EIT
- Bethany Fye, EIT
- Reed Blochberger

Subconsultants:

- Mussetter Engineering (Fort Collins, CO)
- Arizona Geological Survey (Tucson, AZ)

Blue Ribbon Panel (Peer Review)

- Dick French, PhD, PE – Hydraulics Professor, Univ Texas San Antonio
- Gary Parker, PhD, PE – Hydraulics Professor, Univ Illinois Carbondale
- Bob Mussetter, PhD, PE – Consulting Engineer.
- Kyle House, PhD – Research Geologist, Nevada Bureau of Mineral Technology
- Phil Pearthree, PhD – Research Geologist, AZ Geological Survey
- Ramon Arrowsmith, PhD – Geology Professor, AZ State University
- Mark Schmeeckle, PhD – Geography Professor, AZ State University
- Roger Hooke, PhD – Geology Professor, Univ. of Maine – Orono
- Doug Hamilton, PE – Consulting Engineer
- Dusty Williams, PE – Riverside County Flood Control District
- Jeremy Lancaster, RG – California Geological Survey
- Ed Curtis, PE – FEMA Region IX
- Joe Kuechenmeister, CFM – Michael Baker Jr., RiskMAP Program
- Ricardo Pineda, PE – California Department of Water Resources
- Vic Baker, PhD – University of Arizona, Hydrology
- Bill Bull, PhD – University of Arizona, Geosciences
- Ron Dorn, PhD – Arizona State University, Geography

Appendix N:
District Review Comments

Memorandum JE Fuller/ Hydrology & Geomorphology, Inc.

DATE: December 15, 2009

TO: Greg Jones, PE/ FCDMC

FROM: Jon Fuller, PE

RE: FCD2008C007 – PFHAM Historical Fan Report
Response to District Comments

CC: Kathryn Gross, CFM/ FCDMC

Thank you for your careful review of the above-referenced report. We have addressed each of the red-line comments made in the text of the report, and offer the following responses to your written comments provided in the memorandum from Kathryn Gross to Greg Jones dated August 28, 2009.

1. Executive Summary.

   JEF Response: Requested changes have been made.

2. Introduction.

   JEF Response: Requested changes have been made.

3. Ahwatukee.

   JEF Response: No District comments.

4. Pima.

   JEF Response: Requested change has been made.

5. Reata.

   JEF Response: A specific polygon was not delineated because we are considering the entire upper portion of the surface, with the exception of the terrace shown in Figure 5-5, to be active. All other requested changes have been made.

6. Lost Dog.

   JEF Response: Requested changes have been made.

Memorandum JE Fuller/ Hydrology & Geomorphology, Inc.

DATE: February 10, 2010

TO: Greg Jones, PE / FCDMC

FROM: Jon Fuller, PE

RE: FCD2008C007 – Work Assignment #1
Task 2.6: Dating Techniques
Response to District Comments

CC: File

Thank you for your careful review of our report. The following summarize our responses to the District review comments. The final review comments were received on February 4, 2010 and included a comment memorandum from Kathryn Gross (12-11-09) and red-lined comments from Greg Jones (1-11-10).

Comments from Kathryn Gross

1. Introduction, Subtleties of Dating Holocene Dating Techniques, page 2. Consider removing the word subtleties from title.

   JEF Response: Done.

2. Applicable Dating Techniques, page 4. Consider adding a sentence, or sentences, at the beginning of this section specifically listing all dating methods investigated and then transition into the current text which covers which methods are not applicable and which ones are.

   JEF Response: Done.

3. Report Outline. Outline of report is reasonable.

   JEF Response: I concur.

4. Typographic Item. Please correct the following typographic errors:

   JEF Response: Done.

   - Page 1, first paragraph, line 9 – add an "s" to technique.
   - Page 1, second paragraph, line 12 – correct "has used" with "has been used".
   - Page 3, fourth paragraph, line 11 – correct "very similar age" with "very similar in age"
   - Page 6, third paragraph, line 14 – correct "must measured" with "must be measured"
   - Page 7, first paragraph, line 5 – correct "were dating" with "were dated"

- Page 8, first paragraph, second to last line – clarify middle of sentence: "because most like, like"
- Page 9, fourth paragraph, line 6 – correct "meaning age" with "meaningful age"
- Page 10, second paragraph, line 8 – correct "tapped" with "taped"
- Page 14, second paragraph, line 4 – correct "will result disequilibrium" with "will result in disequilibrium"
- Page 15, first paragraph, line 7 – correct "were tdense" with "were dense"
- Page 23, first paragraph, line 5 – correct "which in term" with "which in turn"

Red-Lined Comments from Greg Jones

JEF Response: All red-lined comments were addressed.

Memorandum — JE Fuller/ Hydrology & Geomorphology, Inc.

DATE: February 12, 2010

TO: Greg Jones, PE / FCDMC

FROM: Jon Fuller, PE

RE: FCD2008C007 – Work Assignment #1
Task 2.6: Debris Flow Assessment Report
Response to District Comments

CC: File

Thank you for your careful review of our report. The following summarize our responses to the District review comments. The final review comments were received on February 4, 2010 and included comment memoranda from Apurba Borah (2-2-10) and Kathryn Gross (12-15-09), and red-lined comments from Greg Jones (1-11-10).

Comments from Apurba Borah

1. The report does not contain a Table of Content.

   JEF Response: Done.

2. Executive summary should include detailed summary of the report

   JEF Response: Done.

3. Φ is the internal friction angle of soil used in equation 1 (Page 14); the text in Page 14 says $\tan\Phi$ is the internal friction angle of the soil which needs to be corrected. Please also correct the typo "tan[?]" in the text (Page 14).

   JEF Response: Corrected.

4. The conclusion section needs to be expanded with a few sentences to include the type of debris flows that can occur in Maricopa County and the methods to assess the potential for debris flow.

   JEF Response: Done.

Comments from Kathryn Gross

1. Please consider removing the third-person language ("We") from the text.

   JEF Response: Done.

2. Executive Summary. Consider expanding this section to cover all subjects discussed in the memorandum (definitions, historical debris flows, methods, etc.)

JEF Response: Done.

3. Introduction, page 2, first paragraph line 15-16. Consider re-phrasing this sentence without the use of "we are not aware".

   JEF Response: Done.

4. Initiation models, page 14 and 15. The two equations shown are blurry. Can this be corrected?

   JEF Response: Done.

5. Table 2 Page 18, last column and row. Should "active" be added before alluvial fan?

   JEF Response: Done.

6. Page 23, last sentence. The report states that previous studies provide some intriguing ideas for identifying debris-flow prone basins that may be applicable to Maricopa County but does not elaborate it here or discuss where in the report an elaboration is presented.

   JEF Response: Some of the dialogue you're looking for is now in the paragraph, and I added some clarification as well. A full discussion of identifying debris flow prone basins would make for its own report or chapter of a textbook, so I took a minimalist approach.

7. Page 24, Recommendations. Regarding initiation modeling, this section states that it would require significant resources but does not state that it is not recommended. However, in the Executive Summary it specifically states that initiation modeling is not recommended. Should that "not recommended" language be included here to match the Executive Summary?

   JEF Response: Done.

8. Conclusions. Please expand this discussion to include anticipated types of debris flows that could occur in Maricopa County to tie back into that section of the report. Consider adding one or two sentences more to the importance of geologic mapping and modeling approaches to consider.

   JEF Response: Done.

9. Report Outline. Outline of report is reasonable.

   JEF Response: Good.

10. Typographic Items. Please correct the following typographic errors:

    JEF Response: All noted typo's were corrected.

- Page 11, second paragraph, third line from bottom – remove "is" from "County are is likely"
- Page 17, first paragraph, line 2 – correct "All of the author noted" with "All of the authors noted"
- Page 22, second paragraph, line 11 – correct "Melton Ration" with "Melton Ratio"
- Page 22, second paragraph, line 13 – correct "angle to determined debris-flow" with "angle to determine debris-flow"
- Page 26, second paragraph, line 8 – sentence is awkward.

Red-Lined Comments from Greg Jones

JEF Response: All red-lined comments were addressed.

Memorandum **JE Fuller/ Hydrology & Geomorphology, Inc.**

DATE: July 22. 2010

TO: Greg Jones, PE/ FCDMC

FROM: Jon Fuller, PE

RE: 2008C007 – Work Assignment #1: PFHAM
Response to Consolidated Comments on Final Report

CC: File

Thank you for the thoughtful comments from your team on our PFHAM deliverables. District comments were provided by you via email on June 30, 2010, and are listed as originally enumerated below. Our responses are indicated by indented 10 point bold font. The following summarize our responses:

Reviewer: Planning Branch, 5-24-2010

1. General Comment. Per the Scope of work a decision tree/matrix is required. Please update the report to include.

   JEF Response: The report has been updated to include a decision tree.

2. Page i. Add a statement to indicate that this will be developed after the blue ribbon panel.

   JEF Response: The executive summary has been added to the report.

3. Page 5, fourth bullet from top of page. Please be more specific on "Most". Give a percentage or number.

   JEF Response: Done.

4. Page 31, Flow Attenuation. Where is section "0" that is referenced? Please correct.

   JEF Response: Done.

5. Page 40, Figure 28. Update figure to match label. The right hand figure should be developed using the 10' DTM.

   JEF Response: Done.

6. Page 57, Sheet Flooding. Just because an area may have sheet flooding does not mean that it is an "active alluvial fan". This need to be defined better through out document. See next comment.

   JEF Response: We could not find a place in the referenced text or elsewhere in the report which suggests that the presence of sheet flooding indicates that the landform is an active alluvial fan.

7. Page 83, This report should provide the clarification between active alluvial fan and active alluvial fan flooding as it relates to FEMA.

   JEF Response: Done.

8. Page 84, Inactive Alluvial Fan. These statements/recommendations need to be revised and toned down.

   JEF Response: Done.

9. Page 98, Table 20, Overview of Stage 3 Methodology. While I understand the use of Manning's to calculate the flow depth. There appears to be a conflict in the document where it previously indicates that Manning's calculations should not be used. Please update the proceeding Documentation to eliminate the discrepancy.

   JEF Response: Done.

Reviewer: Floodplain Mgmt. & Services Division, 5-24-2010

1. Page 3, the word World should be work.

   JEF Response: Done.

2. Page 69, add the word to, to the sentence Surface age estimates are used help identify.

   JEF Response: Done.

3. Page 93, the 50 cfs requirement is from the Floodplain Regulations not the Drainage Regulations.

   JEF Response: Done.

4. Page 93, table 17. Clarify the requirements. High hazard is the 100-Year Discharge greater than 50 cfs plus any of the following the USBR of high, the Risk of Debris Flow, the Risk of Avulsion. Moderate is the 100-Year Discharge greater than 50 cfs plus USBR of Judgment without risk of Debris flow and risk of Avulsion. Low is the 100-Year Discharge greater than 50 cfs and the USBR of low without risk of Debris flow and risk of Avulsion. Not Regulatory Floodplain the only criteria is 100-Year Discharge less than 50 cfs.

   JEF Response: Done.

5. Page 99, add the word to, to the sentence … where development is expected occur, the District.

   JEF Response: Done.

6. Page 99, FEMA Criteria, The Flood Control District will not underwrite structure measure.

   JEF Response: Acknowledged. We did not find a place where the text suggested that District would do so. No change made.

7. Page 100, the wall openings needs to be on all sides not just the downstream side.

   JEF Response: Done.

8. Page 105, define Coalesce.

   JEF Response: Coalesce means to grow together. The term is used in the existing PFHAM document.

Reviewer: Engineering Application Development and River Mechanics Branch, Engineering Division, 5-25-2010

1. Both the final alluvial fan report as well as the avulsion assessment report are signed with expired professional seal.

   JEF Response: The seal expiration date is updated.

2. Please submit the FLO-2D animation files.

   JEF Response: Will be provided on documentation DVD with final report.

3. Page 29: Virtual levee implementation is so subjective. 500-year event is beyond FEMA's 100-year requirement. Instead of virtual levee and 500-year, we suggest to use a 100-year with a safety factor (for example 1.5) to account for uncertainties. Bulking factor may serve the same purposes.

   JEF Response: Per direction of the District's project manager, the recommendations of the Blue Ribbon Panel are to be used. See Blue Ribbon Panel summary report.

4. Page 70: 2.5.1 Recommendations: What is the use of doing a regional chronology to date Holocene alluvial fans?

   JEF Response: The regional chronology is recommended to improve resolution of numerical dating methods for Holocene-aged surfaces. A more detailed explanation was provided in the Task 2.6 Report.

5. Page 74: 2.6.1 Recommendations: The document indicates that debris flow do not runout far enough to reach the hydrographic apex. What about the hazard due to debris flow at topographic apex?

   JEF Response: The active alluvial fan does not begin until downstream of the hydrographic apex. For the vast majority of fans in Maricopa County, the fan landform at the topographic apex is a relict or inactive fan. As such, the risk of overtopping due to debris deposition is negligible (i.e., the geology indicates such overtopping has not occurred for 10,000-2,000,000 years). Furthermore,

the Task 2.8 Report indicates that the occurrence of debris flows that pass the mountain front (i.e., topographic apex) is much rarer than a one percent chance event.

6. Page 74: 2.6.1: unlikely to impact flood hazards in alluvial fan, do we need 3-step procedure to evaluate debris flow?

   JEF Response: Yes. It is important to be able to demonstrate to FEMA that debris flows are not a hazard. The analyses done for this study will greatly simplify the required analysis for most fans in Maricopa County.

7. Page 81: The document says "It is further recommended that Maricopa County not develop new definitions that differ from the terminology used by FEMA…Instead, the District should work with FEMA …" These two sentences must be removed from the report because they are not appropriate.

   JEF Response: The cited text has been edited.

8. Please add definition for alluvial slopes, use Rhoads's paper or other geomorphology standard definition.

   JEF Response: The term "alluvial slope" is not commonly used in the literature or in the practice of geomorphology as it relates to alluvial fan flooding. It is not included in Penguin's Dictionary of Geology, the Encyclopedia of Geomorphology, or any of the 19 geomorphology textbooks I own. Note that Rhoad's proposed approach has not been accepted or applied by any regulatory agency, including the City of Scottsdale for which Rhoad's methodology was originally proposed. For these reasons, we do not recommend that "alluvial slope" be included as a category of landform for the PFHAM.

   The underlying issue is addressed in the report under the topic of alluvial plains.

9. Page 83: regarding definition of alluvial fan, the report indicates "Location. Alluvial fans are usually located at mountain front or topographic break." If we use this criterion, some fans are not alluvial fans because they are not near the mountain or at a topographic break. Please clarify.

   JEF Response: The text refers to an alluvial fan <u>landform</u>. Also, note use of the word "usually." Clarifying language and an explanatory footnote was added to the text.

10. Page 84: please remove the fourth bullet. The District's intention is to improve the current methodology and avoid miss-use of the current methodology, i.e., declaring too many channel splits as alluvial fans. Although the splits are unstable, they are on mild slope. In fact, based on FEMA (page G-2) an active alluvial fan must meet ultrahazardous condition created by a combination of sediment availability, slope, and topography. When an alluvial fan is miles away from the mountain base on a very mild slope without topographic break, this alluvial fan should be considered as an inactive alluvial fan.

    JEF Response: The text in the 4th bullet has been modified. Regarding the remainder of this comment, the topic was addressed by the Blue Ribbon Panel. Per direction of the District's project manager, the recommendations of the Blue Ribbon Panel are to be used. See Blue Ribbon Panel summary report.

11. Definition of alluvial plains, page 84-85: Rhoads' paper was given to consultants several times. Why was it NOT discussed in the report? Rhoads' used 0-2% slope, low drainage density to describe alluvial plains.

    JEF Response: Use of Rhoad's methodology was discussed at several team meetings in May 2009, and was not included based on the content of those discussions. To summarize: (1) there is significant overlap in slope between landform categories – thus they are not diagnostic, (2) alluvial plains are considered "high" hazard zones in Rhoad's classification, (3) active alluvial fans are characterized by Rhoads as having "extremely low" slopes in some cases, and (4) Rhoad's management strategies are not compatible with the District's – all Zone 1 surfaces are considered undevelopable & in Zone 3 streets are used to convey flooding. Note that Rhoad's landform characteristics are descriptive of specific surfaces on the McDowell Piedmont and were not intended to be generically diagnostic of piedmont landforms outside his study area.

12. The paper by Blair et al (1994) is the literature search DVD. It clearly puts 15. Degrees as alluvial fan slope minimum. Why does consultant indicate that there is no literature? Why was it not discussed in the report?

    JEF Response: I believe the reviewer meant 1.5 degrees, not 15 degrees. We are not clear what the reviewer meant by "there is no literature." Blair et. al.'s conclusion regarding a minimum slope for alluvial fans is specifically rejected by many authors, and is contradicted by the data presented in the supplemental literature search task (Section 2.1.2 of the report). The notion of a minimum slope for alluvial fans was also dismissed by the Blue Ribbon Panel.

13. Please read Rhoads' paper for alluvial slope which is between alluvial fan and alluvial plain.

    JEF Response: See response to comment #11 above.

14. Page 86, Recommended design frequency: why 100 year? Through recommendation number 3, California task force asks the local flood management agencies to consider higher level of flood management protection above the 100-year FEMA regulatory standard in planning for development in alluvial fan areas.

    JEF Response: The rationale for using the 100-year flood is described in Section 3.2 of the report. The Blue Ribbon Panel also recommended use of the 100-year flood. Per direction of the District's project manager, the recommendations of the Blue Ribbon Panel are to be used. See Blue Ribbon Panel summary report.

15. Page 86: if we are dealing with 100-year only, should we remove geomorphology entirely from the tool box for alluvial fan because geomorphology is based on a much longer time span and has nothing to do with 100-year flood?

    JEF Response: I believe the consensus of the District staff and the Blue Ribbon Panel is that use of geomorphology is an important component of the recommended methodology. This opinion is also supported by FEMA and NRC documents.

16. Page 86: we agree that it is more difficult to convince the public and developers to use an event larger than 100-year. We also recommend 100-year with a safety factor or bulking factor to account for uncertainties.

JEF Response: See response to comment #15 above.

17. Page 87: Table 14 lists FLO-2D as the only hydrology tool. Please list HEC-1 as the potential tool for upstream well-defined channel areas.

    JEF Response: Under the Inactive Alluvial Fan category, HEC-1 is included by reference to the existing District Hydrology Manual. HEC-1 is not recommended for active alluvial fans or alluvial plains.

18. Page 87: Table 14 lists software and methods for engineering tools. Both FLO-2D and HEC-RAS are listed as tools for active alluvial fan modeling. However, based on FEMA appendix G, it seems that Hydraulic Analytical Methods (page G-13) can not be used for active alluvial fan. This put Maricopa County directly contradictory to FEMA's requirement. However, if we better define and interpret "sediment availability, slope, and topography" that creates ultrahazardous condition, we may remove many fans from active fan category, thus, we can use the Hydraulic Analytical Methods for the inactive fans.

    JEF Response: Table G1 in FEMA Appendix G indicates that composite methods may be used. The recommended methodology is a composite method that combines engineering and geomorphic tools.

19. Table 14 on page 87 lists Slope-walk tool as a tool for avulsion. We do not recommend this tool because it is a simple drainage path tool. There are many drainage path tools available. In addition, if we adopt this tool, Maricopa County will be the owner of the Slope-walk tool.

    JEF Response: The text has been revised to clarify the intent and application of the slope-walk tool..

20. Page 88: HEC-1 should not be used for drainage area that is on alluvial fan. But it can be used for drainage areas with well-defined drainage boundaries that drain to alluvial fans.

    JEF Response: We agree.

21. Page 88: Virtual levee scenario method: We think there is too much subjectivity associated with virtual levee method, which defeats the purposes of FLO-2D, an objective method. Although guideline can be developed for virtual levee, the parameters selection are too subjective. We think flow rate with a safety factor or bulking factor should be used.

    JEF Response: See response to comment #3 above.

22. Page 88: Section 3.3.2 indicates that FLO-2D and HEC-RAS should be used for both active alluvial fans and alluvial plains. However, based on FEMA appendix G, it seems that Hydraulic Analytical Methods (page G-13) can not be used for active alluvial fan. This put Maricopa County directly contradictory to FEMA's requirement. However, if we better define and interpret "sediment availability, slope, and topography" that creates

ultrahazardous condition, we may remove many fans from active fan category, thus, we can use the Hydraulic Analytical Methods for the inactive fans.

JEF Response: See response to comment #18 above.

23. Page 89: please remove virtual levee scenario method from Table 15. Instead add 100-year with 1.5 safety factor for the flow hydrograph or a bulking factor.

JEF Response: See response to comment #3 above.

24. Page 90: Regarding avulsion assessment, using Slope walk tool does not provide avulsion potential; rather it provides drainage network similar to Topaz in WMS.

JEF Response: Use of the slope-walk tool was considered by the Blue Ribbon Panel, which recommended that it be included in the recommended methodology. Per direction of the District's project manager, the recommendations of the Blue Ribbon Panel are to be used. See Blue Ribbon Panel summary report.

25. Page 90: Debris flow most likely have impact on the "inactive" fan areas near the mountains. Are we under-estimating the potential hazards near the mountain base?

JEF Response: Debris flow potential is not underestimated if the recommended methodology is followed. Debris flow impacts to inactive alluvial fans are highly unlikely. If debris flow hazards were more common, the surfaces would be active.

26. Page 93: Table 17 presents hazard levels of High, Moderate, Low, and Not Regulatory Floodplain with four criteria. However, the way it is presented is confusing. Are those criteria based on logical operators "AND" or "OR"? For example, is Hazard Level High when four criteria are satisfied or just one of them is satisfied (USBR classification is high, 100-year discharge >50 cfs, Debris Flow is Yes, and Risk of Avulsion is Major)?

JEF Response: See response to Floodplain Management comment #4 above.

27. Fan slope, Page 94: According to NRC, there are three types of fans: stream flow fan, debris flow fan, and composite (Bull 1977, NRC 1996). There are fan slope threshold available for fan hazards. Streamflow or flood fan (3-4 degree), debris flow fan steeper than (6-8 degree), and composite fan—combination of the previous two. Slopes on streamflow fans are generally less than 3-4 degrees, which is considered to be the threshold between streamflow fan deposition and debris flow fan deposition (Jacson et, al., 1987). Blair et al. (1994) states that alluvial fan slopes range from 1.5 degrees to 25 degrees, river slopes are less than 0.5 degrees, and river delta slopes are less than 0.5 degrees. Rhoads (1986)'s classification is as follows: 2%-5% slope and 32 km/km^2 drainage density for alluvial slope and 0-2% slope and 16 km/km62 drainage density for alluvial plains. Although there are fans with a slope less than 3 degrees or 1.5 degrees, majority of fans in the literature have a slope more than 2%. Based on Alluvial Fan Characteristics task by Fuller (2010), most of fans are more than 1 degree or 1.7%. This overwhelming evidence suggests that people are not concerned with flat fans because there is no ultrahazardous condition, therefore, these fans should not be considered active fan based on current FEMA definition. These fans should be considered inactive,

therefore, HEC-RAS and FLO-2D can be used based on FEMA guideline. It should be mentioned that FLO-2D model can be used to model debris flow and can not be used to model both debris flow and sediment transport together.

JEF Response: This comment has been addressed by the Blue Ribbon Panel as well as in responses other comments above. Per direction of the District's project manager, the recommendations of the Blue Ribbon Panel are to be used. See Blue Ribbon Panel summary report.

28. Page 95: Channel capacity discussion needs revision. The report indicates that channels with low capacity on active alluvial fans are more prone to overflow and cause avulsions, and thus may be more hazardous than fans with higher capacity channels. Avulsion depends upon many factors. One of the key factors is upstream flow and sediment flow. Smaller channels may have smaller upstream flow and sediment flow. Using channel capacity may not be appropriate.

    JEF Response: The causes of avulsions are discussed in detail elsewhere in this report and in other reports previously provided to the District. Channel capacity is one of the key factors for identifying avulsion potential. If the channel does not overtop, there can be no avulsion. Channel capacity reflects both water and sediment impacts.

29. Page 95 and page 96: Some simple geomorphic and engineering parameters should be added to Stage 2 to help better define Maricopa County's active alluvial fans. For example, watershed size, flow rate, fan slope, sediment load, distance from hydrographic apex to the mountain base, stream power, and other simple geomorphic and engineering parameters should be added to help remove fans from active fan category. This will help define the magnitude of "active." If the magnitude of "active" is beyond our concern, we should not treat them as active fans.

    JEF Response: This comment was addressed by the Blue Ribbon Panel. Per direction of the District's project manager, the recommendations of the Blue Ribbon Panel are to be used. See Blue Ribbon Panel summary report.

30. Page 97: Adding large grid FLO-2D to the toolbox at Stage 2 is a good step. However, FEMA does not seem to support using Hydraulic Analytic Method for active fans. It seems reasonable to add some simple parameters to better define "active" in this stage.

    JEF Response: See the response to comment #18.

31. Table 20, Page 98: Instead of virtual levee and 500-year flow, use 100 year flow with a safety factor say 1.5 or some value to be determined.

    JEF Response: See response to comment #3.

32. Page 101, add discussion on alluvial slopes

    JEF Response: See response to comment #11.

33. Page 102, Debris flow: Lower gradient fan in Maricopa county, about 4 degrees is the threshold for stream flow fan and debris flow fan. Debris flow potential in majority of Maricopa fans is insignificant.

    JEF Response: See response to comment #27.

34. Appendixes, Page 103: Instead of separate appendixes, it is better to have with the report; examples in the appendixes will clarify the material in the main report.

    JEF Response: We recommend deferring discussion on this comment until such time as the PFHAM is revised. All appendixes will be delivered with the final report.

35. Pediment, Page 103: Is there hazard as sediment accumulation is not a problem in pediments?

    JEF Response: Evaluation of pediment flood hazards were not included in the scope of services for this project. In general, pediments are eroding landforms, although there can be areas of local aggradation. There are definitely flood hazards on pediments, as well as modeling challenges relating to numerous split flows.

36. Two dimensional modeling, page 104: District does not ONLY recommend Flo2D, however this work was done using Flo2D model, if possible other 2d models can be used.

    JEF Response: We agree. See Sections 2.3.2, 2.3.3, and 2.3.5 of the report.

37. Page 104: Please remove sentence "Maricopa County should not develop new definitions that differ from the terminology used by FEMA…"Please also remove "The District should not attempt to redefine the term inactive alluvial fan…"

    JEF Response: See response to comment #7 above.

38. Above apex hydrologic modeling, page 105: Flo2D is not necessary as runoff can be generated by any other hydrologic model.

    JEF Response: While we agree that it is not necessary to use FLO-2D to model tributary watersheds, we believe that the District will begin to see more requests to model many different types of watersheds with FLO2D, and therefore it would be prudent to develop appropriate guidelines. With respect to alluvial fans, since the modeling below the hydrographic apex will be done with a two-dimensional model, we expect that many modelers will wish to streamline the modeling effort and use the same model upstream of the apex.

39. Coalscing alluvial fan, page 105: instead of virtual levee, use 100 yr flood with safety factor.

    JEF Response: See response to comment #3 above.

40. Avulsion frequency, pg 108: lower gradient fan in Arizona, avulsion is insignificant, it may occur only after repeated flooding and aggradation. In fact, the avulsion study (FE

Fuller, 2010) indicates that avulsion is rare. Therefore, study is not necessary because there is no data to do any frequency analysis.

JEF Response: Our report states that it is likely that avulsions probably are rare, but that there is insufficient data collected to date from which to assess the frequency. We do know that avulsions occur on alluvial fans in Maricopa County and that the consequent changes to the flood hazards have been significant. Therefore, we recommended that the District collect the data from which to assess the frequency. If it turns out that it can be documented that avulsion frequency is extremely rare, then it is likely that the recommended alluvial fan delineation methodology can be significantly simplified. We further note that the Blue Ribbon Panel supported the recommendation to evaluate avulsion frequency.

41. Slope walk tool, pg 108: it provides drainage network, not avulsion.

    JEF Response: See response to comment #19 above.

42. High hazard zone, page 109: The extent of the high hazard zones should be a function of other factors such as sediment availability as well as fan slope, drainage area, and discharge.

    JEF Response: This comment was addressed by the Blue Ribbon Panel. Per direction of the District's project manager, the recommendations of the Blue Ribbon Panel are to be used. See Blue Ribbon Panel summary report.

Reviewer: Engineering Division, 5-25-2010

1. 1.2 Scope also includes some of the Objectives (1.1) of this study, but should make clear the results are specific to conditions that occur in Maricopa County.

   JEF Response: Done. See also Section 1.3 of the report.

2. 1.5 Terminology: It would be appropriate to use the Landform definition from FEMA Appendix G, G.2.1., which is also on page 82, Table 13, instead of adding a definition: "An alluvial fan is a sedimentary deposit located at a topographic break such as the base of a mountain front, escarpment, or valley side, that is composed of streamflow and/or debris flow sediments and has the shape of a fan, either fully or partially extended."

   JEF Response: Definitions are discussed in detail in Section 3.1 of the report.

3. It would be nice for the executive summary to include a summary of characteristics found in Maricopa County, that are also limits for this study. Such as:

   Alluvial Fan Characteristics in Maricopa County

   - Low Slopes (less than 2 degrees, many less than 1 degree)
   - Water Flood Dominated
   - Located Away From Mountain Front
   - Limited Aerial Extent (small)

- Relatively Small Peaks (high Q/area)
- Low Flood Volumes (flashy)
- Transitions to Sheet Flow

JEF Response: This was included in the executive summary.

4. At the bottom of page 2, strike the statement "The literature research revealed that Maricopa County is in the forefront of alluvial fan flood hazard assessment in the United States, as well as abroad." This is not borne out by the literature research.

JEF Response: The statement was removed.

5. In the statement on the bottom of page 2 that begins "The FEMA guidelines allow a number of delineation methodologies . . .", add the statement that in the past two decades in Maricopa County, only alluvial fan delineations relying solely on geomorphic methods have been used.

JEF Response: Done.

6. P.3. middle of the page, change to read: "Review of the literature indicated that debris flow hazards in Maricopa County were unlikely."

JEF Response: While that was the conclusion made in the Task 2.8 study, it was not a conclusion made in the task being summarized in the portion of the text referenced by the reviewer.

7. P.3. Alluvial Fan Flood Mitigation Measures. Provide citation for references for "US Army Corps of Engineers".

JEF Response: Done.

8. P.3. The statement "FEMA does not currently have engineering standards . . ." not correct. Engineering guidance is provided starting back with FEMA 165, May 1989.

JEF Response: The text has been clarified. FEMA does not have any detailed guidance or specifications developed specifically for alluvial fans.

9. P.4. bottom of the page, "Most of the fans described had slopes greater than three percent." Should read "five", which is equal to 3 degrees on Figure 1.

JEF Response: The text has been clarified.

10. P.5., bottom of the page, "Based on this analysis, most . . .", the word "all" could be used, or else explain the exception.

JEF Response: To date, no comprehensive survey of characteristics of fans in Maricopa County has been performed. It is possible that some unstudied fan in the county may lie outside (or in a different part of) the cloud of common values shown in the Figure.

11. P 5., The conclusion starting "Therefore . . . can reasonably be assumed to be relevant . . ." is misleading. Most of the literature collected is for fans that have characteristics, conditions and hazards beyond the scope of our situation, and would overstate our flood hazard, except that we are below the threshold of their study conditions.

    JEF Response: The literature search showed that fans in Maricopa County lie within the cloud of common values, not below the threshold of those described in the literature.

12. P.9 through P.20. In the text for each fan that is discussed, include the key fan physical characteristics: Basin area above the apex, basin slope, fan area, fan length, fan slope. In each of the include pictures, show the outline of the fan.

    JEF Response: Done.

13. P.9 through P.20. Additionally, provide a summary table of physical characteristics for all of the fans in the report (expand on Table 1, or add new table).

    JEF Response: Done.

14. P. 14 Table 1, I did not check the entire table, but from memory, Reatta Pass Fan is 3.5% immediately below the apex, but flattens to 2% downstream. Watershed slope should be included in the table. Also the slope of the channel above and below the apex, to account for break in grade, and the fan length.

    JEF Response: Watershed slope is now included in the Table. Fan length can be estimated from the scale shown on the figures provided.

15. P. 16 Figure 7, split to show the full fan, and then also include same scale picture adjacent to the full fan to show the same scale for 2007 photo as the 1949 and 1954 photos.

    JEF Response: Done.

16. P. 81 Recommendations 3.1. "One of the key findings. . .", delete this sentence and the next. Delete the last two sentences that begin "It is further recommended . . ."

    JEF Response: The text has been revised.

17. P. 84 The ASFPM "white paper" should not be cited as if it is an independent paper since it was it was authored by Fuller during the same time as working on this study for us. It is my understanding it may still be a draft or just recently finalized.

    JEF Response: The ASFPM Arid Regions White Paper was not cited as a Fuller reference, although Jon Fuller was in fact the original author. We are unclear why the ASFPM White Paper should not be cited, since other independent papers are cited in the report, as are reports by Fuller, and as are reports that are still in press. The ASFPM Arid Regions white paper describes an effort to modify FEMA Appendix G that closely parallels the District's effort. Currently, there is a narrow window of opportunity for such revisions, due to FEMA's effort to re-evaluate and re-authorize the NFIP. If the District participates in ASFPM process, they have an excellent

opportunity to achieve the District's goals of having the recommended methodology approved by FEMA.

18. p. 84 delete the last bullet "Inactive Alluvial Fan".

JEF Response: See previous responses.

Reviewer: Hydrology/Hydraulics Branch, ENG Division, 5-24-2010.

1. I have finished going through the report. I do have some concerns about what is being presented as the recommended methods but those concerns do not necessarily need to be addressed prior to the panel seeing the report.

JEF Response: No response needed.

2. So I have no new pre-panel concerns/recommendations other than the ones I sent earlier today. Which is probably good because you probably have no more time since it is so late in the day.

JEF Response: No response needed.

3. I noticed that the Stage 3 level of effort that was presented in the methodology recommendation PowerPoint is not included in the final report. I presume there was a shift in thinking from then until now. I somewhat liked the table that presented that in the original PowerPoint. Also, with the dating and debris flow discussions and recommendations the language appears to be presented more as a requirement than an option so I think the future language will need to reflect that more.

JEF Response: The text was revised accordingly.

4. I thought that there would be a few more recommended engineering thresholds where specific values would be called out but maybe I missed some. I think part of this is tied back to how the hazards will now be identified through avulsion "categories" and the Bureau categories.

JEF Response: No response needed.

5. I need to think about which engineering tasks are presented in each Stage some more but it does appear consistent with what was presented in April.

JEF Response: No response needed.

6. I will try to have all my comments for both reports compiled by Wednesday (or Thursday).

JEF Response: No response needed.

7. Excellent work but still expect 2-4 pages of comments.

JEF Response: Does that mean I can ignore pages 5 & following?

Reviewer: Hydrology/Hydraulics Branch, ENG Division, ENG Division, 6-4-2010.

Overall the report provides an excellent summary regarding the research performed for this project and provides a reasonable framework method for updating the District's approach to the 3 Stage process. The comments listed below are not necessarily requirements but are more for consideration in the final product. A list of typographic items found in the report is also included.

Introduction

1. No comments.

   JEF Response: No response needed.

Summary of Findings

1. Section 2.1.1, page 3, third paragraph. Clarify the first sentence. Should the word "world" be in the sentence?

   JEF Response: Done.

2. Section 2.1.1, page 4 second paragraph. Remove "so-called" as an adjective in front of geomorphic methods.

   JEF Response: Done.

3. For Figures 3, 4, and 5, please add the outline of the "active" area. For Figure 6, could the outline stand out a little better?

   JEF Response: Done.

4. Section 2.3.1.1, last sentence. Should Buckeye/Sun Valley ADMS be mentioned as well. Did JEF modify or update BSVADMS hydrology or start new?

   JEF Response: JEF reviewed the BSVADMS hydrology, but basically developed new (but similar) models.

5. Section 2.3.1.3. Please re-verify text. Was RVF #1 identified as a possible "alluvial fan" or a possible "active alluvial fan"?

   JEF Response: Done.

6. Figures 12-15. It is highly recommended that each of these figures be presented as a full page. It is really hard to read the cross-section ids at their current size.

   JEF Response: Done.

7. Section 2.3.2.3, page 28, end of third paragraph. Please include a citation for the White Tank Fan #1 and #2 study and include in the references.

   JEF Response: Done.

8. Section 2.3.2.4. Consider removing the recommendations from this section and present this more as a conclusions section. It is recommended that all recommendations be presented in the overall Recommendations section (Section 3 of the report).

   JEF Response: The text was changed to "Conclusions."

9. Table 6, page 30. White Tank Fan 7, 8, 12 is not included in the table although it is mentioned in the text. Rainbow Valley Fan 12 also needs to be added to the legend.

   JEF Response: Done.

10. Section 2.3.3.2. The text describes the PMP event but no graphic is provided in Figures 23-26. Should the text emphasize the 500 year event more since apparently there is a space issue to show the PMP graphic in these figures?

    JEF Response: A PMP figure was added to illustrate the points made in the text.

11. Section 2.3.3.5, page 43 White Tank Fan paragraph. Regarding the statements in this section that aggradation has occurred or flow has shifted, could the grid scale or 10 foot topo also be responsible for that appearance or was that statement actually based on the 25 ft grid and 2 foot topo mapping model?

    JEF Response: We do not believe it to be a function of map accuracy or scale.

12. Section 2.3.3.5, page 44, top paragraph. The text describes the 500 year event. Should a figure be presented showing those results?

    JEF Response: Done.

13. Section 2.3.3.6, page 47, second bullet. Could a figure be included for the Slope Walk Method?

    JEF Response: Done.

14. Section 2.3.3.6, page 47, second bullet. For each of the avulsion simulation models a brief findings/conclusion is presented in each bullet. However, that appears to be missing for Slope Walk. Could a brief findings be included here?

    JEF Response: Done.

15. Section 2.3.3.6, page 47, fourth bullet. Please verify the description provided for perched channels and the text and graphic for Figure 38.

    JEF Response: Done.

16. Section 2.3.39, page 56, top paragraph. This paragraph covers the conclusions of the hazard modeling. However, the last portion of the discussion is closer to recommendations than conclusions. Should the recommendation portion of the text be moved to Section 3 Recommendations?

    JEF Response: See response to comment #8.

17. Please verify Figure 50 a-d and Figure 51 a-d graphic placement and text.

    JEF Response: Done.

18. Section 2.5.1. It is recommended that this section be re-named Conclusions and that any currently presented recommendations be moved to Section 3 Recommendations.

    JEF Response: The section was renamed.

19. Section 2.6. This section presents a recommended methodology. It is recommended that the recommended methodology be moved to the Recommendations section of the report. This section should just cover what was found in the research on fans and generally describe what methods were found.

    JEF Response: The section summarizes the findings of the scoped analyses.

20. Section 2.6.1, page 74. Replace the recommendations subsection with a conclusions subsection.

    JEF Response: The section heading was renamed.

21. Section 2.7, page 79. This portion of the section presents a recommended methodology. It is recommended that the recommended methodology be moved to the Recommendations section of the report.

    JEF Response: See response to comment #8.

Recommendations

3.1 Definitions

1. In general, the recommendations regarding the definitions are reasonable.

   JEF Response: No response needed.

2. In concept at this stage in the process I feel it is reasonable to consider that areas that fall into the hazard criteria will be deemed "active alluvial fan flooding". Although the definitions of "ultrahazardous" is still elusive, data supporting the other two criteria (flow path uncertainty and abrupt sediment deposition/ensuing erosion) will likely be identified. However, this leaves a gap in the definitions if the upper area is classed active

alluvial fan flooding and it has also been recommended that inactive alluvial fan flooding remain solely used for riverine channels on a fan.

JEF Response: This comment was addressed by the Blue Ribbon Panel. Per direction of the District's project manager, the recommendations of the Blue Ribbon Panel are to be used. See Blue Ribbon Panel summary report.

3. If the "active flooding" near the hydrographic apex and transitions to channelized flow on the lower portion of the "Stage 2 active fan" would it be designated as "inactive alluvial fan flooding?" Could more guidance in this regard be provided?

JEF Response:

- **1st Question: No. Portions of the "active fan" should not be designated "inactive." They should be designated as low hazard flooding on active piedmont surfaces. If there is a transition to channelized (i.e., flow contained in defined channels surrounded by inactive surfaces), that area should not be considered active. It would probably be classified as a stable distributary flow area.**
- **2nd Question: Yes. More detailed discussion of these types of scenarios should be included in the revised PFHAM document.**

4. Section 3.1.1, page 83, second paragraph. Consider replacing "competent investigator" with "investigator with the proper resources".

JEF Response: We believe competence, not resources, is the key success factor.

5. Section 3.1.2, page 85, third paragraph. Consider re-wording to remove "The District would like".

JEF Response: Done.

3.2 Recommended Design Frequency

1. I agree with the recommendation of using the 100-year event as the recommended delineation and design frequency for alluvial fan in Maricopa County.

JEF Response: No response needed.

3.3 Engineering Tools for Alluvial Fan Flood Hazard Assessment

3.3.1 Hydrologic Modeling

1. I agree with the recommendations regarding the use of FLO-2D, or other reasonable two-dimensional model, for hydrologic modeling on active fans and the recommendations presented for the upper watersheds. The recommendations for virtual levees, future conditions etc. are reasonable as well.

JEF Response: No response needed.

3.3.2 Hydraulic Modeling

1. Overall I am in agreement with the recommendations regarding the use of FLO-2D and HEC-RAS on active alluvial fans. However, I offer the following comments on certain specific items.

    - Regarding water surface elevations at building sites, if it is the District's intent to submit the study as Zone AE the water surface elevations generated under the FLO-2D model will need to be used for setting lowest floor elevations. This is the current practice in Rio Verde. I recommend the text and Table 15 be modified to reflect this. This can be discussed further if necessary.

    JEF Response: The text was revised accordingly.

    - Could clarification be provided in the text regarding the statement "include sediment deposition" in Table 15 under the water surface elevation row? Is this a recommendation to require lowest floors be set above the regulatory flood elevation plus the potential sediment depth identified at a given site? Is the sediment deposition determined from the FLO-2D model or another method? Based on what has been presented it was recommended that FLO-2D sediment results be used more for trends only.

    JEF Response: The text was revised accordingly.

3.3.3 Sedimentation Modeling

1. I agree with the recommendations in this section. However, if possible I would recommend including additional discussions regarding which types of FLO-2D sediment modeling approaches seem reasonable to move forward with for the methodology. Should it be mentioned in this section that the Zeller-Fullerton equation appears to be the most reasonable at this point for FLO-2D on alluvial fans?

    JEF Response: Done.

3.3.4 Surficial Dating

1. I agree with the recommendation that surficial dating methods should be incorporated into the overall method. However, I feel that the current text presents the recommendations more as a requirement rather than a method option. I would prefer the recommendations be presented more as an option should the situation arise where either the District or any other individual would be interested in performing dating analysis that we have the method available.

    JEF Response: Text has been modified.

2. Add recommendation text from 2.5 to this subsection. Re-iterate which methods would work best.

    JEF Response: Done.

3.3.5 Debris Flow Assessment

1. I agree with the recommendations and proposed method provided. However, I would recommend that additional language be added to the beginning of this section stating that this method is not necessarily a requirement in the base method and that it is only presented so that the District has a method outlined should the case arise where a debris flow fan is identified.

   JEF Response: Done.

2. Add recommendation text from 2.6 to this subsection.

   JEF Response: Done.

3.3.6 Avulsion Assessment

1. I agree with the avulsion methodologies recommended. Although there are several presented at this point, I believe it is too early to determine whether any method should be abandoned at this point. Additional testing most likely will provide more insight to these approaches and what eventually is adopted in the Manual.

   JEF Response: No response needed.

2. Add recommendation text from 2.7 to this subsection.

   JEF Response: This section describes the recommended engineering tools.

3.3.7 Limitations of the Geomorphic (Only) Approach

1. Not sure this is the best location for this section. Please consider alternate locations. Maybe this could be lumped with other methods with limitations (i.e. FAN)? Perhaps the section could also provide guidance on hydraulic methods within developed active fans.

   JEF Response: This section was added specifically in response to comments by other District staff.

3.4 Flood Hazard Classification Matrix

1. I agree with the recommended hazard zone criteria classification presented. However, it is recommended that additional discussion be provided to state how the classification will be used in the overall method.

   JEF Response: Done.

2. Section 3.4.1, page 93, second paragraph.

   - Please consider repeating the hazard classification scheme instead of the section reference.

JEF Response: Addition of the repeated text in this section made the text cumbersome. We request to leave it as is.

- Please state which Bureau of Rec curve is being used in the hazard classification analysis.

JEF Response: Done.

3. Section 3.4.1, page 93, second bullet set, second bullet. The reference to Section 2.6 may need to be revised based on above comments.

JEF Response: No change needed.

4. Table 17. The text and table need to reflect whether the information presented in Table 17 is an and/or situation.

JEF Response: Done.

3.5 Recommended Integrated Methodology – Flood Hazard Analysis

3.5.1 Stage 1

1. Section 3.5.1, page 96, second paragraph. Consider re-phrasing the first sentence.

JEF Response: Sentence was revised.

3.5.2 Stage 2

1. The recommended approximate methodologies seem reasonable. I recommend that "if needed" be added in parentheses to the debris flow potential and surficial geologic mapping in table 19.

JEF Response: All of the tasks are "if needed." In general, we try to keep the tables as uncluttered as possible.

2. The recommended detailed methodologies seem reasonable. Again I recommend that "if needed" be added in parentheses to a few items such as detailed surficial mapping, numerical surficial dating, and debris flow potential modeling.

JEF Response: See response above.

3. Regarding the coarse hydrologic/hydraulic modeling method in the detailed method. I would recommend that this model be switched to a finer grid model that essentially becomes the base model condition.

JEF Response: Done.

4. The section provides methods but does not discuss how the results of the individual methods allow one to arrive at the results of active and inactive. Should that be discussed here as well?

   JEF Response: We believe that this discussion would be more appropriate in the revised PFHAM Manual when it can be illustrated with examples.

3.5.3 Stage 3

1. The recommended approximate methods appear reasonable. However, I would recommend that either all the debris flow assessment be moved to Stage 2 or Stage 3 presently it is performed in both. Why is it presented that way? My recommendation would be Stage 3.

   JEF Response: A portion of the debris flow analysis is performed to support the active/inactive designation (Stage 2). A portion of the debris flow analysis (if needed) is performed to determine hazard level & flood zone (Stage 3). We anticipate that in most cases in Maricopa County, a Stage 3 debris flow analysis will be unnecessary.

2. The recommended detailed methods appear reasonable. However, as in the above comment I would recommend that either all the debris flow assessment/modeling be moved to Stage 2 or Stage 3 presently it is performed in both. My recommendation would be Stage 3. Also, I am open to the removal of the PMP FLO-2D analysis.

   JEF Response: See previous comment.

3. This section provides methods but does not discuss how the results of the individual methods allow one to arrive at the results of the final floodplain delineation and zone designation. Should that be discussed here as well?

   JEF Response: We believe that this discussion would be more appropriate in the revised PFHAM Manual when it can be illustrated with examples.

3.6 Recommended Design Guidelines

1. I was hoping that additional information could have been provided that provides a greater level of detail as to what should be required.

   JEF Response: There may be some scope of work / level of effort issues at play here. The design guidelines listed in the scope of services (Task 2.9.3) indicate that the design guidelines will consist of a list of engineering tools and methodologies and the flood hazard classification matrix. Perhaps this could be expanded when the PFHAM is revised.

2. Regarding through-flow corridors. Please add a statement that these corridors would be planning activities versus floodplain delineation activities.

   JEF Response: Done.

3. Regarding FEMA criteria. Could additional recommendations regarding what information should be submitted where we feel development could be placed without the additional 65.13 caveats?

   JEF Response: The revised report recommends that Part 65.13 criteria only be applied in areas subject to [ultrahazardous] active alluvial fan flooding.

4. Section 3.6 Floodways and high hazard zone development bullets. These two bullets can be combined.

   JEF Response: We see a subtle, but important difference and recommend they stay as is to address comments by others.

3.7 Recommended PFHAM Refinements

3.7.2 Stage 1 Refinements

1. Overall the recommended refinements are reasonable. I agree that the potential exists to keep Stage 1 simple based on Appendix G; however, I still feel that specific landform identification is valuable on some levels. Perhaps it can be covered in the manual but does not necessarily need to be included in the Chapter on Stage 1. This comment ties into Stage 2 comments as well.

   JEF Response: No response needed.

3.7.3 Stage 2 Refinements

1. Overall the recommended refinements are reasonable. Further discussion is warranted again regarding the need or necessity of identification of specific landforms within the active or inactive portion of the alluvial fan. It still may provide some insight into the process or support the technical data and/or regulatory issues.

   JEF Response: We will be happy to participate in further discussions on this point.

2. Further discussion is needed regarding where the debris flow potential assessments and analyses should be placed within either Stage 2 or Stage 3. Where should the fan type be discussed in the process? Is it a Stage 2 or a Stage 3 issue?

   JEF Response: See response to previous comments.

3. Section 3.7.2 and Section 3.7.3 consistency. In Section 3.7.2 it is recommended that focusing on distinguishing between certain landforms should be saved for Stage 2; however, in Section 3.7.3 it is recommended that distinguishing those landforms is unnecessary. The text in both sections regarding this issue needs to be revised.

JEF Response: The text will be clarified. In Stage 1, there is no need to subdivide types of alluvial fan landforms. In Stage 2, there is no need to distinguish between relict & inactive fans since they are functionally similar.

4. Section 3.7.3, page 102, bullet 5. Regarding the debris flow bullet. The text should be modified to indicate the method is included "should the case occur where a debris flow fan is identified".

JEF Response: The objective of the Stage 2 debris flow analysis is to determine if debris flow potential exists. Given the findings of this study, it is unlikely that a debris flow hazard would be identified, except in rare cases, on fans in Maricopa County. The "should a debris flow fan be identified" suggestion will be applied in the Stage 3 discussion.

3.7.4 Stage 3 Refinements

1. Overall I am in general agreement with the refinement recommendations in this section.

JEF Response: No response needed.

2. Regarding active alluvial fan flood zones, further discussion is warranted. Previous text has stated that "active alluvial fan flooding" will be restricted to portions of the active fan that meet the hazard criteria that have been proposed in this document. I would presume that those conditions will not be met in an area that would be deemed AFZA. How do the active alluvial fan flood zones tie to the "active alluvial fan flooding" definition?

JEF Response: The text was clarified.

3. Page 103, second bullet. For delineation purposes the AAFF should represent areas where channels connected to the upstream hydrographic apex flooding area are identified and exhibit contained flow conditions. I would recommend that the zone designation is only applied in that situation. If a plan identifies a planned corridor on a fan but no significant channel exists naturally, an AAFF corridor should not be used as a "placeholder". Adoption of the planning document should be used to regulate/preserve that planning corridor.

JEF Response: The text was clarified.

4. Section 3.7.4, page 102 and 103, bullet 3. Please consider including the full name of each zone designation. Add a bullet that states that it is recommended that the current UFD zone be removed from the manual.

JEF Response: Done.

3.7.5 General Refinements

1. Overall, I am in general agreement with the refinements presented in this section.

JEF Response: No response needed.

4.0 Summary of Recommendations

1. Section 4.1, page 104, third bullet. Need to discuss further how active alluvial fan flooding is the "ultrahazardous flooding". What zone or classification would we list below our hazard area? Would any of our hazard areas even fit the "ultrahazardous definition? Do you have any recommendation as how to define "ultrahazardous"?

   JEF Response: The text was modified.

2. Section 4.5, page 107, second bullet. Consider adding language that presents the debris flow method as an option instead of so much as a requirement.

   JEF Response: This section lists study recommendations.

3. Section 4.7. This section needs to be modified. At present it is presented more like a requirement instead of an option.

   JEF Response: This section lists study recommendations.

Typos: **JEF Response: All typo's were addressed.**

1. Consistency regarding name of White Tank Fan 36. "White Tanks Fan" and "White Tank Fan" are used interchangeably through-out the report. This really should be consistent through the report.
2. Page 3, second paragraph. Correct "preformed".
3. Page 5, last bullet. Add "ly" to "approximate".
4. Page 6, fourth bullet. Add "to" between "unique sheet".
5. Page 13, Section 2.3, first sentence. Replace "For" with "Four"
6. Page 14, Section 2.3.1.1. In "as one of the site", add an "s" at the end of "site".
7. Page 14, Section 2.3.1.1. Add "the" to "as part of District's".
8. Page 17, Section 2.3.1.2. Remove "Figure 7" from the first sentence.
9. Page 19, Section 2.3.1.4. Remove "Figure 7" from the first sentence.
10. Page 28, first paragraph, second to last sentence. Replace "a" with "at" in "rather than just a pre-determined concentration points".
11. Page 28, second paragraph. Replace "channel" with "channels" in the second and third points within the paragraph.
12. Page 31, third bullet. Be sure to update "Section 0" in the text for the final report.
13. Page 41, 2.3.3.4, middle sentence. Remove either "flow" or "flows" from the end of the sentence.
14. Page 43, Tiger Wash paragraph. Be sure to update "Section 0" in the text for the final report.
15. Page 56, Section 2.3.4, second bullet. Add "ly" to "accurate".
16. Page 58, Section 2.3.5, last bullet, last sentence. Remove the extra ".".
17. Page 59, Section 2.4.1, page 59, first paragraph, middle sentence. Add an "s" to "floodplain".
18. Page 61, Section 2.4.2.4. Correct the font.

19. Page 62. Correct report text combining with Figures.
20. Page 62. In the text Figure 51 should be Figure 49.
21. Page 63, Section 2.4.2.5, last sentence. Please add "the" in front of "FLO-2D algorithm".
22. Page 63, Can Table 10 be presented on 1 page only?
23. Page 68, Section 2.4.3, first sentence. Add an "s" to "fan site".
24. Page 69, Section 2.5 first paragraph. Add "to" in front of "help" and add "a" between "are major".
25. Page 71, Section 2.6, first sentence. Remove "s" from "influences".
26. Table 13. Term: Inactive. Correct "n0t" in the comment column.
27. Table 14, under the Note. Please be sure to update "Section 0" for the final report.
28. Page 96, section 3.5.2, middle of paragraph. Add "ing" to "FLO-2D model".
29. Page 100, Section 3.6, third bullet. Add "be" between "may allowed".
30. Page 100, Section 3.6, first open bullet. Add "un" to "developed.
31. Page 101, Section 3.7.2, last bullet. Replace "with" with "within".
32. Page 103, Section 3.7.5, first bullet. Add "be" between "should updated".

Memorandum JE Fuller/ Hydrology & Geomorphology, Inc.

DATE: July 22, 2010

TO: Greg Jones, PE / FCDMC

FROM: Jon Fuller, PE

RE: FCD2008C007-Avulsion Report Comment Responses

CC: File

Thank you for the thoughtful comments from your team on our PFHAM deliverables. District comments were provided by you via email on June 30, 2010, and are listed as originally enumerated below. Our responses are indicated by indented 10 point bold font. The following summarize our responses:

Proposed Methods

1. The proposed methods listed in the report seem reasonable, should be considered in the final alluvial fan report and should be further tested for refinement.

JEF Response: Done.

Executive Summary

1. It is recommended that a discussion/summary regarding the types of avulsion, classification, and avulsion processes be included in the executive summary.

JEF Response: Addition of the requested items makes the executive summary at least a page longer. We believe the most essential items relative to avulsion hazards are already included in the executive summary. We request that since the requested information is provided in the PFHAM summary report, this document be left as is.

Introduction

1. No comments.

JEF Response: No response.

Background

1. It is recommended to add more parallelism in the discussion topics between each case study site.

JEF Response: We believe the case studies are sufficiently parallel, and request more specific direction on what is missing or needed.

2. Page 8, section 2.4.1 second paragraph. Should the sentence read "key conclusions ... in MC" or "key conclusions.. for Tiger Fan"? The other fan descriptions do not tie their conclusions to MC fans but only to the individual study site.

JEF Response: Done.

3. Section 2.4.1. Could the trench location be added to the figure?

JEF Response: Done.

4. Page 9, last bullet item. There is a disconnect between the text and figure. Could the photos in the figure be connected to the specific type discussed in the text?

JEF Response: Done.

5. Section 2.4.2, page 10, second paragraph. Could the trench location be added to the figure?

JEF Response: Done.

6. Section 2.4.2, page 10, second paragraph. The text stating "lack of major channel avulsion on this fan" should be modified. It might be better to reiterate that this statement is referring to the trenched location on the fan. The aerial photo in the figure does show major avulsions on the fan.

JEF Response: The text was clarified.

7. Section 2.4.3, page 12, first paragraph, last sentence. Consider removing or refining the last sentence.

JEF Response: The text was clarified.

8. Section 2.4.5. Consider adding a figure zoomed in on one of the avulsion locations. Could the trench location be added to the current figure?

JEF Response: The trench location was added. The low resolution of the 1937 photo prevents creation of adequate report graphics.

9. Section 2.4.6. Consider expanding the summary to wrap up what was seen in the case studies to apply in general to "fans in MC".

JEF Response: I believe that the summary does that. Avulsions occur on Maricopa County fans, they are probably rare, and are associated with large floods.

Avulsion Mechanisms

1. Section 3.1, page 14, first bullet, third sentence. Is the word "however" necessary to the sentence?

JEF Response: Done.

2. Section 3.1, page 15, third bullet, second sentence. Consider using a different word other than "purportedly". This word seems to have negative connotation.

JEF Response: Done.

3. Section 3.1, page 15, second paragraph. This section presents the avulsion information from the river article that is not applicable. What about the information in the article/research that does appear applicable? Should both sets of info be presented?

JEF Response: The applicable information is presented in the rest of the report.

4. Section 3.2, page 17, second paragraph, last sentence. Consider re-wording the last sentence. Not sure we want to be in such full agreement with FEMA's position. That area still contains braided channel systems – not necessarily dominated by sheet flow. Channels did relocate not just flow re-distribution in a typical sheet flow condition.

JEF Response: The text was modified.

5. Section 3.3, page 17, second paragraph. Why are these considerations not included in the table? Are they more over-arching issues/themes versus specific variables as listed in Table 2?

JEF Response: Yes to the 2nd question.

6. Section 3.4.4, page 23. Could text be a little clearer where it states the model is relevant to MC by sheet flow transitioning into headward migrating splays? I want to make sure the text is clear that we are not stating that MC fan apexes migrate upstream.

JEF Response: Done.

Predict

1. Section 4.2, page 28. Consider re-evaluating the name of this section. This section covers more than just "Field" items. The only recommendation I have at this time is to "mirror" the section right before and possibly use an "existing behavior" title.

JEF Response: Done.

2. Section 4.2.2, page 23. Consider re-ordering this section's paragraphs. First discuss how surface age is used then follow with the paragraphs discussing the indicators.

JEF Response: Done.

3. Section 4.2.2, page 30, third paragraph, last sentence. The last sentence is awkward please refine.

JEF Response: Done.

4. Section 4.2.2, last paragraph, last sentence. Please re-verify this sentence. Should it read that young surfaces are perched in the topo above the older surfaces? If older surfaces are perched above younger, how can it be "ripe for inundation?"

JEF Response: Done.

5. Section 4.4.1. It appears that this section is more FAN bashing than a discussion on the avulsion prediction capabilities of the FAN program. It is recommended that most of the current text be cut from this report and perhaps placed in the main report. This portion of the report should just address how FAN handles the prediction of avulsions.

JEF Response: We do not believe there is a place for this discussion in the main report. We are not "bashing" the FAN model. We are criticizing it as a method to model the affect of avulsions. The numerous errors in its formation (as underscored by the Blue Ribbon Panel) hamper its ability to achieve its stated objectives. The model has been put forth by FEMA and other parties as the best means to address the flood risk associated with avulsions, and thus we believe it belongs in the Avulsion Report.

6. Section 4.5, page 35. Consider adding sentences on grid size and topographic accuracy.

JEF Response: Done.

7. Section 4.5.1. Please remove superfluous figure graphics.

JEF Response: Done.

8. For Figures 9, 10, and 11. Please consider adding an insert graphic zoomed in to one of the avulsion locations. Please add text describing the outline colors.

JEF Response: Done.

9. Section 4.5.1 page 41, WTF36, bullet 3. Please clarify what a "traditional" type of avulsion is: types and classifications have been presented but none were described as traditional.

JEF Response: The text was modified.

10. Section 4.5.1, page 41, Reata second bullet, second sentence. Consider the use of the word "defined". There is more to the hydrographic apex definition.

JEF Response: Done.

11. Section 4.5.1, page 41, Reata fourth bullet. Please review the topo data for this site. The cutoff of the topo due to development may actually be further north.

JEF Response: Please provide clarification of this comment.

12. Page 42, RVF 12. Should the language address that sheet flow could still concentrate on any portion of the fan (just not channel forming).

JEF Response: Please provide clarification of this comment.

13. For Figures 13-16. Please explain the different colors.

JEF Response: A map key has been added.

14. Section 4.5.7. Please remove the superfluous images in this section.

JEF Response: Done.

15. Section 4.5.8, page 59. Regarding the statement in this section that aggradation has occurred or flow has shifted, could the grid scale or 10 foot topo also be responsible for that appearance or was that statement actually based on the 25 ft grid and 2 foot topo mapping model?

JEF Response: The text has been modified.

16. Page 69, Are there any recommendations regarding how to use the avulsion types and classifications listed in this document for terminology in the final methods?

JEF Response: No.

Typos – **All noted typo's have been corrected.**

1. Page 5, 1.3 last bullet. Add "s" to channel.
2. Page 8, second paragraph, first bullet. Remove "in" from "then in during".
3. Page 21, 3.4.3, first sentence. Please verify the year of the Schumm article. The year listed here is not the year listed in the references. Should there be two Schumm citations in the references?
4. Page 22, second paragraph, first sentence. Change "physically" to "physical".
5. Page 25, 3.5.1, second paragraph, first sentence. Equation 7 is mentioned in the text but is not listed. Should the text read Equation 6?
6. Page 25, 3.5.1, second paragraph, fourth sentence. Add "the" to "terms to right".
7. Page 47, 4.5.3, second bullet. Add "in" to "corridors all of the potential".
8. Page 47, 4.5.3, third bullet. "where" should be "were".
9. Page 50, last para, last sentence. "do no correspond". Replace "no" with "not"
10. Page 50, 4.5.5, second sentence. Change "related loss" to "related to loss".
11. Page 53, 4.5.5, first paragraph, second from last sentence. Replace. "from pre-avulsive" to "from the pre-avulsive".
12. Page 53, 4.5.6. For "unrealistic result through". Add "s" to "result".
13. Page 53, 4.5.6. Replace "and FLO-2D" with "And the FLO-2D".
14. Page 59. In the sentence with "First there a several." Replace "a" with "are".

Flood Control District
of Maricopa County

INTEROFFICE MEMORANDUM

Date: July 31, 2008

To: Kathryn Gross, CFM/FCDMC

From: J. Rafael Pacheco, PhD, Assoc. Engineer and Richard Waskowsky, Hydrologist, Engineering Application Development and River Mechanics Branch, Engineering Division.

CC: Bing Zhao, PhD, PE, Engineering Application Development and River Mechanics Branch Manager, Engineering Division

Subject: Review on "Existing alluvial-fan floodplain delineation methodologies", FCD 2007 C051: Assignment #1, task 1.2.1; prepared by JE Fuller Inc.

The Engineering Application Development and River Mechanics Branch (EADRM) received the report on July 14, 2008 and has the following comments.

1) 252 technical papers/reports were collected in this task. The methodologies discussed in the memorandum were supposed to be taken from these 252 technical papers/reports that describe alluvial fan hazard mapping based on the scope of work. However, the nine methodologies actually discussed in the memorandum were only from nine agencies. Please discuss the 22 references that were ranked "high relevance to Maricopa County" in your spreadsheet and 10 of the 92 references that were ranked "medium relevance to Maricopa County." This discussion should include a summary and the advantages/disadvantages of each methodology and how each methodology can or can not be used in Maricopa County. Please add all these discussions to "Non-Agency Analyses."

JEF Response: The technical papers & reports in the list of 252 ranked with respect to relevance to Maricopa County were collected for a different task under this work assignment and do not necessarily relate to the floodplain delineation methodologies issue. This task was specifically limited to delineation methodologies currently in use by other agencies.

2) There should be documentation about the communication between the consultant and the agencies' contacts. For example, it seems that the methodology for AMAFCA is based on personal communication with Jerry Lovato of AMAFCA. Was it through emails or phone conversations? Is there any documentation? Please provide documentation for each agency where there is no clear written guidelines for fan delineation methodology.

JEF Response: As discussed on page 4 of the JEF memo, the communication with agencies took the form of conversations with agency personnel. Telephone calls were the preferred method. Notes were taken by JEF personnel and the important elements of which are reflected in the agency evaluation summaries. Additional text has been added to page 4 of the JEF memo for clarification of the method of communication with agency personnel. Telephone notes were not a deliverable for this task.

3) The reference title for Desert Research Institute is not clear for "Chapter 3: Identification and Mitigation of Flood Hazard on Alluvial Fans – 1996." Please see "Document Title-Year" on page 11. Please list the complete reference title such as book title, publisher, and so on. We can not find this reference in the CD and spreadsheet.

JEF Response: The reference title for the Desert Research Institute document "Chapter 3: Identification and Mitigation of Flood Hazard on Alluvial Fans" is not presented anywhere in the document. Although the title of the document suggests it's a chapter of a larger report, no reference to such report is presented. The document has been scanned into a digital format and is included on the revised companion disc under the Reports folder.

4) A reference about Pima County's Tortolita Mountain piedmont alluvial fan floodplain delineation was given in the memo. However, the report is not given. Please include the document in the submittal.

JEF Response: As mentioned in the memo, the Tortolita Mountain Piedmont geomorphic assessment report was in progress at the time the memo was submitted, thus was not available. A request to Keith Brann with the City of Marana was made to obtain copies of the documents (if available). If the documents are available they will be submitted to the District upon receipt by JE Fuller.

5) Is the 1989 Borrego Valley Flood Management Report for San Diego County included in the submittal?

JEF Response: The "Borrego Valley Flood Management Report" is a FCDMC library document, thus was not included in the submittal.

6) Please include a reference list at the end of the memo for all references that were cited in the memo.

JEF Response: A reference list has been added to the memo.

7) Based on Task 1.2.1 requirement in the scope of work, the consultant will recommend the most appropriate delineation methods for use in Maricopa County. However, no recommendation was given. Please recommend the most appropriate delineation methods as required by Task 1.2.1 in the scope of work.

JEF Response: A recommendation section has been added to the memo.

8) The Thousand Palms Flood Control project in the Coachella Valley, California is underway with Coachella Valley Water District and the US Army Corps of Engineers receiving the federal funds. This example should be added to the agency methodology list.

JEF Response: The Coachella Valley Water District (CVWD) was added to the memo. The Thousand Palms Flood Control Project is one of multiple flood control projects within Coachella Valley. CVWD does not proactively analyze or map alluvial fan hazards using FEMA Appendix G methodologies. Whole-fan structural solutions have been consistently employed by the CVWD.

9) California Alluvial Fan task force presentations and reports should be added to the agency methodology list.

JEF Response: The Alluvial Fan Task Force draft report was added to the methodology list.

10) Some bullet points required by Task 1.2.1 should have some detailed discussions with examples to support the conclusion. For example, in the section of "Reproducibility," more details should be given to clearly show why they are or are not reproducible rather than a simple sentence. The details may include the input variables, assumptions, limitations, and advantages, and output variables. Which input variable(s) in geomorphic methods are more difficult to define, thus, qualifying for "qualitative"? Even in FAN method, some variables are not certain either such as the avulsion coefficient. Such detailed discussion should be provided.

JEF Response: The overall conclusion of this task was that no new alluvial fan floodplain delineation methodologies outside of FEMA Appendix G are being employed by agencies or non-agencies within the southwest. As such, the delineation characteristics listed in the Task 1.2.1 scope of work were compared only with Appendix G. An analysis of Appendix G methodologies were not the focus of this task as the methodologies are well-established in the engineering community and are currently accepted by FEMA.

Flood Control District
of Maricopa County

INTEROFFICE MEMORANDUM

Date: August 18, 2008

To: Bing Zhao, PhD, PE, Engineering Application Development and River Mechanics Branch Manager, Engineering Division

From: Richard Waskowsky, Hydrologist, Engineering Application Development and River Mechanics Branch, Engineering Division.

Subject: Task 1.2.5 - Frequency of Alluvial Fan Channel Avulsion and Task 1.2.2 - FEMA CLOMR/LOMR Methodologies, prepared by JE Fuller Inc.

The Engineering Application Development and River Mechanics Branch (EADRM) received the report on July 31, 2008 and has the following comments.

Comments for Task 1.2.2 - FEMA CLOMR/LOMR Methodologies

1) Table 1 should have a description in the text. Please provide a description for Table 1.

JEF Response: Text added.

Comments for Task 1.2.5 - Frequency of Alluvial Fan Channel Avulsion

1) Not all of the summarized papers include a paragraph about the applicability to Maricopa County. For example, the Slingerland and Smith (2004) summary at the end of the document only copies the abstract of the paper. It does not present a paragraph about the applicability to Maricopa County. The memorandum would be more substantial if this paragraph is provided for all summarized papers.

JEF Response: There is no requirement in the scope of services for such a summary for each article.

2) The abstract should be given in a different font (or in italics) in order to set it apart from the other parts of the summary.

JEF Response: Text reformatted as suggested.

3) Additional references are given from the Field (1994) reference; however, these additional references are not discussed in the paper. Why provide these additional references if they are not relevant enough to be discussed?

JEF Response: The relevant idea from each cited reference was provided.

4) A copy of the dissertation for the Field (1994) reference is not provided with the memorandum.

JEF Response: No digital copy is available. However, much of Field's work is also reflected in his published journal article (2001) included on the DVD and the AZGS reports (OFR 94-13, 91-10, 91-8) which are readily obtained from AZGS. Please note that the scope did not require that copies of any of the articles be provided.

5) The links to the papers do not need to be provided in the Word document since the links will not work if the addresses of the papers change.

JEF Response: The memos will be added to the revised DVD and the links modified to work from the DVD.

Flood Control District
of Maricopa County

INTEROFFICE MEMORANDUM

Date: August 5, 2008

To: Bing Zhao, PhD, PE, Engineering Application Development and River Mechanics Branch Manager, Engineering Division

From: Apu Borah, PhD, PE, Senior Civil Engineer, Engineering Application Development and River Mechanics Branch, Engineering Division.

Subject: Review on FCD 2007 C051: Assignment #1, task 1.2.2, and Task 1.2.5 prepared by JE Fuller Inc.

Here are my suggestions for the work submitted by JEF that you gave me on 7/31/2008 to review:

Task 1.2.2:

1. LOMAR/CLOMR submittals listed in page 2 and pag3 will be easy to read if it is put in a tabular form as shown below:

Case No.	Approval	Method Used	Community
05-09-0844A	Not Approved	HEC-RAS	Ojai, Ventura County, CA
08-09-0405R	Not Approved	PFHAM & Structural	Buckeye, AZ
08-09-0919P	Approved	Structural, HEC-RAS	Las Vegas, NV
------	--------	----------	----etc

JEF Response: Reformatted as suggested.

Task 1.2.5:

1) JEF needs to check the document for syntax and errors before submitting to FCDX; word tools "Spelling and Grammar" do not work properly at times. Here are a few examples: *one literature sources* (page 1), bullet points need to be parallel (page 2).

JEF Response: Document reviewed and revised as needed.

2) Additional references in Field (1994) on page 3 should be cited properly instead of simply noting the author's last name, year and a title.

JEF Response: Parentheses added around years. Full references available in Field (1994).

3) The references with abstract described on page 3-10 should have same format. The year term is missing after authors' name in some of the references.

JEF Response: Done.

Comments from Kathryn Gross

1. Should the table be broken down to include mitigation measures broken out by active or inactive alluvial fan flooding types?

   JEF Response: Only mitigation measures for (active) alluvial fan flooding are presented. Inactive fans are treated like riverine systems, for which the District already has guidelines.

2. Summary of Findings, first sentence. Should the word active be placed in front of "alluvial fan flooding"? Or would an introductory paragraph about active and inactive alluvial fan flooding be discussed here?

   JEF Response: Done.

3. Summary of Findings, Structural measures paragraph, last sentence. Compatibility with scenic resources, etc is only required if the project is being funded by the District.

   JEF Response: Done.

4. Sources of Information, number two. Typo in the summary "single lots protection measures".

   JEF Response: Done

5. Table 1 page 4, Description: Elevation. For Design Issues, please state that elevation is not acceptable by FEMA for removal of the floodplain. I am presuming a subdivision could elevate but choose not to request removal of the zone designation and FEMA probably would not have a problem with that. Is that mitigation? Or for the purpose of this memo is mitigation removal of the flood designation?

   JEF Response: The table already states that elevation is not acceptable to FEMA. The purpose of this memo is to list measures to mitigate flood hazards on alluvial fans.

6. Table 1 page 4, Description: Density Transfer. Should the "institutional difficulties" discussed in the definition also be listed in Design Issues?

   JEF Response: Done

7. Table 1, page 5 Description: Composite Methods. Please include a summary statement regarding the composite methods.

   JEF Response: Done

Comments from Joe Tram

1. Please differentiate the solutions between active and inactive flooding.

   JEF Response: Done

Comments from Tom Loomis (by memo "Review Comments 1_2_6_62408")

1. Pg. 1 Non-structural measures. The 2nd and 3rd sentences belong under the structural measures heading.

   JEF Response: We respectfully disagree. The sentences explain what is not a non-structural measure.

2. Pg. 3, Structural Measures, Table 1

   a) Detention Basins (on-line), Design Issues: Add Hydraulics, Sediment Transport, Risk Analysis, Geotechnical.

      JEF Response: Done

   b) Diversion Basins (off-line), Definition: Change "but on directly" to "but not directly."

      JEF Response: Done

   c) Diversion Basins (off-line), Design Issues: Add Hydraulics, Sediment Yield/Transport, Geotechnical.

      JEF Response: Done

   d) Debris Basins, Design Issues: Add Hydrology, Hydraulics, Sediment Yield, Risk Analysis.

      JEF Response: Done

   e) Debris Barriers, Design Issues: Add Location, Sediment Yield, Sediment Transport.

      JEF Response: Done

   f) Channels, Design Issues: Add Long-term Sediment Transport Analysis

      JEF Response: Done

3. Pg. 4, Structural Measures, Table 1

   a) Levees, Design Issues: Add Risk Analysis.

      JEF Response: Done

   b) Floodwalls, Design Issues: Same issues as for levees, plus Structural Stability.

      JEF Response: Done

   c) Retaining Walls, Design Issues: Same issues as for levees, plus Structural Stability.

      JEF Response: Done

   d) Composite Methods, Definition: Add "The measures applied may vary with defined degree of hazard."

      JEF Response: Done

4. Pg. 4, Non-Structural Measures, Table 1

   a) Avoidance (no development), Definition: Preservation of active fan flooding areas as undisturbed open space. No development allowed, including golf courses and parking. The goal is to allow the active areas to function naturally. Can be accomplished by zoning, density transfers, or other suitable means.

      JEF Response: Some changes made

   b) Avoidance (no development), Design Issues: Change "Takings" to "Potential Property Rights Issues."

      JEF Response: Done

   c) Acquisition, Definition: Purchase of flood-prone lands for preservation, open space, low-impact recreation, or other uses that preclude habitable structures and disturbance of the natural system and function.

      JEF Response: Done

5. Pg. 5, Non-Structural Measures, Table 1

   a) Composite Methods, Definition: Most non-structural projects may be a composite of any of the above measures. Non-structural measures may be combined with structural measures depending on the defined degree of hazard.

      JEF Response: This category applies only to non-structural measures.

<u>Comments from Ed Raleigh (from email message 6/23/08)</u>

1. Since the task is defined as a brief summary based on the consultant's current experience and knowledge, then it reflects what they are able to provide at this time. However, the scope says "what <u>design criteria</u> should be applied", rather than "Design Issues" used as the heading in their table.

   JEF Response: Changed heading.

2. The table discusses mitigation measures as if all fans had equal risks. The risks, flow path uncertainty and erosion potential are not the same on a steep fan with debris or mudflow compared to a fan on a mild slope where debris and mudflow are not present. As this work proceeds we need to quantify hazards on fans including factors such as debris flow, mud flow, steep slopes versus flat slopes, differences in watershed size, proximity to mountains and canyons, and the applicability and use of additional refinement of hazard identification using two dimensional flow analysis.

   JEF Response: There was no intended implication regarding risk level. We acknowledge that different fans have different hazard levels. The review comment goes beyond the scope of this task, the purpose of which was to list what mitigation measures have been used on active alluvial fans.

<u>Comments from Bing Zhao (from email message 6/23/08)</u>

1. As a follow-up for Ed's comments, "design criteria" should be specific engineering design criteria for basin, levees, diversion channels, and other mitigation measures discussed in Task 1.2.6. At least, specific design guideline/manuals which contain the specific design criteria should be cited.

   JEF Response: Great idea, but not within the scope, which did not allow any time for literature search. Perhaps this could be added in a subsequent work assignment.

2. Somehow down the road (before July 11, 2008, the project ends), the mitigation measures should be tied to the other two major tasks: debris flow and hazard quantification.

   JEF Response: Great idea, but not within the scope. Perhaps this could be added in a subsequent work assignment.

Comments from Burke Lokey (by email message 6/23/08)

1. I did look at the summary. It seems like it's a pretty complete and concise summary of the mitigation measures. IMHO the only thing that might be added or modified is the column with "design issues". My interpretation of the scope language is that this needs to be developed a little more to identify those (engineering) parameters that are related to the design issues.

   JEF Response: Done.

2. For instance, w/ respect to On-Line Detention Basins, inasmuch as the design issues include sediment yield and outlet capacity/clogging, the consultant could identify the kinds of analysis used to quantify these issues and focus on some of the key factors in those analyses, IE, stream power, energy gradient, sediment transport capacity, all related in some way to channel slope S. Perhaps a second matrix could be developed with the different kinds of analytical techniques and their component factors. The idea is to eventually narrow down those parameters that get considered.

   JEF Response: Great idea, but not within the scope. Perhaps this could be added in a subsequent work assignment.

Memorandum JE Fuller/ Hydrology & Geomorphology, Inc.

DATE: September 9, 2010

TO: Greg Jones, PE/FCDMC

FROM: Jon Fuller, PE

RE: FCD2008C007, Final Report Comment Responses

CC: File

Red-Line Comments from GLJ

JEF Response: Red-line comments were provided in a copy of the draft report. All such comments have been discussed with the District Project Manager and have been directly addressed in the final report.

Comments from KAG

Report Content

1. The proposed methodologies and discussions in the report are reasonable.

   JEF Response: No response needed.

2. The additional guidance regarding the "levee scenario" methodology appears reasonable. If possible, consider adding additional guidance regarding how downstream incipient drainage patterns could aid in the determination of number and position of levees.

   JEF Response: Done.

3. The recommendations regarding zone delineations are reasonable. The inclusion of AFAN for the ultrahazardous flood zone is a good option. Based on discussions with District staff, further discussion and consensus will be necessary using the recommendations as a starting point. No further modifications to these sections will be necessary for this report.

   JEF Response: Acknowledged.

Report Text

1. Executive Summary, page ii, Hydraulic modeling fourth bullet. Consider rephrasing last sentence to state that unregulated development will adversely impact downstream areas.

   JEF Response: Done.

2. Decision Tree, Figure E-1
   a. Can the decision tree be more tree-like?
   b. Consider adding Geology mapping under Data Collection
   c. What is the asterisk for after Data Collection?
   d. Can geology be added under Stage 1 analysis and tools?

JEF Response: Done. Except (a) per direction of FCD Project Manager. (c) The asterisk denotes the footnote box below.

3. 2.3.3.6 Avulsion Simulation Models, page 70, Slope Walk Bullet.
    a. Should additional text be added to emphasize the analysis is in the downstream direction?
    b. Consider replacing "flow paths" with "flow areas" in second to last sentence.

JEF Response: (a) Done. (b) The text has been revised to clarify the meaning.

4. Figure 40, page 73. Should text be modified to read "perched channels ripe for avulsive abandonment"?

JEF Response: Done.

5. 2.3.3.9, page 77, USBR Flood Danger Level Charts. Consider using a different word than "purport".

JEF Response: Done.

6. 3.3.7 Limitation of Geomorphic (Only) Approach, page 126. Remove the language "so-called" from geomorphic methodologies.

JEF Response: Done.

7. Figure 64. Same comments as in item #1.

JEF Response: Done.

8. Typos **All typo's have been corrected, except as noted.**
    a. Table 1 – Comma use is inconsistent in the discharges and elevations. Please add a unit for Pima Canyon elevation.
    b. Figure 2 – The labels for the Rainbow Valley Fans and the Ahwatukee and Pima Fans are reversed.
    c. Table 2 – the Reata Pass Fan discharge is different between Table 1 and Table 2. Should this discrepancy be cleared up or the two sources identified?
    d. Page 23, 2.3.1.2, first paragraph, second to last sentence. Should it be "geomorphic landform classification" instead of "geographic landform classification?
    e. Page 30 2.3.2.3, first sentence in Peak Discharges section. "piedmont surfaces" instead of "piedmont surface".
    f. For Tables 3, 4, and 5 and figures 12, 13, and 14, there are discrepancies between cross-sections shown on the figures and cross-sections shown in the table. Some cross-sections are not labeled on the figures. **We believe the figures show the intended information and are sufficient to illustrate the intended point, which is to illustrate discharge changes downstream of the hydrographic apex. Therefore, we**

request to keep the tables as is, since added the additional details changes the formatting in an inconvenient manner.

g. Page 36, Flow Peak Attenuation, middle of paragraph. Add an "s" to "fan" in "observations of alluvial fan in which.."
h. Page 37, Development Impacts, middle of paragraph. Add an "s" to "surface" in "disturbed surface increased"
i. Table 7.
    i. WTF 7-12 is missing in key.
    ii. WTF 7-12 include number of scenarios instead of X.
j. Page 86, first hollow bullet, middle of paragraph. Add an "n" to "given".
k. Page 86, second solid bullet. Add "be" between "site will inundated".
l. Page 93, 2.4.2.5, towards end of paragraph. "additional" should be "addition".
m. 2.4.3 Conclusions, page 103, fifth bullet. Add "on" between "impact fan".
n. 2.5.1 Conclusions, page 105, middle of paragraph. Replace "recommends" with "recommended".
o. Table 14. "T" is not provided in the References.
p. Page 114, bullet Step Two, last sentence. Add "be" between "should conducted"
q. Page 120, eighth bullet at top of page. Replace "dominate" with "dominant".
r. Page 120, middle paragraph. Add "be" between "would problematic".
s. Page 129, top of page. Add "with" between "associated (predicted) low FLO-2D depths".
t. Page 132, first solid bullet. Replace "Implement" with "Implementation".
u. Page 144, third solid bullet. Replace "modeling" with "modeled".
v. Page 145, 4.6, third bullet. Remove "the" from "in the each".
w. Page 152, 5.8, second bullet. Add "s" to "area" in "ultrahazardous area".

9. Table 12. Why do all the discharges and volumes decrease for the cross-sections on RVFan 1 and some of the WTF 36? Does that mean the sediment is pushing the flows elsewhere?

    JEF Response: The differences between with & without sediment runs are minor, well within the accuracy of hydrologic modeling. Yes, the differences are due to changes in bed elevation which redirect small amounts of water in different directions than the water-only models.

10. Page 116 footnote. Could a specific page number in the NRC report be provided? (so that it is perfectly clear)

    JEF Response: Done.

Also regarding my comment from the first review regarding downstream inactive zones, so does that mean that once a landform is classed as active even if the data shows that we have flow containment further down we would not add an "inactive alluvial fan" note to demonstrate that more riverine behavior, and therefore more riverine approaches/regulation/mitigation could be used? I have clipped two areas one being WTF36 where on the left you see the AAFF zones on the DFIRM with the inactive label and the other being WTF3,13, 16 where older surfaces (maybe topographically higher) pop out on the overall "active" fan. That is what I was trying to ask about. Could you could give me an initial thought (even if it matches the same response given in the comment responses)? I know this really most likely should be fleshed out in the PFHAM revision.

JEF Response: The best answer will be that it depends on the specific site characteristics and thus the question cannot be answered with a one-size-fits-all definitive answer. But, in general, where there is secondary incision on the toe of a fan landform downstream of an active area, I would recommend calling the area inactive only if the interfluves had characteristics of inactive (old surfaces, topographically isolated, stable, no upstream avulsions, etc.), and where there is adequate topographic relief between flow corridors. You would also need to address the flow rate uncertainty when assessing the degree of flow containment. I'd be more inclined to call the toes of Fan 38/39 inactive than the toe of Fan 36 due to the minimal topographic confinement and young surface age on Fan 36. I see "active" as rather a broad category, and am not particularly worried about the fan stigma issue.

<u>Supplemental Comments from KAG (8/17/2010)</u>

1. Page 114, Step 3. Statement regarding avulsions should be expected in high hazard classification zones is a somewhat circular statement. Could this be rephrased?
   JEF Response: Done.

2. Page 115, Step Five of avulsion method. Should this be a reference to floodplain delineation or does this connect to the statements made on page 144 under Preliminary AFHH delineation?
   JEF Response: Done.

3. Page 125, sediment guidance is a little generic here. Is there a way to provide more specifics? Is it covered in more detail in Sections 4 or 5?
   JEF Response: Section 3.3.3 is a list of recommended engineering tools (per the scope). A discussion of how to apply those tools relative to the Stage 3 delineation has been added to Section 4.4.

4. Page 127, internal discussions have brought up the issue that flow weighting may not be fully agreed upon by the group.
   JEF Response: The last official communication I received was that the group was in consensus on this item. Perhaps if the District's opinion on this matter continues to evolve, it could be addressed in either the PFHAM revision or in the test case application (Gillespie ADMS).

5. Page 128, Table 19. Does is take only one criteria being met in a hazard category to make that the hazard for that area (ie. Is the table "and" or "or") Consider clarifying the "Multiple Criteria" sentence above the table if it is possible.
   JEF Response: The table was modified to address this issue.

6. Page 128, Table 19. Discharge should be added as a note and not a hazard level criteria. Depth should be added as a note for a floodplain criteria.
   JEF Response: Done.

7. Page 128, Table 19. Should we add "sediment analysis" to the chart (ie is there a sed yield threshold or 100 year sediment deposition (FLO-2D or areal averaged depth of yield volume) that would lead us to choose a different category. It might be a good way to bring some of the sediment info into the forefront of the analysis.
   JEF Response: I do not recommend that sediment analysis be added to Table 19 as a criterion. The available methodologies for estimating sediment delivery are not sufficiently accurate, nor is there an established threshold for hazard that relates to sediment deposition. The table already addresses debris flow (i.e., extreme sedimentation). Sedimentation is likely to be directly related to flow depth and velocity, which are already part of the matrix.

8. Page 131, Conveyance Corridors. Clarify text to distinguish between natural through-flow channels that would be identified individually in a delineation and planning study conveyance corridors which would identify where a corridor may be needed if one does not naturally occur.
   JEF Response: Done.

9. Page 131, FEMA Criteria. Please clarify "mapped active alluvial fan floodplain" and FEMA "active alluvial fan floodplain" in this section. Is this specifically referring to the area that is "Active alluvial fan flooding" within the "alluvial fan floodplain"?
   JEF Response: Done.

10. Page 135, Active Alluvial Fan Flood Zones. The recommended methodology presents both approximate and detailed methods do the results of both of these methods connect with using the same 4 zones?
    JEF Response: A table was added to clarify this issue.

11. Page 135, it is recommended that some discussion be added to this section regarding how these zones would be reflected in the FEMA schema.
    JEF Response: Done.

12. Page 141, table 22. Geotech testing of soils is listed as a method in the table but there is no text discussion regarding this item. Should some reference be added to the text?
    JEF Response: The geotechnical testing category was added in response to District comments during one of the team meeting presentations. I view it as a placeholder for more detailed discussion in the revised PFHAM, since evaluation of geotechnical techniques was deleted from the scope of services for this study. Some text was added to chapter to describe geotechnical tests.

13. Page 142, table 23. Use of Stage 2 delineation should be clarified to state Use of Stage 2 "Active" boundary delineation.
    JEF Response: Done.

14. Page 142, table 23. Under Approximate Method would it be possible to add either here or somewhere in the text how flow depth estimates would be used in the delineation and how debris flow extent is determined in the approx method.
    JEF Response: Text was added after Table 24 to respond to this comment. Note that the debris flow methodology was described in Appendix H and Section 2.6. The extent of the debris flow hazard area is determined either by geologic (field) evidence or LAHAR-Z modeling.

15. Page 142, table 23. Under approximate Method- flow depth estimate, remove "specific sites" from list since it is not applicable to the delineation.
    JEF Response: The table was modified to address this comment.

16. Page 142, table 23, Detailed Method, Sediment Modeling. How does sediment modeling tie to delineation? Or is it supporting documentation for other tasks performed at Stage 3 but not necessarily applied to delineation (i.e., support for hazard classification which leads to delineation zones?)
    JEF Response: Additional text was added after Table 24 to address this comment.

17. Page 142, table 23, avulsion analysis. Sediment model is listed but I do not think the report addresses how it is connected to the analysis. Should that be in report text or somehow bulleted here? Or is it covered under Step four on page 114?
    JEF Response: See Sections 2.7 and Appendix I.

18. Page 142, table 23, geomorphic analysis. This appears as a separate analysis but I do not think it is referenced anywhere in the text. What is meant by this specific historical channel change analysis?
    JEF Response: This item was deleted.

19. Page 142, table 23. It is recommended that debris flow assessment be changed to debris flow evaluation.
    JEF Response: Done.

20. Page 142, table 23, site analyses. It is recommended that this be removed from the Stage 3 table and presented as a separate table possibly elsewhere in the report.
    JEF Response: The table was modified to address this comment.

21. Page 143, last paragraph above Section 4.5. Text states "discussed in Section 3.6.4 below". Does the section number need to change or the below/above reference?
    JEF Response: The text was modified.

22. Page 144, Preliminary AFHH delineation. It is recommended that this section be modified to discuss how the virtual levee locations and lengths can be tied to the results from the avulsion analysis tasks and that those results are presented as some sort of "delineation". Possible new title "composite avulsion potential areas/delineation". This may also need to change in the avulsion appendix report.
JEF Response: Done.

23. Page 149/150, HEC RAS. This section only mentions site specific analysis. However, under the approximate method we would allow a normal depth calc either through Mannings or RAS. Should that be added to this discussion?
JEF Response: Done.

24. Overall Stage 1, 2 and 3 tables and discussions. I think that presently it is easy to get lost in the forest due to the trees to determine what methodologies are supporting what other methods and/or outcome of the various Stages. I think that could be clarified a little better in the tables or possibly in the decision tree (do I dare relate this to "function diagraming"). Is this beyond scope and better served in the formal manual revision?
JEF Response: Since you're asking my opinion, I'd say that this request is beyond the scope of the existing project and would be better addressed in the PFHAM revision.

Reviewer: Engineering Application Development and River Mechanics Branch, Engineering Division's original 5-25-2010 comments and follow up review comments 8-9-2010.

1. Both the final alluvial fan report as well as the avulsion assessment report are signed with expired professional seal.
JEF Response: The seal expiration date is updated.

EADRM (8/9/2010): This problem was corrected only for the main report. But the expired dates still appear in other sealed documents such as appendixes (for example, appendix G, H). Please correct all seals.

JEF Response: All seals have been updated.

2. Please submit the FLO-2D animation files.
JEF Response: Will be provided on documentation DVD with final report.

EADRM (8/9/2010): We will wait to review the final report; animation files are not provided with the draft final report DVD.

JEF Response: The animation files are on the DVD.

4. Page 70: 2.5.1 Recommendations: What is the use of doing a regional chronology to date Holocene alluvial fans?
JEF Response: The regional chronology is recommended to improve resolution of numerical dating methods for Holocene-aged surfaces. A more detailed explanation was provided in the

Task 2.6 Report.

EADRM (8/9/2010): Appendix G of this report explains regional chronology in more details. Based on Blue Ribbon Panel, the fans in Maricopa County are not as serious as expected, the chronology may not be necessary.
JEF Response: No response needed.

8. Please add definition for alluvial slopes, use Rhoads's paper or other geomorphology standard definition.
JEF Response: The term "alluvial slope" is not commonly used in the literature or in the practice of geomorphology as it relates to alluvial fan flooding. It is not included in Penguin's Dictionary of Geology, the Encyclopedia of Geomorphology, or any of the 19 geomorphology textbooks I own. Note that Rhoad's proposed approach has not been accepted or applied by any regulatory agency, including the City of Scottsdale for which Rhoad's methodology was originally proposed. For these reasons, we do not recommend that "alluvial slope" be included as a category of landform for the PFHAM. The underlying issue is addressed in the report under the topic of alluvial plains.

EADRM (8/9/2010): Blue Ribbon Panel also recommended a term called Piedmont Flooding Inundation. Is this term adopted in the final report?
JEF Response: The term "piedmont flooding" is used in the final report.

19. Table 14 on page 87 lists Slope-walk tool as a tool for avulsion. We do not recommend this tool because it is a simple drainage path tool. There are many drainage path tools available. In addition, if we adopt this tool, Maricopa County will be the owner of the Slope-walk tool.
JEF Response: The text has been revised to clarify the intent and application of the slope-walk tool.

EADRM (8/9/2010): The results by using the slope walk method for this project can be kept in the report, but a note should be made in the report to indicate that the tool was not tested by the District. In addition, it should be noted that the slope-walk method will provide the potential drainage path, but not necessarily the avulsion potential. We cannot use this propriety tool which is not owned nor tested by the District.
JEF Response: The District project manager, in response to requests by District staff, have directed JEF to change "slope-walk tool" to "avulsion flow path tool." This has been done. The text was also modified to state that the tool provides potential (avulsive) drainage paths, but not a full assessment of avulsion potential (by itself). The tool will be owned by the District.

24. Page 90: Regarding avulsion assessment, using Slope walk tool does not provide avulsion potential; rather it provides drainage network similar to Topaz in WMS.
JEF Response: Use of the slope-walk tool was considered by the Blue Ribbon Panel, which recommended that it be included in the recommended methodology. Per direction of the District's project manager, the recommendations of the Blue Ribbon Panel are to be used. See Blue Ribbon Panel summary report.

EADRM (8/9/2010): It should be noted in the report that the slope-walk method will provide the potential drainage path, but not necessarily the avulsion potential.
JEF Response: See response to #19 above.

40. Avulsion frequency, pg 108: lower gradient fan in Arizona, avulsion is insignificant, it may occur only after repeated flooding and aggradation. In fact, the avulsion study (FE Fuller, 2010) indicates that avulsion is rare. Therefore, study is not necessary because there is no data to do any frequency analysis.

JEF Response: Our report states that it is likely that avulsions probably are rare, but that there is insufficient data collected to date from which to assess the frequency. We do know that avulsions occur on alluvial fans in Maricopa County and that the consequent changes to the flood hazards have been significant. Therefore, we recommended that the District collect the data from which to assess the frequency. If it turns out that it can be documented that avulsion frequency is extremely rare, then it is likely that the recommended alluvial fan delineation methodology can be significantly simplified. We further note that the Blue Ribbon Panel supported the recommendation to evaluate avulsion frequency.

EADRM (8/9/2010): In the future, District staff will conduct this study if such a study is warranted. Currently, the evidence indicates that it is of less priority. No Action is required to address this comment.
JEF Response: No response needed.

41. Slope walk tool, pg 108: it provides drainage network, not avulsion.
JEF Response: See response to comment #19 above.

EADRM (8/9/2010): It should be noted in the final report that the slope-walk method will provide the potential drainage path, but not necessarily the avulsion potential.
JEF Response: See response to #19 above.

42. High hazard zone, page 109: The extent of the high hazard zones should be a function of other factors such as sediment availability as well as fan slope, drainage area, and discharge.
JEF Response: This comment was addressed by the Blue Ribbon Panel. Per direction of the District's project manager, the recommendations of the Blue Ribbon Panel are to be used. See Blue Ribbon Panel summary report.

EADRM (8/9/2010): Please indicate the specifics for Blue Ribbon Panel's recommendation on this.
JEF Response: The Blue Ribbon Panel summary report is attached to the final report as an appendix. Specifically: (1) The BRP endorsed the methodology. (2) The BRP endorsed the hazard assessment methodology (BUREC curves, depth-velocity, frequency weighting), (3) flow depth & velocity define the hazard, (4) Question Group #1, Question 2 (there is no minimum slope). In addition, the District PFHAM team has previously discussed and rejected use of these additional terms to quantify the hazard. Finally, the rationale for not using fan slope, drainage area, and discharge are given in the final report, Section 3.4.1.

<u>Engineering Division – Avulsion Report</u>

We do not have any further comments about sedimentation analysis as all of our comments dated April 14, 2010 have been taken care of, and we have verified it in the latest submittal. Following are few comments about the avulsion report:

1. Section 4.5.7 (Page 56) needs to be modified based on our discussion dated August 17, 2010.
   JEF Response: Done.

2. Page 22: "eqn. 5" needs to be replaced as " Equation 5".
   JEF Response: We request to stick with "eqn. 5" because it preserves the formatting.

3. Section 3.5 (Page 20), delete "regarding" from the 3rd line.
   JEF Response: Done.

4. Page 70, first bullet point, use 'in" instead of "In".
   JEF Response: Done.

5. Page 70, 4th bullet point, use "Five-Step methodology" instead of "multi-step methodology".
   JEF Response: Done.

6. Page 23, Section 3.5.2, line 1, replace "unknown" with "not well known".
   JEF Response: Done.

Comments from Kathryn Gross

1. Should the table be broken down to include mitigation measures broken out by active or inactive alluvial fan flooding types?

   JEF Response: Only mitigation measures for (active) alluvial fan flooding are presented. Inactive fans are treated like riverine systems, for which the District already has guidelines.

2. Summary of Findings, first sentence. Should the word active be placed in front of "alluvial fan flooding"? Or would an introductory paragraph about active and inactive alluvial fan flooding be discussed here?

   JEF Response: Done.

3. Summary of Findings, Structural measures paragraph, last sentence. Compatibility with scenic resources, etc is only required if the project is being funded by the District.

   JEF Response: Done.

4. Sources of Information, number two. Typo in the summary "single lots protection measures".

   JEF Response: Done

5. Table 1 page 4, Description: Elevation. For Design Issues, please state that elevation is not acceptable by FEMA for removal of the floodplain. I am presuming a subdivision could elevate but choose not to request removal of the zone designation and FEMA probably would not have a problem with that. Is that mitigation? Or for the purpose of this memo is mitigation removal of the flood designation?

   JEF Response: The table already states that elevation is not acceptable to FEMA. The purpose of this memo is to list measures to mitigate flood hazards on alluvial fans.

6. Table 1 page 4, Description: Density Transfer. Should the "institutional difficulties" discussed in the definition also be listed in Design Issues?

   JEF Response: Done

7. Table 1, page 5 Description: Composite Methods. Please include a summary statement regarding the composite methods.

   JEF Response: Done

Comments from Joe Tram

1. Please differentiate the solutions between active and inactive flooding.

   JEF Response: Done

Comments from Tom Loomis (by memo "Review Comments 1_2_6_62408")

1. Pg. 1 Non-structural measures. The 2nd and 3rd sentences belong under the structural measures heading.

   JEF Response: We respectfully disagree. The sentences explain what is not a non-structural measure.

2. Pg. 3, Structural Measures, Table 1

   a) Detention Basins (on-line), Design Issues: Add Hydraulics, Sediment Transport, Risk Analysis, Geotechnical.

   JEF Response: Done

   b) Diversion Basins (off-line), Definition: Change "but on directly" to "but not directly."

   JEF Response: Done

   c) Diversion Basins (off-line), Design Issues: Add Hydraulics, Sediment Yield/Transport, Geotechnical.

   JEF Response: Done

   d) Debris Basins, Design Issues: Add Hydrology, Hydraulics, Sediment Yield, Risk Analysis.

   JEF Response: Done

   e) Debris Barriers, Design Issues: Add Location, Sediment Yield, Sediment Transport.

   JEF Response: Done

   f) Channels, Design Issues: Add Long-term Sediment Transport Analysis

   JEF Response: Done

3. Pg. 4, Structural Measures, Table 1

   a) Levees, Design Issues: Add Risk Analysis.

   JEF Response: Done

   b) Floodwalls, Design Issues: Same issues as for levees, plus Structural Stability.

   JEF Response: Done

   c) Retaining Walls, Design Issues: Same issues as for levees, plus Structural Stability.

   JEF Response: Done

   d) Composite Methods, Definition: Add "The measures applied may vary with defined degree of hazard."

   JEF Response: Done

4. Pg. 4, Non-Structural Measures, Table 1

   a) Avoidance (no development), Definition: Preservation of active fan flooding areas as undisturbed open space. No development allowed, including golf courses and parking. The goal is to allow the active areas to function naturally. Can be accomplished by zoning, density transfers, or other suitable means.

      JEF Response: Some changes made

   b) Avoidance (no development), Design Issues: Change "Takings" to "Potential Property Rights Issues."

      JEF Response: Done

   c) Acquisition, Definition: Purchase of flood-prone lands for preservation, open space, low-impact recreation, or other uses that preclude habitable structures and disturbance of the natural system and function.

      JEF Response: Done

5. Pg. 5, Non-Structural Measures, Table 1

   a) Composite Methods, Definition: Most non-structural projects may be a composite of any of the above measures. Non-structural measures may be combined with structural measures depending on the defined degree of hazard.

      JEF Response: This category applies only to non-structural measures.

<u>Comments from Ed Raleigh (from email message 6/23/08)</u>

1. Since the task is defined as a brief summary based on the consultant's current experience and knowledge, then it reflects what they are able to provide at this time. However, the scope says "what <u>design criteria</u> should be applied", rather than "Design Issues" used as the heading in their table.

   JEF Response: Changed heading.

2. The table discusses mitigation measures as if all fans had equal risks. The risks, flow path uncertainty and erosion potential are not the same on a steep fan with debris or mudflow compared to a fan on a mild slope where debris and mudflow are not present. As this work proceeds we need to quantify hazards on fans including factors such as debris flow, mud flow, steep slopes versus flat slopes, differences in watershed size, proximity to mountains and canyons, and the applicability and use of additional refinement of hazard identification using two dimensional flow analysis.

   JEF Response: There was no intended implication regarding risk level. We acknowledge that different fans have different hazard levels. The review comment goes beyond the scope of this task, the purpose of which was to list what mitigation measures have been used on active alluvial fans.

<u>Comments from Bing Zhao (from email message 6/23/08)</u>

1. As a follow-up for Ed's comments, "design criteria" should be specific engineering design criteria for basin, levees, diversion channels, and other mitigation measures discussed in Task 1.2.6. At least, specific design guideline/manuals which contain the specific design criteria should be cited.

   JEF Response: Great idea, but not within the scope, which did not allow any time for literature search. Perhaps this could be added in a subsequent work assignment.

2. Somehow down the road (before July 11, 2008, the project ends), the mitigation measures should be tied to the other two major tasks: debris flow and hazard quantification.

   JEF Response: Great idea, but not within the scope. Perhaps this could be added in a subsequent work assignment.

Comments from Burke Lokey (by email message 6/23/08)

1. I did look at the summary. It seems like it's a pretty complete and concise summary of the mitigation measures. IMHO the only thing that might be added or modified is the column with "design issues". My interpretation of the scope language is that this needs to be developed a little more to identify those (engineering) parameters that are related to the design issues.

   JEF Response: Done.

2. For instance, w/ respect to On-Line Detention Basins, inasmuch as the design issues include sediment yield and outlet capacity/clogging, the consultant could identify the kinds of analysis used to quantify these issues and focus on some of the key factors in those analyses, IE, stream power, energy gradient, sediment transport capacity, all related in some way to channel slope S. Perhaps a second matrix could be developed with the different kinds of analytical techniques and their component factors. The idea is to eventually narrow down those parameters that get considered.

   JEF Response: Great idea, but not within the scope. Perhaps this could be added in a subsequent work assignment.