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ANALYSIS OF FLOWS ON ALLUVIAL FANS

State of the Art

Final Report

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16. ABSTRACT

A preliminary approach to the analysis of flows on alluvial fans is presented. The specific objective is the design of highway crossings constructed on alluvial fans in Arizona. Hydrologic, hydraulic and sedimentation effects are presented. The effect of development on alluvial fans is addressed and a work plan for future research is presented.

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PREFACE

This report was prepared for the Arizona Transportation Research Center and the Arizona Department of Transportation in order to conduct a state-of-the-art study of the characteristics, capabilities and applicability of several of the more promising methods for planning and designing drainage for highway crossings on alluvial fans. The report was prepared and written by Douglas L. Hamilton and Robert C. MacArthur of Simons, Li & Associates, Inc. in Newport Beach, California. Dr. Ruh-Ming Li was the Principal-in-Charge. Results, discussions and recommendations presented in this report are not intended to be applied directly for design purposes. Further development and testing of the methods presented is necessary before they can be considered for uniform application.

Simons, Li & Associates, Inc. is grateful to the Arizona Transportation Research Center for sponsoring this study and to Mr. V. Ottozawa-Chatupron of the Center for his skill and guidance throughout this project.

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I. INTRODUCTION

Problem Statement and Need for The Study

Most hydraulic studies pertaining to the planning and design of highway drainage systems and highway crossings have been developed in riverine and coastal regions where the characteristics of flooding are well defined. However, there is one type of flooding that is increasingly becoming a problem for highway designers in the western United States as the population and development in the West increases. This type of flooding problem occurs in areas known as alluvial fans. These areas are found in desert and semi-arid regions where runoff from sudden thunderstorms flows down steep mountain drainages and empties onto a broad valley floor (see Figure 1).

Concern for flooding and drainage problems on alluvial fans is increasing as more and more development occurs. Alluvial fans attract development because of their mild slopes, close proximity to the foothills and potential for spectacular views of the valley floor. Descriptions and definitions of alluvial fans are found in the reports by Bull (1977) and Anderson-Nichols (1981).

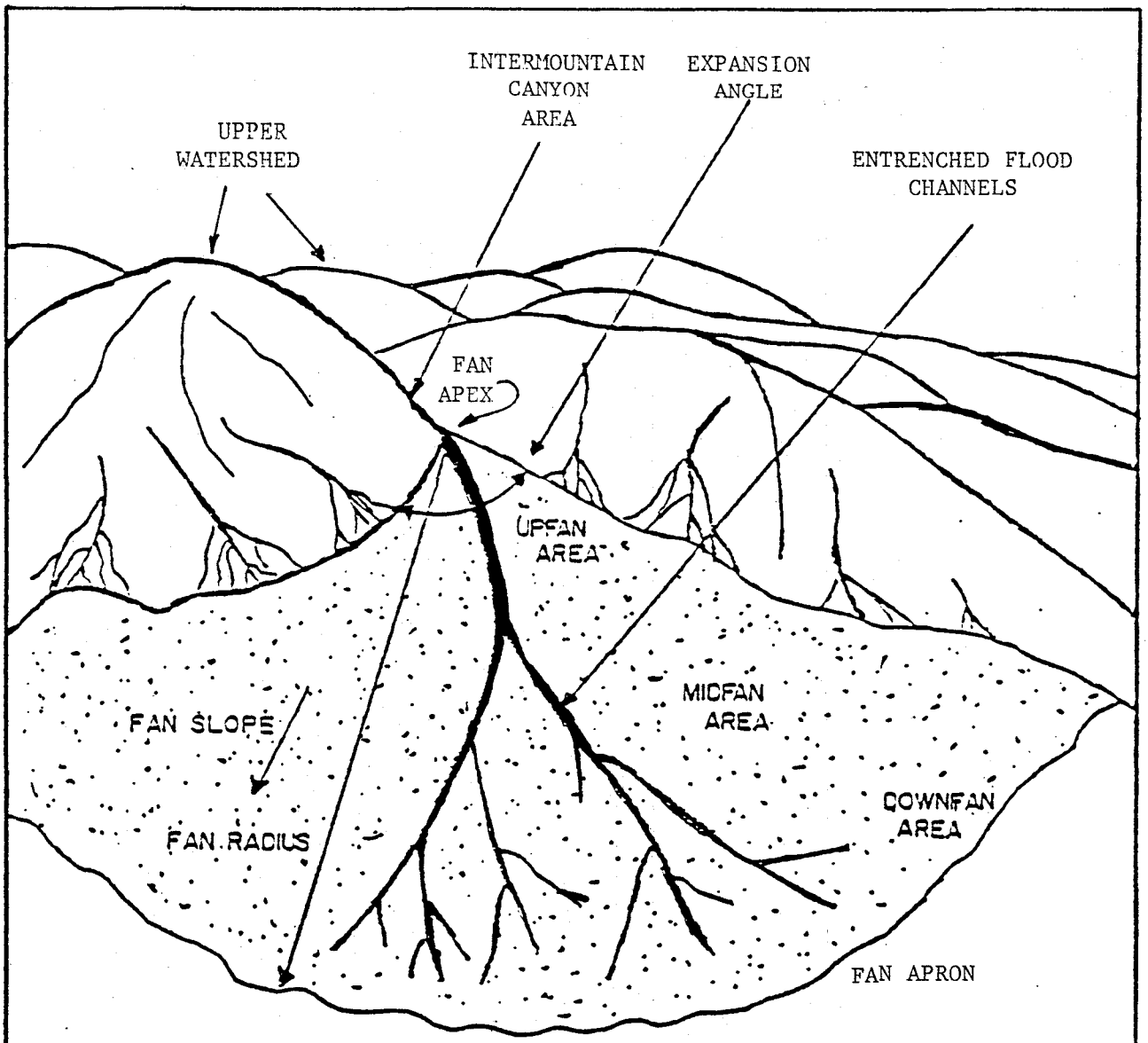
Flood flows on alluvial fans can be very dangerous because of their unpredictability, high velocities, and ability to carry large amounts of sediment and debris. The seriousness of flooding on alluvial fans is related to the quickness and ferocity of the event as well as the unpredictability of the flow direction due to avulsions or drastic channel shifts that result from the accumulation of debris in defined channels.

Although alluvial fans are common geomorphic features around the world, especially in arid and desert regions, the hydraulic processes which form them and continue to modify them are poorly understood from the viewpoint of traditional hydraulics and highway engineering. Therefore, the purpose of this study is to conduct a state-of-the-art study of the capabilities and applicability of several different methods for planning and designing highway crossings on alluvial fans in order to determine an appropriate direction for future research on this topic.

Characteristics of Alluvial Fans

It is essential to first discuss the many unique characteristics of alluvial fans that make analysis of flood problems so difficult. Approximately one third of the land area in the southwestern United States is covered by alluvial fans. Alluvial fans are usually associated with desert and semi-arid regions of the world; however, they do exist (Bull, 1977) in tropical areas as well.

Alluvial fans are generally aggradational in nature (Bull, 1977). French (1984) describes the formation of alluvial fans as follows: "Debris accumulates along the flanks of mountains due to weathering; and when an intense precipitation event occurs, the accumulated debris is transported downslope in an intermountain canyon. At the point where the canyon enters the valley - the apex of the fan - the widening of the flow results in a decrease of its debris carrying capacity, and the debris is deposited at the apex and downslope from it." Over time,



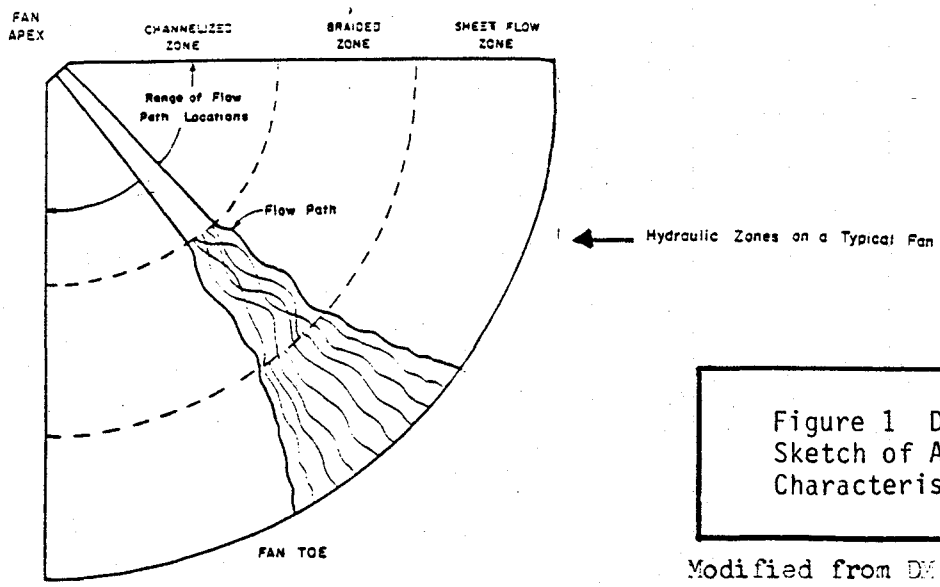


Figure 1 Definition Sketch of Alluvial Fan Characteristics.

Modified from DMA Engrs., 1985

Morphology, hydrology and hydraulic characteristics vary greatly between different fans. Therefore, the extent, severity and behavior of floods on different fans depend heavily on individual fan characteristics. This makes the development of uniform design criteria and analysis methods difficult.

Anderson-Nichols (1981) list many of the following key watershed and fan characteristics which influence fan flooding behavior:

- effective drainage area of the watershed
- watershed slope and aspect
- watershed soil type and vegetation
- frequency of forest fires
- development density within the watershed
- rainfall intensity and duration
- fan slope and topographic shape
- existence of one or several entrenched channels
- degree of entrenchment of main channels, their orientation and stability
- apex discharge conditions (hydraulic conditions)
- sediment characteristics

Urbanization and development pressure on alluvial fans are high. Therefore, the characteristics of the fan today are unlikely to remain the same in the future. Highways built through undeveloped lands usually create accelerated development adjacent to them. The ability to accurately estimate the rate of urbanization and changes that may result with urbanization is essential for proper highway drainage design.

A first step to any highway drainage study should include the identification of the key characteristics of the fan that the highway is to cross. Some of the essential steps to consider include:

many such events cause deposits to accumulate, resulting in the characteristic fan or cone shape.

Dozens of articles and references are available describing the geologic aspects of alluvial fans. Interested readers should refer particularly to Anstey (1965) and Bull (1977). Quantitative methods for hydraulic analysis of these regions, however, are not commonly found in the literature.

To design highway drainage systems on alluvial fans, one must know (1) where the highway will be located on the fan, (2) the location of the major and minor flow channels it crosses and (3) the detailed characteristics about the drainage basin upstream from the highway. Because the characteristics of flows vary so greatly depending upon location on the alluvial fan, design methods and analytical techniques will also vary. In the paper entitled "Generalized Methodology for Simulating Mudflows", MacArthur, et al (1986) divide a drainage basin into three regions. The three regions of concern for highway analysis are similar and include: (a) The upper watershed, (b) the intermountian canyon areas and any stable channels that cross the fan, and (c) the broad alluvial fan itself. Figure 1 presents a sketch of a generalized watershed and alluvial fan drainage system. Three hydraulic zones can be identified on the fan itself: (1) A channelized zone, near the apex, where a single definable channel exists, (2) a braided zone, which is a transition area where the channel becomes unstable and multiple sinuous paths occur, and (3) a sheet flow zone, where flow spreads laterally in the streamwise and transverse directions and is very shallow.

II. DESIGN PROBLEMS FOR HIGHWAY DRAINAGE ON ALLUVIAL FANS

What do highway planners and designers need to know about the characteristics of flood events on alluvial fans? They need to know how to best size and orient culverts and highway crossings to safely handle flows from design events with minimum maintenance or damage. To do this they need to know what the peak discharge and duration for the design event will be, what the flow velocity will be, what the depth of flow will be, and how much sediment movement (scour or deposition) can be expected during the event.

Hydrologic and Hydraulic Problems - Most highway drainage and hydraulic design guidelines are based on traditional hydrologic and hydraulic computational methods. They assume that sufficient data are available to develop the regional hydrology and peak discharges for various design flood events. Often this is not the case because of an insufficient period of record requiring that flood flows be estimated by a variety of rough methods. When results from these rough methods are compared, they often yield a wide range of different peak discharges, hydrograph shapes and flood volumes. Peak flow rates should be estimated by either regional regression models (Chow, 1964) or envelope curve methods as recommended by Crippen (1982). French and Lombardo (1984) have pointed out the limitations that these two methods have in arid areas. Therefore, accepted standardized methods for developing the design hydrology for highway drainages and highway crossings are needed as a first step in the analysis.

- perform thorough aerial and field surveys of the fan and upper watershed areas
- develop detailed topographic mapping of the study area including high resolution aerial photographs
- attempt to locate historical aerial photos, soils data, geological data and flood histories of the fan
- locate the proposed highway on the topographic maps and aerial photographs
- study the proposed alignment for any obvious problems or possible improved alternatives
- classify the fan according to the key characterics observed during this preliminary study
- identify possible drainage alternatives and locate potential highway culverts and crossings based upon preliminary results
- list all additional data needs and possible problems identified during the preliminary study.

Results from the preliminary study will provide essential information for the preliminary design phase of the project (assuming the project is determined previously to be feasible). Discussions in the following sections of this report will explain the kinds of analyses that are required for the different regions and will evaluate several different kinds of analytical tools presently available for analyzing alluvial fan flooding and drainage problems.

in the streamwise and transverse directions, the flow often becomes two-dimensional and often quite shallow. Flows confined within stable channels can still be evaluated with one-dimensional tools (unsteady, or perhaps steady state under some conditions). Sheet flows distributed over the fan surface or broadcast laterally by avulsions from shallow unstable rills are extremely complex in nature. No presently available analytical tools can analyze these kinds of flows directly. Kinematic wave approximation, and some two-dimensional models show promise. Discussions in a later section compare several state-of-the-art models that show promise for these kinds of flows.

Time Scales - Three different time scales are important when analyzing fan flooding dynamics:

(1) geologic time (10^6 years), during which numerous events and flow paths wander over the fan and the fan grows and aggrades,

(2) project time (50 to 100 years), during which several flood events of various magnitudes may occur causing channel shifts and sediment movement, also during which highway modification projects may occur and regional urbanization occurs on the fan,

(3) flood event time (hours to days), during which high intensity, short duration flows race through the project causing topographic adjustment and channel shifts to occur. Local project damages may occur requiring maintenance and repair.

Given a design storm, runoff volume and peak discharge estimates are often obtained by using rainfall-runoff models such as HEC-1 and Tr-20. These models cannot capture the two-dimensional behavior of flows on an unbounded plane; however, they can yield useful results if used with care.

Given the design hydrology, most highway crossings are sized and oriented based on fixed-bed, steady state hydraulic computations such as found in the computer program HEC-2. Unfortunately, flood flows common to alluvial fans are often unsteady, supercritical flows capable of moving large amounts of sediment. The bed and banks of the ephemeral channels found on most alluvial fans are usually unstable and channel avulsions are common. Channel patterns and inundation areas often change with each flood. Sediment scour and deposition occur rapidly during floods and quickly alter channel geometries. This is not to say that traditional hydraulic design methods should not be used at all. Many locations and hydraulic design questions can be roughly solved with HEC-2 type tools. Sediment transport, general scour and local pier scour can then be estimated using methods described by Simons, Li & Associates (1982 and 1986) and others.

No uniform methods exist for analyzing flow problems on alluvial fans because hydraulic and sediment transport characteristics vary greatly over the surface of the fan from its apex to the fan apron (see Figure 1). One-dimensional unsteady flow methods are valid in the confined intermountain channel section upstream from the fan apex. Beyond the point where the flow emerges onto the unbounded fan and spreads out

Highway projects, such as the proposed Outer Loop Freeway project in Phoenix, may be planned for areas where urbanization and development upstream from the proposed highway have very low density. Culverts and crossings located to handle the design event defined by the Highway Department can be built now. Later as more roads are constructed and development occurs, the topographic features of the fan and, therefore, the flood characteristics change drastically. This effect coupled with the nonuniformity in design criteria between the various agencies leads to difficult flood hazard management problems. This situation presently exists throughout much of Phoenix and will cost millions of dollars to improve.

Therefore, in undeveloped areas where highways are planned, it is recommended that at least a basic master plan for flood control and drainage be part of the initial highway siting and feasibility studies. As the project evolves and goes into the design phases, additional detail can be added to the master plan. Funding for this additional work can be shared between the city, counties and developers.

Finally, cities and counties should be encouraged to modify their drainage and/or land grading ordinances to eliminate uncontrolled clearing, grubbing and trenching of alluvial fans. Often land owners will construct a soil berm around undeveloped property to discourage automobile trespassing. This deflects all of the water that formerly moved over the property as shallow sheet flow and concentrates it in other directions. Obviously these kinds of practices may result in significant changes in the flow characteristics downslope. No

Obviously the last two time scales (project and flood event time) are most important to planners and design engineers. They need to determine whether existing entrenched channels will remain stable or are likely to shift location. They need to anticipate the future effects of urbanization (planned or unplanned) on the project, and also anticipate future highway modifications that may be necessary.

Other Problems - Other problems facing highway design engineers are institutional and political problems. The problems result from the fact that basic design criteria (such as the design hydrology, recurrence interval, peak discharge, permissible velocity, freeboard height, etc.) may vary greatly between the various regulating agencies having jurisdiction over the lands on the alluvial fan. Local city and county regulations and design ordinances are often much different from The Federal Highway Administration, the railroads, The Corps of Engineers, The Soil Conservation Service and The Federal Emergency Management Agency. Therefore, if different agencies are designing flood control and drainage systems upstream from the highway and are not using the same basis for design as the highway department, it will be difficult to have an effective integrated flood drainage system. More legislation and interagency cooperation is needed to establish agreed upon design criteria for alluvial fan flooding. Once the design criteria and levels of protection are established, then more definite design methods for meeting the level of protection can be established.

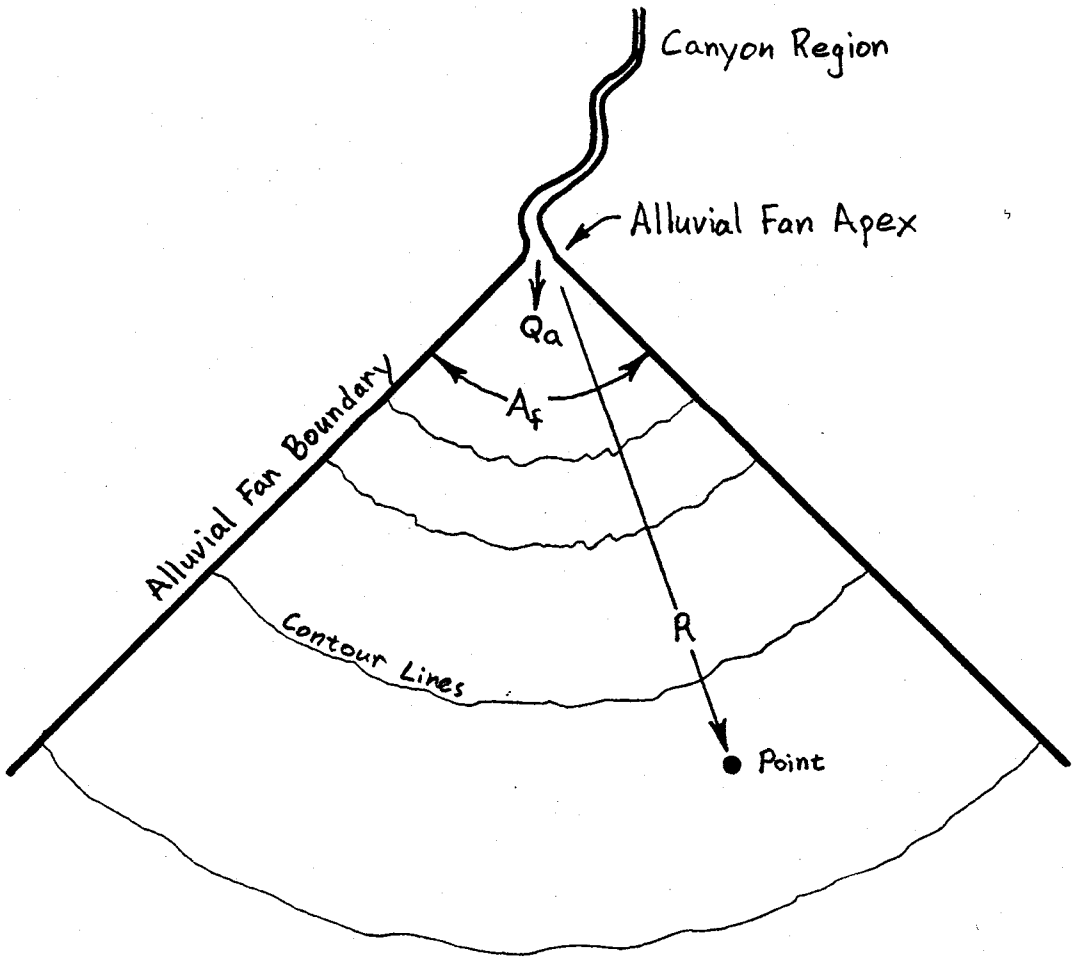
Tettemer (1986) suggests master planning for flood control and drainage ordinances for developers as means for ensuring an integrated flood hazard reduction program.

The next section will identify and evaluate several of the more promising methods presently available for depicting flow conditions on alluvial fans.

sophisticated computer program or detailed design investigation for a highway drainage system accounts for future impacts of these random modifications to the prevailing drainage system. As streets and other improvements are built they should be designed to maintain the existing flow pattern and flow rates. Streets and fills should not divert flow from one drainage area to another. Distributing the flow among as many streets and shallow floodways as possible prevents it from collecting and becoming a flood.

Drainage modifications that concentrate flows that used to spread as sheet flow may cause the character of the local hydraulic zone to shift from being a sheet flow zone previously to either a braided zone or even channelized zone (refer to Figure 1). Once the shift occurs it may take a long distance and many years for the downstream drainage area to readjust to the new increase in flow energy. Increased sediment transport and shifts in the direction and magnitude of the peak discharge may also occur downstream from the point of concentration.

Tettemer (1986) suggests that inadequately designed and improperly placed ditches, walls or berms can develop false security and more problems than they were intended to solve. Also, all drainage and flood control projects adjacent to the highway and upslope on the fan must be maintained regularly to assure their proper function. And, finally the highway department and local city and county governments should regularly monitor all activity on the fans. Flows on the alluvial fan are very sensitive to even minor changes in land form or grading.



Q_a = Point Discharge at Fan Apex (cfs)
A_f = Fan Angle (degrees)
R = Distance from Apex (feet)

Unit Discharge at any distance from Apex (cfs/ft)

$$q = 2\,Q_a/\pi R \quad \text{if} \quad A_f \geq 90^\circ$$
$$q = 2\,Q_a\,90/A_f\,\pi R \quad \text{if} \quad A_f < 90^\circ$$

Figure 2 Idealized alluvial fan.

III. HYDRAULIC ANALYSIS FOR ALLUVIAL FANS

Introduction

Although there has been a great deal of highly significant work done in the field of alluvial fan hydraulics and hydrology, pratical applications of scientific principles for solving alluvial fan flood control problems are rare. This chapter will attempt to (1) generally describe the behavior of flooding on alluvial fans, (2) define the specific parameters required to design highway crossings and (3) discuss some existing and proposed computational methods for analyzing flows on alluvial fans.

General Description

Alluvial fans vary in size from a few square miles such as near Bullhead City, Arizona to hundreds of square miles such as near Phoenix and Tucson. As the fan area increases, flood waters come not only from rainfall in the mountain watershed above but also from rainfall which occurs on the fan itself. Thus the 100 year discharge at the apex of the fan is not always the appropriate quantity to use for flood analysis. Figure 2 shows an idealized situation of flooding on an alluvial fan. This is a symmetrical fan with no flow obstructions. Fehlman (1987) indicates that unbounded flow on an inclined, flat plane expands initially with an apex angle of 90°. Thus if the fan angle A_f is less than 90°, the flow will be spread uniformly across the entire fan. If the fan angle is greater than 90°, the flow will be spread uniformly across 90° of the fan. This is obviously an oversimplification but it

CASE 1: Flow Obstructed by a Levee.

Figure 3 shows a flood control levee of length L which is oriented at an angle to the flow path. The first step is to estimate the concentrated discharge at point 3. This is done by multiplying the average unit discharge by the length of the levee. Note that the sine of the angle between the flow direction and the levee must be used to compute the actual unit discharge that impinges on the levee. The unit discharge at point 4 is based on the uniform expansion of the concentrated discharge from point 3. The unit discharge at point 5 includes the contribution from the fan apex (point 1) and from the end of the levee (point 3). From this example it can be seen that development on an alluvial fan can redirect the natural flow path. Note that an upper case Q is the discharge at a point expressed in cfs and a lower case q is the unit discharge in the direction of flow expressed in cfs/ft.

will serve for purposes of illustration. As the flow spreads out, it is convenient to express its magnitude using the discharge per unit width q. A peak discharge of 1,000 cfs spread out across a 100 foot wide fan contour would yield a unit discharge of 10 cfs/foot. The unit discharge at any distance R from the apex of the idealized alluvial fan is

$$q = 2Q_a/\pi R \quad \text{if } A_f \geq 90°$$

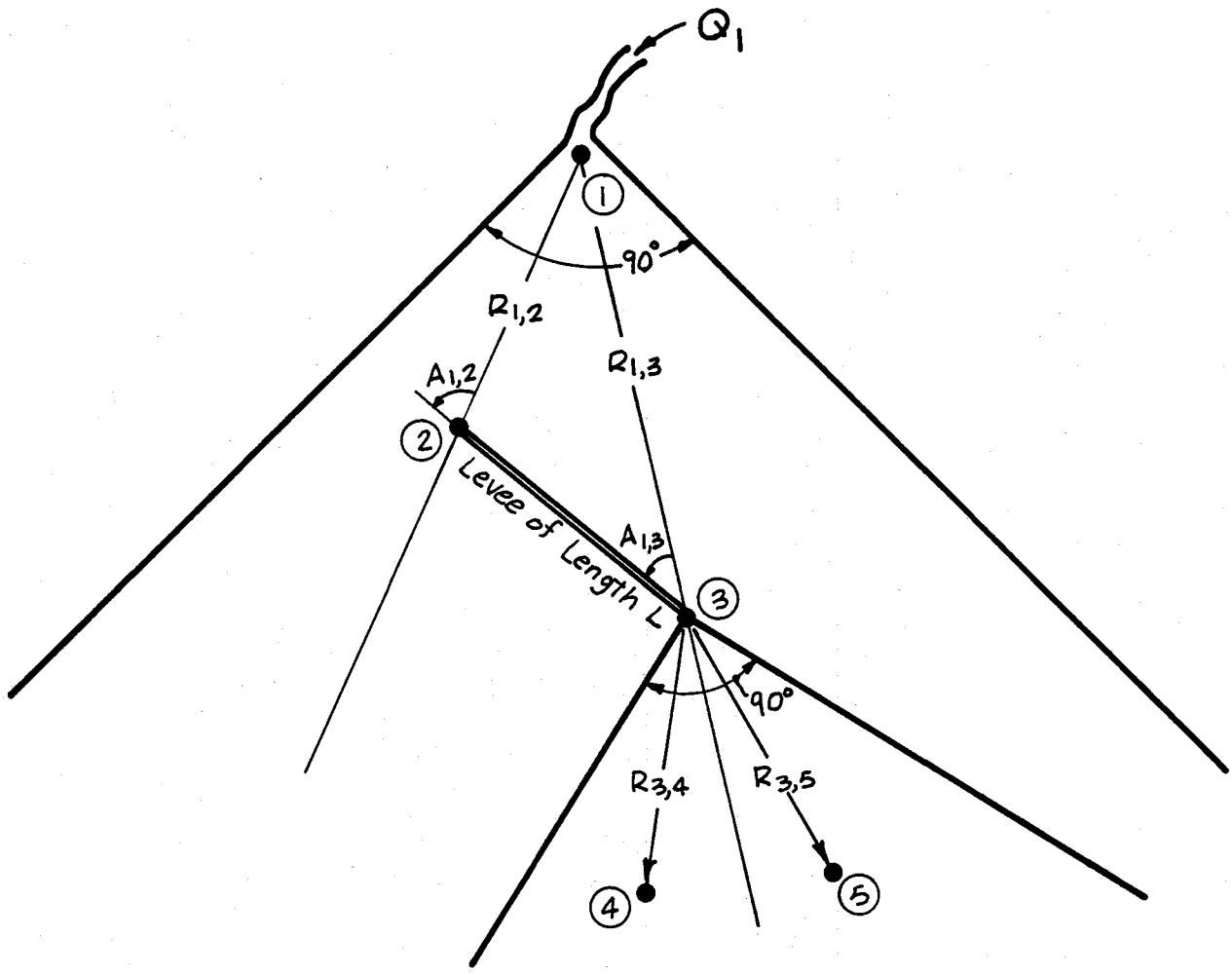
$$q = 2Q_a\, 90/A_f \pi R \quad \text{if } A_f < 90°$$

Where Q_a is the point discharge at the apex of the fan. This assumes an ideal fan with no obstructions and uniformly distributed flow with a maximum expansion angle of 90°. Again the flow expansion angle will be less than this in reality. The purpose of a two-dimensional flow model for alluvial fans is, in fact, to determine the actual flow expansion angle.

This simple model can be used to illustrate four situations which may be encountered in alluvial fan analysis. The treatment that follows does not include the dynamic behavior of the flow; methods which will account for this are described later. These examples provide a framework upon which future research results can be placed. Ultimately a two-dimensional flow analysis technique will be used to determine the flow expansion characteristics for each concentration point. The results can then be superimposed for a coalescing fan situation.

CASE 2: Flow Obstructed by a Housing Development

Figure 4 shows a housing development which intercepts the flow and redirects it around the community. It is then released at point 3 and point 7. The unit discharge at point 8 is computed using the concept presented in case 1.



Find Unit Discharge at Points 4 and 5

$$\left.\begin{aligned} q_2 &= 2Q_1 \sin A_{1,2}/\pi R_{1,2} \\ q_3 &= 2Q_1 \sin A_{1,3}/\pi R_{1,3} \end{aligned}\right\} \quad Q_3 = \frac{1}{2}(q_2+q_3)L = \frac{Q_1 L}{\pi}\left(\frac{\sin A_{1,2}}{R_{1,2}} + \frac{\sin A_{1,3}}{R_{1,3}}\right)$$

$$q_4 = 2Q_3 \sin A_{3,4}/\pi R_{3,4}$$

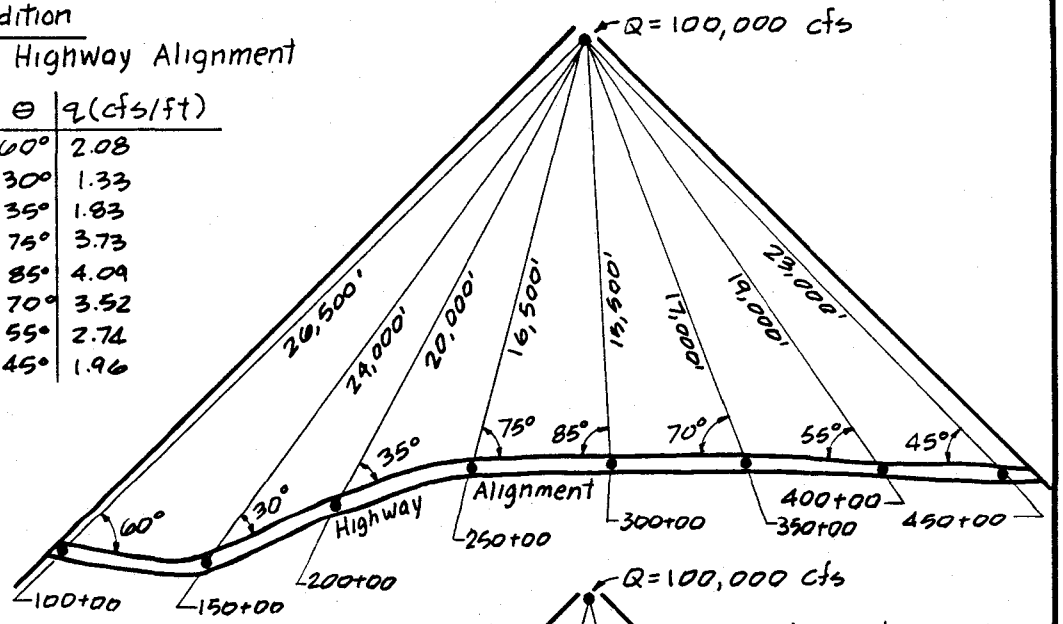
$$q_5 = q_4 + 2Q_1 \sin A_{1,5}/\pi R_{1,5}$$

Figure 3 Flow obstructed by a levee.

Existing Condition

Find q Along Highway Alignment

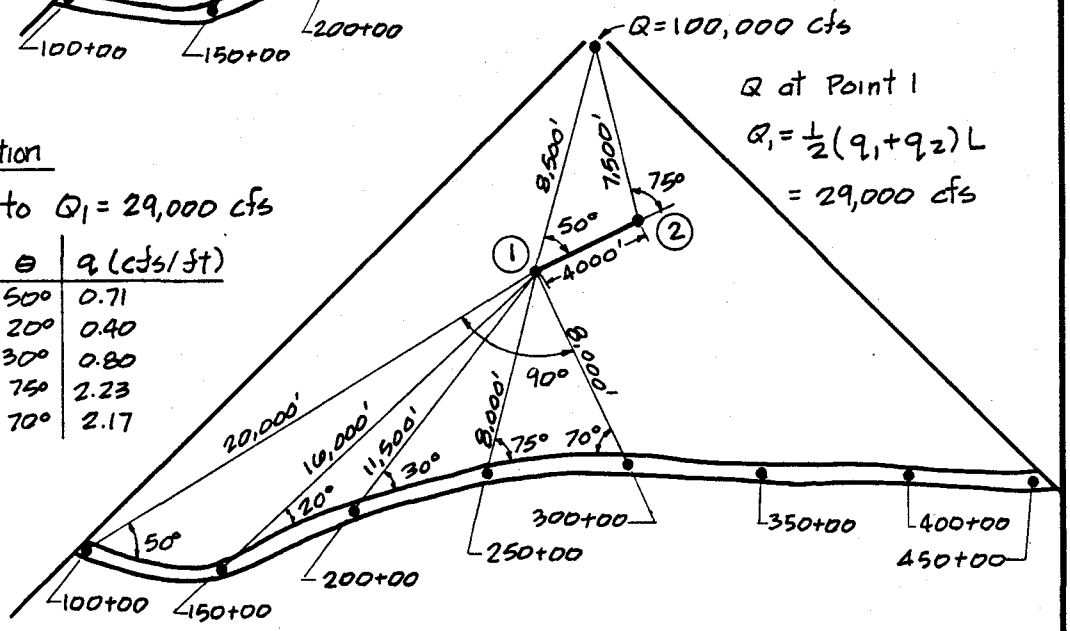
STA	R	θ	q (cfs/ft)
100+00	26,500	60°	2.08
150+00	24,000	30°	1.33
200+00	20,000	35°	1.83
250+00	16,500	75°	3.73
300+00	15,500	85°	4.09
350+00	17,000	70°	3.52
400+00	19,000	55°	2.74
450+00	23,000	45°	1.96



Future Condition

Find q_1 Due to $Q_1 = 29{,}000$ cfs

STA	R	θ	q (cfs/ft)
100+00	20,000	50°	0.71
150+00	16,000	20°	0.40
200+00	11,500	30°	0.80
250+00	8,000	75°	2.23
300+00	8,000	70°	2.17



Total Impact ($q + q_1$)

STA	q	q_1	total q
100+00	2.08	0.71	2.78
150+00	1.33	0.40	1.73
200+00	1.83	0.80	2.63
250+00	3.73	2.23	5.96
300+00	0.00	2.17	2.17
350+00	3.52	0.00	3.52
400+00	2.74	0.00	2.74
450+00	1.96	0.00	1.96

Comparison of Existing and Future Drainage

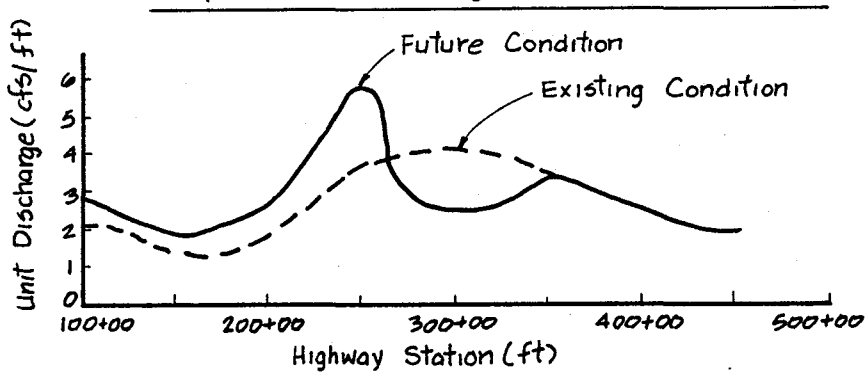
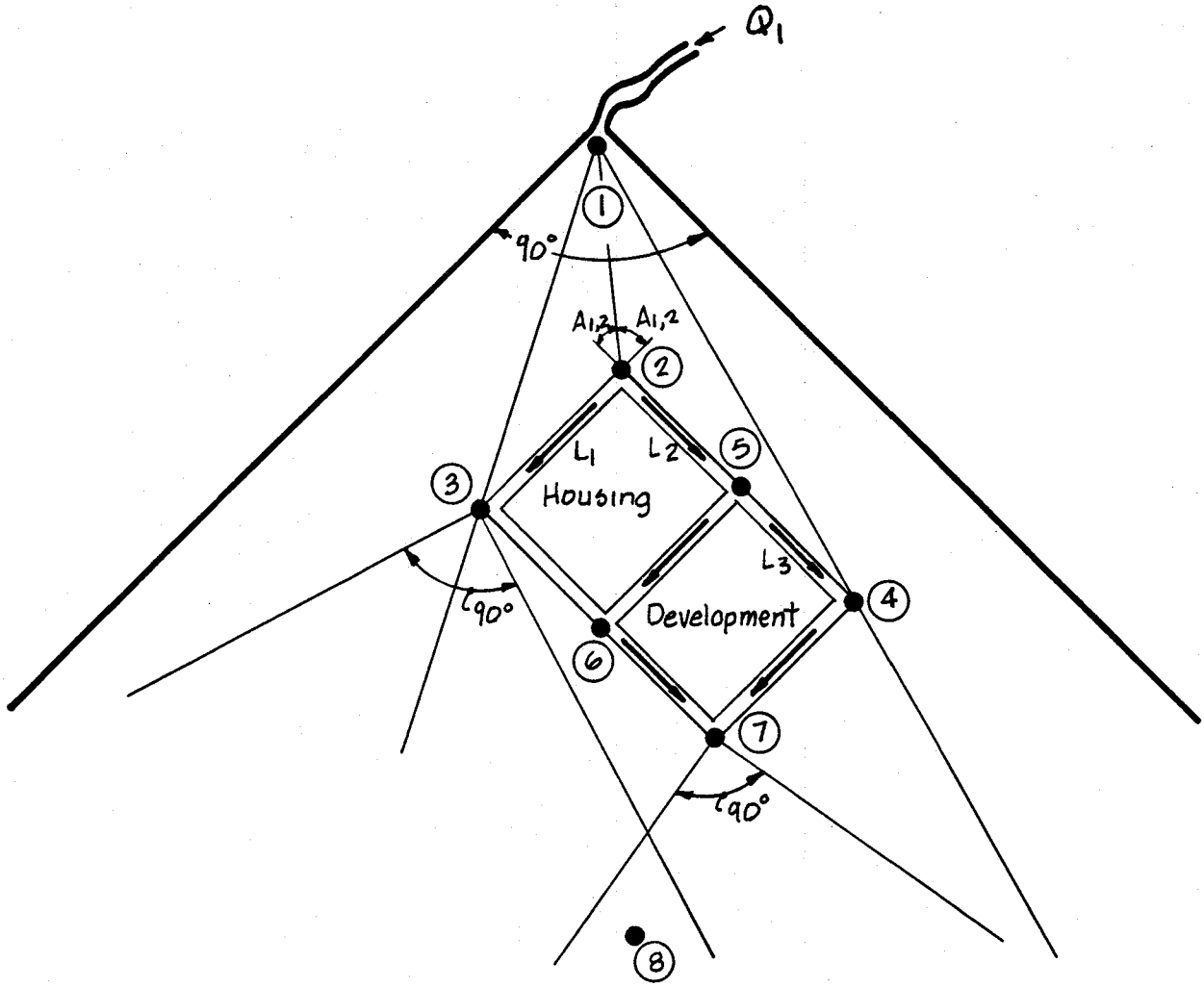


Figure 5 Effect of development on highway drainage.



Find Unit Discharge at Point 8

$$Q_3 = \frac{Q_1 L_1}{\pi}\left(\frac{\sin A_{1,2}}{R_{1,2}} + \frac{\sin A_{1,3}}{R_{1,3}}\right)$$

$$Q_7 = \frac{Q_1 L_1}{\pi}\left(\frac{\sin A'_{1,2}}{R_{1,2}} + \frac{\sin A_{1,5}}{R_{1,5}}\right) + \frac{Q_1 L_1}{\pi}\left(\frac{\sin A_{1,5}}{R_{1,5}} + \frac{\sin A_{1,4}}{R_{1,4}}\right)$$

$$q_8 = \frac{2 Q_3 \sin A_{3,8}}{\pi R_{3,8}} + \frac{2 Q_7 \sin A_{7,8}}{\pi R_{7,8}}$$

Figure 4 Flow obstructed by a housing development.

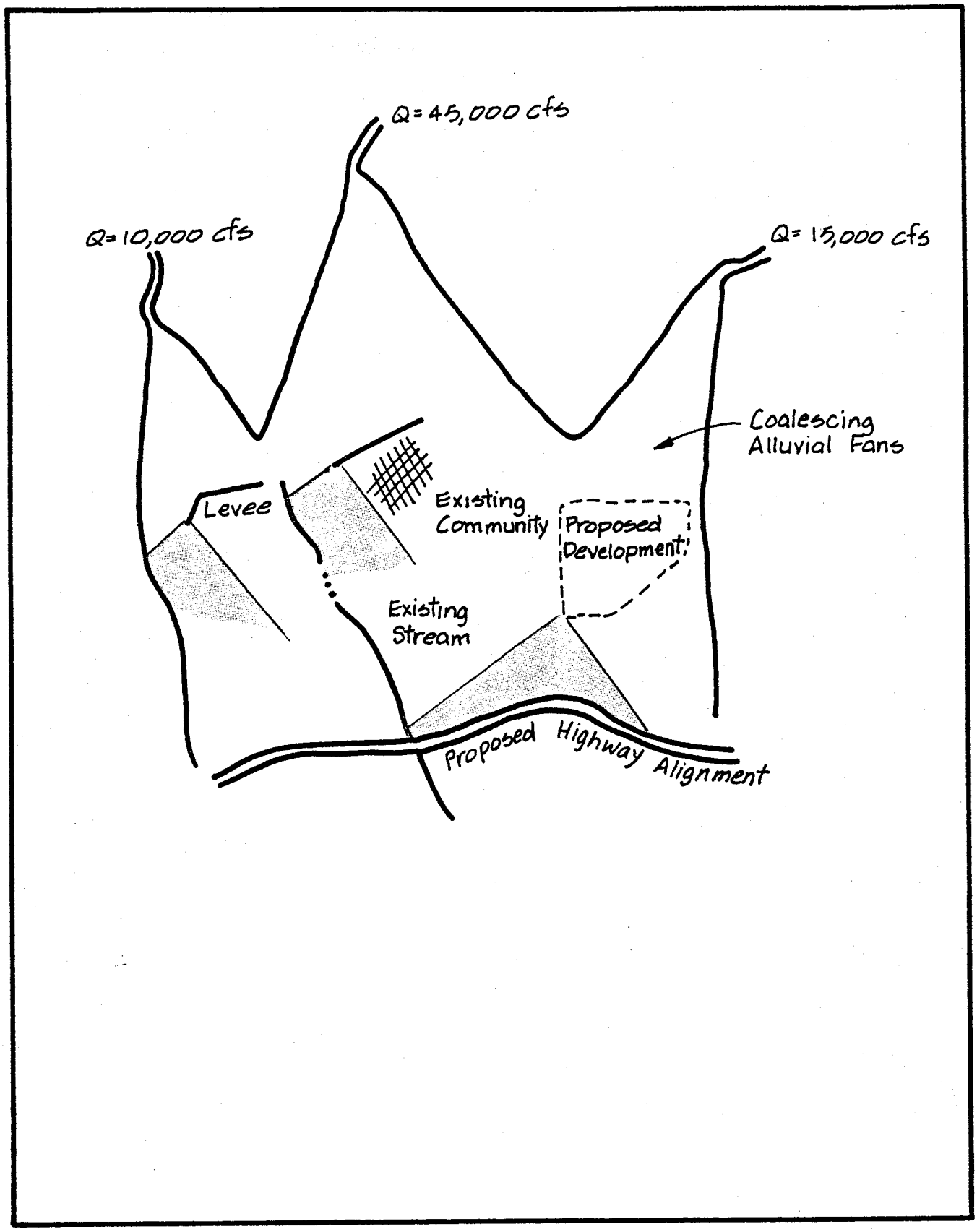


Figure 6 General condition of flooding on an alluvial fan.

CASE 4: General Condition

Figure 6 shows the general situation. Several alluvial fans from different drainages coalesce. Many of the roads, structures and topographic features found on the alluvial fan can cause major changes in flow direction, depth and velocity. Any mathematical model for analyzing alluvial fan hydraulics should be capable of including such effects. Since most parts of the fan have no defined channel, the two dimensional behavior of the flow on an unbounded surface would need to be described. Using this approach would enable the highway designer to account for effects of future development on drainage.

such as near Phoenix or Tucson, the amount of rainfall which occurs on the fan itself should be included. The infiltration rate of the runoff on the fan is a function of time and may be difficult to determine; however, it is also an important factor for large alluvial fans. For illustrative purposes, these two factors are not included in equations (1), (2), and (3).

Equations 1, 2 and 3 describe the flow behavior exactly, within the constraints of the assumptions upon which they were derived. The equations must be solved numerically, however, as no closed form solution exists. In order to make this numerical solution easier to perform, one or more of the terms in equations 2 and 3 are sometimes removed. This may or may not have a large effect on the computed solution depending upon the nature of the problem.

The specific role of two-dimensional flow analysis for alluvial fans can be seen from Figure 7. A point discharge on an unbounded plane will expand initially with an included angle of 90° but will eventually flow perpendicular to the contours. The assumption made in the four example cases that a point discharge will expand uniformly with an angle of 90° for any distance will yield discharges that are lower than would actually occur. Thus unless two-dimensional flow effects are accurately captured, there is a good chance that highway drainage facilities will be underdesigned. An acceptable computational technique should include the capability to describe the expansive nature of the flow, incorporate the effect of both subtle topographic features and abrupt flow obstructions, and should be able to describe supercritical and subcritical flow behavior.

Design Parameters

This section discusses the basis of two-dimensional flow analysis and its role in solving alluvial fan flood problems. In general, flow on an unbound plane is governed by the three-dimensional, unsteady equations of mass and momentum conservation. If there is a hydrostatic pressure distribution, and nearly uniform velocity distribution in the vertical direction, the dimension of the equations can be reduced by one. The only dependent variables are the fluid depth and the unit discharge in the x and y directions (Hamilton, et al., 1987). Mathematically, the two-dimensional equations for unsteady flow are

$$\frac{\partial h}{\partial t} + \frac{\partial p}{\partial x} + \frac{\partial q}{\partial y} = 0 \tag{1}$$

$$\frac{\partial p}{\partial t} + \frac{\partial}{\partial x}\left(\frac{p^2}{h} + g\frac{h^2}{2}\right) + \frac{\partial}{\partial y}\left(\frac{pq}{h}\right) + gh\left(S_{o_x} + S_{f_x}\right) = 0 \tag{2}$$

$$\frac{\partial q}{\partial t} + \frac{\partial}{\partial y}\left(\frac{q^2}{h} + g\frac{h^2}{2}\right) + \frac{\partial}{\partial x}\left(\frac{pq}{h}\right) + gh\left(S_{o_y} + S_{f_y}\right) = 0 \tag{3}$$

in which t = time; x = x-horizontal coordinate; y = y-horizontal coordinate; p and q = the unit discharge in the x and y directions, respectively; h = water depth; g = gravitational constant; S_{ox} and S_{oy} = bed slope in the x and y direcitons; and S_{fx} and S_{fy} = frictional resistance term in the x and y directions. The frictional resistance is usually computed using Mannings equation. For large alluvial fans

Assessment of Random Behavior of Alluvial Fan Flows

As will be discussed in the following section, some deterministic computational methods are available to assess the general trends of alluvial fan hydraulics and hydrology. Many of the phenomena that complicate the analysis of alluvial fan flooding, however, are random, at least in the sense that we do not have the knowledge to predict in advance the specific effects from a given causal event. An example of such a random phenomenon is the pattern of sediment deposition which occurs during a flood on an alluvial fan. In general, the deposition pattern is cone shaped and fairly uniform such as the alluvial fan terrace north of Phoenix shown in Figure 8. Upon close inspection, the contour lines appear jagged and irregular. On a large scale, it is apparent that the contour lines can be approximated by smooth, semi-circular curves. The small fluctuations in elevation are due to the scour, deposition and resuspension of material and is a function of the local geologic, vegetation, soil mosture and topographic conditions. Since there is no direct deterministic computational method to simulate such micro-scale effects accurately, it is more practical to simulate the average hydrologic behavior and use a probabilistic approach to account for microscale deviations from the mean.

The contour line noted on Figure 8 has a maximum deviation of about 2 feet in elevation. This means, historically, that local changes in bed elevation have been up to two feet during a flood event. The average deviation from the mean contour elevation can be computed

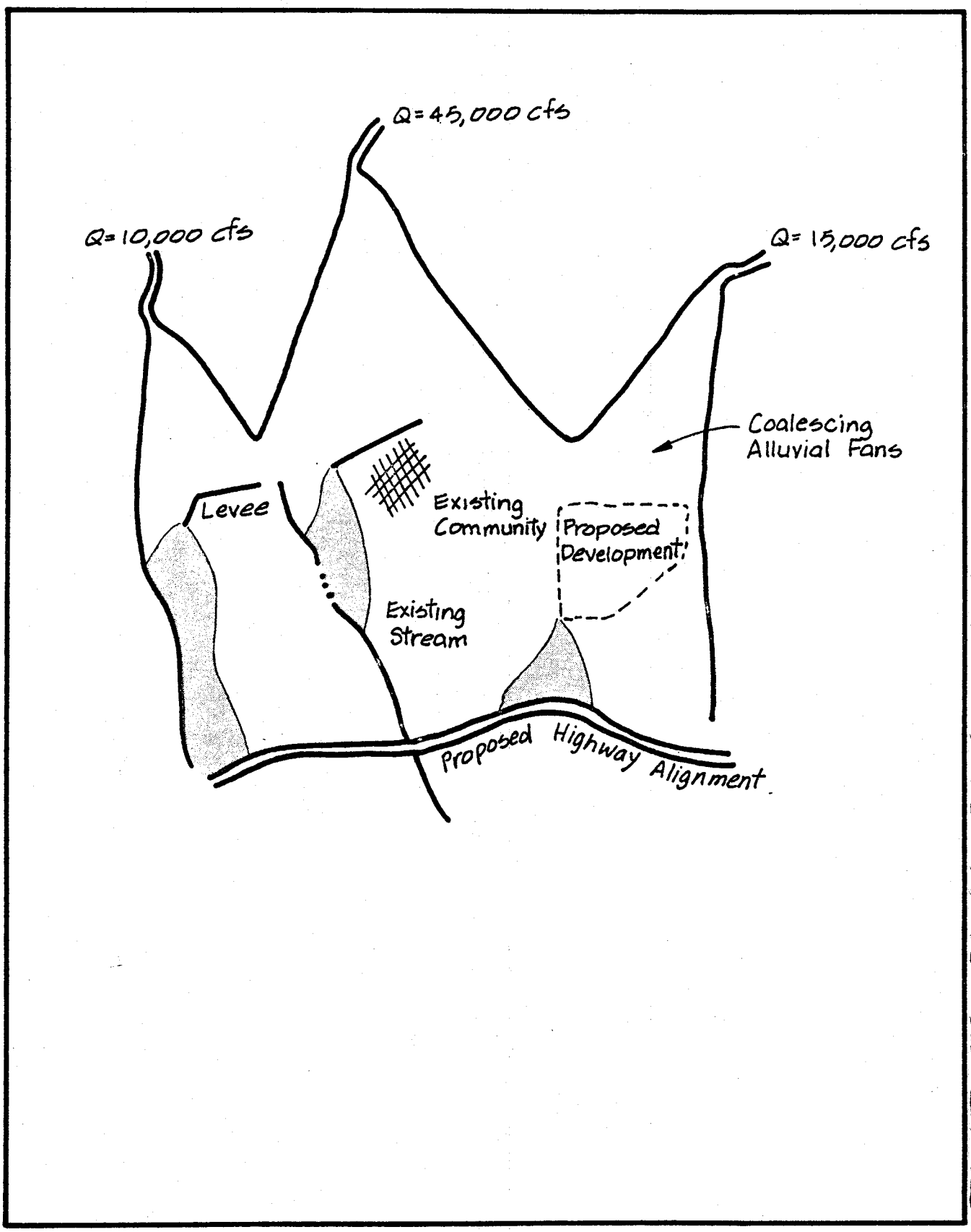


Figure 7 Actual flow paths downstream from obstructions.

and used as a design factor to be added to the results of the deterministic modeling methods.

Computational Techniques

As stated previously, the role of a numerical simulation model is to predict the average hydraulic parameters needed for the design of highway crossings. These parameters are the unit discharge, the depth and velocity of flow and the sedimentation characteristics. This section discusses such numerical models.

Many computational techniques and computer models were reviewed. Five of these are presented here (see Table 1). Most two dimensional flow models were developed for use with defined, bounded geometry. The Schamber model and RMA-2 have potential use for unbounded flow. They are also the only models reviewed that use the full equations of unsteady, two dimensional flow. Both of these models could be used to determine the flow characteristics as discussed in the "Design Parameters" section and as illustrated in Figure 7.

One of these two methods should be further developed for alluvial fan applications as discussed in the proposed work plan, Section VI. The further development should include the incorporation of appropriate boundary conditions and the possibility of supercritical flow depths.

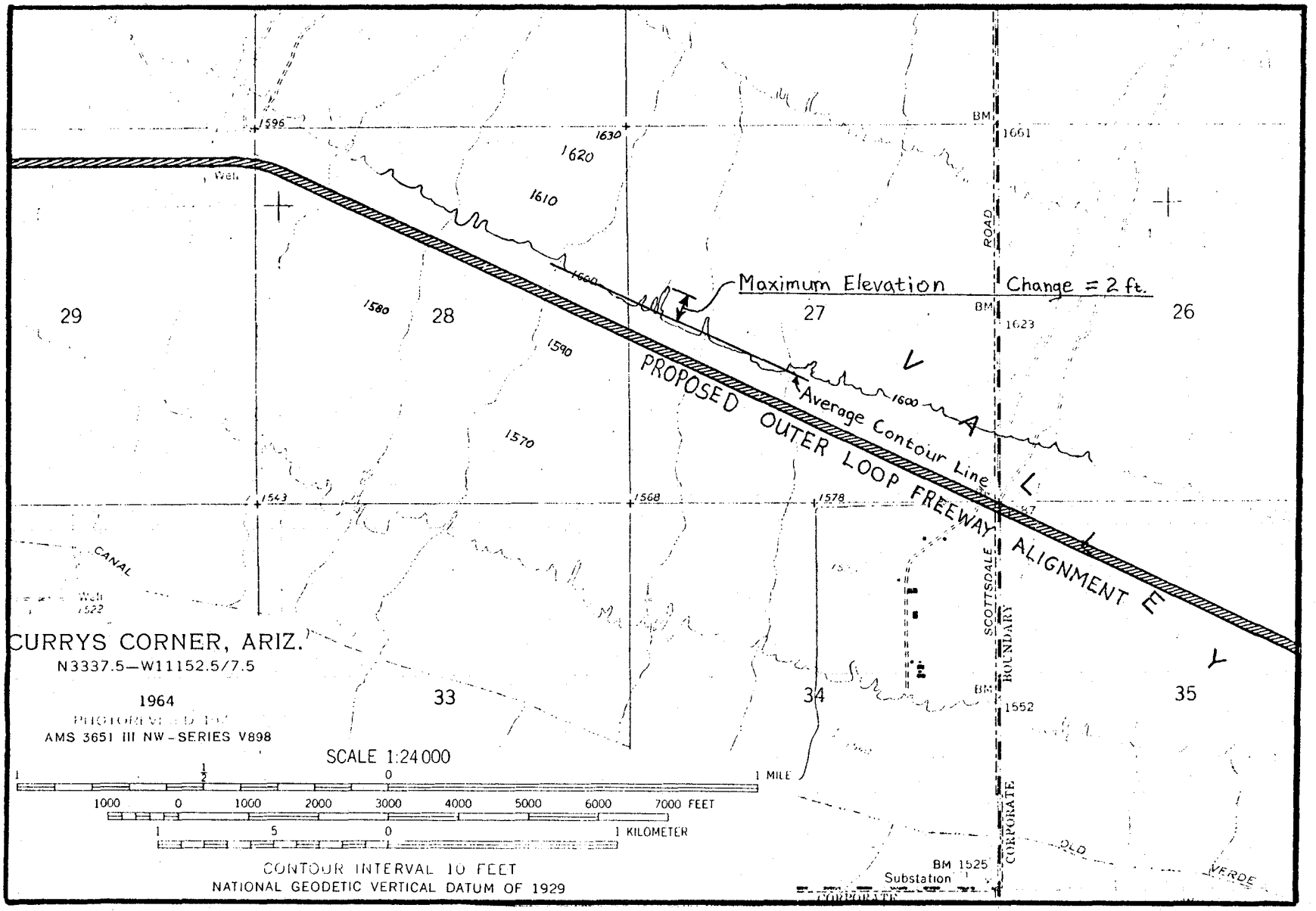


Figure 8 Example of Statistical Deviation from Uniform Deposition.

IV. CONCLUSIONS

1. Alluvial fan flooding and related debris and sediment flow is one of the largest potential hazards in the arid Southwest and one of the most difficult design problems for the Arizona Department of Transportation to deal with.
2. Alluvial fan flooding conditions vary throughout the state of Arizona. The broad alluvial fans near Phoenix are currently under different stages of development but careful land use planning can reduce concentrated runoff hazards. Because the hydrologic and hydraulic charactertistics of fans are so complex and vary greatly, no single methodology is available for designing highway drainage projects on alluvial fans.
3. A thorough reconnaissance and fan characterization study should always be conducted as the first phase of any highway drainage study. This should include an assesment of existing and proposed land use, drainage features, soil types and vegetation.
4. Uniform and consistent guidelines, master planning studies and design criteria must be developed for the large metropolitan regions of Arizona. Land clearing, grading and construction activities on alluvial fans must be strictly regulated to insure an integrated flood hazard reduction program.
5. The hydraulics of alluvial fan flooding are far more complex and erratic than that of riverine floods. Therefore, tradi-

TABLE 1 SURVEY OF COMPUTER MODELS FOR ANALYSIS OF FLOWS ON ALLUVIAL FANS.

NAME OF METHOD	REFERENCE	DESCRIPTION	PREVIOUS APPLICATIONS	MATHEMATICAL SOLUTION TECHNIQUES	APPLICABILITY FOR ALLUVIAL FAN MODELING
Dawdy Method	Dawdy, 1979 Edwards and Thielmann, 1983	This technique was developed specifically for conducting flood insurance studies on alluvial fans. Although it is a simple technique and can be applied uniformly, there is no direct way to account for topographic features or existing structural elements.	Various Flood Insurance studies and planning studies in southern California and Arizona.	Probabalistic approach with critical depth assumed and an empirical relationship between width and depth.	Very useful for general planning, regulation and flood insurance but does not yield detailed enough results for design purposes.
RMA-2 Model	Gee and MacArthur, 1982 MacArthur, et. al. 1985	This is one of the most widely used and tested two-dimensional flow models. It solves the full equations of unsteady flow in two dimensions using the finite element method. The elements can become wet and dry during the simulation whic is a necessary requirement for alluvial fan analysis. The graphics for this program is very strong which aids in the interpretation of results. There may be a problem as flow changes from subcritical to supercritical.	Hydraulic Simulations for San Francisco Bay, Columbia River, Sacramento River. No alluvial fan case studies were located.	The complete St. Venant equations are solved using the method of finite elements.	This model is a good candidate for alluvial fan modeling because of its general application capabilities and wetting and drying of elements feature.
Schamber Model	Schamber, 1985 Hamilton, Schamber & MacArthur, 1987	This model was recently developed for conducting a flood insurance study in an alluvial fan region near the Wasatch Front Mountains, Utah. The full equations of unsteady flow in two dimensions are solved using the method of finite elements. An interesting aspect of this model is that it uses an expanding computational grid. This is quite useful for alluvial fan analysis since an unbounded flow situation can be simulated. This model is currently being improved by its author and it is a good candidate for generalized application to alluvial fans.	Simulation of alluvial fan debris flows for a flood insurance study along the Wasatch Mountains, Utah. Flood analysis near Mt. Saint Helens, Washington.	The complete two dimensional flow equations are solved using the method of finite elements. An inflow hydrograph boundary condition and the alluvial fan topography are the main input requirements.	This model is a good candidate for alluvial fan modeling because of its ability to simulate an expanding flow situation on an unbounded plain.
Link-Node Model	Gurule, 1982 Orlob, 1978	The link-node model is a pseudo two dimensional approach for analyzing flow on a horizontal plane. This technique allows for spatial variation of the one dimensional equations of unsteady flow. This simplified approach has been used largely for estuary studies. This model may be difficult to use in an alluvial fan situation because the geometry does not have fixed, bounded topography in which to confine the flow.	San Francisco Bay circulation and water quality. Many estuary and tidal applications.	The one dimensional equations for unsteady flow are solved using an explicit finite difference method.	This model is not a good candidate for alluvial fan simulations because of the restrictions on specifying the topographic features.
Diffusion Analogy Hydrodynamic Model	Hromadka, 1985	This model, called DHM, uses a simplified version of equations (2) and (3) called the diffusion analogy. An explicit finite difference formulation is used thus computation time tends to be large and computer memory requirements tend to be small. The diffusion analogy may be a good approximation for steep alluvial fans because the flows upon them are governed more by the bed resistance rather than inertial effects. The model has a fixed computational grid which limits the accurate description of topographic features.	Plano Trabuco flood plain study, Orange County, CA. Retention basin analysis, Orange County, CA.	The diffusion analogy of the two dimensional flow equations are solved using an explicit finite difference method on a fixed coputational grid.	Although this model can simulate flow on a flood plain, the constraints on the specification of the topographic data may cause difficulty in general application.

V. RECOMMENDED FURTHER WORK

1. Numerical models capable of estimating the location and size of channels formed by unsteady, supercritical flows in erodible alluvial fans must be developed and tested.
2. Laboratory and field verification of these tools are essential (see MacArthur, et al, 1987).
3. In areas where there are insufficient stream gaging records, techniques which are superior to the regional method of peak flood flow analysis and the envelope curve method can be employed.
4. Uniform and regionally consistent design guidelines need to be established.
5. A case study such as the proposed Outer Loop Freeway should be used to test and compare the capabilities of several of the more promising computational methods. The same models should be applied to any case studies that may exist with actual measured flood event data and observed project performance information.
6. Regional emergency management procedures should also be developed to minimize downfan flooding problems that may result form upperfan flood repair work.
7. Existing computational techniques can be tailored to be used directly by highway drainage designers. This will involve some further research, simple laboratory experiments and computer model development. The benefits will be a significant advance in the state of the art and a more unified, compre-

tional gradually varied, steady state, fixed bed methods for analyzing hydraulic problems are often inadequate for alluvial fan flooding problems.

6. Regular project maintenance is essential to insure proper project function.

7. Quick field-engineered solutions to alluvial fan flooding and drainage problems often create more problems than they were intended to solve.

8. Although there is a computer model for two-dimensional flow that can be tailored to fit the needs of the Arizona Department of Transportation, none of the models will yield directly the desired highway drainage design parameters if used "off the shelf."

9. Generalized methodology for two-dimensional flow analysis combined with site specific hydrology and topographic features can play a major role in developing a uniform procedure for proper design of highway drainage on alluvial fans.

10. Flood protection on alluvial fans conflicts with a dominant geological process which wants to bury development with a layer of sediment. Successful drainage must be designed to transport the sediment as far down the fan as possible.

11. All drainage facilities should be designed to account for the presence of debris and should be part of a strict maintenance program.

12. The Schamber model and RMA-2 show the most promise for two-dimensional flow analysis for alluvial fans.

VI. PROPOSED WORK PLAN FOR ANALYSIS OF FLOWS ON ALLUVIAL FANS

Purpose

The purpose of this section is to outline a program to develop reliable methods for planning and designing highway crossings and drainage projects on alluvial fans. The program will be conducted in three phases and consist of research, model development , data collection, model calibration and verification, methods documentation, and field testing.

General Approach

A program to develop reliable methods for simulating flows on alluvial fans requires work and results from the following areas: (1) basic research into the physics of shallow flow on alluvial fans, (2) field monitoring and data collection, (3) numerical model development , (4) model testing and sensitivity analyses, (5) model calibration and verification, (6) physical modeling (This may be necessary to provide data for items 1 and 5), (7) field applications, (8) documentation and reporting, and (9) review, improvement, expansion and updating of model capabilities as more information and field data becomes available.

Many of the hydraulic characteristics of alluvial fans and the subsequent movement of sediment and debris during flow events are poorly understood. Therefore a combined program of basic research into the physics of shallow flows on alluvial fans and field monitoring of representative fan areas are essential components of any meaningful development program. Development of a mathematical model, or perhaps a

hensive approach to highway drainage on alluvial fans.

8. The sediment aggradation and degradation which occurs during an alluvial fan flood should be recorded and analyzed to obtain quantitative techniques for estimating sedimentation behavior.

improvement to the modeling methods will occur as new issues are identified by the ATRC and new methods for simulating them are identified by field needs and/or basic research.

Finally, several field applications will be made using the modeling methodology for problems found in Arizona. The intent of the field applications will be to test the capability of the model to duplicate actual flow conditions.

Model structure and design shall be as generalized as practical while realizing the applications will be primarily for flow problems on alluvial fans found in Arizona. The latest techniques in structured programming and software engineering will be applied during model development.

Proposed Methodology

An essential first phase of any model development will be to meet with staff from the ATRC to discuss specific components of alluvial fan flow problems that affect the proper design of highway projects. Specific capabilities and general design features of the proposed modeling methods for a first generation model must be identified and agreed upon. Future generation models can be improved to make the methods more generalized as our knowledge of the flow physics improves.

An integrated anaylses system is proposed. The approach would allow users to apply several alternative fluvial systems analysis tools representing a variety of study levels from a simple steady-flow back water computation such as HEC-2, to a one-dimensional unsteady flow

family of mathematical models, capable of simulating the hydraulics of alluvial fans can be initiated once the desired capabilities and model features have been defined and agreed upon with ATRC staff. Model developers must work closely with staff from ATRC to insure proper direction and emphasis of the model development program. Development should proceed in phases. A first generation set of models should be prepared and tested initially. Improvements and model expansion can follow as future phases once the first generation modeling package has been thoroughly tested. Development of an all-purpose universal model should not be attempted as part of the first phase. A computer model for the simulation of unbounded shallow flow such as described in the "Design Parameters" section would be more appropriate. Careful model testing and field application will identify capabilities that future generation models must have.

Results form the basic research and field monitoring tasks must be intigrated into the design of the model(s) and carefully tested. Following preliminary testing, numerical sensitivity analyses should be performed to quantify the numerical stability, accuracy and convergence of the model. Physical modeling tests may be necessary to both identify certain key hydraulic flow characteristics of alluvial fans, and to develop sufficient data to be able to verify the capabilities of the numerical model(s).

Each phase of development and testing shall be fully documented. Review comments and feedback from the ATRC will be incorporated on a regular basis into the approach. Continuous expansion, updating and

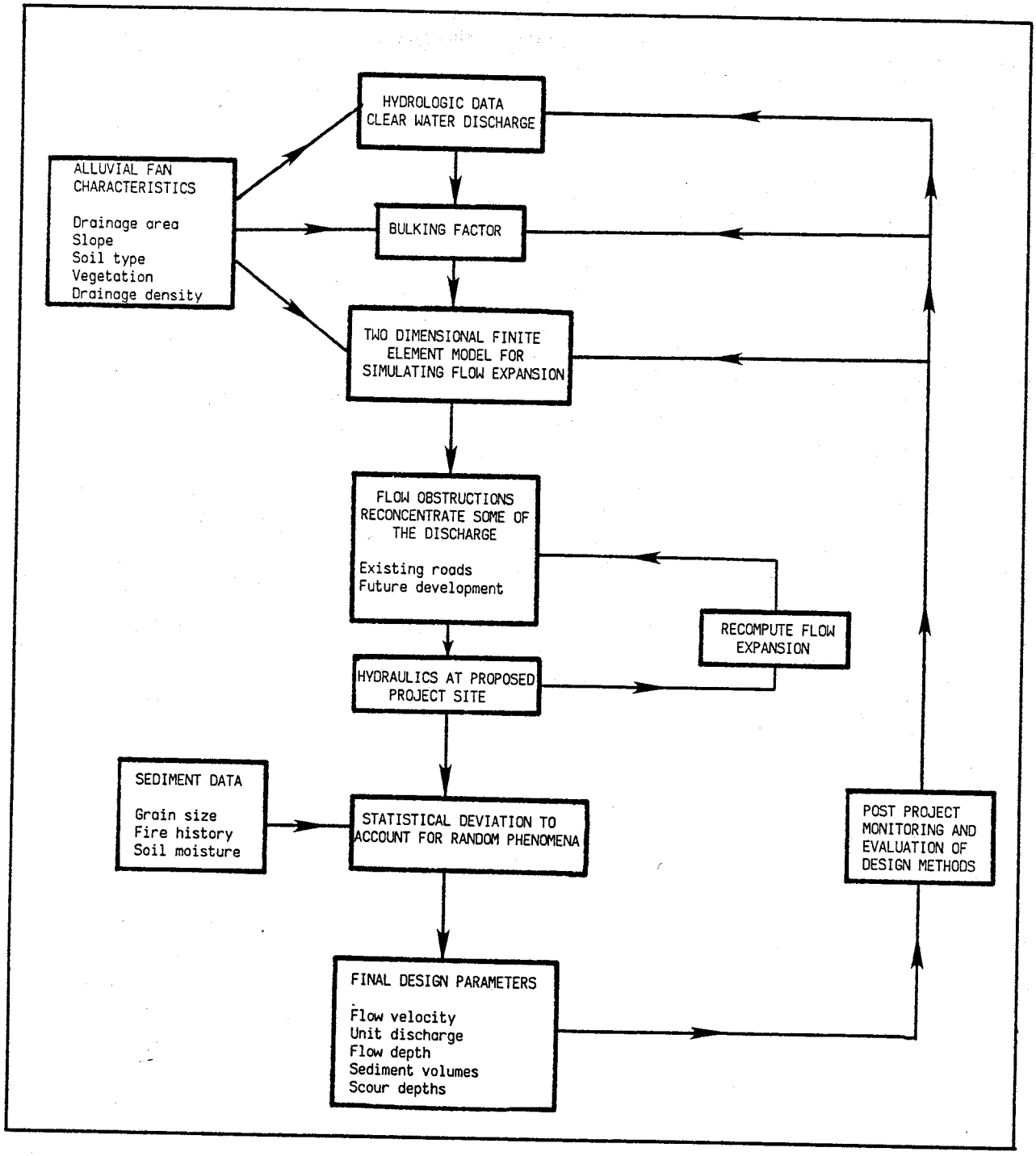


FIGURE 9 DIAGRAM FOR AN INTEGRATED SYSTEM OF ALLUVIAL FAN HYDRAULIC AND SEDIMENTATION ANALYSIS

routing, to a fully two-dimensional dynamic flow and sediment routing tool (mobil boundary modeling). Existing software, and traditional methods will be used wherever possible and wherever applicable. Development or improvement of new unsteady two-dimensional modeling tools is also requried.

The emergence of uniform and widely available operating systems such as MS-DOS and UNIX provides an opportunity for the creation of much improved user interfaces to a fluvial hydraulics system. The system would be developed by improving and integrating existing software wherever possible and developing "shells" to manage data and program operation. The ability to use various levels of analysis with input data shared by each program will provide users with the flexibility to perform several levels of analysis quickly and uniformly. Planning and/or design decisions can be made more readily with this type of approach.

Figure 9 presents a flow diagram of a possible integrated alluvial fan analysis system.

Generalized Analysis Procedures

Once an integrated package of programs has been developed the following procedures may be used to evaluate highway crossing designs on alluvial fans.

1. Site investigation and basin characterization

Conduct a thorough site investigation of the project area and examine the drainage basin and alluvial fan areas upstream and downstream

Interagency Committee, ATRC, and others to develop sediment loading bulking factors for the flood flows developed in step 2 above. The bulked flows will account for the increase in total water and sediment flow volume that results from entrainment of sediment during flood flows.

4. Determine the hydraulic characteristics of the project site by several methods

Determine the hydraulic characteristics of the project site using traditional steady state fixed bed backwater methods, such as HEC-2 if applicable. Examine the computed velocity, flow depth and other hydraulic characteristics with respect to anticipated design features. Prepare and execute advanced two-dimensional hydrodynamic simulation models such as RMA-2 or the modified Schamber model for unbounded flow situations. Use the Schamber model to determine the flow spreading angle (A_f, Figure 2) for the fan for the various design floods. Route the flood using advanced methods (RMA-2 or Schamber Model) down to the project site. Determine the flow per unit length along the proposed highway and the velocity and depth of flow expected as a result of the dynamic routing.

5. Determine the representative alluvial fan sediment scour and deposit depths from statistical methods

Determine the representative alluvial fan sediment scour and deposition depths from measured contour profiles along the fan at several locations. Perform statistical evaluations of the depths of rills and gullies as well as berms and deposits for different drainage zones on the fan. Compute scour or deposit depths using traditional scour

from the project site. Examine past aerial photographs and topographic maps of the area. Identify the dominant soil types, erodibility, and amount of vegetative cover for the drainage area upstream from the site. Determine grain size distribution of bed and bank materials in the immediate vicinity of the proposed highway crossing. Determine whether the alluvial fan area draining into the project area is predominately in a channelized zone, braided zone or sheet flow zone as shown in Figure 1. Examine past historical data and information regarding storm intensities and flow characteristics of the area. Examine previous highway and channel maintenance and/or damage reports if available. Develop a thorough characterization of the drainage basin and estimate the sediment transporting ability, debris loading or scour and deposition potential for the project site.

2. Develop representative hydrology

Collect the necessary hydrologic data and combine it with the basin characterization data from task one above. Use these data and accepted hydrologic procedures to develop the expected flood hydrology for the project site. Develop design flood hydrographs, peak discharges, flow duration, and flood volume for design floods for the project area. Estimate future changes in hydrology that may occur as a result of upstream urbanization. Develop future hydrology for these conditions as well.

3. Estimate sediment load bulking factors

Use methods prescribed by the Los Angeles County Flood Control District, The U.S. Army Corps of Engineers, The Pacific Southwest

8. Monitor the project and re-evaluate and modify design procedures as necessary

Evaluate project performance with respect to the original design procedures. If project performance varies greatly from the design calculation, attempt to determine where and why the modeling methods failed and develop revised procedures that are more reliable. As second and third generation models are developed the accuracy and reliability of the design methods will improve. By the end of the 4 to 5 year study period, the models and design methods should be well refined and reasonably generalized.

calculation methods and the hydraulic characteristics determined from step 4. Adjust these depths of scour, deposit, flow velocity etc. by adding the statistical deviation values that were just determined (see section on this topic). That is, determine depths of scour as the scour of the computed depth plus some deviation away from the mean depth determined from the statistical evaluation. An example equation for scour depth is :

$$d_{scour} = d_{calculated} + d_{statical\ deviation}$$

This approach can be used to adjust flow depths flow velocities and alter hydraulic characteristics of the flow.

6. <u>Perform highway crossing design calculations</u>

Using the information and results from the previous steps 1 through 5, determine the best orientation, sizing and design of the proposed highway crossing. The hydraulic characteristics (flow depth and velocity) now reflect the characteristics of flows found on alluvial fans.

7. <u>Evaluate potential maintenance requirements</u>

Perform additional analyses to estimate the amount of sediment accumulation and/or debris accumulation that may occur in the project area. Perform this analysis for several different upstream drainage basin modifications that may occur as a result of urbanization activities. Modify the design based on the effects of anticipated drainage basin changes.

8. Monitor the project and re-evaluate and modify design procedures as necessary

Evaluate project performance with respect to the original design procedures. If project performance varies greatly from the design calculation, attempt to determine where and why the modeling methods failed and develop revised procedures that are more reliable. As second and third generation models are developed the accuracy and reliability of the design methods will improve. By the end of the 4 to 5 year study period, the models and design methods should be well refined and reasonably generalized.

VII. TENTATIVE TIME SCHEDULE

A four to five years program is necessary in order to properly address the analysis and highway design problems associated with alluvial fans in Arizona. The following tme schedule is proposed but will need further refinement following detailed discussions with staff from ATRC. Many of the proposed activities will be occurring simultaneously in order to complete the project in 4 to 5 years, and, of course, practical analysis methods will be available for use before the end of the study period.

Phase I Problem Identification

	Calendar Months
1. Evaluate characteristics, capabilities and applicability of several of the more promising state-of-the-art methods for planning and designing highway crosing on alluvial fans (present study).	6 months
2. Meet with staff from ATRC, develop a list of specific capabilities and features which the methods should have. Select example drainage basin and alluvial fan areas to monitor.	1 month
3. Identify specific areas where data must be collected. Identify specific basic research tasks that are necessary in order to complete the project.	1 month
4. Prepare a detailed scope of work, time schedule and estimate of costs.	1 month

Phase II Model Design Basic Research and Field Monitoring

	Calendar Months
1. Design and conduct field monitoring of the flow and sediment transport characteristics on the test fan sites. Continuously monitor these sites for four years, prepare summary report of results.	48 months
2. Initiate basic research studies outlined in item I-3 above. Prepare summary reports throughout study.	36 months

3. Design the structure, capabilities and linkages for the various models and computational methods to be intergrated into the analysis package. Construct paper models of the I/O and data flow. Decide on the character and types of solutions (output) users may require identify specific software engineering tasks for model development. 4 months

4. Begin model development and testing. 12 months

5. Perform detailed sensitivity study of the modeling modeling package. Develop and document a test data set and preliminary users manual. 4 months

Phase III Detailed Model Testing Calibration and Verification

Calendar Months

1. Perform additional model testing, and documentation.

2. Perform detailed calibration and verification of the model using data collected during the field studies.

3. Use laboratory physical modeling as an additional method for developing verificational data.

4. Make computer model modificaions and thoroughly document how to use the package.

5. Apply the modeling package to actual field design problems work closely with ATRC to make model improvements and adjustments if necessary.

6. Conduct a one-week training course and workshop for staff from ATRC on how to use the design analysis package.

12 to 24 months

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16. ABSTRACT

A preliminary approach to the analysis of flows on alluvial fans is presented. The specific objective is the design of highway crossings constructed on alluvial fans in Arizona. Hydrologic, hydraulic and sedimentation effects are presented. The effect of development on alluvial fans is addressed and a work plan for future research is presented.

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PREFACE

This report was prepared for the Arizona Transportation Research Center and the Arizona Department of Transportation in order to conduct a state-of-the-art study of the characteristics, capabilities and applicability of several of the more promising methods for planning and designing drainage for highway crossings on alluvial fans. The report was prepared and written by Douglas L. Hamilton and Robert C. MacArthur of Simons, Li & Associates, Inc. in Newport Beach, California. Dr. Ruh-Ming Li was the Principal-in-Charge. Results, discussions and recommendations presented in this report are not intended to be applied directly for design purposes. Further development and testing of the methods presented is necessary before they can be considered for uniform application.

Simons, Li & Associates, Inc. is grateful to the Arizona Transportation Research Center for sponsoring this study and to Mr. V. Ottozawa-Chatupron of the Center for his skill and guidance throughout this project.

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I. INTRODUCTION

Problem Statement and Need for The Study

Most hydraulic studies pertaining to the planning and design of highway drainage systems and highway crossings have been developed in riverine and coastal regions where the characteristics of flooding are well defined. However, there is one type of flooding that is increasingly becoming a problem for highway designers in the western United States as the population and development in the West increases. This type of flooding problem occurs in areas known as alluvial fans. These areas are found in desert and semi-arid regions where runoff from sudden thunderstorms flows down steep mountain drainages and empties onto a broad valley floor (see Figure 1).

Concern for flooding and drainage problems on alluvial fans is increasing as more and more development occurs. Alluvial fans attract development because of their mild slopes, close proximity to the foothills and potential for spectacular views of the valley floor. Descriptions and definitions of alluvial fans are found in the reports by Bull (1977) and Anderson-Nichols (1981).

Flood flows on alluvial fans can be very dangerous because of their unpredictability, high velocities, and ability to carry large amounts of sediment and debris. The seriousness of flooding on alluvial fans is related to the quickness and ferocity of the event as well as the unpredictability of the flow direction due to avulsions or drastic channel shifts that result from the accumulation of debris in defined channels.

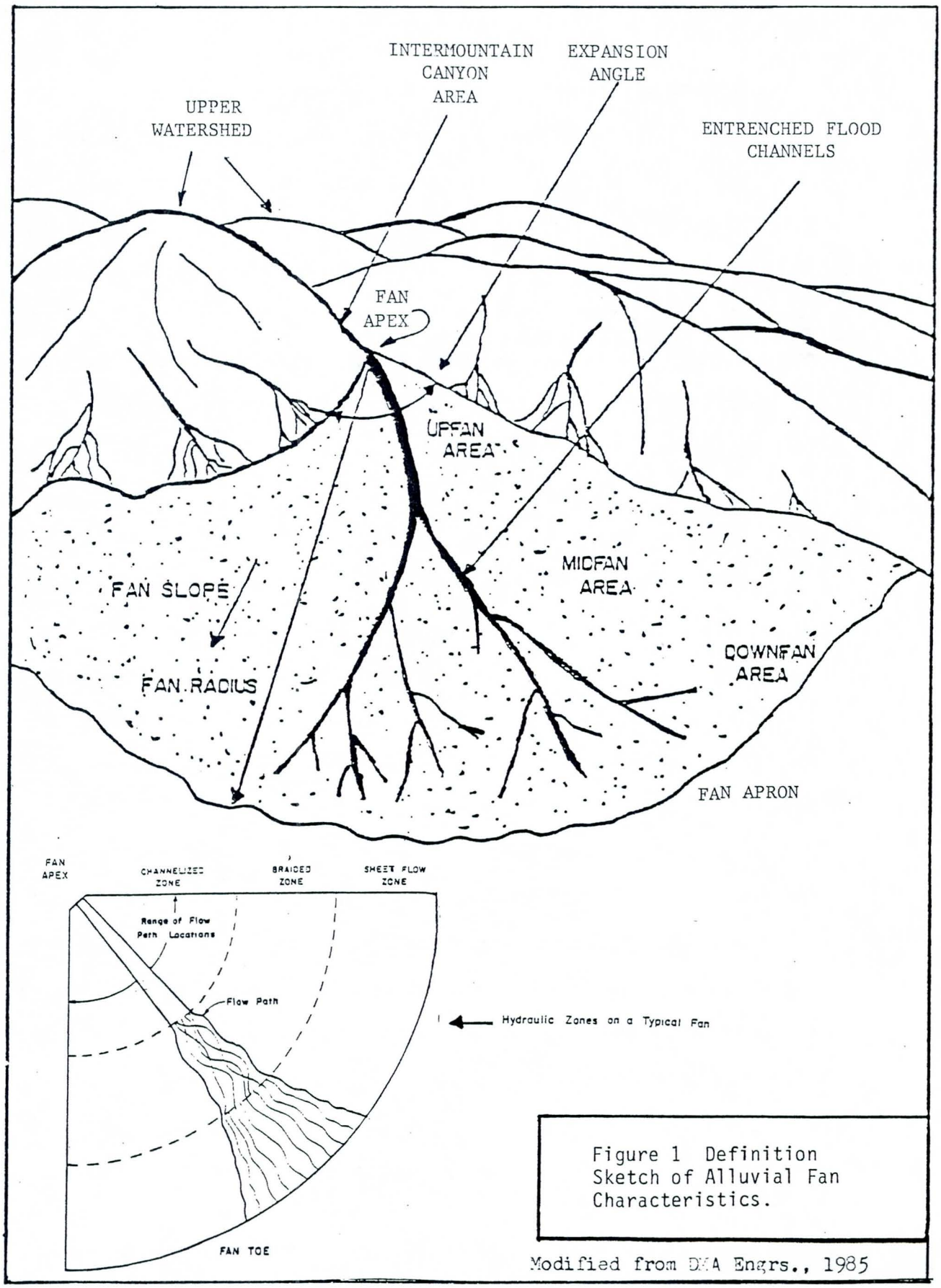


Figure 1 Definition Sketch of Alluvial Fan Characteristics.

Modified from DMA Engrs., 1985

Although alluvial fans are common geomorphic features around the world, especially in arid and desert regions, the hydraulic processes which form them and continue to modify them are poorly understood from the viewpoint of traditional hydraulics and highway engineering. Therefore, the purpose of this study is to conduct a state-of-the-art study of the capabilities and applicability of several different methods for planning and designing highway crossings on alluvial fans in order to determine an appropriate direction for future research on this topic.

Characteristics of Alluvial Fans

It is essential to first discuss the many unique characteristics of alluvial fans that make analysis of flood problems so difficult. Approximately one third of the land area in the southwestern United States is covered by alluvial fans. Alluvial fans are usually associated with desert and semi-arid regions of the world; however, they do exist (Bull, 1977) in tropical areas as well.

Alluvial fans are generally aggradational in nature (Bull, 1977). French (1984) describes the formation of alluvial fans as follows: "Debris accumulates along the flanks of mountains due to weathering; and when an intense precipitation event occurs, the accumulated debris is transported downslope in an intermountain canyon. At the point where the canyon enters the valley - the apex of the fan - the widening of the flow results in a decrease of its debris carrying capacity, and the debris is deposited at the apex and downslope from it." Over time,

many such events cause deposits to accumulate, resulting in the characteristic fan or cone shape.

Dozens of articles and references are available describing the geologic aspects of alluvial fans. Interested readers should refer particularly to Anstey (1965) and Bull (1977). Quantitative methods for hydraulic analysis of these regions, however, are not commonly found in the literature.

To design highway drainage systems on alluvial fans, one must know (1) where the highway will be located on the fan, (2) the location of the major and minor flow channels it crosses and (3) the detailed characteristics about the drainage basin upstream from the highway. Because the characteristics of flows vary so greatly depending upon location on the alluvial fan, design methods and analytical techniques will also vary. In the paper entitled "Generalized Methodology for Simulating Mudflows", MacArthur, et al (1986) divide a drainage basin into three regions. The three regions of concern for highway analysis are similar and include: (a) The upper watershed, (b) the intermountian canyon areas and any stable channels that cross the fan, and (c) the broad alluvial fan itself. Figure 1 presents a sketch of a generalized watershed and alluvial fan drainage system. Three hydraulic zones can be identified on the fan itself: (1) A channelized zone, near the apex, where a single definable channel exists, (2) a braided zone, which is a transition area where the channel becomes unstable and multiple sinuous paths occur, and (3) a sheet flow zone, where flow spreads laterally in the streamwise and transverse directions and is very shallow.

Morphology, hydrology and hydraulic characteristics vary greatly between different fans. Therefore, the extent, severity and behavior of floods on different fans depend heavily on individual fan characteristics. This makes the development of uniform design criteria and analysis methods difficult.

Anderson-Nichols (1981) list many of the following key watershed and fan characteristics which influence fan flooding behavior:

- effective drainage area of the watershed
- watershed slope and aspect
- watershed soil type and vegetation
- frequency of forest fires
- development density within the watershed
- rainfall intensity and duration
- fan slope and topographic shape
- existence of one or several entrenched channels
- degree of entrenchment of main channels, their orientation and stability
- apex discharge conditions (hydraulic conditions)
- sediment characteristics

Urbanization and development pressure on alluvial fans are high. Therefore, the characteristics of the fan today are unlikely to remain the same in the future. Highways built through undeveloped lands usually create accelerated development adjacent to them. The ability to accurately estimate the rate of urbanization and changes that may result with urbanization is essential for proper highway drainage design.

A first step to any highway drainage study should include the identification of the key characteristics of the fan that the highway is to cross. Some of the essential steps to consider include:

- perform thorough aerial and field surveys of the fan and upper watershed areas
- develop detailed topographic mapping of the study area including high resolution aerial photographs
- attempt to locate historical aerial photos, soils data, geological data and flood histories of the fan
- locate the proposed highway on the topographic maps and aerial photographs
- study the proposed alignment for any obvious problems or possible improved alternatives
- classify the fan according to the key characterics observed during this preliminary study
- identify possible drainage alternatives and locate potential highway culverts and crossings based upon preliminary results
- list all additional data needs and possible problems identified during the preliminary study.

Results from the preliminary study will provide essential information for the preliminary design phase of the project (assuming the project is determined previously to be feasible). Discussions in the following sections of this report will explain the kinds of analyses that are required for the different regions and will evaluate several different kinds of analytical tools presently available for analyzing alluvial fan flooding and drainage problems.

II. DESIGN PROBLEMS FOR HIGHWAY DRAINAGE ON ALLUVIAL FANS

What do highway planners and designers need to know about the characteristics of flood events on alluvial fans? They need to know how to best size and orient culverts and highway crossings to safely handle flows from design events with minimum maintenance or damage. To do this they need to know what the peak discharge and duration for the design event will be, what the flow velocity will be, what the depth of flow will be, and how much sediment movement (scour or deposition) can be expected during the event.

Hydrologic and Hydraulic Problems - Most highway drainage and hydraulic design guidelines are based on traditional hydrologic and hydraulic computational methods. They assume that sufficient data are available to develop the regional hydrology and peak discharges for various design flood events. Often this is not the case because of an insufficient period of record requiring that flood flows be estimated by a variety of rough methods. When results from these rough methods are compared, they often yield a wide range of different peak discharges, hydrograph shapes and flood volumes. Peak flow rates should be estimated by either regional regression models (Chow, 1964) or envelope curve methods as recommended by Crippen (1982). French and Lombardo (1984) have pointed out the limitations that these two methods have in arid areas. Therefore, accepted standardized methods for developing the design hydrology for highway drainages and highway crossings are needed as a first step in the analysis.

Given a design storm, runoff volume and peak discharge estimates are often obtained by using rainfall-runoff models such as HEC-1 and Tr-20. These models cannot capture the two-dimensional behavior of flows on an unbounded plane; however, they can yield useful results if used with care.

Given the design hydrology, most highway crossings are sized and oriented based on fixed-bed, steady state hydraulic computations such as found in the computer program HEC-2. Unfortunately, flood flows common to alluvial fans are often unsteady, supercritical flows capable of moving large amounts of sediment. The bed and banks of the ephemeral channels found on most alluvial fans are usually unstable and channel avulsions are common. Channel patterns and inundation areas often change with each flood. Sediment scour and deposition occur rapidly during floods and quickly alter channel geometries. This is not to say that traditional hydraulic design methods should not be used at all. Many locations and hydraulic design questions can be roughly solved with HEC-2 type tools. Sediment transport, general scour and local pier scour can then be estimated using methods described by Simons, Li & Associates (1982 and 1986) and others.

No uniform methods exist for analyzing flow problems on alluvial fans because hydraulic and sediment transport characteristics vary greatly over the surface of the fan from its apex to the fan apron (see Figure 1). One-dimensional unsteady flow methods are valid in the confined intermountain channel section upstream from the fan apex. Beyond the point where the flow emerges onto the unbounded fan and spreads out

in the streamwise and transverse directions, the flow often becomes two-dimensional and often quite shallow. Flows confined within stable channels can still be evaluated with one-dimensional tools (unsteady, or perhaps steady state under some conditions). Sheet flows distributed over the fan surface or broadcast laterally by avulsions from shallow unstable rills are extremely complex in nature. No presently available analytical tools can analyze these kinds of flows directly. Kinematic wave approximation, and some two-dimensional models show promise. Discussions in a later section compare several state-of-the-art models that show promise for these kinds of flows.

Time Scales - Three different time scales are important when analyzing fan flooding dynamics:

(1) geologic time (10^6 years), during which numerous events and flow paths wander over the fan and the fan grows and aggrades,

(2) project time (50 to 100 years), during which several flood events of various magnitudes may occur causing channel shifts and sediment movement, also during which highway modification projects may occur and regional urbanization occurs on the fan,

(3) flood event time (hours to days), during which high intensity, short duration flows race through the project causing topographic adjustment and channel shifts to occur. Local project damages may occur requiring maintenance and repair.

Obviously the last two time scales (project and flood event time) are most important to planners and design engineers. They need to determine whether existing entrenched channels will remain stable or are likely to shift location. They need to anticipate the future effects of urbanization (planned or unplanned) on the project, and also anticipate future highway modifications that may be necessary.

Other Problems - Other problems facing highway design engineers are institutional and political problems. The problems result from the fact that basic design criteria (such as the design hydrology, recurrence interval, peak discharge, permissible velocity, freeboard height, etc.) may vary greatly between the various regulating agencies having jurisdiction over the lands on the alluvial fan. Local city and county regulations and design ordinances are often much different from The Federal Highway Administration, the railroads, The Corps of Engineers, The Soil Conservation Service and The Federal Emergency Management Agency. Therefore, if different agencies are designing flood control and drainage systems upstream from the highway and are not using the same basis for design as the highway department, it will be difficult to have an effective integrated flood drainage system. More legislation and interagency cooperation is needed to establish agreed upon design criteria for alluvial fan flooding. Once the design criteria and levels of protection are established, then more definite design methods for meeting the level of protection can be established.

Tettemer (1986) suggests master planning for flood control and drainage ordinances for developers as means for ensuring an integrated flood hazard reduction program.

Highway projects, such as the proposed Outer Loop Freeway project in Phoenix, may be planned for areas where urbanization and development upstream from the proposed highway have very low density. Culverts and crossings located to handle the design event defined by the Highway Department can be built now. Later as more roads are constructed and development occurs, the topographic features of the fan and, therefore, the flood characteristics change drastically. This effect coupled with the nonuniformity in design criteria between the various agencies leads to difficult flood hazard management problems. This situation presently exists throughout much of Phoenix and will cost millions of dollars to improve.

Therefore, in undeveloped areas where highways are planned, it is recommended that at least a basic master plan for flood control and drainage be part of the initial highway siting and feasibility studies. As the project evolves and goes into the design phases, additional detail can be added to the master plan. Funding for this additional work can be shared between the city, counties and developers.

Finally, cities and counties should be encouraged to modify their drainage and/or land grading ordinances to eliminate uncontrolled clearing, grubbing and trenching of alluvial fans. Often land owners will construct a soil berm around undeveloped property to discourage automobile trespassing. This deflects all of the water that formerly moved over the property as shallow sheet flow and concentrates it in other directions. Obviously these kinds of practices may result in significant changes in the flow characteristics downslope. No

sophisticated computer program or detailed design investigation for a highway drainage system accounts for future impacts of these random modifications to the prevailing drainage system. As streets and other improvements are built they should be designed to maintain the existing flow pattern and flow rates. Streets and fills should not divert flow from one drainage area to another. Distributing the flow among as many streets and shallow floodways as possible prevents it from collecting and becoming a flood.

Drainage modifications that concentrate flows that used to spread as sheet flow may cause the character of the local hydraulic zone to shift from being a sheet flow zone previously to either a braided zone or even channelized zone (refer to Figure 1). Once the shift occurs it may take a long distance and many years for the downstream drainage area to readjust to the new increase in flow energy. Increased sediment transport and shifts in the direction and magnitude of the peak discharge may also occur downstream from the point of concentration.

Tettemer (1986) suggests that inadequately designed and improperly placed ditches, walls or berms can develop false security and more problems than they were intended to solve. Also, all drainage and flood control projects adjacent to the highway and upslope on the fan must be maintained regularly to assure their proper function. And, finally the highway department and local city and county governments should regularly monitor all activity on the fans. Flows on the alluvial fan are very sensitive to even minor changes in land form or grading.

The next section will identify and evaluate several of the more promising methods presently available for depicting flow conditions on alluvial fans.

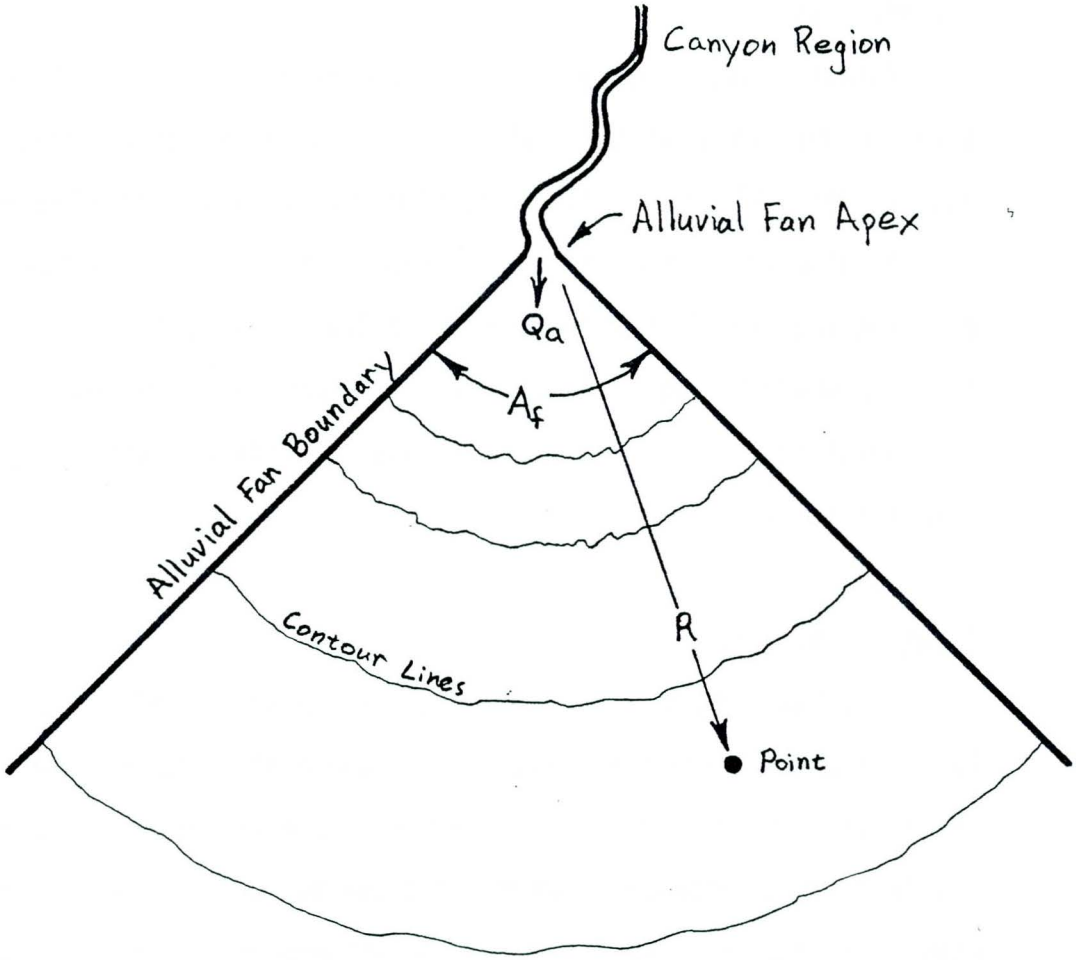
III. HYDRAULIC ANALYSIS FOR ALLUVIAL FANS

Introduction

Although there has been a great deal of highly significant work done in the field of alluvial fan hydraulics and hydrology, pratical applications of scientific principles for solving alluvial fan flood control problems are rare. This chapter will attempt to (1) generally describe the behavior of flooding on alluvial fans, (2) define the specific parameters required to design highway crossings and (3) discuss some existing and proposed computational methods for analyzing flows on alluvial fans.

General Description

Alluvial fans vary in size from a few square miles such as near Bullhead City, Arizona to hundreds of square miles such as near Phoenix and Tucson. As the fan area increases, flood waters come not only from rainfall in the mountain watershed above but also from rainfall which occurs on the fan itself. Thus the 100 year discharge at the apex of the fan is not always the appropriate quantity to use for flood analysis. Figure 2 shows an idealized situation of flooding on an alluvial fan. This is a symmetrical fan with no flow obstructions. Fehlman (1987) indicates that unbounded flow on an inclined, flat plane expands initially with an apex angle of 90°. Thus if the fan angle A_f is less than 90°, the flow will be spread uniformly across the entire fan. If the fan angle is greater than 90°, the flow will be spread uniformly across 90° of the fan. This is obviously an oversimplification but it



Q_a = Point Discharge at Fan Apex (cfs)
A_f = Fan Angle (degrees)
R = Distance from Apex (feet)

Unit Discharge at any distance from Apex (cfs/ft)

$$q = 2\,Q_a/\pi R \quad \text{if} \quad A_f \geq 90^\circ$$
$$q = 2\,Q_a\,90/A_f\,\pi R \quad \text{if} \quad A_f < 90^\circ$$

Figure 2 Idealized alluvial fan.

will serve for purposes of illustration. As the flow spreads out, it is convenient to express its magnitude using the discharge per unit width q. A peak discharge of 1,000 cfs spread out across a 100 foot wide fan contour would yield a unit discharge of 10 cfs/foot. The unit discharge at any distance R from the apex of the idealized alluvial fan is

$$q = 2Q_a/\pi R \quad \text{if } A_f \geq 90°$$

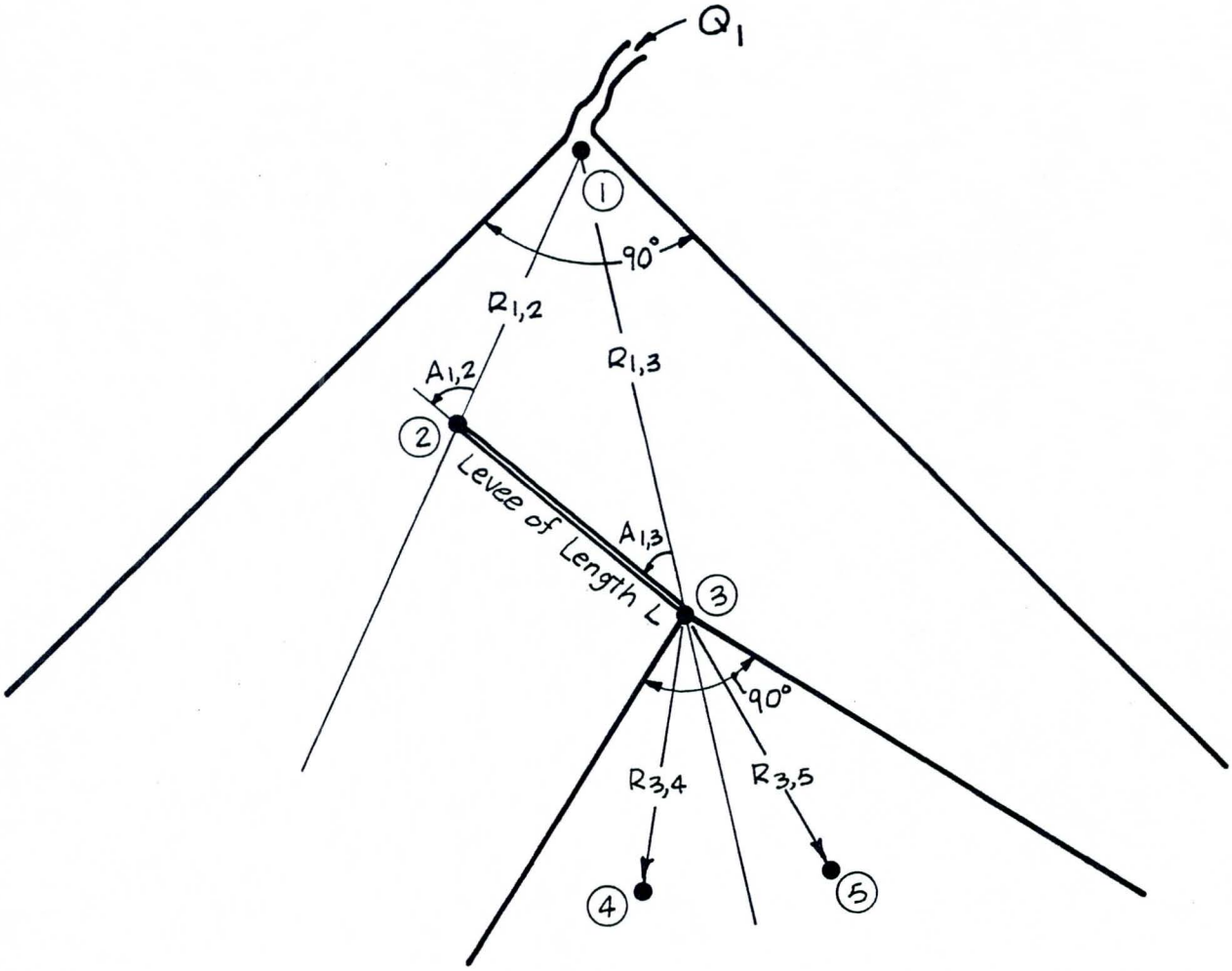
$$q = 2Q_a\ 90/A_f\pi R \quad \text{if } A_f < 90°$$

Where Q_a is the point discharge at the apex of the fan. This assumes an ideal fan with no obstructions and uniformly distributed flow with a maximum expansion angle of 90°. Again the flow expansion angle will be less than this in reality. The purpose of a two-dimensional flow model for alluvial fans is, in fact, to determine the actual flow expansion angle.

This simple model can be used to illustrate four situations which may be encountered in alluvial fan analysis. The treatment that follows does not include the dynamic behavior of the flow; methods which will account for this are described later. These examples provide a framework upon which future research results can be placed. Ultimately a two-dimensional flow analysis technique will be used to determine the flow expansion characteristics for each concentration point. The results can then be superimposed for a coalescing fan situation.

CASE 1: Flow Obstructed by a Levee.

Figure 3 shows a flood control levee of length L which is oriented at an angle to the flow path. The first step is to estimate the concentrated discharge at point 3. This is done by multiplying the average unit discharge by the length of the levee. Note that the sine of the angle between the flow direction and the levee must be used to compute the actual unit discharge that impinges on the levee. The unit discharge at point 4 is based on the uniform expansion of the concentrated discharge from point 3. The unit discharge at point 5 includes the contribution from the fan apex (point 1) and from the end of the levee (point 3). From this example it can be seen that development on an alluvial fan can redirect the natural flow path. Note that an upper case Q is the discharge at a point expressed in cfs and a lower case q is the unit discharge in the direction of flow expressed in cfs/ft.



Find Unit Discharge at Points 4 and 5

$$\left.\begin{aligned} q_2 &= 2Q_1 \sin A_{1,2}/\pi R_{1,2} \\ q_3 &= 2Q_1 \sin A_{1,3}/\pi R_{1,3} \end{aligned}\right\} \quad Q_3 = \frac{1}{2}(q_2+q_3)L = \frac{Q_1 L}{\pi}\left(\frac{\sin A_{1,2}}{R_{1,2}} + \frac{\sin A_{1,3}}{R_{1,3}}\right)$$

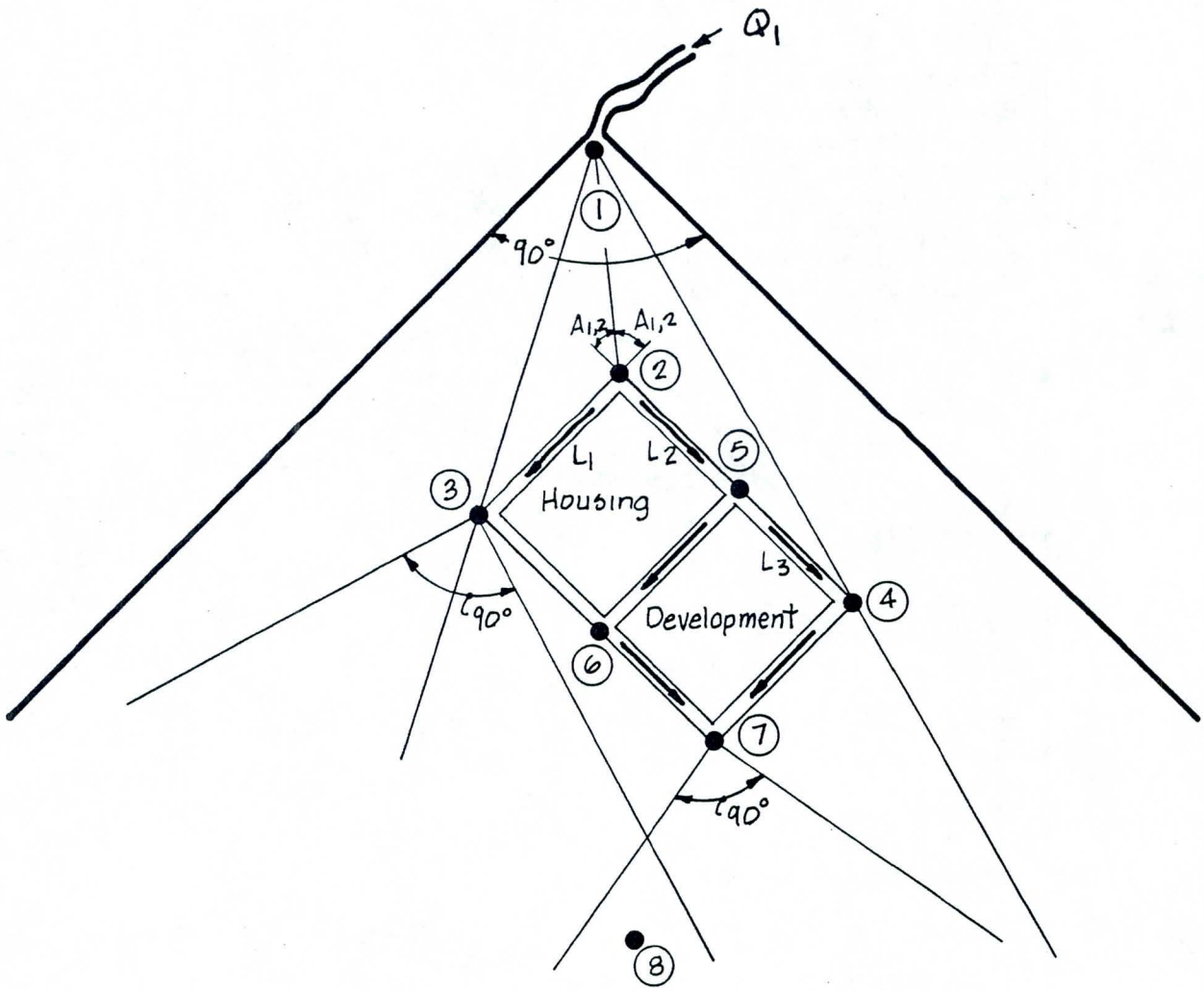
$$q_4 = 2Q_3 \sin A_{3,4}/\pi R_{3,4}$$

$$q_5 = q_4 + 2Q_1 \sin A_{1,5}/\pi R_{1,5}$$

Figure 3 Flow obstructed by a levee.

CASE 2: Flow Obstructed by a Housing Development

Figure 4 shows a housing development which intercepts the flow and redirects it around the community. It is then released at point 3 and point 7. The unit discharge at point 8 is computed using the concept presented in case 1.



Find Unit Discharge at Point 8

$$Q_3 = \frac{Q_1 L_1}{\pi}\left(\frac{\sin A_{1,2}}{R_{1,2}} + \frac{\sin A_{1,3}}{R_{1,3}}\right)$$

$$Q_7 = \frac{Q_1 L_1}{\pi}\left(\frac{\sin A'_{1,2}}{R_{1,2}} + \frac{\sin A_{1,5}}{R_{1,5}}\right) + \frac{Q_1 L_1}{\pi}\left(\frac{\sin A_{1,5}}{R_{1,5}} + \frac{\sin A_{1,4}}{R_{1,4}}\right)$$

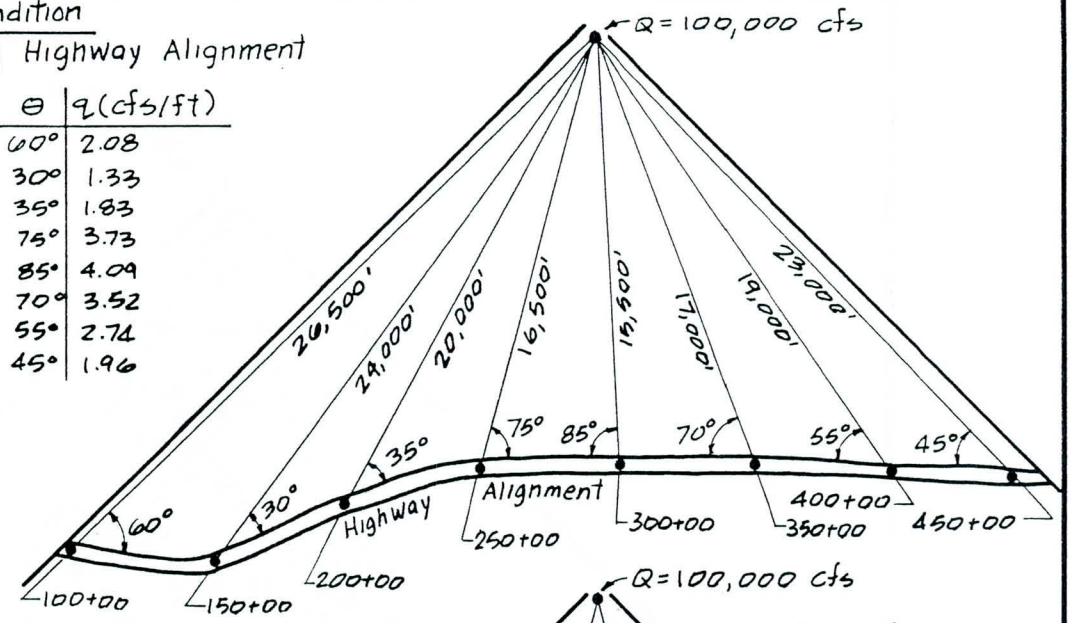
$$q_8 = \frac{2 Q_3 \sin A_{3,8}}{\pi R_{3,8}} + \frac{2 Q_7 \sin A_{7,8}}{\pi R_{7,8}}$$

Figure 4 Flow obstructed by a housing development.

Existing Condition

Find q Along Highway Alignment

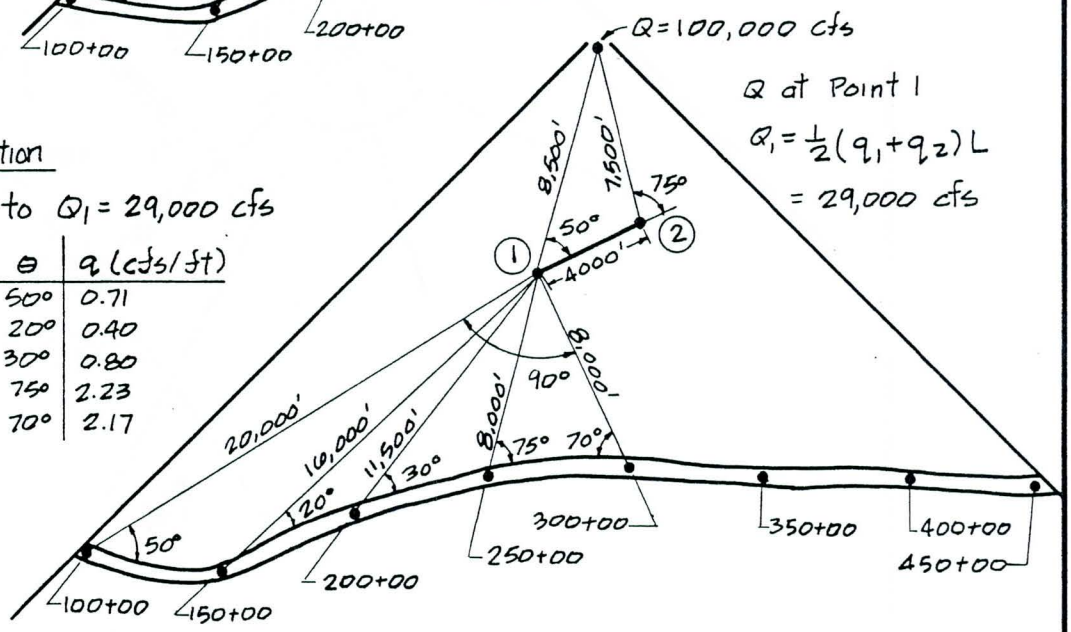
STA	R	θ	q (cfs/ft)
100+00	26,500	60°	2.08
150+00	24,000	30°	1.33
200+00	20,000	35°	1.83
250+00	16,500	75°	3.73
300+00	15,500	85°	4.09
350+00	17,000	70°	3.52
400+00	19,000	55°	2.74
450+00	23,000	45°	1.96



Future Condition

Find q_1 Due to $Q_1 = 29,000$ cfs

STA	R	θ	q (cfs/ft)
100+00	20,000	50°	0.71
150+00	16,000	20°	0.40
200+00	11,500	30°	0.80
250+00	8,000	75°	2.23
300+00	8,000	70°	2.17



Total Impact ($q + q_1$)

STA	q	q_1	total q
100+00	2.08	0.71	2.78
150+00	1.33	0.40	1.73
200+00	1.83	0.80	2.63
250+00	3.73	2.23	5.96
300+00	0.00	2.17	2.17
350+00	3.52	0.00	3.52
400+00	2.74	0.00	2.74
450+00	1.96	0.00	1.96

Comparison of Existing and Future Drainage

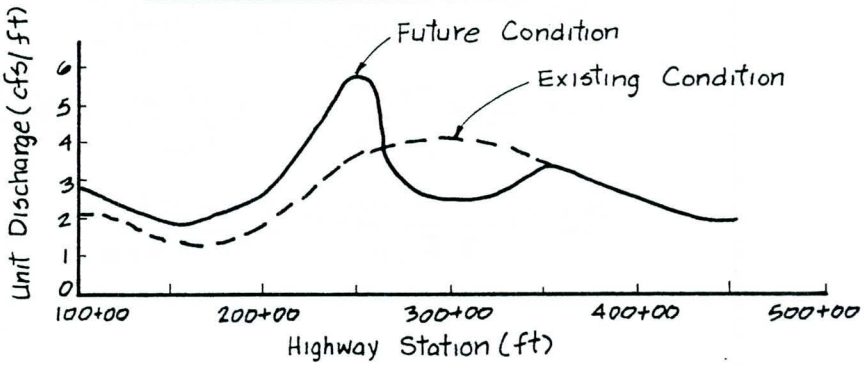


Figure 5 Effect of development on highway drainage.

CASE 4: General Condition

Figure 6 shows the general situation. Several alluvial fans from different drainages coalesce. Many of the roads, structures and topographic features found on the alluvial fan can cause major changes in flow direction, depth and velocity. Any mathematical model for analyzing alluvial fan hydraulics should be capable of including such effects. Since most parts of the fan have no defined channel, the two dimensional behavior of the flow on an unbounded surface would need to be described. Using this approach would enable the highway designer to account for effects of future development on drainage.

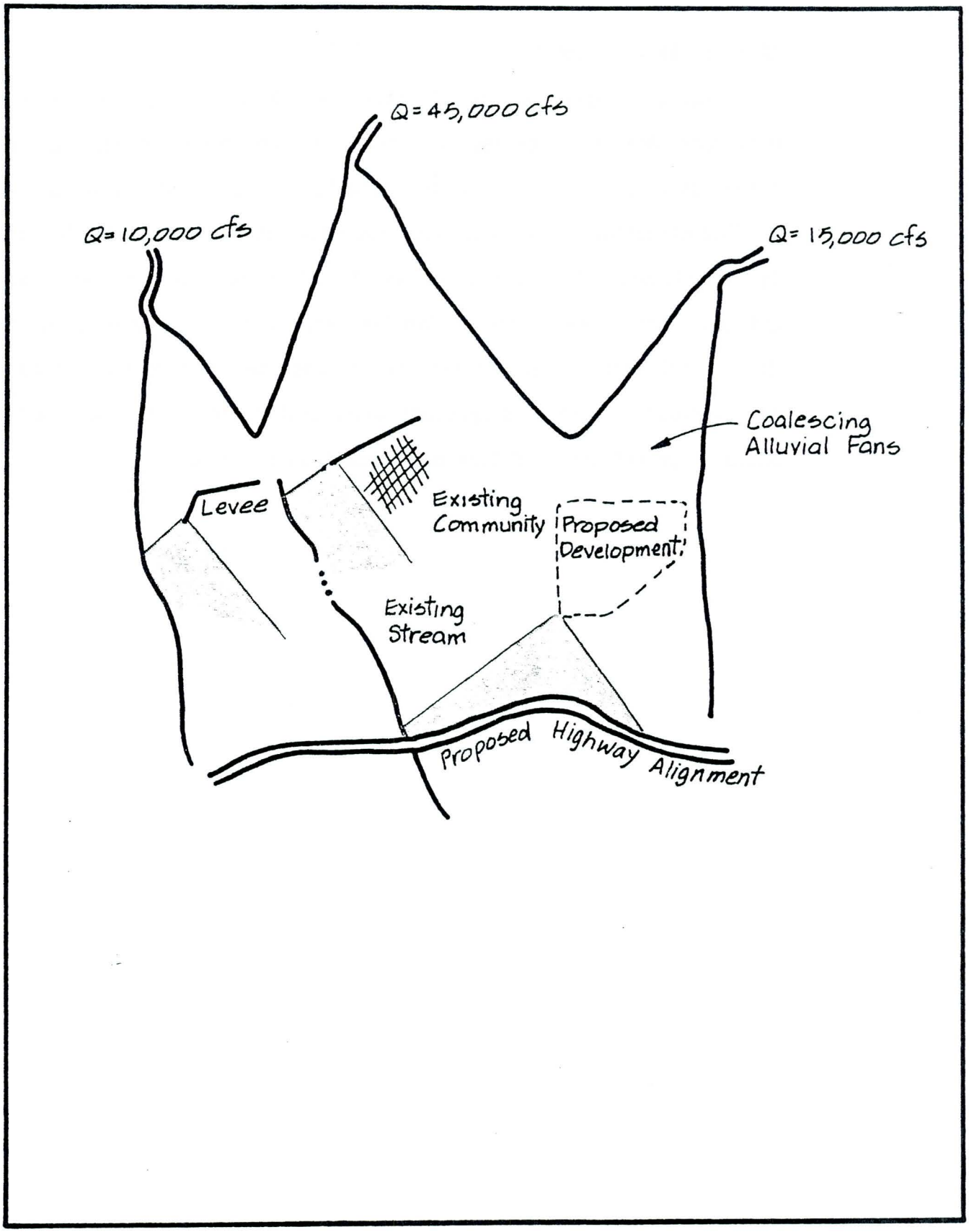


Figure 6 General condition of flooding on an alluvial fan.

Design Parameters

This section discusses the basis of two-dimensional flow analysis and its role in solving alluvial fan flood problems. In general, flow on an unbound plane is governed by the three-dimensional, unsteady equations of mass and momentum conservation. If there is a hydrostatic pressure distribution, and nearly uniform velocity distribution in the vertical direction, the dimension of the equations can be reduced by one. The only dependent variables are the fluid depth and the unit discharge in the x and y directions (Hamilton, et al., 1987). Mathematically, the two-dimensional equations for unsteady flow are

$$\frac{\partial h}{\partial t} + \frac{\partial p}{\partial x} + \frac{\partial q}{\partial y} = 0 \tag{1}$$

$$\frac{\partial p}{\partial t} + \frac{\partial}{\partial x}\left(\frac{p^2}{h} + g\frac{h^2}{2}\right) + \frac{\partial}{\partial y}\left(\frac{pq}{h}\right) + gh\left(S_{o_x} + S_{f_x}\right) = 0 \tag{2}$$

$$\frac{\partial q}{\partial t} + \frac{\partial}{\partial y}\left(\frac{q^2}{h} + g\frac{h^2}{2}\right) + \frac{\partial}{\partial x}\left(\frac{pq}{h}\right) + gh\left(S_{o_y} + S_{f_y}\right) = 0 \tag{3}$$

in which t = time; x = x-horizontal coordinate; y = y-horizontal coordinate; p and q = the unit discharge in the x and y directions, respectively; h = water depth; g = gravitational constant; S_{ox} and S_{oy} = bed slope in the x and y direcitons; and S_{fx} and S_{fy} = frictional resistance term in the x and y directions. The frictional resistance is usually computed using Mannings equation. For large alluvial fans

such as near Phoenix or Tucson, the amount of rainfall which occurs on the fan itself should be included. The infiltration rate of the runoff on the fan is a function of time and may be difficult to determine; however, it is also an important factor for large alluvial fans. For illustrative purposes, these two factors are not included in equations (1), (2), and (3).

Equations 1, 2 and 3 describe the flow behavior exactly, within the constraints of the assumptions upon which they were derived. The equations must be solved numerically, however, as no closed form solution exists. In order to make this numerical solution easier to perform, one or more of the terms in equations 2 and 3 are sometimes removed. This may or may not have a large effect on the computed solution depending upon the nature of the problem.

The specific role of two-dimensional flow analysis for alluvial fans can be seen from Figure 7. A point discharge on an unbounded plane will expand initially with an included angle of 90° but will eventually flow perpendicular to the contours. The assumption made in the four example cases that a point discharge will expand uniformly with an angle of 90° for any distance will yield discharges that are lower than would actually occur. Thus unless two-dimensional flow effects are accurately captured, there is a good chance that highway drainage facilities will be underdesigned. An acceptable computational technique should include the capability to describe the expansive nature of the flow, incorporate the effect of both subtle topographic features and abrupt flow obstructions, and should be able to describe supercritical and subcritical flow behavior.

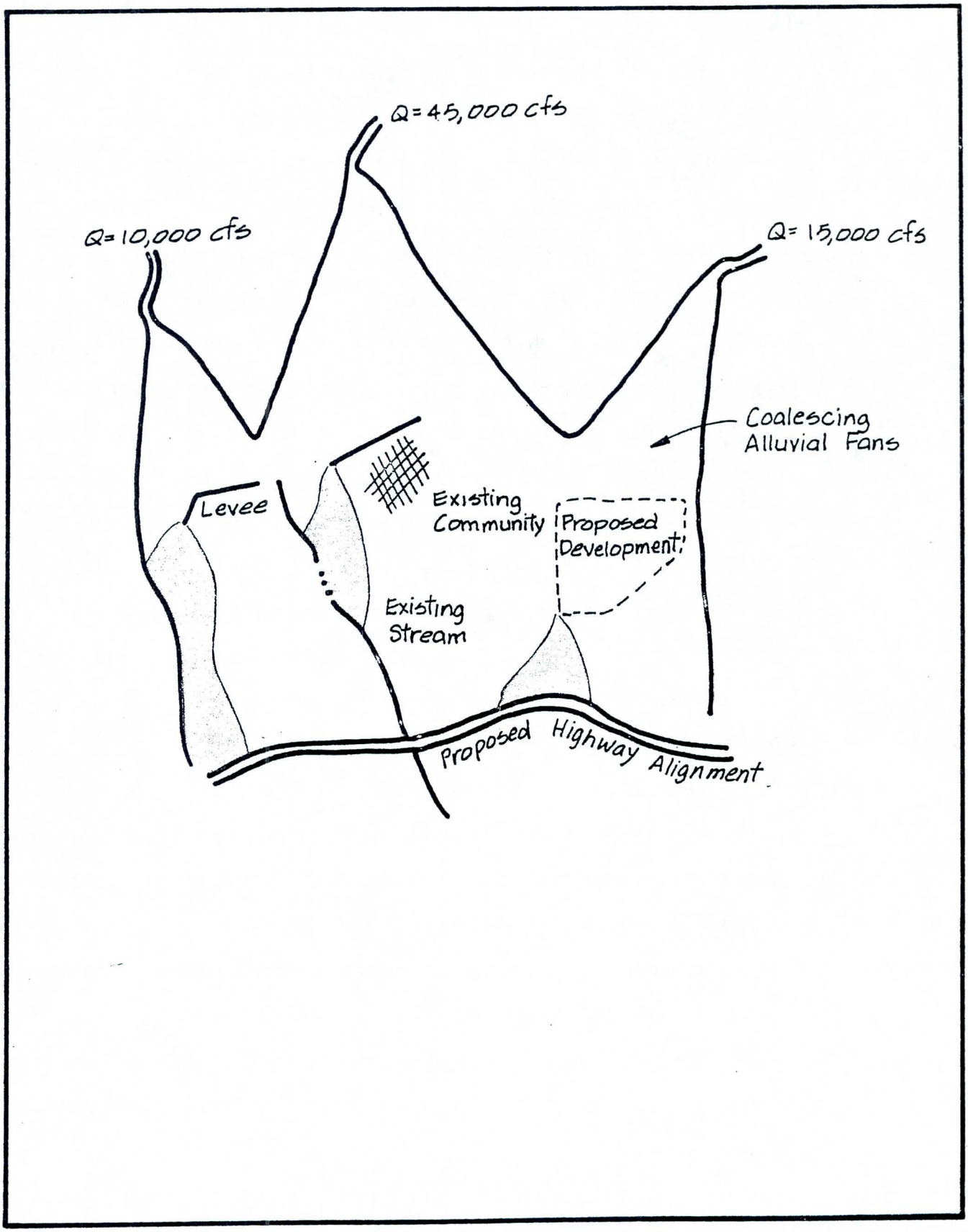


Figure 7 Actual flow paths downstream from obstructions.

Assessment of Random Behavior of Alluvial Fan Flows

As will be discussed in the following section, some deterministic computational methods are available to assess the general trends of alluvial fan hydraulics and hydrology. Many of the phenomena that complicate the analysis of alluvial fan flooding, however, are random, at least in the sense that we do not have the knowledge to predict in advance the specific effects from a given causal event. An example of such a random phenomenon is the pattern of sediment deposition which occurs during a flood on an alluvial fan. In general, the deposition pattern is cone shaped and fairly uniform such as the alluvial fan terrace north of Phoenix shown in Figure 8. Upon close inspection, the contour lines appear jagged and irregular. On a large scale, it is apparent that the contour lines can be approximated by smooth, semi-circular curves. The small fluctuations in elevation are due to the scour, deposition and resuspension of material and is a function of the local geologic, vegetation, soil mosture and topographic conditions. Since there is no direct deterministic computational method to simulate such micro-scale effects accurately, it is more practical to simulate the average hydrologic behavior and use a probabilistic approach to account for microscale deviations from the mean.

The contour line noted on Figure 8 has a maximum deviation of about 2 feet in elevation. This means, historically, that local changes in bed elevation have been up to two feet during a flood event. The average deviation from the mean contour elevation can be computed

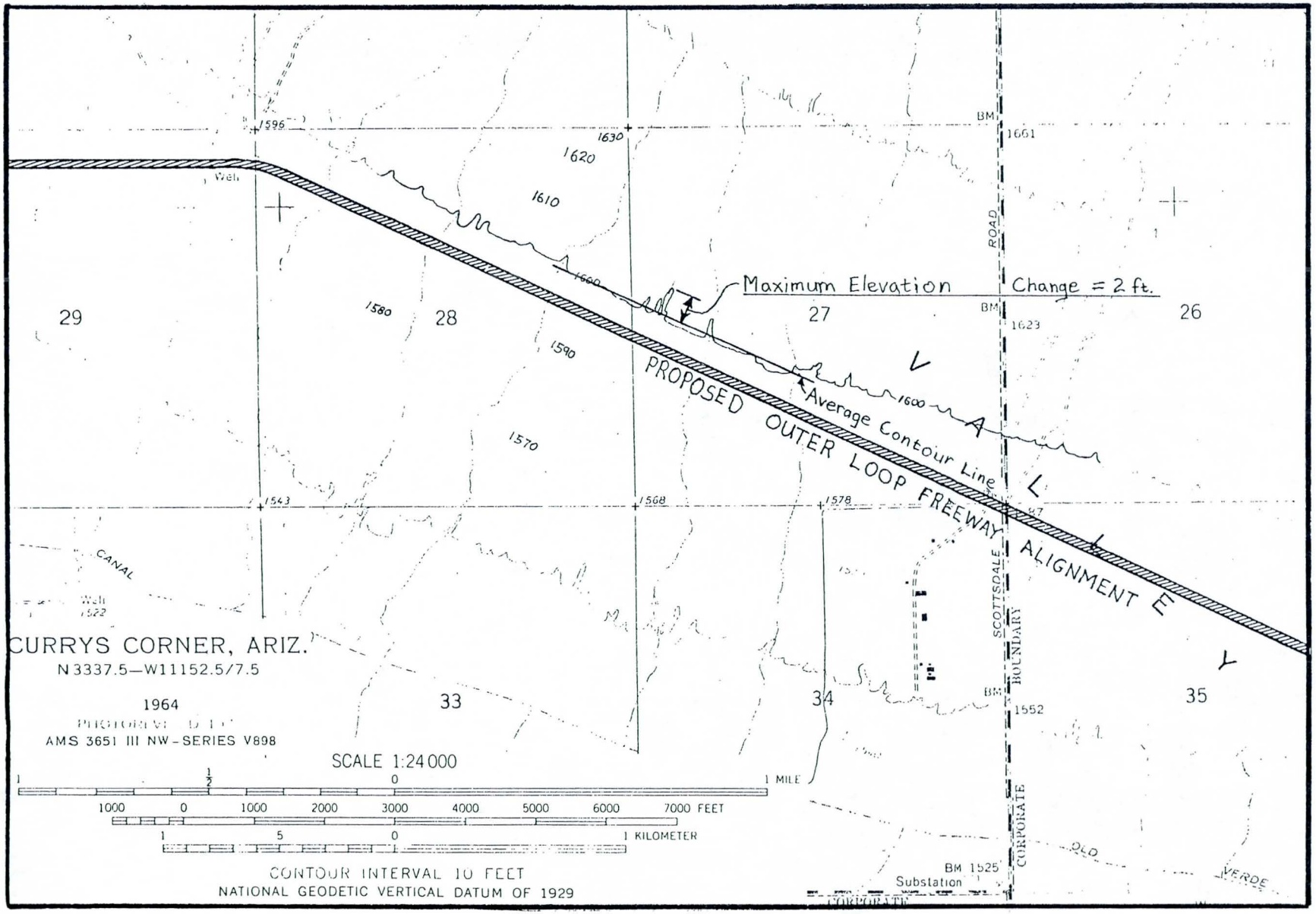


Figure 8 Example of Statistical Deviation from Uniform Deposition.

and used as a design factor to be added to the results of the deterministic modeling methods.

Computational Techniques

As stated previously, the role of a numerical simulation model is to predict the average hydraulic parameters needed for the design of highway crossings. These parameters are the unit discharge, the depth and velocity of flow and the sedimentation characteristics. This section discusses such numerical models.

Many computational techniques and computer models were reviewed. Five of these are presented here (see Table 1). Most two dimensional flow models were developed for use with defined, bounded geometry. The Schamber model and RMA-2 have potential use for unbounded flow. They are also the only models reviewed that use the full equations of unsteady, two dimensional flow. Both of these models could be used to determine the flow characteristics as discussed in the "Design Parameters" section and as illustrated in Figure 7.

One of these two methods should be further developed for alluvial fan applications as discussed in the proposed work plan, Section VI. The further development should include the incorporation of appropriate boundary conditions and the possibility of supercritical flow depths.

TABLE 1 SURVEY OF COMPUTER MODELS FOR ANALYSIS OF FLOWS ON ALLUVIAL FANS.

NAME OF METHOD	REFERENCE	DESCRIPTION	PREVIOUS APPLICATIONS	MATHEMATICAL SOLUTION TECHNIQUES	APPLICABILITY FOR ALLUVIAL FAN MODELING
Dawdy Method	Dawdy, 1979 Edwards and Thielmann, 1983	This technique was developed specifically for conducting flood insurance studies on alluvial fans. Although it is a simple technique and can be applied uniformly, there is no direct way to account for topographic features or existing structural elements.	Various Flood Insurance studies and planning studies in southern California and Arizona.	Probabalistic approach with critical depth assumed and an empirical relationship between width and depth.	Very useful for general planning, regulation and flood insurance but does not yield detailed enough results for design purposes.
RMA-2 Model	Gee and MacArthur, 1982 MacArthur, et. al. 1985	This is one of the most widely used and tested two-dimensional flow models. It solves the full equations of unsteady flow in two dimensions using the finite element method. The elements can become wet and dry during the simulation whic is a necessary requirement for alluvial fan analysis. The graphics for this program is very strong which aids in the interpretation of results. There may be a problem as flow changes from subcritical to supercritical.	Hydraulic Simulations for San Francisco Bay, Columbia River, Sacramento River. No alluvial fan case studies were located.	The complete St. Venant equations are solved using the method of finite elements.	This model is a good candidate for alluvial fan modeling because of its general application capabilities and wetting and drying of elements feature.
Schamber Model	Schamber, 1985 Hamilton, Schamber & MacArthur, 1987	This model was recently developed for conducting a flood insurance study in an alluvial fan region near the Wasatch Front Mountains, Utah. The full equations of unsteady flow in two dimensions are solved using the method of finite elements. An interesting aspect of this model is that it uses an expanding computational grid. This is quite useful for alluvial fan analysis since an unbounded flow situation can be simulated. This model is currently being improved by its author and it is a good candidate for generalized application to alluvial fans.	Simulation of alluvial fan debris flows for a flood insurance study along the Wasatch Mountains, Utah. Flood analysis near Mt. Saint Helens, Washington.	The complete two dimensional flow equations are solved using the method of finite elements. An inflow hydrograph boundary condition and the alluvial fan topography are the main input requirements.	This model is a good candidate for alluvial fan modeling because of its ability to simulate an expanding flow situation on an unbounded plain.
Link-Node Model	Gurule, 1982 Orlob, 1978	The link-node model is a pseudo two dimensional approach for analyzing flow on a horizontal plane. This technique allows for spatial variation of the one dimensional equations of unsteady flow. This simplified approach has been used largely for estuary studies. This model may be difficult to use in an alluvial fan situation because the geometry does not have fixed, bounded topography in which to confine the flow.	San Francisco Bay circulation and water quality. Many estuary and tidal applications.	The one dimensional equations for unsteady flow are solved using an explicit finite difference method.	This model is not a good candidate for alluvial fan simulations because of the restrictions on specifying the topographic features.
Diffusion Analogy Hydrodynamic Model	Hromadka, 1985	This model, called DHM, uses a simplified version of equations (2) and (3) called the diffusion analogy. An explicit finite difference formulation is used thus computation time tends to be large and computer memory requirements tend to be small. The diffusion analogy may be a good approximation for steep alluvial fans because the flows upon them are governed more by the bed resistance rather than inertial effects. The model has a fixed computational grid which limits the accurate description of topographic features.	Plano Trabuco flood plain study, Orange County, CA. Retention basin analysis, Orange County, CA.	The diffusion analogy of the two dimensional flow equations are solved using an explicit finite difference method on a fixed coputational grid.	Although this model can simulate flow on a flood plain, the constraints on the specification of the topographic data may cause difficulty in general application.

IV. CONCLUSIONS

1. Alluvial fan flooding and related debris and sediment flow is one of the largest potential hazards in the arid Southwest and one of the most difficult design problems for the Arizona Department of Transportation to deal with.
2. Alluvial fan flooding conditions vary throughout the state of Arizona. The broad alluvial fans near Phoenix are currently under different stages of development but careful land use planning can reduce concentrated runoff hazards. Because the hydrologic and hydraulic charactertistics of fans are so complex and vary greatly, no single methodology is available for designing highway drainage projects on alluvial fans.
3. A thorough reconnaissance and fan characterization study should always be conducted as the first phase of any highway drainage study. This should include an assesment of existing and proposed land use, drainage features, soil types and vegetation.
4. Uniform and consistent guidelines, master planning studies and design criteria must be developed for the large metropolitan regions of Arizona. Land clearing, grading and construction activities on alluvial fans must be strictly regulated to insure an integrated flood hazard reduction program.
5. The hydraulics of alluvial fan flooding are far more complex and erratic than that of riverine floods. Therefore, tradi-

tional gradually varied, steady state, fixed bed methods for analyzing hydraulic problems are often inadequate for alluvial fan flooding problems.

6. Regular project maintenance is essential to insure proper project function.

7. Quick field-engineered solutions to alluvial fan flooding and drainage problems often create more problems than they were intended to solve.

8. Although there is a computer model for two-dimensional flow that can be tailored to fit the needs of the Arizona Department of Transportation, none of the models will yield directly the desired highway drainage design parameters if used "off the shelf."

9. Generalized methodology for two-dimensional flow analysis combined with site specific hydrology and topographic features can play a major role in developing a uniform procedure for proper design of highway drainage on alluvial fans.

10. Flood protection on alluvial fans conflicts with a dominant geological process which wants to bury development with a layer of sediment. Successful drainage must be designed to transport the sediment as far down the fan as possible.

11. All drainage facilities should be designed to account for the presence of debris and should be part of a strict maintenance program.

12. The Schamber model and RMA-2 show the most promise for two-dimensional flow analysis for alluvial fans.

V. RECOMMENDED FURTHER WORK

1. Numerical models capable of estimating the location and size of channels formed by unsteady, supercritical flows in erodible alluvial fans must be developed and tested.
2. Laboratory and field verification of these tools are essential (see MacArthur, et al, 1987).
3. In areas where there are insufficient stream gaging records, techniques which are superior to the regional method of peak flood flow analysis and the envelope curve method can be employed.
4. Uniform and regionally consistent design guidelines need to be established.
5. A case study such as the proposed Outer Loop Freeway should be used to test and compare the capabilities of several of the more promising computational methods. The same models should be applied to any case studies that may exist with actual measured flood event data and observed project performance information.
6. Regional emergency management procedures should also be developed to minimize downfan flooding problems that may result form upperfan flood repair work.
7. Existing computational techniques can be tailored to be used directly by highway drainage designers. This will involve some further research, simple laboratory experiments and computer model development. The benefits will be a significant advance in the state of the art and a more unified, compre-

hensive approach to highway drainage on alluvial fans.

8. The sediment aggradation and degradation which occurs during an alluvial fan flood should be recorded and analyzed to obtain quantitative techniques for estimating sedimentation behavior.

VI. PROPOSED WORK PLAN FOR ANALYSIS OF FLOWS ON ALLUVIAL FANS

Purpose

The purpose of this section is to outline a program to develop reliable methods for planning and designing highway crossings and drainage projects on alluvial fans. The program will be conducted in three phases and consist of research, model development , data collection, model calibration and verification, methods documentation, and field testing.

General Approach

A program to develop reliable methods for simulating flows on alluvial fans requires work and results from the following areas: (1) basic research into the physics of shallow flow on alluvial fans, (2) field monitoring and data collection, (3) numerical model development , (4) model testing and sensitivity analyses, (5) model calibration and verification, (6) physical modeling (This may be necessary to provide data for items 1 and 5), (7) field applications, (8) documentation and reporting, and (9) review, improvement, expansion and updating of model capabilities as more information and field data becomes available.

Many of the hydraulic characteristics of alluvial fans and the subsequent movement of sediment and debris during flow events are poorly understood. Therefore a combined program of basic research into the physics of shallow flows on alluvial fans and field monitoring of representative fan areas are essential components of any meaningful development program. Development of a mathematical model, or perhaps a

family of mathematical models, capable of simulating the hydraulics of alluvial fans can be initiated once the desired capabilities and model features have been defined and agreed upon with ATRC staff. Model developers must work closely with staff from ATRC to insure proper direction and emphasis of the model development program. Development should proceed in phases. A first generation set of models should be prepared and tested initially. Improvements and model expansion can follow as future phases once the first generation modeling package has been thoroughly tested. Development of an all-purpose universal model should not be attempted as part of the first phase. A computer model for the simulation of unbounded shallow flow such as described in the "Design Parameters" section would be more appropriate. Careful model testing and field application will identify capabilities that future generation models must have.

Results form the basic research and field monitoring tasks must be intigrated into the design of the model(s) and carefully tested. Following preliminary testing, numerical sensitivity analyses should be performed to quantify the numerical stability, accuracy and convergence of the model. Physical modeling tests may be necessary to both identify certain key hydraulic flow characteristics of alluvial fans, and to develop sufficient data to be able to verify the capabilities of the numerical model(s).

Each phase of development and testing shall be fully documented. Review comments and feedback from the ATRC will be incorporated on a regular basis into the approach. Continuous expansion, updating and

improvement to the modeling methods will occur as new issues are identified by the ATRC and new methods for simulating them are identified by field needs and/or basic research.

Finally, several field applications will be made using the modeling methodology for problems found in Arizona. The intent of the field applications will be to test the capability of the model to duplicate actual flow conditions.

Model structure and design shall be as generalized as practical while realizing the applications will be primarily for flow problems on alluvial fans found in Arizona. The latest techniques in structured programming and software engineering will be applied during model development.

Proposed Methodology

An essential first phase of any model development will be to meet with staff from the ATRC to discuss specific components of alluvial fan flow problems that affect the proper design of highway projects. Specific capabilities and general design features of the proposed modeling methods for a first generation model must be identified and agreed upon. Future generation models can be improved to make the methods more generalized as our knowledge of the flow physics improves.

An integrated anaylses system is proposed. The approach would allow users to apply several alternative fluvial systems analysis tools representing a variety of study levels from a simple steady-flow back water computation such as HEC-2, to a one-dimensional unsteady flow

routing, to a fully two-dimensional dynamic flow and sediment routing tool (mobil boundary modeling). Existing software, and traditional methods will be used wherever possible and wherever applicable. Development or improvement of new unsteady two-dimensional modeling tools is also requried.

The emergence of uniform and widely available operating systems such as MS-DOS and UNIX provides an opportunity for the creation of much improved user interfaces to a fluvial hydraulics system. The system would be developed by improving and integrating existing software wherever possible and developing "shells" to manage data and program operation. The ability to use various levels of analysis with input data shared by each program will provide users with the flexibility to perform several levels of analysis quickly and uniformly. Planning and/or design decisions can be made more readily with this type of approach.

Figure 9 presents a flow diagram of a possible integrated alluvial fan analysis system.

Generalized Analysis Procedures

Once an integrated package of programs has been developed the following procedures may be used to evaluate highway crossing designs on alluvial fans.

1. Site investigation and basin characterization

Conduct a thorough site investigation of the project area and examine the drainage basin and alluvial fan areas upstream and downstream

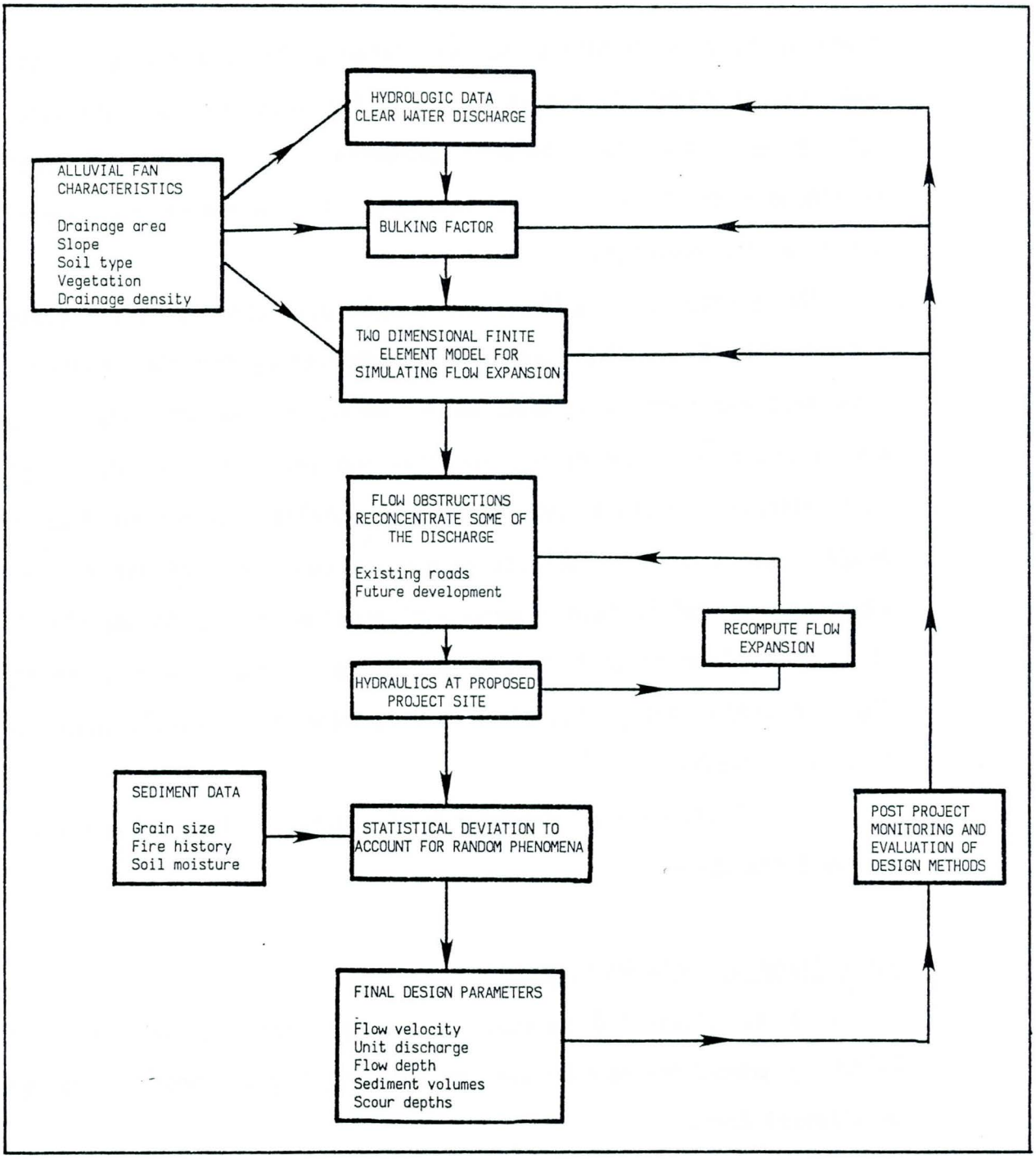


FIGURE 9 DIAGRAM FOR AN INTEGRATED SYSTEM OF ALLUVIAL FAN HYDRAULIC AND SEDIMENTATION ANALYSIS

from the project site. Examine past aerial photographs and topographic maps of the area. Identify the dominant soil types, erodibility, and amount of vegetative cover for the drainage area upstream from the site. Determine grain size distribution of bed and bank materials in the immediate vicinity of the proposed highway crossing. Determine whether the alluvial fan area draining into the project area is predominately in a channelized zone, braided zone or sheet flow zone as shown in Figure 1. Examine past historical data and information regarding storm intensities and flow characteristics of the area. Examine previous highway and channel maintenance and/or damage reports if available. Develop a thorough characterization of the drainage basin and estimate the sediment transporting ability, debris loading or scour and deposition potential for the project site.

2. Develop representative hydrology

Collect the necessary hydrologic data and combine it with the basin characterization data from task one above. Use these data and accepted hydrologic procedures to develop the expected flood hydrology for the project site. Develop design flood hydrographs, peak discharges, flow duration, and flood volume for design floods for the project area. Estimate future changes in hydrology that may occur as a result of upstream urbanization. Develop future hydrology for these conditions as well.

3. Estimate sediment load bulking factors

Use methods prescribed by the Los Angeles County Flood Control District, The U.S. Army Corps of Engineers, The Pacific Southwest

Interagency Committee, ATRC, and others to develop sediment loading bulking factors for the flood flows developed in step 2 above. The bulked flows will account for the increase in total water and sediment flow volume that results from entrainment of sediment during flood flows.

4. Determine the hydraulic characteristics of the project site by several methods

Determine the hydraulic characteristics of the project site using traditional steady state fixed bed backwater methods, such as HEC-2 if applicable. Examine the computed velocity, flow depth and other hydraulic characteristics with respect to anticipated design features. Prepare and execute advanced two-dimensional hydrodynamic simulation models such as RMA-2 or the modified Schamber model for unbounded flow situations. Use the Schamber model to determine the flow spreading angle (A_f, Figure 2) for the fan for the various design floods. Route the flood using advanced methods (RMA-2 or Schamber Model) down to the project site. Determine the flow per unit length along the proposed highway and the velocity and depth of flow expected as a result of the dynamic routing.

5. Determine the representative alluvial fan sediment scour and deposit depths from statistical methods

Determine the representative alluvial fan sediment scour and deposition depths from measured contour profiles along the fan at several locations. Perform statistical evaluations of the depths of rills and gullies as well as berms and deposits for different drainage zones on the fan. Compute scour or deposit depths using traditional scour

calculation methods and the hydraulic characteristics determined from step 4. Adjust these depths of scour, deposit, flow velocity etc. by adding the statistical deviation values that were just determined (see section on this topic). That is, determine depths of scour as the scour of the computed depth plus some deviation away from the mean depth determined from the statistical evaluation. An example equation for scour depth is :

$$d_{scour} = d_{calculated} + d_{statical\ deviation}$$

This approach can be used to adjust flow depths flow velocities and alter hydraulic characteristics of the flow.

6. <u>Perform highway crossing design calculations</u>

Using the information and results from the previous steps 1 through 5, determine the best orientation, sizing and design of the proposed highway crossing. The hydraulic characteristics (flow depth and velocity) now reflect the characteristics of flows found on alluvial fans.

7. <u>Evaluate potential maintenance requirements</u>

Perform additional analyses to estimate the amount of sediment accumulation and/or debris accumulation that may occur in the project area. Perform this analysis for several different upstream drainage basin modifications that may occur as a result of urbanization activities. Modify the design based on the effects of anticipated drainage basin changes.

8. Monitor the project and re-evaluate and modify design procedures as necessary

Evaluate project performance with respect to the original design procedures. If project performance varies greatly from the design calculation, attempt to determine where and why the modeling methods failed and develop revised procedures that are more reliable. As second and third generation models are developed the accuracy and reliability of the design methods will improve. By the end of the 4 to 5 year study period, the models and design methods should be well refined and reasonably generalized.

VII. TENTATIVE TIME SCHEDULE

A four to five years program is necessary in order to properly address the analysis and highway design problems associated with alluvial fans in Arizona. The following tme schedule is proposed but will need further refinement following detailed discussions with staff from ATRC. Many of the proposed activities will be occurring simultaneously in order to complete the project in 4 to 5 years, and, of course, practical analysis methods will be available for use before the end of the study period.

Phase I Problem Identification

	Calendar Months
1. Evaluate characteristics, capabilities and applicability of several of the more promising state-of-the-art methods for planning and designing highway crosing on alluvial fans (present study).	6 months
2. Meet with staff from ATRC, develop a list of specific capabilities and features which the methods should have. Select example drainage basin and alluvial fan areas to monitor.	1 month
3. Identify specific areas where data must be collected. Identify specific basic research tasks that are necessary in order to complete the project.	1 month
4. Prepare a detailed scope of work, time schedule and estimate of costs.	1 month

Phase II Model Design Basic Research and Field Monitoring

	Calendar Months
1. Design and conduct field monitoring of the flow and sediment transport characteristics on the test fan sites. Continuously monitor these sites for four years, prepare summary report of results.	48 months
2. Initiate basic research studies outlined in item I-3 above. Prepare summary reports throughout study.	36 months

8. Monitor the project and re-evaluate and modify design procedures as necessary

Evaluate project performance with respect to the original design procedures. If project performance varies greatly from the design calculation, attempt to determine where and why the modeling methods failed and develop revised procedures that are more reliable. As second and third generation models are developed the accuracy and reliability of the design methods will improve. By the end of the 4 to 5 year study period, the models and design methods should be well refined and reasonably generalized.

3. Design the structure, capabilities and linkages for the various models and computational methods to be intergrated into the analysis package. Construct paper models of the I/O and data flow. Decide on the character and types of solutions (output) users may require identify specific software engineering tasks for model development. 4 months

4. Begin model development and testing. 12 months

5. Perform detailed sensitivity study of the modeling modeling package. Develop and document a test data set and preliminary users manual. 4 months

Phase III Detailed Model Testing Calibration and Verification

Calendar Months

1. Perform additional model testing, and documentation.

2. Perform detailed calibration and verification of the model using data collected during the field studies.

3. Use laboratory physical modeling as an additional method for developing verificational data.

4. Make computer model modificaions and thoroughly document how to use the package.

5. Apply the modeling package to actual field design problems work closely with ATRC to make model improvements and adjustments if necessary.

6. Conduct a one-week training course and workshop for staff from ATRC on how to use the design analysis package.

12 to 24 months

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