Skunk Creek

Watercourse Master Plan

ATTACHMENT 6

LATERAL STABILITY ASSESSMENT REPORT

Flood Control District of Maricopa County

AUGUST 2001

Skunk Creek/Sonoran Wash Watercourse Master Plan Report

Attachment 6: Lateral Stability Assessment

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Final Report

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Chapter 1
Introduction

The Flood Control District of Maricopa County (FCDMC) is preparing a watercourse master plan for Skunk Creek and Sonoran Wash. The watercourse master plan was prepared by a team of consultants led by Tetra Tech, Inc. Infrastructure Southwest Group (TTI),[1] who identified and evaluated structural and non-structural flood control alternatives to protect properties within and adjacent to the regulatory floodplain from flood damage. JE Fuller/ Hydrology & Geomorphology, Inc. (JEF) has prepared this lateral stability assessment to support the watercourse master planning process.

Study Location

The Skunk Creek/Sonoran Wash study area is located within the corporate limits of the City of Phoenix and in portions of unincorporated Maricopa County, (Figure 1-1). The Skunk Creek Watercourse Master Plan includes the following reaches:

- Skunk Creek – CAP Canal to New River Road (13 miles)
- Sonoran Wash – CAP Canal to 7th Avenue Alignment (3 miles)

Skunk Creek was evaluated in two phases. The Phase 1 reach consisted of the segments of Skunk Creek and Sonoran Wash located within the City of Phoenix, and extended from the CAP canal to Carefree Highway. The Phase 2 reach consisted of stream segments of Skunk Creek located mostly within unincorporated Maricopa County, and extended from Carefree Highway to a point about 700 feet upstream of the New River Road Bridge.

Objectives

The primary objectives of the Skunk Creek Watercourse Master Plan Lateral Stability Assessment were to determine the potential for lateral migration of the Skunk Creek and Sonoran Wash, and to determine the benefits of and opportunities for non-structural flood control. The Watercourse Master Plan identified and evaluated traditional structural and non-structural flood control alternatives based in part upon the results of the lateral migration assessment. This report summarizes the methods used to evaluate the potential for lateral channel migration within the study area.

Data Sources

The methods used to assess the potential for lateral channel migration in the study area relied on a variety of existing information, field data, and new analyses. Existing information was collected from the following key sources:

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[1] Formerly ASL Consulting Engineers, Inc.

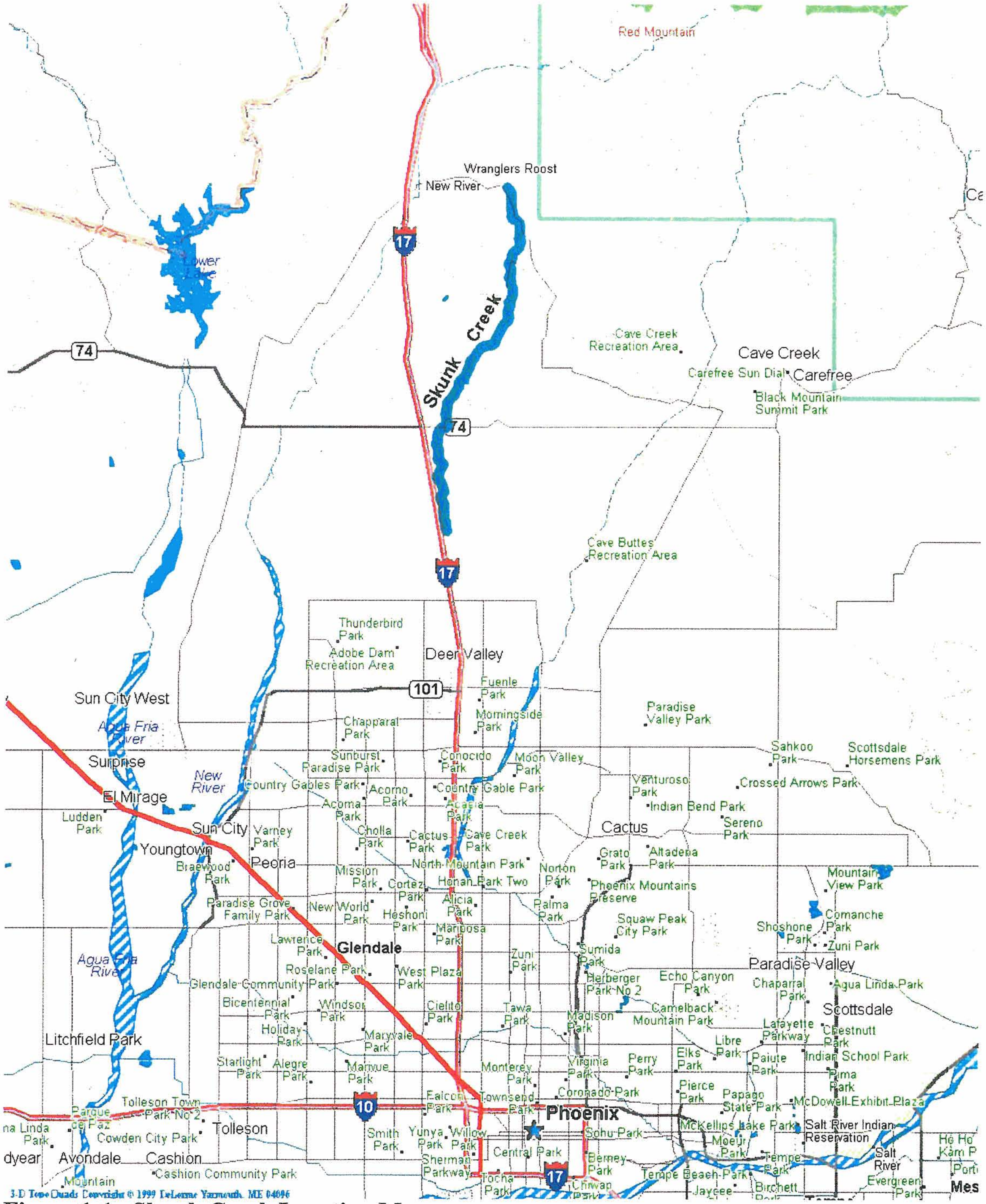


Figure 1-1. Skunk Creek Location Map.

- Arizona Geological Survey (AZGS)
- Arizona State Land Department (ASLD)
- Arizona State University – Geology Department (ASU)
- City of Phoenix (COP)
- Federal Emergency Management Agency (FEMA)

- Flood Control District of Maricopa County (District)
- U.S. Army Corps of Engineers – Los Angeles District (USACOE)
- U.S.D.A – Soil Conservation Service (SCS or NRCS)
- U.S.D.A – Agricultural Stabilization Conservation Service (ASCS)
- U.S. Geological Survey – Water Resources Division (USGS Water Resources)
- U.S. Geological Survey – EROS Data Center (USGS - EROS)
- U.S. Bureau of Land Management (BLM)
- U.S. Bureau of Reclamation (BUREC)

Existing information collected for the study included the following:

- Historical and recent aerial photographs
- Historical and recent topographic maps
- Historical survey records and channel descriptions
- Published and unpublished engineering reports
- Published detailed soils mapping
- Published and unpublished mapping of surficial geology
- Bridge and roadway as-built construction plans
- Regional and local streamflow gauging records
- Regional and local precipitation records

Field data collected for the streams included the following:

- Descriptions of channel bed and bank conditions
- Ground photographs of significant channel features
- Surface sediment samples (boulder counts)
- Subsurface sediment samples (sieve analyses)
- Soil pit descriptions for channel, floodplain, and terrace sites
- Descriptions of watershed conditions
- Descriptions of significant tributaries

A listing of references used for the lateral stability assessment is provided in Chapter 8. Summaries of key field data are provided in the Appendixes to this report. A glossary of key terms is provided in Chapter 9.

Limitations & Assumptions

Any technical analysis is limited by the data available, the contracted scope of services, and the assumptions of the methodologies used. For the Skunk Creek Watercourse Master Plan, the following general limitations apply:

- Period of Record. Streamflow data are available for only a portion of the period of interest for the study area (Chapter 2). Collection of additional streamflow data in the future could improve the accuracy of the hydrologic and geomorphic analyses.

- Hydrologic Data. No streamflow gauging data were available for Sonoran Wash. Estimates of the 100-year discharges were obtained from Floodplain Delineation Studies performed by others, as described in Chapter 3. Estimates of the 2- and 10-year discharges were obtained by uncalibrated HEC-1 modeling performed by others for this study (ASL, 1999). Availability of historical streamflow data for these streams and more detailed modeling of high frequency flow events could improve the accuracy of the lateral stability assessment.
- Hydraulic Modeling. HEC-2 (Montgomery Watson, 1997; Erie and Associates, 1996; Hoskins Engineering Consultants, 1999) and HEC-RAS (Stantec, 2000) models were prepared by others for the purpose of depicting the 100-year flood characteristics. As described in Chapter 5, some modifications of the input code were required prior to using the models to assess lateral channel stability. Other modifications of the HEC-2 input code could not be made without additional survey and mapping, which were not part of the scope of services. Field calibration of the HEC-2 and HEC-RAS models for the high frequency flow events could improve the accuracy of the hydraulic data used in the lateral stability assessment.
- Topographic Mapping. Detailed topographic mapping for Skunk Creek was provided from previous projects completed by others (Montgomery Watson, 1997; Erie and Associates, 1996; Hoskins Engineering Consultants, 1999). New topographic mapping was prepared for Sonoran Wash in conjunction with the Flood Insurance Study (Stantec, 2000).
- Sediment Continuity Modeling. Sediment modeling was performed for the Skunk Creek Watercourse Master Plan by others (Stantec, 2000) using HEC-6, a one-dimensional hydraulic model. The applicability of the results of the HEC-6 modeling to the study area is discussed in Chapter 5.
- Geotechnical Data. No geotechnical data were available for the study area, except for limited boring details provided on as-built construction plans for the drainage structures along Carefree Highway and New River Road. More accurate predictions of lateral stability could be made if extensive geotechnical investigations were conducted along the channel bed and banks.
- Scale of Analysis. This study considered approximately 17 miles of river corridor. It is possible that more detailed evaluation of shorter reaches or specific sites could improve the accuracy of the predictions of future channel behavior.

Other assumptions and limitations of this evaluation are discussed in the following chapters for each of the specific methodologies used.

Report Overview

This report summarizes the methods used to evaluate the potential for lateral channel migration within the study area. Specific chapters in this report cover the following topics:

- Chapter 1 – Project overview and introductory information

- Chapter 2 – Description of the study area watershed, geologic setting, hydrology, stream classification, and definition of stream reaches used for the study.

- Chapter 3 – Chronology of channel change, including description of historical and prehistoric changes in channel conditions including lateral and vertical channel changes, and changes in channel shape or pattern.

- Chapter 4 – Discussion of geomorphic methods of lateral stability assessment, including field data, visual assessment techniques, geomorphic mapping, longitudinal profile, regime equations, channel pattern, and hydraulic geometry.

- Chapter 5 – Discussion of engineering approaches to assessing lateral stability including allowable velocity, equilibrium slope, armoring, scour, sediment continuity modeling (HEC-6), Lane's Relation, and Arizona Department of Water Resources (ADWR) State Standard 5-96 methodology.

- Chapter 6 – Discussion of the development and application of erosion hazard management zones.

- Chapter 7 – Summary and Recommendations

- Chapter 8 – Bibliography

- Chapter 9 –Glossary of technical terms used in this report.

Chapter 2
Study Area Description

This chapter provides the basic information about the following characteristics of the Skunk Creek Watercourse Master Plan study area that affect the lateral stability assessment:

- Watershed Description
- Geologic Setting
- Hydrologic Data
- Stream Classification
- Reach Definition

The interrelated watershed, geologic, and hydrologic characteristics of a stream combine to determine its unique geomorphology, which can be described using a stream classification system. These data can then be used to define specific stream reaches for more detailed analyses.

Watershed Description

The lateral stability of the Skunk Creek system is directly impacted by watershed characteristics such as drainage area, type of development, vegetative cover, elevation, and other physiographic information. Watershed characteristics for the streams in the study area are described below.

Drainage Area
Skunk Creek and its principal tributaries form a moderately large stream system (about 64 $mi.^2$) that heads in the New River Mountains east of the town of New River and flows into the northern Phoenix metropolitan area (Figure 2-1). The drainage areas and 2- and 100-year peak discharges (existing conditions) at several key concentration points within or near the study area are shown in Table 2-1.

In addition to several Sonoran watercourses, the significant tributaries of Skunk Creek upstream of the Central Arizona Project Canal include the following:

- Cline Creek (16.1 mi^2)
- Rodger Creek (5.1 mi^2)
- Skunk Creek Tank Wash (4.8 mi^2)
- Sonoran Wash (13.4 mi^2)

All of these significant tributaries enter Skunk Creek from the east. No significant tributaries join Skunk Creek within the study limits from the west side of the watershed.

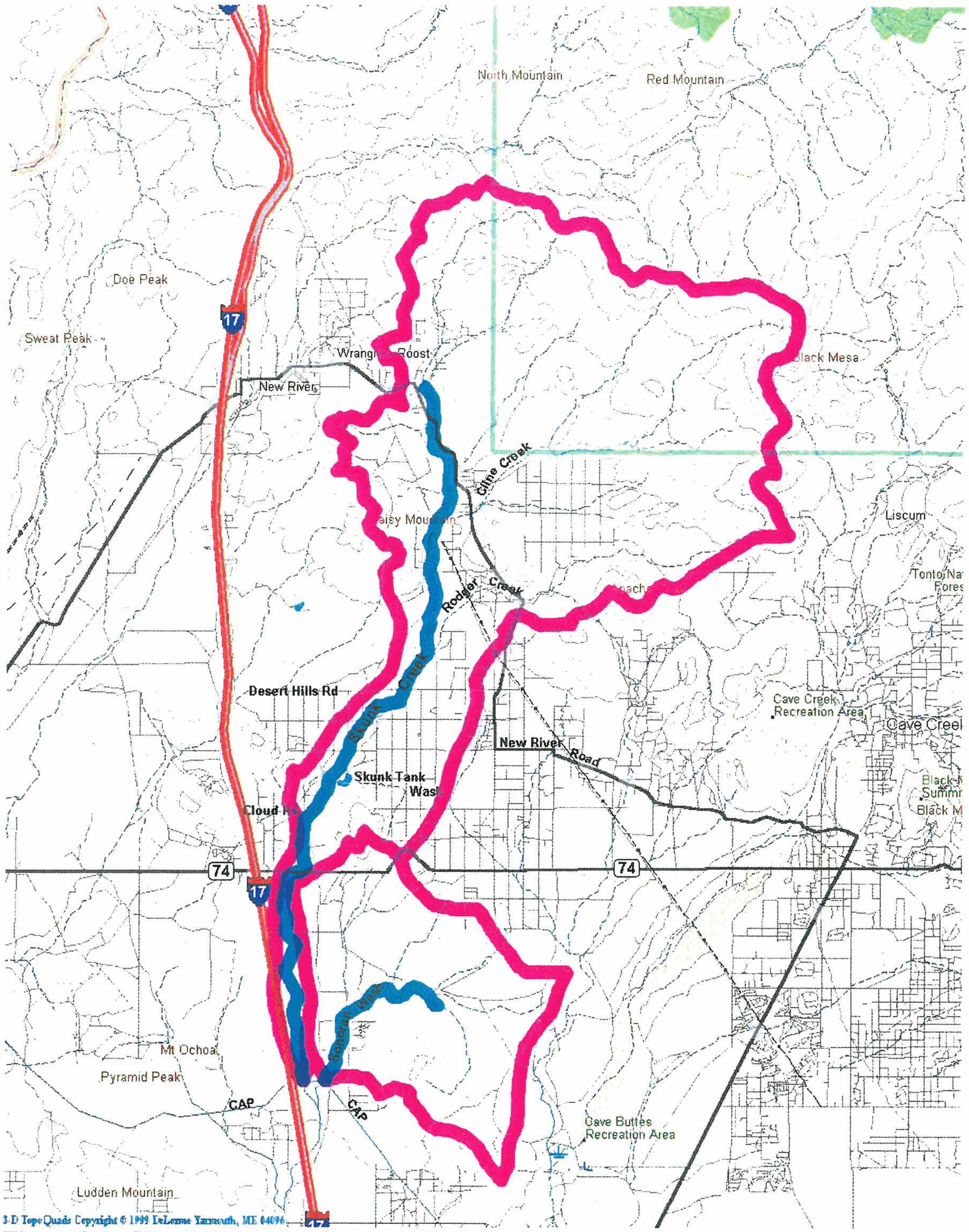


Figure 2-1. Skunk Creek and Sonoran Wash Watershed Location.

Table 2-1. Skunk Creek Watercourse Master Plan Watershed Characteristics: Drainage Area and Peak Discharge (Existing Conditions)			
Concentration Point	**Drainage Area (mi^2)**	**2-Year Peak (cfs)**	**100-Year Peak (cfs)**
Skunk Creek			
@ New River Road	8.0	1,500	7,800
Downstream of Cline Creek	32.7	3,800	24,400
Downstream of Rodger Creek	40.1	4,900	27,300
Downstream of Skunk Creek Tank Wash	42.3	4,700	26,700
@ Carefree Highway	48.6	4,900	27,300
@ Central Arizona Project Canal	50.3	4,700	26,500
Cline Creek			
@ Skunk Creek Confluence	16.1	2,100	13,700
Rodger Creek			
@ Skunk Creek Confluence	5.1	1,700	5,600
Skunk Tank Wash			
@ Skunk Creek Confluence	4.8	1,500	5,300
Sonoran Wash			
@ Upstream Study Limit (About 1500 Ft West Of 7th Ave Alignment)	5.0	2,000	6,500
About 800 Ft Upstream Of 19th Ave Alignment	7.7	2,200	8,400
About 400 Ft Upstream Of Montgomery Rd Alignment	11.1	2,300	9,700
@ Central Arizona Project Canal	13.4	2,100	9,800
Source of data: Tetra Tech, Inc., 2001			

Urbanization

The Skunk Creek watershed encompasses portions of the City of Phoenix, unincorporated Maricopa County, and the Tonto National Forest. Much of the watershed is comprised of undeveloped desert mountain terrain or desert upland foothills with low density suburban ranch development. Downstream of Interstate-17, which is located about 1.5 miles downstream of the Central Arizona Project Canal (CAP)) and outside the watercourse master plan study area, the watershed is more heavily urbanized. Higher density commercial, industrial, and residential development is planned or under construction in the lower portion of the study area, especially within the City of Phoenix limits in the Phase 1 Reach downstream of Cloud Road. Construction of the 1,100 acre Tramonto development between Cloud Road and Carefree Highway is currently underway, with numerous other large developments in the planning phases downstream of Carefree Highway. The Del Webb Anthem development also extends into the study area between Desert Hills and Rockaway Hills Roads, although the portions along Skunk Creek have yet to be constructed. Therefore, future urbanization of the study area should be expected in the near future.

Physiographic Setting

The headwaters of the Skunk Creek watershed are located in the rugged Transition Zone[1] Physiographic Province of central Arizona. Skunk Creek flows southward from the Transition Zone to the margins of the Basin and Range Physiographic Province, across the Little Deer Valley, and into the Adobe Dam impoundment area. Prior to construction of Adobe Dam in 1982, Skunk Creek flowed freely through the Little Deer Valley, around the east end of the Hedgpeth Hills (where the dam is now located), and then southwest across Deer Valley in northern Glendale, Arizona toward its confluence with the New River.

Elevations in the watershed range from about 4,080 feet on New River Mesa in the Tonto National Forest to about 1,520 feet at the Central Arizona Project canal. Elevations, average channel slopes, and stream lengths for the streams and major tributaries within the study area are shown in Table 2-2.

Table 2-2. Skunk Creek Watercourse Master Plan
Stream Physiographic Characteristics

Stream Name	Elevation (ft.)		Average Channel Slope (ft./ft.)	Stream Length (mi.)
	Upstream Limit	Downstream Limit		
Skunk Creek	2122	1518	0.0087	13.2
Sonoran Wash	1622	1518	0.0059	3.3
Cline Creek	3000	2000	0.0283	6.7
Rodger Creek	2680	1880	0.0208	7.3
Skunk Tank Wash	1928	1756	0.0071	4.6

All of the streams within the study limits are *ephemeral*. The average annual rainfall for the watershed above the USGS stream gauge upstream of Interstate-17 is reported as 12.2 inches per year (Pope et. al., 1998). About three percent (3%) of the annual rainfall over the watershed becomes *runoff* at the gauging station location.

More detailed descriptions of specific watershed characteristics are provided in the Hydrologic Modeling Section of the Skunk Creek Watercourse Master Plan Final Report (Tetra Tech, 2001).

Geologic Setting

Understanding the overall geology of the study area is fundamental to understanding and predicting the types and magnitude of channel processes such as lateral migration. The geologic setting of the study area is discussed below.

Geologic History

The Skunk Creek study area is located at the margin of the Basin and Range and

[1] a.k.a., the Central Highlands

Transition Zone Physiographic Provinces (Figure 2-2). The headwaters of Skunk Creek are within the Transition Zone, although most of the study reach is within the Basin and Range Province. The Basin and Range Province is characterized by a series of narrow, north- and northwest-trending, linear mountain ranges separated by valleys filled with alluvium eroded from the mountains. Within in the study area, Skunk Creek cuts through several basins (e.g., Paradise Valley, Biscuit Flat) and ranges (e.g., northern extension of Union Hills range, Daisy Mountain-Pyramid Peak range). Sonoran Wash drains the basin area adjacent to parts of the Union Hills range. The Transition Zone is characterized by "tight-clustered ranges and narrower, shallower and less numerous basins" (Chronic, 1989) than the Basin and Range, but also has some features similar to the Colorado Plateau.

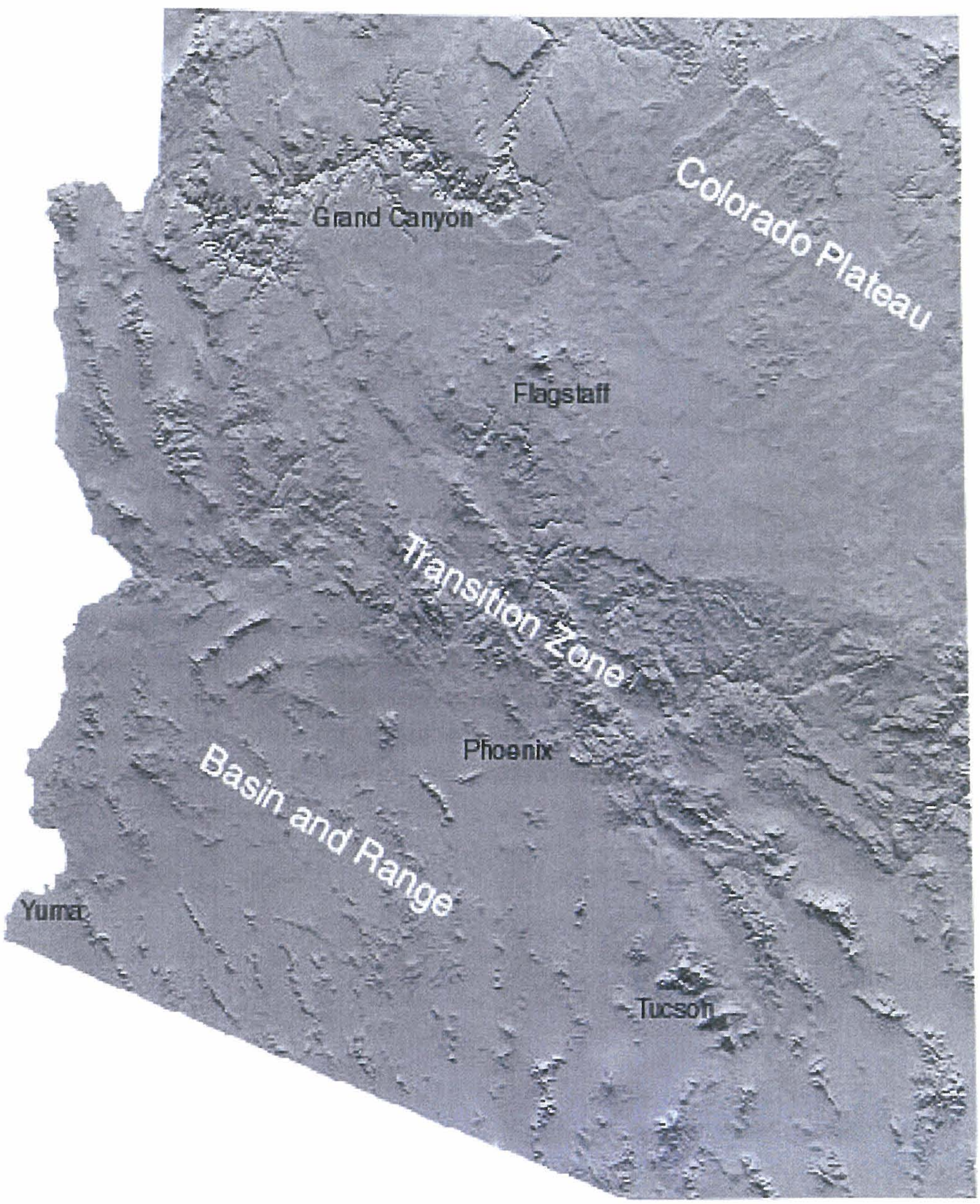


Figure 2-2. Physiographic Provinces of Arizona.

Table 2-3. Skunk Creek Watercourse Master Plan The Geologic Time Scale			
Era	**Period**	**Epoch**	**Time (Years Before Present)**
Cenozoic	Quaternary	Holocene	0-10,000
		Pleistocene	10,000-2 ma[1]
	Tertiary	Pliocene	2-5 ma
		Miocene	5-24 ma
		Oligocene	24-38 ma
		Eocene	38-55 ma
		Paleocene	55-63 ma
Mesozoic	Cretaceous		63-138 ma
	Jurassic		138-205 ma
	Triassic		205-240 ma
Paleozoic	Permian		240-290 ma
	Pennsylvanian		290-330 ma
	Mississippian		330-365 ma
	Devonian		365-410 ma
	Silurian		410-435 ma
	Ordovician		435-500 ma
	Cambrian		500-570 ma
Precambrian	Younger		570-1,700 ma
	Older		1,700-4,600 ma
Note: 1. ma = million years			

The study area has a long, complex history of geologic activity (Leighty & Huckleberry, 1998; Leighty, 1998; Leighty & Holloway, 1998). The extensional tectonism of the middle to late Tertiary Period which formed the physiography of the Basin and Range Province can be divided into two phases. Early Miocene extension was accompanied by deposition of basaltic lavas over much of the north Phoenix area. These lavas now cap many of the ranges in the study area. The middle to late Miocene basin and range disturbance included a period of graben subsidence that extended until about eight million years ago, when vertical movement ceased, pediments formed, and the basins filled with alluvium and other sedimentary deposits. Geophysical evidence suggests that the depth of alluvium in the Paradise Valley basin exceeds 10,000 feet, but becomes shallower to the northwest where it is traversed by Skunk Creek. The depth of alluvium in the Sonoran Wash basin between the Union Hills and the North Union Hills and the basins underlying Biscuit Flat is shallow and may consist of buried pediment surfaces.

Quaternary-aged basin fill deposits cover most of study area, especially the areas closest to Skunk Creek and Sonoran Wash. The basin-fill deposits consist of piedmont and fluvial deposits. Piedmont deposits were shed from the mountain ranges into the broad plains below, and have been eroded into shallow valleys and low ridges due to development of a drainage network on the piedmont surface. Fluvial deposits include active channels and terraces that record former, higher channel positions of the main drainage systems. Fluvial deposits are distinguished from piedmont deposits by their more diverse lithologic composition, greater degree of clast rounding, and their landform morphology, which is generally parallel to the existing drainage system.

The piedmont and fluvial deposits associated with Skunk Creek and Sonoran Wash mapped by the Arizona Geological Survey (AZGS; Figure 2-3) provide evidence of the geomorphic evolution of the fluvial system over the past several million years. The piedmont surfaces in the study area experienced net deposition up until the middle Pleistocene. During this time, alluvial fans were deposited in the Paradise Valley and along the margin of Biscuit Flat, and the drainage system was poorly defined. During the late Pleistocene and Holocene, the study area experienced net degradation and developed more defined stream corridors, and transformed the much of the piedmont into a relict alluvial fan. As the fluvial system was transformed from net aggradation to net degradation, the apex of the alluvial fan shifted downstream. During the early to middle Pleistocene, the primary apex of alluvial fan was probably located immediately upstream the Rodger Creek confluence. A secondary or later alluvial fan apex may have been present just downstream of Cloud Road at the location of the former flow split on Skunk Creek now filled by the Tramonto development. By the late Pleistocene, the primary alluvial fan apex had shifted downstream to about the Lone Mountain Road alignment. Currently, Skunk Creek has entrenched to the degree that it no longer has alluvial fan characteristics within the study area.

The geologically-recent fluvial deposits along the Skunk Creek and Sonoran Wash corridors are bounded by middle Pleistocene piedmont surfaces or bedrock outcrops. late Pleistocene and Holocene-aged terraces along Skunk Creek and Sonoran Wash record geologically-brief episodes of aggradation that occurred within the overall degradational history of the past 500,000 years. After these brief periods of deposition, the main streams continued to degrade, leaving terrace surfaces along the stream corridor that record former floodplain elevations, as illustrated in Figure 2-4. Terraces of late Pleistocene and Holocene age were mapped by the AZGS as shown in Figure 2-3. Field and photographic evidence suggests that the AZGS map units could be further subdivided into more age-specific categories, if more detailed mapping were required. More detailed mapping efforts conducted for this study are summarized in Chapter 4 of this report.

Skunk Creek Watercourse Master Plan

Figure 2-3 AZGS Surficial Geology Map

(blue line)	1999 Thalweg
(red line)	AZGS Geologic Unit Boundary
Xvf	AZGS Geologic Unit

Unit Descriptions

cl	colluvium & weathered bedrock	Tbl	Chalk Canyon Fm.
d	disturbed area	Tbm	Hickey Fm.
Qc	Quaternary colluvium	tl	talus deposits
Qct	Quaternary colluvium & talus	TQo	Pliocene alluvial fan dep.
Ql	L. Pleistocene alluvium	TQor	Pliocene river terr. dep.
Qlr	L. Pleistocene river terrace dep.	Ts	conglomerate & ss
Qm	M. Pleistocene alluvium	Tsy	'Basin-fill' conglomrate
Qmo	E. to M. Pleistocene all. fan dep.	Tt	tuff
Qmr	M. Pleistocene river terrace dep.	Tts	tuff & tuffaceous ss
Qm1	older M. Pleistocene alluvium	Tt2	M. E. Miocene tuff
Qm2	younger M. Pleistocene alluvium	Tt3	U. E. Miocene tuff
Qo	E. Pleistocene alluvial fan dep.	Xad	andesite-diorite complex
Qor	E. Pleistocene river terrace dep.	Xf	felsic volcanics
Qs	alluvium, undivided	Xf2	additional felsic volcanics
Qy	Holocene alluvium	Xgd	granodiorite
Qycr	active channel dep.	Xv	inter. to felsic volcanics
Qyr	Holocene river terrace dep.	Xva	andesitic & bas. volcanics
D	not described	Xvad	andesitic to dacitic metavolcanics
Tb	basaltic rocks, undivided	YXg	granite

Scale

1 Inch = 4000 Feet

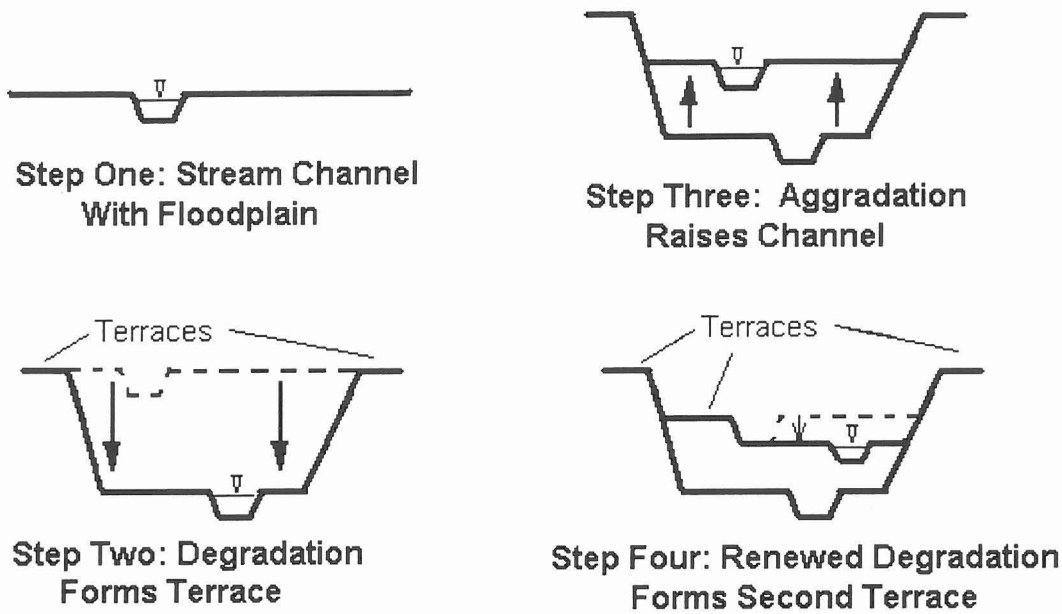


Figure 2-4. Example of Terrace Formation by Degradation or Aggradation.

Summary

The presence and characteristics of the fluvial terraces along Skunk Creek and Sonoran Wash provide the following types of information about the existing and future risk of lateral erosion:

- Erosion limits. Over the past 500,000 years, lateral erosion has been limited to the area of the 500 to 3,500 foot wide stream corridors located between the middle Pleistocene surfaces. Within the past 10,000 years, lateral erosion has been limited to the area of the 500 to 2,000 foot wide stream corridors located between the late Pleistocene surfaces. Future lateral erosion is most likely within areas composed of the most recent geomorphic surfaces.

- Erosion corridor width. The width of the modern geomorphic surfaces increases and the height of the fluvial terraces generally decreases in the downstream direction, indicating an increased potential for lateral erosion in the downstream direction.

- Net degradation. The height of the fluvial terraces above the existing channel bed suggests that a maximum of about 25 feet of net vertical erosion has occurred since the middle Pleistocene, with a maximum of about 10 feet since the late Pleistocene.

- Episodes of aggradation. Episodes of aggradation (e.g., channel filling, floodplain deposition) have occurred at numerous times in the past, and should be expected in the future. During periods of aggradation, the stream corridor tends to occupy a wider portion of the geologic floodplain.

- Cline Creek terraces. The terraces along Cline Creek appear to be more closely correlated with the Skunk Creek terraces downstream of the Skunk/Cline confluence than are the terraces along Skunk Creek upstream of confluence. Therefore, it is assumed that Cline Creek may be a more important source of runoff and sediment than Skunk Creek upstream of the confluence.

Within the study area, the existing channels of Skunk Creek and Sonoran Wash have experienced net degradation over the past 500,000 years. Therefore, net degradation is expected to continue in the future. Entrenchment during recent geologic time has created a series of older, stable terraces that confine the existing active channels within a relatively well-defined corridor. Likewise, future channel movement is most likely to be confined within the corridor of geologically recent surfaces located near the main channels. More detailed discussion of the local geology and geomorphology of the stream terraces along Skunk Creek and Sonoran Wash is provided in the geomorphic mapping discussion in Chapter 4 of this report.

Hydrology

The hydrologic characteristics of a stream have a direct impact on its morphology and behavior. The hydrology of the streams segment in the study area are discussed below.

Data Sources
Hydrologic data for Skunk Creek were collected from USGS stream gauge records (Pope et. al., 1998), FCDMC ALERT gauge records, HEC-1 modeling performed by others for previous Flood Insurance Studies (Montgomery-Watson, 1996) and for this study (ASL Consulting, 2000), and from application of USGS regression equations for peak discharge (Thomas et. al. 1994). USGS stream-gauging stations on or near Skunk Creek are listed in Table 2-4.

No stream gauging stations exist on Sonoran Wash. Therefore, it is assumed that the gauge data for Cave Creek and Skunk Creek represent the best available estimates of the historical trends in flow for the Sonoran Wash system.

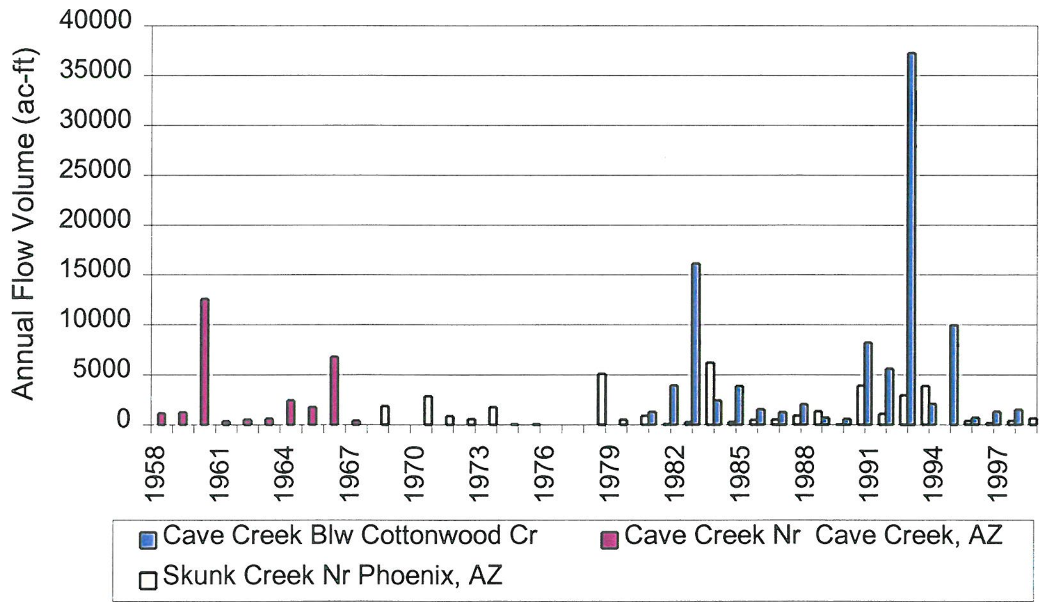
Table 2-4. Skunk Creek Watercourse Master Plan Stream Gauge Stations in Study Area Vicinity				
Name	**Operator**	**Station #**	**Period of Record**	**Drainage Area (mi^2)**
Skunk Creek near New River	FCDMC	5583	1995-2000	4.3
Skunk Creek near Phoenix, AZ[3]	USGS	09513860	1960-2000	64.9
Cave Creek below Cottonwood Ck.	USGS	09512280	1981-2000	82.7
Cave Creek near Cave Creek, AZ[1,2]	USGS	09512300	1958-2000	121
New River near Rock Springs, AZ	USGS	09513780	1966-2000	68.3

Notes:
1. Station is now operated by the Flood Control District of Maricopa County.
2. Station operated only as a crest-stage gauge after 1967.
3. Station operated as a crest stage gage only from 1960-1967.

Annual Flow

Lateral channel movement is strongly related to volume of flow. In addition to the effects saturating the bank materials has on bank stability, long duration periods of high flow have the energy and time to perform significant amounts of geomorphic work. Therefore, years of high annual flow volume are related to likely periods of channel change. Figure 2-5 shows the flow volumes for Skunk Creek and nearby streams with USGS gauges.

Figure 2-5. Total Annual Flow Volume for Skunk Creek & Adjacent Streams



The following conclusions may be drawn from the annual flow volume data shown in Figure 2-5:

- Variability. There is a wide range in flow volume between wet years and dry years. There are more than three orders of magnitude of difference between the annual volume of the driest year[2] and the wettest year[3] during the period of record.

- Cyclical Change. The period from about 1967 to about 1980 was relatively dry compared to wetter periods experienced during the early 1980's and mid-1990's.

- Drainage Area. The data from the Cave Creek gauging stations indicate that annual flow volume is inversely related to drainage area, indicating that high transmission losses occur as flow reaches the alluvial fill valley within the study limits. Similar conclusions are probably valid for Skunk Creek, and are supported by anecdotal accounts of more frequent runoff upstream of the New River Road bridge and on Cline Creek. However, it is noted that the upper Cave Creek watershed drains an area of generally higher elevation than the upper Skunk Creek watershed. Therefore, Cave Creek may be capable of generating larger runoff volumes than Skunk Creek.

Seasonal Flow

Flow volume varies seasonally, as well as annually. Seasonal trends in flow volume can be used to determine likely periods of high or low flow, and consequently, seasonal periods of increased susceptibility to lateral erosion and channel change. Monthly average flow rates for the Skunk Creek and Cave Creek gauges are summarized in Figure 2-6.

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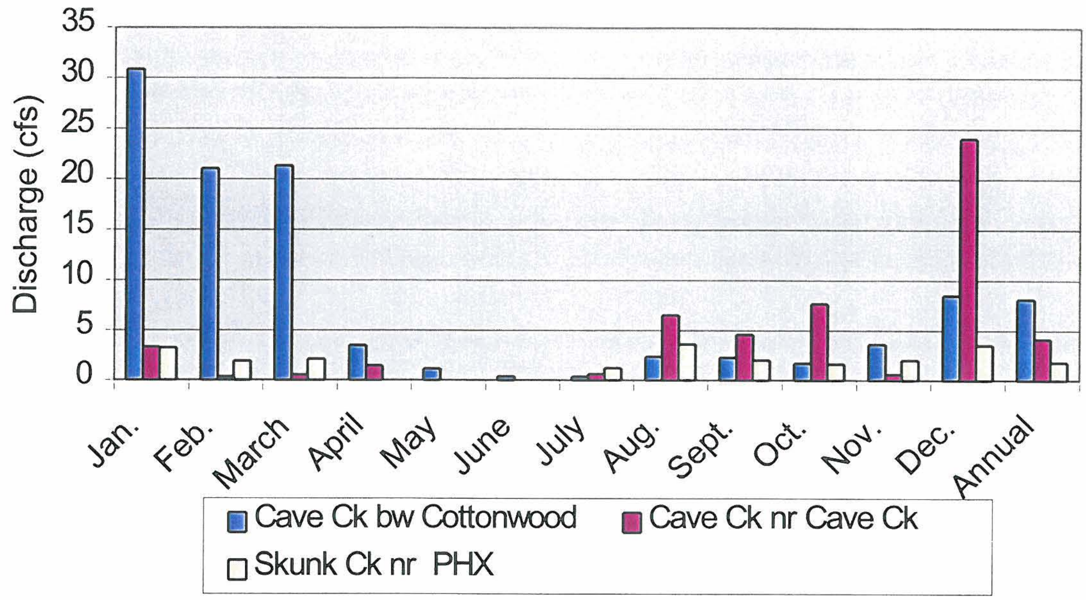
[2] 0 acre-feet measured at Skunk Creek near Phoenix in 1969 and 1984.

[3] 6,213 acre-feet measured at Skunk Creek near Phoenix in 1983.

Figure 2-6. Monthly Average Flow Rate at USGS Gauges



The following conclusions can be drawn from the monthly flow data summarized in Figure 2-6:

- Seasonality. Two seasons of high flow occur on Skunk Creek: (1) winter storm-induced runoff during November through March, and (2) summer monsoon-induced runoff during the months of July through October. The period of seasonal low flow occurs in late spring and early summer from April to June.

- Location. The Skunk Creek watershed probably does not exhibit the seasonal spatial variability trends demonstrated by the two Cave Creek gauges due to differences in characteristics of the two streams' upper watersheds. These differences are readily seen by comparing the Daisy Mountain (Cave Creek) and New River Mesa (Skunk Creek) quadrangles. The watershed upstream of the Cave Creek below Cottonwood Creek station is generally much more mountainous than the Skunk Creek watershed, and is also located within a reach that experiences intermittent flow. Conversely, the Skunk Creek watershed has a lower proportion of mountainous area and does not have similar intermittent reaches.

- Erosion. Within the Skunk Creek/Sonoran Wash study area, seasonal channel change can be expected in response to late summer monsoon flooding and early winter floods during the periods of highest average monthly flow.

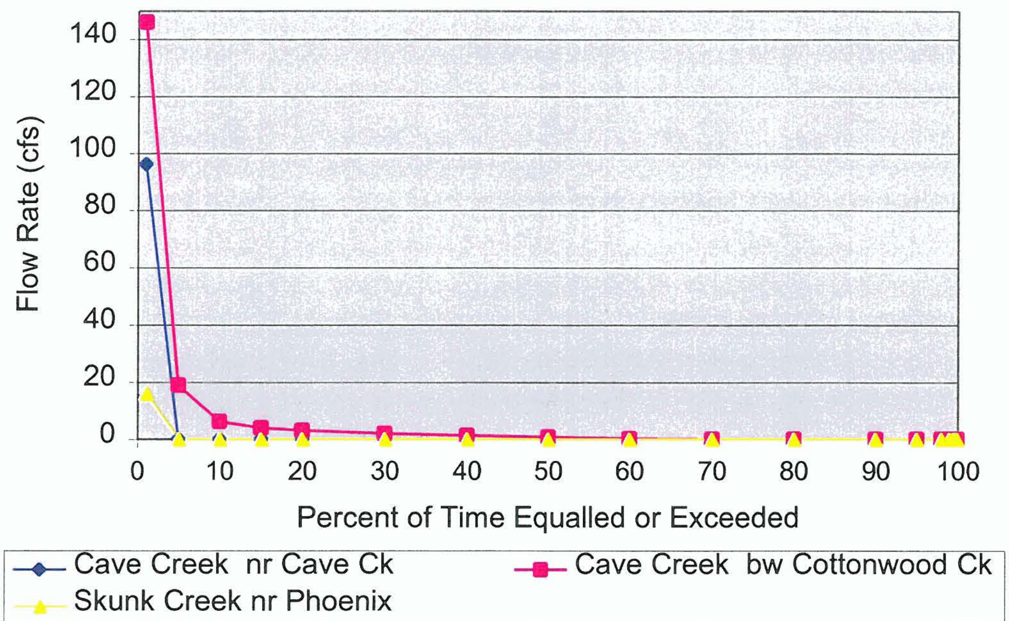
- Similarity to Cave Creek. Of the gauges listed in Table 2-4, the Skunk Creek flow data are most similar to the data from Cave Creek near Cave Creek USGS station.

This probably reflects the fact that both gauges are located on the piedmont downstream of the primary source area for runoff.

Flow Duration

Flow duration statistics depict the percent of time a given flow rate is exceeded at a gauging station. For streams with high flood to normal flow ratios (Q_{peak}:$Q_{average}$) flow duration statistics depict typical flow conditions more realistically than average flow statistics, which tend to be skewed upward by the large volumes of rare flash floods relative to normal conditions. Comparison of flow duration and average flow data help identify streams subject to flash floods. Flow duration statistics for Skunk Creek are shown in Figure 2-7.

Figure 2-7. Flow Duration Statistics for Skunk Creek



The following conclusions can be drawn from the flow duration data summarized in Figure 2-7:

- Flow Rate. Flows in the study area are rare, and occur only during floods. Therefore, much of the geomorphic work of channel change will occur during floods. More than 95 percent of the time, no natural channel change can occur on Skunk Creek because there is no flow.

- Flood Potential. Comparison of average flow data and flow duration data indicate that Skunk Creek (and its tributaries) are subject to flash floods. Average flow data for Skunk Creek are skewed by the effects of rare floods.

Precipitation Records
For ephemeral streams like Skunk Creek and Sonoran Wash, runoff is directly related to precipitation. Precipitation records can be used to identify wet/dry cycles, climatic variation, and other trends that may affect stream stability or explain historical channel change. For streams like Sonoran Wash which lack any systematic gauge record, precipitation data can be used to identify potential flood years or periods of frequent flow. Also, precipitation records are valuable because they are available dating back to the late 1800's, whereas streamflow records on Skunk Creek date only to 1960.

Long-term precipitation data were obtained for the Phoenix metropolitan region and for the Skunk Creek watershed from the Western Regional Climate Center web site operated by the Desert Research Institute in Nevada.[4] The station names and period of record are listed in Table 2-5. Station locations are shown in Figure 2-8. Long-term average annual and monthly precipitation data are shown in Figures 2-9 and 2-10. Average annual runoff computed as a percent of the long-term regional average precipitation is shown in Figure 2-11

.

Table 2-5. Skunk Creek Watercourse Master Plan
Regional Long-Term Precipitation Stations

Station Name	Period of Record	Average Annual Precipitation (in)
Mesa	1896-1999	8.33
Buckeye	1893-1999	7.74
Alhambra	1948-1976	7.77
Bartlett	1939-1999	13.66
Carefree	1962-1999	13.37
Deer Valley	1950-1985	8.64
Litchfield Park	1917-1999	8.13
Marinette	1913-1964	7.90
Paradise Valley	1955-1970	8.46
Phoenix City	1948-1998	7.89
Youngtown	1964-1999	9.17

[4] The internet address for the Western Regional Climate Center precipitation data is http://www.wrcc.dri.edu/index.html. A link describing their mission and personnel is http://www.wrcc.dri.edu/wrccmssn.html.

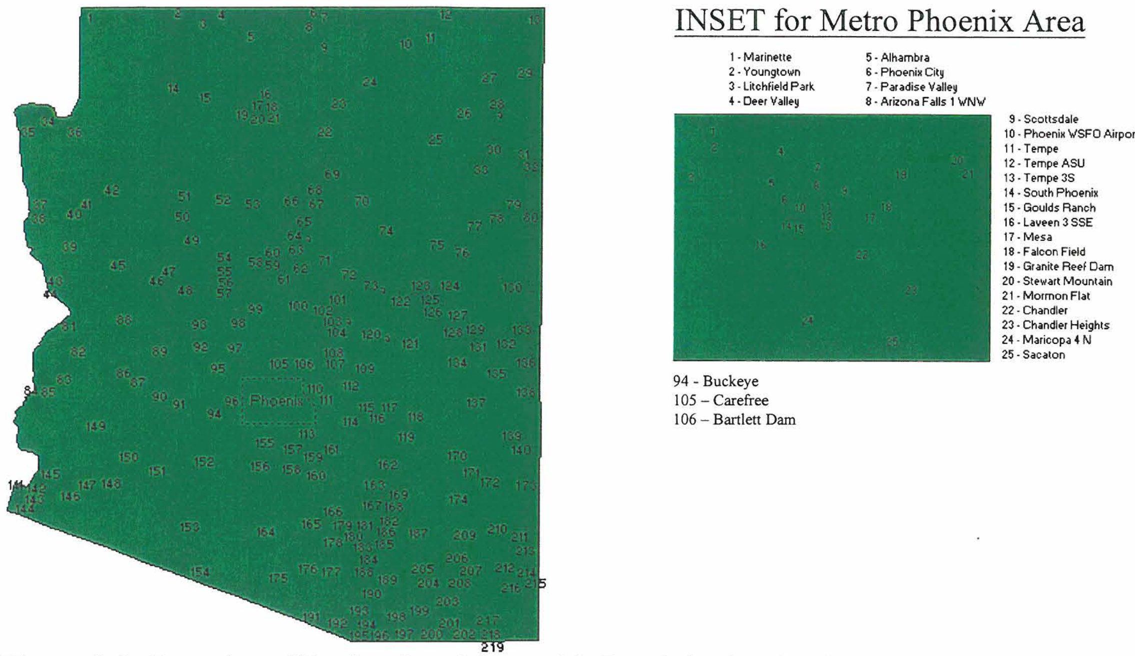


Figure 2-8. Location of Regional and Statewide Precipitation Stations.

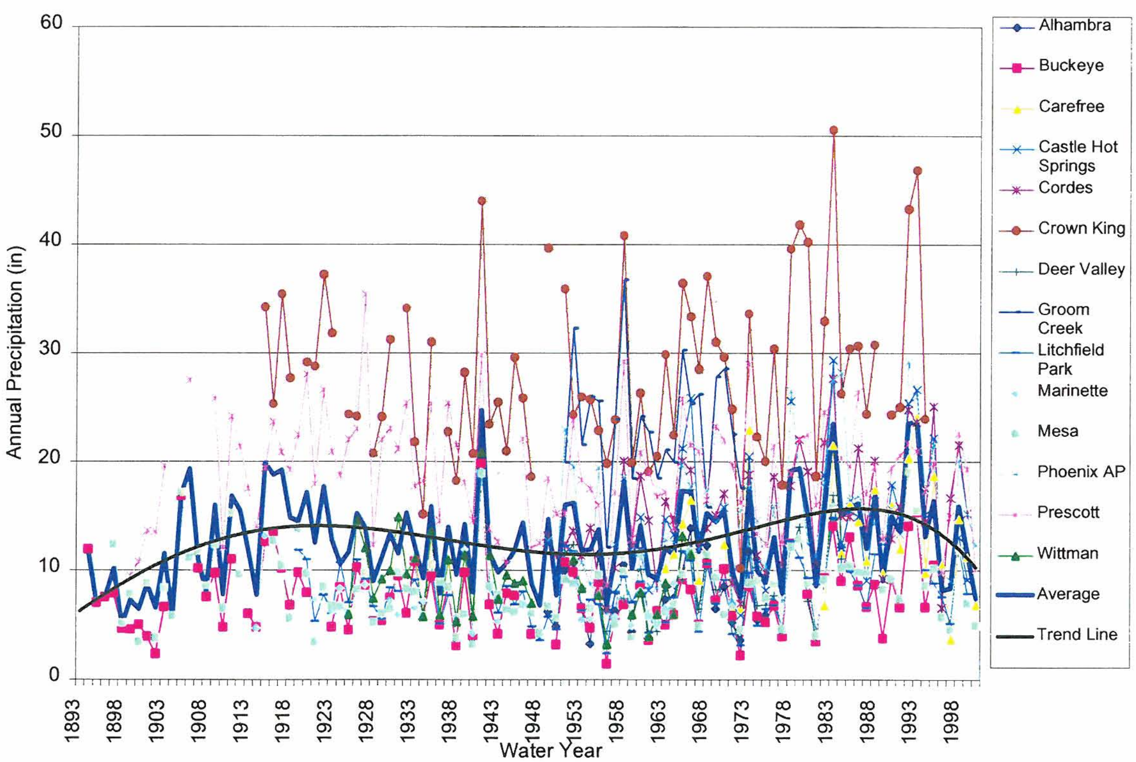


Figure 0-9. Historical Precipitation Data and Average for Stations in Central Arizona, 1893-2000.

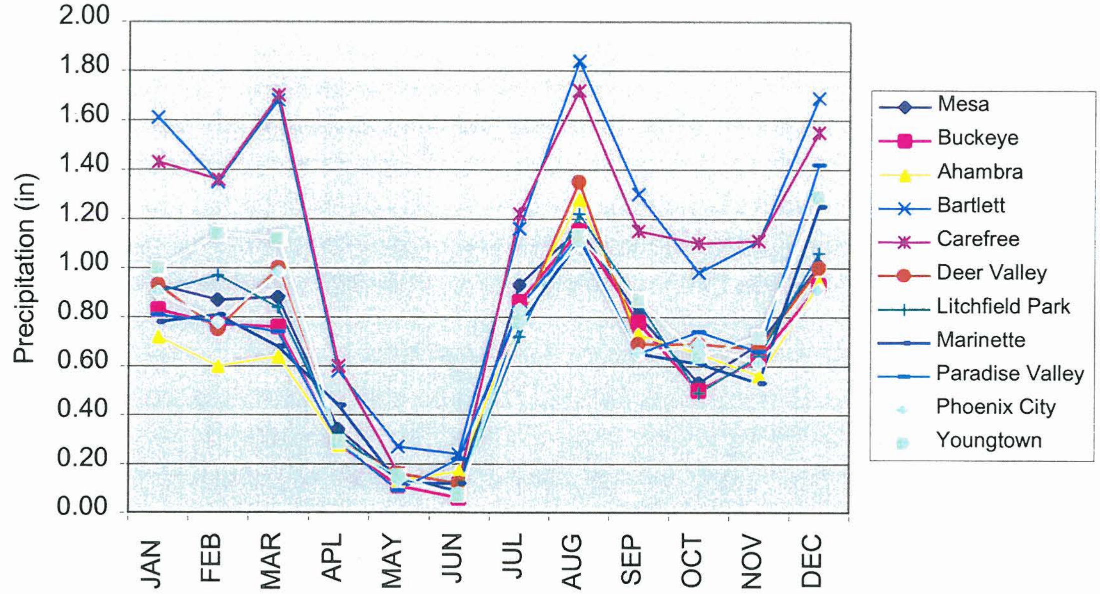


Figure 2-10. Long-Term Average Monthly Precipitation for Stations Near Skunk Creek.

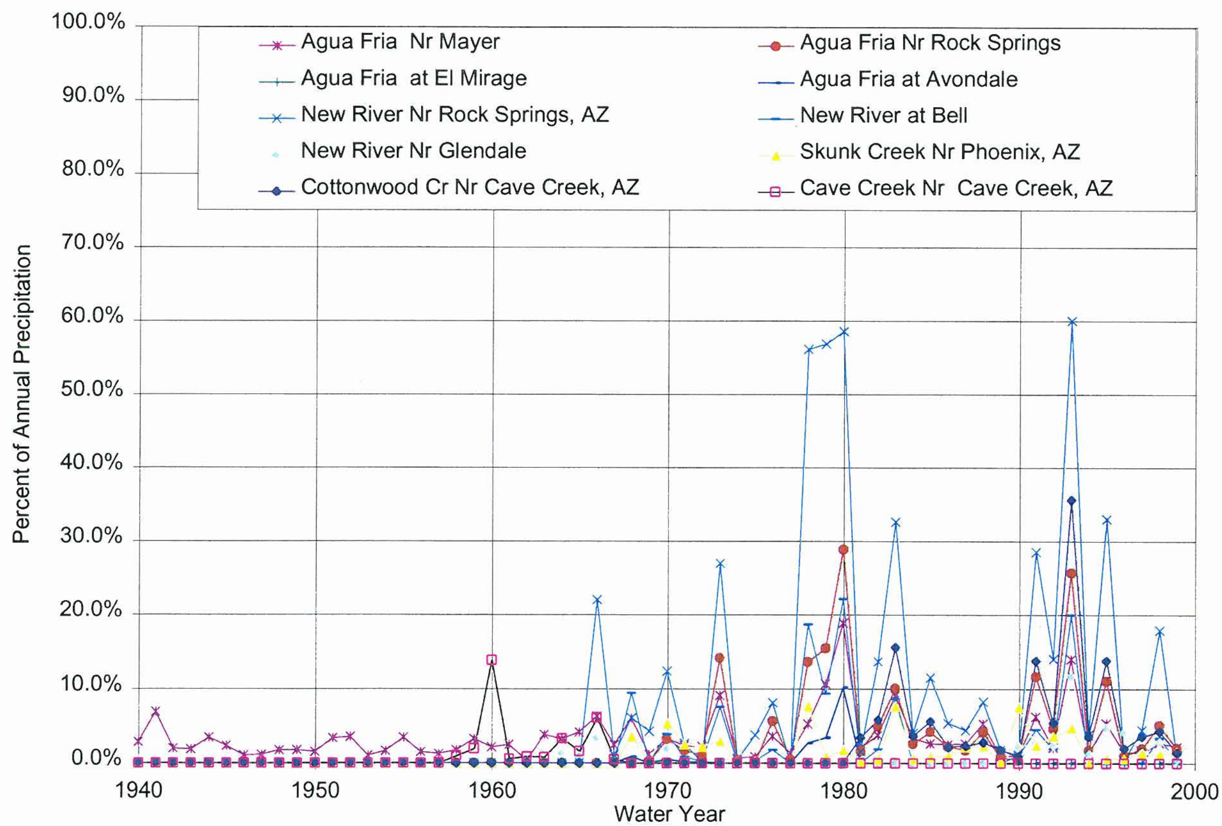


Figure 2-11. Runoff as a Percentage of Regional Average Precipitation, 1940-1999.

From the data presented in Table 2-5 and Figures 2-8 to 2-11, the following conclusions can be drawn:

- Long-Term Trends. Figure 2-9 shows the regional average annual precipitation,[5] as well as a 5-year moving average and the trend line of the annual values. The trend line indicates that annual precipitation volume has increased during most of the latter half of the 20th century until about 1996, increasing the likelihood of runoff that could cause channel change.

- Wet/Dry Cycles. Sustained periods of above average precipitation, or wet cycles, occurred from about 1904 to 1922, from 1938 to 1944, from 1978 to 1986, and from 1990 to 1995. Sustained periods of below average precipitation, or dry cycles, occurred from 1896 to 1904, from 1943 to 1963, and 1968 to 1978. Channel change should be expected during periods of high runoff resulting from extreme precipitation, particularly when wetter periods immediately follow periods of sustained drought.

- Wet Years. Years of unusually high annual precipitation occurred in 1905, 1941, 1965, 1978, and 1993. The percent of rainfall that became runoff typically spiked during the wet years, according to the data presented in Figure 2-11.

- Floods. The occurrence of floods during wet years or wet cycles is discussed in the following section of this chapter. A comparison of Figures 2-5 and 2-9 indicates that years of high annual precipitation correlate moderately well to years of high annual runoff volume, with one notable exception in 1960.

- Seasonal Variation. Precipitation records support the conclusion of a winter and late summer period of seasonal high flow indicated in Figure 2-10. These seasonal variations in precipitation are expressed more strongly in the precipitation records of the Carefree and Bartlett stations than in stations located elsewhere in the Phoenix area. This difference noted at the Carefree and Bartlett stations may be the result of the generally higher elevation and somewhat more northerly location of these stations as compared to the other stations. The upper portion of the Skunk Creek watershed lies north of, and at an elevation more comparable to, the Carefree station. The lower, downstream end of the study area watershed extends closer to the Deer Valley station whose record matches more closely with the other Phoenix area stations.

More detailed interpretation of the implications of these long-term precipitation records will be provided in the following section and in later chapters of this report.

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[5] Average of the annual precipitation totals for all of the stations shown in Table 2-5.

Flooding
Much of the geomorphic work of channel change occurs during the largest floods. Records of large and small floods were obtained primarily from USGS gauge records. No suitable sites for paleoflood reconstruction of the pre-gage flood history were found within the study area.

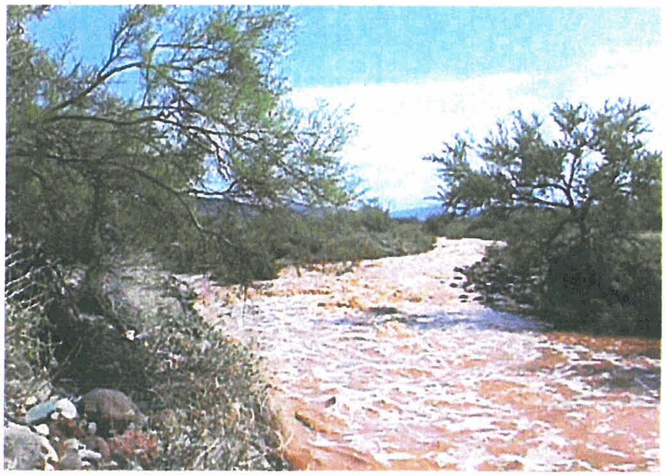


Figure 2-12. July 15, 1999 flood on Skunk Creek downstream of Carefree Highway.

Historical Floods. Historical records of floods on Skunk Creek and its tributaries were obtained from engineering reports, historical documents, newspaper articles and the files of the Phoenix and Cave Creek Historical Societies. A list of large floods that impacted the study area is provided in Tables 2-6 and 2-7. Several small floods occurred on Skunk Creek during the course of this study, including the one shown in Figure 2-12.

Table 2-6. Skunk Creek Watercourse Master Plan
Historical Floods on Skunk Creek

Date	Details	Source	Location
1943 8/3/43	"…overflow from Skunk Creek drainage areas…"	Desert Flood of August 3, 1943	FCD (802.010)
1964 8/3/64	Photos	Skunk Creek Photographs and Newspaper Articles 1964-1965	FCD (007.125)
1967 12/16, 20/67	"Heavy rains a hardship to Valley residents."	Arizona Republic	FCD (007.114)
	Photos (12/20/67)	Newspaper Articles and Photos: Flooding Events 1966-70	FCD (007.105.2)
1988 April	Flooding	Flood Alert Summary for the Month of April 1988	FCD (802.040)
1990 9/4/90	Photos	Newspaper Articles and Photos: Flooding Events 1983-1990	FCD (007.108)
1993 January	Flood report	Storm Report: After Action Report: The Floods of January 1993	FCD (802.050)

NOTES:
1. No published flood records for the Sonoran Wash system were identified. Field evidence suggests that at least one event exceeded the bankfull discharge and inundated the floodplains of Sonoran Wash within the past 20 years.
2. References listed with FCD (##) codes in this Table are on file at the FCDMC Library.

Table 2-7. Skunk Creek Watercourse Master Plan Dates of Regional Floods in Central Arizona			
Date	**Stream Names**	**Notes**	**Source**
March, 1884		Heavy rain, rain on snow	Durrenberger, 1978
February 19-22, 1890	Salt, Gila, many others	Heavy rain, rain on snow	USACOE, 1982
February 16-23, 1891	Agua Fria, Salt, many others	Heavy rain, rain on snow	USACOE, 1982
Winter, 1905	Regional	Sustained rainfall	USACOE, 1982
January 28-30, 1915	Agua Fria	High intensity rain	USACOE, 1982
January, 1916	Agua Fria	Heavy rain on snow pack	USACOE, 1982
July 24-30, 1917	Agua Fria	High intensity rain	USACOE, 1982
November 22-28, 1919	Agua Fria	Heavy rain on snow	USACOE, 1982
September 1-2, 1922	Agua Fria	High intensity rain	USACOE, 1982
February 11-17, 1927	Agua Fria, Hassayampa	Heavy rain on snow	USACOE, 1982
1935	"Severe local storms"	Intense rainfall	USACOE, 1964
1936	"Severe local storms"	Intense rainfall	USACOE, 1964
1939	"Severe local storms"	Intense rainfall	USACOE, 1964
1943	"Severe local storms"	Intense rainfall	USACOE, 1964
August 26-29, 1951	Trilby Wash, Hassayampa	High intensity rain	USACOE, 1982
August 19, 1954	Queen Creek	High intensity rain. COE estimates Q=60,000 cfs had storm centered on Cave Ck.	USACOE, 1982 USACOE, 1964
1956	"Severe local storms"	Intense rainfall	USACOE, 1964
1957	"Severe local storms"	Intense rainfall	USACOE, 1964
1963	"Severe local storms"	Intense rainfall	USACOE, 1964
September 3-7, 1970	Agua Fria, Hassayampa, New River	High intensity rain	USACOE, 1982

Gauged Floods. Gauge records dating back to 1960 exist for Skunk Creek. The annual peak flood series for Skunk Creek and Cave Creek are shown in Figure 2-13. A depiction of the distribution of flood occurrence by month is shown in Figure 2-14. A list of significant floods on Skunk Creek over 3,000 cfs is provided in Table 2-8.

Figure 2-13. Annual Peak Discharges @ USGS Gauge Stations

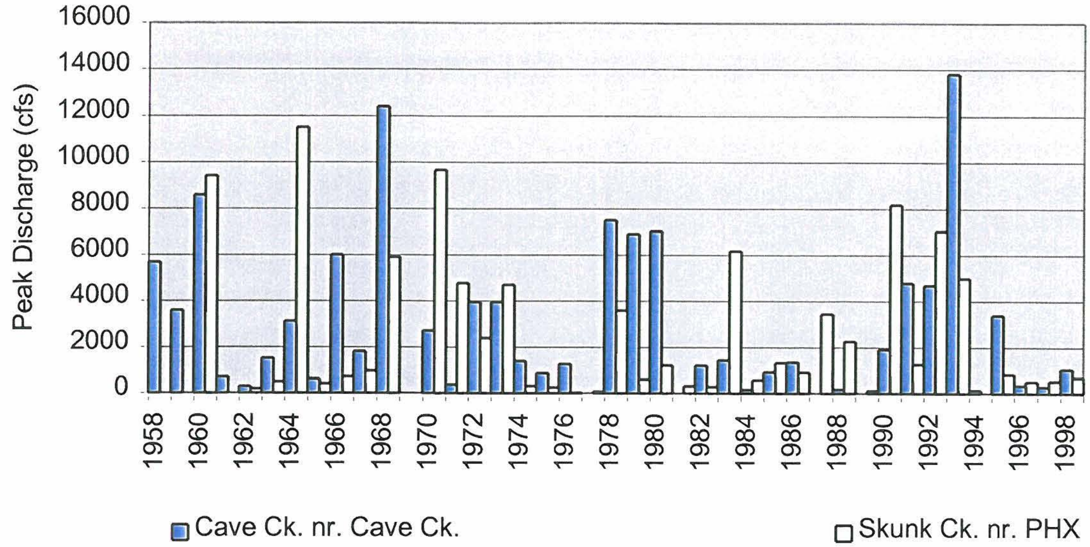


Figure 2-14. Seasonal Distribution of Floods

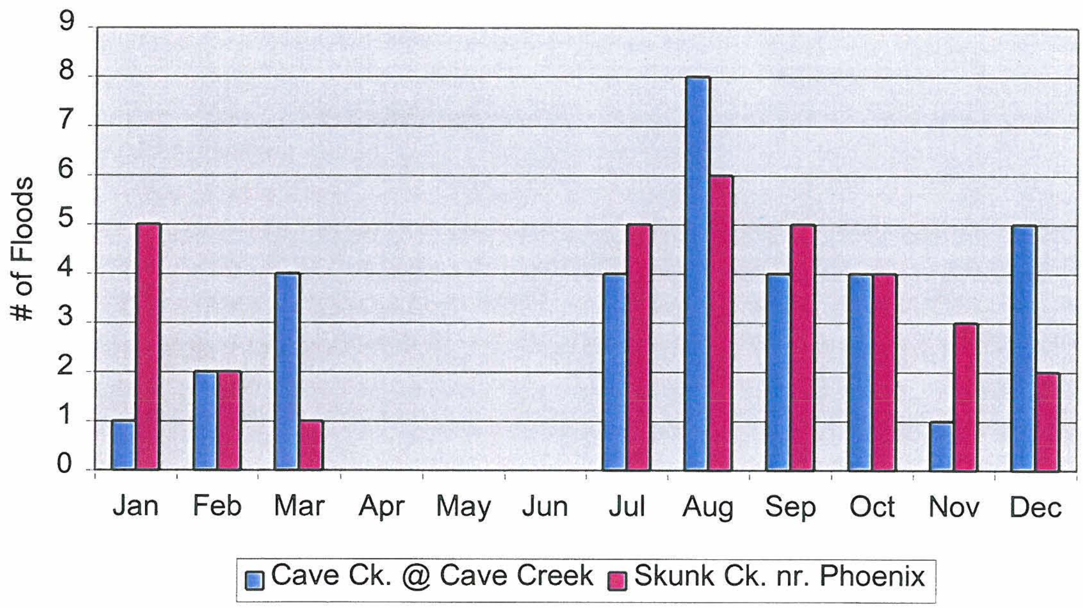


Table 2-8. Skunk Creek Watercourse Master Plan Distribution of Annual Peak Discharge, in cfs											
Skunk Creek near Phoenix (09513860): 1960-1999											
Jan	Feb	March	April	May	June	July	August	Sept	Oct	Nov	Dec
70	400	3590				2380	11500	950	4700	6170	9400
600	1210					300	700	9650	240	2250	5900
1320	676					13	4770	565	281	500	
111						311	8160	822	3440		
4990						906	1250	531			
						2620	7020				
Cave Creek near Cave Creek (09512300): 1958-1999											
Jan	Feb	March	April	May	June	July	August	Sept	Oct	Nov	Dec
3380	279	1420				610	148	332	132	856	280
13800	1260	4780				1350	170	696	1200		910
		7500				1900	364	1800	3950		6000
		1040				3950	1390	2700	8570		6900
						390	1510	5680			12400
							3120				
							3590				
							4680				

Table 2-9. Skunk Creek Watercourse Master Plan
Significant Gauged Floods on Skunk Creek and Flood Peaks on Adjacent Streams (cfs)

Date Of Flood	USGS Streamflow Station				
	Skunk Creek near Phoenix	**Rank of Skunk Ck. Flood**	**Cave Creek near Cave Ck.**	**Cave Creek Below Cottonwood Ck.**	**New River Rock Springs**
1959 (10-29-59)	9,400	3	8,570	-	-
1964 (8-1-64)[1]	11,500	1	2,900[2]	-	4,900[3]
1968 (12-19-67)	5,900	7	12,400	-	10,600
1970 (9-5-70)	9,650	2	2,700	-	18,600
1971 (8-21-71)	4,770	9	-	-	-
1972 (7-17-72)	4,700	10	-	-	-
1978 (3-2-78)	3,590	11	7,500	-	13,600
1979 (12-18-78)	600	14	6,900	-	6,530
1980 (2-20-80)	1,210	13	7,020	-	9,350
1982 (11-30-82)	6,170	6	-	-	-
1990 (8-12-90)	8,160	4	-	-	-
1992 (8-23-92)	7,020	5	-	-	-
1993 (1-8-93)	4,990	8	13,800	9,200	12,600
1999 (7-15-99)	2,620	12	390	1,640	529

Notes:
1. Skunk Creek gauge operated as crest stage gauge only at that time.
2. Therefore, the date reported for peak discharge on Skunk Creek must be considered an estimate.
3. On August 2, 1964 a peak of 3,120 cfs is also reported by the USGS at this station.

The flood data shown in Figures 2-13 and 2-14, and Tables 2-8 to 2-9 indicate that most (~60%) of the annual floods on Skunk Creek during the period of record occurred during the late summer monsoon. Similarly, eight of the 14 largest annual peak discharges between 1959 and 1999 also occurred during the summer monsoon, which typically occurs between late June and mid September (Table 2-9). In contrast, all but one of the six largest floods on Cave Creek occurred during winter.

Flood Frequency. Estimates of flood frequency were obtained from the work of others, including the USGS (Pope et. al., 1998) and Tetra Tech Inc. (2001). The HEC-1 modeling methodology used to estimate flood magnitude and frequency for the Skunk Creek Watercourse Master Plan is presented in a companion volume prepared by Tetra Tech Inc. (2001). Peak discharge and volume estimates accepted by the FCDMC for use in the Watercourse Master Plan are shown in Table 2-10. Estimates of peak discharge obtained by statistical analysis of USGS streamflow records are shown for comparison in Table 2-11, and USGS regression equation results are shown in Table 2-12. Note that the decrease in future condition 100-year discharges modeled using HEC-1 is due to consideration of the County's 2-hour 100-year retention requirement.

Table 2-10. Skunk Creek Watercourse Master Plan
Summary of HEC-1 Computed Peak Discharges

HEC-RAS Section	HEC-1 Concentration Point	Peak Discharge in cfs					
		2-year		10-year		100-year	
		Existing	Future	Existing	Future	Existing	Future
Skunk Creek							
25.72	S6C	1,463	1,985	3,718	4,464	7,840	8,811
24.74	S10C	1,674	2,642	4,494	5,925	9,741	11,837
24.12	S13C	2,070	2,749	5,485	6,221	11,811	12,587
23.55	S14C	3,845	3,983	11,155	9,852	24,427	20,910
22.08*	S16C	4,868	5,046	12,778	11,462	27,332	23,669
18.57	S21C2	4,948	4,994	12,807	11,796	27,733	24,642
17.95	S22C	4,872	4,881	12,583	11,663	27,283	24,474
16.68	S23C	4,712	4,740	12,229	11,425	26,513	24,126
Sonoran Wash							
3.70	C002L	1,068	120	2,498	1,798	3,267	3,454
2.73	C002	2,008	121	4,892	3,295	6,492	7,246
---	C003L	1,882	74	4,829	2,227	6,303	5,695
2.08	C003	2,241	74	6,235	2,477	8,359	6,861
---	C007L	2,063	49	5,754	3,893	8,039	5,856
0.52	C007	2,338	65	6,785	2,539	9,664	6,671
---	C009 (U13A)	127	152	343	388	472	525
---	C010L	2,044	52	6,369	2,176	9,203	5,889
---	C010	2,098	52	6,712	2,241	9,825	6,098

Notes:

- Original FEMA FIS showed addition of Rodger Creek discharge at RM 22.79. JEF interprets more correct location to be at RM 22.08 for the 100-yr discharge and RM 21.41 for the 2-, and 10-yr discharges.
- HEC-1 concentration point locations are provided in the Hydrology Report (Tetra Tech, 2001).

Table 2-11. Skunk Creek Watercourse Master Plan USGS Flood Frequency Estimates For Skunk Creek								
Station	Area (mi^2)	Mean Elev. (ft)	Recurrence Interval (yrs)					
			2	5	10	25	50	100
Skunk Creek nr. Phoenix, AZ (Pope & others, 1998)	64.9	2,180	940	3,230	6,120	12,100	18,700	27,600
Using station skew and data through 1999 (JEF, 2000)	64.9	-	1,100	3,910	6,870	11,500	16,150	21,000

Table 2-12. Skunk Creek Watercourse Master Plan USGS Regression Equation Discharge Estimates for Skunk Creek and Sonoran Wash (cfs)									
HEC-RAS Section	HEC-1 Concen'n Point	Area (mi^2)	Mean Elev. (ft)	Recurrence Interval (yrs)					
				2	5	10	25	50	100
Skunk Creek									
26.17	S6C	8.04	2492	150	720	1,320	2,470	4,500	7,100
24.74	S10C	12.66	2392	200	1,000	1,810	3,340	6,200	9,600
24.12	S13C	15.76	2369	230	1,160	2,100	3,850	7,100	10,900
23.55	S14C	32.67	2605	370	1,850	3,280	5,870	10,500	15,900
22.08	S16C	40.10	2558	420	2,150	3,780	6,730	11,900	17,900
18.57	S21C2	42.33	2522	430	2,240	3,940	7,000	12,400	18,500
16.68	S22C	48.58	2433	470	2,490	4,380	7,740	13,600	20,300
13.28	S23C	50.30	2405	480	2,570	4,500	7,940	13,900	20,700
Sonoran Wash									
2.93	C002	5.00	1753	110	590	1,110	2,090	3,900	6,100
2.35	C003	7.72	1754	150	790	1,480	2,750	5,100	8,100
1.72	C007	11.12	1725	190	1,020	1,890	3,490	6,600	10,200
0.92	C009	0.35	1709	20	100	190	400	500	800
0.52	C010	13.39	1711	210	1,170	2,150	3,930	7,400	11,500

The following conclusions can be drawn from the data summarized in Tables 2-10 to 2-12:

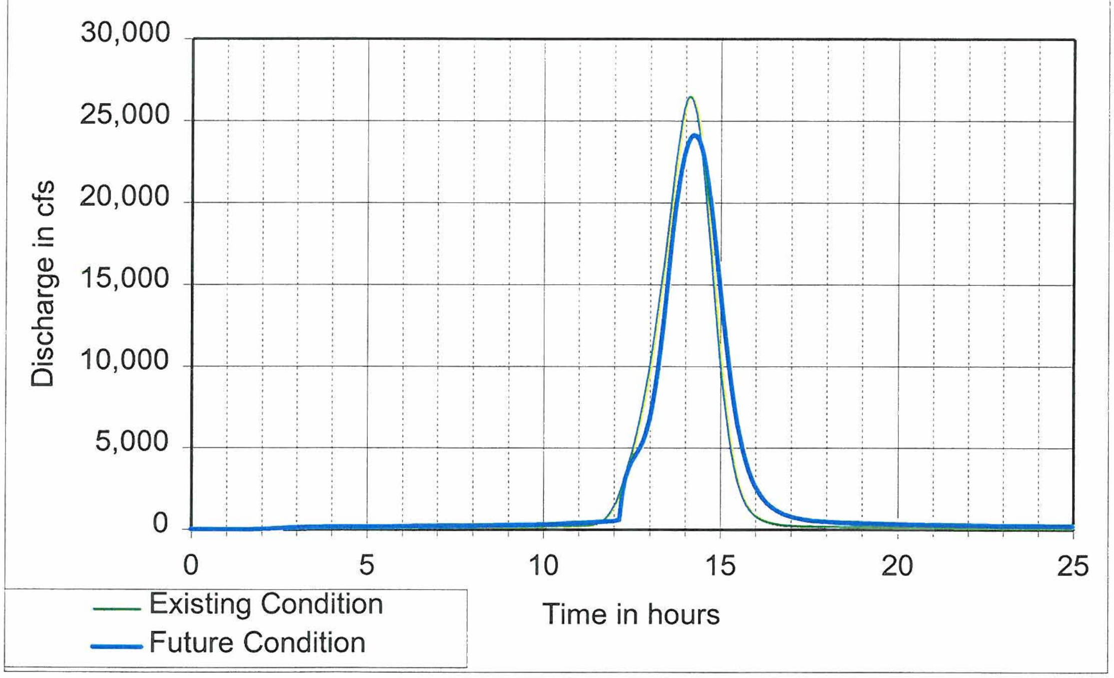
- Recurrence Interval of Gauged Floods. The largest flood on Skunk Creek during the period of record occurred on August 1, 1964. This flood had a recurrence interval of about a 25-year event at the Skunk Creek near Phoenix station, according to the USGS statistical summary (Pope et. al., 1998). The 1959 and 1970 floods had a recurrence interval about equal to the 15-year event. All other gauged floods had recurrence intervals of less than 15 years. The study reach has not experienced a 100-year flood, or even an event close to the 100-year event during the 40 year period of record or during the period for which historical aerial photographs are available.

- Peak Discharge Estimates. Comparison of the USGS flood frequency results and the HEC-1 modeling results shown in Tables 2-10 to 2-12 indicates that the estimates of 100-year peak discharge used for the Watercourse Master Plan are conservative (i.e.

higher than the estimates based on regression equations or statistical analysis of gauge data). HEC-1 modeling results are even more conservative for the 2- and 10-year events.

Hydrologic Modeling
Design hydrographs for existing conditions and future conditions were generated from the HEC-1 modeling results (Tetra Tech Inc., 2001). For modeling purposes in this study, "future condition" was defined as full build-out of the watershed at the densities and types of development allowed in the existing zoning plan, including application of county and city retention/detention policies. The HEC-1 peak discharge estimates for existing and future conditions were listed in Table 2-10 above. For application to the geomorphic analysis, individual hydrographs were discretized into constant discharge segments of known duration so that hydraulic data could be applied over the full hydrograph. In general, the geomorphic analyses used the future condition hydrograph where prediction of future trends in river morphology or channel movement was evaluated.

Figure 2-15. Skunk Creek HEC-1 100-year Storm Hydrograph



The 100-year hydrograph at the downstream study limit of Skunk Creek is shown in Figure 2-15. A complete description of the hydrographs for each of the stream segments within the study area is provided in the Hydrology Report (Tetra Tech Inc., 2001).

Stream Classification

The primary objective of stream classification is to match measurable stream characteristics with expected river responses. The following two classification systems were applied to the stream segments within the Skunk Creek study area: (1) a descriptive classification system based on the Brice system, and (2) the morphologic and field-based Rosgen system. Data for the stream classification were obtained from field surveys of the project site, topographic mapping, aerial photographs, and published reports. Only the channel characteristics required to perform the stream classification are presented here. More detailed discussions of specific channel characteristics and specific reaches are provided in Chapter 4 of this report.

Brice Classification System

The Brice system was developed primarily for the evaluation of stream stability near roadways or bridge structures, but is not limited to highway design applications. The Brice System uses readily identified stream characteristics to make subjective predictions of lateral stability (FHWA, 1991; Brice and Blogett, 1978). Use of the Brice Classification system is appropriate for the Skunk Creek Watercourse Master Plan since one of the primary objectives is to assess stream stability and the potential for lateral migration. The Brice system assigns relative erosion potential classifications based on the 13 stream characteristics summarized below (Table 2-13). These classifications can be used to prepare a subjective, relative assessment of the potential for lateral migration. Where high or moderate potential for lateral migration is identified, more detailed analysis of lateral erosion potential is warranted.

Table 2-13. Skunk Creek Watercourse Master Plan Brice Classification System		
Stream Characteristic	**Skunk Creek**	**Sonoran Wash**
Stream Size	Medium (100-500 ft) Average channel width = 130 ft.	Small (<100 ft) Average channel width = 76 ft.
Flow Habit	Ephemeral Flashy	Ephemeral Flashy
Bed Material	Gravel (med. gravel to small cobbles) D_{50} = 9mm; D_{90} = 102 mm	Gravel (med. gravel to small cobbles) D_{50} = 14mm; D_{90} = 78mm
Valley Setting	Relict alluvial fan Low relief (<100 ft.)	Relict alluvial fan Low relief (<100 ft.)
Floodplain	Narrow (2-10x chl width) Avg. floodplain width = 1140 ft. (9x Skunk Creek channel width)	Narrow (2-10x chl width) Avg. floodplain width = 560 ft. (7x Sonoran Wash channel width)
Natural Levees	Little or none	Little or none
Apparent Incision	Slightly incised Average bank height = 5-11 ft.	Slightly incised Average bank height = 3-6 ft.
Channel Boundaries/ Bank Materials	Alluvial Local bedrock in banks upstream Cline Ck, @ Carefree Hwy	Alluvial Local bedrock
Bank Vegetative Cover	< 50 percent Average = 49 %; Range = 0-90 %	50-90 percent Average = 65 %; Range = 40-95 %
Sinuosity (S)	Straight (S = 1.0-1.05) Average sinuosity = 1.05	Sinuous (S = 1.06-1.25) Average sinuosity = 1.07
Braiding	Locally braided (24 %) Braided low flows	Locally braided (18 %) Braided low flows
Anabranching	Locally anabranched	Locally anabranched
Width Variability Bar Development	Random variation Irregular point & lateral bars	Random variation Irregular point & lateral bars

Each of the Brice classification system categories are discussed briefly below. More detailed descriptions of the geomorphic characteristics of the study area are provided in Chapters 3 and 4, and in Appendix A. Definitions of key terms are provided in the Glossary (Chapter 9).

1. Stream Size. The potential for, and scale of, lateral erosion generally increase with stream size. Skunk Creek has a larger active channel (130 feet) than Sonoran Wash, and thus has a larger potential for lateral channel movement based on its size alone.
2. Flow Habit. Perennial streams tend to experience more frequent erosion than ephemeral streams in equivalent climates. However, in arid regions where flash floods and unstable bank materials can cause significant lateral erosion, ephemeral streams are often highly erosive. Skunk Creek and Sonoran Wash are ephemeral and experience flash floods, and thus are subject to rapid rates of lateral movement and long-term fluctuations in bed elevation.
3. Bed and Bank Material. The streams in the study area have bimodal bed sediment distributions, with clast sizes ranging from fine sands to boulders. For Skunk Creek, the observed median (D_{50}) bed sediment diameter ranged from 5.3 to 16.0 mm, all

within the gravel size classification. For Sonoran Wash, the observed median bed sediment diameter ranged from 3.8 to 18.7 mm, all within the gravel size classification. Bed and bank materials typically are stratified with sizes varying widely with depth and distance. Stream banks with stratified sediments may be more vulnerable to scour and bank erosion than stream banks with comparable uniform sediment material due to the potential for selective erosion of less resistant layers.

4. Valley Setting. Channel reaches with low valley relief (< 100 ft.) typically have more erosion-prone banks than streams in valleys with high relief. The streams in the study area have low relief. Both Skunk Creek and Sonoran Wash were formed within an entrenched middle Pleistocene-aged alluvial fan complex, a landform which does not fall into the Brice valley setting categories, but is most similar to a low relief valley.
5. Floodplains. Channels with wide floodplains (> 10 times channel width) typically experience more lateral channel movement than channels with little or no floodplain (< 2 times channel width). Skunk Creek and Sonoran Wash have narrow floodplains (2-10 times channel width), which corresponds to an intermediate risk of lateral erosion. Archaeological data suggest that Skunk Creek had a wider floodplain during prehistoric times, prior to regional incision around 1200 A.D., and was subject to higher rates of lateral erosion.
6. Natural Levees. Streams with natural levees tend to have low rates of lateral migration. Skunk Creek and Sonoran Wash do not have natural levees.
7. Apparent Incision. Streams with vertical cut banks are generally unstable. Skunk Creek has incised up to 8 feet within the project reach during the past 800 years, leaving many reaches with near vertical cut banks. Field evidence suggests that about 16 and 10 percent of the banks on Skunk Creek and Sonoran Wash are cut banks, respectively. The degree of incision on the Sonoran Wash system is considerably lower than the incision on Skunk Creek. Channel banks along the Sonoran Wash systems are generally lower, flatter, and better vegetated, and therefore, are less susceptible to some types of lateral erosion.
8. Channel Boundaries and Bank Materials. Alluvial streams are more susceptible to lateral erosion than non-alluvial streams. Bedrock crops out in numerous places on the bed and banks of Skunk Creek upstream of the Cline Creek confluence, and rarely downstream of the confluence. Bedrock crops out in several places in the middle reaches of Sonoran Wash. The channel banks and floodplain in the remainder of the study area are comprised of alluvium. However, where the channel intersects geomorphic surfaces of middle to late Pleistocene age, carbonate (caliche) accumulation cements some layers to near bedrock hardness.
9. Vegetation. Streams that lack adequate vegetative cover along banks tend to be more susceptible to erosion. Dense, woody vegetation may also slow flood velocities against the banks, as well as redirect flow away from the banks. Roots can also stabilize the soils in the banks, by providing a structure that tends to hold bank materials together. Deeper and denser root networks provide greater stability than shallow, less dense roots which tend to be undercut. In general, field evidence

indicates that the banks of Skunk Creek are only moderately well vegetated, with some perched or shallow-rooting species. Sonoran Wash had more well-vegetated banks, with good cover over the entire bank surface.

10. Sinuosity. The streams in the study area have sinuosity values of less than 1.2 and are not considered "meandering" streams. Therefore, their patterns cannot be accurately predicted by published meander geometry relationships.[6]
11. Degree of Braiding. Braided streams tend to be laterally unstable. Skunk Creek and Sonoran Wash are locally braided, especially at very low flow rates. More strongly braided reaches occur where the channel widens, becomes choked with vegetation, and is subject to deposition of coarse sediments. Archaeological evidence suggests that Skunk Creek may have been more braided prior to pre-historic channel incision.
12. Degree of Anabranching. Skunk Creek is locally ananbranched, especially in the reach upstream of the CAP crossing. Sonoran Wash has two reaches with small anabranched channels. Anabranching on Skunk Creek and Sonoran Wash is probably the result of avulsions that formed semi-permanent channels away from the main channel. Anabranching streams are subject to high rates of lateral erosion.
13. Variability of Width and Development of Bars. Streams with relatively uniform width and narrow, regular point bars tend to have slow lateral migration rates. Skunk Creek and Sonoran Wash have irregular channel widths, irregular point bars, and are subject to rapid lateral migration except where bank resistance is increased by soil conditions or bank vegetation.

According to the Brice classification scheme, Skunk Creek and Sonoran Wash exhibit many characteristics that indicate that they are subject to lateral erosion. These broad stream characteristics indicate potential for frequent bank erosion and rapid lateral channel movement within the study area.

Rosgen Classification System

The Rosgen classification system (Rosgen, 1996) is based on measurable channel characteristics observed on streams located primarily in the western mountain region of the United States, although the classification system is now used in many parts of North America. The Rosgen (1996) system was applied to the study area because it has many adherents among State and Federal agencies in the western United States. The field survey techniques used for the study reach incorporated procedures recommended by Rosgen (1996) for obtaining channel sections, pool and riffle spacing, bankfull elevations, entrenchment ratio, slope, meander geometry, bank characteristics, and bed sediment distribution.

The Skunk Creek and Sonoran Wash stream segments in the study area appear to best match Rosgen's D4 (Table 2-14) category, although there are a few significant differences from Rosgen's criteria. Both streams clearly have gravel beds, with slopes

[6] By definition, meandering streams have sinuosity greater than 1.2. Therefore, meander relationships are not applicable to streams with sinuosity less than 1.2.

between 0.003 and 0.013 ft./ft. and sinuosity of less than 1.2, all of which are criteria that fit within the range of expected stream type D characteristics. The width/depth ratio is generally close to, but less than 40 on Sonoran Wash, the cutoff for Rosgen's D4 category.[7] However, the streams are not truly braided during flows that impact its banks, except for a few local subreaches. But because the Rosgen classification system is strongly weighted to low flow conditions (2-year or less) and the channel experiences some braiding at very low flow rates, the D category was assumed to be the most applicable. The Rosgen entrenchment ratio parameter indicates only moderate entrenchment (1.4 – 2.2), although archaeological data (Chapters 3 and 4) have been interpreted by some investigators (Earl, 1983) to indicate that significant entrenchment occurred on Skunk Creek in the past 800 years. Field evidence (Chapter 4) suggests that no more than one to ten feet of degradation may have occurred throughout the study area in the past 100 years.

Table 2-14. Skunk Creek Watercourse Master Plan
Rosgen Classification Data

	Reach #						
Skunk Creek	SR	6	5	4	3	2	1
Rosgen Classification	C/D4	D4	D4	D4	D4	D4	D4
Entrenchment Ratio	3.0	1.7	1.7	1.5	1.5	1.3	1.2
Width/Depth Ratio	24	47	45	48	83	67	91
Sinuosity	1.06	1.06	1.06	1.02	1.02	1.04	1.07
Channel Slope	0.013	0.0093	0.01	0.0085	0.0082	0.008	0.0057
Channel Materials (D50)	9 mm MG	16 mm MG	9 mm MG	9 mm MG	6 mm FG	6 mm FG	5 mm FG
Channel Pattern	S	S	S	S	S	B	S&B

Sonoran Wash	6	5	4	3	2	1
Rosgen Classification	D4	D4	D4	D4	D4	D4
Entrenchment Ratio	1.2	1.5	1.7	1.7	1.9	1.0
Width/Depth Ratio	35	33	34	28	34	78
Sinuosity	1.07	1.07	1.07	1.07	1.07	1.07
Channel Slope	0.0084	0.0069	0.0074	0.006	0.006	0.0032
Channel Materials (D50)	19 mm CG	19 mm CG	19 mm CG	19 mm CG	5 mm FG	4 mm FG
Channel Pattern	S	S	S	S	S	B

Notes:
1. Sinuosity – measured on 1999 aerial photographs
2. Entrenchment *ratio* – Larger of channel or total flow topwidth ÷ Q_2 topwidth (data from HEC-RAS)
3. Width/Depth ratio – Q_2 flow width ÷ Q_2 flow depth (data from HEC-RAS)
4. Channel slope – reach average of HEC-RAS S_o values
5. Channel materials – best fit sediment distribution from sieve and boulder count data
6. Channel pattern codes: B = braided; MC = multiple channel; S = single channel; DIST = disturbed
7. Channel materials codes: F = fine; M = medium; C = coarse; G = gravel; V = very (SCS gradations)
8. SR = Supply reach (upstream of project limits)

[7] The Rosgen categories with lower width/depth ratios have much higher sinuosity and lower entrenchment

The Rosgen description of D4 stream types follows:

> *The D4 stream types are multiple channel systems, described as braided streams found within broad alluvial valleys and on alluvial fans consisting of coarse depositional materials formed into moderately steep terrain. Primarily, the braided system consists of interconnected distributary channels formed in depositional environments. The D4 stream type occurs in moderately steep, narrow, U-shaped glacial valleys; on alluvial fans; and in gentle gradient alluvial valleys. This stream type can also occur on low relief river deltas, as well as on the upper lobes of glacial outwash valleys. The D4 stream channel may be found in Valley Types III,V, VIII,IX, X, and XI*[8]*. Channel bed materials are predominantly gravel, with a strong bi-modal distribution of sands. Cobble may also be found in lesser amounts, often imbedded with sands. The braided channel system is characterized by high bank erosion rates, excessive deposition occurring as both longitudinal and transverse bars, and annual shifts of the bed locations. Bed features are developed from convergence/divergence processes. Bed morphology is characterized by a closely spaced series of rapids and scour pools formed by convergence/divergence processes that are very unstable. The channels generally are at the same gradient as their parent valley. A combination of adverse conditions are responsible for channel braiding, including high sediment supply, high bank erodibility, moderately steep gradients, and very flashy runoff conditions which can vary rapidly from a base flow to an overbank high flow on a frequent basis. Characteristic width/depth ratios are very high, exceeding values of 40 to 50 with values of 400 or larger often noted. D4 channel gradients are generally less than 2%, however, D4 types can also develop within alluvial fans which have slopes of 2% to 4% (D4b). The D4 system is a very high sediment supply system and typically produces high bedload sediment yields. (Emphasis added.)*

The primary differences between the stream segments in the Skunk Creek/Sonoran Wash system and Rosgen's D4 category, as described above, include the following:

- Distributary channel pattern. Except for localized reaches, the streams in the study area do not exhibit a braided or distributary channel pattern as expected for the Rosgen classification.
- Depositional environment. The streams in the study area have experienced net degradation during the past 800 years, as opposed to the net aggradation defined by Rosgen. Evidence of localized deposition of sand and gravel was observed throughout the study area.
- Bed material. Cobbles and boulders material comprise a significant percentage of the bed material, rather than a small percentage as described by Rosgen.

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ratios, and are therefore, a worse fit than the D4 category selected.

[8] These valley types encompass the range of valley types found in the study area.

- Instability. The bed features and channel characteristics, while certainly not stable, are not as unstable as implied in the Rosgen definition.
- Overbank flow. The streams in the study area do not experience frequent overbank flow, as defined by the Rosgen classification system.
- Width/depth ratio. Sonoran Wash generally has a width/depth ratio less than 40, as described above.
- Highly active bank erosion. The streams in the study area have not been subject to extreme rates of bank movement (relative to other Arizona streams) or annual shifts of bed locations. Channel movement typically occurs during floods.
- Pool and riffle. Portions of Skunk Creek and Sonoran Wash have irregular but well developed pool and riffle sequences defined by accumulations of large cobbles and boulders.

The reasons for these discrepancies may include the following:

- Adjustment of the stream channel to entrenched conditions over the past 100 to 800 years.
- Bank vegetation that provides additional stability to the stream banks, effectively altering width/depth ratios and reducing erodibility.
- Inadequacy of the Rosgen system for incised, ephemeral, coarse-bed streams in central Arizona.

Regardless of these differences, if the Rosgen classification is applicable to streams in central Arizona, then the expected channel processes on the Skunk Creek system include high rates of sedimentation, susceptibility to bank erosion, and potential shifts in low flow channel characteristics.

Summary
Stream classification data presented above indicate that Skunk Creek has many characteristics typical of braided, ephemeral streams, although the channel pattern itself is not braided along its entire length. More detailed discussion of specific channel characteristics will be provided in Chapter 4 of this report. The classification systems indicate that lateral channel movement should be expected for the stream segments in the study area and that more detailed evaluation of lateral stability is warranted.

Reach Definition

The gradually changing differences in geomorphic characteristics within the study area, such as those used to perform the stream classification, were not sufficient to define boundaries between adjacent reaches. Therefore, stream reaches were defined based primarily on geographic or hydrologic features such as the following:

- Tributary confluences
- HEC-1 model concentration points
- Bridge or culvert crossings
- Areas of change in channel planimetric form

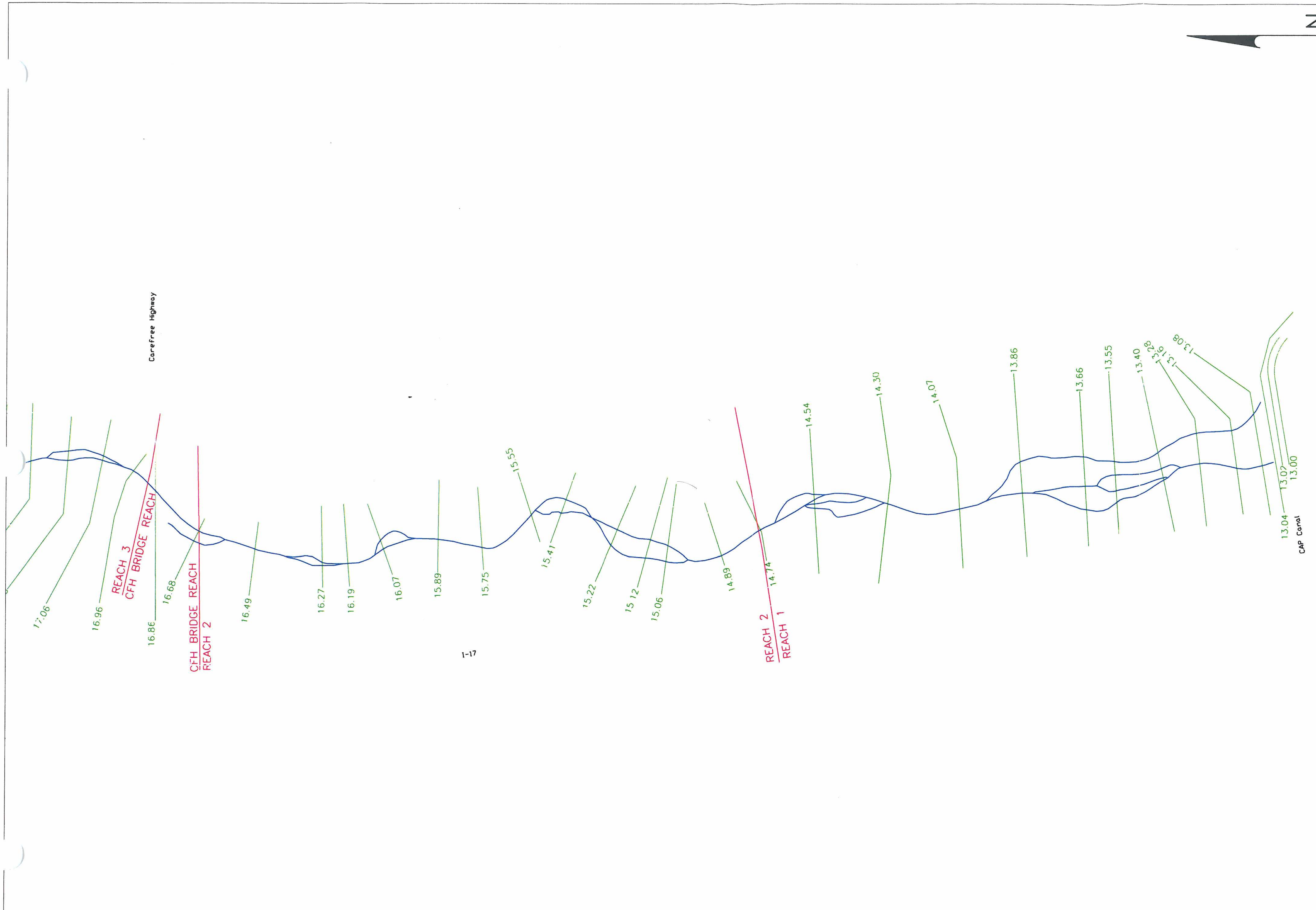
Defining the stream segments based on these geographic features seemed to incorporate the more subtle variations in geomorphic parameters such as bank height, channel pattern, floodplain width, and bank materials. Reaches near bridge and culvert crossings were considered as separate reaches to distinguish the hydraulic impacts of upstream flow contraction, acceleration through the structures, and downstream expansion from the natural characteristics of the less disturbed adjacent reaches. A supply reach was defined for each stream to account for the effects of upstream hydraulics and geomorphology on the study area.

The reaches defined for the Skunk Creek Watercourse Master Plan are listed in Table 2-15 and illustrated in Figure 2-16 and Exhibit 1. Field photographs showing typical conditions in each of the study reaches are shown in Figures 2-17 to 2-32.

Table 2-15. Skunk Creek Watercourse Master Plan
Stream Reach Designation

Reach Code	HEC-RAS Section		Description	Comment	
	D/S End	U/S End			
Skunk Creek					
Supply Reach	25.83	26.17	Upstream of New River Road	Upstream supply reach	
NR Bridge	25.63	25.78	New River Road Bridge	"New River" Reach	
6	23.87	25.56	New River Road to Cline Creek	"New River" Reach	
5	22.15*	23.55	Cline Creek to Rodger Creek	Q100	"Cline Creek"
	21.49	23.55		Q10 & Q2	"Rodger Creek"
4	18.74	22.08*	Rodger Creek to Skunk Tank	Q100	"Rodger Creek"
	18.74	21.41		Q10 & Q2	"Skunk Tank"
3	16.96	18.57	Skunk Tank to Carefree Highway	"Skunk Tank/Carefree" Reach	
CFH Bridge	16.86	16.87	Carefree Highway Bridge		
2	14.89	16.68	Sec. 14 to Carefree Highway	"Cutbank/Knoll" Reach	
1	13.00	14.74	CAP Canal to Sec.14	"Braided/Greasewood" Reach	
Sonoran Wash					
6	3.61	3.84	Upstream end of study reach	"Hackberry" Reach	
5	2.93	3.54	Tributary to double tributary	"Hackberry" Reach	
4	2.35	2.88	19th Ave to tributary	"Ironwood" Reach	
3	1.72	2.28	¼ section to 19th Ave	"Ironwood" Reach	
2	1.15	1.65	Dixileta Dr. to ¼ section	"Main Stem" Reach	
1	0.52	1.09	CAP to Dixileta Dr.	"Sandy" Reach	

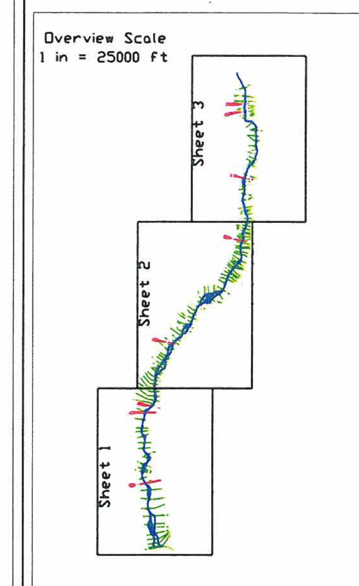
* FEMA FIS HEC-2 model shows addition of discharge from Rodger Creek at RM 22.79. The Reach 5–Reach 4 boundary differs for the 100-yr and the 2-yr & 10-yr models due to intermingling of flood waters from Rodger Creek further upstream in the 100-yr flood than for the 2- or 10-yr floods.



Skunk Creek WCMP

Figure 2-15
Reach Divisions

1999 Thalweg
25.02 HEC-RAS XN
ROADS
REACH LIMIT



DRAWING SCALE
1 INCH = 1500 FEET

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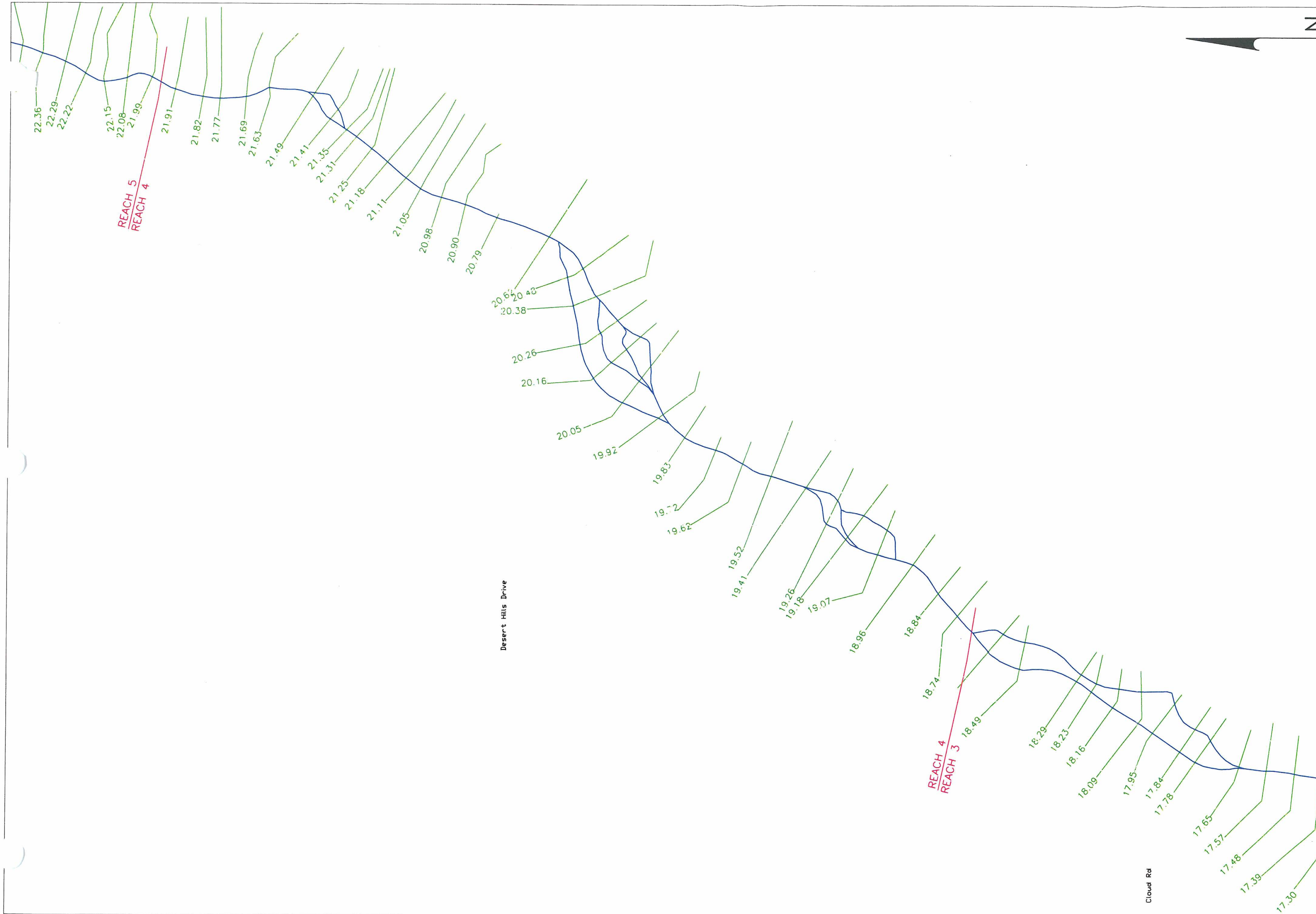
Sheet 1 of 3



Skunk Creek WCMP

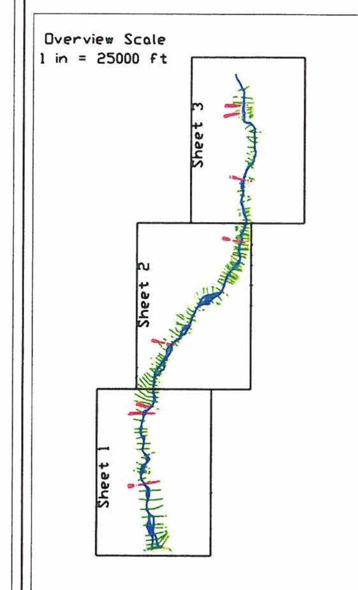
Figure 2-15
Reach Divisions

1999 Thalweg

25.02 HEC-RAS XN

ROADS

REACH LIMIT



DRAWING SCALE
1 INCH = 1500 FEET

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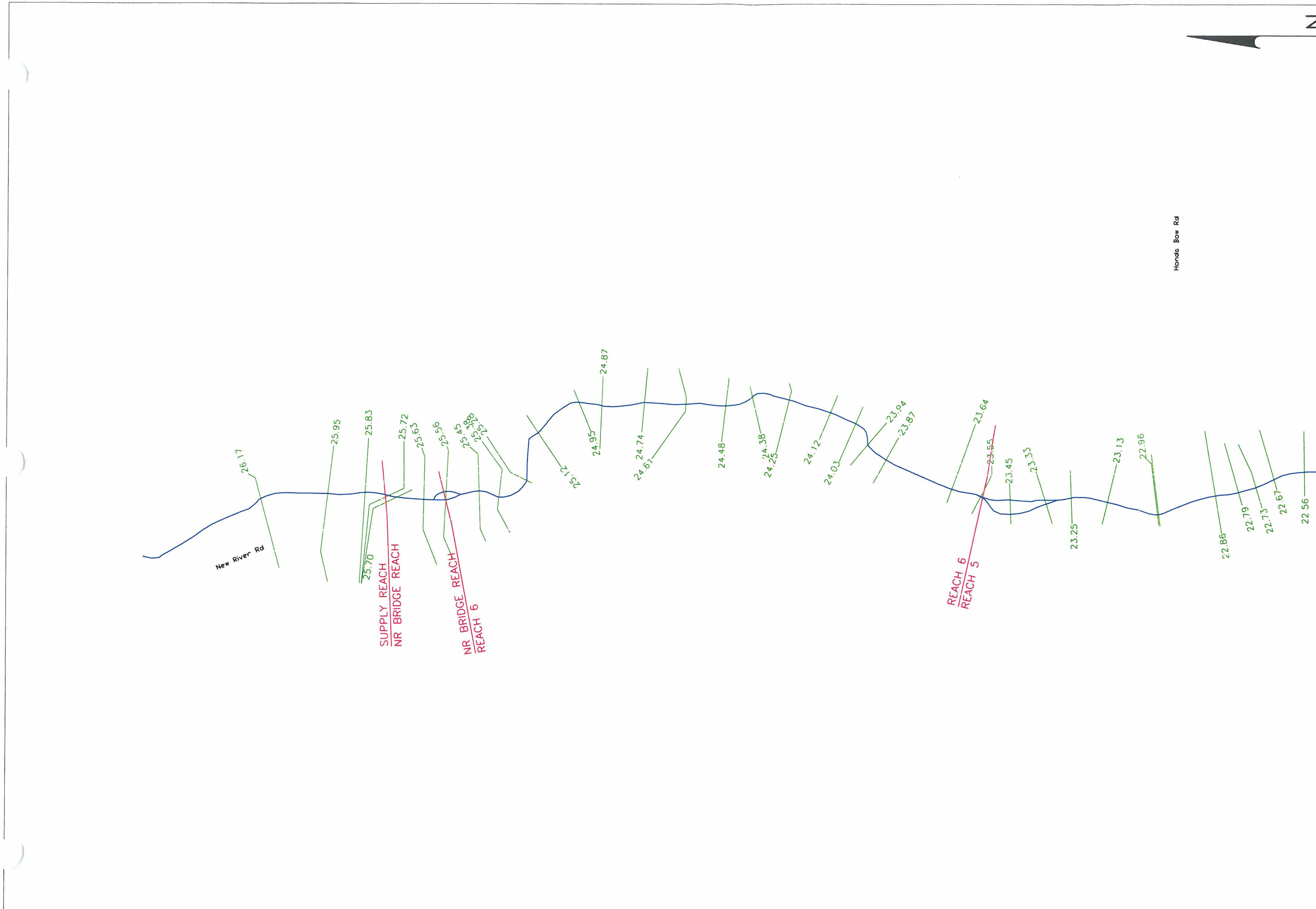
Sheet 2 of 3

Skunk Creek WCMP

Figure 2-15
Reach Divisions

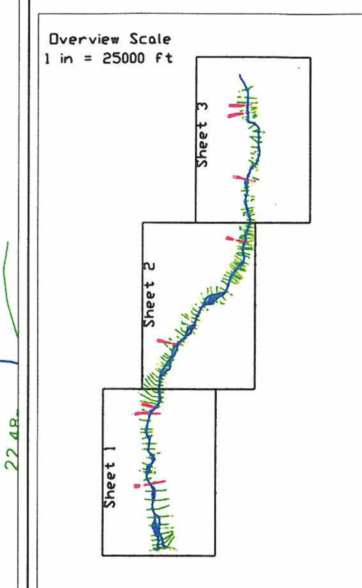


1999 Thalweg

25.02 HEC-RAS XN

ROADS

REACH LIMIT



DRAWING SCALE

1 INCH = 1500 FEET

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The reaches designated in Table 2-15 will be used throughout the remainder of this report.

Figure 2-17. Skunk Creek Reach 1 west channel with cobble bed and channel vegetation.

Figure 2-18. Skunk Creek Reach 1 east channel with sand and boulder bed.

Figure 2-19. Skunk Creek Reach 2 in boulder riffle with sparse channel vegetation.

Figure 2-20. Carefree Highway Bridge over Skunk Creek during July 15, 1999 flood.

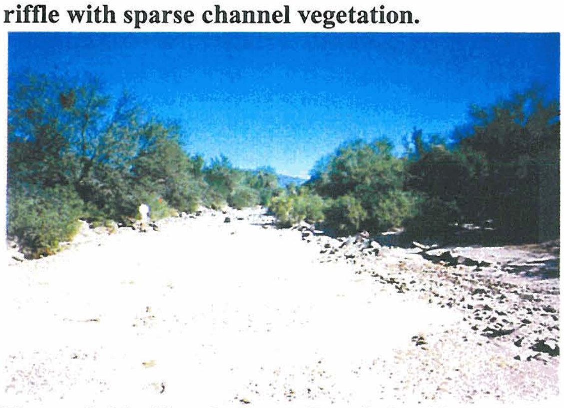

Figure 2-21. Skunk Creek Reach 3 with sand bed in pool reach.

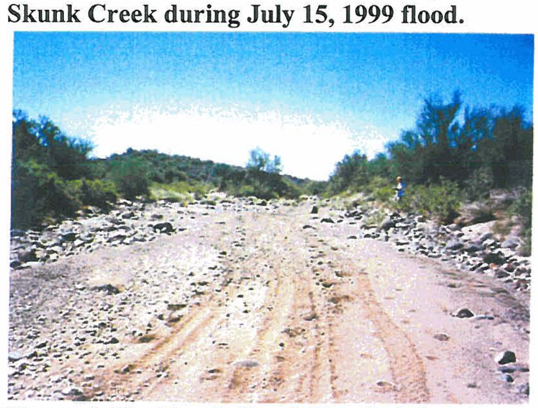

Figure 2-22. Skunk Creek Reach 4 showing contrast in bed and bank materials.

Figure 2-23. Skunk Creek Reach 5 with dense bank vegetation and gravel bed.

Figure 2-24. Skunk Creek Reach 6 with loose sand bed and dense bank vegetation.

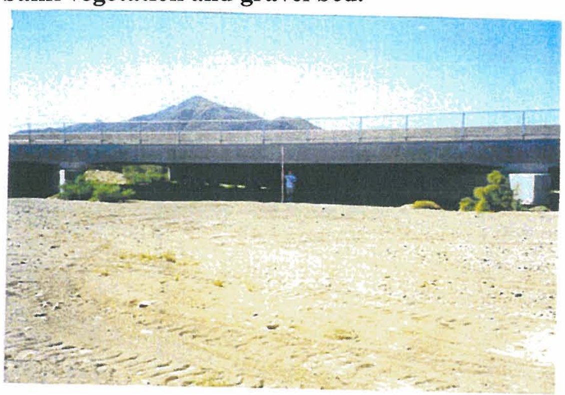

Figure 2-25. New River Road Bridge over Skunk Creek. Site of recent aggradation.

Figure 2-26. Skunk Creek Supply Reach at eroded concrete sill.

Figure 2-27. Sonoran Wash Reach 1 near CAP overchute. Note evidence of aggradation and very dense bank and floodplain vegetation.

Figure 2-28. Sonoran Wash Reach 2 with dense bank vegetation.

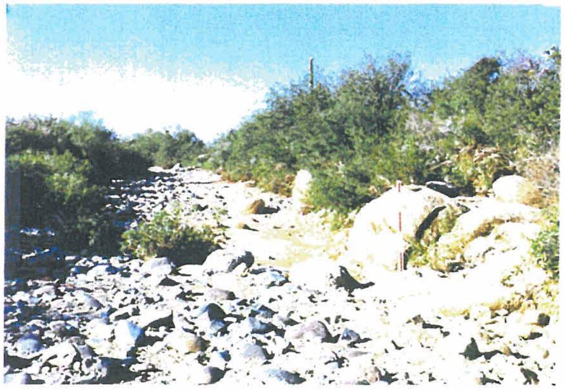

Figure 2-29. Sonoran Wash Reach 3 showing bedrock outcrop in channel bank.

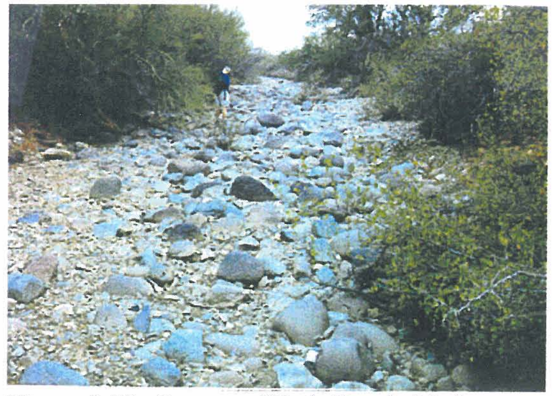

Figure 2-30. Sonoran Wash Reach 4 in long boulder riffle.

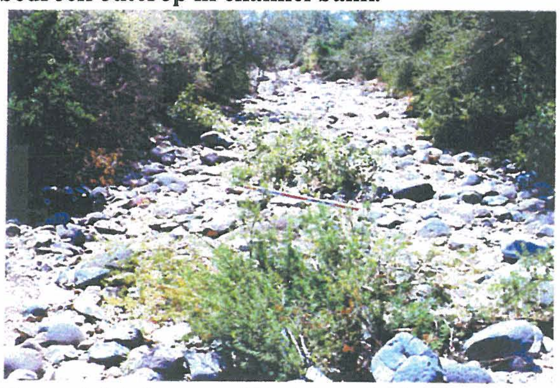

Figure 2-31. Sonoran Wash Reach 5 with boulder bed material and channel vegetation.

Figure 2-32. Sonoran Wash Reach 6 with narrow channel, overhanging vegetation and gravel bed material.

Summary

Understanding the watershed characteristics, regional geologic setting, and hydrologic inputs is fundamental for explaining past stream behavior, for predicting future river processes, and for selecting appropriate tools for analysis of the stream behavior. These fundamental data represent the most important independent variables that control lateral migration. The analyses presented in the following chapters of this report rely heavily on the background data provided in the preceding paragraphs.

Chapter 3
Historical Analysis

A basic assumption of any geologic analysis is that understanding "the past, as preserved in the geologic record, is the key to understanding the future" (NRC, 1996). In the case of the Skunk Creek Watercourse Master Plan geomorphic analysis, this dictum means that to predict future lateral migration, past river behavior must be thoroughly understood. This chapter examines the history of Skunk Creek and Sonoran Wash within the study area.

The primary data sources for the evaluation of the historical geomorphology of Skunk Creek and its tributaries consisted of the following:

- Published summaries of the local archaeological record
- Published descriptions of regional geology
- Historical maps and aerial photographs
- Channel descriptions from historical General Land Office (GLO) surveys
- Field evidence of past channel and floodplain changes

These data sources were used to interpret the history of the Skunk Creek system within the study area, and are presented in the following sections of this Chapter:

- Archaeological Evidence of Channel Change
- Chronology of Documented Channel Change
- Evidence of Historical Channel Change
- Field Evidence of Historical Channel Change
- Historical Human Impacts on Channel Morphology

A summary of the regional geologic history of the study area was presented in Chapter 2 of this report. The locations of stream reaches, channel section locations, and key geographic features referred to in the following sections of this Chapter are shown in Exhibit 1.

Archaeological Evidence of Channel Change

The archaeological history of Skunk Creek is moderately well known due to studies by Arizona State University (Dittert, 1974), investigations completed in conjunction with construction of Adobe Dam (Rodgers, 1974; Bruder, 1982), and the Class I survey completed for this study (Rodgers, 1999). No specific information on the archaeology of Sonoran Wash was available, except for the Class I survey completed to support the right-of-entry permit for access to State Trust land for this project (Rodgers, 1999). The following publications were used to develop the summary of archaeological information presented below:[1]

- The Upper Skunk Creek Watercourse Master Plan Archaeological Assessment of Northern Maricopa County. Rodgers, J.B., 1999
- Prehistoric Settlement and Subsistence Strategies in the Carefree Area, South Central Arizona. Bruder, J.S., 1982
- An Archaeological Survey in the Gila River Basin, New River and Phoenix City Streams, Arizona Project Area. Dittert, A.E., Editor, 1974

Overview

The prehistoric history of central Arizona is divided into several broad time periods. The Paleo-Indian (10,000 to 8,000 B.C.) and Archaic (7,500 to 200 B.C.) periods are the earliest named time periods. However, no fully documented evidence of occupation of the Skunk Creek watershed exists for these early periods, although some archaeologists have speculated that pre-Hohokam occupation of some sites near New River may have occurred (Rodgers, 1999). The period of Hokokam occupation of central Arizona is traditionally divided into four periods: the Pioneer (300 B.C. to 800 A.D.), the Colonial (800 to 1,000 A.D.), the Sedentary (1,000 to 1,200 A.D.), and the Classic (1,200 to 1,450 A.D.). Hohokam farming in central Arizona began as early as 300 B.C. in the Salt/Gila River valleys downstream of the study area, but did not reach the northern portions of the Phoenix basin until the Sedentary or Classic period.[2]

Sherd fragments, radiocarbon dates, and paleomagnetic dates of material found on or below the soil units exploited by the Hohokam indicate that occupation of the Skunk Creek region may have extended from about 800 to 1300 A.D. Hohokam sites on adjacent streams such as Cave Creek, New River, and the Agua Fria River included such features as irrigation and water distribution systems, large villages and farms, and a variety of temporary sites and structures. Sites identified along Skunk Creek were not as large, numerous, or complex as those found along adjacent streams. Rodgers (1999) identified 10 archival sites in the Skunk Creek project area, five of which of were undesignated dirt roads in use between 1894 and 1933. The other five were prehistoric Hohokam sites which may be eligible for Arizona Register of Historic Places nomination. The five sites noted by Rodgers (1999) were designated as follows:

- AZ T:4:2 ASU. This site was recorded by Treat and Dittert (1976), and was located on the low rise between Skunk Tank Wash and Skunk Creek north of the Skunk Tank. The site consists of sparse artifact scatter interpreted to have been a Hohokam temporary campsite or limited activity locus. No date has yet been assigned to the site.

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[1] See bibliography for full references.

[2] The most recent archaeological studies have theorized that the prehistoric occupation of the north Phoenix basin may not have been by the Hohokam culture, but by a cultural group more related to groups in north central Arizona (personal communication from Lynn Neal/SWCA on November 6, 2000). For this report, the more traditional interpretation of Hohokam occupation of the study area will be used.

- AZ T:4:5 ASU. This site was recorded by Treat and Dittert (1976), and was located on the north side of Sonoran Wash at about the 19th Avenue-Lone Mountain alignment. The site is believed to have been several campsites associated with seasonal exploitation of indigenous plant resources. No date has yet been assigned to the site.

- AZ T:4:119 ASM. This site was recorded by Neal (1994) for the Anthem project archaeological survey, and was located within the east floodplain of Skunk Creek at about the Saddle Mountain Road alignment. The site consisted of a temporary surface habitation or field house constructed of dry laid cobble masonry.

- AZ T:4:120 ASM. This site was recorded by Neal (1994) for the Anthem project survey, and was located above the west bank of Skunk Creek at about the Saddle Mountain Road alignment. The site is believed to have been a campsite at which stone tools were made and plant foods were ground and prepared.

- AZ T:4:121 ASM. This site was recorded by Neal (1994) for the Anthem project survey, and was located east of the Skunk Creek channel at about the Saddle Mountain Road alignment adjacent to AZ T:4:119 ASM. The site consisted of a masonry field house and five possible field terraces.[3]

Of the five designated sites listed above, three are small campsites, the other two are single surface habitations of cobble masonry that probably date to the Sedentary period (1000-1200 A.D.) and were probably used in conjunction with local dry farming. None of the archaeological features identified indicate that flow from Skunk Creek was diverted to support farming, or that permanent flow existed in Skunk Creek during the period of Hohokam occupation.

Other archaeological sites identified near the study area include the following:

- NA 17, 222 (Bruder, 1982) identified a site called the "levee site" located along Skunk Creek about 1,000 feet northeast of where Skunk Creek now flows under Interstate-17. This site reportedly had possible remnants of a field house, hearths, boulder-bordered fields,[4] and "a slightly depressed path" which may have actually been a canal, although all evidence of these features was apparently removed during construction of the channelization of Skunk Creek at the I-17 bridge.

- AZ T:4:35 ASM (Rodgers, 1999). This site has been surveyed by Prescott College, Pueblo Grande Museum, and the Bureau of Land Management, but was documented in detail by Rodgers (1985). The site is located about one mile west of Skunk Creek

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[3] Field terraces were associated with capture of sheet and tributary flow, and did not use flow diverted from Skunk Creek (personal communication from L. Neal/SWCA on November 6, 2000).

[4] Boulder-borders identified by Bruder are probably related to diversion of tributary runoff and sheet flow (personal communication from Jim Rodgers/SAS on November 2, 2000 & November 17, 2000; and L. Neal/SWCA on November 6, 2000). Pollen evidence collected by Bruder at the site did not confirm the existence of agriculture at the site.

and upstream of New River Road outside the Watercourse Master Plan study limits, and consists of a large site which includes Hohokam field houses, a hill top fortification, dry farm features such as check dams, linear borders and contour terraces.

- NA 15, 909 (Earl, 1983). Five Hohokam sites near the Adobe Dam that were occupied during 800-1200 A.D. were identified by Bruder (1982). Only one site (NA 15, 909) included habitation units, where a small number of Hohokam gathered and processed native plants and manufactured stone tools (Burder, 1982). Pollen and flotation analyses (Gish, 1982) indicated that a limited amount of agriculture was also practiced at the site. The five Hohokam sites near Adobe Dam are located several miles downstream of the Watercourse Master Plan study limits.

Of all the Hohokam sites near Skunk Creek that are documented in the literature, none have any direct connection to flowing water in Skunk Creek. Earl (1983) incorrectly concluded that the small irrigation features found at Hohokam sites near Adobe Dam relied on extended intermittent runoff from Skunk Creek. However, with the single exception of Earl (1983),[5] archaeologists have interpreted the archaeological sites along Skunk Creek as associated with temporary, seasonal occupation, exploitation of indigenous food supply, and practice of desert (upland) agriculture. Irrigation features in the Skunk Creek watershed, unlike those on Cave Creek and New River, were used to collect and distribute ephemeral runoff from small tributaries. There is no evidence of post-Hohokam occupation of the Skunk Creek region by native American peoples until arrival of Euro-American settlers in the mid-1800's.

Regionally, the Hohokam abandoned farm systems on Cave Creek and New River between 1200 A.D. and 1400 A.D., probably due to declining conditions (Phillips, 1998; Rankin & Katzer, 1989). The reasons suggested by archaeologists for the abandonment include several factors relating to stream stability, such as climatic variability or drought, declining groundwater levels, stream entrenchment, and transition from intermittent to ephemeral stream conditions. Interpretation of the archaeological record of occupation and abandonment of sites along the Cave Creek and New River systems provides several lines of evidence with implications for the Skunk Creek channel stability assessment. These lines of evidence include the following:

- Prehistoric channel conditions
- Prehistoric channel incision
- Climate change
- Prehistoric lateral channel instability
- Prehistoric vegetation cover

Prehistoric Channel Conditions

Prehistoric channel conditions have been inferred from stratigraphic and geomorphic interpretation of the soils surrounding Skunk Creek. Geologic mapping published by the

[5] Mr. Earl was a physical geographer, not an archaeologist.

Arizona Geological Survey (Chapter 2, cf. Holloway & Leighty, 1998) concluded that surfaces adjacent to the active channel of Skunk Creek consist of a series of inset fill terraces ranging in age from Middle Pleistocene (highest terraces) to late Holocene (lowest terraces). The AZGS mapping implies progressive incision of Skunk Creek over the past 10,000 to 100,000 years, with brief periods of filling in response to minor climatic fluctuations. Interpretation of soil profiles examined for this study indicate that Skunk Creek had a roughly consistent regime throughout most of the Holocene, but had considerably less energy than its Pleistocene ancestor.

In direct contrast to the AZGS mapping, Earl (1983) constructed a chronology of channel change based on definition of six regionally-pervasive soils units that represent five aggradational phases during the Holocene. The youngest three of the soil units were assumed to have been deposited by Skunk Creek which existed as a "low energy…small meandering channel" from about 4,000 to 100 b.p. Earl's chronology is founded on the mistaken assumption that the Hohokam required reliable seasonal flows from Skunk Creek to support irrigated agriculture at the Adobe Dam cultural sites. Unfortunately, Earl's chronology and assumptions about late Holocene channel morphology are based on a incomplete understanding of Hohokam irrigation practices, and require the following improbable scenarios:

1. Mid-Holocene tectonic uplift of the Skunk Creek headwaters,
2. Aggradation of gravels and cobbles on the floodplain by a small meandering Skunk Creek channel,
3. Substantially reduced channel transmission losses and extended intermittent flow in Skunk Creek from about 4,000 to 100 b.p., and
4. Occurrence of only passive floods that did not disturb the channel morphology or channel bed sediment characteristics during a period of reduced transmission losses.

Furthermore, soils data collected by JEF for the Skunk Creek Watercourse Master Plan geomorphic analysis do not support the soil unit divisions proposed by Earl. Therefore, while Earl's thesis of radical channel morphology change is an intriguing and attractive explanation for Hohokam abandonment of irrigated farm systems on Cave Creek and New River, the data do not support it.

The common theme between stratigraphic relationships implied by AZGS surficial mapping and Earl's soil chronology is that after a sustained period of floodplain formation and/or channel aggradation, Skunk Creek became entrenched. The interpretation of geologically-recent entrenchment of Skunk Creek is supported by field evidence, regional chronologies of historic arroyo-cutting, and modern topographic data. The exact date of entrenchment is more difficult to determine, but is discussed in more detail later in this chapter.

Skunk Creek Entrenchment

Earl (1983) cites Hohokam-aged artifacts found at shallow depths in the silty sand cap unit of the Skunk Creek floodplain as evidence of post-Hohokam entrenchment. A more logical explanation of buried artifacts is floodplain aggradation during flooding. Artifacts left unburied on a floodplain that appears active, or buried on a floodplain elevated well above the 100-year flood elevation would be more compelling evidence of main channel entrenchment. For example, Hohokam artifacts are commonly found on top of, as well as within, the analogous silty sand cap units on the Cave Creek floodplain, suggesting that regional entrenchment may have occurred around 1200 A.D., at the end of the period of Hohokam occupation. Earl (1983) also cites channel descriptions by GLO surveyors and early 1900's accounts of arroyo-cutting throughout the Southwest as evidence of entrenchment within the past 100 years. However, the channel "descriptions" by GLO surveyors for locations within the watercourse master plan study area include no information on channel depth or bank height, and generally record greater widths than those of the existing channel. Therefore, archaeological and historical data can provide no reliable information on the date of channel entrenchment, but generally support the conclusion that channel incision did occur.

Climate Change

Earl (1983) reports that the late Pleistocene climate was about 8 °F cooler and had about 8 inches per year more precipitation than the present climate. This cooler and wetter late Pleistocene climate generated high magnitude perennial flows which formed a broad low-relief alluvial fan piedmont surface composed of coarse sediments. During the mid-Holocene altithermal, from 8,000 to 4,000 years b.p., the climate was about 3.6 °F warmer and had about 2.8 inches per year more precipitation than the present climate (Earl, 1983). During the altithermal, the wetter climate produced high energy floods which formed large braided channels that transported very coarse bed materials. The seasonality of precipitation has also varied during the Holocene, from predominantly winter storms in the early Holocene, to summer storm-dominated climate during the altithermal, to the current period of relatively low summer and winter precipitation (Earl, 1983).

Archaeological and environmental data collected along Cave Creek (Phillips, 1998) and New River (Rankin and Katzer, 1989) support the model of more recent prehistoric climate change summarized the following paragraphs.

> In the A.D. 800's, cool temperatures combined with wet winters and summers produced high effective precipitation. Rainfall frequency was unpredictable, but it was more spatially uniform than today. Low watertables and channel erosion occurred along the streams of the Colorado Plateau to the north, but floodplain deposition continued in the north Phoenix basin due to favorable local conditions.
>
> Precipitation decreased during the A.D. 900's, with rare winter frontal storms and summer monsoons. Records of dry winters in the Phoenix Basin during this period conflict with regional records of frequent El Niños and associated winter storms and regionally rising water tables. Locally cool temperatures apparently kept effective precipitation at levels sufficient to maintain floodplain aggradation. Rainfall remained temporally variable and spatially uniform.

By 1000 A.D., the most favorable climatic conditions of the entire prehistoric period were established. Winters were reliably wet, with regular seasonal overbank floods. Warmer temperatures were moderated by more frequent thunderstorms. Floodplain aggradation was sustained in part by a relatively high water table. However, near the end of the century the spatial variability of precipitation increased, signaling oncoming climatic and environmental deterioration. Adjustments in stream morphology lagged behind these late-century climatic changes, and favorable farming conditions persisted into the 1100's.

With the beginning of the Medieval Warm Period (1100-1300 A.D.), winter frontal storms declined and temperatures increased, culminating in an intense drought in the 1130's. Decreased vegetative cover in the watershed increased the percent of rainfall that became runoff and resulted in shorter duration (flashy) floods. Concurrently, water tables dropped and erosion of the formerly stable floodplains probably occurred. Following the period of incision and bank erosion, floodwaters would have been more frequently confined to the main channel, making deposition on the higher terraces and cultural sites more rare. Because extensive modern erosion has erased nearly all traces of the prehistoric channels, the timing and degree of incision can only be inferred from indirect evidence, such as land use information preserved in the archaeological record.

The A.D. 1200's were marked by a slow, steady climatic decline. Winter and summer rains were increasingly sparse and variable. Regional arroyo cutting elsewhere in central Arizona was associated with an intense 25-year drought near the end of the century, although this event has not yet been recognized in stratigraphic records of the northern Phoenix Basin. Either the area was spared channel entrenchment, erosion was minor, or the evidence has been removed by modern erosion. Climatic conditions ameliorated in subsequent centuries, allowing formation of a cap unit of fine-grained flood deposits on the floodplain. However, it is clear that by 1500 A.D., channel incision was widespread and many local streams had become ephemeral.

Thus, archaeology-based climatic reconstructions suggest that enough change in the seasonality and magnitude of precipitation and temperature has occurred to cause significant channel change along Skunk Creek and Sonoran Wash over the past several hundred to thousand years. Climate change should be considered a significant cause of long-term lateral erosion and channel incision.

Prehistoric Lateral Channel Instability

No archaeological sites along Skunk Creek were identified close enough to the main channel to provide information on lateral stability. However, cultural features at two archaeological sites along Cave Creek downstream of Carefree Highway were interpreted as evidence of prehistoric channel erosion on Cave Creek (Phillips, 1998). At one site, lateral bank erosion was successfully stopped by placing rock along the bank to protect the edge of a farm field. Following placement of the rock, about 0.5 to 0.6 meters of deposition occurred over the rock. At the second site, a new channel was formed, probably by headcutting, along the western margin of an agricultural field. The Hohokam placed check dams in the channel to prevent further incision and to prevent destruction of the irrigated fields. These erosional events took place near the end of the period of Hohokam occupation, indicating a increased tendency for channel change around 1200 to 1400 A.D. These data indicate the lateral erosion has impacted regional watercourses for hundreds of years, and is not a recent development.

Prehistoric Vegetative Cover

Inferences about prehistoric channel changes can also be made from archaeological data regarding vegetation changes along Skunk Creek (Earl, 1983). Historical records describe sheep and cattle grazing on "lush growth of green grass" near Cave Creek during the late 1800's. Over-grazing of these grassy surfaces probably reduced ground cover and enhanced runoff, which could have led to widespread channel incision around 1900. Regardless of the impact on channel morphology, it is known that grass cover was more abundant prior to 1900 A.D. Pollen samples, though subject to poor control due to site conditions (Phillips, 1998), indicate Upper Sonoran plants such as bursage, goosefoot, and amaranth were common in the area during the prehistoric period. However, pollen data also indicate that seep willow, desert broom, and grass were more common than today.

The pollen signals obtained from regional cultural sites indicate that more water was available during the prehistoric period than it is today. Grass was also more prevalent, not only on the floodplain, but on the higher Pleistocene terraces as well. Riparian zones along adjacent stream systems such as Cave Creek included more cottonwoods, cattails and willows. Pollen data also suggest locally higher water tables and evidence of more frequent overbank flooding, both of which are characteristics of intermittent or perennial, non-incised streams.

Summary

Archaeological records imply that channel erosion has affected the Skunk Creek stream corridor throughout the past 10,000 years. Channel erosion is not simply the result of modern human impacts on the channel and watershed. Therefore, natural cycles of stream degradation, local aggradation, lateral migration, and climate change must be accounted for in development of the erosion hazard zones and the watercourse management plan.

Chronology of Documented Channel Change

A chronology of known channel and watershed changes was developed from historical maps and aerial photographs, channel descriptions, and other reports. The dates and brief descriptions of the data sources used are summarized in Table 3-1. Chronologies for Skunk Creek and Sonoran Wash are summarized in Tables 3-2 and 3-3. Discussions and analyses of the changes documented in Tables 3-2 and 3-3 are provided in other sections of this chapter.

Table 3-1. Skunk Creek Watercourse Master Plan Summary of Historical Records Used			
Year	**Scale**	**Type of Record**	**Description/Source**
1894	n/a	GLO Survey	General Land Office (BLM) original notes for J.H. Mantineau survey
1910	n/a	GLO Survey	General Land Office (BLM) original notes for S.E. Blout survey
1917	n/a	GLO Survey	General Land Office (BLM) original notes for G.F. Rigby survey
1922	n/a	GLO Survey	General Land Office (BLM) original notes for S.E. Blout survey
1933	n/a	GLO Survey	General Land Office (BLM) original notes for B.J. Kinsey survey
1940 (9/7/40)	1:16,700	Black & white Partial stereo Partial coverage	9 photos #COU 2-11, 64, 66, 68, 70, 116, 118, 120, 122 From FCDMC Archives
1953	1:28,800	Black & white Stereo Full coverage	14 photos 4/10/53: 1959-1961, 2036-2039, 2042-2045 (11 photos) 5/8/53: 3198-3200 (3 photos) From USGS EROS Center (#VV BE M 16 AMS)
1960 (2/60)	1:24,000	Black & white Stereo Full coverage	20 photos 30.12-16, 31.11-14, 32.12-15, 33.10-13, 34.13-15 Collected by ASL
1961 (2/61)	1:12,000	Black & white Partial Stereo Partial coverage	Coverage @ Cave Creek Dam only Includes oblique photographs looking upstream from Dam From FCDMC Archives
1962 (9/62)	1:12,000 (1" =1000 ft.)	Black & white Stereo Full coverage	45 photos 9/10/62: 1.85-1.87, 1.124-1.126 (6 photos) 9/15/62: 3.13-3.17, 3.49-3.51, 3.80-3.86, 3.105-3.113 9/30/62: 5.17-5.20, 5.37-5.44, 5.47, 5.62-5.64 (15 photos) From USGS EROS (#GS-VAOB)
1967	1:24,000	Topographic map	USGS 7.5 minute topographic maps – 20 ft. contour interval, based on 1962 aerial photographs. Maps photorevised in 1981.
1971	1:28,800	False color Stereo Full coverage	4 photos: 135, 163-165 (blue) 2 photos: 009, 009 (pink) From USGS EROS (#NASA JSC)
1978 (3-7-78)	1:12,000 (1" =1000 ft.)	Black & white Stereo Partial coverage	4 photos: 1, 3, 5, 6 From Landis Aerial Co. & FCDMC Archives
1979	1:4,800	Topo. Map Partial coverage	Base mapping for FEMA Flood Insurance Study. 2 ft. contour interval. Harris Toups, Inc.
1984 (2-5-84)	1:31,680 (1" =½ mi.)	False color Stereo Full coverage	8 photos: 4195, 4236, 4237, 4238, 4194, 4196, 4248, 4249 From USGS EROS
1985 (3/2/85)	1:31,680	Black & white Stereo Full coverage	6 photos: F-26, G-26, H-25, H-26, I-25, I-26 Collected by ASL
1989 (8/2/89)	1:18,000	Black & white Stereo	Coverage area is upstream of Carefree Highway Collected by ASL
	1:4,800	Topographic Map	Base mapping for FCDMC Floodplain Delineation Study. 2 ft. contour interval. Kenney Aerial Mapping Co.

Table 3-1. Skunk Creek Watercourse Master Plan Summary of Historical Records Used			
Year	**Scale**	**Type of Record**	**Description/Source**
1996 (3/18/96)	1:12,000	Black & white Full coverage	Many photos From FCDMC Flood Insurance Studies
1999 (1/9/99)	1:9,600	Black & white Full coverage	Many photos From FCDMC WMP Study

Table 3-2. Skunk Creek Chronology Based on Aerial Photograph Interpretation		
Date	**Description**	**Source Info.**
1953 (4/10)	• Very limited development in study area – no buildings or road crossings on Skunk Creek • I-17 not constructed, but small road with bridge in I-17 alignment • Recently formed overbank channel scar in floodplain at Dixileta Rd. alignment • Dirt road at-grade crossing at Dove Valley Rd. alignment • Possible small sand & gravel excavation in splay at Lone Mountain Rd. alignment • Multiple channel & splay near tributary at Cloud Road alignment • Skunk Tank already constructed, large sandy deposit & low ponding elevation • Wide bend to east at future Carefree Highway alignment, main channel along butte	B&W Stereo d/s of Skunk Tank Coverage d/s Skunk Tank
1962 (9/15)	• Sand & gravel excavation in splay at Lone Mtn. alignment expanded, dark area on terrace scarp may be dumped rock from processing • Dirt roads in area, at-grade crossing at Dove Valley alignment may be slightly elevated above channel bed (< 2 ft.) • Carefree Highway constructed with at-grade crossing – appears recently washed out. Low flow channel shifted several hundred feet to the west away from butte • Split flow channel in Tramonto area appears more active than in 1999, possibly due to recent flood • Cloud Road (dirt) extends to east section line, but no northern extension of 27th Ave. • Rectangular grid of roads constructed between Cloud Rd. & Desert Hills Road – at-grade crossings at Joy Ranch Rd. (weak & off section line), 17th Ave (weak) and Desert Hills Rd – no homes yet in road grid area • Left bank of at grade crossing at Desert Hills Rd. may be washed out • Road grid constructed east of Skunk Creek in Rodger Creek area, < 10 homes built • At grade crossing at Honda Bow Rd. may be washed out • House on right bank downstream of Honda Bow with stock pond upslope; house removed between 1992 and 1999, adjacent channel becomes more vegetated • At-grade crossing at Circle Mtn Rd. – dense vegetation upstream of Circle Mtn Rd. • Low bank vegetation density (less than Sonoran Wash) • Almost no trees on terraces and floodplain – brush or grass only • Bright deposits upstream of most splays may be evidence of recent large flood	B&W Stereo CAP to Desert Hills Coverage to Circle Mtn Rd. Same scale as 1992 and 1999 aerials – view concurrently to compare
1971 (7/23)	• I-17 constructed with new bridges (downstream of study reach) • Sand & gravel excavation at Lone Mtn alignment mostly filled by deposition • Channel may have filled relative to floodplain since 1962 • Dirt, at-grade crossings at Dove Valley Rd. & Joy Ranch Rd. washed out, discontinuous • Carefree Highway at-grade crossing rebuilt, channel on right side of downstream floodplain • Small ranch roads on Tramonto site built, one crosses Skunk Creek at grade • Skunk Tank is dry • Major erosion at Joy Ranch Rd since 1962 – crossing washed out • Small homes on 17th Ave built well outside floodplain • More buildings at home site downstream of Honda Bow • At least four homes on left bank between Honda Bow and Circle Mtn, channel moved from left to right side of floodplain between 1962 and 1971, and widened. • Development on right and left side of floodplain upstream of Circle Mtn. • At-grade crossing at Shangri La Lane, Shangri-La compound built	B&W Partial stereo – CAP to Shangri La Lane

Table 3-2. Skunk Creek Chronology Based on Aerial Photograph Interpretation		
1988 (12/12)	• CAP constructed, with overchute at Skunk Ck, ponding areas to east near Sonoran Wash • Dirt at-grade crossing at Dixeleta alignment • Building at Lone Mtn alignment on left bank terrace • Increase in bank vegetation near Lone Mtn alignment • Carefree Highway bridge constructed, concentrates downstream flow to left floodplain, upstream channel realigned, spur dike constructed along new left bank • Power substation constructed at Carefree Highway • More ranch roads built on Tramonto property • Skunk Tank nearly filled by ponded water from recent floods • Residential development in geologic floodplain between 19th Ave. & Desert Hills, new at-grade crossing at 13th Ave. • Scour and channel widening in splay at Rodger Creek confluence • New homes in floodplain between Honda Bow Rd. and Circle Mtn. Rd. • Some narrowing of main channel near Rodger and Cline Creek confluences since 1971 • Increased development between Honda Bow and Circle Mtn.	B&W Partial stereo – CAP to Shangri La Lane
1992 (9/6)	• Evidence of large flow in right overbank downstream of splay at Lone Mtn. Rd. alignment, and extensive erosion of splay area. Evidence of floodplain flow elsewhere in study reach • Tramonto breakout significantly less active looking • Continued erosion of left floodplain downstream of Carefree Highway bridge, excessive widening upstream of bridge and in bridge section • Probable incision upstream of Carefree Highway, leaving perched right overbank channels • Cloud Road to 27th Ave curve constructed through Skunk Ck. floodplain and channels • Skunk Tank nearly full of ponded water from recent floods • Significant residential development in watershed upstream of Skunk Tank since 1988 • At-grade crossings on 17th Ave (good) and Desert Hills Dr. paved, 15th Ave. crossing in poor condition • At-grade crossing New River Rd.	B&W Full stereo coverage Earliest coverage upstream of Shangri-La Lane
1995 (12/1)	• Left braid upstream of CAP better connected to main stem than in previous aerials • Multiple (3) washed out at-grade crossings at Lone Mtn alignment • Avulsion occurred since 1992 approx. 2400 ft downstream Carefree Highway, channel scour along left margin of floodplain immediately downstream of Carefree Highway – main channel may be perched • Incision of several feet since 1992 downstream of Carefree Highway • Skunk Tank nearly dry, but wet soils on downstream face indicate recent overtopping • Numerous ranch roads constructed between Cloud Rd. and Joy Ranch Rd., dirt at-grade crossings reestablished at Joy Ranch, new dirt crossing at Irvine • Desert Hills Dr. at-grade crossing elevated several feet above natural channel invert • Cline Creek confluence area overgrown with vegetation, channel narrowing • Continued residential development near floodplain between Honda Bow and Zorrillo Rd. • New River Rd. bridge constructed and road realigned	B&W Stereo, except Anthem
1999 (10/17)	• New bridge at Carefree Highway, numerous new at-grade crossings • Extensive movement of low flow & braided channels between 27th Ave. and Desert Hills Dr. compared to 1962. Movement brackets entire floodplain width • Extensive movement of low flow & braided channels at Cline Creek confluence compared to 1962 aerial • Continued residential development in existing development areas upstream Skunk Tank	Color Full stereo coverage
Notes: 1. LOB = left overbank; ROB = right overbank 2. See Figures 1-1 and 2-15 for place names and locations		

Table 3-3. Sonoran Wash Chronology Based on Aerial Photograph Interpretation		
Date	**Description**	**Source Info.**
1940 (10/14)	• No visible roads • One stock tank in place north of upstream study limit on tributary • Channel vegetation similar to 1962 condition • No evidence of recent incision • CAP not constructed yet	B&W No stereo Coverage of Sonoran Wash Reach 4-6 only
1953 (4/10)	• No evidence of recent incision • No significant changes from 1940 coverage in area of overlap • Road to mine graded, no wash crossings	B&W Stereo coverage of entire study reach
1962 (9/15)	• Ranch roads graded around perimeter of west ½ of section 24 near mine, at-grade crossings • Additional dirt at-grade crossing due north of mine • New small ranch roads and stock tanks in watershed • Channel banks well vegetated, no large trees in floodplain • Main channel widens opposite mine (widening not related to mine), with splay just downstream of Dixileta Rd. alignment	B&W Full stereo coverage Same scale as 1999
1971 (7/23)	• Continued excavation at mine • No observed changes since 1962	B&W Partial coverage
1988 (12/12)	• CAP constructed • Dirt Rd. on 23rd Ave alignment extended north across wash (at-grade) • At-grade ranch road crossing at Lone Mtn alignment • Additional ranch roads on east-west ½ section 24 line • Vegetation density increase at CAP ponding area	B&W Partial stereo coverage
1992 (9/6)	• Cave Buttes Dam west dike constructed • North braid at at-grade crossing near dike becomes more active • New ranch roads graded in watershed • New mine access road constructed on 23rd Ave alignment • Splay downstream of Dixileta Rd. becomes more defined like single braided channel • Splay at Lone Mountain Rd. extended further downstream into right floodplain	B&W Full stereo coverage
1999 (10/17)	• Continued expansion of mine • No observed changes from 1992, except possible slight incision at west dike road crossing of north braid	Color Full stereo coverage
Notes: 1. LOB = left overbank; ROB = right overbank 2. See Figures 1-1 and 2-15 for place names and locations		

The following conclusions can be drawn from the chronology of channel change developed from aerial photographs:

- Human impacts. Direct human impacts on Skunk Creek have been limited to construction of bridge and at-grade road crossings, construction of the CAP, and minor sand and gravel excavations. Direct human impacts on Sonoran Wash have been limited to construction of the CAP and several at-grade ranch road crossings. Indirect human impacts on Skunk Creek and Sonoran Wash include construction of stock ponds, moderate urbanization of the watershed, and cattle grazing. The degree of urbanization in the watershed has accelerated during the past several years relative to the pace of development prior to 1988.
- Channel change. While significant lateral channel movement was observed in many places on Skunk Creek and Sonoran Wash, overall channel movement during the period of record for the aerial photographs has been moderate, probably due to the lack of large floods. The types of channel changes observed on the aerial photographs included avulsions, bank failure, channelization, channel width changes, formation of multiple channels, braiding, deposition, and movement of splays.

Scanned and reprinted copies of key portions of the aerial photographs listed in Tables 3-1 to 3-3 above are included in Appendix D. More detailed discussions of the channel changes observed on the aerial photographs are presented in the following sections of this chapter.

Evidence of Historical Channel Change

The following four types of historical channel change were identified and documented for the Skunk Creek/Sonoran Wash system:

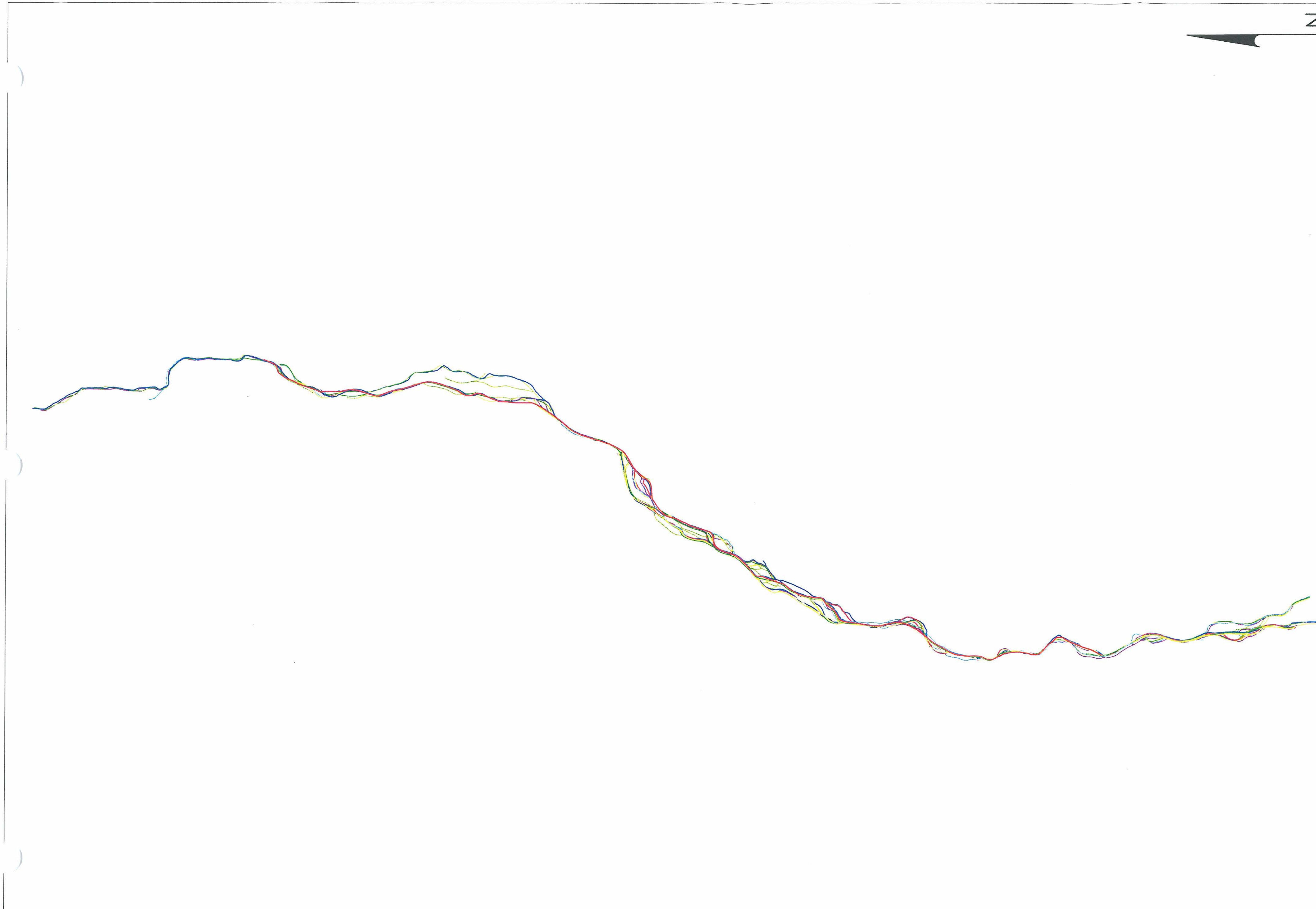
- Lateral channel change
- Vertical channel change
- Channel geometry change
- Channel planform change

Lateral channel movement is defined as any change in the horizontal position of the stream, and includes gradual bank erosion or rapid avulsions. Vertical channel change is defined as change in the elevation of the stream bed, and includes local scour, long-term scour (degradation), and deposition (aggradation). Channel geometry changes may be the result of lateral or vertical adjustments, and are measured by adjustments of the total width and/or depth of the main channel. Change in channel pattern includes adjustments of channel sinuosity, or shifts from a single to multiple channel pattern. Evidence of each of these four types of channel change was analyzed for short-term (single event) changes and long-term (progressive trends) change, as described below. The plot of channel thalweg position from each of the years of photographic and map coverage shown in Figure 3-1 illustrates the frequency and scale of possible channel change within the Skunk Creek and Sonoran Wash study reaches.

Lateral Channel Change

Single Event Changes. Many alluvial streams are subject to rapid lateral migration during floods. Bank erosion exceeding several hundred feet during a single storm has been reported on some streams in central Arizona (c.f. Kresan, 1988). Unfortunately, due to the low population density (few observers), paucity of roads and structures (few damages), limited aerial coverage (infrequent mapping), and lack of large floods (few newsworthy events) during the period of record, no systematic records of single event bank erosion could be established for either Skunk Creek or Sonoran Wash. That is, either no extraordinary single event bank erosion occurred or it occurred only in places where it could not be readily observed and recorded. The USGS gauge (Table 2-9) recorded no floods greater than a 15-year event since 1970, and no floods greater than a 25-year event since before 1959, indicating that severe erosion was not very likely during the period of observation.

To compensate for the lack of single event erosion data, estimates of maximum channel change between dates of coverage by historical aerial photographs were computed. The



Skunk Creek WCMP

Figure 3-1
Historical Channel Position

Thalweg	Year
	1953
	1962
	1964
	1971
	1988
	1992
	1995
	1999

ROADS

DRAWING SCALE

1 INCH = 4500 FEET

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Sheet 1 of 1

measured channel change between years of coverage may be used as the upper limit of possible single event change during that period, as shown in Table 3-4. Comparison between multiple years of aerial photograph coverage (long-term changes) are discussed in more detail in the next section of this chapter.

Table 3-4. Skunk Creek Watercourse Master Plan
Maximum Channel Width Change & Thalweg Movement – Skunk Creek & Sonoran Wash

Stream Name	Maximum[3] Width Change (ft.)	Average[1] Width Change	Time Period (Dates of Coverage)	Large Floods During Period		
				Date(s)	Peak Discharge	Recurrence Interval
Skunk Creek	414 [4]	30	1962-1971	1964 1967 1970	11,500 cfs 5,900 cfs 9,650 cfs	25 yr < 10 yr 15 yr
Sonoran Wash	32	3	1971-1988	No records available for Sonoran No floods > 10-year on Skunk Ck.[2]		
Stream Name	**Maximum Thalweg Change (ft.)**		**Time Period (Dates of Coverage)**	**Large Floods During Period**		
				Date(s)	**Peak Discharge**	**Recurrence Interval**
Skunk Creek	414 [4]		1962-1971	1964 1967 1970	11,500 cfs 5,900 cfs 9,650 cfs	25 yr < 10 yr 15 yr
Sonoran Wash	Measured thalweg movement within error of measurement.					

Notes:
1. Average width change during period of maximum width change.
2. Flood record available only for Skunk Creek. No gauge existed on Sonoran Wash.
3. Width measured from furthest left bank to furthest right bank, includes widest braids.
4. 414 ft. estimate width change for Skunk Creek represents probable avulsion.

The August 1964 flood was the largest event during the 40-year period of record, and occurred during the period of greatest measured channel movement on Skunk Creek. The 1964 flood had a recurrence interval equal to about a 25-year flood (4%). In addition, the floods of September 1970 (15-year; 2nd largest in record) and December 1967 (10-year, 7th largest in record) also occurred during the 1962 to 1971 period bracketed by dates of aerial coverage. The October 1959 event, the third largest flood during the period of record, occurred just prior to the period of coverage. During the 1962 to 1971 period, the maximum change in total width as expressed by the distance between the furthest left and furthest right banks or braids was 414 feet on Skunk Creek. This width change was due to development of an avulsion channel in what was an overbank floodplain prior to 1962. Therefore, the upper limit of single event erosion on Skunk Creek was taken to be about 400 feet.

Given that the largest measured width change on Sonoran Wash occurred between 1971 and 1988, it may be assumed that the flood peaks and lateral channel movement are not typically coincident on Skunk Creek and Sonoran Wash. During this period, the maximum measured change in width was 32 feet, which is therefore the assumed upper limit of measured single event channel change. Field evidence suggests that larger avulsive channel changes have occurred in the recent past, but that those larger changes probably occurred prior to the period of coverage by historical aerial photographs.

Long-Term Changes. Long-term changes in channel position were evaluated by comparison of thalweg locations digitized from historical aerial photographs, and by comparison of channel position recorded in historical General Land Office (GLO) surveys with modern USGS topographic maps.

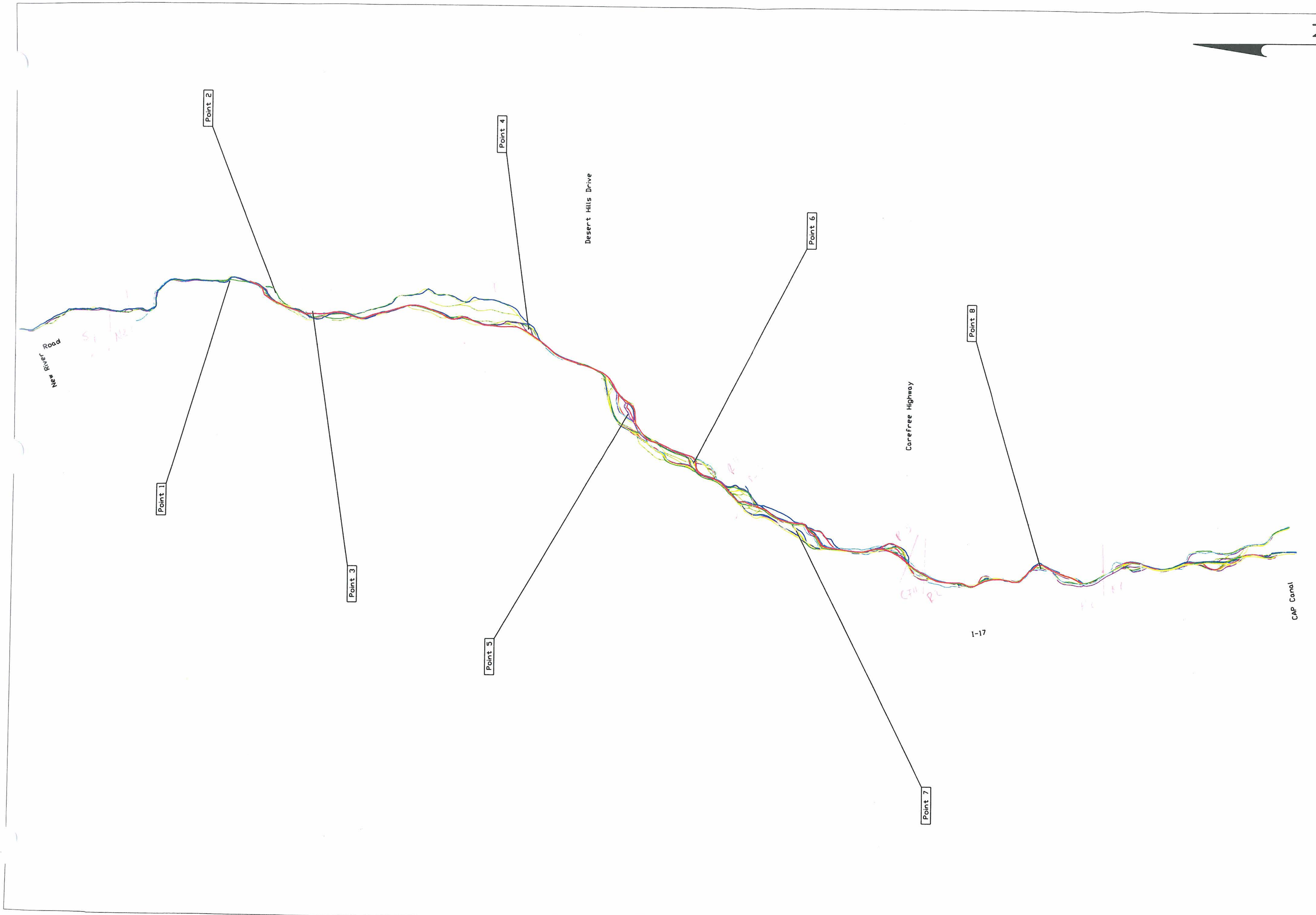
Historical Aerial Photograph Data. Aerial photographs of Skunk Creek and Sonoran Wash from each year of available coverage (Table 3-1) were digitized and semi-rectified to match the USGS topographic maps for the study area.[6] The thalweg position was then digitized for each year of coverage as shown in Figures 3-1 and 3-2.

Methodology. Quantification of thalweg position changes was completed in several steps. First, digitized thalweg lines were compared to identify areas where apparent channel position changes had occurred. Where certain years of coverage contained thalweg lines that deviated from the trends of earlier and/or later years of coverage, the digitized lines were examined in greater detail. In some cases, where the apparent offset was parallel to other years of coverage, the differences were interpreted to be the result of incomplete rectification. Once rectification problems had been eliminated as a probable cause, the original aerial photographs were examined under magnification to further verify that digitized channel position depicted actual channel movement. Following this process, areas of significant channel movement were isolated, and the distance tool in AutoCAD was used to measure the amount of thalweg movement between the dates of the aerial photographs.

Eight points along Skunk Creek where significant lateral movement were identified (Figure 3-2) are described in the following paragraphs. No points of significant lateral thalweg movement were identified along Sonoran Wash during the period of record.

Point 1 – Shangri La Lane: Prior to 1971, the channel of Skunk Creek at Point #1 consisted of a wide corridor, where flow was conveyed from bank to bank, with an approximate width of 175 to 250 feet. By 1988 the channel width had decreased, and in many places had narrowed by more than 50 percent. Just upstream of the outlined areas in Figure 3-3, the channel narrowed significantly and confined itself to the eastern edge of the corridor, moving a distance of about 85 feet. In the reach just downstream of the outlined area on Figure 3-3, the majority of the flow was initially conveyed along the western side of the creek, but eventually shifted about 190 feet to the eastern side of the creek. Note that it is possible that the observed changes in 1988 were due to floodplain grading and improvements made to the Shangri La Lane at-grade crossing. By 1995 the area outlined in Figure 3-3 had changed from the original wide channel to a well-defined, narrow split, where the majority of flow is carried by the right channel, a condition that persisted through 1999. A total lateral change of approximately 250 feet occurred between 1971 and 1995.

[6] USGS quadrangles: Daisy Mountain, AZ; Union Hills, AZ; New River SE, AZ. Topography by photogrammetric methods from aerial photographs taken 1962. Field checked 1964. Contour interval = 20 to 40 feet.



Skunk Creek WCMP

Figure 3-2
Location of Detailed Channel Position Assessment

Thalweg	Year
yellow-green line	1953
yellow line	1962
blue line	1964
green line	1971
light yellow line	1988
red line	1992
light blue line	1995
purple line	1999

ROADS

DRAWING SCALE
1 INCH = 4500 FEET

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Sheet 1 of 1

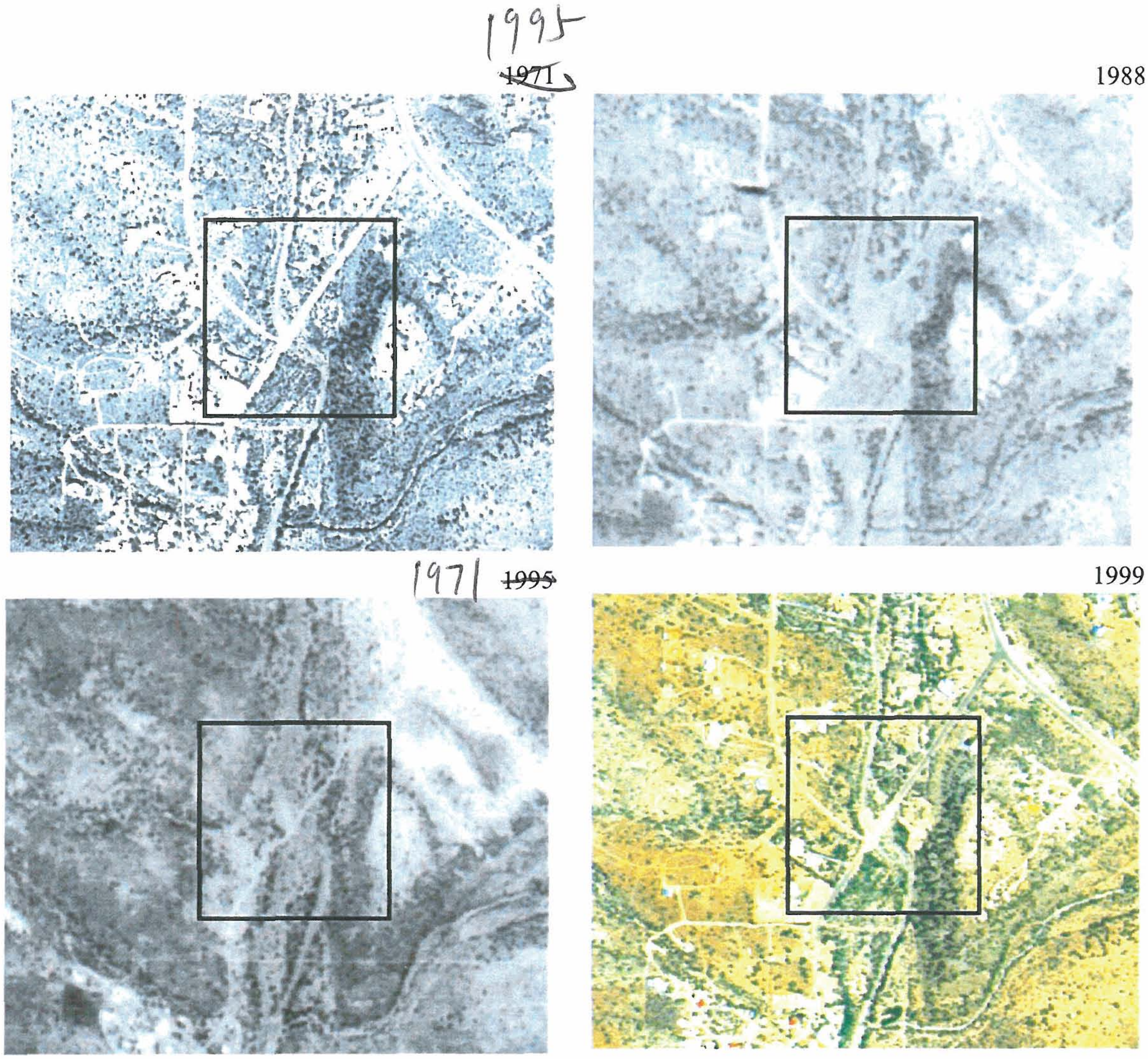

Figure 3-3. Point 1 aerial photo comparison, 1971-1999. Skunk Creek at Shangri La Lane.

Point 2 – Skunk Creek Upstream of Circle Mountain Road. In 1971 Skunk Creek was divided into two primary flow paths upstream of Circle Mountain Road (Figure 3-4). The majority of flow was carried in the right, larger channel, with a smaller proportion of the flow conveyed in the left channel. The aerial photographs from 1988 and 1995 indicate that the left channel was progressively abandoned, filled and revegetated. In the 1999 aerial photographs, the left channel is only faintly visible and the right (main) channel has become braided and narrower, and a new cut bank has formed along the left bank. The distance of abandonment from the former left channel to existing right channel was approximately 420 feet.

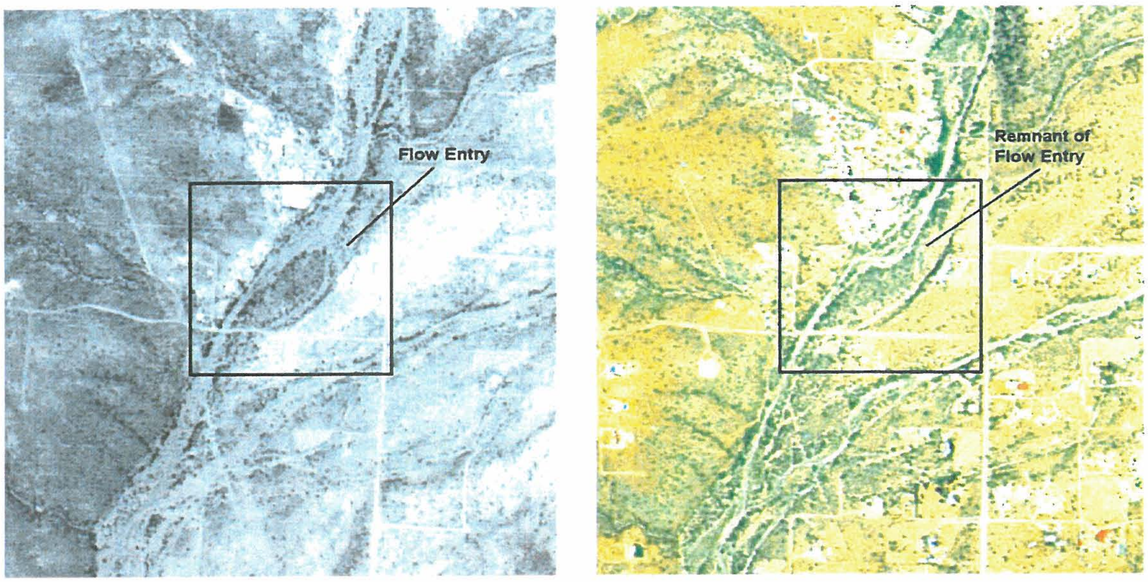

Figure 3-4. Point 2 aerial photo comparison, 1971-1999, Skunk Creek above Circle Mountain Rd.

Point 3 – Skunk Creek at Cline Creek Confluence. In 1962, Skunk Creek at the Cline Creek confluence consisted of several well defined channel braids within a shallow, vegetated floodplain (Figure 3-5). The typical main channel width was approximately 50 feet. Prior to 1971, flooding and erosion widened the channel by about 100 feet, effectively eliminating many of the braids visible in the 1962 photograph. By 1988, the stream had recovered many of its 1962 braided characteristics, although the width of individual braids remained wider than in 1962 and the individual braids were in different locations. The 1999 aerial photographs indicate that overbank vegetation density and degree of braiding has continued to increase, and the channel widths have narrowed. The maximum distance of movement at the river right location between 1962 and 1971 was 100 feet, and from 1971 to 1999 approximately 265 feet at the "Overflow – Unconfined" location.

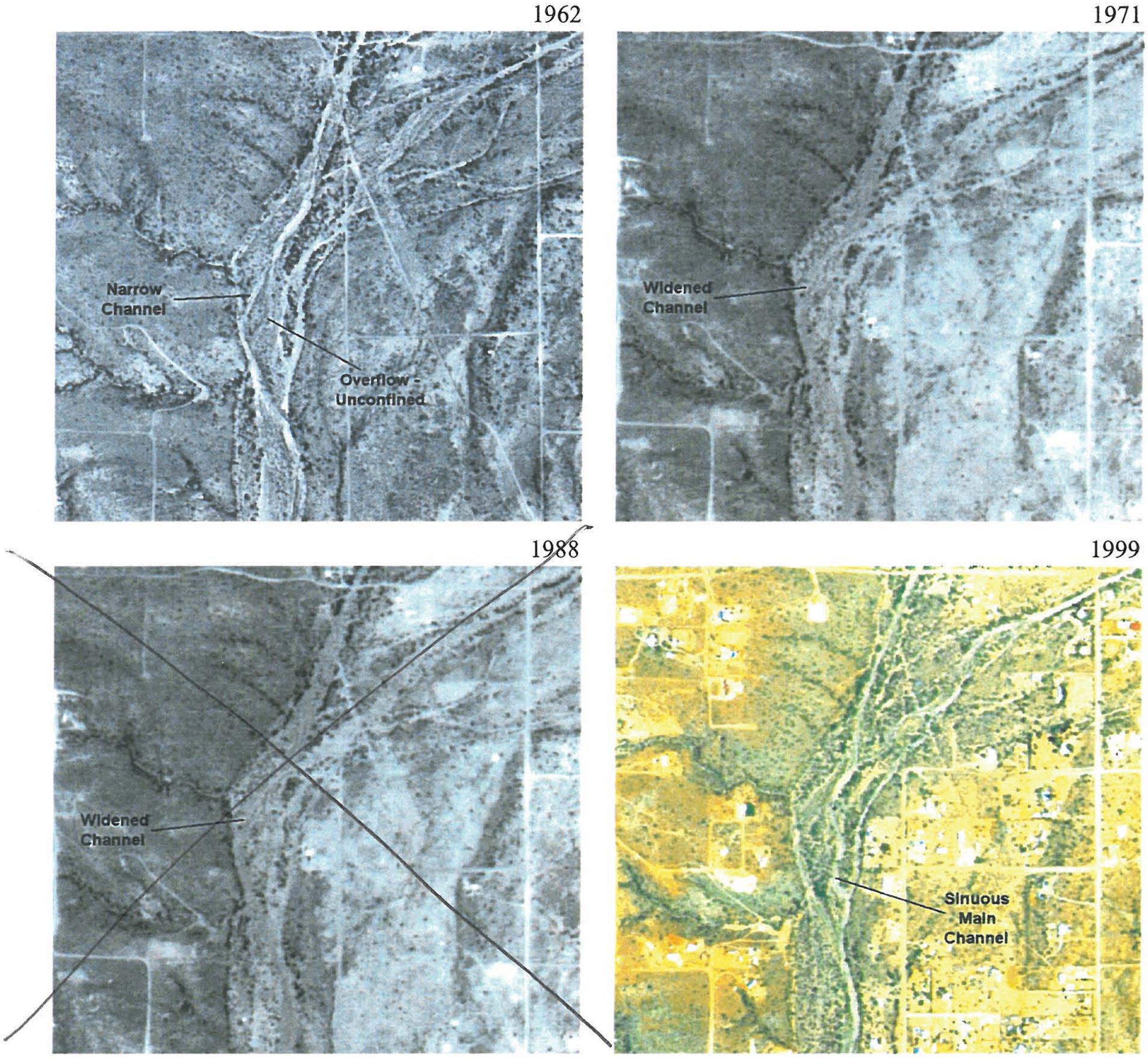

Figure 3-5. Point 3 photo comparison, 1962-1999, Skunk Creek at Cline Creek confluence.

Point 4 – Skunk Creek at Rodger Creek Confluence. Two types of channel change are recorded at one location at Point 4 (Figure 3-6). One change resulted from a channel avulsion and the other resulted from a simple shift in channel position by bank erosion. The first stage in the avulsive process can be seen in the 1962 aerial photography, towards the right side of the active floodplain where a headcut is progressing upstream. By 1971 the headcut had not migrated further upstream and the overbank flow path appears to have remained undefined, but by 1988 a continuous channel had developed linking the overbank channel with the main channel. By 1999 the avulsive channel had become more well defined. The measured change in thalweg position caused by this avulsion was approximately 175 feet.

Changes in channel width due to lateral movement of the main channels are also recorded at Point 4. The active channel at the Rodger Creek confluence was widened by about 210 feet between 1962 and 1971, presumably by the three moderate floods which occurred during that period (Table 3-4). By 1999, much of the 1962 channel width had been recovered due primarily to growth of floodplain and bank vegetation, and the channel had returned to a more braided condition.

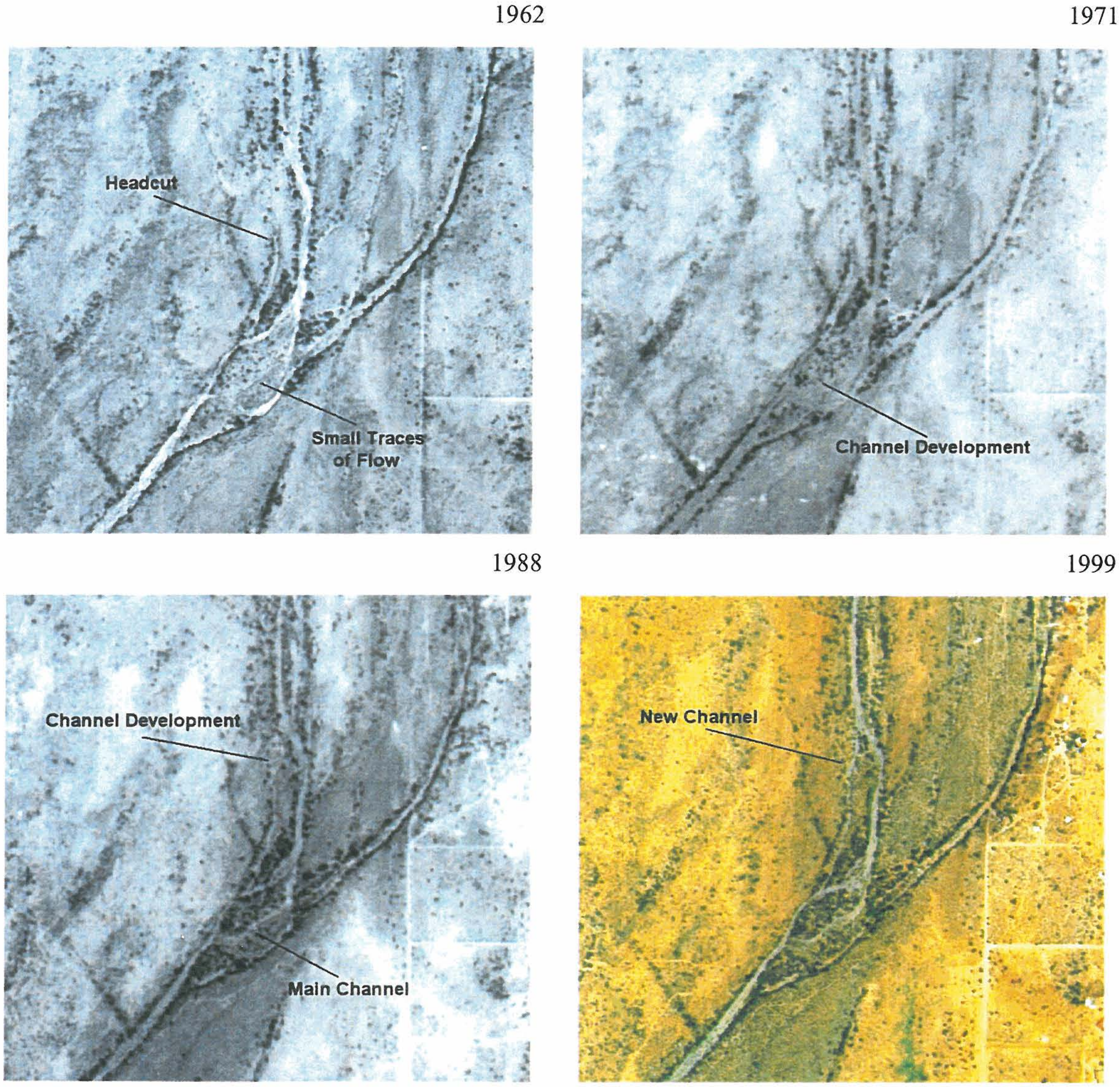

Figure 3-6. Point 4 photo comparison, 1962-1999, Skunk Creek at Rodger Creek confluence.

Point 5 – Skunk Creek at Irvine Road. Point 5 is located between Desert Hills Drive and Irvine Road in a "splay" area (Figure 3-7). The 1999 aerial photography shows four main channels in this reach. However, in 1962 there were only two main channels, with the two additional flow paths starting to form channel corridors (Figure 3-7, "Flow Traces"). The absence of defined flow paths is substantiated by USGS 7.5 minute quadrangles, which were also based on 1962 aerial photography. By 1971 the corridors were well defined (not shown), and by 1988 the channels were incised enough to be clearly distinguished on the aerial photographs. The 1999 photography shows a decrease in the channel width of the far left channel, as flow conveyance was distributed throughout the three far left channels. The distance involved in this channel change, from far left to the third channel to the north was measured at about 600 feet. The distance of the channel change from far left to the second channel to the north was approximately 315 feet.

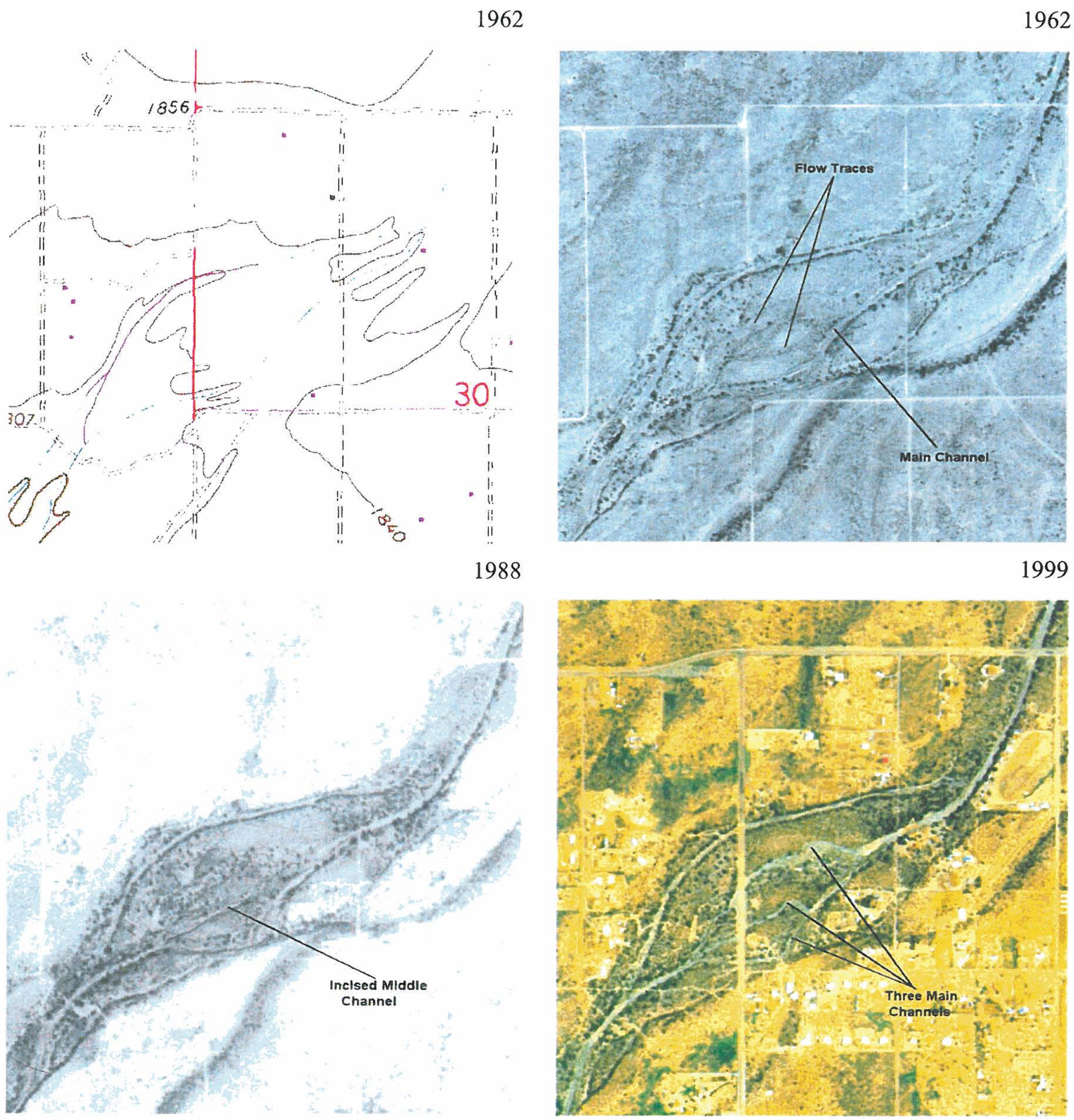

Figure 3-7. Point 5 photo comparison, 1957-1999, Skunk Creek at Irvine Road.

Point 6 – Skunk Creek at Joy Ranch Road. Examination of the 1962 to 1999 aerial photographs of Point 6 reveals a history of avulsive new channel formation (Figure 3-8). In 1962, aerial photographs do not show a channel in the location marked as "No Channel" in Figure 3-8. However, by 1971 a new channel had formed that by 1999 became the main channel. The total distance of channel change involved in formation of this new channel was measured at approximately 300 feet. In addition, the channel to the southeast, noted as "Straight Channel" on the 1962 aerial photography, shifted its position by bank erosion roughly 130 feet further southeast by 1971, a rate of about 15 feet per year, the maximum documented rate of long-term erosion in the study area.

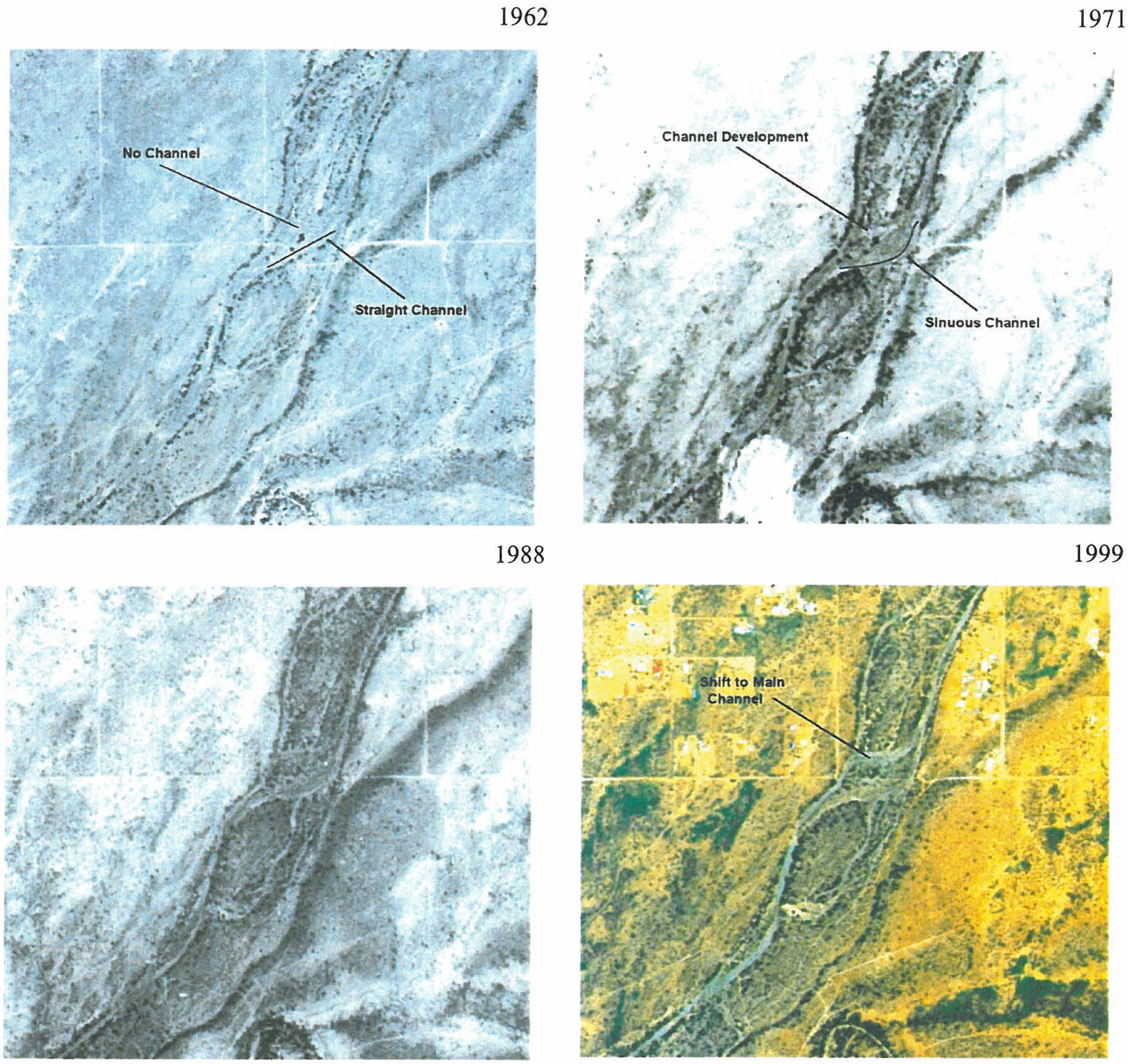

Figure 3-8. Point 6 photo comparison, 1962-1999, Skunk Creek at Joy Ranch Road.

<u>Point 7 – Skunk Creek at Cloud Road</u>. Measurable channel change occurred between each year of aerial coverage shown in Figure 3-9. The far left channel braid widened about 65 feet from 1962 to 1971, and an additional 55 feet from 1971 to 1988. From 1988 to 1999, the left braid incised and shifted to river right, leaving a low floodplain terrace in what was the left side of the active channel in 1988. The total distance of movement of the right bank of the left channel from 1962 to 1999 was about 230 feet. Channel change caused by human impacts are also illustrated in Figure 3-9. Prior to 1995, Cloud Road was an unpaved road which extended into the main channel. Travel to the north from Cloud Road appears to have occurred along the 29th Avenue alignment, which was located about ¼ mile west of the main channel of Skunk Creek. Around 1995,

Cloud Road was paved and extended along the section line and connected to 27th Avenue between the two primary braids of Skunk Creek. The elevated section of Cloud Road prevents floods from flowing over most of the right side of the floodplain and concentrates flow along the left channel braid which has experienced the channel widening.

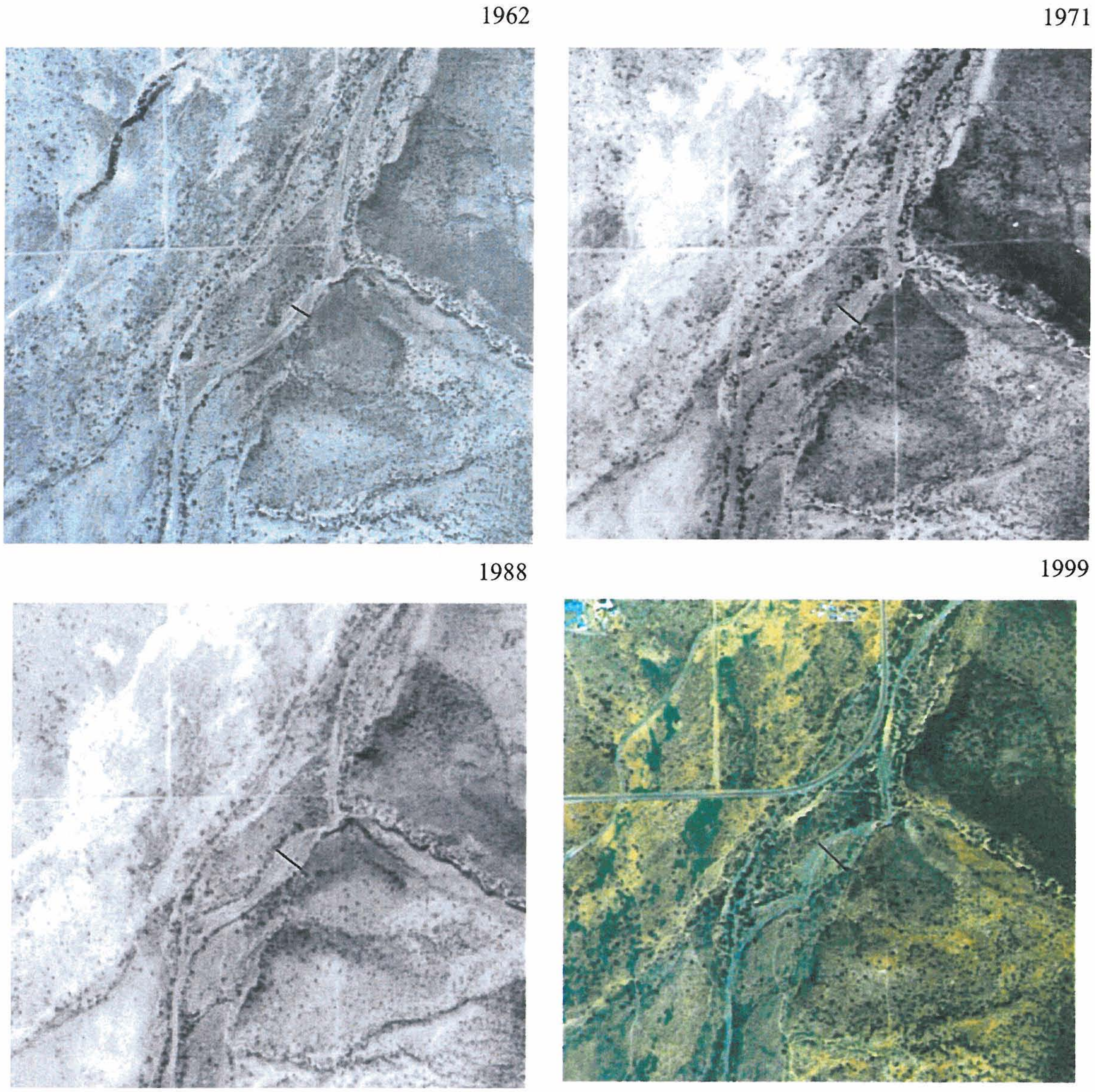

Figure 3-9. Point 7 photo comparison, 1962-1999, Skunk Creek at Cloud Road.

Point 8 – Skunk Creek at Dove Valley Road Alignment. In 1962, Skunk Creek consisted of a single channel with a low right floodplain which was inundated by moderate to high flows (Figure 3-10). By 1971, the single thalweg was still present, but the bank had receded by about 275 feet. In addition, between 1962 and 1971, a pile of cobbles and boulders had been dumped on the far right side of the floodplain, which limited further bank erosion at that location (Figure 3-10). By 1988, the opposite bank had receded an additional 30 feet, and another less defined flow path had formed along the right side of the floodplain about 218 feet from the main channel. The current channel consists of a small splay with multiple small channels and moderately dense channel vegetation. Downstream of the splay, the main channel is actively undercutting the cliff along the left bank at the margin of the Middle Pleistocene terrace.

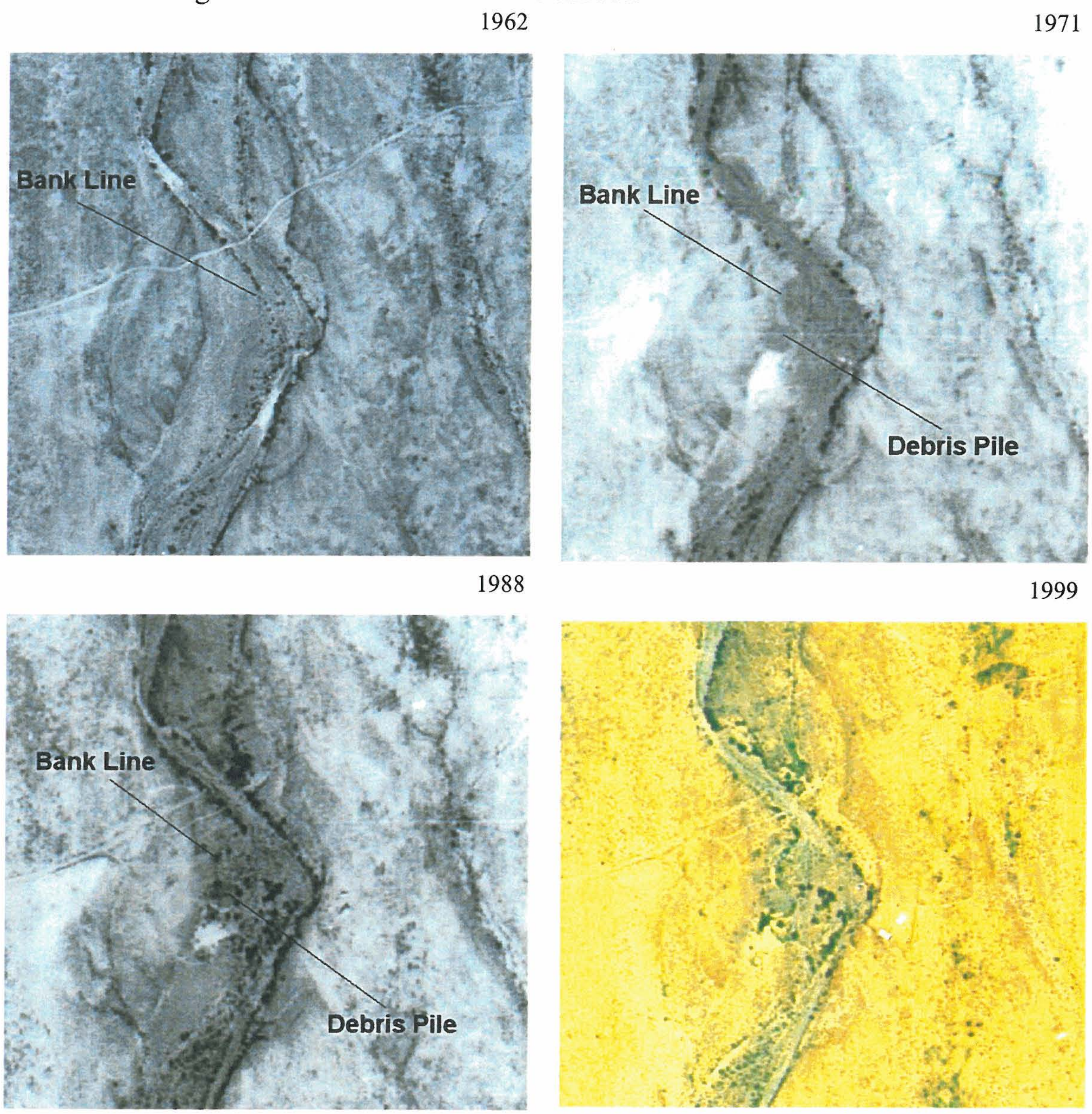

Figure 3-10. Point 8 photo comparison, 1962-1999, Skunk Creek at Dove Valley Road alignment.

Summary. Comparison of the thalweg position digitized from historical aerial photographs indicates that the most significant channel changes occurred in between 1962 and 1971 (Table 3-5). During this period, shifts in channel positions, avulsions, and lateral bank erosion occurred. Additional bank erosion and channel widening occurred between 1988 and 1999. Few significant channel changes were observed between 1971 and 1988, except for the headcut advance at Point 4, and narrowing at Point 1. During the period of record, the primary mechanism for the most significant channel movement was avulsions, which resulted in up to several hundred feet of thalweg movement. However, measured bank erosion distances in some reaches were also significant, with more than 100 feet of erosion recorded in several locations, despite having few major floods during the period of record.

Table 3-5. Skunk Creek Watercourse Master Plan
Channel Change Measured From Aerial Photographs at Selected Locations Along Skunk Creek

Time Period	Site #							
	1	2	3	4	5	6	7	8
1962-1971	No Coverage		100 ft	-	-	130 ft	65 ft	275 ft
1971-1988	85 ft	-	-	175 ft	-	-	55 ft	30-218 ft
1988-1999	190-250 ft.	-	-	-	-	-	110 ft	-
1971-1999	-	420 ft	275 ft	-	-	-	-	-
1962-1999	-	-	-	211 ft	315-600 ft	300 ft	-	-

Note: See text and Figure 3-2 for site locations. Blank fields indicate no measured change.

TABLE 3-5

General Land Office Survey Records. Long-term channel change was also documented by comparing channel positions recorded in the original General Land Office (GLO) section line surveys from the 1800's and early 1900's with channel locations shown on modern USGS topographic maps (USGS, 1981). Use of the GLO surveys enabled extension of the historical record by up to 68 years beyond the date of the oldest aerial photographs used in the channel position comparison described above.

Methodology. The General Land Office of the United States Department of the Interior conducted detailed boundary surveys to establish the original Township, Range, and Section line grid in the Arizona Territory. In addition to the legal boundary measurements along section lines, the GLO surveyors also noted the position of significant geographic features, such as watercourses. The surveyed position of the watercourses at section lines can be used to provide information on long-term lateral stability by comparing the position recorded in the GLO survey notes with the channel position shown on modern maps. Historical GLO survey data were gathered from original field notes from GLO surveys in 1894, 1910, 1917, 1922, and 1933, as summarized in Table 3-1. Although GLO surveys record stream position only at section lines, sketches of channel locations between section lines were sometimes provided in the field notes and on plat maps which provide (less reliable) information on channel position between section lines. Modern channel position data were obtained from USGS 7.5-minute topographic maps (1981).[7] To increase the accuracy of channel position comparison, measurements on the USGS maps were taken from the section corners along the same headings as the GLO surveys.

GLO survey distances were measured in Gunter's Chains (= 66 feet), and were reported to two decimal places. Therefore, the accuracy of measurements using the GLO survey

[7] The USGS 7.5-minute topographic maps for the Skunk Creek/Sonoran Wash study area were originally created in 1965 from 1962 aerial photographs, but were photo-revised in 1981.

notes can be no better than ± 0.66 feet (0.01 chain). The accuracy of measurements made from the 1:24,000 USGS topographic maps is limited to 1/60 of an inch (the smallest increment on an engineering scale), or ± 33 feet. Therefore, for the purposes of this analysis, any measured channel position change less than 33 feet was considered as a record of no change. The stream position shown on the USGS maps is considered to be the channel centerline for the purpose of comparison with GLO survey measurements. The channel centerline for the GLO data was estimated as the midpoint of the bank stations recorded in the GLO survey notes. The GLO thalweg position was included on the channel position plots shown in Figures 3-1 and 3-2.

Results. The results of the comparisons of estimated channel centerline position for Skunk Creek and Sonoran Wash are summarized in the following paragraphs. Descriptions of the lateral movement of the channel will be presented from downstream to upstream along each stream at each section line crossing.

Skunk Creek: Township 5 North, Range 2 East

In Township 5 North Range 2 East there is no evidence that Skunk Creek moved more than 100 feet laterally between 1894 and 1981, although the data suggest that Skunk Creek experienced a different kind of radical change. At the section 23-26 boundary, the centerline position moved approximately 94 feet to the east (Figure 3-11). At the section 14-23 boundary, the centerline position moved about 80 feet to the west (Figure 3-11). Channel position at the section 11-14 and 2-11 boundaries could not be compared, as described below and shown in Figure 3-12. Comparison of the channel position shown on 1995 aerial photographs with the GLO channel position indicates that the left (east) bank position has not changed significantly since 1894, and that the movement of the channel center between 1894 and 1981 was partially the result of a widening of the channel in the westward direction.[8]

Between sections 23 and 26, from corner of sections 23, 24, 25, and 26, heading west

1894	1981
Left Bank..............1782.0 ft (27.0 chains)	
Channel Center.......1910.7ft	Channel Center.................. 1816.67 ft
Right Bank............2039.4 ft (30.9 chains)	

Summary of movement: ***Moved east 94 feet (river left)***

Between sections 14 and 23, from corner of sections 13, 14, 23, and 24, heading west

1894	1981
Left Bank.............. 1801.8 ft (27.3 chains)	
Channel Center...... 1920.6 ft	Channel Center.................. 2000.00 ft
Right Bank............2039.4 ft (30.9 chains)	
Second Wash........ 2290.2 ft (34.7 chains)	

Summary of movement: ***Moved west 79 feet (river right)***

[8] 1894 width = 238 ft.; 1995 width = 293 ft. The width difference of 55 feet compared to the estimated channel centerline difference illustrates the difficulty of determining the exact location of a channel bank on modern maps or in the field and comparing it to the bank definition used by GLO surveyors.

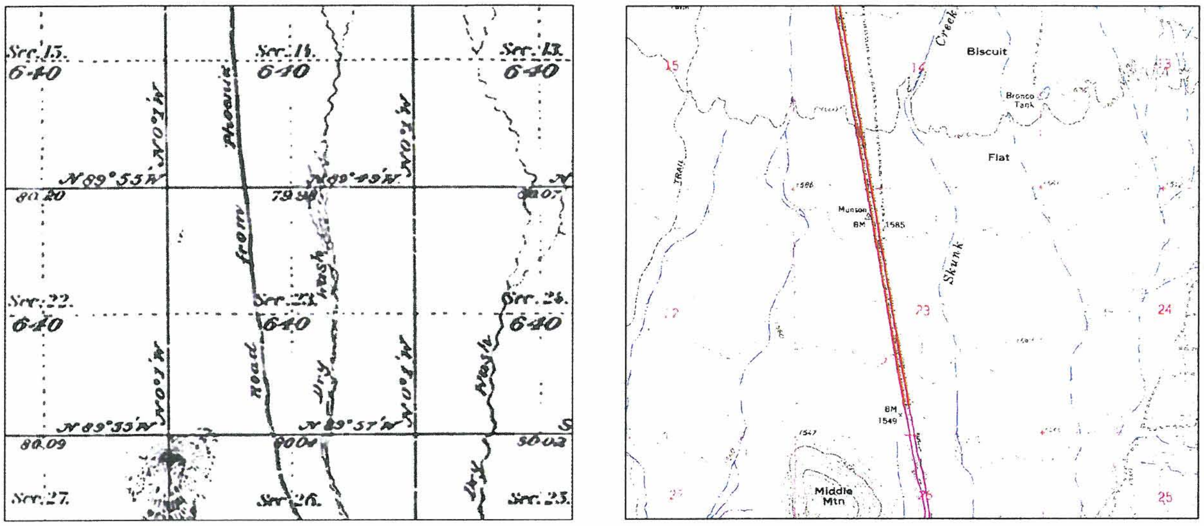

Figure 3-11. Sections 23/26 and 14/23 - 1894 GLO survey map compared to 1981 USGS map.

Between the midpoint of section 2 and the northern portion of section 14, the GLO surveyors mapped Skunk Creek as discontinuous, with no channel positions recorded at the section 11-14 and 2-11 boundaries (Figure 3-12). In addition, the sketch of the channel location in the 1894 GLO survey notes shows that Skunk Creek disappears in this reach. Although the GLO survey notes do not include an explanation of why no channel position was recorded, it is most likely that in 1894 Skunk Creek had an ephemeral, distributary, multiple-channel pattern with numerous shallow channels that were too small to record in the field. The following lines of evidence support this explanation:

- Other small streams were recorded by the GLO. The GLO surveyors recorded the channel positions of many local streams, such as Apache Wash, Desert Hills Wash, Sonoran Wash, and Paradise Wash, that are smaller than Skunk Creek is today. Therefore, Skunk Creek must have been very small to escape the notice of the GLO surveyors.
- Existing channel conditions. Today, at the section 2/11 and 11/14 boundaries, Skunk Creek has vertical banks up to 15 feet high. Evidence of historic incision such as perched channels and multiple terraces was observed in this reach. It would be difficult for GLO surveyors to miss Skunk Creek in its existing condition at the section lines. Simply finding a suitable place to climb down the vertical cliff banks would have been enough to alert the GLO surveyors to the presence of a stream channel if Skunk Creek were similar to its existing conditions.
- Alluvial fan apex. Interpretation of the local geology supports the possibility that the apex of an small inset alluvial fan was located near the midpoint of section 2 where the GLO surveyors stopped mapping Skunk Creek.[9] At an alluvial fan apex, a defined channel often splits into multiple small channels that may be too small or numerous to record.

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[9] The possible apex point is located at the flow split now confined by the Tramonto Subdivision.

- Historic incision. Other investigators (e.g., Earl, 1983) have postulated that Skunk Creek became incised in this reach between 1894 and 1933. Incision could have changed Skunk Creek from a poorly defined distributary reach to the more confined, well defined channel present today.

By 1981, Skunk Creek had evolved into a single channel at the section 11-14 boundary, and into two distinct channels within a well-defined corridor at the section 2-11 boundary.

Between sections 11 and 14, from corner of sections 11, 12, 13, and 14, heading west

1894	1981
No record of Skunk Creek	Channel Center.................. 2816.67 ft

Summary of movement: ***Changed from ill-defined wash to defined wash***

Between sections 2 and 11, from corner of sections 1, 2, 11, and 12, heading west

1894	1981
No record of Skunk Creek	East Channel Center............ 1450.00 ft
	West Channel Center............ 1916.67 ft
	Median Position.................. 1683.33 ft

Summary of movement: ***Changed from ill-defined wash to defined wash***

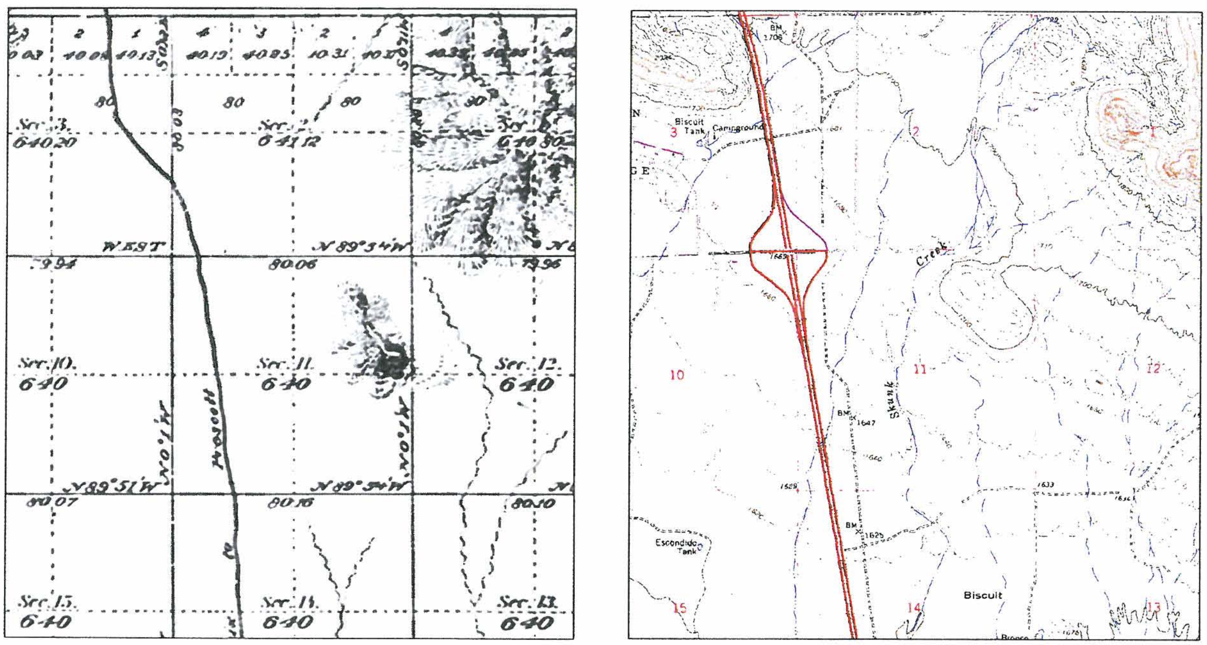


Figure 3-12. Sections 11/14 & 2/11 - 1894 GLO survey map compared to 1981 USGS map.

Skunk Creek: Township 6 North, Range 2 East

Skunk Creek is dominated by multiple channel reaches in Township 6 North 2 East. Historical lateral channel movement documented by comparing GLO data with USGS mapping often included creation of new channels, as described below.

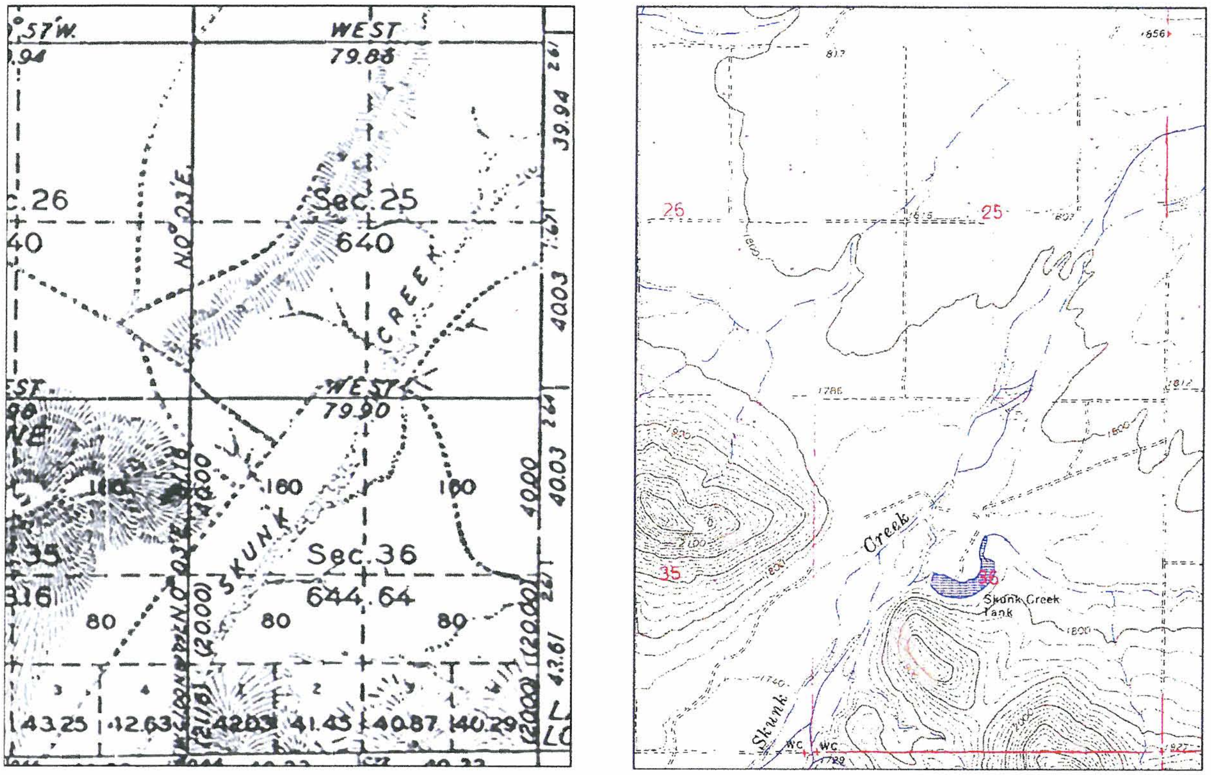


Figure 3-13. Sections 36/35/1/2 & 25/36 - 1933 GLO survey map compared to 1981 USGS map.

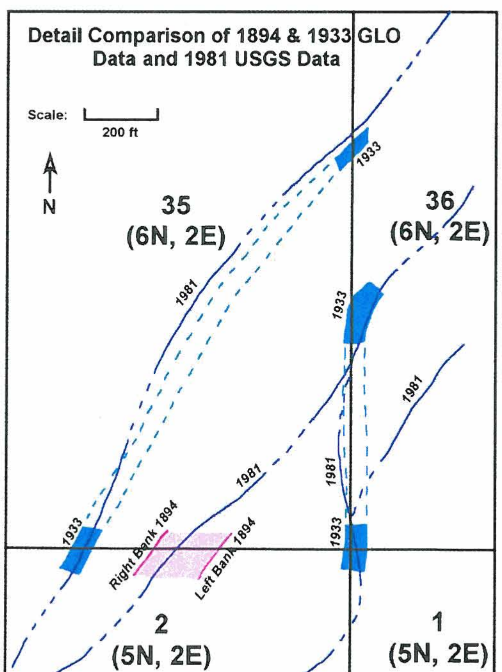


Figure 3-14. Illustration of channel position change in T6N, R2E, S35.

A complex series of changes occurred at the boundaries between Sections 35 and 36 in Township 6 North 2 East and Sections 1 and 2 in Township 5 North 2 East (Figures 3-13 and 3-14). Figure 3-14 compares channel positions obtained from USGS and GLO data in more detail than Figure 3-13. At the boundary between Township 5 North 2 East and Township 6 North 2 East, Skunk Creek shifted from a single wide channel in 1894 (Figure 3-13) to a double channel in 1933, and to a triple channel in 1981 (Figure 3-14). Today, there is one main channel and at least three secondary channels at this alignment, although the natural channel pattern was disturbed by construction of Cloud Road through the floodplain. The GLO data indicate that a 165 foot wide channel split into two narrower channels and abandoned the 1984 flow path sometime between 1894 and 1933. The two narrow channels were outside the bank positions of the 1894 channel. By 1981, Skunk Creek had apparently reoccupied the 1894 channel position, if it had ever truly abandoned it, while at the same time maintaining the east and west side channels formed before 1933. The total width of the floodplain bracketed by Skunk Creek channels increased from 165 feet in 1894 to over 700 feet in 1981, a change of 535 feet. At present, the bend in Cloud Road generally follows the alignment of the 1981 center wash, a fact which does not bode well for the long-term stability of Cloud Road.

In 1933, the eastern channel of Skunk Creek flowed along the section 35-36 boundary, with a second channel to the north (Figure 3-14). By 1981, the total width of the multiple channels changed very little at the section line, but the northern channel shifted about 44 feet further north and new channels had formed to the east within section 36 and to the west within section 35. The 1933 eastern channel remained generally in the same position. Unfortunately, no GLO survey of Township 6 North 2 East was done in 1894, so there are no data for channel location along the section boundary before 1933.

TOWNSHIP 6 NORTH RANGE 2 EAST

Between sections 2(5N,2E) and 35(6N,2E), from corner of sections 1&2(5N,2E), and 35&36(6N,2E), heading west

1894
Left Bank.............. 356.4 ft (5.4 chains)
Channel Center...... 438.9 ft
Right Bank............ 521.4 ft (7.9 chains)
Total Width........... 165 ft

1933
East Channel Center............13.2 ft ***E of corner*** (0.2 chains)
East Channel Width..............46.2 ft (70 links)
West Channel Center............706.2 ft (10.2 chains)
West Channel Width.............46.2 ft (70 links)
Total Width.........................765.6 ft

1981
East Channel...................... 0 ft
Center Channel................... 466.67 ft
West Channel..................... 700.00 ft
Total Width...................... 700.00 ft +

Summary of movement: ***Changed from single channel (1894) to double channel (1933) to triple channel (1981)***
Abandoned 1894 channel when it split to two channels by 1933, then remained in two new channels and reoccupied the 1894 channel by 1981 to create three channel configuration
Total width of channels increased from 165 feet (1894) to over 700 feet (1981)

Between sections 35 and 36, from corner of sections 35&36(6N,2E) and 1&2(5N,2E), heading north

1933
East Channel...................... channel follows section line
Right Bank, East Channel......660.0 ft (10.0 chains)
Est. Width of East Channel.... 46.2 ft (70 links)
Center of West Channel......... 1089.0 ft (16.5 chains)
Width of West Channel......... 39.6 ft (70 links)
Total Width.........................495 ft
Median Position 862.95 ft

1981
East Channel Center............ 100.00 ft
Center Channel Center......... 500.00 ft
West Channel Center............ 1133.33 ft
Total Width......................... 1033.33 ft
Median Position 616.67 ft

Summary of movement: ***Changed from double channel (1933) to triple channel (1981)***
1981 west and center channels are same as 1933 east and west channels
1981 east channel is new since 1933

Skunk Creek was a double channel at the section 25/36 boundary in 1933 (Figure 3-15), with a 250.8 wide western channel. By 1981, the distinct western channel was reduced to approximately 40 feet wide but was still located within the old 1933 channel location. The small eastern channel shifted approximately 40 feet to the west. Also, a new connecting channel had formed between the east and west channels by 1981. The most recent aerial photographs indicate that the western channel is now the main channel.[10]

Between sections 25 and 36, from corner of sections 25, 26, 35, and 36, heading west

1933		1981	
East "Wash"	2039.4 ft (30.9 chains)	East Channel	2083.33 ft
Left Bank	2376.0 ft (36.0 chains)	Center Channel	2216.67 ft
Right Bank	2626.8 ft (39.8 chains)	West Channel	2550.00 ft
Total Width	587.4 ft	Total Width	466.67 ft +
Median Position	2333.1 ft	Median Position	2316.67 ft

Summary of movement: ***Eastern wash shifted 44 feet to the west***
250 ft. wide 1933 channel was possibly incised and reduced to 40 ft wide
New connecting channel between east and west channel formed by 1981

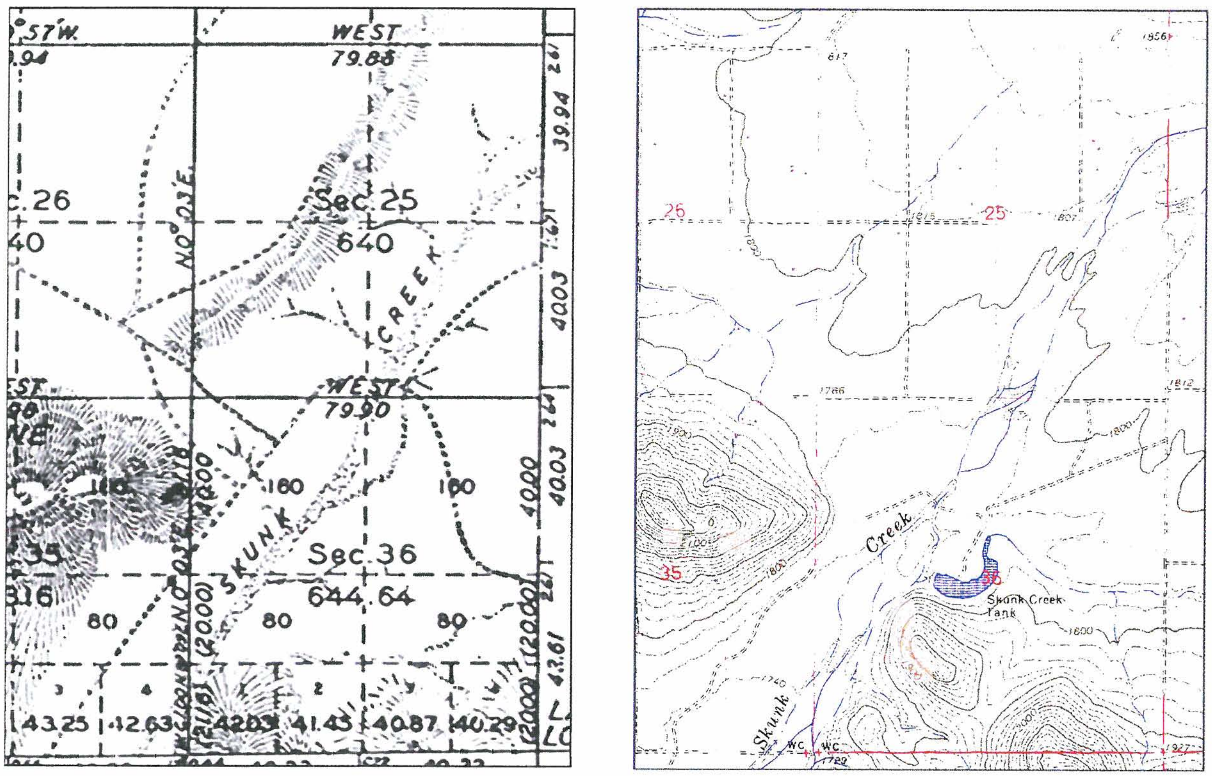


Figure 3-15. Sections 25/36 & 25/30 - 1933 GLO survey map compared to 1981 USGS map.

Skunk Creek is composed of multiple channels at the Township 6 North 2 East and Township 6 North 3 East boundary (sections 25-30; 19th Avenue alignment, Figure 3-15). Since 1910, the three channels recorded at this location have moved in conjunction with each other, generally moving in the same direction and with the same magnitude. The channels shifted to the south between 1910 and 1922. Between 1922 and 1933, the channels shifted to the north. Between 1933 and 1981, the channels again shifted to the south. The eastern channel has migrated back and forth within a 170 foot wide corridor.

[10] It is also noted that Skunk Tank was not shown in the 1933 GLO surveyor notes, although it may have been missed because it is not located on a section line. The water right for Skunk Tank was filed in 1893, according to records at the Arizona Department of Water Resources.

The middle channel has migrated within a 162 foot wide corridor. The center of the western channel migrated laterally within a 202 foot wide corridor.

In 1922, the middle channel at the R2E-R3E boundary (section 25/30) was identified as Skunk Creek, suggesting that it was the main flow channel at the time. Although a middle channel is not delineated on the 1981 USGS topographic map, 1995 aerial photographs show the existence of the middle braid. In 1933, the western channel was identified as Skunk Creek, suggesting that main flow had shifted from the middle channel to the western channel sometime between 1922 and 1933.

Sections 25(6N,2E) and 30(6N,3E), from corner of sections 25&36(6N,2E) and 30&31(6N,3E), heading west

1910		1922	
East Wash	2937.0 ft (44.5 chains)	East Wash	2768.04 ft (41.94 chains)
Middle Wash	3498.0 ft (53.0 chains)	Middle Wash	3335.64 ft (50.54 chains)
West Wash	3979.8 ft (60.3 chains)	"Skunk Creek"	3791.04 ft (57.44 chains)
Total Width	1042.8 ft	Total Width	1023.00 ft
Median Position	3458.4 ft	Median Position	3279.54 ft

1933		1981	
East Wash	2930.4 ft (44.4 chains)	East Channel	2766.67 ft
"Skunk Creek"	3432.0 ft (52.0 chains)		
West Wash	3993.0 ft (60.5 chains)	West Channel	3850.00 ft
Total Width	1062.6 ft	Total Width	1083.33 ft
Median Position	3461.7 ft	Median Position	3308.34 ft

Summary of movement: ***East channel center moved 169 ft south between 1910 and 1922***
East channel center moved 162 ft north between 1922 and 1933
East channel center moved 164 ft south between 1933 and 1981
Middle channel center moved 162 ft south between 1910 and 1922
Middle channel center moved 84 ft north between 1922 and 1933
West channel center moved 189 ft south between 1910 and 1922
West channel center moved 202 ft north between 1922 and 1933
West channel center moved 143 ft south between 1933 and 1981

Skunk Creek: Township 6 North Range 3 East

The changes in lateral position of Skunk Creek are less complex at the section 19-30 boundary (Desert Hills Drive alignment; Figure 3-16) than at most of the section boundaries upstream or downstream. The channel center of Skunk Creek migrated west nearly 150 feet along the section 19/30 boundary (Figures 3-16 and 3-17) between 1922 and 1981.[11] Upstream, along the boundary of sections 19 and 20, the center of the east channel of Skunk Creek, as recorded in 1922, moved 64 feet towards the south. The eastern channel also crosses the section 17/20 boundary just upstream, where it migrated about 193 feet to the east between 1922 and 1981. Interpretation of recent aerial photographs indicates that this "eastern channel" is probably the main channel of Rodger Creek.

Between sections 19 and 30, from corner of sections 19 & 30 (6N,3E) and 24 & 25 (6N,2E), heading east

1922		1981	
Channel Center	2546.94 ft (38.59 chains)	Channel Center	2400.0 ft
Channel Width	462.0 ft (7.0 chains)		

Summary of movement: ***Moved west 147 feet (river right)***

[11] No photorevision is shown on the USGS maps at the section 19-30 and 19-20 boundaries, so the movement probably occurred between 1922 and 1962.

Between sections 19 and 20, from corner of sections 19, 20, 29, and 30, heading north

1922		1981	
East Channel Center...........	3564.00 ft (54.00 chains)	East Channel Center...........	3500.0 ft
East Channel Width.............	66.0 ft (1.0 chain)		

Summary of movement: ***Moved south 64 feet (river left)***

Between sections 17 and 20, from corner of sections 17, 18, 19, and 20, heading west

1922		1981	
East Channel Center...........	5016.00 ft (76.00 chains)	East Channel Center...........	4816.67 ft
East Channel Width.............	132.0 ft (2.0 chains)		

Summary of movement: ***East channel moved east 193 feet (river left)***

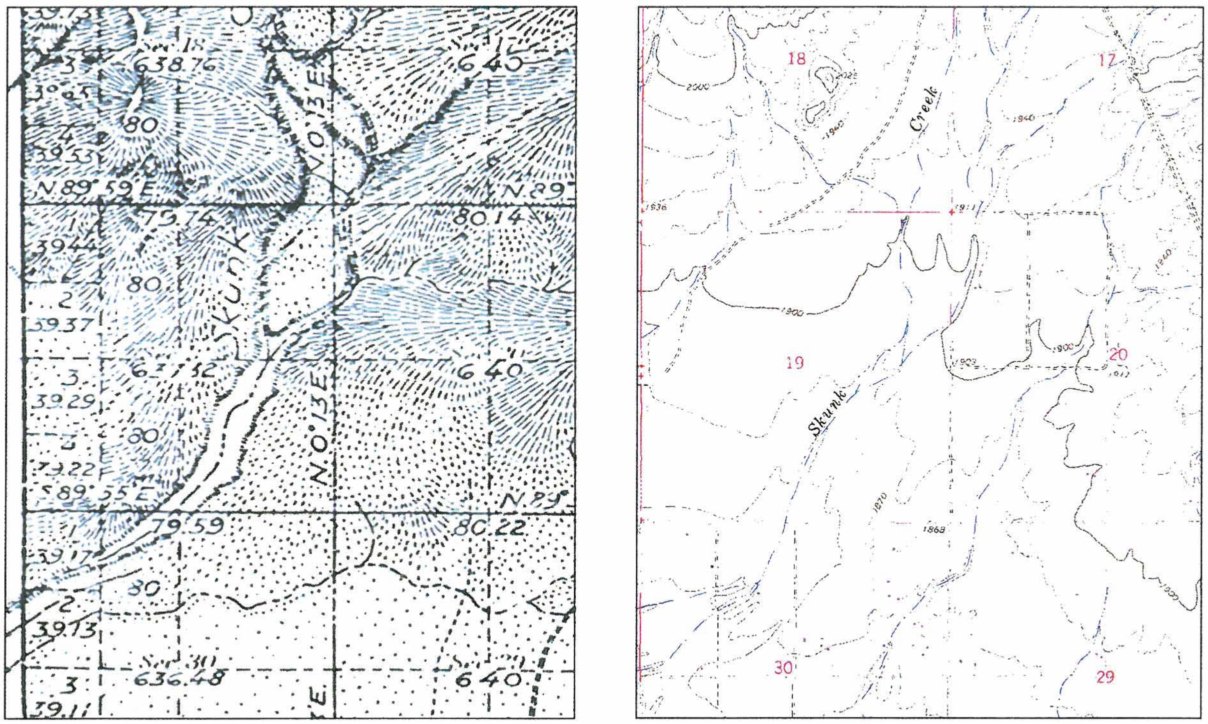


Figure 3-16. Section 30/19 & 17/18/19/20 - 1922 GLO survey map compared to 1981 USGS map.

At the section 18-19 boundary, the GLO surveyors recorded two channels in 1922. In 1922, the western channel was 132.0 feet wide. By 1981, the channel center had shifted about 40 feet to the west and the channel width had decreased. The 1999 aerial photographs indicate that the channel is now about 83 feet wide. A small middle channel was also recorded in 1922, although the channel is not shown on the 1981 USGS topographic map. However, the middle channel is visible on the 1999 aerial photographs in approximately the same location that was recorded in the 1922 GLO survey.

Between sections 18 and 19, from corner of sections 18 & 19 (6N,3E) and 13 & 24 (6N,2E), heading east

1922		1981	
West Channel Center..........	4590.3 ft (69.55 chains)	West Channel Center..........	4550.0 ft
West Channel Width............	132.0 ft (2.0 chains)		
Middle Channel Center.........	5123.58 ft (77.63 chains)	No Middle Channel Recorded	
Middle Channel Width...........	6.6 ft (10 links)		

Summary of movement: ***West channel moved west 40 feet (river right)***

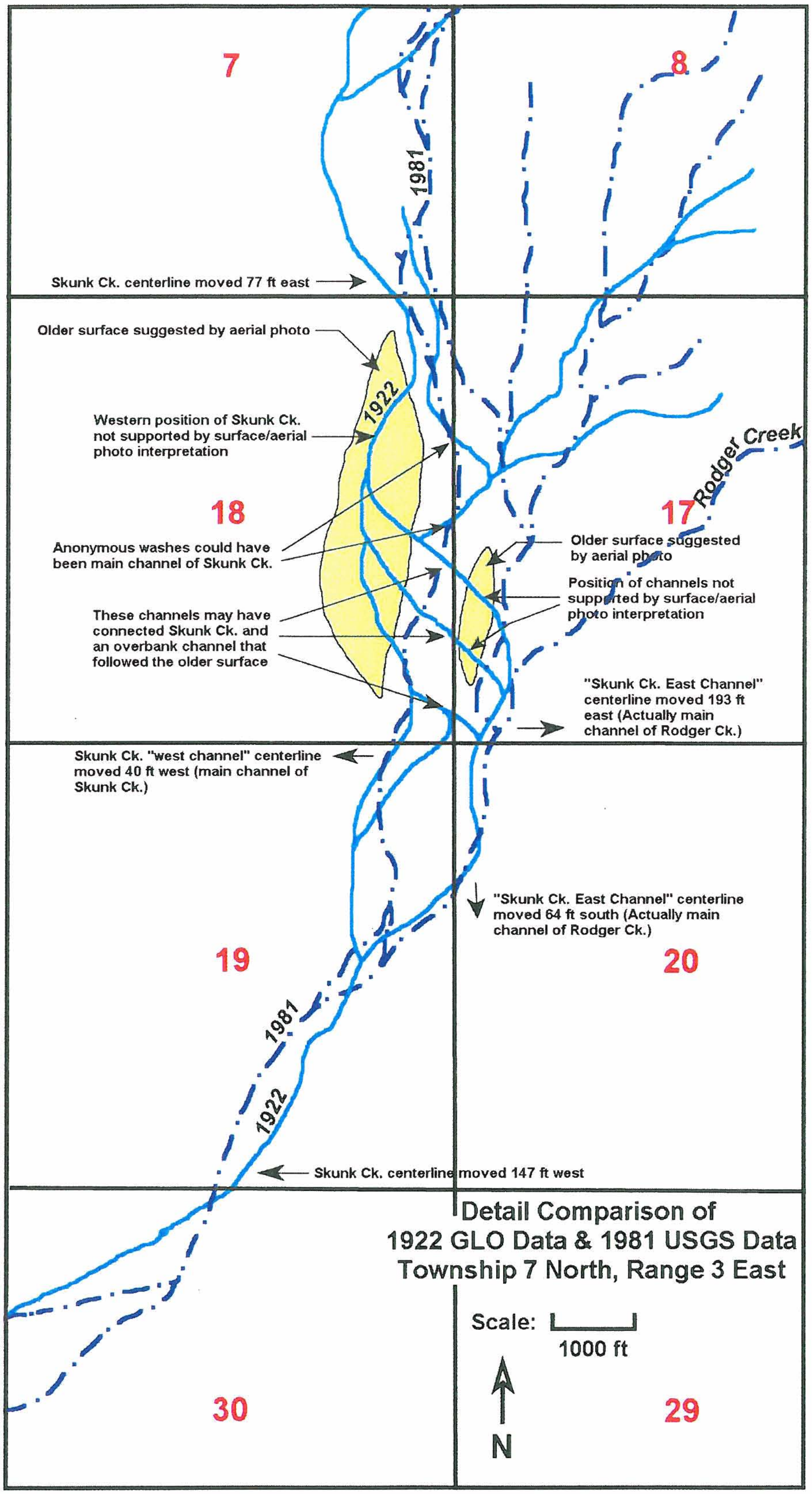


Figure 3-17. Detail Comparison of 1922 GLO Data and 1981 USGS Data

The 1922 GLO surveyors sketch map is difficult to reconcile with current or historical aerial photographs, field data, and regional geomorphic mapping. The 1922 GLO sketch of the channel position south of the section 7-18 boundary shows Skunk Creek flowing over an area which is now more than 20 feet above the channel bottom and which is underlain by bedrock. Comments shown on Figure 3-16 explain the changes that occurred from 1922 to 1981 along this reach of Skunk Creek. The two northernmost washes that cross the section 17-18 boundary, although not named by the 1922 survey, may well have been the main channel of Skunk Creek. If this is the case, then the meander radius decreased significantly since 1922. The center of "wash 4" on Figure 3-16 moved approximately 80 feet north, while the center of "wash 5" on Figure 3-16 moved approximately 97 feet south between 1922 and 1981. The 1981 east channel appears to be an overbank channel in the 1999 aerial photographs, not directly connected to the main channel of Skunk Creek, as is suggested by the 1981 USGS topographic map. Regardless of the exact interpretation, the GLO and USGS data indicate that substantial channel change occurred in the past 80 years on this reach of Skunk Creek.

The centerline of Skunk Creek moved approximately 77 feet east along the section 7-18 boundary from 1922 to 1981. The overbank channel just east of the main channel exhibited no movement during this period (See Figures 3-16 and 3-17).

Between sections 17 and 18, from corner of sections 17, 18, 19, and 20, heading north

1922		**1981**	
Wash 1Center	297.0 ft (4.5 chains)		
Wash 1 Width	33.0 ft (50 links)		
Wash 2 Center	1221.0 ft (18.50 chains)		
Wash 2 Width	66.0 ft (1.0 chain)		
"East Channel" Center	1980.0 ft (30.00 chains)		
"East Channel" Width	66.0 ft (1.0 chain)		
Wash 4 Center	2653.2 ft (40.2 chains)	West Channel	2733.33 ft
Wash 4 Width	165 ft (250 links)		
Wash 5 Center	3630.0 ft (55.0 chains)	West Channel	3533.33 ft
Wash 5 Width	13.2 ft (20 links)		
		East Channel	4500.00 ft

Summary of movement: ***Center of wash4/west channel moved approximately 80 feet north between 1922 and 1981***
Center of wash5/west channel moved approximately 97 feet south between 1922 and 1981
Three southernmost washes in 1922 were abandoned by 1981

Between sections 7 and 18, from corner of sections 7 & 18 (6N,3E) and 12 & 13 (6N, 2E), heading east

1922		**1981**	
"Skunk Creek" Center	4639.8 ft (70.3 chains)	West Channel Center	4716.67 ft
"Skunk Creek" Width	132 ft (2.0 chains)		
Wash Center	5062.2 ft (76.70 chains)	East Channel Center	5066.67 ft
Wash Width	19.8 ft (30 links)		

Summary of movement: ***West channel moved east 77 feet (river left)***
East channel moved east 4 feet (river left) – no significant movement

The historical movement of Skunk Creek is more clearly understood in the northern part of Township 6 North Range 3 East (Figure 3-17), although the 1922 GLO survey uses different names for the Skunk Creek and its tributaries. In 1922, present-day Skunk Creek apparently was known as Cottonwood Creek upstream of the Cline Creek confluence, while present-day Cline Creek was considered the northern extension of

Skunk Creek. This situation could suggest that Cline Creek delivered more water to the system than did the portion of (present-day) Skunk Creek upstream of the confluence. Also, on the 1981 USGS map, Cline Creek is represented as a wide multiple channel system similar to the downstream reaches of Skunk Creek, whereas upper (present-day) Skunk Creek is shown as a narrow single channel. Finally, the terraces on Skunk Creek downstream of the confluence are more continuous with the terraces on Cline Creek than with the terraces on (present-day) upper Skunk Creek.

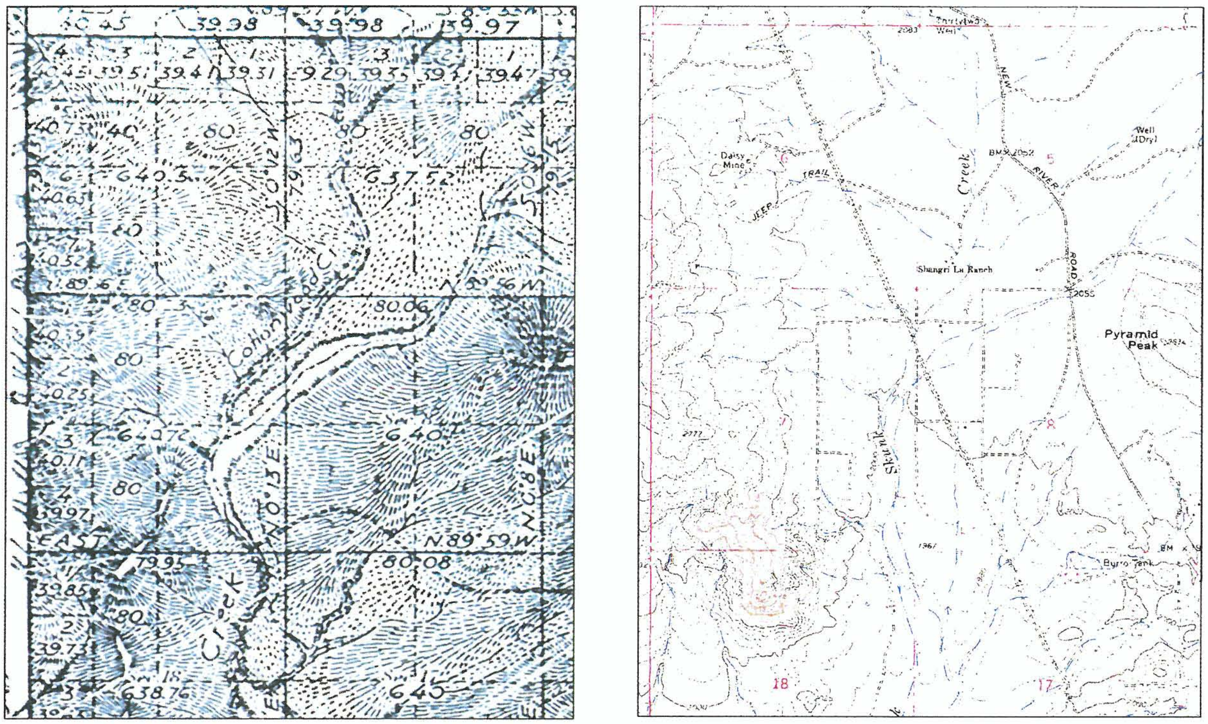


Figure 3-18. Section 7/18, 7/8, & 5/8 - 1922 GLO survey map compared to 1981 USGS map.

Between 1922 and 1981, the centerline of Skunk Creek moved 110 feet to the north at the section 7-8 boundary. The centerline of Skunk Creek moved about 113 feet to the east at the section 5-8 boundary (Figure 3-18). Skunk Creek exhibited no measurable movement along the northern border of Township 7 North Range 3 East.

Between sections 7 and 8, from corner of sections 7, 8, 17, and 18, heading north

1922		1981
"Skunk Creek" Center........... 3300.0 ft (50.0 chains)		Cline Creek Center............... 3366.67 ft
"Skunk Creek" Width........... 528.0 ft (8 chains)		
"Cottonwood Creek" Center... 4290.0 ft (65.0 chains)		Skunk Creek Center............. 4400.0 ft
"Cottonwood Creek" Width..... 132.0 ft (2.0 chains)		

Summary of movement: ***Skunk Creek moved north 110 feet (river right)***
Note: Skunk Creek known as "Cottonwood Creek" in 1922
Cline Creek moved north 67 feet (river right)
Note: Cline Creek known as "Skunk Creek" in 1922

Between sections 5 and 8, from corner of sections 4, 5, 7. and 8, heading west

1922		1981
"Skunk Creek" Center........... 1920.6 ft (29.10 chains)		Cline Creek East Channel Center...1866.67 ft
"Skunk Creek" Width 132 ft (2 chains)		Cline Creek West Channel Center.. 2166.67 ft

"Cottonwood Creek" Center... 4646.4 ft (68.40 chains) Skunk Creek Center.................4533.33 ft
"Cottonwood Creek" Width.... 198 ft (3 chains)

Summary of movement: ***Skunk Creek moved east 113 feet (river left)***
Note: Skunk Creek known as "Cottonwood Creek" in 1922
Cline Creek split into two channels, affected width increased from 132 feet (single channel) to 300 feet (channel center to channel center)
Note: Cline Creek known as "Skunk Creek" in 1922

Between sections 5(6N,3E) and 32(7N,3E), from section corner 5 & 6 (6N,3E) and 31 & 32 (7N,3E), heading west

1916
Skunk Creek Center............ 4612.08 ft (69.88 chains)

1922
Cottonwood Ck Center...4618.02 ft (69.97 chains)
Cottonwood Creek Width 66.0 ft (1.0 chain)

1981
Skunk Creek Center............ 4600.0 ft

Summary of movement: ***Moved west 5.94 feet (river right) between 1916 and 1922***
Moved east 18.02 feet (river left) between 1922 and 1981
Note: Skunk Creek known as "Cottonwood Creek" in 1922

Skunk Creek: Township 7 North, Range 3 East

Skunk Creek showed a general trend of movement towards river left in Township 7 North 3 East (Figure 3-19) from 1922 to 1981. At the section 31/32 boundary, the center of Skunk Creek moved northeast (river left) only about 35 feet. This difference is barely outside the margin of measurement error, and thus indicates a very slight shift. The shift was more significant at the section 30/31 boundary where the center of Skunk Creek moved about 143 feet to the east.

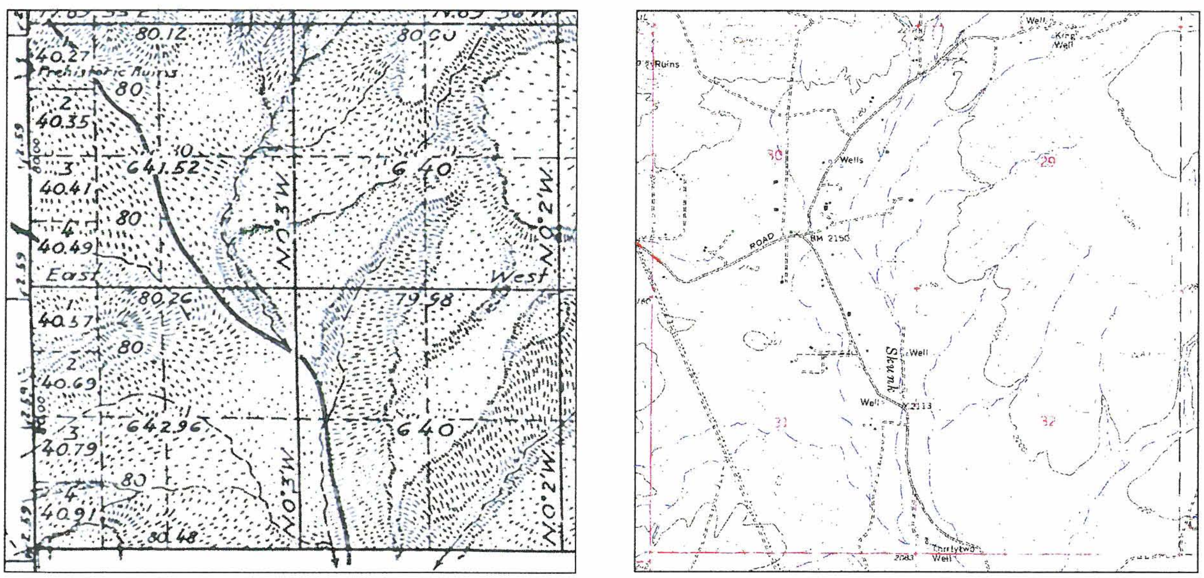


Figure 3-19. Section 30/31 & 31/32 - 1922 GLO survey map compared to 1981 USGS map.

Between sections 31 and 32, from corner of sections 31 & 32 (7N3E) and 5 & 6 (6N,3E), heading north

1916
Skunk Creek...................... 132.0 ft (2.0 chains)

1981
Skunk Creek...................... 166.67 ft

Summary of movement: ***Moved north 35 ft (river left)***

Between sections 30 and 31, from corner of sections 29, 30, 31, and 32, heading east

1916		1981	
Skunk Creek	4373.82 ft (66.27 chains)	Skunk Creek	4516.67 ft

Summary of movement: ***Moved east 143 ft (river left)***

Channel changes between 1922 and 1981 were also evaluated at several section boundaries upstream of the Skunk Creek study reach, and are summarized in tabular format below. In general, Skunk Creek upstream of the study area has remained a single channel stream with decreasing historical changes in the upstream direction.

Between sections 29 and 30, from corner of sections 29, 30, 31, and 32, heading north

1916		1981	
Skunk Creek	4191.0 ft (63.5 chains)	Skunk Creek	4016.67 ft

Summary of movement: ***Moved south 174 ft (river left)***

Between sections 20 and 29, from corner of sections 20, 21, 28, and 29, heading west

1916		1981	
Skunk Creek	4948.02 ft (74.97 chains)	Skunk Creek	4933.33 ft

Summary of movement: ***Moved south 15 ft (river left)***

Between sections 19 and 20, from corner of sections 19, 20, 29, and 30, heading north

1916		1981	
Skunk Creek	2112.0 ft (32.0 chains)	Skunk Creek	2183.33 ft
Skunk Creek	4026.0 ft (61.0 chains)	Skunk Creek	4033.33 ft

Summary of movement: ***D/s section moved north 71 ft (river right)***
U/s section moved north 7 ft (river left)

Between sections 17 and 20, from corner of sections 16, 17, 20, and 21, heading west

1916		1981	
Skunk Creek	4910.4 ft (74.4 chains)	Skunk Creek	4850.00 ft

Summary of movement: ***Moved south 60 ft (river left)***

Between sections 8 and 17, from corner of sections 8, 9, 16, and 17,heading west

1916		1981	
Skunk Creek	2993.1 ft (45.35 chains)	Skunk Creek	3016.67 ft

Summary of movement: ***Moved west 24 ft (river right)***

Sonoran Wash

Records of the Sonoran Wash in early GLO survey records are sparse, due to the short reach length and some uncertainty in the GLO records regarding what was a small unnamed wash. There are only three instances of dry washes crossing section lines that can be considered records of the Sonoran Wash's location. The movement indicated by the GLO/USGS comparisons at two of the locations is greater than 200 feet, more than any of the lateral shifts indicated on Skunk Creek and more than any movement recorded by comparison of aerial photographs dating back to 1940, making the identification of the wash somewhat tenuous. Descriptions of the lateral movement of Sonoran Wash are presented in the upstream direction, beginning at the CAP crossing.

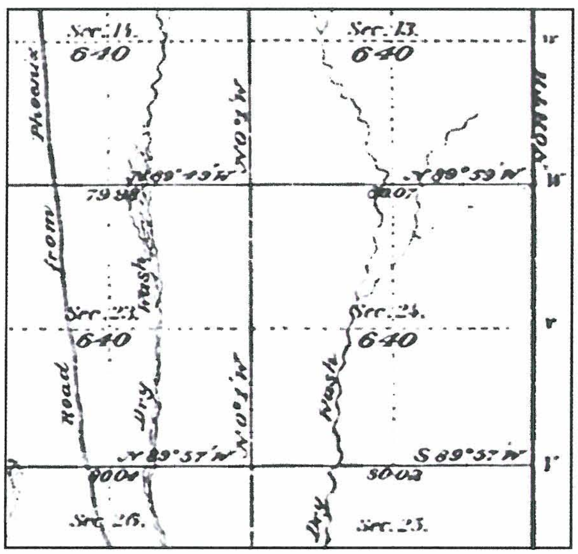
Sonoran Wash: Township 5 North, Range 2 East

Sonoran Wash crosses the section 24/25 boundary (Figure 3-20) just upstream of the CAP. Based on a comparison of the 1894 GLO surveys and the 1981 USGS topographic map, the data indicate that Sonoran Wash shifted approximately 260 feet to the west between 1894 and 1981. Although this amount of movement appears improbable, the 1999 aerial photographs indicate that an overbank channel exists approximately where the 1894 channel would have been. This overbank channel may once have been the main channel, but was abandoned following an avulsion.

Between sections 24 and 25, from corner of sections 19, 24, 25, and 30, heading west

1894	1981
Dry Wash..............3636.6 ft (55.1 chains)	Channel Center.................. 3900 ft

Summary of movement: ***Moved west 263 feet (river right)***



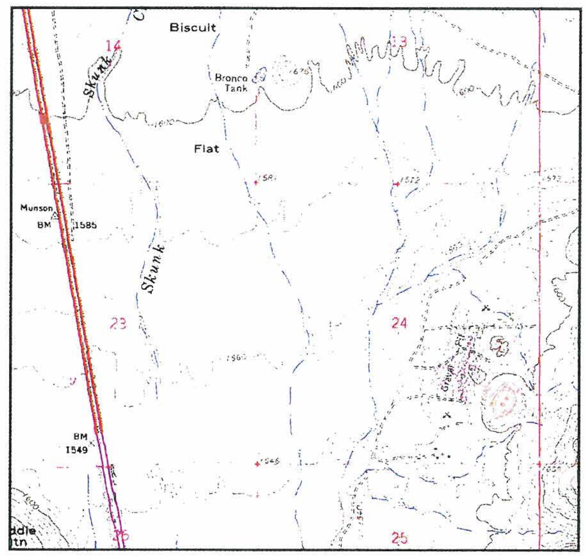


Figure 3-20. Section 24/25 & 24/19 - 1894 GLO survey map compared to 1981 USGS map.

Township 5 North, Range 3 East

The 1894 GLO survey recorded what is apparently the Sonoran Wash crossing two section lines in Township 5 North Range 3 East (Figure 3-21). Based on the comparison between 1894 GLO surveys and the 1981 USGS topographic map, the following lateral movements can be reported: The Sonoran Wash moved approximately 64 feet towards the south (river left) at the section 19/24 boundary and approximately 276 feet north (river right) at the section 19/20 boundary.

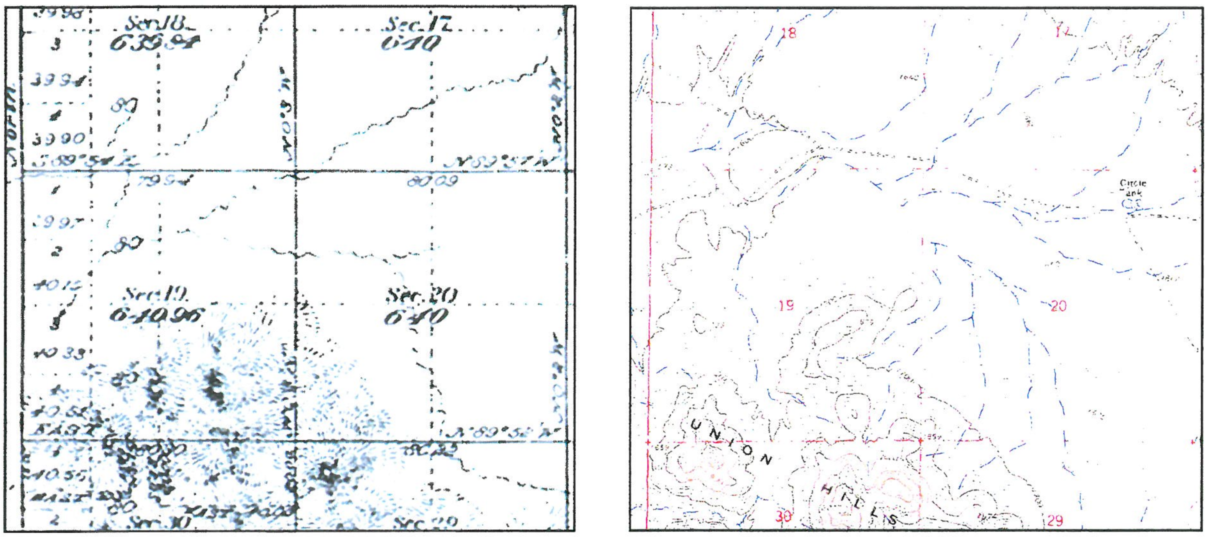


Figure 3-21. Section 19/20 - 1894 GLO map (left) compared to 1981 USGS topographic map (right).

Between section 19 (5N3E) and section 24 (5N2E) from the corner of sections 19,30,24, and 25, heading north

<u>1894</u>	<u>1981</u>
Dry Wash..............5214.0 ft (79.0 chains)	Channel Center..................5150.0 ft

Summary of movement: ***Moved south 64 feet (river left)***

Between sections 19 and 20, from corner of sections 19, 20, 29, and 30, heading west

<u>1894</u>	<u>1981</u>
Dry Wash..............3590.4 ft (54.4 chains)	Channel Center..................3866.67 ft

Summary of movement: ***Moved north 276 feet (river right)***

The four crossings of the section 19/18 boundary shown on the 1981 USGS map were not recorded by the GLO surveyors, indicating that the stream alignment may have remained south of the section line, or that the GLO surveyors simply omitted any description of Sonoran Wash at this location. Based on the GLO descriptions of Sonoran Wash at upstream and downstream section lines, the former explanation may be the most likely explanation, particularly given the well-defined channel that exists in this reach today. If the 1894 channel did remain south of the section 18/19 boundary, the 1981 channel position shown on the USGS map implies lateral movement of at least 120 feet to the north. This degree of movement is significantly greater than was measured by comparing channel positions digitized from historical aerial photographs. However, such movement would be possible given the width of the active floodplain and evidence of past avulsions observed in the field and in soil pits, and given the potential for historical degradation that could have altered the stream from a shallow braided avulsive channel to a more incised single channel.

Summary. Extension of the historical record of channel position by considering GLO survey records reveals that Skunk Creek and Sonoran Wash are subject to significant long-term lateral movement. Measurable channel movement was recorded at all but one of the 21 section line crossings in the study area. At many locations on Skunk Creek, the records indicate that new channels were formed, old channels were abandoned, and channel widths changed dramatically. The amount of estimated lateral erosion at each section line boundary in the study area is summarized in Table 3-6. The average long-term rate of lateral movement was about 1 foot per year during the longest periods of record. However, more than 200 feet of lateral movement was recorded at specific locations on both Skunk Creek and Sonoran Wash, with a maximum rate of movement of about 18 feet per year.

Table 3-6. Skunk Creek Watercourse Master Plan
Measured Channel Position Change, 1894-1999

Location (TR/Section)		Movement (ft)	Time Period	Rate (ft/yr)	Notes
Skunk Creek					
T5N R2E	23/26	94	1894-1981	1	
	14/23	79	1894-1981	1	
	11/14		1894-1981		Channels become defined & incised
	2/11		1894-1981		Channels become defined & incised
T6N R2E	2/35		1894-1981		New channels form, width changes
	35/36		1894-1981		New channels form, width changes
	25/36	44	1894-1981	1	New channels form
	25/30	EC - 169	1910-1922	14	Multiple channel changes in planform, location and width
		EC - 162	1922-1933	15	
		EC - 164	1933-1981	3	
		CC - 162	1910-1922	14	
		CC - 84	1922-1933	8	
		WC - 189	1910-1922	16	
		WC - 202	1922-1933	18	
		WC - 143	1933-1981	3	
T6N R3E	19/30	147	1922-1981	2	
	19/20	64	1922-1981	1	
	17/20	193	1922-1981	3	
	18/19	40	1922-1981	1	
	17/18	EC - 80	1922-1981	1	Channel abandoned
		WC - 97		2	
	7/18	EC - 77	1922-1981	1	
		WC - NM		0	
	5/8	113	1922-1981	2	
T7N R3E	31/32	35	1916-1981	1	
	30/31	143	1916-1981	1	
Sonoran Wash					
T5N R2E	24/25	263	1894-1981	3	
T5N R3E	19/24	64	1894-1981	1	
	19/20	276	1894-1981	3	
	18/19	> 120	1894-1981	1	

Notes:
EC = east channel CC = central channel NM = No measurable change
WC = west channel NC = no measurable change

Vertical Channel Change

Single Event Changes. No data were available from which to accurately quantify estimates of vertical channel change due to any single historical flow event. Scour computations (Chapter 5) and HEC-6 modeling results (Stantec, 2001) indicate that general scour depths will be moderate, except in bends or where local scour around structures occurs. Qualitative estimates of historical scour depths were made from field evidence. The following types of information were observed:

- Scour holes. Scour holes ranging from 0.5 feet to more than 3 feet were observed in Skunk Creek and Sonoran Wash at sharp channel bends, at points where bedrock impinges on the main channel, around mid-channel vegetation (Figures 3-22 and 3-24, and around some bridge piers (Figure 3-23). Presumably, these scour holes formed during individual events, although they may form repeatedly in the same locations due to persistent hydraulic conditions. Scour through sub-channel caliche layers was also observed in several places on Skunk Creek (Figure 3-25).

Figure 3-22. Scour and deposition of sand and gravel sediment near mid-channel vegetation.

Figure 3-23. Pier scour at New River Road bridge over Skunk Creek.

Figure 3-24. Scour and deposition of sand and gravel sediment near mid-channel vegetation.

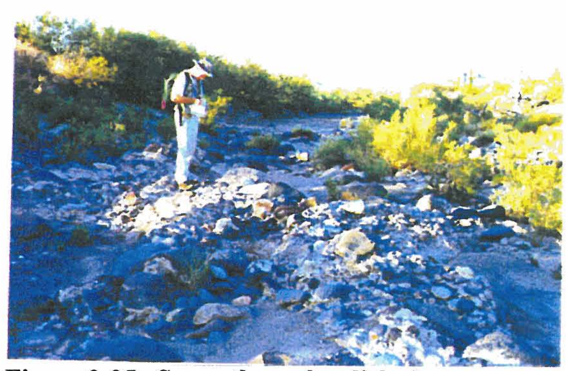


Figure 3-25. Scour through caliche layer on braid of Skunk Creek.

- Deposition. Deposition, rather than scour, occurs where velocities decrease. The backwater areas upstream of the CAP overchutes are characterized by net deposition (Figure 3-26). Deposition also occurs at the mouths of the tributaries that enter

Skunk Creek and Sonoran Wash, but are especially visible along Sonoran Wash due to the contrast in bed materials (See Figure 4-70).

Figure 3-26. Sediment deposition upstream of the CAP overchute.

- General Degradation. Field evidence suggests that portions of Sonoran Wash have recently incised by about one foot (Figure 3-27). In other places, slope breaks and small headcuts indicate that some incision has occurred on Skunk Creek. Field evidence of these features is discussed in Chapter 4.

Figure 3-27. General degradation expressed in bank by vegetation line on Sonoran Wash.

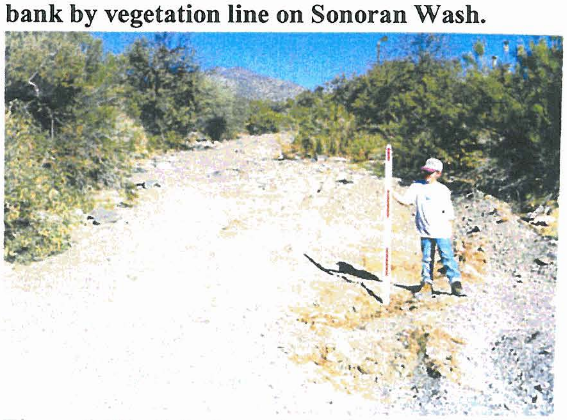


Figure 3-28. Subchannel clay layer exposed in bed of Skunk Creek.

Figure 3-29. Subchannel clay layer exposed in soil pit at depth of about 1.5 feet in Skunk Creek.

- Clay Layer Depth. A clay-rich layer was observed in most of the soil test pits excavated in the main channels of both Skunk Creek and Sonoran Wash (Figures 3-28 and 3-29). The top of the clay layer was interpreted as the limit of recent general scour, since the clay material would not be likely to remain in place if it were subject to periodic scour. The depth of the clay-rich layer ranged from zero depth (exposed on the bed itself at one location on Skunk Creek; Figure 3-28) to several feet below the channel bed (Figure 3-29). Generally, the depth of the clay-rich layer decreased in the upstream direction.

These field data indicate that single event scour does occur in the study area and is generally limited to less than a few feet, except where unusual conditions exist.

Long-Term Changes. Long-term vertical changes in the bed elevations of Skunk Creek and Sonoran Wash were estimated using the following methods:

- Analysis of longitudinal profiles
- Comparison of topographic data at bridges
- Interpretation of historical stereo photographs
- Interpretation of archaeological/geologic data

Data Sources. The sources of aerial photographs and topographic information used in the vertical channel movement analysis are shown in Table 3-7. Topographic data obtained from printed maps have several types of potential errors. Measurement error associated with the longitudinal profile comparison is a function of the map scale and contour interval, as shown in Table 3-7, and results from manually measuring distances on printed maps. Measurement error was estimated as half the smallest unit (0.02 inch) of measurement on the engineering scale used to determine distances on the paper copy of the map. Vertical error associated with topographic maps is generally considered to be half the contour interval, and is therefore related to the survey accuracy.

Table 3-7. Skunk Creek/Sonoran Wash Watercourse Master Plan
Topographic Data Used for Longitudinal Profile Analysis

Date	Scale	Contour Interval	Measurement Error		Extent	Source
			Vertical	Horizontal		
1962	1:24,000	10 ft.	±5 ft.	±40 ft.	Entire reach	USGS
1976	n.a.	4 ft.	±2 ft.	n.a.	CAP to Carefree Highway	FEMA
1977	1:4,800	4 ft.	±2 ft.	±8 ft.	Carefree Highway to New River Rd.	FEMA
1995	1:2,400	2 ft.	±1 ft.	±4 ft.	CAP to Desert Hills Rd. Honda Bow Rd. to New River Rd.	FCDMC
1996	1:1,200	1 ft.	±0.5 ft	±2 ft.	Desert Hills Rd. to Honda Bow Rd.	Erie
1999	1:2,400	2 ft.	±1 ft.	±4 ft.	Sonoran Wash study limits	FCDMC

Longitudinal Profiles - Skunk Creek. The longitudinal profiles of Skunk Creek from 1962, 1976-77, and 1995 are shown in Figure 3-30. No clear trends toward net aggradation or degradation for the entire study reach were visible in the longitudinal profiles shown Figure 3-30, so elevation data were obtained from the profiles for specific points and are summarized in Figures 3-31 to 3-34.

Figure 3-30. Skunk Creek Longitudinal Profiles, 1962-1995

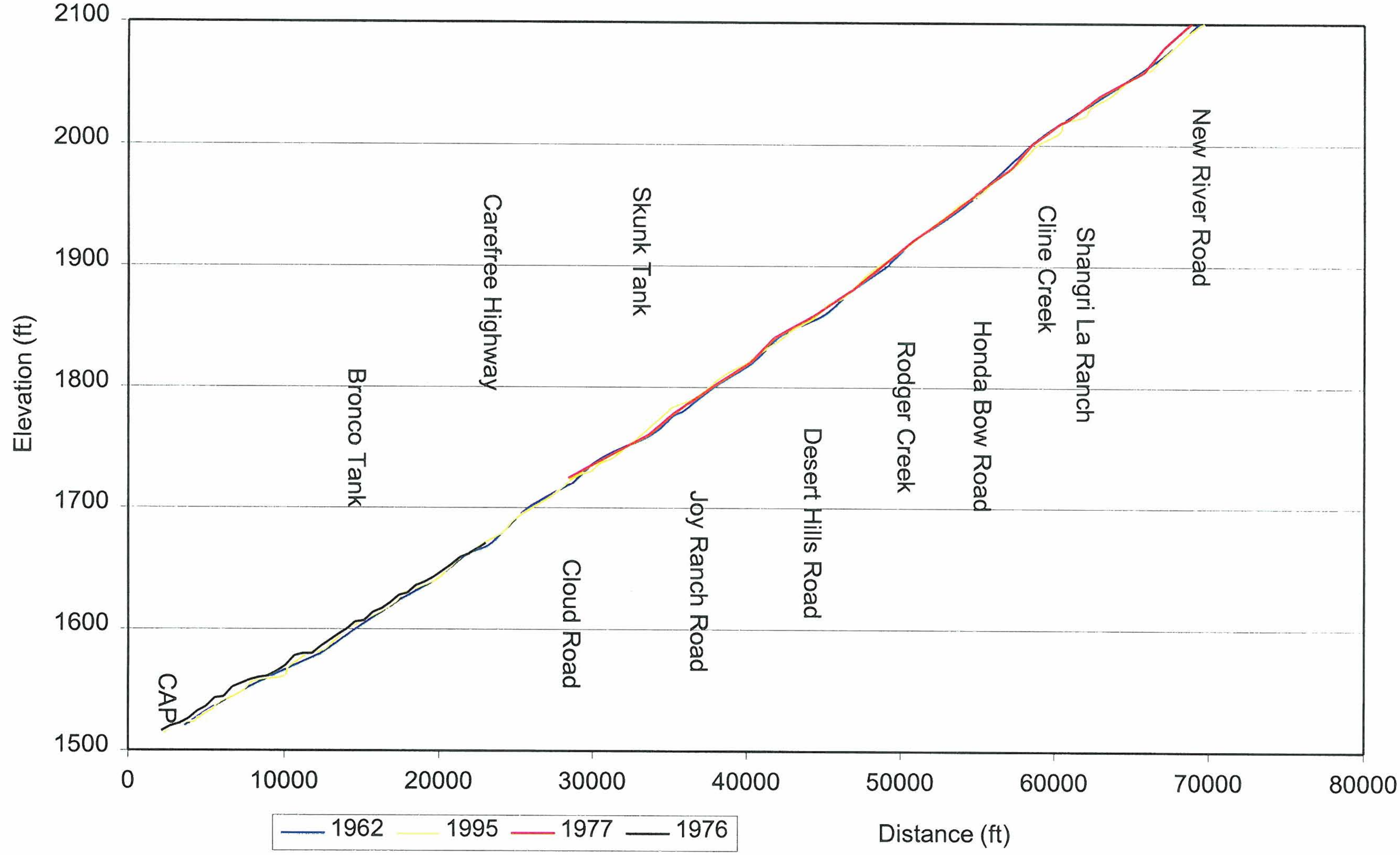
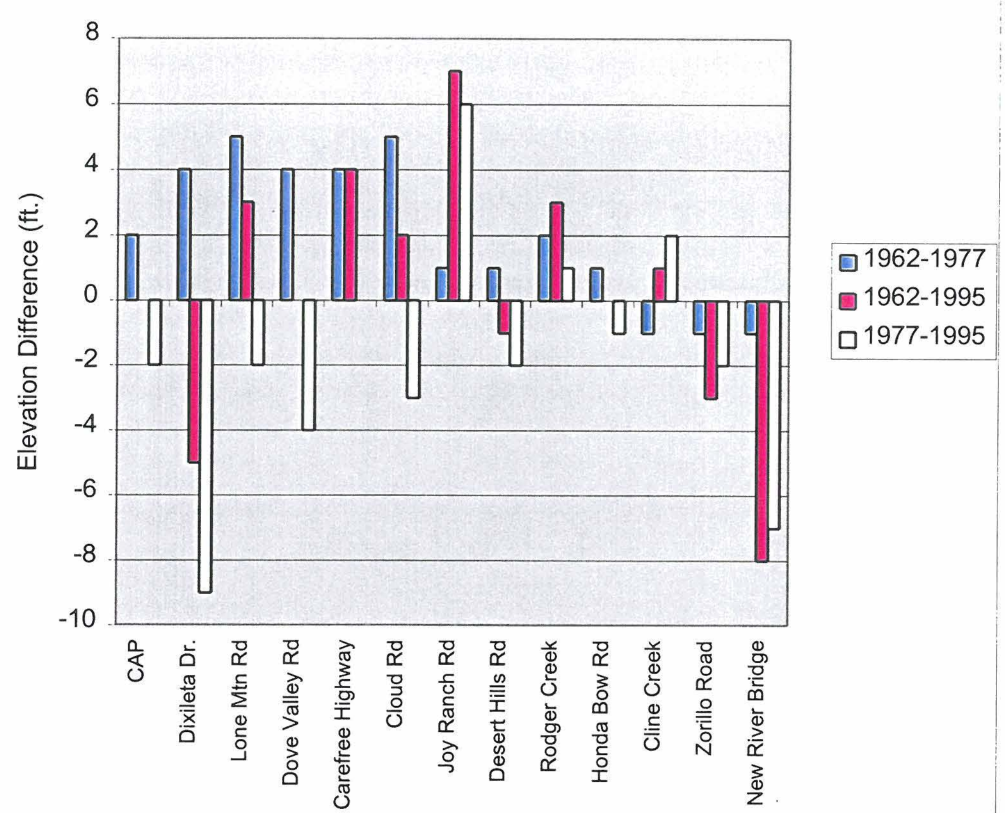


Figure 3-31. Skunk Creek Bed Elevation Change 1964-1995



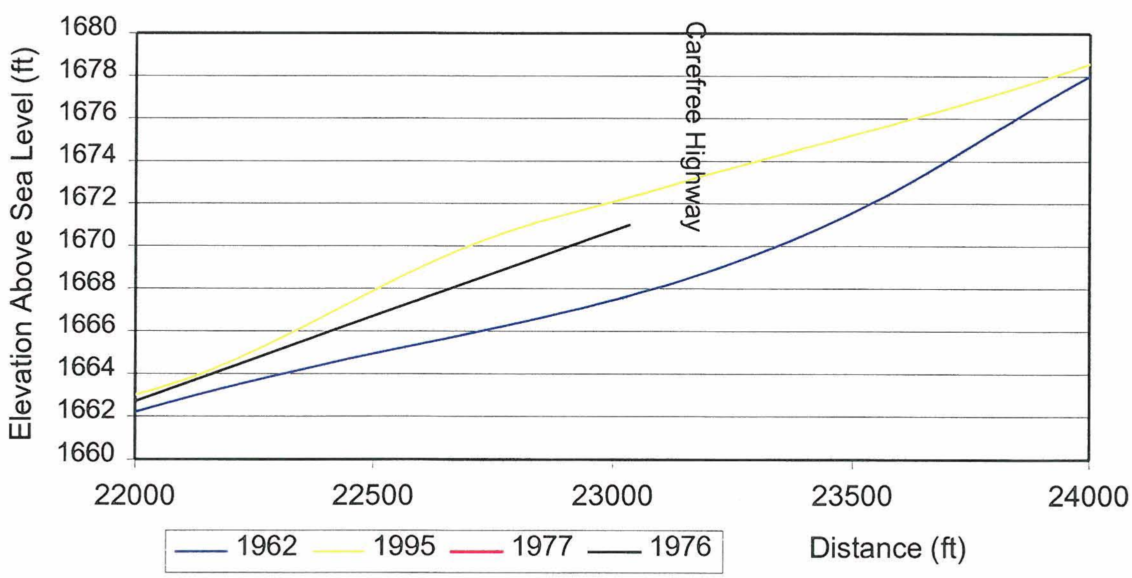
The data shown in Figure 3-31 reveal the following broad trends in long-term bed elevation changes from 1962 to 1999:

- 1962-1977. Skunk Creek was characterized by net aggradation downstream of Honda Bow Road from 1962 to 1977, and net degradation upstream of Zorillo Road. Upstream of Cloud Road, the measured bed elevation changes during this period were generally less than the map accuracy. Estimated movement within the level of map accuracy could easily depict normal movement of bars and other bed sediments, rather than a long-term slope adjustment.
- 1977-1995. Skunk Creek was characterized by net degradation from 1977 to 1995, except at Cline Creek, Rodger Creek, and Joy Ranch Road.
- 1962-1995. Examination of the entire period of record indicates that net aggradation occurred from about the Lone Mountain Road alignment to the Cline Creek confluence, with net degradation upstream and downstream.

The longitudinal profile data are somewhat surprising for several reasons. First, a stronger trend toward aggradation in the CAP backwater area was expected after 1977 based on hydraulic modeling, HEC-6 results, and field observations. However, some evidence of headcutting upstream of the Dixileta Road alignment was observed during the field work. Second, it is noted that bridge construction at New River Road and Carefree Highway was completed during or after 1995. Therefore, expected and observed vertical adjustments of the bed elevation in response to channelization of the bridge sections had not yet occurred during the period of record. Third, the period between 1962 and 1977 was characterized by larger flood peaks, which typically would be associated with long-term degradation. However, USGS gauge data indicate that the period from 1977 to 1995 had higher average flow volumes than the period from 1962 to 1977. The five largest recorded flow volume years on Skunk Creek occurred between 1978 and 1993. These data indicate that flow volume was more important than peak discharge for long-term bed elevation adjustments on Skunk Creek.

Longitudinal profiles at three specific reaches of Skunk Creek where significant changes occurred were also examined to detect trends in bed elevation changes. These reaches included Carefree Highway (Figure 3-32), Joy Ranch Road (Figure 3-33), and Cline Creek (Figure 3-34). The measurable aggradation of 3 to 4 feet at the Carefree Highway bridge may be due to bridge construction and maintenance practices. The Carefree Highway at-grade crossing was replaced by a bridge just prior to 1977. Channelization of Skunk Creek which occurred during bridge construction included relocating, widening and possibly deepening the channel to improve conveyance under the bridge. Unfortunately, overwidening the main channel led to decreased velocities and sediment deposition (aggradation), which continued from 1962 to 1995. Recent field evidence suggests that the section has continued to aggrade with each flood.

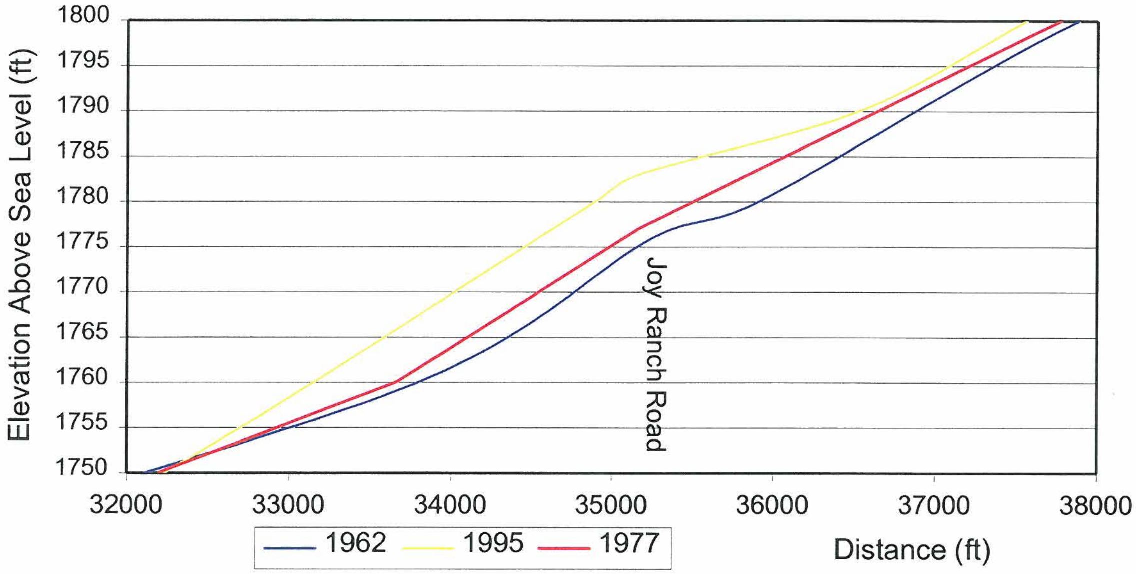
Figure 3-32. Longitudinal Profile - Skunk Creek at Carefree Highway



Near Joy Ranch Road, the data indicate that the main channel of Skunk Creek aggraded by up to 8 feet between 1962 and 1995 (Figure 3-33). The channel planform in this reach of Skunk Creek is highly braided with a splay located directly at the Joy Ranch Road alignment. This reach was also a site of major lateral channel changes between 1896 and

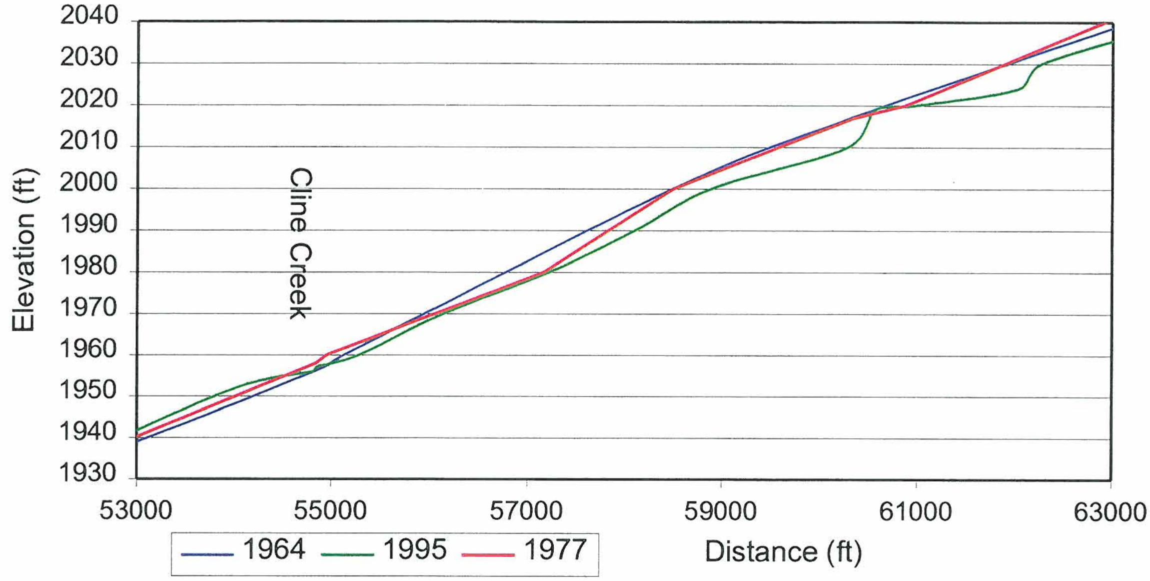
1999, as shown by the analysis of historical aerial photographs and GLO survey records. Also, the longitudinal profile indicates that the profile shape is concave down at Joy Ranch Road, which is an indication of sediment deposition. Future deposition and aggradation should be expected upstream of Joy Ranch Road in the short-term, with later headcutting downstream that will eventually re-establish a more uniform profile.

Figure 3-33. Longitudinal Profile of Skunk Creek at Joy Ranch Road



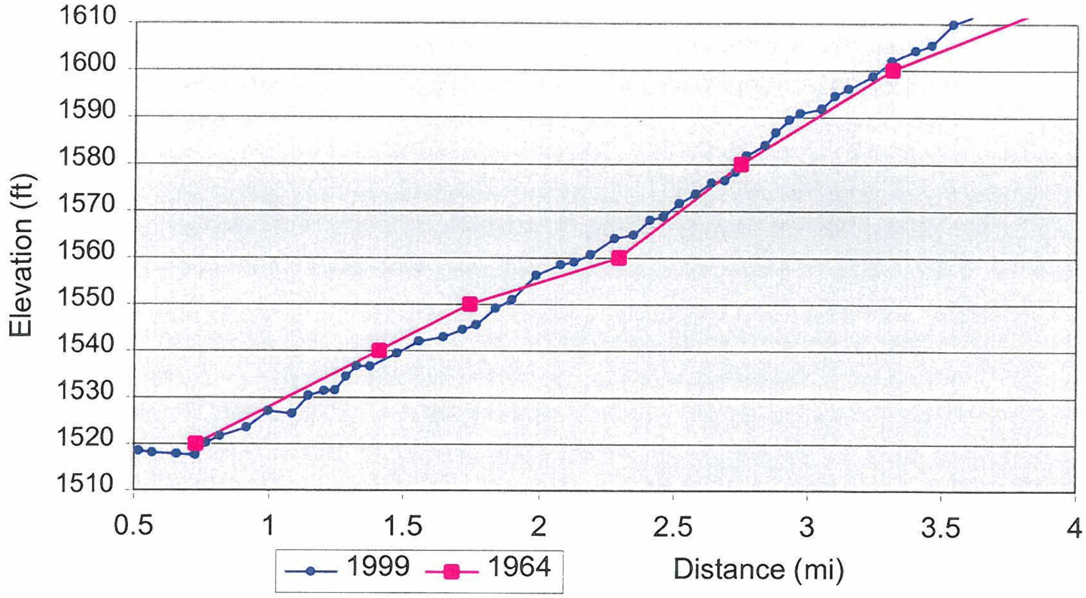
The maximum measurable degradation recorded by the longitudinal profiles was in the reach between the Cline Creek confluence and the New River Road bridge (Figure 3-34). According to the profile data, most of the vertical movement occurred between 1979 and 1995. Interestingly, an opposite trend (degradation) occurred downstream of the Cline Creek confluence.

Figure 3-34. Longitudinal Profile Skunk Creek Upstream of Cline Creek



Longitudinal Profiles - Sonoran Wash. The longitudinal profile for Sonoran Wash is difficult to interpret due to scale and rectification problems, map accuracy issues, and limited verification data. The broad trends indicated by comparing the 1962 and 1999 longitudinal profiles (Figure 3-35) are exactly opposite of the trends indicated by field data. That is, field evidence and hydraulic modeling indicate that deposition (aggradation) should have occurred immediately upstream of the CAP, and that degradation was more likely near the headwaters. Given the problems with rectification caused by the lack of geographic information in the study reach, professional judgment indicates that the longitudinal profile results for Sonoran Wash should be viewed with extreme caution.

Figure 3-35. Sonoran Wash Longitudinal Profile, 1962-1999



Elevation Data at Bridge Locations. Permanent structures in or adjacent to streams are optimum benchmarks from which to measure channel change. Two such structures, the Carefree Highway bridge and the New River Road bridge, exist on Skunk Creek. No permanent structures exist within the study limits of Sonoran Wash.

Skunk Creek at Carefree Highway. Detailed examination of available elevation data for Skunk Creek at Carefree Highway reveals a trend of net aggradation since 1962 (Table 3-8). Much of the aggradation can be attributed to widening the main channel over three times the natural channel width during construction of the original Carefree Highway Bridge. Continued aggradation and/or sediment maintenance should be expected in the future.

Table 3-8. Skunk Creek/Sonoran Wash Watercourse Master Plan
Vertical Channel Change – Skunk Creek @ Carefree Highway Bridge, 1962-2001

Date	Source	Channel Elevation	Change (ft)	Comments
1962	USGS Topographic Map	1669 ft.		Interpolated elevation from topo map
1979	Harris-Toups FIS Worksheet	1673.0 ft.	+ 4 ft.	
1995	FCDMC Topographic Map	1671.0 ft.	- 2.0 ft.	Max. bed elevation = 1674.0 ft.
1997	ADOT Engineering Drawings	1671.7 ft.	+ 1.7 ft.	
2000	JEF Field measurements	1675.4 ft.	+ 3.7 ft.	Max. bed elevation on 12/5/00 Min. bed elevation = 1673.2 ft

Note: As-built plans for the original (1981) Carefree Highway bridge were not available from MCDOT.

Skunk Creek at New River Road. The New River Road bridge was constructed between late 1995 and early 1996. As part of the bridge construction, the bed of the main channel was lowered by about 6 feet within the bridge. Upstream and downstream of the bridge section the bed elevation was not altered. Effectively, the bridge channelization created a hole which has filled by more than three feet since 1996. Because the channel under the bridge was also widened, and because the downstream end of the bridge channel is blocked by natural high ground at the right-of-way limit, the channel under the bridge is likely to continue to aggrade until a more natural channel size is re-established. The data in Table 3-9 indicate that the bed elevation has about three more feet of aggradation to recover the pre-channelization grade. If an additional three feet of aggradation occurs, the channel bed will be only about two feet from the low chord of the bridge.

Table 3-9. Skunk Creek/Sonoran Wash Watercourse Master Plan
Vertical Channel Change – Skunk Creek @ New River Road Bridge, 1962-2001

Date	Source	Channel Elevation	Change (ft)	Comments
1962	USGS Topographic Map	2107 ft		Interpolated elevation from topo map
1979	Harris-Toups FIS Worksheet	2106.0 ft.	- 1.0 ft.	
1995	FCDMC Topographic Map	2100.0 ft.	- 6.0 ft.	Topo prepared during construction
1996	MCDOT As-Built Plans	2099.5 ft.	- 0.5 ft.	
1999	JEF Field Measurements	2102.8 ft.	+ 3.2 ft.	Max. bed elevation on 10/15/99 Min. bed elevation = 2101.2 ft
2000	JEF Field Measurements	2102.7 ft.	- 0.1 ft.	Max. bed elevation on 6/21/00 Min. bed elevation = 2101.3 ft
2001	JEF Field Measurements	2102.8 ft.	+ 0.1 ft.	Max. bed elevation on 12/13/00 Min. bed elevation = 2101.1 ft

Aerial Photograph Interpretation. A chronology of channel change developed by interpreting recent and historical aerial photographs was presented in Tables 3-2 and 3-3. Where significant degradation occurs within the period of photographic record, changes in bank height can be quantified using a parallax bar and stereo photographs. However, while significant lateral channel change and human impacts to the study area were observed, no conclusive evidence of vertical channel change was obtained solely from the aerial photographs. That is, whatever long-term vertical changes occurred on Skunk Creek and Sonoran Wash were outside the accuracy limits of measurement that could be made with parallax bar technology.

Interpretation of Archaeological and Geological Data. The age of the terrace and floodplain surfaces adjacent to a stream can be used to estimate the direction and rate of long-term vertical bed elevation change. The main channels of Skunk Creek and Sonoran Wash are inset into a descending series of progressively younger terraces. The elevations of the middle Pleistocene terraces (> 250,000 years before present [b.p.]) average about 16 feet above the beds of both streams. The elevation of Holocene terraces (< 10,000 yrs. b.p.) average 4 to 7 feet above the bed of Sonoran Wash, and 6 to 8 feet above the bed of Skunk Creek. These elevation and age data imply that net long-term degradation has averaged 10^{-4} to 10^{-5} feet per year over the past several hundred thousand years. Given that the observed rate of degradation during the period of historical record exceeds the implied long-term geologic rate by several orders of magnitude, and that aggradation has also been recorded in some reaches, it may be concluded that the elevations of the channel beds will fluctuate around a slight degradational trend.

Channel Geometry Change
The geometry of a stream channel is defined primarily by its width and depth. The channel planform is expressed by the channel pattern and sinuosity. Historical changes in channel geometry and planform can be used to calibrate predictions of future channel change. Historical changes in channel geometry and planform were measured from aerial photographs, topographic maps, and GLO survey data.

Channel Width. Channel width is defined as the distance between the left and right primary stream banks. Historical changes in channel width were measured using the following data sources:

- Historical aerial photographs
- GLO survey records

Historical Aerial Photograph Width Measurements. Channel widths were measured on aerial photographs of Skunk Creek and Sonoran Wash from 1962, 1971, 1988, 1992, 1995, and 1999. Comparisons of channel widths from different years revealed periods of bank erosion or channel narrowing, and documented the scale of potential future width adjustments.

Methodology. Measurements of channel width were taken in 1,000 foot increments along Skunk Creek and Sonoran Wash. A grid system that referenced specific landmarks and geographic features was established to assure that widths were measured in identical locations on each year of coverage. Where multiple channels were present, width was assumed to be the difference between the furthest left and right channels, i.e., islands were included in the width measurement. Stream banks were identified on aerial photographs using the following visual criteria:

- Color contrast. Bright toned channel bed sediments contrast with darker toned floodplain soils.
- Vegetation. The densest vegetation typically occurs on the bank slope.
- Topography. Stereo photographs provide a three dimensional image from which the bank toe and top could be identified. Where no stereo coverage was available, shadows often revealed topographic features.
- Reach characteristics. Where bank stations were indistinct at a given cross section, the bank characteristics immediately upstream and downstream were used.

Changes in channel width were computed relative to the next older set of aerial photographs so that positive difference indicated widening and a negative difference indicated narrowing.

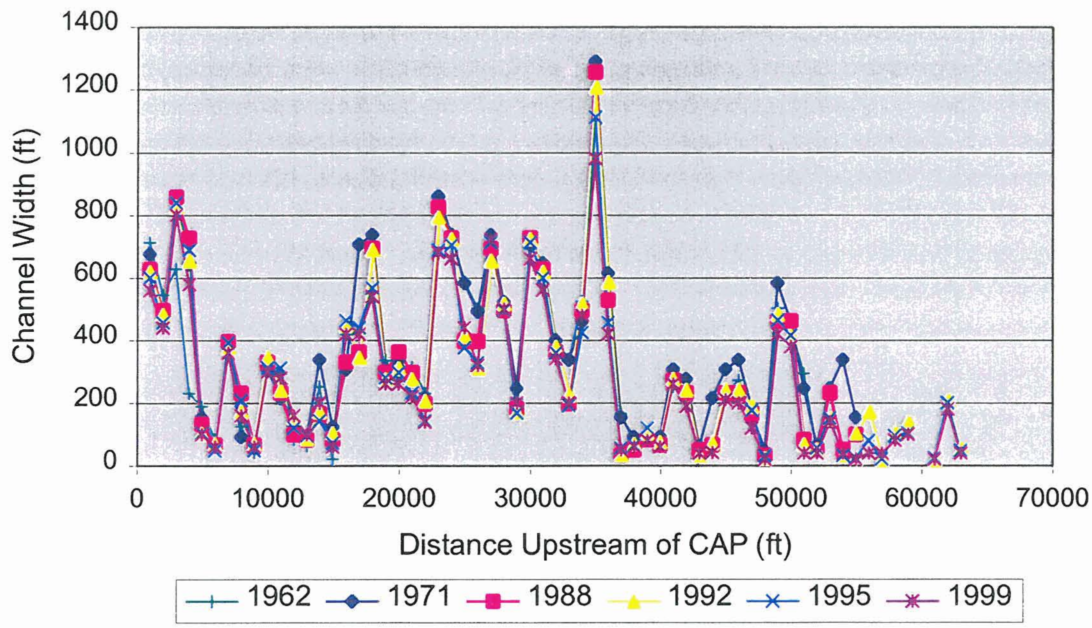
Measurement Error. The accuracy of the channel width measurements is a function of the scale of the aerial photographs and the smallest scale increment on the engineering ruler used to measure stream width. The measurement itself could be no more accurate than 1/60 inch, the smallest visible increment on an engineering ruler. The scale and potential measurement error for each set of aerial photographs used is shown in Table 3-

10. Measured channel change less than the potential error should be considered as no measurable change unless other supporting documentation can be identified.

Table 3-10. Skunk Creek/Sonoran Wash Watercourse Master Plan Potential Channel Width Measurement Error from Aerial Photographs		
Year	**Photo Scale**	**Error**
1962	1:25,140	+/- 21
1971	1:36,840	+/- 31
1988	1:39,600	+/- 33
1992	1:41,400	+/- 35
1995	1:9,600	+/- 8
1999	1:24,000	+/- 20

Results.
Skunk Creek. Changes in channel widths in Skunk Creek from 1962 to 1999 are illustrated in Figure 3-36. In general, changes in channel width during the 37-year period of record were small to moderate relative to the scale of changes determined by consideration of GLO records extending back an additional 68 years. Small to moderate width changes are appropriate given the small to moderate-sized floods which occurred after 1962.

Figure 3-36. Skunk Creek Channel Widths, 1962-1999



The following paragraphs discuss significant changes in channel width for specific time periods and specific years of coverage.

1962-1971: In general, the width change between 1962 and 1971 was measurable. Out of 52 reference locations, 23 had measurable estimates of bank change, most of which were increases in channel width. The increase in width was probably due to the 1964 (11,500 cfs, flood of record) and 1970 (9,650 cfs, 2nd largest peak) floods. It is noted that much of the bank and floodplain vegetation was lost during this period, and vegetated bars and islands that had divided the main channel into multiple channels in 1962 were lost by 1971. Representative results are listed in Table 3-11:

Table 3-11. Skunk Creek/Sonoran Wash Watercourse Master Plan
Measured Width Changes: Skunk Creek 1962-1971

Station	Width Change (ft)	Notes
3000	231 ft	-avulsion at left bank
4000	414 ft	-same avulsion at left bank as at 3000
15000	102 ft	-channel widening at left bank
16000	-112 ft	-smaller channel towards left bank disappeared by 1971
17000	350 ft	-channel widened towards right bank, loss of vegetation
44000	152 ft	-avulsion at left bank, plus widening and destruction of vegetation

1971-1988: A series of floods with small to moderate peaks, but above-average volumes occurred between 1971 and 1988. This period of low peak, high volume flow resulted in overall narrowing of Skunk Creek. It is noted that since the longitudinal profile comparison indicated some degradation during this period, the high volumes may have increased bank vegetation density. Better vegetated, more resistant channel banks would have induced narrowing and increased the chance that sediment deficits be satisfied from the bed materials (degradation). Representative width changes are shown in Table 3-12.

Table 3-12. Skunk Creek/Sonoran Wash Watercourse Master Plan
Measured Width Changes: Skunk Creek 1971-1988

Station	Width Change (ft)	Notes
8000	139 ft	-widening at left and right banks
14000	-173 ft	-abandoned channel at left bank
17000	-343 ft	-limitation of flow at right bank
25000	-187 ft	-encroachment of left bank
33000	-140 ft	-significant flow at right bank in '71
37000	-121 ft	-narrowing of right bank
44000	-149 ft	-break in left bank recovered, revegetated
51000	-163 ft	-revegetation and stabilization on both banks
54000	-288 ft	-complete revegetation and stabilization of right bank (construction)

1988-1992: Little change in channel width occurred between 1988 and 1992 (Table 3-13), despite the occurrence of the 4th and 5th largest floods (1990 & 1992) in the period of record. Width stability may be attributed to above-average flow volumes which may have stabilized banks and prevented widespread lateral erosion. Most measurable changes were positive, indicating a slight increase in channel width. Representative width changes are shown in Table 3-13.

Table 3-13. Skunk Creek/Sonoran Wash Watercourse Master Plan Measured Width Changes: Skunk Creek 1988-1992		
Station	**Width Change (ft)**	**Notes**
16000	119 ft	-avulsion at left bank
26000	-86 ft	-overall width decrease

1992-1995: Little change in channel width occurred between 1992 and 1995 (Table 3-14). Most of the measurable width changes indicate a decrease in channel width. The flood of 1993 probably affected several location that show width increases, but the majority of the measured locations were unaffected. Representative width changes are shown in Table 3-14.

Table 3-14. Skunk Creek/Sonoran Wash Watercourse Master Plan Measured Width Changes: Skunk Creek 1988-1992		
Station	**Width Change (ft)**	**Notes**
18000	-122 ft	-right bank encroachment (result of construction?)
23000	-106 ft	-left bank encroachment
36000	-131ft	-channel width decrease

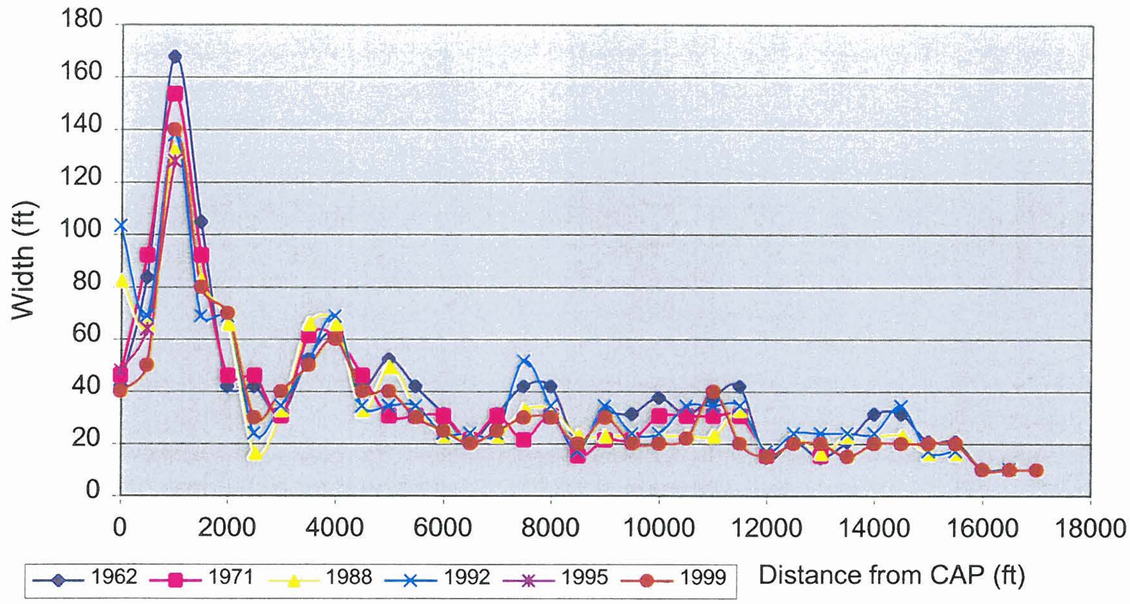
1995-1999: Overall, channel width decreased from 1995 to 1999, a period marked by few large floods and moderate flow volumes. Representative width changes are shown in Table 3-15.

Table 3-15. Skunk Creek/Sonoran Wash Watercourse Master Plan Measured Width Changes: Skunk Creek 1988-1992		
Station	**Width Change (ft)**	**Notes**
4000	-108 ft	-overall decrease in width
35000	-132 ft	-overall decrease in width

1962-1999: The net channel width change in Skunk Creek for the entire period of aerial photo coverage is negative. Width increases were recorded at only 11 of the 52 locations, and only five of those were large enough to account for the measurement error. Channel widths upstream of Cline Creek have remained essentially constant in the last twenty years.

Sonoran Wash. Changes in channel width of Sonoran Wash are shown in Figure 3-36. In general, changes in channel width during the 37-year period of record were small relative to the scale of changes determined by consideration of GLO records extending back an additional 68 years. So few of the measured changes in channel width were greater than the measurement error that they are not reported in detail.

Figure 3-37. Sonoran Wash Channel Width Change, 1962-1999



Summary. Measured historical channel widths for Skunk Creek and Sonoran Wash are shown in Table 3-16.

Table 3-16. Skunk Creek/Sonoran Wash Watercourse Master Plan
Historical Channel Width Change Measured from Aerial Photographs, 1962-1999 (ft.)

Reach	Time Period					
	1962-1971	1971-1988	1988-1992	1992-1995	1995-1999	1962-1999
Skunk Creek						
CAP to Carefree Hwy	54	23	-27	3	-35	18
CFR Hwy to Rodger Ck	45	-57	21	-8	-4	-2
Rodger Ck to Cline Ck	9	-35	-18	-21	-6	-71
Cline Ck to Study Limit	26	-64	1	-25	-18	-68
Average:	30	-44	-3	-17	-15	-42
Maximum:	414	139	119	95	64	350
Sonoran Wash						
Average:	-8	3	3	-4	-	-39
Maximum:	9	36	21	11	-	0

The following conclusions may be reached from the data shown in Table 3-16.

- Sonoran Wash. Average channel width changes on Sonoran Wash between 1962 and 1999 were less than the measurement error. A slight net trend toward narrowing occurred during the period of record.
- Skunk Creek. Skunk Creek generally increased its width during the 1960's, but has narrowed since 1971. Regardless of the average trend in width, the maximum change in width was a significant increase (64 to 414 feet) of width during every time period considered. Therefore, significant erosion should be expected somewhere on Skunk Creek during any significant flood.

- Avulsions. The greatest measured width changes correspond to formation of new channels within the floodplain by avulsive processes.

Comparison of GLO Survey Data and Modern Channel Widths. Survey data obtained from the General Land Office (GLO) boundary surveys were summarized previously in this chapter. These survey data also provide information on the channel width at the time of the GLO survey which can be compared to the channel widths measured from aerial photographs at identical locations to estimate width changes over the past to 66 to105 years (Table 3-17). These data indicate that, on average, Skunk Creek narrowed slightly over the past 100 years, primarily by abandoning overbank channels.

Table 3-17. Skunk Creek/Sonoran Wash Watercourse Master Plan
Comparison of Channel Width from GLO Survey Data and 1999 Aerial Photos

Location		Channel	GLO Survey Data		1999	Width
Township	Section		Date	Width (ft)	Width (ft)	Change (ft)
T5NR2E	23/26	Skunk Creek	1894	257.4	567	310
	14/23	Skunk Creek	1894	237.6	133	-105
	11/14	No Record	1894	0	67	67
	2/11	CFH Bridge	1894	0	267	267
T6NR2E	35/2	Skunk Creek	1894	165	-	-
		East Channel	1933	46.2	67	21
		West Channel	1933	46.2	33	-13
		Total Width	1933	765.6	700	-66
	35/36	East Channel	1933	46.2	50	4
		West Channel	1933	39.6	33	-7
		Total Width	1933	495	200	-295
	25/36	Total Width	1933	587.4	500	-87
T6NR3E	25/30	Total Width	1910	1042.8	-	-
		Total Width	1922	1023	-	-
		Total Width	1933	1062.6	933	-130
	19/30	Skunk Creek	1922	462	100	-362
	19/18	West Channel	1922	132	67	-65
	7/18	Skunk Creek	1922	132	33	-99
	8/7	Skunk Creek	1922	132	50	-82
	5/8	Skunk Creek	1922	198	167	-31
T7NR3E	32/5	Skunk Creek	1922	66	33	-33
	31/32	Not Recorded	1922	-	-	-
	30/31	Not Recorded	1922	-	-	-

Channel Depth. Changes in channel depth were summarized in the discussion on long-term vertical channel changes (Tables 3-7 and 3-9, Figures 3-30 to 3-35). In general, the depth of the main channel of Skunk Creek has fluctuated in response flooding, urbanization, and watershed impacts without any system-wide trend. While historical data are generally lacking for Sonoran Wash, field data indicate that the main channel of Sonoran Wash may have become deeper and more incised in the past century. Where the channel depth and width have increased, the channel capacity has increased exponentially. Increased channel capacity leads to higher channel velocities and accelerated lateral erosion rates. Where channel depth and width have decrease, channel capacity decreases exponentially, leading to increased overbank flooding and higher potential for avulsive channel change. The implications of changed channel capacity will be discussed in more detail in Chapter 4.

Channel Planform. Channel planform describes the shape, distribution, and pattern of a stream's channels observed in map view. For the purposes of this report, changes in channel planform were described by comparing the channel pattern and sinuosity observed on historical maps and aerial photographs.

Channel Pattern. Plots of historical channel positions shown in Figure 3-1 illustrate the channel pattern of Skunk Creek and Sonoran Wash. While there have been significant changes in channel position on each stream, the overall pattern has remained substantially unchanged. Skunk Creek and Sonoran Wash are straight braided streams with anastomosing multiple channel reaches, separated by slightly sinuous single channel reaches. No permanent changes in channel pattern were observed on historical maps or aerial photographs in Skunk Creek or Sonoran Wash, except where Skunk Creek had been channelized for construction of the New River Road and Carefree Highway bridges and the CAP overchutes. Archaeological data have been interpreted to indicate that the Skunk Creek may have changed from a shallow, single channel with frequent overbank flooding to a more incised channel pattern with rare floodplain flows (Earl, 1983), although no change in the channel pattern is required to allow such a change. Channel pattern is discussed in more detail in the stream classification section of Chapter 2 and the geomorphic evaluation in Chapter 4.

Sinuosity. Sinuosity is a measure of the "curviness" of a stream, and is calculated by dividing the stream length measured along the thalweg by the valley length. Measures of sinuosity have been used to define the terms listed in Table 3-18. Measurements of sinuosity for Skunk Creek and Sonoran Wash for each period of photographic record are shown in Tables 3-19 and 3-20.

Table 3-18. Skunk Creek/Sonoran Wash Watercourse Master Plan Descriptive Terms for Channel Sinuosity

Term	Sinuosity
Straight	1.00 – 1.05
Sinuous	1.06 – 1.25
Meandering	1.25 – 2.00
Highly Meandering	> 2.0

According to the data summarized in Table 3-19, Skunk Creek is slightly sinuous and has been since at least 1962. There was a slight increase in sinuosity from 1971 to 1988, followed by a net decrease. The change in sinuosity does not correlate well with observed changes in channel width or bank erosion. It is noted that, except for the 1995 data, the sinuosity differences shown in Table 3-19 would not be discernable if the values were printed to only one decimal place.

Table 3-19. Skunk Creek/Sonoran Wash Watercourse Master Plan Skunk Creek – Sinuosity Measurements from Historical Aerial Photographs, 1962-1999						
Reach	**1962**	**1971**	**1988**	**1992**	**1995**	**1999**
CAP to Carefree Hwy	1.06	1.00	1.10	1.13	1.05	1.07
CFR Hwy to Rodger Ck	1.08	1.02	1.07	1.09	1.10	1.04
Rodger Ck to Cline Ck	1.10	1.09	1.04	1.04	1.06	1.02
Cline Ck to Study Limit	1.02	1.09	1.16	1.09	0.98	1.06
Entire Stream Reach	1.05	1.06	1.11	1.08	1.03	1.05

According to the data summarized in Table 3-20, Sonoran Wash is slightly sinuous and has been since at least 1962. There was a slight increase in sinuosity from 1962 to 1988, followed by a net decrease. It is noted that the sinuosity differences shown in Table 3-19 would not be discernable if the values were printed to only one decimal place, and that some of the differences may be due to the scale and resolution of the aerial photographs.

Table 3-20. Skunk Creek/Sonoran Wash Watercourse Master Plan Sonoran Wash – Sinuosity Measurements from Historical Aerial Photographs, 1962-1999					
Reach	**1962**	**1971**	**1988**	**1992**	**1999**
6	1.06	1.14	1.23	1.17	1.11
5	1.06	1.04	1.05	1.06	1.08
4	1.09	1.05	1.06	1.03	1.03
3	1.01	1.05	1.24	1.04	1.11
2	1.26	-	1.04	1.13	1.16
1	1.18	-	-	1.02	1.05
Entire Stream Reach	1.06	1.07	1.06	1.12	1.06

Field Evidence of Historical Channel Change

A record of historical channel change is often preserved in the physical characteristics of the modern stream channel and its floodplain. Field observations of these stream and floodplain characteristics can be used to interpret the history of channel change. The following types of historical information were gleaned from field data:

- Bank Erosion. Bank erosion probably occurred throughout the period of historical and prehistoric record. Field evidence of bank erosion documented in Chapter 4 includes numerous cut and undercut channel banks, hanging fence posts, exposed tree roots in channel banks, unstable fresh cut banks, and impassable farm road crossings.

- Channel Avulsions. Remnants of former, abandoned channels were identified by their topographic expression, alignments of buried trees located well away from existing channels, and areas of distinctly younger soils within older floodplain units.

- Tree Cutting. The stumps of many large Ironwood trees were observed along Apache Wash and Paradise Wash, a feature that was also observed in the adjacent Skunk Creek watershed. The saw-hewn stumps were not excessively weathered, and ranged in size from 12 to 24 inches. Vegetation grown up around the stumps was typically mature, with some palo verde, mesquite, and ironwood trees that were more than 12 inches in diameter. The ironwood trees were probably cut less than 40 years ago, but may have been cut more than 60 years ago. The earliest aerial photographs indicate that the channel banks were somewhat less well vegetated prior to the 1970's. Elsewhere in Arizona, concerns about water supply led to publicly-funded programs to remove riparian vegetation during the 1960's. No excessive bank erosion occurred during the period of tree removal, either due to lack of large erosive floods or because other bank vegetation was preserved.

- Grazing. The entire study area has been leased for cattle grazing over the past 150 years. Earl postulated that tens of thousands of cattle and livestock were held in the Skunk Creek area in the 1900's. Poorly managed grazing is thought to destroy bank vegetation and increase lateral erosion rates, decrease watershed cover and increase runoff rates, and decrease the frequency of sustained stream runoff.

Field observations and their implications for predicted lateral channel movement are described in more detail in Chapter 4.

Historical Descriptions of Channel Conditions

Except for the occasional margin note by the GLO surveyors, no historical descriptions of Skunk Creek exist for the period before aerial photographic records. The text descriptions of Skunk Creek and Sonoran Wash recorded in the GLO surveys are summarized below. The summaries are organized by township, beginning at the downstream end of the study reach.

Township 5N Range 2E. All references to Skunk Creek and Sonoran Wash are to "a dry wash" (Martineau, 1894). The survey was conducted in February and March. No indications of bed material composition that might be expected from a general survey (i.e. sandy or cobbly) were recorded.

Township 5N Range 3E. All references to Sonoran Wash are to "a dry wash" (Martineau, 1894). The survey was conducted in February and March. No indications of bed material composition that might be expected from a general survey (i.e. sandy or cobbly) were recorded.

Township 6N Range 2E. Each reference to Skunk Creek is in the form "# links wide, # feet deep" (Kinsey, 1933). Because the depths listed by the GLO surveyors range from 4 to 25 feet deep, too deep to be flowing water, and because there is no explicit mention of running water, one can assume the wash was dry. Also, the surveyors typically made note of running water where they encountered it on other streams in central Arizona. The survey was conducted in December, a month during which flow would be likely if the stream were perennial or intermittent. No indications of bed material composition that might be expected from a general survey (i.e. sandy or cobbly) were recorded.

Township 6N Range 3E. Survey notes by Blout (1922) referencing Skunk Creek and Cottonwood Creek (present-day Skunk Creek upstream of the Cline Creek confluence) indicate specifically that the wash was dry, implying that it was an unusual condition. The 1922 survey was conducted in August and September. Other references to Skunk Creek (Oliver, 1910; Kinsey, 1933) are nonspecific about running water, but the tendency of surveyors to record instances of running water and its depth in similar surveys would tend to indicate that the wash was dry. The 1910 survey was conducted in May, and the 1933 survey was conducted in December. No indications of bed material composition that might be expected from a general survey (i.e. sandy or cobbly) were recorded.

Township 7N Range 3E. Cottonwood Creek (present-day Skunk Creek) was alternately referred to as a gulch, wash, or draw. The features were not specifically described as dry, but there was no reference to running water (Oliver, 1917). The survey was conducted in December 1916 and January 1917. No indications of bed material composition that might be expected from a general survey (i.e. sandy or cobbly) were recorded.

The historical descriptions by the GLO surveyors indicate that channel conditions from 1890 to 1933 probably were not much different than modern conditions. Skunk Creek and Sonoran Wash were dry streams without unusual characteristics.

Historical Human Impacts on Channel Morphology

The geological and archaeological records (as well as common sense) indicate that channel change occurs with or without human activities in the watershed. However, human activities can alter the type, magnitude, and rate of channel change. The following types of human activities have occurred during the historical period along the streams in the study or their watersheds:

- Sand and Gravel Mining. Sand and gravel mining occurred along Skunk Creek at the Lone Mountain Road alignment in the 1960's. Remnants of the mining operation are still visible and include large piles of cobbles lining the west slope of the floodplain terrace. A small sand and gravel mine exists near Irvine Road and 19th Avenue. During the field work, the pit filled much of the east floodplain and had been excavated about 10 feet below the natural stream bed elevation. The typical response to in-stream sand and gravel mining is channel degradation and increased lateral instability (ADOT, 1985).

- Cattle Grazing. The entire study area was used for cattle grazing throughout the period of Euro-American settlement, since about the 1880's to the present. There is considerable debate about the effects of grazing on stream stability (e.g., Hereford, 1984), ranging from no measurable impact to a significant increase in erosion hazard. Grazing impacts observed in the study area included damage to stream banks (Figure 3-37), cutting trails on bank slopes, construction of fences across channels, and removal of floodplain and bank vegetation.

Figure 3-38. Cattle damage by hoofs on nearby Apache Wash.

- Road & Bridge Construction. The Carefree Highway bridge was originally constructed in 1981, with an additional bridge added in 1997. During construction, Skunk Creek was widened to more than three times the natural channel width, which has led to several feet of sediment deposition in the bridge section. Likewise, New River Road was changed from an at-grade crossing to a bridge in 1999, and the channel was widened and deepened, resulting in significant long-term deposition. Other paved at-grade crossings of Skunk Creek include 19th Avenue, Desert Hills Road, Shangri La Lane and Zorillo Road. Unpaved improved roads crossing Skunk Creek at grade include Honda Bow Road and Circle Mountain Road. A number of unpaved, poorly maintained ranch roads cross Skunk Creek and Sonoran Wash in several places. The remnants of a poorly constructed low bridge were observed in Reach 3 of Sonoran Wash. Except for the two bridges on Skunk Creek, road crossings have had little impact on the streams. The streams, however, frequently impact the at-grade crossings by depositing sediment, destroying pavement, and disrupting traffic.

- Stock Tanks. A number of stock tanks are present in the Skunk Creek and Sonoran Wash watersheds. Skunk Tank is the largest of the existing tanks, but was breached in August 2000 during a small flood. Stock tanks reduce the volume of water and sediment supplied to the study reach, although the impact of such obstructions is probably minor relative to other human impacts.

- Urbanization. Most of the study area watershed is either suburban ranch land, low-density residential, or National Forest land. Recently, plans to urbanize portions of lower Skunk Creek and Sonoran Wash have been approved by the City of Phoenix, and are currently in various phases of design and construction. Urbanization tends to increase the volume of runoff and decrease the long-term sediment supply, leading to increased stream erosion.

Summary

Historical information summarized in this chapter illustrates the types of channel changes that have occurred in the study area during the past, and suggests the types of channel change that can be expected in the future. Archaeological records imply that channel erosion has affected Skunk Creek for at least 10,000 years. That is, channel erosion is not simply the result of modern human impacts on the channel and watershed. Therefore, natural cycles of stream degradation, local aggradation, lateral migration, and climate change must be accounted for in development of the erosion hazard zones and the watercourse management plan. Climate change should be considered a significant cause of long-term lateral erosion and channel incision.

Review of features observed on historical aerial photographs indicates that direct human impacts on Skunk Creek have been limited to construction of bridge and at-grade road crossings, construction of the CAP, and minor sand and gravel excavations. Direct human impacts on Sonoran Wash have been limited to construction of the CAP and several at-grade ranch road crossings. Indirect human impacts on Skunk Creek and Sonoran Wash include construction of stock ponds, moderate urbanization of the watershed, and cattle grazing. The degree of urbanization in the watershed has accelerated during the past several years relative to the pace of development prior to 1988. The types of channel changes observed on the aerial photographs included avulsions, bank failure, channelization, channel width changes, formation of multiple channels, braiding, deposition, and movement of splays.

Historical channel width and channel position were compared on historical aerial photographs dating to 1940 and GLO survey records dating to 1894. On Skunk Creek, the maximum change in total width as expressed by the distance between the furthest left and furthest right banks or braids was 414 feet due development of a channel avulsion in what was an overbank floodplain. More than 100 feet of lateral erosion is recorded by the aerial photographs in several locations, despite having few major floods during the period of record. The primary mechanism for the most significant channel movement was avulsions, with an upper limit of single event erosion on Skunk Creek of about 400 feet, and the maximum rate of lateral movement of about 18 feet per year. The average long-term rate of lateral movement over the entire study area is about 1 foot per year.

Vertical channel changes were analyzed by comparing topographic records dating to 1962. The record indicates that net aggradation has occurred on Skunk Creek since 1962 from about the Lone Mountain Road alignment to the Cline Creek confluence, with net degradation upstream and downstream. Topographic data regarding long-term channel elevation changes for Sonoran Wash were inconclusive. Geologic evidence implies that net long-term degradation has averaged 10^{-4} to 10^{-5} feet per year over the past several hundred thousand years. However, given that the observed rate of degradation during the period of historical record exceeds the implied long-term geologic rate by several orders of magnitude, and that aggradation has also been recorded in some reaches, it may be concluded that the elevations of the channel beds will fluctuate around a slight degradational trend.

Changes in channel width of Sonoran Wash and Skunk Creek during the 37 year period of photographic records were small relative to the scale of changes determined by consideration of GLO records extending back an additional 68 years. Despite an overall average narrowing of Skunk Creek and Sonoran Wash in the 100 year period of record, the maximum change in width was more than 400 feet. Width increases someplace in the study area were recorded during every time period considered. Therefore, significant erosion should be expected somewhere on Skunk Creek during any significant flood. The greatest measured width changes correspond to formation of new channels within the floodplain by avulsive processes. No significant changes in channel pattern or sinuosity were detected. The historical descriptions by the GLO surveyors indicate that channel conditions between 1890 and 1933 probably were not much different than modern conditions. Skunk Creek and Sonoran Wash were dry streams without unusual characteristics.

Chapter 4
Lateral Stability Assessment: Geomorphology

Introduction

A variety of geomorphic assessment techniques have been developed for analysis of river systems. This chapter summarizes the techniques that were deemed most applicable to the Skunk Creek/Sonoran Wash Watercourse Master Plan study area. They include the following:

- Field assessment
- Geomorphic mapping
- Geomorphic assessment

Field Assessment

Geomorphology is a field-based science of observation that relies heavily on the judgment of the investigator. Therefore, it was prudent to include a significant number of field visits and to develop a systematic approach to collecting field observations. Field visits included the following:

- Initial reconnaissance trips. These trips included personnel from the overall project team who had expertise in a broad range of disciplines such as hydraulic engineering, hydrologic modeling, sedimentation engineering, floodplain management, land planning, environmental management, resource management, biology, and archaeology.

- Detailed field investigations. These trips were conducted by JEF geomorphologists, and consisted of walking the entire channel reach several times and collecting systematic field notes and photographs of channel conditions at sections spaced at 2,000-foot increments throughout the study reach. Exhibit 1 shows the locations of the channel sections used to collect field data. A copy of the field data collection form is provided in Figure 4-7. Copies of the field notes and photographs, a log of field photographs, and a summary of field data are provided in Appendix A.

- Detailed soil investigations. These trips were also conducted by JEF project geomorphologists, and consisted of examination and description of 21 soil pits excavated into the terraces and channels of the study area. The results of the soil investigation are described in the geomorphic mapping section of this chapter. Copies and summaries of field notes, soil descriptions, and field photographs are provided in Appendix A.

- Follow-up trips. Several additional field tours were conducted to present field findings to the rest of the project team, agency stakeholders, and the media.

- Flood visits. A series of moderately large storms caused small floods on Skunk Creek and its tributaries on July 15, 1999 and October 22, 2000. JEF staff visited the study area during or after these floods to document and observe channel conditions during rare flow events. Some of the photographs from this field trip are shown in Figures 4-1 to 4-6. The entire log of field photographs is provided in Appendix A.

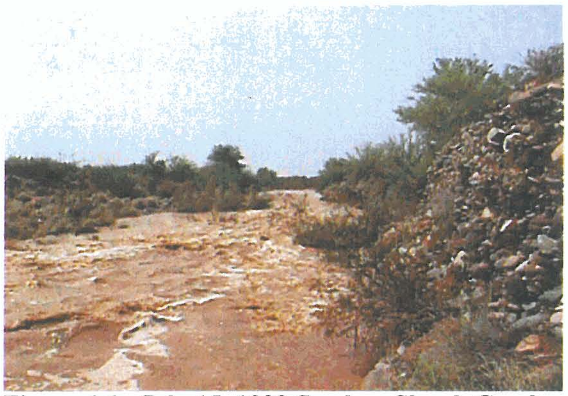


Figure 4-1. July 15, 1999 flood on Skunk Creek downstream of Carefree Highway.

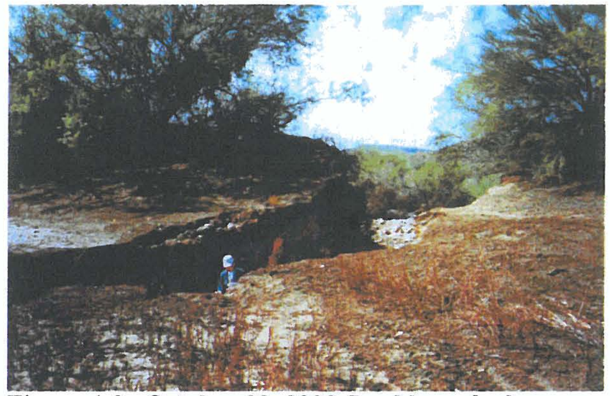


Figure 4-2. October 22, 2000 flood breached Skunk Tank.

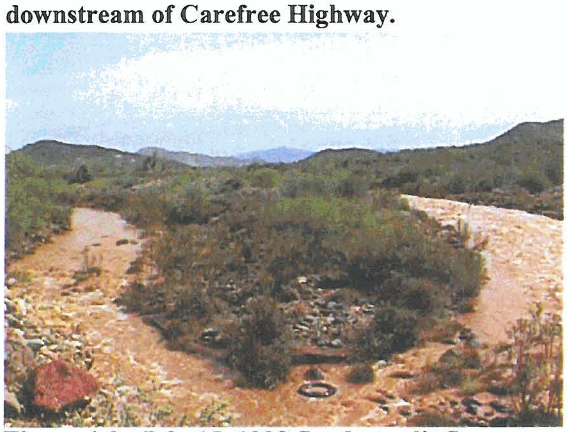


Figure 4-3. July 15, 1999 flood at split flow on Skunk Creek.

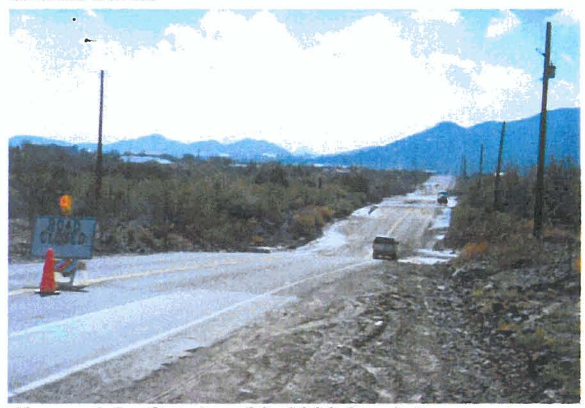


Figure 4-3. October 22, 2000 flood damage to 19th Avenue at Skunk Creek.

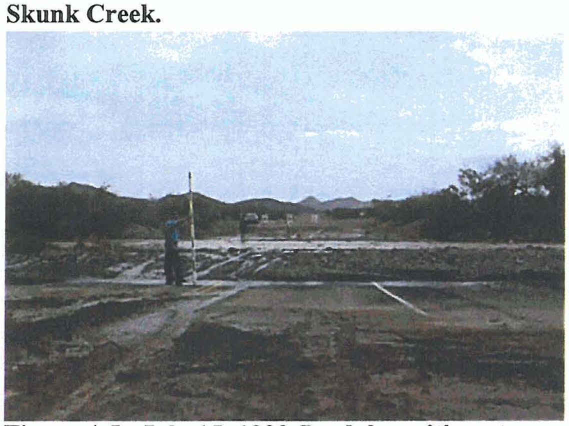


Figure 4-5. July 15, 1999 flood deposition at Desert Hills Drive.

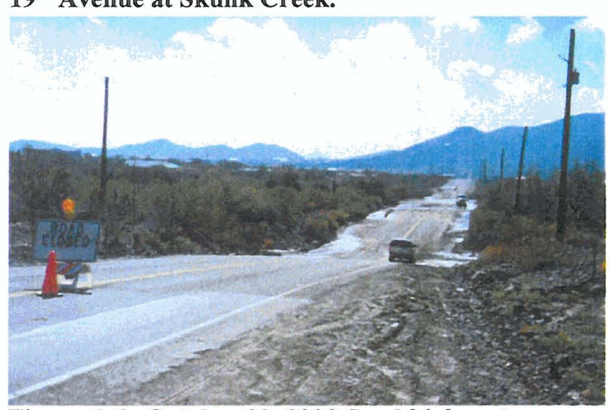


Figure 4-6. October 22, 2000 flood high water marks on Desert Hills Drive.

Visual Assessment Techniques
Guidelines for performing geomorphic field analyses have been published by a variety of agencies and individuals. The field forms shown in Figure 4-7 were developed to apply basic visual assessment techniques described in the following documents:

- Thorne, C.R., 1998, *Stream Reconnaissance Handbook – Geomorphological Investigation and Analysis of River Channels*. John Wiley & Sons, New York.

- US Army Corps of Engineers, 1989, *Sedimentation Investigations of Rivers and Reservoirs, EM 1110-2-4000*. Appendix E: Field Reconnaissance Procedure for Sediment Studies.

- Rosgen, D., 1996, *Applied River Morphology*. Wildland Hydrology, Pagosa Springs, Colorado.

Some of the key observations made regarding stream stability are listed below for each of the four major streams in the study area. Copies of the field notes and field photographs are provided in Appendix A. Locations of field cross sections (e.g., UT-4000, SC-68000) where detailed channel descriptions were made, soil test pits (e.g., SC 1 LOB1, UT-CHL), and other field features are shown on Exhibit 1.

FIELD CHECK LIST – CHANNEL CHARACTERISTICS
SKUNK CREEK/SONORAN WASH WATERCOURSE MASTER PLAN

STREAM NAME:		SECTION NUMBER:	
DESCRIPTION OF SECTION LOCATION:			
DATE:	TIME: (BEGIN/END)	FIELD CREW:	CHECKED BY: (NAME, DATE)

1. PHOTO-DOCUMENTATION **(RECORD PHOTO # & TIME)**

NOTES: 1. INCLUDE SCALE IN PHOTOGRAPHS 2. PLOT PHOTO LOCATION & ASPECT ON TOPO

DATA TYPE	PHOTO #	NOTES
LEFT/RIGHT ORIENTATION IS LOOKING DOWNSTREAM IN CHANNEL		
LEFT BANK (SURVEY ROD FOR SCALE) LOOKING DIRECTLY AT BANK LOOKING UPSTREAM ALONG BANK LOOKING DOWNSTREAM ALONG BANK		
RIGHT BANK (SURVEY ROD FOR SCALE) LOOKING DIRECTLY AT BANK LOOKING UPSTREAM ALONG BANK LOOKING DOWNSTREAM ALONG BANK		
INTERMEDIATE BANKS & ISLANDS (SCALE) LOOKING DIRECTLY AT BANK LOOKING UPSTREAM ALONG BANK LOOKING DOWNSTREAM ALONG BANK		
HIGHWATER MARKS		
BED MATERIAL - CLOSE UP		
VIEW OF ENTIRE CHANNEL SECTION		
FLOODPLAIN LEFT OVERBANK RIGHT OVERBANK		
NOTABLE FEATURES: (LIST)		

3. CROSS SECTION LOCATION

- ☐ PLOT ON TOPOGRAPHIC MAP________________(TYPE) ______________________(NAME)
- ☐ PLOT ON AERIAL _____________(SOURCE) _________(PHOTO NUMBER) _______(DATE)
- ☐ GPS SECTION LOCATION ______________________________(PT. I.D, TIME, ETC.)
- ☐ FLAG SECTION LOCATION______________________________________(NOTES)

Figure 4-7. Field Data Collection Form (Sheet 1 of 6).

4A. DESCRIPTION OF PRIMARY CHANNEL BANK CHARACTERISTICS				
☐ BANK VEGETATION	LEFT		RIGHT	
TYPE				
ROOT MAT				
CANOPY (HEIGHT, DENSITY)				
PERCENT OF BANK COVER				
APPROXIMATE AGE OF VEGETATION				
RIPARIAN BELT THICKNESS				
SUITE OF AGES OF RIPARIAN SPECIES				
☐ BANK MATERIAL CHARACTERISTICS:	LEFT		RIGHT	
GENERALLY COHESIVE?				
GENERALLY RESISTANT/ WEAK?				
LAYERED/ UNIFORM MATERIAL?				
PERCENT SILT/CLAY IN BANKS				
BRAY BANK MATERIAL CLASS:	SI & CL	SA & GR	SA & CO	SI OVER GR
LARGEST DIAMETER LAYER D_{50}: LAYER THICKNESS: $CaCO_3$ DEVELOPMENT: SORTING: SHEAR VANE TEST: PENETROMETER TEST: HAMMER TEST: OTHER:	MAX/MIN MAX/MIN		MAX/MIN MAX/MIN	
FINEST DIAMETER LAYER D_{50}: LAYER THICKNESS: $CaCO_3$ DEVELOPMENT: SORTING: SHEAR VANE TEST: PENETROMETER TEST: HAMMER TEST: OTHER:	MAX/MIN MAX/MIN		MAX/MIN MAX/MIN	
WEAKEST/ MOST RESISTANT LAYER D_{50}: HEIGHT ABOVE BED: CONDITION:	WEAK/ RESISTANT		WEAK/ RESISTANT	
☐ BANK EROSION SIGNS	LEFT (YES/NO/PERCENT)		RIGHT	
CUT BANKS				
VERTICAL BANKS				
UNDERCUT BANKS				
TENSION CRACKS				
EXPOSED ROOTS				
VEGETATION REMOVED FROM BANKS				
VEGETATION TIPPED? ANGLE?				
PILES OF ALLUVIUM AT BANKS				
PIPING				
RILLING OF BANKS				
ISLANDS OR BARS (U/S-D/S)				
OTHER EVIDENCE				

Figure 4-7. Field Data Collection Form (Sheet 2 of 6)

P E N T R O M T R	S H E A R V A N E	4B. BANK PROFILE SKETCH		P E N T R O M T R	S H E A R V A N E
		LEFT BANK	**RIGHT BANK**		

SHOW THE FOLLOWING IN THE BANK PROFILE SKETCHES:

- ☐ BANK HEIGHT
- ☐ SOIL STRUCTURE
- ☐ BANK MATERIAL GRAIN SIZE
- ☐ CRITICAL BANK HEIGHT
- ☐ ROOTING LAYER DEPTH
- ☐ RESISTANCE (HAMMER TEST)
- ☐ BANK SLOPE
- ☐ SOIL HORIZONS
- ☐ LAYER THICKNESS
- ☐ FAILURE MECHANISMS
- ☐ ROSGEN BANKFULL/ OHM
- ☐ PENETROMETER VALUES
- ☐ STRATIFICATION/ BEDDING
- ☐ COLOR
- ☐ CARBONATE DEVELOPMENT
- ☐ BASAL ENDPOINT
- ☐ COHESION
- ☐ SHEAR VANE READINGS

☐ BANK FAILURE MECHANISM: SKETCH:

GRAIN-BY-GRAIN EROSION?

MASS-WASTING?

KEY EVIDENCE:

CAUSE(S)

SUMMARY OF BANK CONDITIONS	**LEFT**	**RIGHT**
STABLE/UNSTABLE: (SEVERE – HIGH – MEDIUM – LOW)		
RECENT EROSION: (ON-GOING – HISTORIC – GEOLOGIC)		
RATE OF BANK EROSION: (RAPID – SLOW)		
TYPE OF LATERAL MOVEMENT: (MEANDER–AVULSION–BRAIDING –IRR)		
ESTIMATE OF AGE OF SOIL UNIT ON BANK: (MODERN –HOLOCENE –PLEISTOCENE) (BASIS OF ESTIMATE)		
LEVEL OF CONFIDENCE IN ESTIMATES: (0 10 20 30 40 50 60 70 80 90 100%)		

Figure 4-7. Field Data Collection Form (Sheet 3 of 6).

5. DESCRIPTION OF PRIMARY CHANNEL BED CHARACTERISTICS

☐ CHANNEL VEGETATION (TYPE & PERCENT COVER) *BED VS. BARS

☐ BED MATERIALS (VISUAL ESTIMATE) ☐ UNITS

D90________ D50 ________ D10________ VS. BANK MATERIALS (FINER/COARSER/SAME)
DOMINANT SEDIMENT SHAPE (ROUND, OBLONG, FLAT, ANGULAR, SUBANGULAR, IMBRICATED)
LITHOLOGY____
UPSTREAM LAMINATION____

☐ ARMORING POTENTIAL (HIGH/ MEDIUM/ LOW)
Q100__________ Q2 ____________ (VISUAL ESTIMATE)

☐ DEPTH TO BEDROCK (FT., UNKNOWN)
BEDROCK EXPOSED? __________________ GRADE CONTROL? ______________(TYPE, PHOTO)

☐ BEDFORMS (DUNES/RIPPLES/ARMOR/PLAIN)

☐ TYPE OF BARS (LONGITUDINAL/ POINT/ MID-CHANNEL – CHARACTERISTICS/ GRAIN SIZE)

☐ SKETCH

6. EVIDENCE OF VERTICAL INSTABILITY

☐ SHORT-TERM SCOUR EVIDENCE ☐ PHOTOGRAPH
- SCOUR HOLES
- BEDFORMS
- BRIDGE DATA (PIER CAPS, ABUTMENTS, ETC)

☐ LONG-TERM SCOUR EVIDENCE ☐ PHOTOGRAPH
- HANGING TRIBUTARIES
- STREAM TERRACES ☐ SKETCH
- OVERSTEEPENED BANKS
- PERCHED CHANNELS
- ARMORING
- HEADCUTS
- SLOPE BREAKS
- RECENT INCISION
- BRIDGE DATA (PIER CAPS, ABUTMENTS, ETC)
- GRAVEL MINING (DISTANCE, EXTENT)
- OTHER

☐ EVIDENCE OF AGGRADATION ☐ PHOTOGRAPH
BURIED VEGETATION BRAIDED LOW FLOW MOUNDED BED LOW WIDE TERRACES
OTHER:

SUMMARY OF VERTICAL INSTABILITY

EXPECTED VERTICAL ADJUSTMENT: SCOUR AGGRADATION NO CHANGE
ESTIMATE OF MAXIMUM LONG-TERM SCOUR
RECENT HISTORICAL: DEPTH: __________FEET/ _____________YEARS
RECENT GEOLOGIC: DEPTH: __________FEET/ _____________YEARS
LEVEL OF CONFIDENCE IN ESTIMATES: 0 10 20 30 40 50 60 70 80 90 100%

Figure 4-7. Field Data Collection Form (Sheet 4 of 6).

7. DESCRIPTION OF GENERAL CHANNEL & REACH CHARACTERISTICS
☐ CHANNEL PATTERN (BRAIDED, SINGLE CHANNEL, STRAIGHT, SINUOUS, MEANDERING)
☐ LOW FLOW CHANNEL PRESENT?
☐ TRIBUTARIES NEARBY?
☐ BANKFULL CHARACTERISTICS (VELOCITY, DEPTH, TOPWIDTH) ☐ HOW MEASURED?
☐ FLOW CHARACTERISTICS (VELOCITY, DEPTH, TOPWIDTH) ☐ HOW MEASURED?
☐ FLOW TYPE (UNIFORM, RAPID/TRANQUIL, POOL & RIFFLE, STEEP STEP/POOL)
☐ HIGH WATERMARKS TYPE AND STAGE (FEET ABOVE BED) FLOTSAM SLACKWATER EROSION SCAR TREE SCAR GRUS LINE OTHER
☐ FENCES (PLOT LOCATION, PHOTO) OBSTRUCT FLOW?
☐ HUMAN IMPACTS ON CHANNEL (STRAIGHTENING, BANK PROTECTION, ETC)
☐ SKETCH CHANNEL CROSS SECTION (LOOKING DOWNSTREAM) SHOW THE FOLLOWING: ☐ VEGETATION ☐ MAIN CHANNEL/ OVERFLOW CHANNEL ☐ LEVEES ☐ MANNING'S N VALUES ☐ ACTIVE CHANNEL LIMITS ☐ BARS ☐ ISLANDS ☐ FLOODPLAIN DIMENSIONS ☐ SCOUR/EROSION ☐ FLOODPLAIN/ TERRACES ☐ ROSGEN BANKFULL ELEVATION ☐ DIMENSIONS ☐ EROSION BANKFULL ELEVATION
☐ SKETCH CHANNEL PLANFORM

Figure 4-7. Field Data Collection Form (Sheet 5 of 6)

8. BOULDER COUNT

☐ SECTION NUMBER:

☐ LOCATION OF SAMPLING SECTION

POOL______________ RIFFLE ______________ OTHER ______________

CHANNEL FEATURES:

☐ VISUAL ESTIMATE OF D50

☐ BRIEF DESCRIPTION OF BED SEDIMENT

SIZE ______________ ALIGNMENT ______________

SHAPE ______________ SORTING ______________

LITHOLOGY ______________ OTHER ______________

☐ BOULDER COUNT DATA

TRANSECT A-CHANNEL WIDTH:__________ POSITION:__________ DATA PTS:______

TRANSECT B-CHANNEL WIDTH:__________ POSITION:__________ DATA PTS:______

TRANSECT C-CHANNEL WIDTH:__________ POSITION:__________ DATA PTS:______

SAMPLING INTERVAL______________ FT/M BOULDER SIZE UNITS: FT / M

1	26	51	76	101	126
2	27	52	77	102	127
3	28	53	78	103	128
4	29	54	79	104	129
5	30	55	80	105	130
6	31	56	81	106	131
7	32	57	82	107	132
8	33	58	83	108	133
9	34	59	84	109	134
10	35	60	85	110	135
11	36	61	86	111	136
12	37	62	87	112	137
13	38	63	88	113	138
14	39	64	89	114	139
15	40	65	90	115	140
16	41	66	91	116	141
17	42	67	92	117	142
18	43	68	93	118	143
19	44	69	94	119	144
20	45	70	95	120	145
21	46	71	96	121	146
22	47	72	97	122	147
23	48	73	98	123	148
24	49	74	99	124	149
25	50	75	100	125	150

Figure 4-7. Field Data Collection Form (Sheet 6 of 6)

Field Observations From Skunk Creek

- Artifacts. Few archaeological or historical artifacts were observed in the channels or floodplains of Skunk Creek and Sonoran Wash. A matate was identified in an upland area located several thousand feet north of the Sonoran Wash floodplain. An archaeologist working on private property north of Sonoran Wash reported finding a Archaic point, small flakes and associated nondescript sherds in the same upland area between Skunk Creek and Sonoran Wash.[1] No evidence of irrigation features similar to those observed along the Cave Creek floodplain to the east of Skunk Creek was identified in the field.

- Armoring. Portions of the channel bed are covered by very coarse sediment that may armor parts of the channel during small floods (Figure 4-8 and 4-9). During the small flood observed on July 15, 1999, the largest sediment sizes previously (and later) observed on the channel bed did not appear to be in motion, although large volumes of very coarse bed material were deposited on the at-grade road crossings at 19th Avenue and Desert Hills Drive. Almost all of the large diameter bed sediment observed in the field appeared to be imbricated, which indicates transport during floods. Therefore, field data suggest that the channel bed is not armored, at least during the largest historical floods.

Figure 4-8. Possible armor layer in riffle.

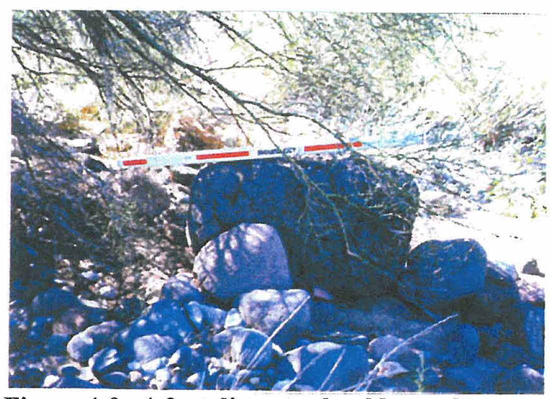


Figure 4-9. 4-foot diameter boulder on bar.

- Avulsions. The multiple channel pattern and remnants of abandoned flow paths observed in the field suggest that Skunk Creek is subject to avulsive channel changes. However, due to the time-dependent nature of avulsive channel change, direct field evidence of specific avulsions is difficult to obtain. However, strong evidence of a relatively recent avulsion was observed on Skunk Creek (Figure 4-10). An abandoned former channel bed is still visible about ½ mile downstream of Carefree Highway. The abandoned channel is several feet higher than the new channel, and now conveys flows only during large floods. More convincing evidence of past avulsions obtained

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[1] Personal communication from an anonymous archaeologist from Soil Systems, Inc. met during field work on Sonoran Wash on February 16, 2000.

by comparing channel position shown on historical maps and photographs was described in Chapter 3.

Figure 4-10. Perched channel (left) formed by avulsion and degradation of main channel (right).

- Bank erosion. Evidence of recent bank erosion was observed throughout the Skunk Creek study reach (Figure 4-11 to 4-14), and included such features as tree roots exposed in vertical cut banks, fresh cut banks, undercut banks, fallen bank vegetation, and hanging fence posts. The most stable-appearing alluvial banks were in Reach 1. Banks that lacked vegetative cover were generally cut to vertical slopes. Data obtained during the field visit indicate that about 16 percent of channel banks are vertical or recently cut by erosion. Banks with good vegetative cover had more gently sloped banks.

Figure 4-11. Cut bank with exposed roots and hanging fence post in Reach 5.

Figure 4-12. Cut bank with basal talus pile.

Figure 4-13. Active cut bank near new church construction site in Reach 6.

Figure 4-14. Cut bank in cobble material.

- Bedrock control. Bedrock crops out in several places on the banks and bed of Reach 6, and in isolated places in Reaches 5, 3, and 2 (Figure 4-15 and 4-16). Even where it does not crop out, bedrock is likely buried at very shallow depths in much of Reach 6. Where it is present, bedrock is the effective limit of lateral erosion. Data collected during field visits indicates that bedrock crops out in only about two percent of the channel banks.

Figure 4-15. Bedrock on left bank and bed of Reach 3 near the Tramonto subdivision.

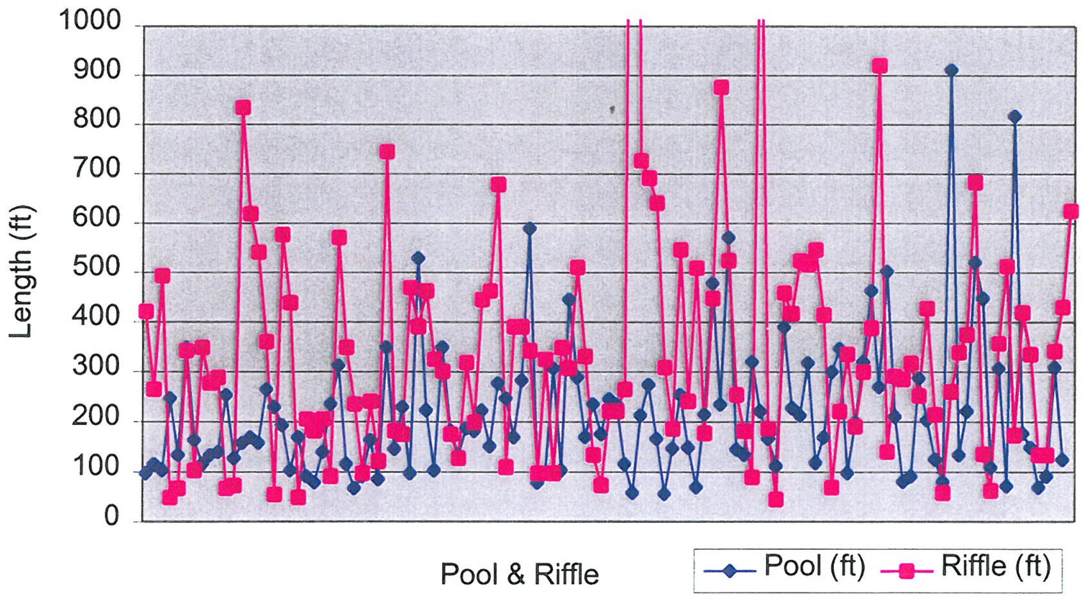
Figure 4-16. Bedrock cliff on right bank of Reach 6.

- Boulder riffles. Most of the Skunk Creek study reach has a pool and riffle pattern. Riffles composed of boulders or cobbles are unevenly spaced along the study reach (Figure 4-17). The lengths and spacing of the pools and riffles measured on Skunk Creek are illustrated in Figure 4-18 and Table 4-1.

Figure 4-17. Pool (sandy surface in foreground) and riffle (cobble surface in background) on Skunk Creek.

Table 4-1. Skunk Creek/Sonoran Wash Watercourse Master Plan Pool and Riffle Sequence Length and Ratio: Skunk Creek and Adjacent Streams			
Stream Name	**Average Pool Length (ft)**	**Average Riffle Length (ft)**	**Ratio (Pool/Riffle)**
Skunk Creek	218	355	0.61
Sonoran Wash	160	287	0.56
Cave Creek	291	250	1.16
Apache Wash	176	185	0.95
Paradise Wash	136	183	0.75

Figure 4-18. Pool & Riffle Spacing on Skunk Creek



- Caliche. Carbonate cemented soils were observed in numerous places in the bed and banks of Skunk Creek (Figure 4-19). Although the caliche material is generally more resistant than unconsolidated alluvium, field data clearly indicate that floods on Skunk Creek are able to erode through the caliche layers. Data collected in the field indicates that caliche is exposed in about seven percent of the main channel banks.

Figure 4-19. Erosion through cemented caliche layer on overflow channel in Reach 3. Caliche cemented boulders are shown directly behind person and in foreground. Erosion has removed the caliche layer between the foreground and background units.

- Carefree Highway Bridge. Skunk Creek was realigned during construction of the original Carefree Highway bridge. Remnants of the original channel alignment are visible east of the spur dike upstream of Carefree Highway. In addition to the realignment, Skunk Creek was significantly widened to increase the bridge capacity. Overwidening of the channel has induced sedimentation in the bridge section. Finally, during construction of the new Carefree Highway bridge expansion, Skunk Creek was excavated below the pre-construction bed elevation. After construction, sediment deposition during small floods filled in the excavated area under the bridge, raising the bed elevation by several feet. Unfortunately, the excavation ended at the downstream right-of-way limit, effectively creating a small dam in the main channel and redirecting flows to the right floodplain downstream of the bridge. Upstream of the bridge, a spur dike controls the new stream alignment at river left and engineered bank protection controls bank erosion on river right (Figures 4-20 and 4-21).

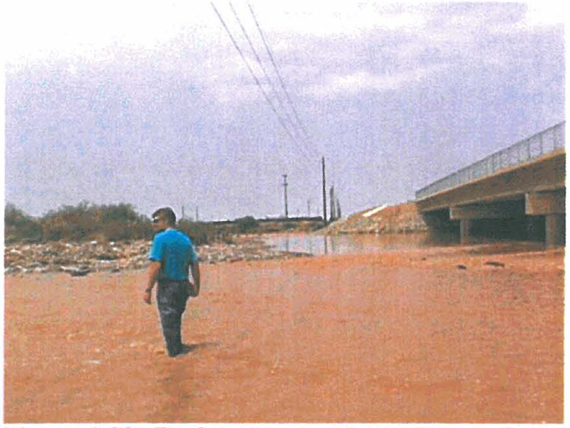


Figure 4-20. Backwater area downstream of Carefree Highway bridge caused by excavation of channel bed in bridge section. Note diversion of flow to west into right floodplain. Photo looking west on July 15, 1999.

Figure 4-21. Look downstream at Carefree Highway Bridge over Skunk Creek. Note evidence of recent grading and disturbance of channel bed in bridge section.

- New River Road Bridge. At the recently constructed New River Road bridge, the main channel of Skunk Creek was widened by about 400 percent, and excavated well below the natural bed elevation (Figures 4-22 to 4-27). Due to the increased width at the bridge, the flatter slope through the bridge section, and the constriction at the downstream right-of-way limit, excessive sediment deposition now occurs in the bridge section. The bed elevation has increased several feet during the course of this study (See Table 3-9), and has increased about 3.2 feet since completion of the as-built construction plans.

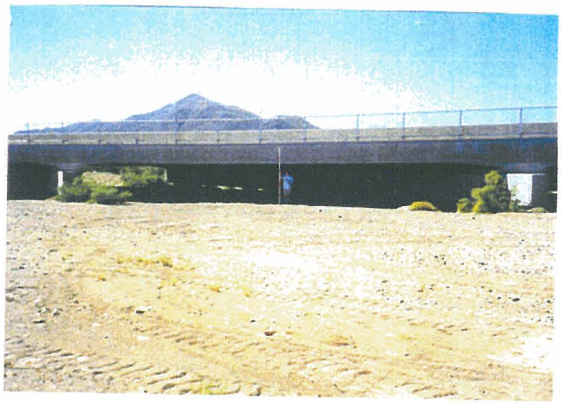


Figure 4-22. New River Road bridge on October 15, 1999. Note person for scale.


Figure 4-23. Match photo in Figure 4-22 on December 6, 2000. Note increase in bed elevation.


Figure 4-24. New River Road bridge on October 15, 1999. Compare to Figure 4-25 after recent small flood.

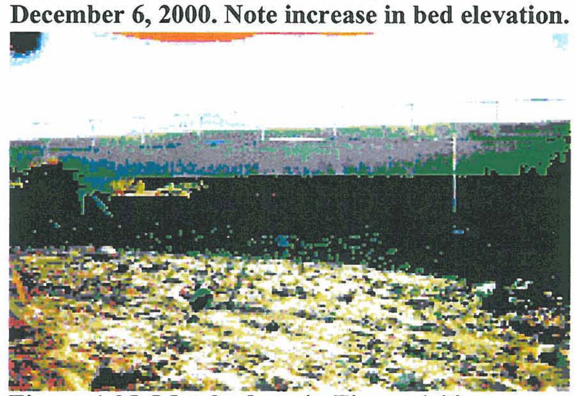


Figure 4-25. Match photo in Figure 4-23 on December 6, 2000. Note increase in bed elevation.

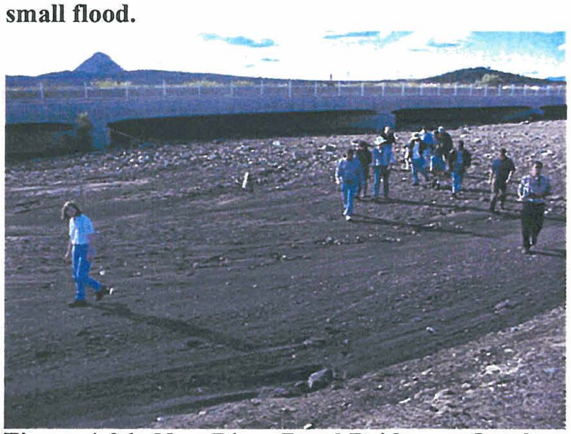


Figure 4-26. New River Road Bridge on October 31, 2000. Note flow lines in left expansion area from recent flood.

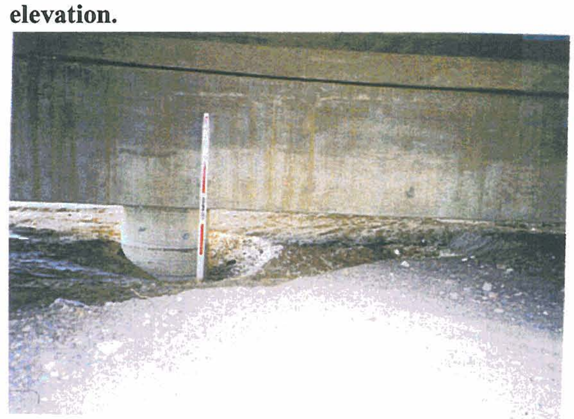


Figure 4-27. Pier scour and recent fine grained sediment deposition under New River Road.

- Central Arizona Project (CAP). Skunk Creek crosses the CAP (Figures 4-28 and 4-29) in a concrete overchute structure which is much narrower than the natural floodplain. Sediment deposition occurs in the backwater area upstream of the overchute constriction, resulting in lower bank heights, finer-grained bed material, frequent overbank flow, dense bank vegetation, and diversion of flow toward Sonoran Wash.

Figure 4-28. Fine-grained sediment deposition and low bank heights upstream of CAP.

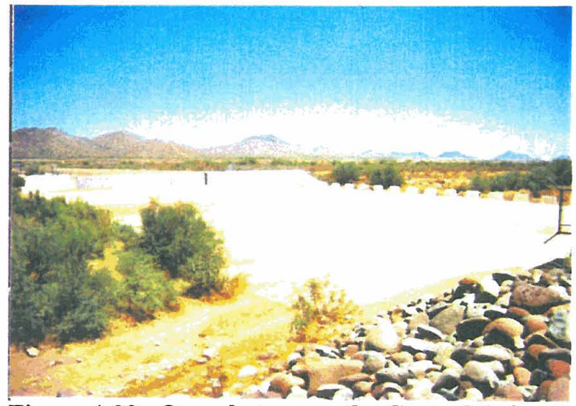


Figure 4-29. Overchute over the Central Arizona Project Canal (CAP) at Skunk Creek.

- Cliffs. A 10 to 15 foot tall cliff is present along the west bank of Skunk Creek downstream of Carefree Highway (Figures 4-30 and 4-31). The cliff is composed primarily of carbonate-cemented cobbles and boulders. In some places the cliff is unvegetated and is vertical (or overhanging) from the base to the top, with the stream abutting the toe of the cliff. Elsewhere, where the stream is not flowing directly at its base, the bank slope has relaxed to about a 2:1 slope and is more well vegetated. While the carbonate in the banks gives the appearance of complete resistance to lateral erosion, evidence such as exposed roots, undercutting, and fallen blocks of bank materials indicate that the cliffs are subject to erosion.

Figure 4-30. Vertical caliche cliff with less cemented base unit.

Figure 4-31. Overhanging cliff in Reach 2. Note well vegetated low slope banks opposite the cliff.

- Cliff Stratigraphy. The tall cliffs which form the right bank in parts of Reach 2 have very resistant layers that allow the 15-foot tall banks to stand at a vertical slope (Figures 4-32 and 4-33). However, there are weaker, more erodible layers that apparently fail where the stream directly impinges on the bank. These erodible layers are also removed by piping, by dissolving the carbonate matrix, or by slope processes.

Figure 4-32. Vertical bank with piping and solution failure.

Figure 4-33. Sloped, vegetated caliche cemented bank not actively eroding.

- Development. Until recently, only minimal development had occurred along Skunk Creek and had been limited to rural, low density uses. Currently, the 1100-acre Tramonto subdivision is under construction in Reach 3 (Figure 4-34), and much of Reaches 1 and 2 are planned for residential and commercial development (Figure 4-35). All of the existing development observed in the field, except for road crossings and the CAP, occur outside of the main channel.

Figure 4-34. Mass grading for Tramonto in left overbank floodplain of Reach 3.

Figure 4-35. Rural ranch in left overbank floodplain of Reach 4.

- Discontinuous channels. The main channel of Skunk Creek alternates between a well-defined single channel and poorly-defined multiple channels (Figure 4-36). The multiple channel braids often decrease in size or become so choked with vegetation that they become too diffuse to follow and give the appearance of being discontinuous. At these discontinuities, the bed slope flattens and the channel splits into multiple flow paths referred to in this report as "splays."

Figure 4-36. Looking downstream at vegetation and sediment choking channel in a "splay" or discontinuous channel reach upstream of Skunk Tank in Reach 4.

- Flood damages. Due to the low density development along Skunk Creek, few significant flood damages to structures were observed in the study area except at road crossings. Local residents and road maintenance crews interviewed in the field report that even small floods frequently damage the pavement section in the at-grade crossings (Figure 4-37). Long-term local residents report that they have observed bankfull conditions on several occasions.

Figure 4-37. Bed elevation drop at undercut concrete sill in Skunk Creek supply reach.

Figure 4-38. Small mid-channel headcut in Skunk Creek Reach 2 downstream of Carefree Highway during the July 15, 1999 storm.

- Headcuts. Small headcuts were observed in several places (Figure 4-38 and 4-40), although the normal mode of long-term degradation appears to be more gradual slope adjustments (Figure 4-39). The bed material is typically too weakly consolidated to maintain vertical headcuts.

Figure 4-39. Steep slope break (at boulders) due to historical incision in Reach 2 adjacent to cliffs in Skunk Creek.

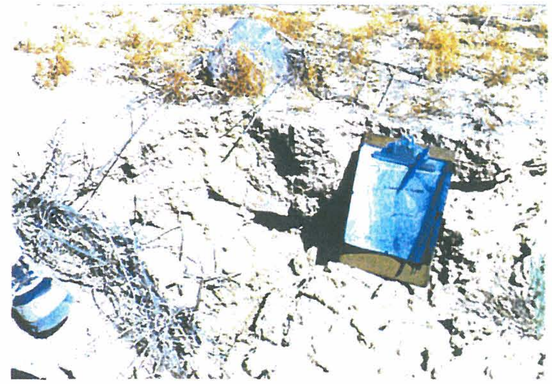


Figure 4-40. Small headcut exposed after July 15, 1999 floods. Tin can exposed in headcut indicates incision into modern deposits.

- High-water marks. Flotsam wrapped around trees, deposited on islands, and left on the floodplain indicates that at least one bankfull flood has occurred in the past 10 years (Figures 4-41 and 4-42).

Figure 4-41. Debris accumulation at the base of vegetation in shallow floodplain.

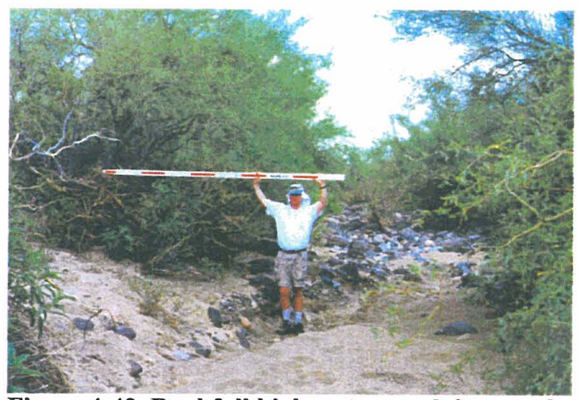


Figure 4-42. Bankfull high water mark in one of several multiple channels in Reach 1.

- Imbrication. The largest boulders on the channel bed and in riffles, up to two feet in diameter, are imbricated in the direction of flow (Figure 4-43). Imbrication is a domino-like streamlined alignment of the coarse sediment on a stream bed which indicates that the bed material is transported by floods.

Figure 4-43. Imbrication of boulders in riffle on Skunk Creek. Imbrication is a downstream alignment of sediment on a stream bed. Boulders are aligned so that they lean in the downstream direction.

- Incision. Field evidence of historically recent channel degradation (Figure 4-44) observed in the field included perched, abandoned channels, over-steepened vertical cut banks, small terrace remnants along the channel margins, and at least one perched tributary (Skunk Tank Wash).

Figure 4-44. Recent incision of overbank channel in Reach 4.

- Overbank flow channels. Field evidence suggests that the multiple channel reaches of Skunk Creek experience frequent overbank flooding (Figures 4-45 and 4-46). Where flow concentrates in the floodplain, new flow paths form that will likely become future avulsive channels.

Figure 4-45. Depositional floodplain without overbank channel in Reach 4 floodplain.

Figure 4-46. Incipient overbank channel in Reach 3.

- Sub-channel clay layer. A red clay-rich layer was observed in each of the channel pits at depths of up to three feet below the surface (Figures 4-47 to 4-49). This clay layer was assumed to be the maximum limit of recent scour. The layer probably formed by infiltration of floodwater that drove fine sediment into the coarse channel bed matrix. In one location the clay layer was exposed on the surface of the channel bed.

Figure 4-47. Clay-Rich Sublayer in Skunk Creek.

Figure 4-48. Clay-Rich Sublayer in Skunk Creek.

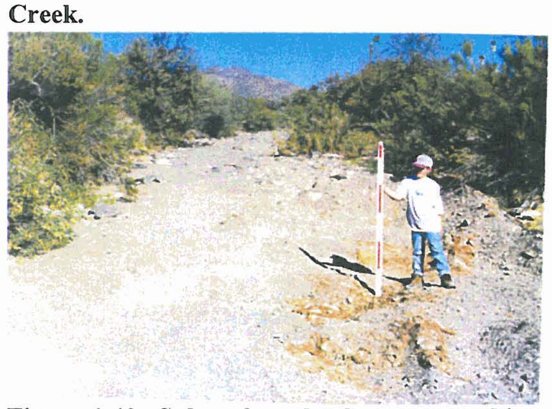


Figure 4-49. Subsurface clay layer exposed in channel bed.

- Variable Bank Stratigraphy. Bank materials are not uniform or homogenous along Skunk Creek (Figure 4-50). The variation of the bank materials did not just consist of the variation over the length of the stream, but also by vertically variable stratigraphy at any given cross section. The variation in bank composition mimics the variability of the composition of the channel bed and bars, indicating that the existing mode of deposition and transport is similar to the prehistoric conditions.

Figure 4-50. Variable coarse and fine sediment stratigraphy exposed in cut banks along Skunk Creek.

- Vertical Cliff Slopes. The presence of vertical cliff slopes indicates that the stream is actively (but slowly) eroding the cliffs. If the cliffs were not subject to erosion, they would gradually relax to a lower angle, become more vegetated, and develop large talus piles at their bases (Figure 4-12 and 4-33).

- Ustream lamination of boulders. The largest boulders on the channel bed appear to be very stable and not transported even by large floods. The upstream faces of these large boulders have been polished and shaped by the abrasive action of sediment laden floodwaters, while the downstream faces are pitted and rounded (Figure 4-51). The upstream laminations were interpreted to mean that the boulders had remained unmoved over the duration of a great number of floods. Imbrication of these boulders indicates that floods do align the largest bed material parallel to flow.

Figure 4-51. Upstream lamination of cobbles. Lamination is interpreted as evidence of non-movement during most if not all floods.

Field Observations from Sonoran Wash

- Aggradation. Net sediment deposition has occurred in Reaches 1 and 2 of Sonoran Wash, resulting in lower bank heights, formation of multiple and braided channels, and expansion of the floodplain (Figures 4-52 and 4-53). Large wedge-shaped deposits of sediment were observed in several places.

Figure 4-52. Sediment deposition burying bank vegetation and widening main channel.

Figure 4-53. Scour and fill of recently deposited sediment.

- Bedrock. A granitic bedrock sill extends across the Sonoran Wash floodplain and crops out in portions of the channel bank and bed of Reaches 3 and 4 (Figure 4-54).

Figure 4-54. Bedrock outcrop on right bank of Reach 4.

- Bank Erosion. Evidence of bank erosion observed in the field included numerous cut banks, overhanging banks, leaning bank vegetation, roots exposed on the banks, and collapsed banks (Figures 4-55 to 4-58).

Figure 4-55. Cut bank in fine grained material, with undercut vegetation.

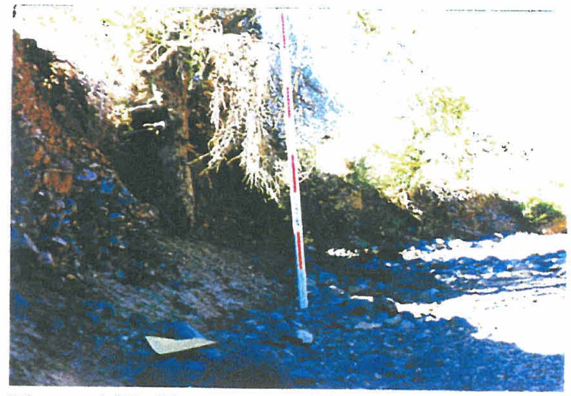


Figure 4-56. Roots exposed by undercutting bank erosion.

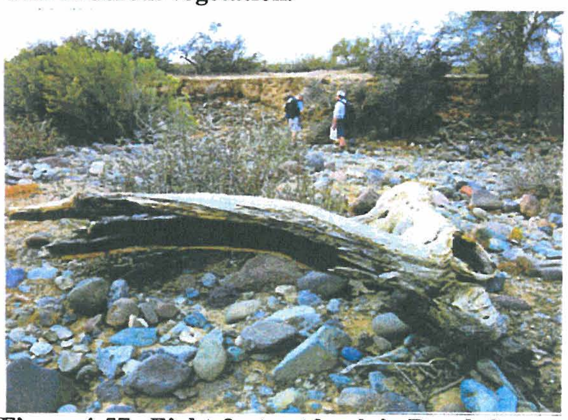


Figure 4-57. Eight-foot cut bank in Reach 3. Note contrast in bed and bank sediment sizes.

Figure 4-58. Exposed roots in right bank of Reach 3.

- Bank Vegetation. Channel banks are well-vegetated throughout the study reach, except at cut banks (Figures 4-59 to 4-60). In Reaches 3 to 6, where apparent long-term degradation has deepened the channel by several feet, existing bank vegetation may be undercut. Where it can be undercut, bank vegetation provides no stability and may actually increase the rate of erosion because when it fails, large blocks of material cemented by the roots are ripped from the banks. Where deep rooting vegetation is not undercut, it may remain intact after the bank has retreated from the root base.

Figure 4-59. Undercut bank vegetation failure.

Figure 4-60. Large mesquite tree with exposed root base indicating past bank retreat.

- Channel Vegetation. Excessive vegetative growth in Reach 1 obstructs the main channel increasing the frequency of overbank flooding, creating a braided channel pattern (Figure 4-61). Elsewhere on Sonoran Wash, vegetation in the channel is generally limited to small annual growth that is removed or flattened during floods.

Figure 4-61. Mid-channel vegetation in Reach 1.

- Central Arizona Project Canal (CAP). Sonoran Wash crosses the CAP in a concrete overchute structure (Figure 4-62). The overchute appears to have been constructed above the natural grade of the wash, resulting in sediment deposition upstream of the overchute, ponding of flood water, and excessive vegetative growth.

Figure 4-62. CAP overchute on Sonoran Wash with evidence of recent upstream ponding.

- Development. Except for the CAP and several unpaved at-grade crossings, the floodplain of Sonoran Wash is undeveloped (Figure 4-63). However, most of the floodplain is currently in the platting and planning process by a number of developers.

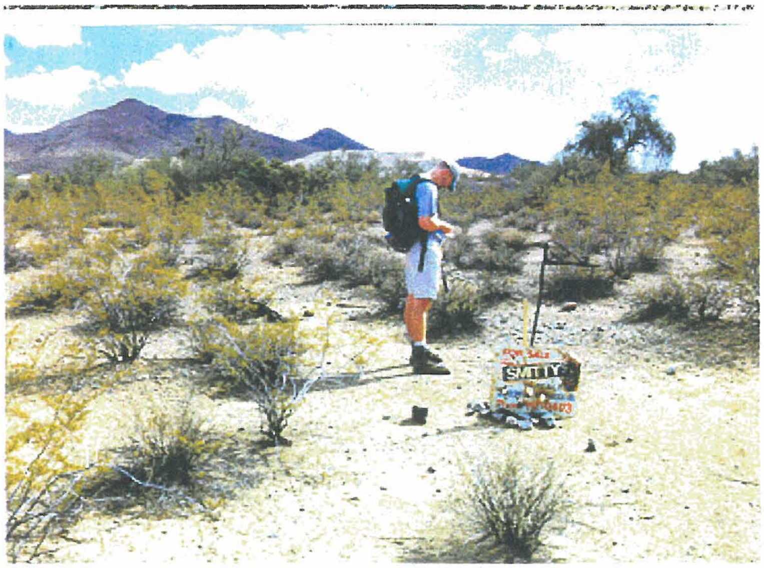


Figure 4-63. Evidence of future development of Sonoran Wash floodplain.

- Incision. The primary field evidence of historic incision on Sonoran Wash is depth of the main channel and the unvegetated toe of the banks that appears to have been recently exposed by degradation (Figure 4-64). These features were observed in Reaches 3 to 6, but not in Reaches 1 and 2 which are affected by deposition upstream of the CAP.

Figure 4-64. Oversteepened banks and unvegetated base of channel bank.

- Levees. Small natural levees have formed (and are hidden) within the dense vegetation lining the channel banks in Reaches 5 and 6. The height of the fine-grained levees is generally less than one foot. No photograph of these levees is provided because the features are obscured from view by very dense bank vegetation.

- Local scour. Scour holes up to four feet deep were observed at natural obstructions such as mid-channel vegetation (Figures 4-65 to 4-67).

Figure 4-65. Mid-channel scour hole and sediment wedge in Reach 2.

Figure 4-66. Scour in gravel deposit and flood debris.

Figure 4-67. 5.5 foot deep scour hole at channel constriction in Reach 1.

- Recent flooding. A moderately large flood occurred on Sonoran Wash in the months prior to the January, 2000 field work. Evidence of the flood included scour holes, flotsam on the floodplain, and a thin coating of fine-grained sediments that marked the limits of the flooding in Reaches 4 to 6 (Figure 4-68). The extent of the flood deposits nearly matched the 100-year floodplain limits.

Figure 4-68. Fine-grained flood deposit on floodplain showing the limits of recent flooding.

- Riffle/Pool Sequence. Sonoran Wash exhibits a pool and riffle pattern, with boulder-sized material in the riffles and fine gravel in the pools (Figure 4-69). Pool and riffle measurements were shown in Table 4-1.

Figure 4-69. Long boulder riffle in Reach 5. Note imbrication of largest boulders in riffle.

- Sediment supply. Several small tributaries supply significant sediment loads to Sonoran Wash, and occasionally deposit small deltas of sandy material when tributary peaks are not coincident with main stem floods (Figure 4-70).

Figure 4-70. Gravel delta at mouth of small tributary. Note contrast in bed material size and color. Portly gentleman with nerdy black socks (right) is standing in Sonoran Wash. Dashing figure on left is standing on granitic gravel deposit from small tributary flood.

- Split Channels. Several moderately large, low islands are formed by flow splits in Reaches 4 to 6 (Figure 4-71). Field evidence suggests that both splits actively convey flood runoff. Field and soils data indicate that the flow splits probably formed by concentration of overbank flow, which led to channel avulsions.

Figure 4-71. Flow split around low island in Reach 4 due to avulsion.

- Trash. Illegal dumping of trash occurs in Reaches 3 to 5, and consists of appliances, household waste, and other material (Figure 4-72).

- Stratigraphy. The bank materials along Sonoran Wash vary in grain size, degree of cementation, resistance to erosion, thickness, and distribution (Figure 4-73). Typically, the bank stratigraphy consists of horizontally bedded alluvium that ranges from silty fine sand to large boulders.

- Stumps. Numerous very large ironwood and mesquite stumps up to 2.5 feet in diameter were observed near the banks of Sonoran Wash (Figures 4-74 and 4-75).

The combined age of the trees before and after they were cut indicates that the rate of bank migration has been low along Sonoran Wash in the past.

Figure 4-72. Trash and debris dumped in the main channel of Reach 4.

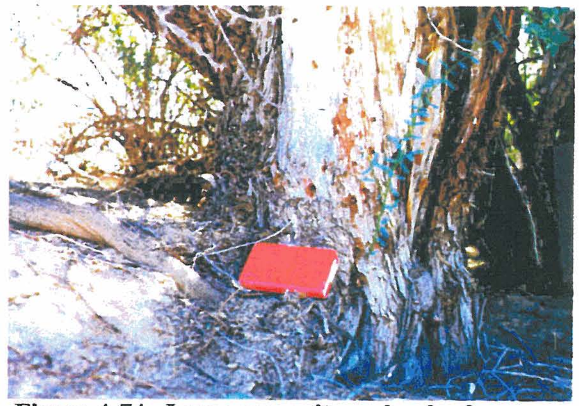


Figure 4-74. Large mesquite on bank of Sonoran Wash in Reach 3.

Figure 4-73. Variable stratigraphy of bank materials results in differential erosion and undercutting of less resistant layers.

Figure 4-75. Ironwood stump and re-sprouted shoots on main channel bank in Reach 5.

Summary. In general, field observations made along Skunk Creek and Sonoran Wash indicate that the study reaches are subject to lateral erosion, channel avulsions, and scour, and have experienced historical degradation. Evidence of human impacts is minimal. Observations made along Sonoran Wash indicate that it is more laterally stable than Skunk Creek. Field data suggest that the frequency of channel avulsions on Skunk Creek is greater than on Sonoran Wash.

Geomorphic Mapping

Alluvial deposits and soils associated with terraces along Skunk Creek and Sonoran Wash were analyzed to assess lateral stream stability. Information describing the age of geomorphic surfaces adjacent to the stream corridor can be used to document the areas that have been subject to erosion and deposition over the past several hundred to several hundred thousand years. The techniques used to estimate the ages of geomorphic surfaces and conclusions regarding the lateral stability of Skunk Creek and Sonoran Wash drawn from these estimates are described below.

Geomorphic Mapping and Lateral Stability

When a stream channel moves because of channel incision or lateral migration, the abandoned area continues to be inundated by floods. Flooding of the former channel area continues until further channel incision (degradation) and/or floodplain aggradation leaves the abandoned surface above the flood-water level. Analysis of the sediment characteristics of the floodplain indicates the type of flood inundation that occurs. Active channels typically have coarser sediments such as sand, gravel and cobbles. Floodplain areas outside the main channel typically are composed of finer sediments such as sand, silt, and clay. After a stream channel moves, fine-grained sediments will be deposited over the generally coarser streambed alluvium originally left by the relocated stream.

Later, when the surfaces once subject to overbank flooding are no longer subject to inundation and sediment deposition, soil development processes modify the alluvium in the first few feet below the surface. The extent of soil development observed in the soil profile on abandoned floodplain surfaces can be used to estimate the period of time since that surface was subject to active channel processes. This period of inactivity (or soil development) defines the period of channel stability (lack of erosion and deposition) for that portion of the stream corridor, and can be used to estimate minimum rates of channel change due to lateral migration.

The following types of information can be gained from geomorphic mapping of alluvial surfaces adjacent to a stream:

- Geologic context. Geomorphic mapping provides a geologic context for expected channel change. Geologic information extends the period of record thousands to millions of years beyond the historical record. The types, rates, and scale of future channel change can then be predicted from evidence of the types, rates, and scale of channel change preserved in the geologic record.

  As shown in Figure 4-76, a minimum rate of lateral erosion for any surface can be estimated (X/Z), where X represents the width of a geomorphic surface within the river corridor, and Z represents the difference in age between two geomorphic surfaces. In addition, the total magnitude of lateral migration and vertical change can be estimated by mapping the geomorphic surfaces at a given location.

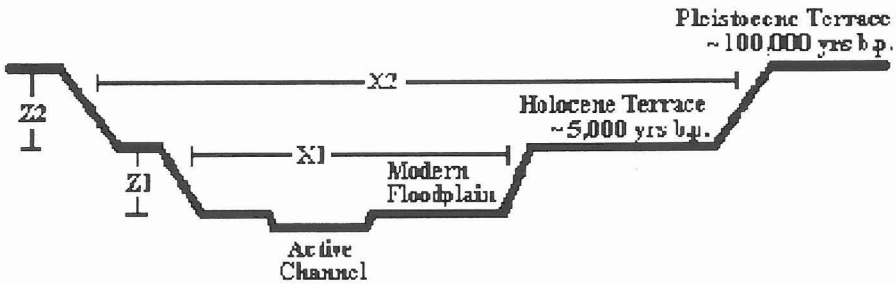


Figure 4-76. Idealized Sketch of Riverine Terraces and Ages

- Modern anomalies. Estimated historical rates of lateral and vertical channel change (See Chapter 3) can be compared to geologic information derived from mapping of geomorphic surfaces to determine if the rate of change has accelerated or slowed in modern times. If the historical rate of change is significantly different than the long-term geological rate of change, an investigation of potential human impacts on the rate of change may be warranted.

- Limits of channel change. The limits (magnitude) of channel processes preserved in the geologic record may indicate physical boundaries for future channel movement. At minimum, geologic evidence of no change on a geomorphic surface over long periods of time indicates a low probability of future change on that surface, unless a clear cause for future change can be identified.

- Channel processes. Geologic information can often provide a record of the types of stream and geomorphic processes active in a stream reach that have been obscured by historical or human interference. For example, soil data can be used to identify currently single channel reaches that are or were subject to avulsions, or that formerly had a braided channel pattern.

- Flood hazards. Geologic information can be readily used to identify surfaces subject to frequent flood inundation and sediment deposition, as well as surfaces that have not been affected by flooding for thousands to millions of years. If soil characteristics have developed, then that surface has not been subject to significant flood inundation or deposition by the active stream over the amount of time necessary to produce those soil characteristics. If a surface has not been inundated for a long period of time, the implication is that a human structure erected on that surface is less likely to be harmed during the inevitable flood events than a structure built on a surface whose surficial characteristics indicate that it is frequently flooded.

Methodology

Surfaces of different geologic age adjacent to the current active channel were mapped using stereo aerial photographs, field observations, previous regional geologic maps, and topographic mapping of the study area. Topographic mapping and aerial photography coverage for the study area were summarized in Chapter 3. Field notes and photographs are provided in Appendix A.

Field data were obtained from visual observation of the geomorphic surfaces of the study area, with more detailed soils information obtained from descriptions of soil profiles from soil pits. Twenty-five backhoe pits were excavated on alluvial terraces and in the main channels within the study area to investigate sediment properties and soil development. The pit locations were chosen so that the soil would be representative of the surface as a whole, and so that the sampled area had not experienced more erosion, recent deposition, or biologic activity than the rest of the surface. Pits averaged about six feet deep, and exposed the soil column for a length of 10 to 20 feet. The soils were described using nomenclature developed by the Natural Resource Conservation Service (NRCS, 1975), with observations recorded on a soil development form (Birkeland et al., 1991) to maintain consistency. A copy of the soils form is shown in Figure 4-77. Pit locations are shown on Exhibit 1. Data from the different soil pits were compared for relative development or accumulation of soil structure, clay, and calcium carbonate. Color, gravel content, texture, stratigraphy, and cohesiveness and resistance to impact were also noted.

Channel Deposition Description (Unified Soil Classification System)

Location: **Site #:** **Date:** **Time:** **Described by:**

Depth (cm)	Color		Percent (%) Grain Size Distribution (Visual)					Dry Strength of Fines	Tough-ness of Fines	Cement-ation	Fines Symbol	Name	Round-ing	Sort-ing	Strat-ification Size	$CaCO_3$
	Dry	Moist	Fines < 0.08 mm	Sand 0.08-4.8mm	Gravel 4.8-7.5 mm	Cobbles 7.5 mm -30 cm	Boulders > 30 cm									Coat, Size, Contin

Figure 4-77. Soils Data Collection Form. See Table 4-3 and Appendix A for Soils Data for Specific Pits.

Geomorphic Surface Age Analysis. The age of stream terraces provides information on past stream bed elevations and positions that can be used to forecast where the stream may be located in the future. Geomorphic surface characteristics were used to compare terraces within the study limits to surfaces in the local area previously evaluated by Gorey (1990) and Leighty et al. (1997). Those characteristics included the following:

- Soil development
- Desert pavement
- Desert varnish
- Archaeological information
- Topographic relief
- Vegetative characteristics

Individually, these age-indicating characteristics provide a relatively low degree of confidence in age estimates. Considered together, the characteristics provide a higher degree of confidence.

Soil Development. Characteristics of soil development considered included the color and relative development of soil structure, clay, and calcium carbonate. The following major divisions within a soil are usually distinguished (Figure 4-78):

- A Horizon. The A horizon occurs at or near the ground surface, and contains more organic material than the underlying horizons.
- B Horizon. The B horizon occurs where fine-grained or water-soluble material accumulates from weathering of parent material or by translocation from the upper horizons.
- C Horizon. The C horizon consists of slightly weathered to unweathered parent material.

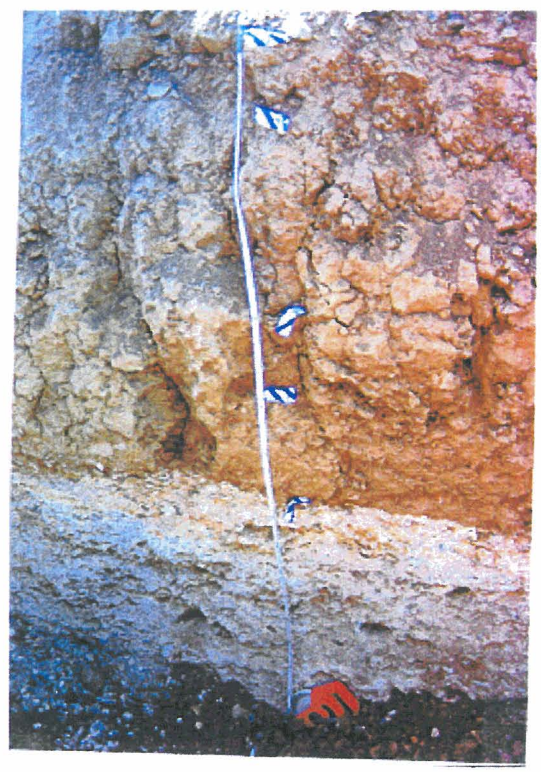


Figure 4-78. Soil profile showing B horizon development – clay and CaCO3 accumulation.

<u>A Horizon</u>. The A horizons observed in the soil pits in the study area typically were very thin or non-existent due to the arid climate, the lack of surface vegetation, and slow rate of decay of biotic material. Therefore, descriptions of A horizons are generally not provided in the field notes and soil profiles, and are not discussed in further detail here.

B Horizon - Clay Accumulation. In B horizons, clay accumulation increases with time. In addition to the clay present initially in a deposit, clay forms over time from the chemical and physical weathering of the alluvium within a soil (pedogenic clay). Clay is also introduced into soils of desert regions as windblown dust (aeolian clay). Aeolian and pedogenic clay particles are moved downward in a soil column by infiltrating rainfall or floodwater, and may be deposited as clay films on the faces of individual peds, in pores between soil grains, or as a bulk increase in clay content at a certain depth (Birkeland et al., 1991). Descriptions of the texture and clay films in soil layers allow for the detection of an increase in clay content (Figure 4-79). In the study area, a loamy sand texture is characteristic of young (Holocene) soils and may vary to sandy or silty clay loams in Pleistocene soils.

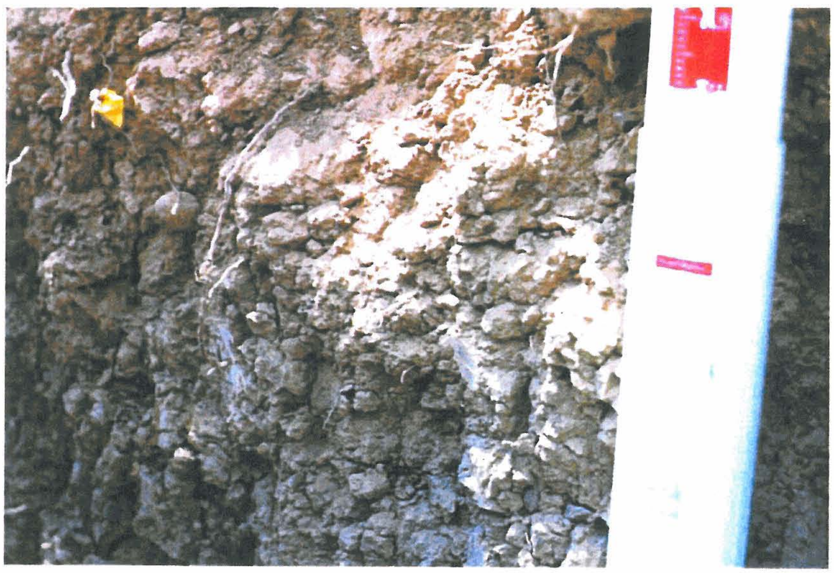


Figure 4-79. Subangular blocky soil texture developed in clay-rich B horizon in soil profile.

Given enough time, the increase in clay content or other soil constituents commonly causes the development of soil structure in the B horizon (Birkeland et al., 1991). The shape and size of the soil structure reflects the time since development began (soil age), the materials in which the structure developed, and the regional climate (Birkeland, 1984). The soil structure becomes more strongly developed with time.

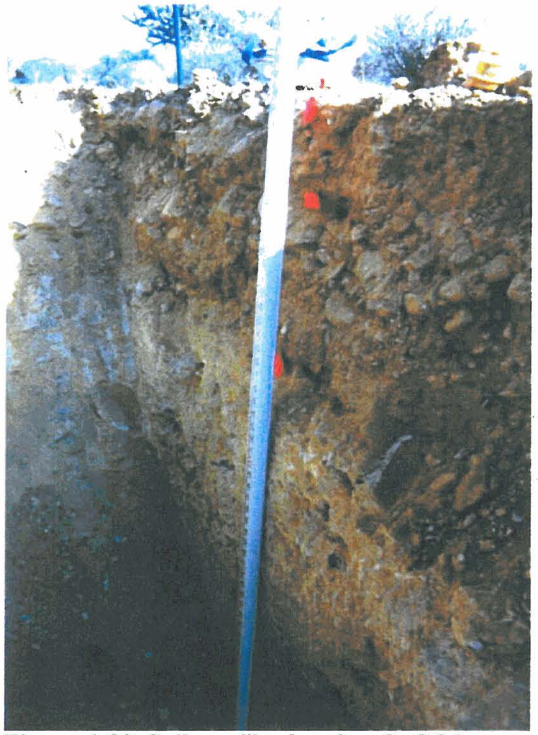


Figure 4-80. Soil profile showing CaCO3 accumulation at depth indicated by hard whitish layers.

Figure 4-81. Soil profile showing clay accumulation and reddening with depth.

B Horizon – Carbonate Accumulation (Figure 4-80). In the desert soils of the Southwest, the amount of calcium carbonate ($CaCO_3$) in a soil layer can be used to estimate the period of time over which the carbonate accumulated. The degree of carbonate development is assigned a stage, with Stage I representing incipient (youngest) soil formation, and Stage VI representing maximum (oldest) accumulation of carbonate (Birkeland et al., 1991). The accumulation can be compared with other soils of known age and similar environment to estimate the soil age (Birkeland, 1984; Machette, 1985) and the age of the geomorphic surface. The degree of carbonate accumulation is measured by the reaction of the soil to the application of dilute hydrochloric acid, by the rind thickness which occurs on gravel clasts, or by the interval of maximum carbonate cementation. The gravel content of the soil must be considered when evaluating carbonate development, since carbonate accumulates more quickly in coarse alluvium than in fine alluvium.

Soil Color. Soil color also may change with time (Figure 4-81). Older desert soil horizons typically develop a more reddish color near the surface where minerals can be oxidized, and a whitish color below the reddish horizons where calcium carbonate accumulates. The color change becomes greater over time, such that material that is tan or gray will become more red or white with increased soil age.

Desert Pavement. Desert pavement (Figure 4-82) consists of a concentration of gravel on a ground surface underlain by finer-grained clay and silt-rich alluvium (Dohrenwend, 1987; Vanden Dolder, 1992). The concentration of gravel increases with time as the repeated swelling of clay particles pushes the pebbles and cobbles upwards and allows finer material to accumulate between the gravel clasts, as well as in the shrink/swell cracks formed by the soil expansion (Dohrenwend, 1987; Field and Pearthree, 1992). In arid environments, pavements develop over hundreds to tens of thousands of years. The degree to which the gravel has concentrated can be used to estimate the relative amount of time since the surface was reworked by flood waters. Flowing water mixes the surficial gravel and silt and destroys the pavement. In general, the denser and more uniform the pavement network, the older the surface. However, pavements can also be disturbed by animals (burrowing or grazing), plants (stem or root growth), human intervention (farming or development), or erosion from sheet flow. Therefore, although the presence of a well-developed pavement surface implies an old surface, the lack of a pavement layer does not necessarily imply a young surface.

Figure 4-82. Desert pavement surface

Desert Varnish. Desert varnish (Figure 4-83), or rock varnish, is a black or red patina that forms on certain gravel, cobble, and boulder clasts exposed at the ground surface in arid environments (Dohrenwend, 1987). The black varnish consists of manganese oxides and clay minerals. The manganese oxides are precipitated from wind-blown dust and rainwater by microbial organisms. Clay minerals are generally of aeolian origin. (Dorn and Oberlander, 1982; Dohrenwend, 1987; Field and Pearthree, 1992). It takes thousands to tens of thousands of years for a varnish to cover a rock completely, during which time the varnish coating progressively thickens (Vanden Dolder, 1992). The best developed desert varnishes are a thick, shiny black patina that forms on portions of boulders exposed at the surface. If a terrace is flooded and the surface materials are reworked by the flood waters, the desert varnish surfaces are commonly removed.

Figure 4-83. Desert varnish on boulders

Therefore, the presence of well-varnished clasts is interpreted to indicate a significant time period since flooding. However, since varnish can be removed by bioturbation or other surface disturbances in addition to flooding, and because varnish development is inhibited on some rock types or in certain climates, the lack of desert varnish does not necessarily imply a young surface age.

Archaeological Information. The presence of archaeological artifacts on a terrace surface indicates that surface was present during the time that the people who produced the artifacts were living. Conversely, archaeological artifacts buried beneath a surface imply that the surface has been modified by channel or floodplain processes since the period of occupation.

Topographic Relief. Height of the surface above the active channel is an indication of its age, since climatic change, tectonic activity, and lowering of base-level generally have resulted in the inset of younger terraces into older ones (Doorn and Pewe, 1991; Field and Pearthree, 1992). The elevation of a surface above the active channel is also a useful characteristic to evaluate whether the surface will be flooded. For example, if a terrace exists 25 feet above a broad active channel, then it would take a very large flood to fill up the channel and overtop the high surfaces. In contrast, low terraces only 5 feet above the channel bottom may be inundated during a moderately large flood. In other words, topographic lower surfaces are more likely to be flooded than higher surfaces. Surfaces that are flooded more frequently are generally more likely to be subject to lateral erosion.

Vegetative Characteristics. Local vegetation in the study area is characteristic of the Arizona Upland subdivision of the Sonoran Desertscrub biotic community (Brown, 1982). Creosote, mesquite, palo verde, saguaro, and other cacti are common species. The alluvial terraces of Skunk Creek tend to have more shrubs, especially creosote, and fewer trees and cacti than the higher, older terraces. Active floodplains tend to have younger, denser, more uniform vegetative cover than upland surfaces. The most dense vegetation tends to occur along the primary channel banks, except where it has been removed by erosion. More detailed descriptions of the biotic communities in the study area were provided by Logan Simpson Design (1999).

Results

Geomorphic surfaces adjacent to the four major streams in the study area were mapped using the principles outlined above and was shown in Figure 2-3. The mapping basically conforms to the surficial geology maps prepared by the Arizona Geological Survey (Leighty et. al., 1997; Leighty, 1998; Leighty & Holloway, 1998). Descriptions for each of the geomorphic surfaces mapped in Figure 2-3 are provided below and in Table 4-2. A comparison of the map units used for this study relative to previous geologic mapping studies is provided in Table 4-2.

The geomorphic surfaces observed in the study area were divided into the following landform-based classifications, with a total of six subunits:

- High Relict Alluvial Fan Terraces – Map units Q_{mo} and Q_m

- High River Terraces – Map units Q_{mr}
- Intermediate River Terraces – Map unit Q_{lr}
- Historical Floodplains and Low Terraces – Map unit Q_{yr}
- Active Channels – Map unit Q_{yc}

Disturbed areas extensively modified by historical human activities and areas of bedrock outcrop were also mapped, and are shown on Figure 2-3. The descriptions of the mapped soil units presented in the paragraphs below are based on field observations, as well as on text modified from Leighty et. al. (1997), Leighty and Huckleberry (1998), Holloway and Leighty (1998), and Leighty and Holloway (1998). A discussion of the regional bedrock geology was provided in Chapter 3, and no further discussion or more detailed mapping of bedrock units was included in the geomorphic analyses summarized below.

High Relict Alluvial Fan Terraces. Two relict alluvial fan terrace units were mapped in the study area. Q_{mo} surfaces were distinguished from Q_m surfaces based primarily on the following characteristics:

- Strength of argillic and calcic horizon development
- Degree of desert pavement and varnish development
- Proximity to bedrock ranges

<u>Q_{mo}: 250,000 to 1,600,000 years old, Early to Middle Pleistocene Alluvial Fan Deposits</u>. The soil profile associated with the older of the two alluvial fan terrace units, a relict Pleistocene alluvial-fan complex, is characterized by white cemented carbonate horizons overlain by structurally-developed reddish accumulations of clay. The relict fan surface is typically more than 20 feet above the active channel. A typical soil profile in a high terrace surface consists of a thin A horizon with moderately developed platy structure and a reddened color. The oldest high terraces may show laminations in the upper portion of the cemented carbonate zone. Well-developed calcic or petrocalcic horizons are also common (Stage III-V). Q_{mo} terrace soils are classified as Calciortids, Paleorthids, and Paleargids. The Q_{mo} unit is roughly equivalent to the Mesquite Tank terrace of Doorn and Pewe (1991) and the Mesa terrace of the Salt and Verde Rivers (Pewe, 1978).

Surficial characteristics of the Q_{m1} surface include a moderately developed desert pavement which is developed locally on the surfaces of the high relict alluvial fan complex. Disturbances of the ground by animals (e.g., burrowing or grazing), plants (e.g., plant heave when a plant falls over), development of a secondary drainage network, and slope processes probably hinder the pavement development in some areas. Desert varnish is moderately to well developed, commonly with a shiny black patina on the tops and red varnish on the bottoms of surface clasts.

<u>Q_m: 250,000 to 750,000 years old, Middle Pleistocene Alluvial Fan Deposits</u>. The profile for the younger of the two relict alluvial fan units, a Middle Pleistocene alluvial fan terrace, consists of moderately to strongly developed soils, with surfaces ranging in color from strong brown to reddish brown. The Arizona Geological Survey (AZGS) mapping divides portions of the Qm surface in a younger Q_{m2} and older Q_{m1} units (Leighty and

Holloway, 1998). For the purposes of the Skunk Creek/Sonoran Wash Watercourse Master Plan, such a definition was superfluous and was not included. The Q_m terraces are typically about 10 to 25 feet above the active channel. Soil material is composed of sandy to loamy layers, with sand- to boulder-sized clasts. The soil profile typically contains reddened argillic (B) horizons that are moderately to strongly enriched in pedogenic clay. Argillic horizons are moderately developed where alluvial surfaces are well preserved; on the eroded valley slopes, argillic horizons are weak due to erosion. Calcic horizon development is typically fairly strong (Stage II-IV), but Q_m soils generally do not have cemented petrocalcic horizons (caliche). These soils are classified as Calciorthids and Haplargids. Q_m surfaces are not prone to flooding, except within the limits of small tributary washes which dissect the surface.

Desert pavement and rock varnish development is moderate to strong on stable surfaces, but variable to weak on surfaces that have been significantly dissected. A dull black desert varnish has accumulated on some of the surface clasts. Q_m surfaces have typically been eroded into shallow valleys and low ridges; original depositional surfaces may be preserved along ridge crests.

Intermediate Terraces. One intermediate terrace unit was mapped in the study area, shown as the Q_{lr} surface on Figure 2-3.

Q_{lr}: 10,000 to 250,000 years old, Late Pleistocene River Terraces. The intermediate terrace is of late Pleistocene age and is comprised primarily of river terraces. The soil materials consist of moderately to poorly sorted, subrounded to rounded sand- and gravel-sized clasts in a sandy to silty matrix. Q_{lr} soils have moderately clay-rich, tan to red-brown argillic horizons that are weakly to moderately strongly developed; these soils contain moderate amounts of pedogenic clay and some calcium carbonate, resulting in relatively low infiltration rates. Thus, these surfaces favor plants that draw moisture from near the surface. Q_{lr} soils typically have Stage II-III calcium carbonate development. Q_{l1} soils are more strongly developed than Q_{yr} soils. Q_{lr} soils are classified as Haplargids, Camborthids, and Calciorthids.

Q_{lr} terrace surfaces range from about 6 to 15 feet above the modern channel. Q_{lr} surfaces typically are moderately incised by stream channels, but still contain constructional, relatively flat, interfluvial surfaces, with some subdued bar and swale topography. Desert pavement and rock varnish development ranges from nonexistent to moderate. Surface colors are slightly more red (light brown to reddish yellow) than Q_{yr} surfaces. Q_{lr} surfaces are generally not prone to frequent flooding, except immediately adjacent to active washes. This surface is roughly equivalent to the Cahava Ranch terrace of Doorn and Pewe (1991).

Historic Floodplains and Low Terraces. One Holocene age surface was distinguished for the purposes of this study. An attempt to construct a more detailed delineation of Holocene surfaces was made, but no consistent relationship between subunits could be established, nor did these divisions appear to affect the final erosion hazard zone boundaries.

Q_{yr}: less than 10,000 years old, Holocene River Terraces. Historical floodplains and low terrace deposits are composed of unconsolidated, moderately to poorly sorted, sub-rounded to rounded sand- and gravel-sized clasts in a sandy to silty matrix. Landforms typically are low terraces less than ten feet above the modern channel bed. Primary fluvial bedforms (gravel bars, fine-grained swales) near the surface are absent or weakly expressed due to bioturbation. These deposits have weakly developed soils that are light brown to yellowish brown on the surface, with a slight reddening with depth. There is typically organic accumulation in the uppermost soil horizons, with slightly oxidized horizons at deeper levels. Weak calcic horizons (<Stage 1) are present in Middle and Early Holocene soils. Q_{yr} terrace soils are Torrifluvents and Camborthids. Because surface soils are not indurated with clay or calcium carbonate, Q_{yr} surfaces have relatively high permeability and porosity. Portions of Q_{yr} surfaces have been inundated during historical floods, and lateral bank erosion is also a hazard. The surface is equivalent to the Hidden View terrace of Doorn and Pewe (1991).

Q_{yr} soils were distinguished from Q_{yc} soils primarily on the bases of topography (higher) and frequency of inundation (less frequent). Q_{yr} surfaces were distinguished from Q_{lr} surfaces primarily by the degree of soil development (less), grain size (coarser), and elevation (lower). Historical and/or prehistorical channel incision have perched some of the Q_{yr} surfaces above the 100-year floodplain.

Hohokam artifacts generally were not observed on the Q_{yr} surfaces. A metal can, found in a very recent silty sand deposit downstream of the Carefree Highway, was exposed by a small headcut that formed during the July 15, 1999 flood (Figure 4-40). The presence of the buried can indicates that portions of the Q_{yr} terrace were flooded historically, and the top layer of alluvium was deposited in the past 50 years. The lack of Hohokam artifacts on the low terraces suggests that the maximum age of the surface is less than 700 years, after the Hohokam abandoned the area, or that the surface has been significantly reworked since that time.

Active Channels: Q_{yc} – 0 to 100 years old. The active channels in the study area were also mapped. Tan to gray channel materials vary from silt to boulders, with sand and gravelly sand most common. The active channel deposits of Skunk Creek typically are somewhat coarser that the channel material in its tributaries. Individual clasts are sub- to well-rounded. The lithologies of the alluvial material vary substantially. Distributary channel patterns are common. Most of the channel surfaces are modern in age, but some vegetated bars may range up to several hundred years old. The channel materials have been deposited during historical time and are likely reworked in each sizable flow event. Thus they do not show soil, pavement, or varnish development. Exceptions occur where buried soils are exposed below the loose channel material. Buried soils result from incision into a previously formed terrace followed by subsequent sediment deposition from the wash. Q_{yc} soils are typically classified as Torrifluvents or Torriorthents. Q_{yc} surfaces are prone to flooding and are subject to lateral erosion and scour.

Table 4-2. Skunk Creek/Sonoran Wash Watercourse Master Plan
Comparison of Published Geomorphic Mapping Units With Map Units Used in This Study

River Deposits (Leighty et. al, 1997)		Piedmont Deposits (Leighty et. al, 1997)		Approx. Age	Skunk Creek/Sonoran Wash WMP Mapping		
Symbol	**Name**	**Symbol**	**Name**		**Symbol**	**Description**	**Age**
Qycr	Active Channel Deposits	Qyc	Active Channel Deposits	0-1ka [1]	Qyc	Active Channel Deposits	0-100 yrs
Qyr	Holocene River Terrace Deposits	Qy	Holocene Alluvium	0-10ka	Qyr	Holocene River Terrace Deposits	< 10ka yrs
		Qylf	Holocene To Late Pleistocene Fine-Grained Alluvium	1-250 ka			
Qlr	Late Pleistocene River Terrace Deposits	Ql	Late Pleistocene Alluvium	10-250ka	Qlr	Late Pleistocene Alluvium	10-250ka
Qmr	Middle Pleistocene River Terrace Deposits	Qm	Middle Pleistocene Alluvium	250-750ka	Qm	High Relict Fan Terraces	250-750 ka
		Qmm	Middle Pleistocene metamorphic alluvium	250-750ka			
Qor	Early Pleistocene River Terrace Deposits	Qo	Early Pleistocene Alluvium	750ka-1.6ma [2]	Qmo	Early Pleistocene Terraces	250ka -1.6 ma
Tqor	Pliocene To Early Pleistocene River Terrace Deposits	TQo	Pliocene to Early Pleistocene alluvial fan deposits	1-3 ma		Not mapped	

Notes:
1. ka = 1,000 years
2. ma = 1,000,000 years

Table 4-3. Skunk Creek/Sonoran Wash Watercourse Master Plan
Soil Pit Test Results

Pit #:	1LOB1	Relative Age:			Watercourse: Skunk Creek				Artifacts found:			
Depth (cm)	Bound-ary	Munsell Color Moist	Munsell Color Dry	Soil Structure	Gravel %	Consistence Wet	Consistence Dry	Texture	Clay Films	Carbonate Stage	effervescence	Notes
2	a,s	2.5YR 4/2	10YR 4/2	m	<10	so,po	lo	L	none		ve	
14	a,s	10YR 3/2	10YR 4/2	1,f,sbk	<10	so,po	so	L	none		ve	
57	a,w	7.5YR 3/2	7.5YR 5/3	1,m,sbk	<10	so,po	so	SL	none		e	
122	c,w	7.5YR 4/3	7.5YR 5/3	Sg	75	so,po	lo	SL	none		es	
142		10YR 4/3	10YR 5/3	2,m,sbk	<10	ss,po	so	L	none		vs	

Pit #:	1LOB2	Relative Age:			Watercourse: Skunk Creek				Artifacts found:			
Depth (in)	Bound-ary	Munsell Color Moist	Munsell Color Dry	Soil Structure	Gravel %	Consistence Wet	Consistence Dry	Texture	Clay Films	Carbonate Stage	effervescence	Notes
4	a,w		7.5YR 5/4	2,m,sbk	40	so,ps	sh	L	None		ve	
17	a,w		7.5YR 4/4	2,m,sbk	25	ss,p	sh	SiL	V1	I	es-ev	
24	s,s		7.5YR 4/4	M	75	so,po	lo	S	V1,f	I+	es-ev	
40	a,w		5YR 5/6	sg	75	so,po	lo	S	V1,f	I	e	

Pit #:	1LOB3	Relative Age:			Watercourse: Skunk Creek				Artifacts found:			
Depth (cm)	Bound-ary	Munsell Color Moist	Munsell Color Dry	Soil Structure	Gravel %	Consistence Wet	Consistence Dry	Texture	Clay Films	Carbonate Stage	effervescence	Notes
12	a,s	7.5YR 5/4	7.5YR 6/4	1,f,pl	10	ss,p	so	CL	none	I-	es	
21	c,w	7.5YR 4/4	7.5YR 5/4	2,c,sbk	<10	ss,p	h	CL	V1	I-	es	
75	c,s	7.5YR 5/3	7.5YR 5/4	2,c,sbk	<10	s,p	vh	SiC	V1,f	I	e	
100	c,w	7.5YR4/4	7.5YR5/4	C	<10	ss,p	vh	SiCL	None	I	es	
120	c,s	7.5YR 5/3	7.5YR 7/3	2,f,sbk	<10	s,vp	vh	SiC	None	II+	ev	
145	c,w	10YR 7/3	10YR 8/2	1,f,sbk	25	so,po	eh	S	none	III+	ev	

Table 4-3. Skunk Creek/Sonoran Wash Watercourse Master Plan
Soil Pit Test Results

Pit #:	1ROB1	Relative Age:			Watercourse: Skunk Creek				Artifacts found:			
Thickness (cm)	Bound-ary	Munsell Color		Soil Structure	Gravel %	Consistence		Texture	Clay Films	Carbonate Stage	effervescence	Notes
		Moist	Dry			Wet	Dry					
4	s,w	10YR 4/2	10YR 6/4	1,c,abk	<10	Ss,ps	sh	SiCL	none		ve	
11.5	s,s	10YR 3/2	10YR 5/4	1,m,abk	<10	Ss,p	so	SiCL	none	I	e	
6.5	s,s	10YR 3/4	10YR 5/3	1,m,sbk	<10	Ss,po	sh	SiCL	none	I	es	
7.5	s,s	10YR 3/4	10YR 5/3	2,c,abk	<10	Ss,ps	sh	SiCL	None	I+	ev	
9.5	s,s	10YR 3/4	10YR 6/3	1,f,abk	<10	S,p	sh	SiC	2,f	II	ev	
10.5	s,s	10YR 4/3	10YR 5/3	2,f,sbk	10	Ss,p	sh	SCL	1,f	II+	ev	
>13.5		10YR 4/3	10YR 5/3	1,f,sbk	25	S,p	h	SCL	V1	III	ev	

Pit #:	2LOB1	Relative Age:			Watercourse: Skunk Creek				Artifacts found:			
Depth (cm)	Bound-ary	Munsell Color		Soil Structure	Gravel %	Consistence		Texture	Clay Films	Carbonate Stage	effervescence	Notes
		Moist	Dry			Wet	Dry					
2	A,s	10YR 3/2	10YR 5/3	1,f,pl	25	So,po	So	SL	none		Ne	
10	C,w	10YR 3/3	10YR 5/4	1,m,sbk	0	So,po	So	DL	none		Ve	
36	C,w	10YR 3/3	7.5YR 5/4	M	<10	So,po	So	Ls	none		Es	
60	w	10YR 3/2	7.5YR 5/4	Sg	75	So,po	Lo	SL	none		Es	
1.4		7.5YR 4/3	7.5YR 5/4	m	10	So,po	sh	SL	none		es	

Pit #:	2LOB2	Relative Age:			Watercourse: Skunk Creek				Artifacts found:				
Depth (ft)	Bound-ary	Munsell Color		Soil Structure	Gravel %	Consistence		Texture	Clay Films	Carbonate Stage	effervescence	PEN	Hammer St.
		Moist	Dry			Wet	Dry						
.05	a,w	7.5 YR 4/3	7.5 YR 5/4	1,f,pl	25	ss,ps	sh	L	v1,f			0	L
.8/5	c,w	7.5 YR 4/3	7.5 YR 5/4	2,c,sbk	<10	ss,vp	sh	SC	v1,f	I-		18	S
2.35	c,w	7.5 YR 4/3	7.5 YR 4/4	2,vc	75	s,ps	sh	CL	v1,f	I	es	12	MH
3.45	c,w	7.5 YR 5/4	7.5 YR 5/4	1,m,sbk	75	so,p	sh	L	2,f	I	es	15	H
5.35		7.5 YR 4/4	5 YR 4/6	Sg,f,sbk	>75	ss,ps	sh	L	1,f	I	e	14	S

Table 4-3. Skunk Creek/Sonoran Wash Watercourse Master Plan
Soil Pit Test Results

Pit #:	2ROB1	Relative Age:			Watercourse: Skunk Creek				Artifacts found:			
Depth (ft)	Bound-ary	Munsell Color		Soil Structure	Gravel %	Consistence		Texture	Clay Films	Carbonate Stage	effervescence	Notes
		Moist	Dry			Wet	Dry					
5	a,s	10YR 3/2	10YR 5/4	1,f,pl	50	ss,ps	so	SL	V1,f		se	
4.55	c,s	7.5YR 5/4	7.5YR 6/4	1,m,sbk	10	ss,vp	sh	SL	V1,f	I	es	
3.75	a,w	7.5YR 4/3	7.5YR 4/4	2,f,sbk	<10	s,p	sh	SiC	V1,f	I+	ev	
2.6	a,w	7.5YR 5/4	7.5YR6/3	1,m,sbk	75	ss,p	h	SVL	1,f	III	ev	
0	c,w	7.5YR 5/4	7.5YR 7/3	2,c,sbk	75	ss,po	vh	S	none	III+	ev	

Pit #:	3B ROB1	Relative Age:			Watercourse: Skunk Creek				Artifacts found:			
Depth (ft)	Bound-ary	Munsell Color		Soil Structure	Gravel %	Consistence		Texture	Clay Films	Carbonate Stage	effervescence	Notes
		Moist	Dry			wet	dry					
.2	a,w	7.5YR 5/4	7.5YR 4/4	1,fabk	25	s,vp	sh	SiCL	V1,f			
.2	c,w	5YR 4/3	10YR 5/4	2,f,abk	50	s,vp	sh	SiC	V1,f			
1.4	c,w	5YR 4/4	7.5YR 4/4	3,c,sbk	<10	s,vp	h	SiC	V1,f			
2.6	a,w	7.5YR 4/4	7.5YR 4/4	3,vc,abk	10	s,vp	h	SiC	1,d			
5.2		5YR 4/4	5YR 5/6	1,c,abk	75	s,vp	so	SiCL	2,d			

Pit #:	3LOB1	Relative Age:			Watercourse: Skunk Creek				Artifacts found:			
Depth (ft)	Bound-ary	Munsell Color		Soil Structure	Gravel %	Consistence		Texture	Clay Films	Carbonate Stage	effervescence	Notes
		Moist	Dry			Wet	Dry					
.1	A,w	10YR 3/3	10YR 5/4	2,f,pl	<10	So,po	So	SL	V1		E	
.7	S,w	10YR 3/4	10YR 5/4	M,vc,pl	<10	So,po	Sh	SL	V1		Ve	Flood deposits layered w/fines and coarse sand layers
1.2	S,w	10YR 3/4	10YR 5/4	M	<10	So,po	So	SL	V1		E	
3.5	S,w	7.5YR 4/3	2.5Y 5/3	M	<10	Ss,p	So	L	V1		E	
5.7		10YR 3/4	2.5 Y 5/3	M	50	So,po	lo	SL	V1	I-	es	

Table 4-3. Skunk Creek/Sonoran Wash Watercourse Master Plan
Soil Pit Test Results

Pit #:	3LOB2	Relative Age:			Watercourse: Skunk Creek				Artifacts found:			
Depth (ft)	Bound-ary	Munsell Color		Soil Structure	Gravel %	Consistence		Texture	Clay Films	Carbonate Stage	effervescence	?Stage (see field notes)
		Moist	Dry			Wet	Dry					
.1	A,w	7.5YR 5/4	7.5YR 5/6	2,f,pl	<10	Ss,ps	So	SiL	V1		E	L
.4	S,w	7.5YR 5/6	10YR 6/6	2,c,sbk	<10	Ss,ps	Sh	SCL	V1	I+	Es	S
1.2	A,w	7.5YR 4/6	7.5YR 5/6	2,c,sbk	<10	Ss,vp	Sh	SiL	V1	I+	Ev	H
2.3	C,s	10YR 8/3	5YR 8/2	M	10	Ss,po	Sh	SL	V1	II+, IV	Ev	Eh
4.7	G,w	10YR 7/4	5YR 8/2	M	75	So,po	Vh	SL	1,f	III	Ev	H
7.1		7.5YR 6/4	7.5YR 7/3	M	50	So,po	Eh	S	V1	II+	Ev	h

Pit #:	3ROB2	Relative Age:			Watercourse: Skunk Creek				Artifacts found:			
Depth (ft)	Bound-ary	Munsell Color		Soil Structure	Gravel %	Consistence		Texture	Clay Films	Carbonate Stage	effervescence	Notes
		Moist	Dry			Wet	Dry					
.1	a,s	10YR 3/2	10YR 5/4	2,f,pl	<10	Ss,p	lo	cl	V1,f			
.8	c,w	10YR 3/2	10YR 4/4	2,c,sbk	<10	S,p	sh	sicl	V1			
1.8	a,w	10YR 4/3	10YR 5/3	M	75	Ss,p	so	sil	V1			
4.7		10YR 4/4	7.5YR 4/4	m	75	So,vp	so	sl	V1			Abrupt change to red color in this layer.

Pit #:	4LOB1	Relative Age:			Watercourse: Skunk Creek				Artifacts found:			
Depth (ft)	Bound-ary	Munsell Color		Soil Structure	Gravel %	Consistence		Texture	Clay Films	Carbonate Stage	effervescence	Rinds
		Moist	Dry			wet	dry					
.05	A,s	10YR 3/2	10YR 5/3	1,f,pl	<10	Ss,ps	So	L	none		Ne	
.5	A,w	10YR 3/3	10YR 5/3	3,m,sbk	10	So,po	Sh	LS	none	I	Ve	Thin disc. coatings
5.0	C,w	10YR 4/2	10YR 5/2	M	75	Ss,po	Lo	S	none	I,I+,I	Es-ev	Thin disc. coatings
5.7		10YR3/4	10YR5/3	1,vf,gr	75	Ss,po	sh	SL	none	II	ev	Cont. mod. Thin coatings. Calcareous matrix

Table 4-3. Skunk Creek/Sonoran Wash Watercourse Master Plan
Soil Pit Test Results

Pit #: 4LOB2 | **Relative Age:** | **Watercourse: Skunk Creek** | **Artifacts found:**

Depth (ft)	Bound-ary	Munsell Color Moist	Munsell Color Dry	Soil Structure	Gravel %	Consistence wet	Consistence dry	Texture	Clay Films	Carbonate Stage	effervescence	Notes
.1	A,w	7.5YR 3/3	7.5YR 5/4	1,f,pl	<10	Ss,p	So	SiCL	None			
.4	S	7.5YR 4/4	7.5YR 5/4	3,c,abk	<10	Ss,p	Sh	SiCL	V1			
1.3	C,w	5YR 4/3	5YR 5/4	3,m,sbk	<10	Ss,p	Sh	SiCL	1,f			
1.7	C,w	7.5YR 4/4	7.5YR 5/4	F,sbk	50-75	Ss	So	SiCL	2,d			
2.9	G,w	7.5YR 5/3	5YR 8/2	M	50	So,po	H	SL	None			
4.4		7.5YR 5/3	5YR 8/2	m	50	So,po	h	LS	none			

Pit #: 5ROB1 | **Relative Age:** | **Watercourse: Skunk Creek** | **Artifacts found:**

Depth (ft)	Bound-ary	Munsell Color Moist	Munsell Color Dry	Soil Structure	Gravel %	Consistence wet	Consistence dry	Texture	Clay Films	Carbonate Stage	effervescence	Notes
.1	A,s	7.5YR 4/3	7.5YR 5/3	2,m,pl	<10	So,po	Sh	SL	none		E	
.7	A,w	7.5YR 3/3	7.5YR 5/3	2,c,sbk	<10	So	So	SL	none	I	Ve	Thin discontinuous coatings and flecks
1.8	G,w	7.5YR4/3	7.5YR 5/4	1,v,sbk	<10	So	So	SL	none	I+	Es	Thin discontinuous coatings, some flecks
3.3	C,w	7.5YR4/2	7.5YR 5/3	M	10	So	So	DL	none	I+	Es	Thin discontinuous coatings, some flecks
4.2	C,w	7.5YR 2.5/2	7.5YR 5/3	Sg	75	So	Lo	S	none	I+	Es	Thin discontinuous coatings, some flecks,
6.1		7.5YR 2.5/1	7.5YR 3/2	sg	50	So	lo	S	none	I-	ne	

Pit #: 6LOB2 | **Relative Age:** | **Watercourse: Sonoran Wash** | **Artifacts found:**

Depth (in)	Bound-ary	Munsell Color Moist	Munsell Color Dry	Soil Structure	Gravel %	Consistence Wet	Consistence Moist	Consistence Dry	Texture	Clay Films	Carbonate	Other	Hammer Test
.05	A,s	7.5YR 4/4	7.5YR 6/4	2,f,pl	50	ss,p	vfi	sh	SiCL	none		es	
.4	A,s	7.5YR 4/6	7.5YR 6/4	2,c,sbk	10	ss,p		sh	SiCL	none	I	es	
.8	A,w	7.5YR 5/4	7.5YR 6/4	1,?,sbk	25	ss,ps		so	SCL	none	I+	es	
2.4	C,w	7.5YR 6/4	7.5YR 7/2	?,f,,sbk	75	so,ps		sh	L	none	III+	ev	
4.4	C,w	7.5YR 5/3	7.5YR 7/2	Sg,?,?	>75	so,po		eh	S	none	III+	Possible colluvium ev	

Table 4-3. Skunk Creek/Sonoran Wash Watercourse Master Plan
Soil Pit Test Results

Pit #:	6ROB1	Relative Age:			Watercourse: Sonoran Wash				Artifacts found:			
Depth (cm)	Boundary	Munsell Color		Soil Structure	Gravel %	Consistence		Texture	Clay Films	Carbonate Stage	effervescence	Notes
		Moist	Dry			Wet	Dry					
5	a,s	7.5YR 4/3	7.5YR 5/4	2,f,sbk	25	ss,ps	sh	SiCL	2,f	0	ne	
21	c,w	7.5YR 5/4	7.5YR 4/4	2,c,sbk	<10	ss,p	h	SiCL	1,f	0	ne	
60	c,w	7.5YR 4/3	7.5YR 4/4	3,vc,sbk	<10	s.vp	h	SiC	1,f	I-	ve	
80	c,s	7.5YR 4/3	7.5YR 5/4	3,v,sbk	<10	s.vp	vh	SiC	2,f	I	e	
95	a,s	7.5YR 4/4	7.5YR 4/3	2,c,abk	<10	s,vp	h			I	es	
190		7.5YR 6/4	7.5YR 7/3	2,f,sbk	75	ss,p	vh	SCL	1,m	III+	ev	Pockets of clay accumulation

Pit #:	6LOB1	Relative Age:			Watercourse: Sonoran Wash				Artifacts found:			
Depth (cm)	Boundary	Munsell Color		Soil Structure	Gravel %	Consistence		Texture	Clay Films	Carbonate	Other	PEW
		Moist	Dry			Wet	Dry					
5	a,w	7.5YR 4/3	7.5YR 5/4	1,f,pl	<10	so,ps	so	L	V1,f	0	nr	0
13	c,w	7.5YR 4/3	7.5YR 5/4	1,c,sbk	10	ss,p	so	L	V1,f	0	ve	0
	c,w	7.5YR 4/3	7.5YR 5/4	1,m,sbk	25	ss,ps	so	L	None	I-	es	14
98	g,w-i	7.5YR 3/3	7.5YR 5/4	1,f,gr-sbk	75	so,ps	sh	L	None	I+	ev	14
165		7.5YR 3/3	7.5YR 5/6	1,vf,sbk	75	so,po	sh	L	S,f	I	ev	17

Summary
The ages and relative heights of the geomorphic surfaces near the major streams in the study area provide information on how recently they have been flooded. Knowing approximately when the terraces were last flooded allows the team to predict the potential for future flooding. In addition, the geomorphic mapping of these surfaces defines the limits of where the streams have actively eroded their banks over the past few hundred thousand years.

Geologic context. Geomorphic mapping provides a geologic context for the types, rates, and scale of the expected channel change.

- Type of channel change. The oldest surfaces mapped (Q_{mo}) were deposited by the channels of a very large, Pleistocene-aged alluvial fan that was the predecessor of Skunk Creek.[1] The depositional and erosion processes active during that period were significantly different than the riverine processes active today. Since the late Pleistocene, the study area has been dominated by riverine erosion and floodplain sedimentation processes, rather than by alluvial fan building processes. The geologic record also indicates that portions of Skunk Creek and Sonoran Wash have been subject to channel avulsions for at least the past 10,000 years. All of the streams in the study area have experienced net degradation over the last million years.

- Rate of channel change. Except in reaches affected by channel avulsions, geologic evidence preserved in the soils record indicates that the rate of net channel change has been slow (< 1ft/yr laterally, <0.01 ft/year vertically), although episodes of faster local change undoubtedly occurred.

- Scale of channel change. The scale of lateral channel change observed in the recent geologic record was not significantly different than the scale of historical changes documented in Chapter 3.

Modern anomalies. The historical rate of change can be compared to the long-term average geological rate of change.

- Vertical change. The rates of net degradation since the middle Pleistocene and early Holocene were estimated from average terrace heights at about 10^{-4} ft./yr., and 10^{-2} ft./yr., respectively. Modern rates of incision (1960-1999) estimated from topographic mapping and aerial photographic interpretation average about 10^{-1} ft./yr to 10^{-2} ft./yr. (Chapter 3), somewhat faster than, but within the range of, long-term geologic rates of incision.

- Lateral change. Channel movement recorded in historical aerial photographs is somewhat lower than the rate and scale than the rate suggested by interpretation of the geomorphic surficial mapping, but within the range suggested by consideration of GLO survey records. The rates of lateral movement have been fastest on the

[1] See Chapter 2 for a discussion of the geologic history of the study area.

youngest, less indurated surfaces and slowest along the margins of the older, more well indurated surfaces.

Limits of channel change. The limits of channel processes preserved in the geologic record indicate that a physical boundary exists for past channel movement.

- Skunk Creek and Sonoran Wash are located within a descending series of inset and progressively younger terraces. The older terrace margins serve as a practical limit for predicted future rapid channel change, although the older terraces are also subject to lateral erosion (at slower rates than the younger surfaces).

Channel processes. Geologic information often provides information on types of stream and geomorphic processes active in the study reach that are currently obscured by the modern history of the stream corridor.

- The short period of modern occupation of Skunk Creek and Sonoran Wash limited the potential for observation of the types of channel changes preserved in the geologic record. Use of geologic data extends the period of observation so that likely, but not documented, hazards are appropriately considered.

Flood hazards. Geologic information can be readily used to identify surfaces subject to frequent flood inundation and sediment deposition, as well as surfaces that have not been affected by flooding or lateral erosion for thousands to millions of years.

- The high relict alluvial-fan surfaces and intermediate terraces of Pleistocene age (Q_m and Q_{lr} surfaces), have not been flooded significantly for tens to hundreds of thousands of years. Many of the Pleistocene deposits are coarse and well indurated and are resistant to bank erosion over short time periods.

- The terraces of late Pleistocene and Holocene age at intermediate (Q_{lr}) and moderate (Q_{yr}) heights above the active channel have higher potential for significant flood inundation than older surfaces. However, because the deposits associated with the lower set of these terraces (Q_{y1}) are typically more weakly consolidated, these areas may be more susceptible to lateral erosion than the higher terraces along the wash.

- The low terraces of Holocene age have a high potential for being flooded and are highly susceptible to lateral stream erosion. Information obtained from the soil pits indicates that the active channel has shifted rapidly across the low terrace surfaces within the past several hundred to thousand years. This type of erosion should be expected in the future.

Geomorphic Assessment

Although geomorphology has its roots in qualitative field observations, much of the data collected for river systems can be used quantitatively as well. Some of the qualitative and quantitative geomorphology approaches are applicable to Skunk Creek and Sonoran Wash, and were applied using the topographic and hydraulic data described previously. The following quantitative geomorphic analyses are presented in this section:

- Longitudinal Profile
- Bankfull Discharge
- River Classification Methods
- Hydraulic Geometry/Regime Equation Methods

Longitudinal Profile

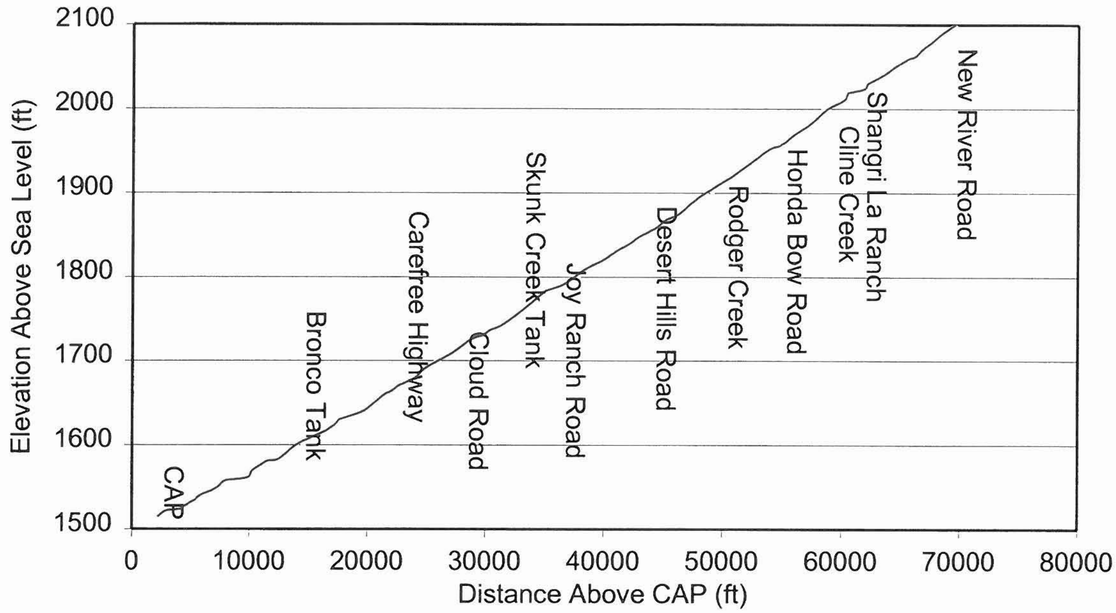
The longitudinal profile is a plot of the channel elevation versus distance along the stream bed. Analysis of the longitudinal profile can be used to identify slope irregularities, over-steepened or flat reaches, headcuts, and areas of natural grade control. Interpretation of the longitudinal profile also provides information on the expected lateral stability of the stream. Reaches with lower slopes than upstream reaches will tend to experience net deposition (aggradation) and bank erosion associated with braiding and avulsions. Reaches with steeper slopes than upstream reaches will tend to experience net degradation and bank erosion associated with undercutting and scour. Comparison of historical profiles with modern profiles can be used to indicate where degradation and aggradation have occurred in the recent past, and where future adjustments of channel geometry are most likely to occur.

Methodology. Longitudinal profiles for Skunk Creek and Sonoran Wash were constructed from topographic data from the most recent floodplain delineation studies (Table 4-4). Historical longitudinal profiles were also constructed for each stream, as described in Chapter 3 (Figures 3-30 to 3-34, Table 3-7). Topographic data obtained from floodplain delineation studies printed maps have two main types of potential error. Measurement error is a function of the map scale, as shown in Table 4-4, and results from manually measuring distances on printed maps. Measurement error was estimated as half the smallest unit (0.02 inch) of measurement on the engineering scale used to determine distances on the paper copy of the map. Vertical error is a function of level of detail of the survey data used to generate the topographic map. Vertical accuracy of a topographic map is generally considered to be half the contour interval.

Results. The longitudinal profiles for Skunk Creek and Sonoran Wash are shown in Figures 4-84 and 4-85. Topographic data source for the longitudinal profiles in Figures 4-84 and 4-85 are listed in Table 4-4.

Table 4-4. Skunk Creek Watercourse Master Plan Topographic Data Used for Skunk Creek Longitudinal Profile Analysis					
Date	**Scale**	**Contour Interval**	**Stream Name**	**Extent**	**Source**
1995	1:2,400	2 ft.	Skunk Creek	CAP to Desert Hills Rd. Honda Bow Rd. to New River Rd.	FCDMC
1996	1:1,200	1 ft.	Skunk Creek	Desert Hills Rd. to Honda Bow Rd.	Erie
1999	1:2,400	2 ft.	Sonoran Wash	CAP to study limit	Tetra Tech

Figure 4-84. Longitudinal Profile of Skunk Creek



Skunk Creek. The following conclusions about lateral stability and erosion hazards can be drawn from the longitudinal profile of Skunk Creek, as shown in Figure 4-84:

- Profile Shape. The longitudinal profile of Skunk Creek has a concave up shape, which is typical of most alluvial streams.[2] The concave profile shape is due to the decrease in channel slope in the downstream direction. Channel slope ranges from 0.0093 ft./ft. from New River Road to Desert Hills Drive, to 0.0089 ft./ft. from Desert Hills Drive to the Carefree Highway, to 0.0075 ft./ft. from Carefree Highway to the CAP overchute. The profile shape indicates that downstream reaches of Skunk Creek will tend to transport less sediment than upstream reaches, and will consequently be subject to deposition of coarse grained sediments during floods.
- Profile Irregularities. The longitudinal profile of Skunk Creek downstream of the Carefree Highway and at the Cline Creek confluence has a jagged, irregular shape which is in contrast to the relatively smooth profile elsewhere within the study reach. A stream which has achieved some level of equilibrium will have a smooth longitudinal profile that indicates water and sediment continuity between cross

[2] Some aggrading streams and channels on some alluvial fans have concave down profiles.

sections, and gradually varied geometry changes. The irregular profile downstream of Carefree Highway probably reflects historical degradation, formation of avulsions, transitions from single channel (chutes) to multiple channel reaches (splays), and historical disturbance of the natural channel.

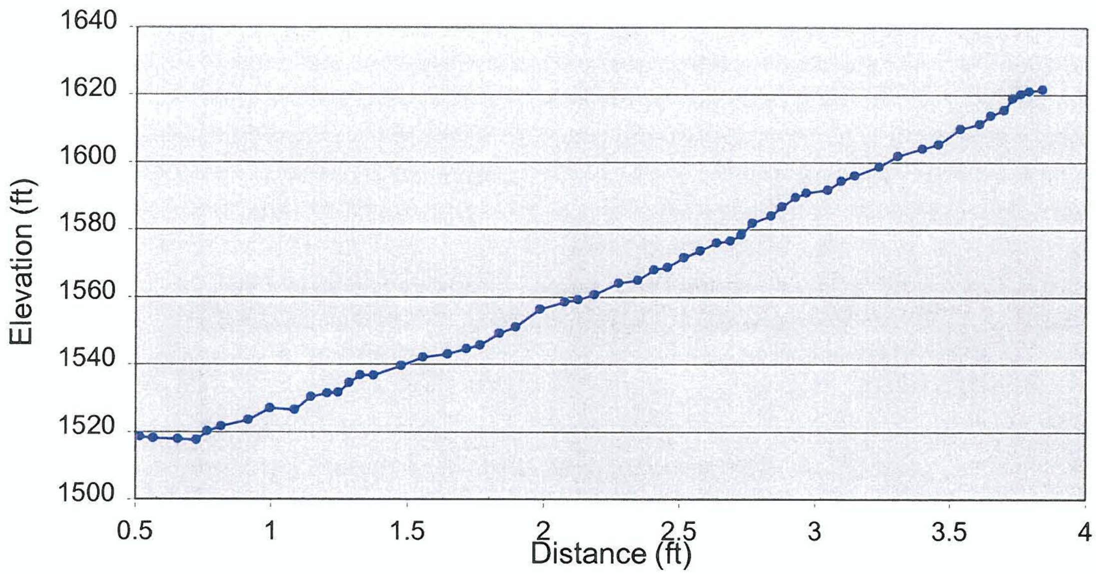
- Slope Breaks. No significant reaches of over-steepened or over-flattened slope are visible on the longitudinal profile of Skunk Creek. Instead, many local variations in slope are visible that result in the irregular profile reaches described above. Area of local slope irregularities are likely to experience net change in bed elevations that will remove the irregularity. When these future adjustments occur, they are often accompanied by bank erosion in response to aggradation or degradation.
- Headcuts. Small, local headcuts were observed in the field, most of which were rotated from vertical, that are consistent with the reaches which have the irregular profile. However, the overall shape of the longitudinal profile indicates that these headcuts are localized, rather than indicative of regional degradation.
- Natural Grade Control. Bedrock crops out in isolated portions of the bed of Skunk Creek between New River Road and Circle Mountain Road, as well as in one place within the Tramonto development near the Carefree Highway. Inspection of the longitudinal profile indicates that bedrock reaches do not have measurably different slopes than non-bedrock reaches. The similarity of slope in alluvial and bedrock reaches suggests equilibrium, or at least adjustment to slope over geologic time.

Sonoran Wash. The following conclusions about lateral stability and erosion hazards can be drawn from the longitudinal profile of Sonoran Wash, as shown Figure 4-85:

- Profile Shape. The longitudinal profile of Sonoran Wash has a concave up shape, due to the decrease in channel slope in the downstream direction. Channel slope ranges from 0.0068 ft./ft. from the upstream study limit to about river mile 2.2, to 0.0048 ft./ft. from river mile 2.2 to about 0.5 miles upstream of the CAP overchute. Immediately upstream of the CAP overchute, Sonoran Wash has a negative or near-zero slope, probably due to construction of the overchute above the natural grade of the wash. The profile shape indicates that downstream reaches of Sonoran Wash will tend to transport less sediment than upstream reaches, and will consequently be subject to deposition of coarse grained sediments during floods.
- Profile Irregularities. The longitudinal profile of the Sonoran Wash study reach has a moderately irregular shape. A stream which has achieved some level of equilibrium will have a smooth longitudinal profile that indicates water and sediment continuity between cross sections, and gradually varied geometry changes. The irregular profile of Sonoran Wash is most likely due to historical avulsions, transitions from single channel to multiple channel reaches, and deposition of sediment from tributaries.
- Slope Breaks. No significant reaches of over-steepened or over-flattened slope are visible on the longitudinal profile of Sonoran Wash. Instead, many local variations in slope are visible that result in the irregular profile reaches described above. Area of local slope irregularities are likely to experience net change in bed elevations that will remove the irregularity. When these future adjustments occur, they are often accompanied by bank erosion in response to aggradation or degradation.

- Headcuts. No headcuts were observed in the field, nor are any visible on the longitudinal profile.
- Natural Grade Control. Bedrock crops out in isolated portions of the bed of Sonoran Wash. Inspection of the longitudinal profile indicates that bedrock reaches do not have measurably different slopes or profile shapes than non-bedrock reaches. The similarity of slope in alluvial and bedrock reaches suggests equilibrium, or at least adjustment to slope over geologic time.

Figure 4-85. Sonoran Wash Longitudinal Profile



The longitudinal profiles of the Skunk Creek and Sonoran Wash indicate that the streams have probably adjusted to an equilibrium slope, and that future lateral movement will be related to depositional processes in the downstream reaches, avulsions in reaches of irregular slope, and local scour throughout the study area.

Bankfull Discharge

Bankfull discharge is defined as the flow rate which fills the active channel just prior to inundating the floodplain. For alluvial streams, the bankfull discharge is thought to represent the "effective" or "channel-forming" discharge, or the flow rate responsible for moving the greatest time-integrated volume of sediment (Wolman and Miller, 1960). Much of the recently published literature asserts that the recurrence interval of bankfull discharge is less than the 2-year event (c.f., Rosgen, 1996), although the applicability of that standard to streams in the arid west has been questioned (c.f., Williams, 1978; Hedman and Oosterkamp, 1982; JEFuller, Inc., 1996; Fonstadt, 2000). Because many geomorphic analyses are based on the bankfull discharge, an evaluation of the flow rate and frequency of bankfull discharge for Skunk Creek and Sonoran Wash was performed.

The following guidelines were considered when delineating bankfull stage on the HEC-RAS cross section plots:

1. Bank stations – the position of the bank stations defined by the crews responsible for field work.
2. Floodplain elevation – the elevation of the first geomorphic surface flooded after overtopping a channel bank. Since the floodplain elevations are highly variable, an approximate elevation was estimated.
3. Discharge – where the bankfull stage was not obvious, the computed WSEL for Q2, Q10, Q100 was used to discern frequently and rarely flooded surfaces.
4. Geometry – the top of bank is often expressed as a break between a flat overbank and an incised channel.
5. Lowest bank – where multiple or inset banks were present, the first significant bank overtopped was usually used as the top of bank.
6. Cliff vs. bank top – where tall cliffs were on one bank, the elevation of the opposite bank was used as the top of bank.
7. Overflow channels – where overbank channels are lower than the main channel, the top of bank of the main channel was used as the bankfull elevation.
8. Geomorphology – bankfull discharge should fill the main channel and be large enough to flow against both banks.
9. Sediment transport – the bankfull discharge should be large enough to transport the bed material in the main channel.
10. Judgment –engineering judgment was necessary to distinguish the bankfull elevation in cases where the guidelines listed above indicated conflicting results.

Methodology. Bankfull discharges were estimated using a combination of field and hydraulic data. HEC-RAS models were developed for this study from HEC-2 and HEC-RAS models prepared for floodplain delineation studies of Skunk Creek and Sonoran Wash as described in Chapter 5 of this report. Bankfull elevations were delineated on plots of each cross section in the HEC-RAS model after comparison with field photographs, review of field notes, inspection of aerial photographs, comparison with adjacent cross sections, and analysis of the individual cross section geometry. Then, the HEC-RAS models were run using a range of discharges between 100 cfs and the 100-year peak discharge. The discharge which produced a water surface equal to the bankfull elevation was then identified for each individual cross section.[3] The recurrence interval of the bankfull discharge was then estimated from a probability plot of the recommended existing conditions flow rates adopted for this study (Table 2-10).

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[3] In cases in which HEC-RAS indicated that multiple discharges had the same water surface elevation at bankfull, the lowest value was used, assuming that the lowest discharge was the earliest that bankfull stage would be reached. In cases in which the bankfull elevation was higher than the 100-year water surface elevation, the 100-year water surface elevation was used.

Hydraulic variables associated with the bankfull discharge for each cross section were then copied from HEC-RAS output files into separate spreadsheets for each wash. The hydraulic geometry variables obtained in this manner included the following:

- Total discharge
- Channel discharge
- Channel top width
- Maximum channel depth
- Hydraulic radius of the channel
- Mean channel velocity

Results. The bankfull discharge hydraulic values indicate the water and sediment transport capacity of the channel, as well as how that capacity changes over the length of the wash with respect to width, depth, area, velocity, discharge, etc. Reach averages reported below may be used to indicate general trends over the length of the stream.

Hydraulic data for individual cross sections also provide useful information for predicting lateral stability. Plots of the variation in bankfull discharge, bankfull width/depth ratio, bankfull channel topwidth, bankfull depth, and bankfull velocity for Skunk Creek and Sonoran Wash are shown in Figures 4-86 to 4-95. These plots are useful for locating points along the channel where bankfull conditions change rapidly. For example, interpretation of the longitudinal plots of channel velocity and width/depth ratio indicate areas of probable erosion (large increases in velocity, low width/depth ratio) or deposition (sharp decreases in velocity, high width/depth ratio).

Skunk Creek. A plot of estimated bankfull discharge for each HEC-RAS cross section is shown in Figure 4-86. A five-station moving-average trend line is also plotted on Figure 4-86 (black line) to illustrate the broad trends in bankfull characteristics. Table 4-5 shows the reach-averaged hydraulic values associated with bankfull discharge, as well as an estimate of the recurrence interval of the bankfull discharge.

Figure 4-86. Skunk Creek Bankfull Discharge

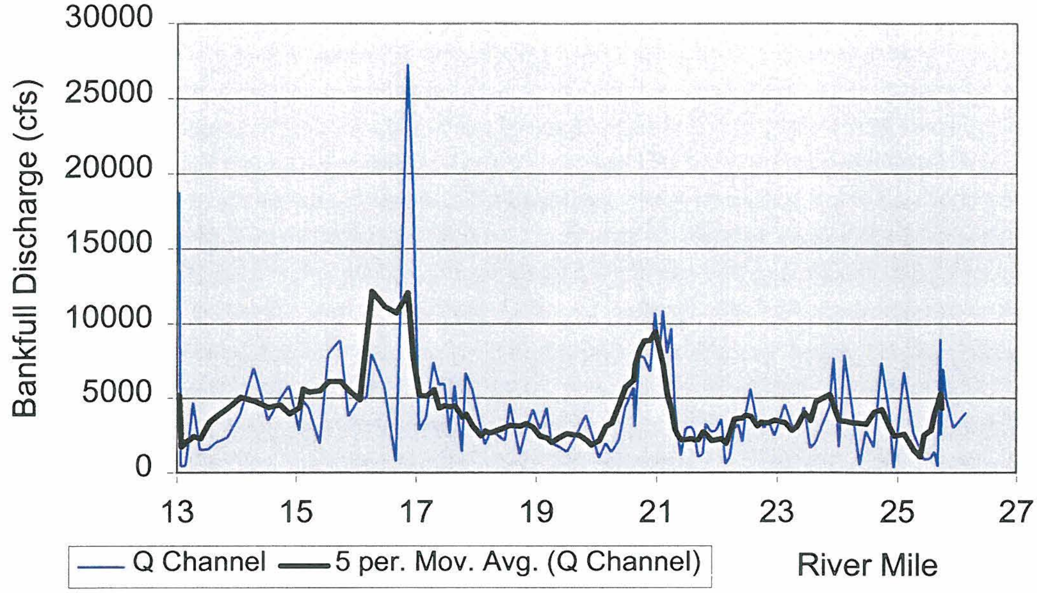


Table 4-5. Skunk Creek/Sonoran Wash Watercourse Master Plan Reach-Average Bankfull Discharge Hydraulic Variables – Skunk Creek							
Reach	Recurrence Interval (yrs)	Channel Discharge (cfs)	Total Discharge (cfs)	Top Width Channel (ft)	Maximum Channel Depth (ft)	Hydraulic Radius Channel (ft)	Mean Channel Velocity (ft/s)
SR	30	4020	4333	96	9.0	4.3	9.6
NR B	60	6167	6167	197	8.2	4.3	7.3
6	10	2850	3506	93	6.7	3.4	7.4
5	10	3104	4085	100	7.6	4.1	7.7
4	10	4414	6543	113	7.1	4.2	8.6
3	10	4640	6874	144	6.2	3.7	8.0
CFR B	100	27298	27300	297	15.2	11.4	7.9
2	10	5224	6178	123	6.5	4.3	9.1
1	10	4319	6669	123	7.3	4.1	7.6
Note: Channel discharge is the flow contained in the main channel when the bankfull elevation is reached. The total discharge indicates the flow contained in the entire cross section including low overbank areas when the bankfull elevation is reached.							

As shown by the five-station trend line in Figure 4-86 and the data in Table 4-5, the magnitude and recurrence interval of the bankfull discharge varies over the length of the study reach, but is generally less than 5,000 with about a 10-year recurrence interval. However, there is little consistency in the bankfull discharge estimates between adjacent cross sections or the five-station trend line, a pattern which may indicate a high potential for future channel changes. In general, bankfull capacity increases in the downstream direction. The values of bankfull discharge are highest near the historically channelized reach near the Carefree Highway (river mile 16.8) and on the Anthem parcel (river mile

21). There is no conclusive explanation for the increase in bankfull discharge on the Anthem parcel, but the stark contrast from adjacent reaches suggests that aggradation and increased inundation of the floodplain should be expected in the future. While the bankfull channel discharge estimate at the New River Road bridge is higher than for the adjacent reaches (Table 4-5), the five-station trend line shown in Figure 4-86 indicates that, unlike the Carefree Highway bridge reach (River Mile 16.9), channel modifications at the New River Road bridge (River Mile 25.7) have not significantly impacted upstream or downstream channel geometry.

Bankfull width/depth ratios depict an interesting trend within the Skunk Creek study reach. The width/depth ratio increases rapidly and consistently from a value of about 15 near the CAP to about 33 at Cloud Road, after which the ratio drops markedly to below 15 and fluctuates cyclically from 12 to 21 for the remainder of the study reach. The cyclical fluctuations in width/depth ratio reflect the chute and splay pattern formed by the alternating single and multiple reaches. Comparison of Figure 4-87 with Figures 4-88 and 4-89 indicates that the significant increase in width/depth ratio downstream of Cloud Road is due to the decrease in channel depth upstream of Carefree Highway, and an increase in width at and downstream of Carefree Highway. The depth increase upstream of Carefree Highway is probably due to several feet of recent headcutting, possibly caused by channel excavation at the Carefree Highway bridge section. The width increase at Carefree Highway was caused solely by construction of the channel at the bridge section. Elsewhere in the study reach, fluctuations in the width/depth ratio are controlled primarily by changes in channel width, especially at transitions from single- to multiple- channel reaches.

Figure 4-87. Skunk Creek Bankfull Discharge Width/Depth Ratio

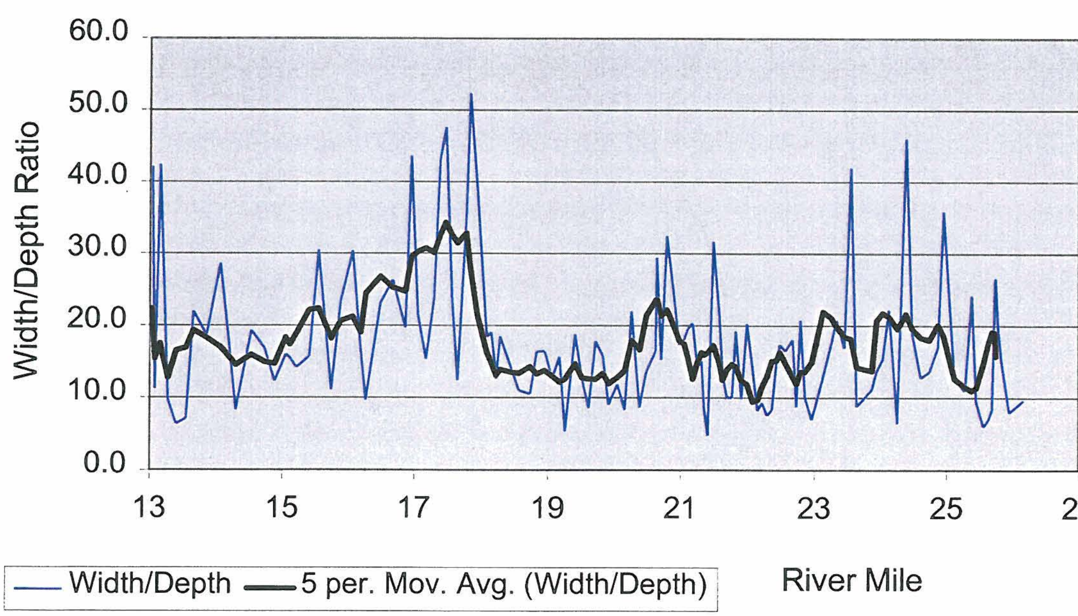


Figure 4-88. Skunk Creek Bankfull Discharge Channel Topwidth

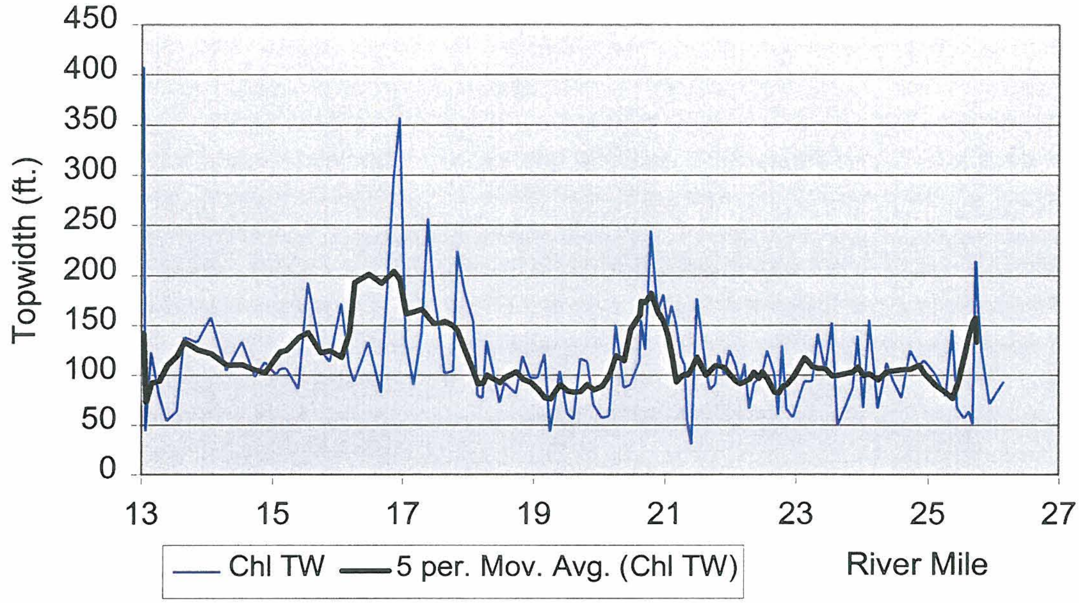
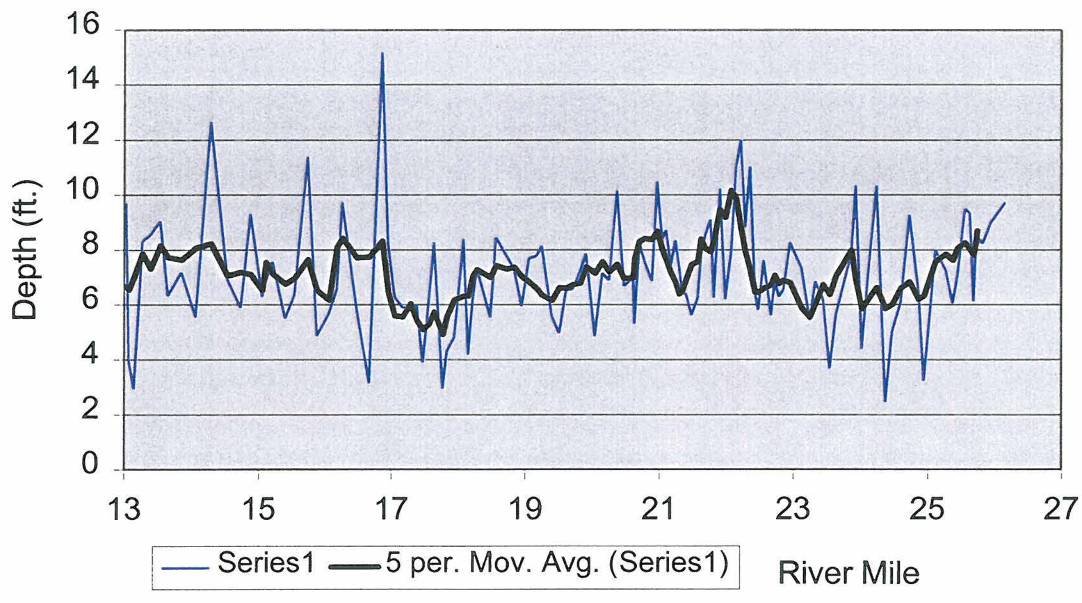
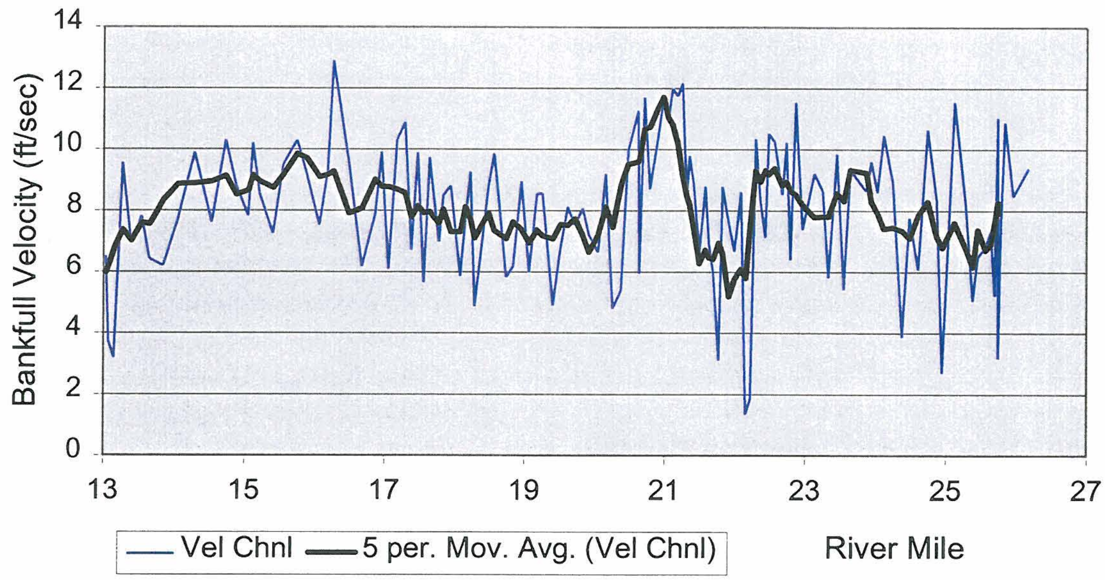


Figure 4-89. Skunk Creek Bankfull Discharge Maximum Depth



Bankfull velocities for Skunk Creek shown in Figure 4-90 indicate that channel velocity varies widely between adjacent cross sections. The five-station trend line reveals two key areas of concern. The first area is located upstream of the CAP (River Mile 13), where low velocities indicate a potential for continued sediment deposition. Aggradation resulting from deposition may lead to increased overbank flooding and formation of avulsive channel changes. The second area is in the reach between river mile 21 and 23, where bankfull velocities vary the most. In general, reaches of below average velocity are likely to experience excess deposition. Similarly, reaches of above average velocity are likely to experience excess scour during bankfull events. However, velocity generally increases with discharge, resulting in an increase where channel capacity is large. Therefore, because channel capacity also varies in this reach (Figure 4-86), a bankfull event for the reach upstream of the second area is unlikely to fill the large channel in the second area, which will tend to fill by deposition. Conversely, a large bankfull discharge in the second area is likely to exceed the capacity of the downstream reach, resulting in scour and bank erosion.

Figure 4-90. Skunk Creek Bankfull Velocity



Sonoran Wash. A plot of estimated bankfull discharge for each HEC-RAS cross section is shown in Figure 4-91. Table 4-6 shows the reach-averaged hydraulic values associated with bankfull discharge, as well as an estimate of the recurrence interval of the bankfull discharge.

Figure 4-91. Sonoran Wash Bankfull Discharge

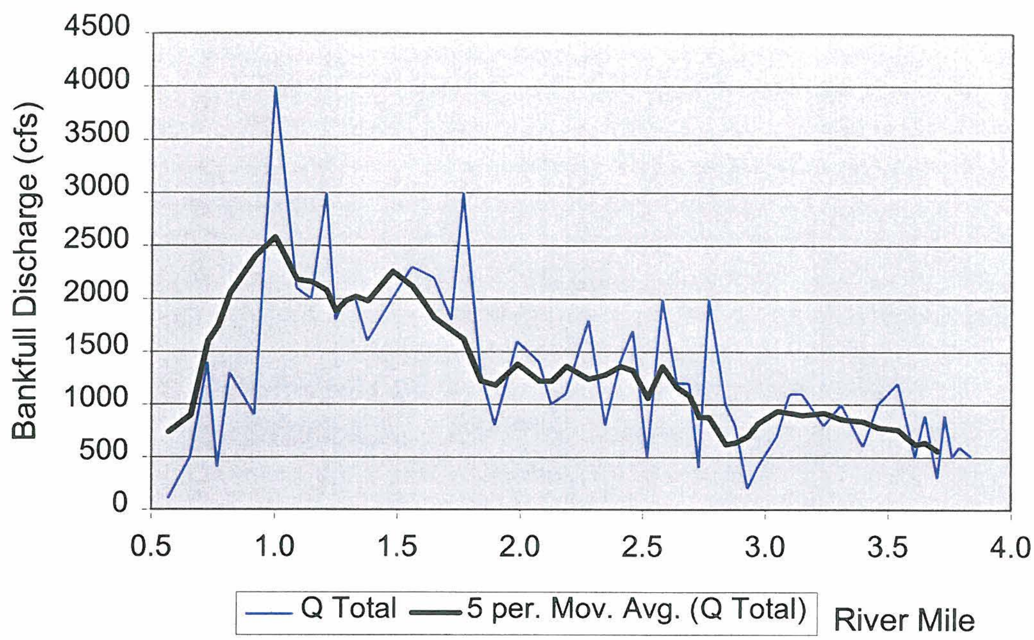
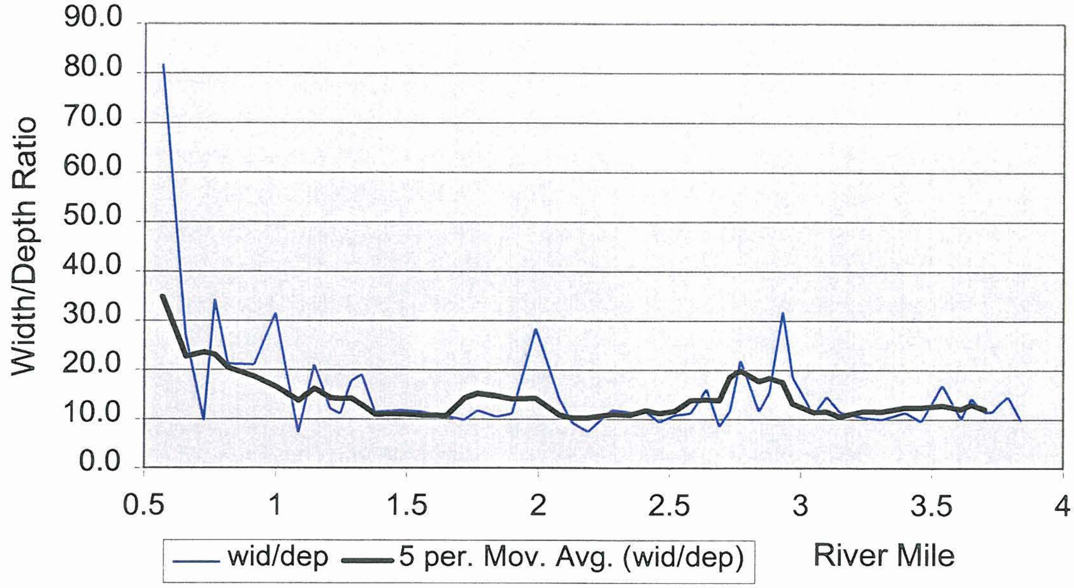


Table 4-6. Skunk Creek/Sonoran Wash Watercourse Master Plan Reach-Average Bankfull Discharge Hydraulic Variables – Sonoran Wash							
Reach	**Recurrence Interval (yrs)**	**Channel Discharge (cfs)**	**Total Discharge (cfs)**	**Top Width Channel (ft)**	**Maximum Channel Depth (ft)**	**Hydraulic Radius Channel (ft)**	**Mean Channel Velocity (ft/s)**
6	4	456	600	43	3.6	2.1	4.5
5	6	769	810	54	4.1	2.7	5.1
4	6	1028	1182	55	4.5	2.8	6.0
3	6	1325	1533	65	5.4	3.3	5.9
2	8	1958	2113	79	6.2	3.8	6.5
1	4	1055	1411	90	4.2	2.3	4.5
Note: Channel *discharge* is the flow contained in the main channel when the *bankfull elevation* is reached. The total *discharge* indicates the flow contained in the entire cross section including low overbank areas when the *bankfull elevation* is reached.							

As shown by the five-station trend line in Figure 4-91, although the magnitude of the bankfull discharge increases progressively through the study reach, the recurrence interval of bankfull discharge is fairly consistent over the three-mile-long study reach. These data indicate that the main channel geometry of Sonoran Wash is formed by about a 5- to 10-year event. Unlike the five-station trend values, the bankfull discharge estimate (Figure 4-91) varies significantly between adjacent cross sections, indicating that local adjustments of channel geometry are very likely in the future.

Figure 4-92. Sonoran Wash Bankfull Width/Depth Ratio



Bankfull width/depth ratios are very consistent over the length of the study reach, except near the CAP (Figure 4-92). The increase in bankfull width/depth ratio is probably due to sediment deposition and long-term aggradation in the CAP backwater area. Comparison of the bankfull width/depth ratio shown in Figure 4-92 with the bankfull channel topwidth and maximum flow depth in Figures 4-93 and 4-94, indicates that the increase in the width/depth ratio is due primarily to a decrease in channel depth. This conclusion is consistent with field observations of decreased bank height upstream of the CAP.

Figure 4-93. Sonoran Wash Bankfull Discharge Channel Topwidth

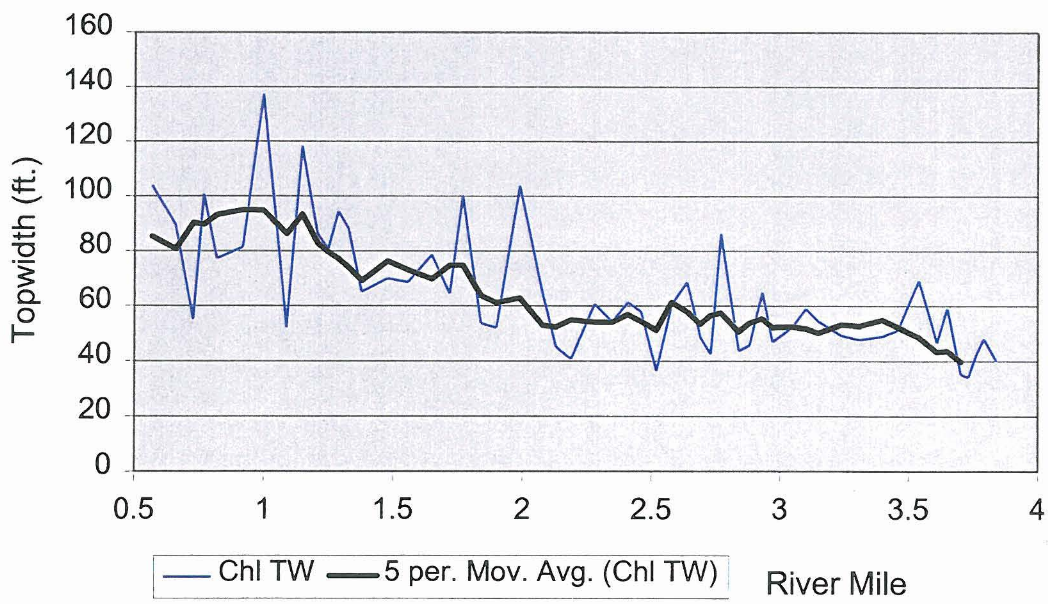
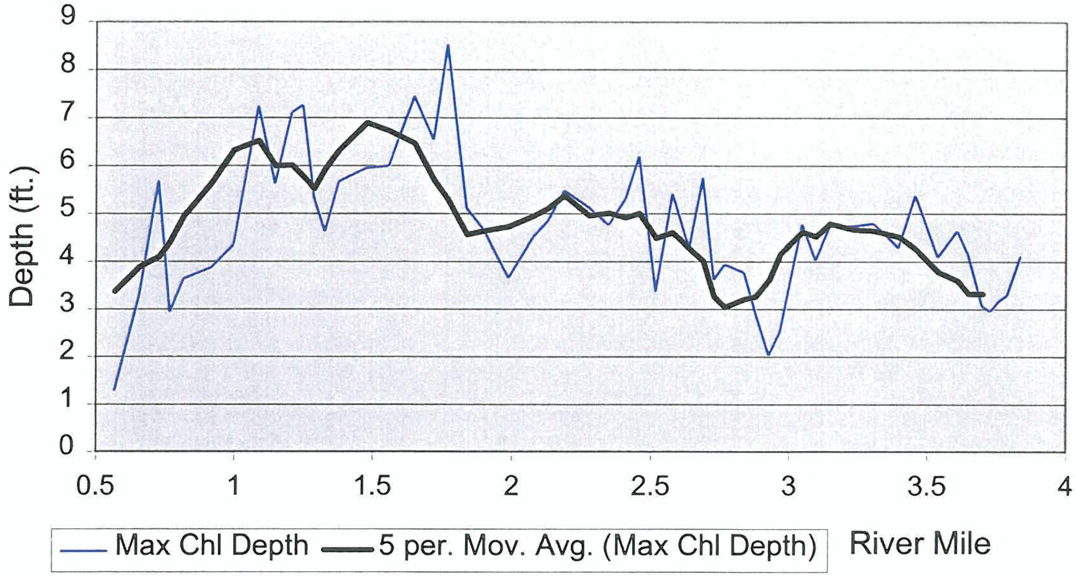
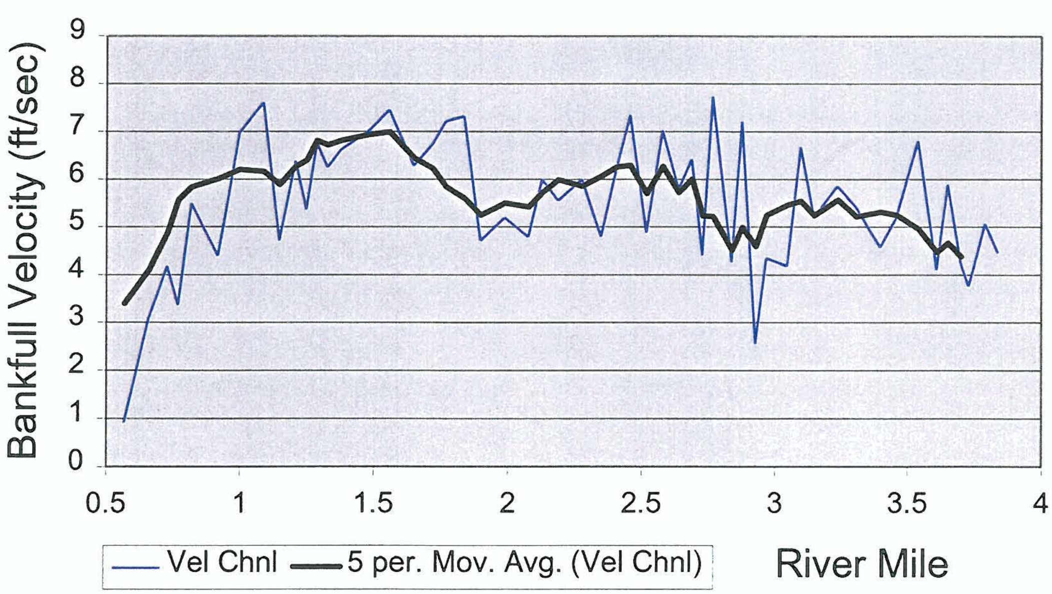


Figure 4-94. Sonoran Wash Bankfull Maximum Channel Depth



The trend in bankfull velocity for Sonoran Wash shown in Figure 4-95 reflects the trend in channel capacity. Velocity generally increases with discharge, resulting in an increased velocity where channel capacity is large. Again, the decrease in velocity upstream of the CAP is indicative of the tendency for deposition and long-term aggradation at the lower end of the study reach.

Figure 4-95. Sonoran Wash Bankfull Velocity



Summary. The following conclusions can be drawn from the bankfull discharge analysis:

- Bankfull recurrence interval. Bankfull discharge has recurrence interval of about 5- to 10 years, except where the channels have been extensively modified by humans.
- Slow channel recovery. The poor continuity in bankfull discharge magnitude and frequency between individual adjacent cross sections in the study area is interpreted to indicate that the streams recover slowly from local erosion. That is, local perturbations such as bank failures that lead to channel widening tend to persist over long periods of time.
- Channel forming discharge. The channel geometry of the streams in the study area is shaped primarily by the large floods. Small floods (recurrence interval less than 5 years) do not fill the channels or flow against the banks, and thus cannot perform significant geomorphic work.
- Stability analysis. Bankfull discharge estimates for the streams in the study area indicate that stream stability is influenced more by the large floods, rather than the small annual floods. Therefore, the stability analyses should focus on the effects of the largest floods.
- Skunk Creek. An unusual peak in bankfull discharge at the Anthem parcel (River Mile 21, Figure 4-86) indicates a high probability for future changes in channel geometry in this reach. The nature of the future changes is difficult to predict, but may include elimination of one or more multiple channels by consolidation into a single, smaller main channel.

River Classification Methods

Stream classification data were presented in Chapter 2 of this report. The objective of stream classification is to group similar stream types so that their behavior can be predicted. The stability predictions associated with the modified Brice classification scheme shown in Table 2-13 indicated that Skunk Creek and Sonoran Wash are susceptible to rapid lateral migration and bank erosion. Similarly, the Rosgen classification system indicated that the streams in the study area are subject to lateral migration.

Rosgen (undated) has also developed a bank erosion evaluation matrix based on his classification scheme. The bank erosion matrix assigns point values to measurable parameters that describe bank conditions. These parameters include the following: (1) bank height/bankfull height,[1] (2) root depth/bank height, (3) root density, (4) bank angle, in degrees, and (5) surface protection. Point totals are assigned to each parameter value, and then are summed, with an adjustment for bank material composition and stratification, as shown in Table 4-7. The adjusted point total is then assigned to one of six qualitative erosion risk categories ranging from "very low" to "extreme."

Data describing the Rosgen criteria were collected at index cross sections described and documented during the field work. Bank height and bankfull height were measured in the field using a survey rod or tape measure. Bank angle was measured with a compass inclinometer. Surface protection was estimated from field observations of vegetative cover. Root depth relative to bank height was estimated by evaluating the percent of vegetative cover over the bank slope, the type of bank vegetation (deep or shallow rooting), and observed evidence of root depth at cut banks. Where quantitative measurements of some these parameters, such as root density, were not available for the study reaches, visual estimates of these parameters were made. For the purposes of this analysis, root density was estimated as half the observed vegetative cover density on the banks. Point totals were computed for each index section described during the field work. The values reported in Table 4-7 represent the reach average of the index sections within each reach. Values are reported separately for the left and right bank to depict the variability of bank stability within the study area.

The results shown in Table 4-7 depict several trends. First, the range of bank erodibility estimates for Skunk Creek varies from moderate to high. This result is somewhat lower than would be expected given the Rosgen classification for Skunk Creek, but is consistent with qualitative field observations. Second, the range of bank erodibility values for Sonoran Wash varies from low to moderate. This result is consistent with field observations of greater bank stability along Sonoran Wash compared to Skunk Creek. Third, predicted values of bank erodibility at individual cross sections ranged from low to extreme, indicating that bank erosion potential may be severe at some locations in the study area.

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[1] Rosgen's (1996) definition of bankfull discharge differs from the one used in this study. Rosgen's classification scheme is oriented to evaluating low flow channel processes and habitat values on non-incised streams. The Rosgen bankfull discharge definition was used for the values shown in the bank erosion matrix shown in Table 4-7.

Table 4-7. Skunk Creek/Sonoran Wash Watercourse Master Plan
Rosgen Bank Erosion Potential Matrix

Criteria	Very Low		Low		Moderate		High		Very High		Extreme	
	Value	Index	Value	Index	Value	Index	Value	Index	Value	Index	Value	Index
Bank Ht./Bankfull Ht.	1.0-1.1	1.0-1.9	1.0-1.19	2.0-3.9	1.2-1.5	4.0-5.9	1.6-2.1	6.0-7.9	2.1-2.8	8.0-9.0	>2.8	10
Root Depth/Bank Ht.	1.0-0.90	1.0-1.90	0.89-0.50	2.0-3.90	0.49-0.30	4.0-5.90	0.29-0.15	6.0-7.9	0.14-0.05	8.0-9.0	0.05	10
Root Density (%)	80-100	1.0-1.9	55-79	2.0-3.9	30-54	4.0-5.9	15-29	6.0-7.9	5-14	8.0-9.0	<50	10
Bank Angle (^{o})	0-20	1.0-1.9	21-60	2.0-3.9	61-80	4.0-5.9	81-90	6.0-7.9	90-119	8.0-9.0	120+	10
Surface Protection (%)	80-100	1.0-1.9	55-79	2.0-3.9	30-54	4.0-5.9	15-29	6.0-7.9	10-15	8.0-9.0	<10	10
TOTALS		**5.0-9.5**		**10-19.5**		**20-29.5**		**30-39.5**		**40-45**		**46-50**

Adjustments

Bank Materials Bedrock: Bank erosion is always low — Sand: Adjust values up by 10 points

Boulders: Bank erosion potential low — Silt/Clay: No adjustment

Cobble: Decrease by one category unless mixture of gravel/sand is over 50%, then no adjustment

Gravel: Adjust values up by 5-10 points depending on composition of sand

Stratification: 5-10 points upward depending on position of unstable layers in relation to bankfull stage.

	Skunk Creek Reach #							Sonoran Wash Reach #					
Criteria	**SR**	**6**	**5**	**4**	**3**	**2**	**1**	**6**	**5**	**4**	**3**	**2**	**1**
Bank Ht./Bankfull Ht.	10	10	10	10	10	10	9.3	8.9	10	10	10	10	10
Root Depth/Bank Ht.	4.1	1.2	1.4	1.4	1.0	1.8	1.0	1.0	1.0	1.0	1.0	1.0	1.0
Root Density (%)	3.9	3.4	2.9	2.9	3.4	3.0	3.1	2.6	2.1	2.1	2.4	1.0	1.1
Bank Angle (^{o})	3.0	2.4	3.5	2.9	3.3	3.1	2.0	3.5	2.8	2.6	2.7	1.4	1.4
Surface Protection (%)	7.7	6.8	5.7	5.7	6.9	5.9	6.2	5.2	4.2	4.2	4.7	1.9	2.2
TOTALS	28.7	23.8	23.5	22.9	24.6	23.8	21.6	21.2	20.1	19.9	20.8	15.3	15.7
Adjustments Bank Materials	-	-	-	+ 3.3	+ 3.3	+ 2.8	+ 5.0	-	-	-	-	-	+ 10
Stratification	-	-	-	+ 1.2	-	-	-	-	-	-	-	-	-
TOTAL (LEFT BANK)	28.7	23.8	23.5	27.9	27.9	26.6	26.6	21.2	20.1	19.9	20.8	15.3	25.7
EROSION RATING	Mod	Mod	Mod	Mod	Mod	Mod	Mod	Mod	Mod	Low	Mod	Low	Mod
TOTAL (RIGHT BANK)	35.3	27.1	23.9	26.0	24.6	30.3	26.8	19.3	19.4	18.7	19.9	11.3	26.4
EROSION RATING	High	Mod	Mod	Mod	Mod	High	Mod	Low	Low	Low	Low	Low	Mod

Note: Bridge reaches are not included. Rosgen methodology criteria not readily applicable to highly channelized reaches.

Hydraulic Geometry/Regime Equations
Regime equations and hydraulic geometry analyses attempt to relate measurable stream characteristics, such as sediment size, mean annual discharge or bankfull discharge, to equilibrium channel geometry characteristics such as stream width, channel depth, flow velocity or channel slope. Regime theory originated from studies of non-scouring and non-silting stable alluvial canals (e.g., Kennedy, 1895), and has been extended to a wide variety of stream types (e.g., Ackers & Charlton, 1971; Blench, 1951). Regime equations are typically based on discharge, sediment characteristics, and channel geometry. Hydraulic geometry analyses are theoretically similar to regime theory, but are based on empirical data gathered from natural streams or flumes and are typically based solely on discharge. Hydraulic geometry expresses the variation of channel characteristics with increasing discharge at a single section or along the length of a stream. The U.S. Geological Survey (e.g., Leopold & Maddock, 1953) published the most widely used hydraulic geometry data.

Regime equation and hydraulic geometry analyses were applied to the Skunk Creek and Sonoran Wash study reaches to evaluate the following stream characteristics:

- Channel pattern
- Channel geometry
- Hydraulic geometry

Lateral stability was evaluated by comparing predicted stream characteristics from one or more of these methodologies to the observed characteristics. These analyses assume that over the long-term the alluvial rivers will tend to erode their bed and banks, or adjust their slope or channel pattern to better match the expected characteristics. In addition, even though regime equations and hydraulic geometry relationships are empirically derived using data sets from very specific stream types (e.g., sand-bed rivers, canals, etc.), the data typically still have a large amount of scatter. The scatter in the original data limits the accuracy of the results. To increase the accuracy of the results, the equations selected for this study were based on data sets from stream which were the most similar to the study area characteristics. It is noted that ephemeral streams in central Arizona are unique, and therefore the results obtained by applying these equations must be interpreted cautiously. In general, the results are best interpreted as order-of-magnitude estimates of the direction of expected change, rather than precise predictions of the magnitude of future channel adjustments.

Data Sources. Stream characteristics and other data used in the analyses described below were obtained from the following sources described elsewhere in this report:

- Recent topographic mapping – Chapters 2 and 3
- USGS gauge records for Skunk Creek – Chapter 3
- HEC-1 modeling – Chapter 3
- Field measurements – Chapter 4
- HEC-RAS modeling – Chapter 5

Channel Pattern Relationships - ***Methodology***. The slope of a stream has a strong influence on the channel pattern for a given discharge. Numerous researchers have used empirical data, flume studies, and theoretical relationships to establish a threshold slope that separates braided and meandering stream patterns. Four slope-discharge relationships were selected for evaluation of the streams in the study area.

Lane Equations. Lane (1952) published an empirical formulas to define the threshold slope for channel pattern, based on data from alluvial sand bed rivers. His equations leave an intermediate zone between the lines defined by the two slope equations where either pattern occurs. The Lane equations for channel pattern are:

$S_o > 0.010\ Q_m^{-0.25}$ (Braided channels)
$S_o < 0.001\ Q_m^{-0.25}$ (Meandering channels)

Where S_o = channel slope (ft./ft.), and
Q_m = mean annual discharge (cfs)

The mean annual discharge for Skunk Creek was estimated from USGS gauge records from the Skunk Creek near Phoenix station (Table 2-4). Mean annual discharge for Sonoran Wash was estimated from a regression equation relating annual precipitation to mean annual flow (Renard and Stone, 1982).

Ackers & Charlton Equations. The Ackers and Charlton (1971) equations are based on data obtained from flume studies. The results generally agree with the results of the Lane equations (MacBroom, 1981).

$S_o > 0.0015\ Q_m^{0.12}$ (Straight channels)
$S_o < 0.0021\ Q_m^{-0.12}$ (Meandering channels)

Where S_o = channel slope (ft./ft.), and
Q_m = mean annual discharge (cfs)

The data sources were the same as for the Lane equation.

Leopold & Wolman Equations. The Leopold and Wolman equations (1957) were developed using data from rivers with coarse bed material (D50 > ¼ inch).

$S_o > 0.06\ Q_{maf}^{-0.44}$ (Braided channels)
$S_o < 0.06\ Q_{maf}^{-0.44}$ (Meandering channels)

Where S_o = channel slope (ft./ft.), and
Q_{maf} = mean annual flood (cfs)

The equations are based on bankfull discharge, which Leopold and Wolman determined to be equal to the mean annual flood. The mean annual flood has a recurrence interval of about 2.33 years (ADWR, 1985). It is noted that the bankfull discharge for the streams in the study area is significantly greater than the 2.3 year flood (Compare Table 2-11 with Tables 4-5 and 4-6). Therefore, a range of discharges including the mean annual flood were used in the Leopold and Wolman equations. Leopold and Wolman found that straight channels could occur on all slopes, and that the occurrence of straight channels had poor correlation to bankfull discharge.

Henderson Equation. Henderson (1961) used Leopold's and Wolman's data, but added a variable describing the mean bed sediment diameter.

$$S_o > 0.06\, D_{50}^{1.14}\, Q_{maf}^{-0.44} \qquad \text{(Braided channels)}$$

Where S_o = channel slope (ft./ft.), and
Q_{maf} = mean annual flood (cfs), and
D_{50} = mean sediment diameter (ft.)

Sediment diameter data were obtained from sieve analyses and boulder count procedures as described in Chapter 5.

Results. Application of the four channel pattern equations to the study area are shown in Table 4-8. For Skunk Creek, the measured slope for the entire study reach is about twice the threshold slope for a braided channel pattern. Field observations suggest that flow in Skunk Creek is often braided, especially at below bankfull flow rates. At higher flows, many reaches have an intermediate, straight or anastomosing channel pattern. For Sonoran Wash, the measured slope is approximately equal to the threshold for a braided channel pattern. Field observations suggest that flow in Sonoran Wash has braided characteristics at low flow rates, but has more of a straight or intermediate pattern at bankfull or higher discharges. Because Sonoran Wash is close to the threshold for braiding, slight changes in watershed or channel characteristics could lead to major changes in channel pattern.

Table 4-8. Skunk Creek/Sonoran Wash Watercourse Master Plan
Channel Pattern Relationships: Threshold Slope for Braided Channels

Name	**Equation**	**Threshold Slope for Braided Channel (ft/ft)**	
		Skunk Creek	**Sonoran Wash**
Lane	$S_o > 0.01\, Q_m^{-0.25}$	0.0086	0.0126
Ackers & Charlton	$S_o > 0.0015\, Q_m^{0.12}$	0.0016	0.0013
Leopold & Wolman	$S_o > 0.06\, Q_{maf}^{-0.44}$	0.0058	0.0076
Henderson	$S_o > 0.64\, D_{50}^{1.14}\, Q_{maf}^{-0.44}$	0.0011	0.0024
	Average:	0.004	0.006
	Measured Channel Slope	0.009	0.006
	Predicted Pattern	Braided	Braided

Notes: S_o = Slope for braided channel Q_{maf} = Bankfull discharge Qm = Average annual discharge
Where the measured slope exceeds the threshold slope, a braided channel pattern is predicted.

The channel pattern equations were also applied on a reach-by-reach basis for the streams in the study area (Tables 4-9 and 4-10). The 2- and 10-year discharges were substituted for the mean annual discharge and the mean annual flood to examine whether the channel pattern was better adjusted to a less frequent flow event. Tables 4-9 and 4-10 compare the predicted channel pattern (braided, intermediate, meandering, single channel, etc.) with the channel pattern observed in the field and on aerial photographs. The predicted channel pattern was indicated by applying the equations described in the previous paragraphs.

Skunk Creek. As shown in Table 4-9, the channel pattern equations generally predict a straight braided channel pattern for Skunk Creek, with a slight trend toward a less braided pattern with increasing discharge. The coarse bed material in Skunk Creek may inhibit the expression of classic braided channel characteristics. The channel pattern predictions for Skunk Creek are shown graphically in Figures 4-96 to 4-99. Based on the data shown in Table 4-9, slightly less braiding should be expected along Skunk Creek in the future if peak discharges increase, and all other input parameters remain unchanged.

Table 4-9. Skunk Creek/Sonoran Wash Watercourse Master Plan
Predicted Channel Pattern Relationships for Skunk Creek

Name	Predicted Channel Pattern													
	SR		6		5		4		3		2		1	
	Q2	Q10	Q2	Q10	Q2	Q10	Q2	Q10	Q2	Q10	Q2	Q10	Q2	Q10
Lane	B_{67}	B_{67}	B_{56}	I_{75}	B_{59}	I_{41}	B_{55}	I_{62}	IB_{47}	I_{53}	I_{62}	I_{62}	I_{64}	I_{93}
Ackers & Charlton	S_{100}	S_{100}	S_{100}	S_{100}	S_{100}	S_{74}	S_{100}	S_{100}	S_{94}	S_{100}	S_{100}	S_{100}	S_{100}	S_{93}
Leopold & Wolman	B_{67}	B_{100}	B_{94}	B_{69}	B_{96}	B_{59}	B_{93}	B_{100}	B_{62}	B_{97}	B_{92}	B_{100}	B_{79}	B_{64}
Henderson	B_{100}	B_{100}	B_{100}	B_{100}	B_{100}	B_{81}	B_{100}	B_{100}	B_{94}	B_{100}	B_{100}	B_{100}	B_{100}	B_{100}
Observed Pattern	S		S		S						B		B	

Notes: S = Straight Channel I = Intermediate Form B = Braided M = Meandering

1. The subscript number after the pattern code (S, I, B, M) indicates the percent of sections predicted for the given pattern, e.g. B_{87} = 87% braided.
2. Channel patterns are not reported for the bridge reaches due to the historical and expected future disturbance.

Sonoran Wash. As shown in Table 4-10, the channel pattern equations generally predict an intermediate or inconsistent channel pattern for Sonoran Wash, with no clear trend with recurrence interval. This prediction generally conforms to field observations of a relatively narrow single channel that is weakly braided at flow expansions and where overflow channels form. Although field observations suggest that Sonoran Wash becomes more strongly braided in the CAP backwater area (Reach 1), the data in Table 4-10 indicate the long-term equilibrium channel pattern may be meandering for this reach because of the flatter slope. Slight changes in discharge and/or sediment supply could cause significant changes in channel pattern on Sonoran Wash.

Figure 4-96. Expected Channel Pattern Lane Equation

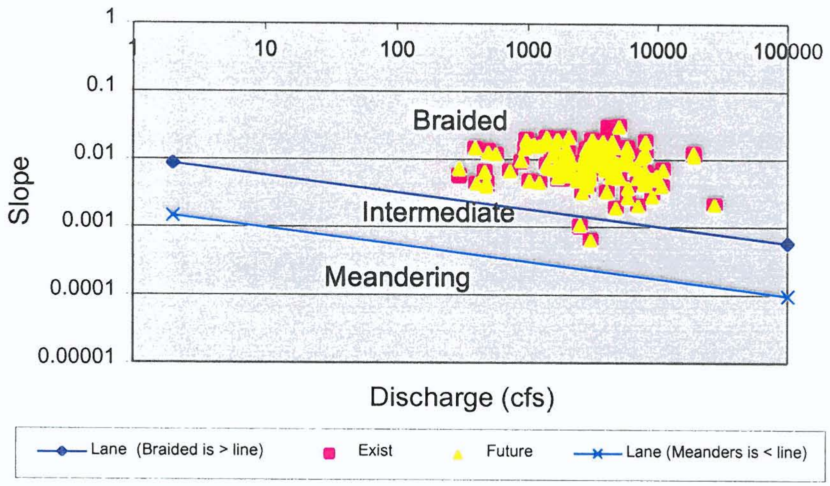


Figure 4-98. Expected Channel Pattern Leopold and Wolman Equation

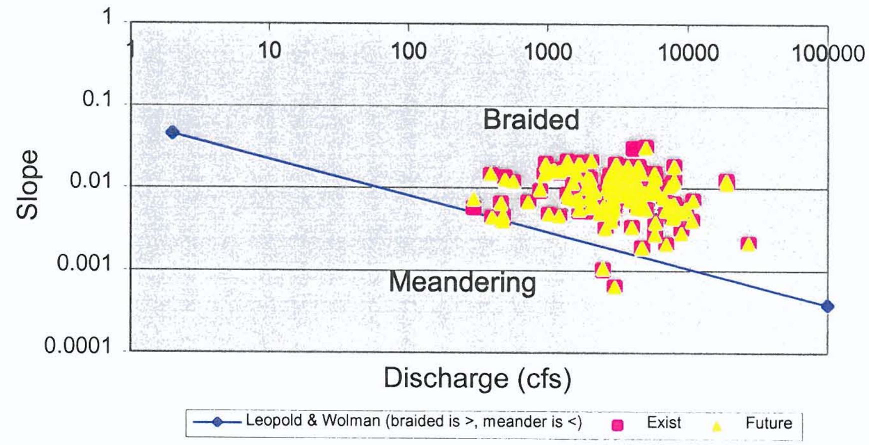


Figure 4-97. Expected Channel Pattern Ackers & Charleton Equation

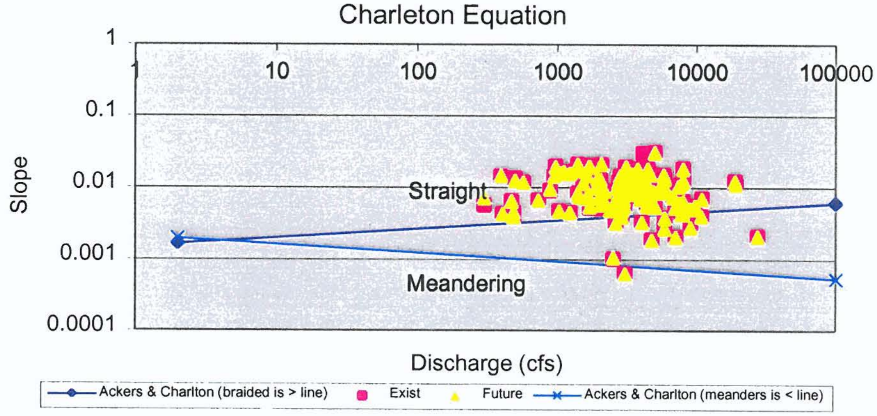


Figure 4-99. Expected Channel Pattern Henderson Equation

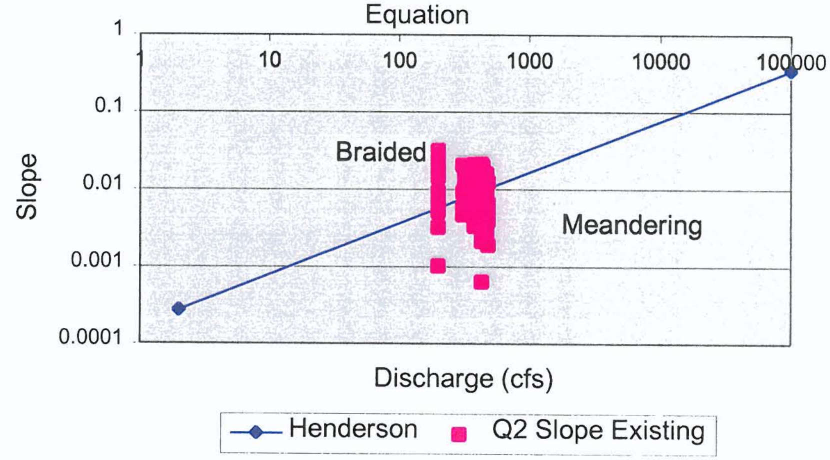


Table 4-10. Skunk Creek/Sonoran Wash Watercourse Master Plan Predicted Channel Pattern Relationships for Sonoran Wash												
Name	**Predicted Channel Pattern**											
	6		**5**		**4**		**3**		**2**		**1**	
	Q2	Q10	Q2	Q10	Q2	Q10	Q2	Q10	Q2	Q10	Q2	Q10
Lane	I_{71}	I_{100}	I_{80}	I_{100}	B/M	I_{90}	I_{78}	I_{100}	I_{89}	I_{100}	I_{56}	M_{56}
Ackers & Charlton	S	S	S	S	S	S	S	S	S	S	S_{89}	S_{78}
Leopold & Wolman	M_{71}	B_{71}	M_{80}	M_{70}	B_{55}	M_{55}	M_{67}	B_{56}	M_{67}	M_{56}	M_{78}	M_{66}
Henderson	B_{71}	B	B_{80}	B	B_{82}	B_{91}	B_{89}	B	B	B	B_{67}	B_{44}
Observed Channel Pattern	S		S		S		S		S		B	

Notes: S = Straight Channel I = Intermediate Form B = Braided M = Meandering
1. The subscript number after the pattern code (S, I, B, M) indicates the percent of sections predicted for the given pattern, e.g. B_{87} = 87% braided.

Channel Geometry Relationships – ***Methodology***. Equations for stable channel geometry have been developed from streams that have been stable for long periods of time. These equations relate bankfull channel width, depth, and velocity to a specific discharge rate, such as the average annual flow or the dominant discharge. Several stable geometry equations were applied to Skunk Creek and Sonoran Wash to assess the expected direction of future channel change.

Bray Equation #1. Bray (1979) developed equations for the geometry of alluvial gravel-bed rivers based the 2-year discharge.

$$W = 2.38\ Q_2^{0.527}$$
$$d = 0.266\ Q_2^{0.33}$$
$$V_m = 8.0\ d^{0.6}\ S_o^{\ 0.29}$$

Where W = surface flow width (ft.)
Q_2 = 2-year discharge (cfs.)
d = flow depth (ft.)
V_m = mean channel velocity (ft./sec.)
S_o = channel slope (ft./ft.)

Bray Equation #2. Bray later modified his channel geometry relationships (Hey et. al., 1982) for gravel-bed rivers to include bankfull discharge and the bed material size.

$$W = 2.08\ Q_{bf}^{0.528}\ D_{50}^{-0.07}$$
$$d = 0.256\ Q_{bf}^{0.331}\ D_{50}^{-0.025}$$
$$V_m = 1.87\ Q_{bf}^{0.14}\ D_{50}^{0.095}$$
$$S_o = 0.0965\ Q_{bf}^{-0.334}\ D_{50}^{0.586}$$

Where W = surface flow width (ft.)
Q_{bf} = Bankfull discharge (cfs.)
D_{50} = medium bed sediment diameter (ft.)
d = flow depth (ft.)
V_m = mean channel velocity (ft./sec.)
S_o = channel slope (ft./ft.)

Hey Equation. Hey (1982) developed regime equations for gravel bed rivers in England that relate stable channel geometry to bankfull discharge and bedload transport rate.

$$WP = 2.2\ Q_{bf}^{-0.54}\ D_{50}^{\ -0.05}$$
$$R = 0.161\ Q_{bf}^{0.41}\ D_{50}^{\ -0.15}$$
$$d_{max} = 0.252\ Q_{bf}^{0.38}\ D_{50}^{\ -0.16}$$
$$S_o = 0.679\ Q_{bf}^{-0.53}\ Q_s^{-0.13}\ D_{50}^{\ 0.97}$$

Where WP = Wetted perimeter (m)
Q_{bf} = Bankfull discharge (m)
D50 = Median sediment diameter (m.)
R = Hydraulic radius (m)
d_{max} = Maximum channel depth (m)
S_o = Channel slope (m/m)
Q_s = Bedload sediment discharge (%)

Since Skunk Creek and Sonoran Wash have width/depth ratios greater than 10, the wetted perimeter predicted by the Hey equations will be approximately equal to the width, and is reported as such in Tables 4-11 and 4-12.

Parker Equation (Gravel Bed Rivers). Parker (1979) examined gravel bed rivers to obtain his channel geometry equations. He found that, unlike the bed material in sand bed streams, the gravel and cobble bed material in coarse bedded streams is moved only during larger flows. He also noted that the banks of gravel bed streams tended to be more stable and straighter than streams with finer bed materials (MacBroom, 1981). Parker's equations use a dimensionless discharge parameter (Q_*), as described below.

$$W_{bf} = 0.173\ Q_*^{0.5}\ D_{50}$$
$$d = 0.010\ Q_*^{0.415}\ D_{50}$$
$$S_e = 0.223\ Q_*^{-0.410}$$

Where W_{bf} = bankfull width, width at top of bank (ft)
$Q_* = 0.039\ V_m\, d^{-1}\ D_{50} / ((\rho_s\text{-}1)/\rho)\ g\ d)^{1/2})$ (dimensionless)
V_m = mean velocity (ft./sec.)
ρ_s = density of sediment (lbs/ft^2)
ρ = density of water (lbs/ft^2)
g = gravitation coefficient (32.2 ft./sec.^{2})
D_{50} = mean sediment diameter (ft.)
d = average channel depth (ft)
S_e = energy slope (ft./ft.)

Ackers & Charlton Equation.[2] The Ackers and Charlton (1971) equations were based on data from flume studies which used sand bed materials.

$$W = K_{ac}\, Q^{0.42}$$

Where W = surface channel width (ft.)
Q = discharge (cfs)
K_{ac} = a coefficient varying from 3.6 for straight channels to 7.2 for meandering channels

Lacey Equation. The Lacey equation (1929) was developed to describe the geometry of silt-laden canals in India. However, Bray reported (1979) that in gravel rivers in Canada, the Lacey equation was as accurate for predicting velocity as the Manning's equation.

$$V = 0.8Q^{0.167}$$

Where V = mean channel velocity (ft./sec.)
Q = discharge (cfs)

Chang Equation. Chang's (1988) gravel bed equations for channel geometry support his FLUVIAL-12 sediment transport model, which attempts to simulate channel change from sediment continuity data using minimum stream power concepts. Chang provides equations for channel width, depth, and slope.

$$S_o = 0.000442\, D_{50}^{\;1.15} / Q_{bf}^{\;0.42}$$
$$W = [1.905 + 0.249(\ln(0.001065\, D_{50}^{\;1.15} / (S_o\, Q_{bf}^{\;0.42}))^2]\, Q_{bf}^{\;0.47}$$
$$d = [0.2077 + 0.0418(\ln(0.000442\, D_{50} / (S_o\, Q_{bf}^{\;0.42})))^{1.15}]\, Q_{bf}^{\;0.42}$$

Where S_o = channel slope (ft./ft.)
D50 = median sediment diameter (mm.)
Q_{bf} = bankfull discharge (cfs)
W = channel width (ft)
d = average channel depth (ft)

In general, the Chang equation for slope performed poorly when applied to the Skunk Creek/Sonoran Wash study area. Some of the predicted channel geometry values were well outside the range of possibility (e.g., negative flow depths). Therefore, the results of the Chang equation are included in Tables 4-13 to 4-16, but the predicted values were not used to obtain the average predicted values that were compared with existing reach characteristics.

[2] The results of the Ackers & Charlton (width) and the Lacey (velocity) equations are presented on the same line in Tables 4-13 to 4-16 to reduce the length of the tables.

Kellerhalls Equations. Kellerhals (1967) developed equations for the equilibrium channel width and depth in gravel bed rivers. The Kellerhals equations use the dominant discharge, which is also referred to as the channel-forming or effective discharge.

$$W = 1.8\ Q_{dd}^{0.5}$$
$$d = 0.166\ Q_{dd}^{0.4}\ K_n^{-0.12}$$

Where W = channel width (ft)
Q_{dd} = dominant discharge (cfs)
d = average channel depth (ft)
K_n = Nikuradse's sand grain roughness coefficient

Schumm Equation. Schumm (1961) preferred to examine the width/depth ratio of semi-arid streams, rather than either parameter separately. Schumm's equation is based on the percentage of fine-grained material in the channel banks.

$$F = 255\ M^{-1.08}$$

Where F = width/depth ratio
M = percentage of silt/clay in the bed.

The percentage of silt and clay in the bed material and banks was extracted from detailed SCS soils mapping of the study area (Camp, 1986). Application of the Schumm equation to streams with stratified bank materials is difficult. The results of the Schumm equation are consistent with the AMAFCA (1994) results, and are not specifically reported in Tables 4-13 to 4-16. Schumm results are included in Appendix B.

AMAFCA Equations. The AMAFCA (1994) equations for width and equilibrium slope were developed from empirical and theoretical data for application to the arroyo systems of northern New Mexico.

$$W = 0.5\ F^{0.6}\ Fr^{-0.4}\ Q^{0.4}$$
$$S_o = 18.28\ n^2\ F^{0.133}\ Fr^{2.133}\ Q^{-0.133}$$

Where W = width of channel (ft.)
F = width/depth ratio
Fr = main channel Froude number
Q = discharge (cfs.)
S_o = channel slope (ft./ft.)
n = Manning's n value for channel

Moody & Odem Equations. Moody and Odem (1999) recently completed an investigation of bankfull channel geometry relationships on a variety of stream types in Arizona using Rosgen channel classification methods. Channel geometry relationships were defined for a number of regions in Arizona, including a region near the Skunk Creek and Sonoran Wash study area.

$$Q_{bf} = 52.334\ DA^{0.5766}$$
$$A = 11.428\ DA^{0.5291}$$
$$TW = 12.301\ DA^{0.3756}$$
$$d = 0.9455\ DA^{0.1506}$$

Where Q_{bf} = Bankfull discharge (cfs)
DA = Watershed drainage area (mi^2)
A = Section flow area at bankfull discharge (ft.)
TW = Flow width at bankfull discharge (ft.)
d = Average flow depth at bankfull discharge (ft.)

BUREC Equation. The Bureau of Reclamation (Lane and Carlson, 1953) developed relationships that describe stable channel dimensions for canals cut into coarse grained alluvium.

$$d_{max} = (Q_{bf}/2 \tan \phi)^{0.5}$$
$$A = 2\ d_{max}^{2} / \tan \phi$$
$$V_m = 1/n\ (d_{max} \cos \phi / (0.5\ \pi\ (1 - \cos \phi))^{0.667}\ S_e^{0.5}$$
$$TW = d_{max}\ \pi / \tan \phi$$

Where d_{max} = Maximum depth of flow (ft.)
Q_{bf} = Bankfull discharge (cfs)
ϕ = Angle of repose of bank material
V_m = mean flow velocity (ft./sec.)
n = Mannings n value
S_e = Energy slope (ft./ft.)
TW = Top width of flow (ft.)

Results. The results of applying the channel geometry equations to Skunk Creek and Sonoran Wash are shown in Tables 4-11 and 4-12. The 2-, 10-, and 100-year discharges were substituted for the discharge variable used in the original channel geometry equations to examine the trend of potential adjustments in channel geometry at each flow rate. Predicted values of widths, depths, slopes and velocities from the channel geometry equations were compared to the measured values obtained from field data, topographic mapping and HEC-RAS models. The differences were interpreted as follows:

- Width. Where the predicted channel width is greater than the HEC-RAS modeled channel width, the channel is expected to erode its banks to achieve the greater width during future floods. Where the predicted channel width is less than the HEC-RAS modeled channel width, the channel is assumed to have low potential for lateral movement due to channel widening, and high potential for deposition along the banks, at least at the flow rates considered.

- Depth. Where the predicted channel depth is greater than the HEC-RAS modeled channel depth, the channel is expected to erode its bed (degrade) to achieve the equilibrium depth during future floods. Where predicted channel depth is less than the HEC-RAS modeled channel depth, the channel is expected to aggrade (deposit sediment) to reach the equilibrium state.

- Slope. Where the predicted slope is less than the existing slope, the channel is expected to decrease its slope (scour) to achieve a more stable form. In all but one of the reaches (Skunk Creek Supply Reach Q2) and recurrence intervals analyzed in the study area, the predicted slope was flatter than the existing channel slope.

Table 4-11. Skunk Creek/Sonoran Wash Watercourse Master Plan Observed and Expected Channel Characteristics – Skunk Creek												
Equation	**Channel Width (ft)**			**Flow Depth (ft)**			**Channel Slope (ft/ft)**			**Channel Velocity (ft/s)**		
	Q100	**Q10**	**Q2**	**Q100**	**Q10**	**Q2**	**Q100**	**Q10**	**Q2**	**Q100**	**Q10**	**Q2**
Reach Supply Reach (SR)												
Bray – Equation #1	216	192	39	4.6	4.3	1.6	0.0019	0.0020	0.0058	5.2	5.1	3.3
Bray – Equation #2	243	217	44	4.7	4.4	1.6	0.0007	0.0008	0.0021	4.4	4.3	2.8
Hey	116	104	21	8.3	7.5	2.2	0.0004	0.0005	0.0020			
Ackers & Charlton/Lacey	131	119	33							3.3	3.2	1.9
Parker	284	255	56	4.4	4.0	1.1	0.0004	0.0005	0.0016			
Chang	253	245	39	1.3	0.9	0.7	0.0002	0.0002	0.0006			
Kellerhals	130	116	25	5.3	4.8	1.4	0.0030	0.0033	0.0111	7.6	7.4	5.5
AMAFCA/Schumm	67	61	21									
Moody & Odem	27	27	27	1.3	1.3	1.3						
BUREC	72	63	20	13.3	11.6	3.7				8.5	9.1	4.4
Average	154	140	33	5.4	4.9	1.7	0.0011	0.0012	0.0038	5.8	5.8	3.6
HEC-RAS Data	98	92	33	5.6	4.7	1.4		0.0130		9.8	10.1	4.7
Bankfull Discharge Data		96			4.3			0.0130			9.6	
Expected Behavior	Erosion	Erosion	Stable	Fill	Scour	Scour	Scour	Scour	Fill	Erosion	Erosion	Erosion
Reach New River Bridge (NR)												
Bray – Equation #1	207	145	39	4.3	3.5	1.6	0.0023	0.0030	0.0058	5.0	4.6	3.3
Bray – Equation #2	225	157	42	4.4	3.5	1.6	0.0012	0.0015	0.0028	4.5	4.1	3.0
Ackers & Charlton/Lacey	116	78	21	7.2	5.5	2.0	0.0009	0.0013	0.0032			
Hey	124	93	33							3.2	2.8	1.9
Parker	239	170	49	4.1	3.1	1.1	0.0009	0.0012	0.0026			
Chang	168	114	26	3.2	2.8	1.4	0.0004	0.0005	0.0011			
Kellerhals	56	40	25	5.1	3.4	0.9	0.0016	0.0023	0.0120	6.4	5.8	4.0
AMAFCA/Schumm	102	88	45									
Moody & Odem	27	27	27	1.3	1.3	1.3						
BUREC	81	64	25	14.9	11.8	4.6				6.4	5.1	3.0
Average	135	98	33	5.6	4.4	1.8	0.0012	0.0016	0.0046	5.1	4.5	3.0
HEC-RAS Data	144	133	109	5.3	3.9	1.0		0.0062		6.5	4.9	2.5
Bankfull Discharge Data		197			4.3			0.0062			7.3	
Expected Behavior	Stable	Stable	Stable	Scour	Scour	Scour	Scour	Scour	Scour	Erosion	Erosion	Fill

Table 4-11. Skunk Creek/Sonoran Wash Watercourse Master Plan Observed and Expected Channel Characteristics – Skunk Creek												
Equation	**Channel Width (ft)**			**Flow Depth (ft)**			**Channel Slope (ft/ft)**			**Channel Velocity (ft/s)**		
	Q100	**Q10**	**Q2**	**Q100**	**Q10**	**Q2**	**Q100**	**Q10**	**Q2**	**Q100**	**Q10**	**Q2**
Reach 6												
Bray – Equation #1	225	173	44	4.7	3.9	1.7	0.0020	0.0023	0.0054	5.2	4.9	3.4
Bray – Equation #2	244	188	48	4.8	4.0	1.7	0.0010	0.0012	0.0027	4.7	4.4	3.1
Hey	120	94	24	7.8	6.3	2.2	0.0007	0.0009	0.0031			
Ackers & Charlton/Lacey	134	109	37							3.3	3.1	2.0
Parker	257	200	55	4.5	3.6	1.2	0.0008	0.0010	0.0025			
Chang	196	145	32	2.6	2.4	1.2	0.0003	0.0004	0.0011			
Kellerhals	135	105	29	5.8	4.8	1.7	0.0017	0.0021	0.0055	7.0	6.7	5.2
AMAFCA/Schumm	81	76	38									
Moody & Odem	30	30	30	1.4	1.4	1.4						
BUREC	77	65	23	14.1	11.9	4.3				7.9	6.8	4.0
Average	150	119	36	5.7	4.8	1.9	0.0011	0.0013	0.0034	5.6	5.2	3.5
HEC-RAS Data	103	101	56	6.0	4.6	1.3		0.0093		9.3	7.5	3.8
Bankfull Discharge Data		93			3.4			0.0093			7.4	
Expected Behavior	Erosion	Erosion	Stable	Fill	Scour	Scour	Scour	Scour	Scour	Erosion	Erosion	Erosion
Reach 5												
Bray – Equation #1	251	182	52	5.0	4.1	1.9	0.0018	0.0023	0.0048	5.4	4.9	3.6
Bray – Equation #2	283	206	59	5.2	4.2	1.9	0.0007	0.0008	0.0017	4.6	4.2	3.0
Hey	130	95	28	9.3	7.2	2.8	0.0004	0.0006	0.0015			
Ackers & Charlton/Lacey	146	113	42							3.5	3.1	2.1
Parker	330	243	75	5.0	3.8	1.5	0.0004	0.0005	0.0012			
Chang	298	188	49	1.4	2.0	1.0	0.0001	0.0002	0.0005			
Kellerhals	149	110	34	6.5	5.1	2.0	0.0012	0.0016	0.0038	7.0	6.5	5.2
AMAFCA/Schumm	81	79	36									
Moody & Odem	47	48	48	1.6	1.6	1.6						
BUREC	82	73	26	15.2	13.4	4.9				8.5	6.3	4.4
Average	180	134	45	6.1	5.2	2.2	0.0008	0.0010	0.0023	5.8	5.0	3.7
HEC-RAS Data	105	109	56	6.8	5.4	1.5		0.0100		10.4	7.1	4.3
Bankfull Discharge Data		100			4.1			0.0100			7.7	
Expected Behavior	Erosion	Erosion	Stable	Fill	Fill	Scour	Scour	Scour	Scour	Erosion	Erosion	Erosion

Table 4-11. Skunk Creek/Sonoran Wash Watercourse Master Plan Observed and Expected Channel Characteristics – Skunk Creek												
Equation	**Channel Width (ft)**			**Flow Depth (ft)**			**Channel Slope (ft/ft)**			**Channel Velocity (ft/s)**		
	Q100	**Q10**	**Q2**	**Q100**	**Q10**	**Q2**	**Q100**	**Q10**	**Q2**	**Q100**	**Q10**	**Q2**
Reach 4												
Bray – Equation #1	265	223	56	5.2	4.7	2.0	0.0017	0.0019	0.0046	5.5	5.2	3.6
Bray – Equation #2	299	252	63	5.4	4.8	2.0	0.0006	0.0007	0.0017	4.7	4.4	3.1
Hey	136	117	30	9.6	8.4	2.9	0.0004	0.0004	0.0015			
Ackers & Charlton/Lacey	153	134	45							3.5	3.4	2.2
Parker	345	293	79	5.2	4.5	1.5	0.0004	0.0004	0.0012			
Chang	294	243	51	1.7	1.6	1.0	0.0001	0.0002	0.0005			
Kellerhals	157	134	36	6.8	6.0	2.1	0.0012	0.0013	0.0037	7.0	6.8	5.3
AMAFCA/Schumm	88	84	42									
Moody & Odem	49	49	49	1.6	1.6	1.6						
BUREC	86	74	28	15.8	13.7	5.1				8.8	8.3	4.6
Average	187	160	48	6.4	5.7	2.3	0.0007	0.0008	0.0022	5.9	5.6	3.8
HEC-RAS Data	114	111	62	6.9	5.7	1.6		0.0085		10.5	9.5	4.4
Bankfull Discharge Data		113			4.2			0.0085			8.6	
Expected Behavior	Erosion	Erosion	Stable	Fill	Stable	Scour	Scour	Scour	Scour	Erosion	Erosion	Erosion
Reach 3												
Bray – Equation #1	336	253	53	6.0	5.1	1.9	0.0015	0.0017	0.0048	5.9	5.4	3.6
Bray – Equation #2	390	294	62	6.3	5.3	2.0	0.0004	0.0005	0.0014	4.8	4.4	2.9
Hey	169	130	29	12.4	10.0	3.0	0.0002	0.0003	0.0010			
Ackers & Charlton/Lacey	185	148	43							3.8	3.5	2.1
Parker	483	369	84	6.4	5.1	1.5	0.0002	0.0002	0.0008			
Chang	464	339	56	0.5	0.7	0.8	0.0001	0.0001	0.0003			
Kellerhals	192	148	34	7.9	6.3	1.9	0.0011	0.0014	0.0049	7.5	7.1	5.3
AMAFCA/Schumm	131	122	63									
Moody & Odem	53	53	53	1.7	1.7	1.7						
BUREC	98	80	27	18.1	14.8	4.9				10.4	9.3	4.5
Average	250	194	50	7.4	6.1	2.2	0.0006	0.0007	0.0022	6.5	5.9	3.7
HEC-RAS Data	156	151	87	7.1	5.2	1.3		0.0082		11.8	9.7	3.8
Bankfull Discharge Data		144			3.7			0.0082			8.0	
Expected Behavior	Erosion	Erosion	Stable	Scour	Scour	Scour	Scour	Scour	Scour	Erosion	Erosion	Stable

Equation	Channel Width (ft)			Flow Depth (ft)			Channel Slope (ft/ft)			Channel Velocity (ft/s)		
	Q100	Q10	Q2	Q100	Q10	Q2	Q100	Q10	Q2	Q100	Q10	Q2
Reach Carefree Highway Bridge												
Bray – Equation #1	489	331	58	7.7	6.0	2.0	0.0011	0.0014	0.0044	6.5	5.9	3.7
Bray – Equation #2	571	386	68	8.0	6.3	2.1	0.0003	0.0004	0.0012	5.3	4.7	3.0
Hey	243	168	31	16.8	12.4	3.2	0.0001	0.0002	0.0009			
Ackers & Charlton/Lacey	251	184	46							4.3	3.8	2.2
Parker	700	483	93	8.6	6.3	1.6	0.0001	0.0002	0.0007			
Chang	657	463	59	0.9	0.6	1.0	0.0000	0.0001	0.0002			
Kellerhals				10.4	6.1	0.6	0.0010	0.0016	0.0173	8.3	7.2	4.1
AMAFCA/Schumm	239	210	94									
Moody & Odem	53	53	53	1.7	1.7	1.7						
BUREC	143	101	30	26.3	18.5	5.6				11.3	10.5	4.4
Average	372	264	59	10.1	7.2	2.2	0.0005	0.0007	0.0041	7.1	6.4	3.5
HEC-RAS Data	285	267	187	8.6	5.1	0.9		0.0054		10.9	9.1	2.9
Bankfull Discharge Data		297			11.4			0.0054			7.9	
Expected Behavior	Erosion	Stable	Stable	Scour	Scour	Scour	Scour	Scour	Scour	Erosion	Erosion	Fill
Reach 2												
Bray – Equation #1	328	258	56	6.0	5.1	2.0	0.0015	0.0017	0.0046	5.8	5.5	3.7
Bray – Equation #2	381	299	65	6.2	5.3	2.1	0.0004	0.0005	0.0013	4.8	4.5	3.0
Hey	166	134	30	12.1	10.1	3.1	0.0002	0.0003	0.0010			
Ackers & Charlton/Lacey	182	150	45							3.8	3.5	2.2
Parker	468	373	88	6.2	5.2	1.6	0.0002	0.0002	0.0008			
Chang	444	338	56	0.6	0.8	0.9	0.0001	0.0001	0.0003			
Kellerhals	193	153	36	7.9	6.6	2.1	0.0011	0.0014	0.0042	7.5	7.2	5.4
AMAFCA/Schumm	105	99	55									
Moody & Odem	54	54	54	1.7	1.7	1.7						
BUREC	98	82	28	17.9	15.1	5.2				10.2	9.2	4.5
Average	242	194	51	7.3	6.2	2.3	0.0006	0.0007	0.0020	6.4	6.0	3.7
HEC-RAS Data	125	122	77	7.7	5.9	1.5		0.0080		12.1	10.2	4.0
Bankfull Discharge Data		123			4.3			0.0080			9.1	
Expected Behavior	Erosion	Erosion	Stable	Fill	Scour	Scour	Scour	Scour	Scour	Erosion	Erosion	Erosion

Table 4-11. Skunk Creek/Sonoran Wash Watercourse Master Plan — Observed and Expected Channel Characteristics – Skunk Creek

Table 4-11. Skunk Creek/Sonoran Wash Watercourse Master Plan
Observed and Expected Channel Characteristics – Skunk Creek

Equation	Channel Width (ft)			Flow Depth (ft)			Channel Slope (ft/ft)			Channel Velocity (ft/s)		
	Q100	Q10	Q2	Q100	Q10	Q2	Q100	Q10	Q2	Q100	Q10	Q2
Reach 1												
Bray – Equation #1	266	221	50	5.2	4.6	1.8	0.0018	0.0020	0.0055	5.4	5.2	3.5
Bray – Equation #2	312	258	59	5.4	4.8	1.9	0.0005	0.0005	0.0015	4.4	4.2	2.8
Hey	134	114	27	10.4	9.0	2.9	0.0003	0.0003	0.0011			
Ackers & Charlton/Lacey	153	132	41							3.5	3.3	2.1
Parker	396	332	82	5.3	4.6	1.4	0.0002	0.0003	0.0009			
Chang	312	250	49	1.5	1.4	0.9	0.0001	0.0001	0.0003			
Kellerhals	158	132	32	6.9	6.0	1.9	0.0011	0.0013	0.0042	6.9	6.7	5.0
AMAFCA/Schumm	126	119	72									
Moody & Odem	54	54	54	1.7	1.7	1.7						
BUREC	86	75	25	15.9	13.7	4.7				8.8	8.1	4.5
Average	200	169	49	6.5	5.7	2.1	0.0007	0.0007	0.0022	5.8	5.5	3.6
HEC-RAS Data	155	150	94	6.0	4.9	1.4		0.0057		9.4	8.3	3.7
Bankfull Discharge Data		123			4.1			0.0057			7.6	
Expected Behavior	Erosion	Erosion	Stable	Scour	Scour	Scour	Scour	Scour	Scour	Erosion	Erosion	Stable

Notes:

1. Blank fields indicate that equation used does not predict that variable.
2. Codes: Erosion = lateral channel movement Scour = net long-term degradation Fill = net long-term aggradation

Table 4-12. Skunk Creek/Sonoran Wash Watercourse Master Plan Observed and Expected Channel Characteristics – Sonoran Wash												
Equation	**Channel Width (ft)**			**Flow Depth (ft)**			**Channel Slope (ft/ft)**			**Channel Velocity (ft/s)**		
	Q100	**Q10**	**Q2**	**Q100**	**Q10**	**Q2**	**Q100**	**Q10**	**Q2**	**Q100**	**Q10**	**Q2**
Reach 6												
Bray – Equation #1	147	133	28	3.6	3.4	1.2	0.0025	0.0027	0.0075	4.7	4.6	3.0
Bray – Equation #2	158	143	29	3.6	3.4	1.3	0.0014	0.0015	0.0041	4.3	4.2	2.7
Hey	83	76	15	5.5	5.1	1.5	0.0011	0.0012	0.0053			
Ackers & Charlton/Lacey	96	89	25							2.9	2.8	1.7
Parker	165	150	34	3.2	2.9	0.9	0.0012	0.0013	0.0044			
Chang	109	98	19	2.5	2.4	1.1	0.0005	0.0005	0.0019			
Kellerhals	90	82	18	4.3	4.0	1.2	0.0019	0.0020	0.0067	6.3	6.2	4.6
AMAFCA/Schumm	42	41	22									
Moody & Odem	19	19	19	1.1	1.1	1.1						
BUREC	58	54	18	10.7	9.9	3.4				6.3	6.1	2.9
Average	97	88	23	4.3	4.0	1.5	0.0014	0.0016	0.0050	4.9	4.8	3.0
HEC-RAS Data	50	50	31	5.8	5.1	1.2		0.0084		8.8	8.3	3.1
Bankfull Discharge Data		43			2.1			0.0084			4.5	
Expected Behavior	Erosion	Erosion	Stable	Fill	Fill	Scour	Scour	Scour	Scour	Erosion	Erosion	Stable
Reach 5												
Bray – Equation #1	188	169	33	4.2	3.9	1.4	0.0021	0.0022	0.0064	5.0	4.9	3.2
Bray – Equation #2	202	181	35	4.3	4.0	1.4	0.0012	0.0013	0.0035	4.6	4.5	2.9
Hey	103	93	18	6.7	6.1	1.7	0.0009	0.0010	0.0044			
Ackers & Charlton/Lacey	117	108	29							3.2	3.1	1.8
Parker	209	188	40	3.9	3.6	1.0	0.0010	0.0010	0.0037			
Chang	142	125	22	2.9	2.8	1.2	0.0004	0.0004	0.0016			
Kellerhals	114	103	22	5.5	5.0	1.4	0.0015	0.0016	0.0058	6.7	6.6	4.8
AMAFCA/Schumm	55	53	29									
Moody & Odem	23	23	23	1.2	1.2	1.2						
BUREC	70	65	20	12.8	11.9	3.8				7.1	6.7	3.2
Average	122	111	27	5.2	4.8	1.6	0.0012	0.0013	0.0042	5.3	5.1	3.2
HEC-RAS Data	64	63	37	6.7	6.0	1.3		0.0069		9.6	8.9	3.3
Bankfull Discharge Data		54			2.7			0.0069			5.1	
Expected Behavior	Erosion	Erosion	Stable	Fill	Fill	Scour	Scour	Scour	Scour	Erosion	Erosion	Stable

Table 4-12. Skunk Creek/Sonoran Wash Watercourse Master Plan Observed and Expected Channel Characteristics – Sonoran Wash												
Equation	**Channel Width (ft)**			**Flow Depth (ft)**			**Channel Slope (ft/ft)**			**Channel Velocity (ft/s)**		
	Q100	**Q10**	**Q2**	**Q100**	**Q10**	**Q2**	**Q100**	**Q10**	**Q2**	**Q100**	**Q10**	**Q2**
Reach 4												
Bray – Equation #1	185	166	35	4.2	3.9	1.5	0.0021	0.0023	0.0062	5.0	4.9	3.2
Bray – Equation #2	199	177	38	4.2	3.9	1.5	0.0012	0.0013	0.0034	4.6	4.4	2.9
Hey	102	91	19	6.6	6.0	1.8	0.0009	0.0010	0.0043			
Ackers & Charlton/Lacey	116	106	31							3.2	3.1	1.9
Parker	206	185	43	3.8	3.5	1.0	0.0010	0.0011	0.0035			
Chang	142	125	25	2.9	2.7	1.2	0.0004	0.0004	0.0015			
Kellerhals	111	101	22	5.9	5.2	1.3	0.0014	0.0016	0.0062	6.8	6.6	4.7
AMAFCA/Schumm	61	59	30									
Moody & Odem	25	25	25	1.3	1.3	1.3						
BUREC	69	64	21	12.8	11.7	3.8				7.0	6.7	3.6
Average	122	110	29	5.2	4.8	1.7	0.0012	0.0013	0.0042	5.3	5.1	3.3
HEC-RAS Data	73	72	39	6.2	5.4	1.3		0.0074		9.0	8.4	3.5
Bankfull Discharge Data		55			2.8			0.0074			6.0	
Expected Behavior	Erosion	Erosion	Stable	Fill	Fill	Scour	Scour	Scour	Scour	Erosion	Erosion	Stable
Reach 3												
Bray – Equation #1	192	173	39	4.3	4.0	1.5	0.0021	0.0022	0.0058	5.1	4.9	3.3
Bray – Equation #2	206	186	41	4.3	4.0	1.6	0.0012	0.0013	0.0032	4.6	4.5	3.0
Hey	106	96	21	6.8	6.2	1.9	0.0009	0.0009	0.0040			
Ackers & Charlton/Lacey	119	110	33							3.2	3.1	1.9
Parker	213	193	46	3.9	3.6	1.1	0.0010	0.0010	0.0033			
Chang	138	124	25	3.1	3.0	1.3	0.0004	0.0004	0.0014			
Kellerhals	116	105	25	5.3	4.9	1.6	0.0015	0.0016	0.0050	6.7	6.6	4.9
AMAFCA/Schumm	60	59	30									
Moody & Odem	29	29	29	1.3	1.3	1.3						
BUREC	72	67	23	13.3	12.3	4.2				6.8	6.6	3.4
Average	125	114	31	5.3	4.9	1.8	0.0012	0.0013	0.0038	5.3	5.1	3.3
HEC-RAS Data	73	73	39	6.7	5.9	1.6		0.0060		9.0	8.4	3.6
Bankfull Discharge Data		65			3.3			0.0060			5.9	
Expected Behavior	Erosion	Erosion	Stable	Fill	Fill	Scour	Scour	Scour	Scour	Erosion	Erosion	Stable

Table 4-12. Skunk Creek/Sonoran Wash Watercourse Master Plan Observed and Expected Channel Characteristics – Sonoran Wash												
Equation	**Channel Width (ft)**			**Flow Depth (ft)**			**Channel Slope (ft/ft)**			**Channel Velocity (ft/s)**		
	Q100	**Q10**	**Q2**	**Q100**	**Q10**	**Q2**	**Q100**	**Q10**	**Q2**	**Q100**	**Q10**	**Q2**
Reach 2												
Bray – Equation #1	191	171	40	4.2	4.0	1.6	0.0021	0.0022	0.0057	5.1	4.9	3.3
Bray – Equation #2	224	200	46	4.4	4.1	1.7	0.0006	0.0006	0.0015	4.1	4.0	2.7
Hey	105	94	22	8.1	7.5	2.4	0.0003	0.0003	0.0011			
Ackers & Charlton/Lacey	119	109	34							3.2	3.1	2.0
Parker	290	261	66	4.1	3.8	1.2	0.0003	0.0003	0.0009			
Chang	231	200	37	1.1	1.2	0.8	0.0001	0.0001	0.0003			
Kellerhals	116	104	26	5.6	5.1	1.7	0.0011	0.0012	0.0035	6.4	6.3	4.8
AMAFCA/Schumm	70	68	36									
Moody & Odem	30	30	30	1.4	1.4	1.4						
BUREC	69	65	23	12.7	11.9	4.2				7.4	6.9	3.5
Average	144	130	36	5.2	4.9	1.9	0.0007	0.0008	0.0022	5.2	5.0	3.3
HEC-RAS Data	88	88	47	5.5	5.0	1.4		0.0060		8.8	8.0	3.5
Bankfull Discharge Data		79			3.8			0.0060			6.5	
Expected Behavior	Erosion	Erosion	Stable	Fill	Fill	Scour	Scour	Scour	Scour	Erosion	Erosion	Stable
Reach 1												
Bray – Equation #1	198	171	38	4.3	3.9	1.5	0.0021	0.0023	0.0059	5.1	4.9	3.3
Bray – Equation #2	237	205	45	4.5	4.2	1.6	0.0005	0.0005	0.0013	4.0	3.8	2.6
Hey	112	98	21	8.7	7.8	2.4	0.0002	0.0002	0.0009			
Ackers & Charlton/Lacey	121	108	32							3.2	3.1	1.9
Parker	325	284	67	4.3	3.8	1.2	0.0002	0.0002	0.0007			
Chang	209	187	36	1.8	1.5	0.8	0.0001	0.0001	0.0002			
Kellerhals	119	104	25	6.8	6.1	1.9	0.0003	0.0003	0.0009	5.4	5.2	3.9
AMAFCA/Schumm	90	87	54									
Moody & Odem	30	30	30	1.4	1.4	1.4						
BUREC	78	68	23	14.4	12.5	4.2				6.5	6.5	3.6
Average	152	134	37	5.8	5.1	1.9	0.0005	0.0006	0.0017	4.8	4.7	3.1
HEC-RAS Data	105	105	67	6.5	5.2	1.3		0.0032		7.5	7.1	3.0
Bankfull Discharge Data		90			2.3			0.0032			4.5	
Expected Behavior	Erosion	Erosion	Stable	Fill	Fill	Scour	Scour	Scour	Scour	Erosion	Erosion	Stable

Notes:

1. Blank fields indicate that equation used does not predict that variable.
2. Codes: Erosion = lateral channel movement   Scour = net long-term degradation   Fill = net long-term aggradation

- Velocity. Where the predicted velocity is less than the HEC-RAS modeled velocity, floods will be more erosive than predicted by the channel geometry equations. In all but two reaches in the study area (Skunk Creek New River Bridge Reach Q2, Skunk Creek Carefree Highway Bridge Reach Q2), the HEC-RAS modeled velocities exceeded the predicted channel velocities.

In general, the channel geometry analysis indicates that the streams in the study are more erosive than similar streams in other areas. The slopes are steeper, the channel velocities higher, and the depths greater. Reach-specific results for Skunk Creek and Sonoran Wash are summarized below.

Skunk Creek. The following conclusions can be drawn from the channel geometry information for Skunk Creek summarized in Table 4-11:

- Natural channel width. The main channel of Skunk Creek appears to be adjusted to the flow width of about a 2-year event. At flow rates exceeding the 10-year recurrence interval, the channel will tend to widen. That is, small floods will not significantly change the channel width. Most of the geomorphic work will be accomplished during large floods.
- Bridge reach width. The existing channel width in the bridge sections at New River Road and the Carefree Highway are wider than the 100-year expected width. Therefore, most floods will tend to narrow the channel section by depositing sediment, resulting in loss of conveyance through the bridge section.
- Channel depth. The predicted channel depths are generally greater than the flow depths computed by HEC-RAS modeling. Therefore, degradation during most floods should be expected in the future.
- Channel slope. The predicted channel slope is flatter than the existing channel slope in all reaches of Skunk Creek. Therefore, long-term degradation should be expected.
- Channel velocities. The predicted velocities are lower than the velocities computed by HEC-RAS modeling. Therefore, scour and high rates of sediment transport should be expected. In the two bridge sections, the predicted velocities for the 2-year event were higher than the HEC-RAS modeling of the existing channel. Therefore, sediment deposition and long-term aggradation should be expected in the bridge sections.

The predicted channel geometry values were compared to the estimated bankfull geometry values described elsewhere in this chapter (Table 4-5). The approximate recurrence interval of the bankfull discharge channel geometry computed using HEC-RAS modeling was estimated by plotting the average 2-, 10-, and 100-year channel geometry results on probability paper and interpolating between data points (Table 4-13).

Table 4-13. Skunk Creek/Sonoran Wash Watercourse Master Plan Approximate Recurrence Interval of Bankfull Discharge Geometry Estimated from Channel Geometry Equations – Skunk Creek			
Reach	**Width (ft.)**	**Depth (ft.)**	**Velocity (ft.)**
SR	5 yrs	25 yrs	10 yrs
NR	> 100 yrs	> 100 yrs	10 yrs
6	10 yrs	25 yrs	10 yrs
5	10 yrs	5 yrs	25 yrs
4	10 yrs	10 yrs	10 yrs
3	10 yrs	100 yrs	10 yrs
CFR	10 yrs	100 yrs	10 yrs
2	5 yrs	25 yrs	10 yrs
1	5 yrs	100 yrs	10 yrs

Sonoran Wash. The following conclusions can be drawn from the channel geometry information for Sonoran Wash summarized in Table 4-12:

- Natural channel width. The main channel of Sonoran Wash appears to be adjusted to the flow width of about a 2-year event. At flow rates exceeding the 10-year recurrence interval, the channel will tend to widen. That is, small floods will not significantly change the channel width. Most of the geomorphic work will be accomplished during large floods. The existing and predicted width differ by a factor of two to three for the 100-year event, indicating a strong tendency for lateral erosion during extreme floods.
- Channel depth. The predicted channel depths are generally greater than the flow depths computed by HEC-RAS modeling for the 2-year event, but less than the HEC-RAS values for the 10- and 100-year event. Therefore, degradation during most frequent floods should be expected in the future. The predicted 10- and 100-year depth data probably reflect historic incision which deepened the main channel of Sonoran Wash.
- Channel slope. The predicted channel slope is flatter than the existing channel slope in all reaches of Sonoran Wash. Therefore, long-term degradation should be expected.
- Channel velocities. The predicted velocities are lower than the velocities computed by HEC-RAS modeling of the 10- and 100-year events, but about equal to the 2-year HEC-RAS channel velocities. Therefore, scour and high rates of sediment transport should be expected during the largest floods, but minimal erosion during the smallest floods.
- Reach consistency. The trends of predicted channel characteristics are similar throughout the Sonoran Wash study reach, evidence of minimal disturbance by non-natural factors.

The predicted channel geometry values were compared to the estimated bankfull geometry values described elsewhere in this chapter (Table 4-6). The approximate recurrence interval of the bankfull discharge channel geometry computed using HEC-RAS modeling was estimated by plotting the average 2-, 10-, and 100-year channel geometry results on probability paper and interpolating between data points (Table 4-14).

Table 4-14. Skunk Creek/Sonoran Wash Watercourse Master Plan Approximate Recurrence Interval of Bankfull Discharge Geometry Estimated from Channel Geometry Equations –Sonoran Wash			
Reach	**Width (ft.)**	**Depth (ft.)**	**Velocity (ft.)**
6	5 yrs	5 yrs	2 yrs
5	5 yrs	5 yrs	2 yrs
4	5 yrs	5 yrs	2 yrs
3	5 yrs	5 yrs	2 yrs
2	5 yrs	10 yrs	2 yrs
1	5 yrs	10 yrs	2 yrs

Hydraulic Geometry Regression Equations. HEC-RAS and field data for Skunk Creek and Sonoran Wash were used to develop reach-averaged hydraulic geometry regression equations. No published data base of hydraulic geometry regression equations currently exists for the unique types of streams found in central Arizona. Therefore, the data presented in this section were compared to other data sets from the arid west as well as to data collected for the Upper Cave Creek/Apache Wash Watercourse Master Plan geomorphic analysis. Following additional data collection and completion of geomorphic analyses for other watercourse master plans in Maricopa County, enough data may exist to provide important information on the stable (or unstable) geometry of local watercourses.

Methodology. Hydraulic data were obtained from the HEC-RAS models for Skunk Creek and Sonoran Wash. These data were used to develop reach-averaged regression equations using the form and variables of the classic hydraulic geometry equations established in Leopold and Maddock (1953). The following three equations were developed using the Microsoft Excel multiple regression statistical software package:

$$W \propto aQ^b \qquad d \propto cQ^f \qquad V \propto kQ^m$$

Where W = width; channel topwidth (ft.)
Q = discharge; channel discharge (cfs)
d = depth; hydraulic channel depth (ft.)
V = velocity, channel velocity (ft./s.)
a, c, k = coefficients
b, f, m = exponents

The principles of continuity and dimensional analysis dictate that the regression equation coefficients relating change of depth, width, and velocity to change in discharge should equal one when multiplied together (i.e., $a \times c \times k = 1$). Similarly, the regression equation exponents also should have a sum of one ($b + f + m = 1$). These expectations were met in all instances (Table 4-15). Plots of each of the regression relationships, and a summary of the intercept, slopes, correlation coefficients (R^2), and resulting equations are provided in Appendix B.

The hydraulic geometry regression equations were used to evaluate expected channel change in several ways. First, exponents for velocity (m), depth (f), and width (b) in the study area were compared with the averages for ephemeral streams in the semiarid United States, as well as with previously studied stream segments in the Upper Cave Creek/Apache Wash Watercourse Master Plan study area. In addition, the hydraulic geometry regression equations for each of the subreaches of Skunk Creek and Sonoran Wash were compared to identify anomalies that might indicate lateral or vertical instability. Second, the *m/f* ratio, an indication of the rate of sediment transport within the streams, was compared with the average for ephemeral streams in the semiarid United States. Leopold, Wolman, and Miller (1964) used the *m/f* ratio (change in velocity to change in depth with change in discharge) as an indicator of the rate of sediment transport. The greater the *m/f* ratio, the larger the amount of sediment transported with changes in discharge. Average at-a-station relationships for ephemeral streams in semiarid U.S. are m = 0.34 and f = 0.36. The average *m/f* ratio is thus 0.94.

Results. Table 4-15 lists the computed hydraulic geometry equation exponents for each of the defined subreaches of Skunk Creek and Sonoran Wash in the study area. Hydraulic geometry equation exponents from Cave Creek, Apache Wash, Paradise Wash and Desert Hills Wash are provided for comparison.

Table 4-15. Skunk Creek/Sonoran Wash Watercourse Master Plan
Hydraulic Geometry Equations – Skunk Creek &Adjacent Streams

Stream	Width, ft. ($w=aQ^b$)		Depth, ft. ($d=cQ^f$)		Velocity ($w=kQ^m$)			
Reach	A	b	c	F	K	m	a x c x k	b + f + m
Skunk Creek								
Entire	15.0	0.24	0.099	0.46	0.67	0.300	1.00	1.00
SR	9.8	0.25	0.091	0.49	1.12	0.261	1.00	1.00
NR	40.2	0.15	0.078	0.49	0.32	0.360	1.00	1.00
6	13.2	0.25	0.099	0.47	0.76	0.286	1.00	1.00
5	12.6	0.25	0.103	0.46	0.78	0.287	1.00	1.00
4	13.3	0.24	0.103	0.46	0.73	0.297	1.00	1.00
3	21.4	0.22	0.077	0.47	0.60	0.313	1.00	1.00
CFR	11.5	0.36	0.117	0.39	0.75	0.245	1.01	1.00
2	16.8	0.23	0.091	0.47	0.66	0.308	1.00	1.00
1	15.7	0.26	0.129	0.42	0.49	0.319	0.99	1.00
Sonoran Wash								
Entire	12.1	0.23	0.120	0.47	0.69	0.304	1.00	1.00
6	11.4	0.20	0.120	0.49	0.73	0.314	1.00	1.00
5	16.7	0.16	0.104	0.50	0.58	0.337	1.00	1.00
4	11.4	0.23	0.111	0.48	0.79	0.289	1.00	1.00
3	11.1	0.23	0.131	0.47	0.68	0.306	1.00	1.00
2	14.8	0.22	0.112	0.47	0.60	0.318	1.00	1.00
1	14.4	0.24	0.115	0.46	0.60	0.301	1.00	1.00
Cave Creek								
Entire	17.1	0.28	0.095	0.43	0.62	0.289	1.00	1.00
Apache Wash								
Entire	12.6	0.22	0.087	0.49	0.91	0.292	1.00	1.00
Paradise Wash								
Entire	19.5	0.14	0.063	0.54	0.80	0.319	1.00	1.00
Desert Hills Wash								
Entire	13.9	0.12	0.123	0.51	0.58	0.372	1.00	1.00
Leopold, Wolman & Miller (1964) – Average Ephemeral Stream in Semi-Arid United States								
		0.29		0.36		0.34		0.99

Comparison to Arid West Streams. Leopold, Wolman, and Miller (1964) reported the following hydraulic geometry equation exponents for width:discharge (b), depth:discharge (f), and velocity:discharge (m):

$$b=0.29 \qquad f=0.36 \qquad m=0.34$$

According to the hydraulic geometry equations, the depth of Skunk Creek increases faster as discharge increases than the average for ephemeral washes in semi-arid regions. The width of Skunk Creek increases at a slightly slower rate than that of the average ephemeral wash. The velocity increases at a slower rate than in an average ephemeral wash. Similar trends were identified for Sonoran Wash. This pattern suggests that Skunk Creek and Sonoran Wash are more incised and narrower than typical ephemeral washes. Field observations of high banks and historical data from the study area generally support this conclusion.

Comparison to Central Arizona Streams. The hydraulic geometry equations for Skunk Creek, Sonoran Wash, and other streams in central Arizona are shown in Table 4-16 and are depicted graphically in Figures 4-100 to 4-102. Despite differences in watershed size, flood frequency, and level of disturbance, the hydraulic geometry equations for Skunk Creek and Sonoran Wash are nearly identical. The hydraulic geometry equations for Skunk Creek and Sonoran Wash are also very similar to those for Apache Wash, an expected result given the similarities between these streams. However, compared to Cave Creek, the hydraulic geometry equations indicate that the width of Skunk Creek and Sonoran Wash does not increase as fast with discharge, and that the depth increases faster. This result is somewhat surprising, given the greater evidence of historical and prehistorical degradation along Cave Creek.

The difference between hydraulic geometry equations for Sonoran Wash and Desert Hills Wash or Paradise Wash highlights the complexity of predicting stream behavior. These three streams share a common watershed divide, have similar watersheds, and have a common history of human impacts. The most significant observed difference is in the size and composition of the bank and floodplain sediments. Desert Hills Wash is incised in fine grained materials, probably due to its position at the toe of a Middle Pleistocene alluvial fan. The banks and floodplain of Sonoran Wash are composed of gravel, cobbles, and boulders with several areas of shallow bedrock, conditions which are similar to those of Paradise Wash. However, the hydraulic geometry equations indicate that the width of Sonoran Wash increases with discharge at about twice the rate of Desert Hills Wash or Paradise Wash. The equations also indicate that the depth and velocity of Sonoran Wash increase with discharge at a slower rate than Desert Hills Wash or Paradise Wash.

Figure 4-100. Regional Hydraulic Geometry Equations for Width

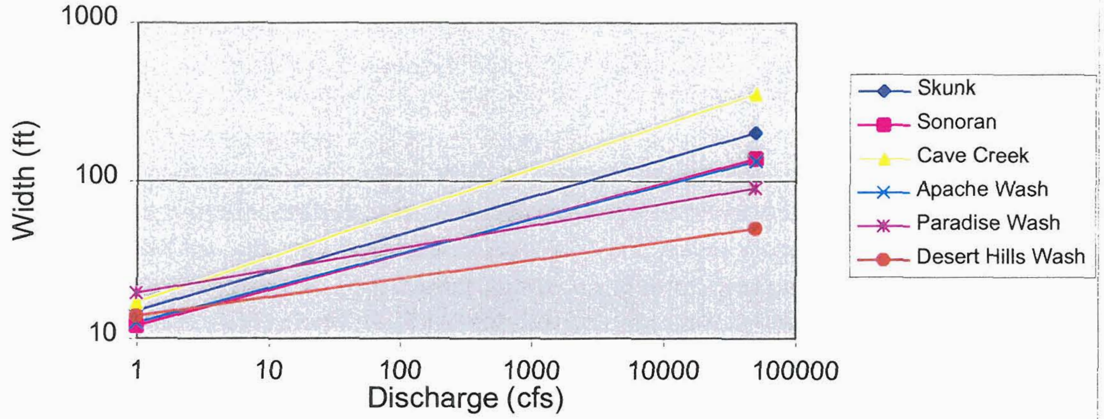


Figure 4-101. Regional Hydraulic Geometry Equations for Depth

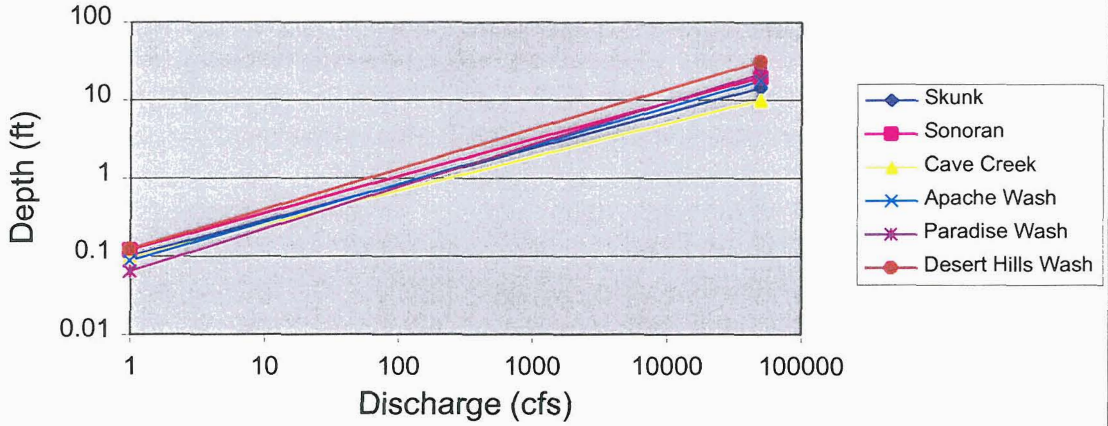
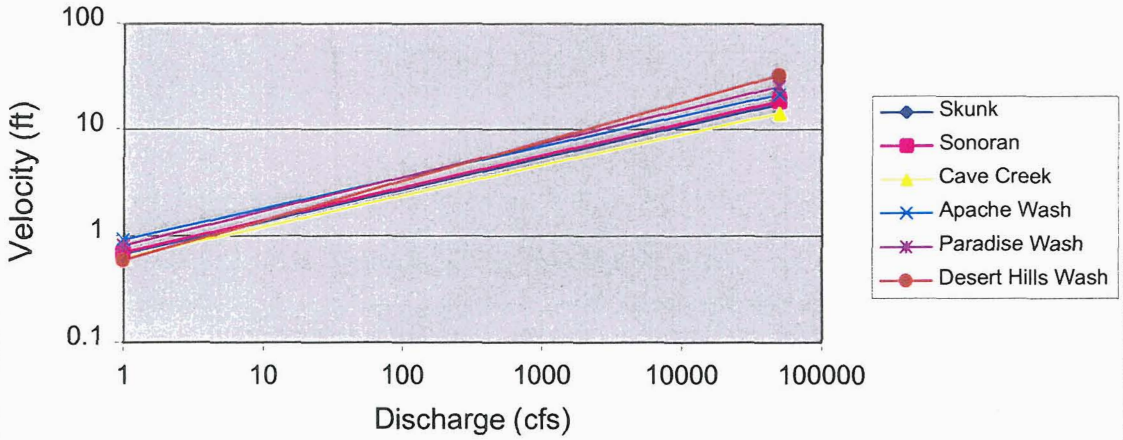


Figure 4-102. Regional Hydraulic Geometry Equations for Velocity



Comparison Between Stream Reaches. Reach by reach comparison of hydraulic geometry equations reveals several trends along the Skunk Creek (Figures 4-103 to 4-

105). The largest departure from the average hydraulic geometry of Skunk Creek occurs in the New River Road Bridge Reach. In the bridge reach, the equations indicate that the width increases with discharge at a much slower rate than in the remainder of the study area. This was interpreted to indicate that the low flow channel has been over-widened by bridge construction, so that increases in discharge do little to increase the width. At the Carefree Highway, the width increases faster with depth than in the rest of the study reach. These opposite trends are best interpreted to indicate that the disturbed bridge reaches are out of equilibrium and will continue to experience stability problems.

Figure 4-103. Skunk Creek Hydraulic Geometry Equations - Width

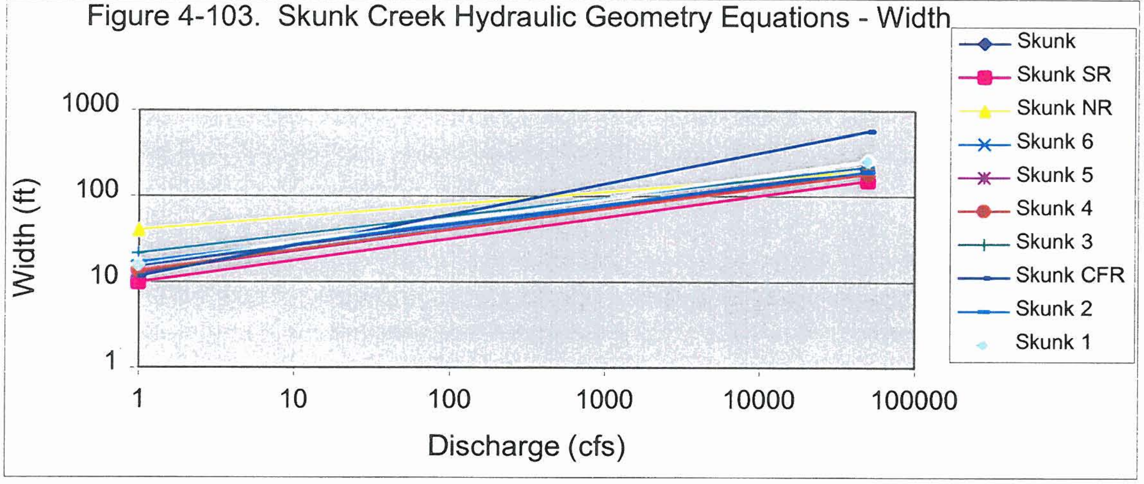
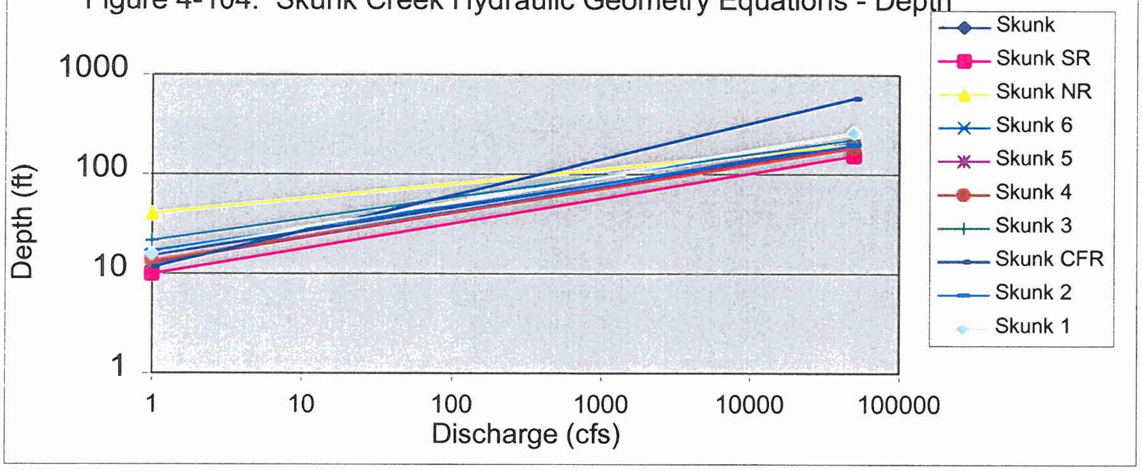
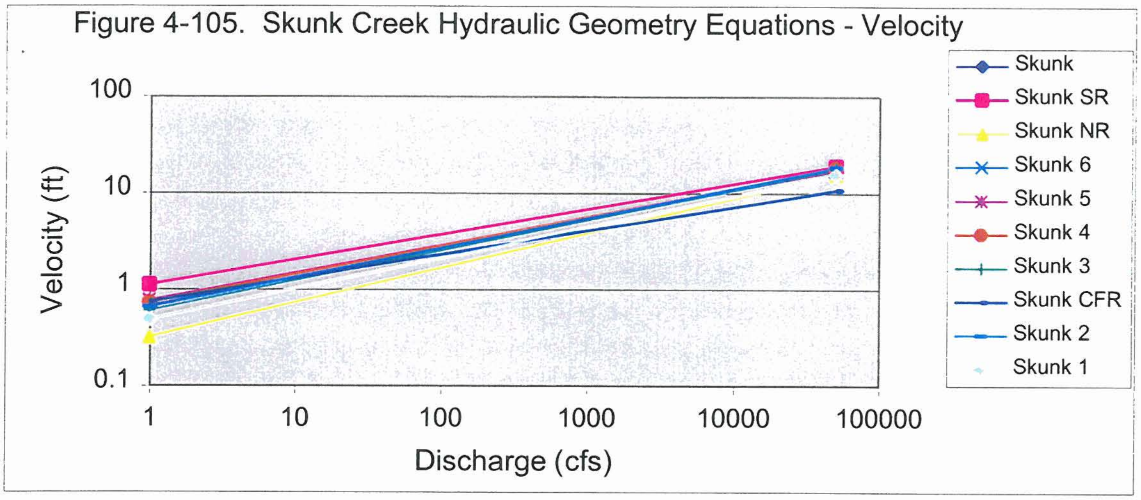


Figure 4-104. Skunk Creek Hydraulic Geometry Equations - Depth





For Sonoran Wash (Figures 4-106 to 4-108), the differences in the hydraulic geometry equations for each reach are more subtle than for Skunk Creek. The exponents are all equivalent within one significant figure. The coefficients have minor differences, perhaps best exemplified by the slight increase in the width coefficient for the reaches nearest the CAP backwater area.

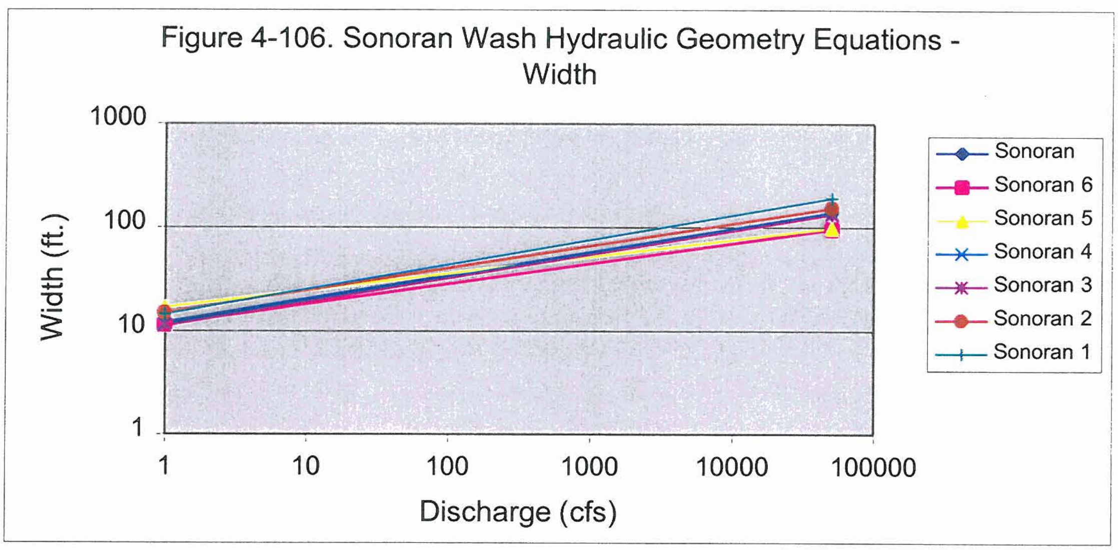


Figure 4-107. Sonoran Wash Hydraulic Geometry Equations - Depth

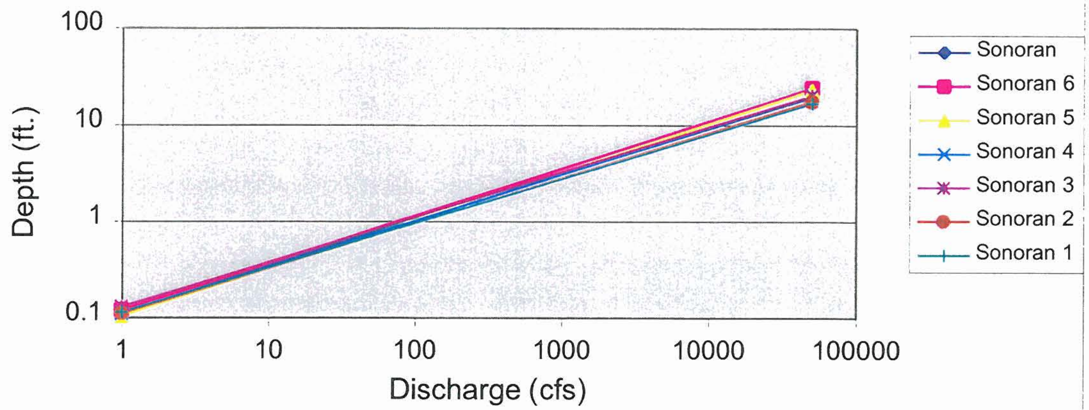


Figure 4-108. Sonoran Wash Hydraulic Geometry Equations - Velocity

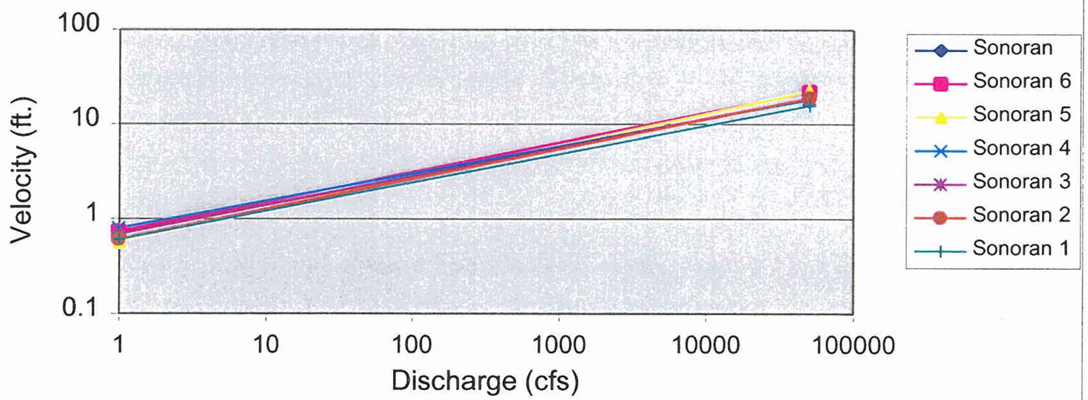


Table 4-16. Skunk Creek/Sonoran Wash Watercourse Master Plan
Comparison of Stream Averages for Skunk Creek/Sonoran Wash Hydraulic Geometry with Semiarid U.S. Averages

Reach	Range	Average	Average Semiarid U.S.	Difference CC Avg – U.S. Avg	Explanation
Skunk Creek					
m (velocity)	0.261-0.319	0.30	0.34	-0.04	as Q increases, velocity increases at a **slower** rate than average
f (depth)	0.424-0.485	0.46	0.36	0.10	as Q increases, depth increases at a **faster** rate than average
B (width)	0.216-0.258	0.24	0.29	-0.05	as Q increases, width increases at a **slower** rate than average
m/f ratio	0.539-0.751	0.65	0.94	-0.29	as Q increases, sediment transport increases at **much slower** rate than average
Sonoran Wash					
m (velocity)	0.289 -0.337	0.30	0.34	-0.04	as Q increases, velocity increases at a **slower** rate than average
f (depth)	0.461-0.499	0.47	0.36	0.11	as Q increases, depth increases at a **faster** rate than average
b (width)	0.164-0.239	0.23	0.29	-0.06	as Q increases, width increases at a **slower** rate than average
m/f ratio	0.601-0.681	0.65	0.94	-0.29	as Q increases, sediment transport increases at **much slower** rate than average
Cave Creek					
m (velocity)	0.259-0.323	0.29	0.34	-0.05	as Q increases, velocity increases at a **slower** rate than average
f (depth)	0.415-0.449	0.43	0.36	0.07	as Q increases, depth increases at a **faster** rate than average
b (width)	0.250-0.327	0.28	0.29	-0.01	as Q increases, width increases at a rate **close to average**
m/f ratio	0.610-0.758	0.67	0.94	-0.27	as Q increases, sediment transport increases at **much slower** rate than average
Paradise Wash					
m (velocity)	0.318-0.322	0.32	0.34	-0.02	as Q increases, velocity increases at a **slightly slower** rate than average
f (depth)	0.540-0.541	0.54	0.36	0.18	as Q increases, depth increases at a **faster** rate than average
b (width)	0.137-0.143	0.14	0.29	-0.15	as Q increases, width increases at a **slower** rate than average
m/f ratio	0.588-0.596	0.59	0.94	-0.35	as Q increases, sediment transport increases at **much slower** rate than average
Desert Hills Wash					
m (velocity)	0.358-0.391	0.38	0.34	0.04	as Q increases, velocity increases at a **faster** rate than average
f (depth)	0.499-0.522	0.51	0.36	0.15	as Q increases, depth increases at a **faster** rate than average
b (width)	0.110-0.121	0.12	0.29	-0.17	as Q increases, width increases at a **slower** rate than average
m/f ratio	0.686-0.783	0.75	0.94	-0.20	as Q increases, sediment transport increases at **much slower** rate than average
Apache Wash					
m (velocity)	0.170-0.350	0.29	0.34	-0.05	as Q increases, velocity increases at a **slower** rate than average
f (depth)	0.419-0.533	0.49	0.36	0.13	as Q increases, depth increases at a **faster** rate than average
b (width)	0.117-0.375	0.22	0.29	-0.07	as Q increases, width increases at a **slower** rate than average
m/f ratio	0.374-0.785	0.59	0.94	-0.35	as Q increases, sediment transport increases at **much slower** rate than average
Note: Data for Skunk Creek does not include m, f, or b values for the disturbed bridge reaches.					

The *m/f* ratio (change in velocity to change in depth with change in discharge) can be used as an indicator of the rate of sediment transport. The greater the *m/f* ratio, the larger the amount of sediment transported with changes in discharge. The average *m/f* ratio for ephemeral streams in semiarid United States is 0.94. Values for the *m/f* ratio for Skunk Creek and Sonoran Wash are listed in Table 4-17.

Table 4-17. Skunk Creek/Sonoran Wash Watercourse Master Plan
Stream Average m/f Ratio Values

Stream	Mean	Minimum	Maximum	Median
Skunk Creek	0.652	0.539	0.751	0.648
Sonoran Wash	0.645	0.601	0.681	0.652

Stream	Reach								
Skunk Creek	SR	NR	6	5	4	3	CFR	2	1
	0.54	0.73	0.61	0.62	0.64	0.66	0.62	0.66	0.75

Stream	Reach					
Sonoran Wash	6	5	4	3	2	1
	0.64	0.68	0.60	0.66	0.68	0.65

The data in Table 4-17 indicate the following trends for Skunk Creek and Sonoran Wash:

- The values for *m/f* ratio sediment transport rate for Skunk Creek and Sonoran Wash are below average for ephemeral streams in the semiarid United States according to Leopold et al (1964). Therefore, as discharge increases, the rate of sediment transport will be lower than average.
- The values for *m/f* ratio are much more variable for Skunk Creek than for Sonoran Wash, probably due to disturbance of the bridge reaches on Skunk Creek. Sediment transport will thus be more variable, and Skunk Creek will tend to have more stability problems.

At the reach scale, all the *m/f* ratios for the study area are below average, as shown in Table 4-17. There are several possible explanations for the below-average *m/f* ratios. Examination of the *m, f,* and *b* values for Skunk Creek and Sonoran Wash reveals that the velocity increases at a slower rate than average (Table 4-16). At the same time, the depths increase at a faster rate than average, while widths are increasing generally at a slower rate. A slower increase in velocity may indicate that larger bed particles are being entrained at a slower rate. A faster increase in depth combined with a slower increase in width points to less interaction of the volume of water with the bed surface, or a slower increase in the wetted perimeter. These two conditions may explain the lower than average increase in the sediment transport rate.

The hydraulic geometry regression equation results provide some insight into the stability of the stream channels in the study area. A faster increase in depth and a slower increase in width indicate a channel configuration that is deeper than average and narrower than average, a conclusion that is supported by the channel geometry equations described above. A slower increase in width as discharge increases might imply that the channel has well-consolidated banks, constraining lateral erosion while concentrating erosive work on the bed of the channel, as was hypothesized by Parker (1979). These factors, along with a faster increase in depth, might indicate that the channels are more incised than the average ephemeral wash.

Summary

The geomorphic analysis techniques summarized in this chapter used field observations, interpretation of the surficial geology, and application of empirical and theoretical data to evaluate the lateral stability of Skunk Creek and Sonoran Wash. Field observations made in the study area indicate that the study reaches are subject to lateral erosion, channel avulsions, scour, and have experienced some historical channel degradation. Evidence of human impacts is minimal. Observations made along Sonoran Wash indicate that it is more laterally stable than Skunk Creek. Field data suggest that the frequency of channel avulsions on Skunk Creek is greater than on Sonoran Wash.

The ages and relative heights of the geomorphic surfaces along Skunk Creek and Sonoran Wash provide information on how recently they have been subject to flood and erosion hazards. Since the late Pleistocene, the study area has been dominated by riverine erosion and floodplain sedimentation processes, rather than by the alluvial fan processes that deposited the alluvium in which the streams are formed. The geologic record also indicates that Skunk Creek and Sonoran Wash have been subject to channel avulsions for at least the past 10,000 years. Both streams have experienced net degradation over the last million years. Except in reaches affected by channel avulsions, geologic evidence indicates that the rate of net channel change has been slow (< 1ft/yr laterally, <0.01 ft/year vertically), although episodes of faster local change undoubtedly occurred. The scale of lateral channel change observed in the recent geologic record was not significantly different than the scale of historical changes documented in Chapter 3. The rates of lateral movement have been fastest on the youngest, less indurated, most frequently inundated surfaces and slowest along the margins of the older, more well indurated, less frequently flooded surfaces. The older terrace margins serve as a practical limit for predicted future rapid channel change, although the older terraces are also subject to (slower) lateral erosion. The low terraces of Holocene age have a high potential for being flooded and are highly susceptible to lateral stream erosion. Information obtained from the soil pits indicates that the active channel has shifted rapidly across the low terrace surfaces within the past several hundred to thousand years. This type of erosion should be expected in the future.

The longitudinal profiles of the Skunk Creek and Sonoran Wash indicate that long-term scour due to responses to existing slope perturbations is not likely. Other analyses described in this chapter indicate that long-term scour due to other factors and processes is likely, as described below. Irregularities in the longitudinal profile indicate that future lateral movement will be related to depositional processes in the downstream reaches, avulsions in reaches of irregular slope, and local scour throughout the study area.

Bankfull discharge has recurrence interval about 5- to 10 years, except where the channels have been extensively modified by humans. The poor continuity in bankfull discharge magnitude and frequency between individual adjacent cross sections in the study area is interpreted to indicate that the streams recover slowly from local erosion. That is, local perturbations such as bank failures that lead to channel widening tend to persist over long periods of time. Furthermore, the bankfull discharge data indicate that the channel geometry of the streams in the study area are shaped primarily by the large floods. Small floods (recurrence interval less than 5 years) do not fill the channels or flow against the banks, and thus cannot perform significant geomorphic work. An unusual peak in bankfull discharge at the Anthem parcel indicates a high probability for future changes in channel geometry.

Bank erodibility estimated using a Rosgen classification scheme indicated that bank erosion potential for Skunk Creek ranges from moderate to high, and from low to moderate for Sonoran Wash. These results are consistent with field observations of greater bank stability along Sonoran Wash compared to Skunk Creek.

Application of channel pattern equations to the study area indicate that for Skunk Creek, the measured slope for the entire study reach is about twice the threshold slope for a braided channel pattern. Field observations suggest that flow in Skunk Creek is often braided, especially at below bankfull flow rates. At higher flows, many reaches have an intermediate, straight or anastomosing channel pattern. For Sonoran Wash, the measured slope is approximately equal to the threshold for a braided channel pattern. Field observations suggest that flow in Sonoran Wash has braided characteristics at low flow rates, but has more of a straight or intermediate pattern at bankfull or higher discharges. Because Sonoran Wash is close to the threshold for braiding, slight changes in watershed or channel characteristics could lead to major changes in channel pattern.

Channel geometry equations indicate the main channel width of Skunk Creek appears to be adjusted to the 2-year event. Therefore, at flow rates exceeding the 10-year recurrence interval, the channel will tend to widen. That is, small floods will not significantly change the channel width. Most of the geomorphic work will be accomplished during large floods. The existing channel width in the bridge sections at New River Road and the Carefree Highway are wider than the 100-year expected width. Therefore, most floods will tend to narrow the channel section by depositing sediment, resulting in loss of conveyance through the bridge section. Predicted channel depths are generally greater than the flow depths computed by HEC-RAS modeling. Therefore, degradation during most floods should be expected in the future. The predicted channel slopes are flatter than the existing channel slope in all reaches of Skunk Creek. Therefore, long-term degradation should be expected. The predicted velocities are lower than the velocities computed by HEC-RAS modeling. Therefore, scour and high rates of sediment transport should be expected. In the two bridge section, the predicted velocities for the 2-year event were higher than the HEC-RAS modeling of the existing channel. Therefore, sediment deposition and long-term aggradation should be expected in the bridge sections.

The channel geometry equations indicate that the main channel width of Sonoran Wash is adjusted to the 2-year event. Therefore, at flow rates exceeding the 10-year recurrence interval, the channel will tend to widen. That is, small floods will not significantly change the channel width. Most of the geomorphic work will be accomplished during large floods. The existing and predicted width differ by a factor of two to three for the 100-year event, indicating a strong tendency for lateral erosion during extreme floods. The predicted channel depths are generally greater than the flow depths computed by HEC-RAS modeling for the 2-year event, but less than the HEC-RAS values for the 10- and 100-year event. Therefore, degradation during most frequent floods should be expected in the future. The predicted 10- and 100-year depth data probably reflect historic incision which deepened the main channel of Sonoran Wash. The predicted channel slope is flatter than the existing channel slope in all reaches of Sonoran Wash. Therefore, long-term degradation should be expected. The predicted velocities are lower than the velocities computed by HEC-RAS modeling of the 10- and 100-year events, but about equal to the 2-year HEC-RAS channel velocities. Therefore, scour and high rates of sediment transport should be expected during the largest floods, but minimal erosion during the smallest floods. The trends of predicted channel characteristics are similar throughout the Sonoran Wash study reach, evidence of minimal disturbance by non-natural factors.

The hydraulic geometry regression equation results also provided insight into the stability of the stream channels in the study area. A faster increase in depth and a slower increase in width indicate a channel configuration that is deeper than average and narrower than average, a conclusion that is supported by the channel geometry equations. A slower increase in width as discharge increases implies that the channel has well-consolidated banks, constraining lateral erosion while concentrating erosive work on the bed of the channel, as was hypothesized by Parker (1979). These factors, along with a faster increase in depth, might indicate that the channels are more incised than those of the average ephemeral wash.

Chapter 5
Lateral Stability Assessment - Engineering Analyses

Introduction

A variety of engineering methodologies for evaluating lateral channel stability have been developed for a wide range of stream conditions. The applicability of these methodologies is a function of the stream conditions present in the study reach, as well as the types and level of detail of the engineering data available.

This chapter consists of the following sections:

- Hydraulic Data
- Sediment Data
- Engineering Methodologies

Hydraulic Data

Hydraulic data used in the engineering and geomorphic analyses were obtained from HEC-RAS modeling. Hydraulic data typically required for lateral stability assessments and sedimentation engineering studies include the following basic parameters:

- Channel width
- Channel depth
- Channel velocity
- Channel discharge
- Channel roughness

However, numerous other variables are also used for some methodologies and equations. A listing of the variables and constants used for the engineering and geomorphic analyses completed for this study is provided in Table 5-1.

Table 5-1. Skunk Creek Watercourse Master Plan
Hydraulic Variable List

Symbol	Variable Name	Units	Source
Δp	Decimal percentage of original bed material larger than Dc	%	Sieve
α	Channel bend angle; Angle formed by the projection of the channel centerline from the point of curvature to a point which meets a line tangent to the outer bank of the channel (degrees)	^{o}	Field
ϕ	*Angle of repose* of bank material	^{o}	Look up
θ	Angle of channel bank	^{o}	Field
τ_b	*Boundary shear stress*	lb/ft^2	Compute
τ_c	Critical tractive force Critical shear stress	lb/ft^2	Compute

Table 5-1. Skunk Creek Watercourse Master Plan Hydraulic Variable List			
Symbol	**Variable Name**	**Units**	**Source**
τ_o	Average tractive force Average shear stress	lb/ft^2	Compute
ω	Terminal fall velocity	ft/sec	Compute
A	Channel section flow areas	$ft.^2$	RAS
B	Channel width	ft.	RAS
d	Mean depth (channel)	ft.	RAS
d_{max}	Maximum channel depth	ft.	RAS
D	Particle diameter	Mm	Sieve
$D_{15.9}$	15.9 % finer diameter particle size	Mm	Sieve
D_{50}	Median diameter particle size	Mm	Sieve
D_{90}	90 % finer particle size	Mm	Sieve
$D_{84.1}$	84.1 % finer diameter particle size	Mm	Sieve
DA	Drainage area	Mi^2	Compute
D_c	Diameter of sediment particle forming armor layer	Mm	Compute
D_m	Mean sediment diameter	Mm	Compute
F	Width-depth ratio	-	Compute
F_r	Maximum Froude number	-	Compute
G	Gradation coefficient	-	Compute
M	Percentage of silt & clay in the channel bed	%	Sieve
N_s	Manning's n value (channel)	-	RAS
Q_*	Dimensionless discharge	-	Compute
Q_2	2-year peak discharge	Cfs	Hydro
Q_{bf}	Discharge over the channel bed; Bankfull discharge	Cfs	RAS
Q_{dd}	Dominant discharge	Cfs	Hydro
Q_m	Mean annual discharge	Cfs	Hydro
Q_{maf}	Mean annual flood	Cfs	Hydro
q_s	Unit sediment discharge	cfs/ft	Compute
Q_T	Total discharge	Cfs	RAS
r_c	Radius of curvature along centerline of channel	ft.	Compute
R	Hydraulic radius	ft.	RAS
R_*	Boundary Reynold's number	-	Compute
S_e	Energy slope	ft./ft.	RAS
S_L	Stable slope (equilibrium slope)	ft./ft.	Compute
S_s	Maximum stable slope	ft./ft.	Compute
T_*	Dimensionless shear stress	-	Compute
TW	Total flow width	ft.	RAS
U_*	Shear velocity	ft./sec	Compute
V_{cr}	Dimensionless critical velocity	-	Compute
V_e	Erodible velocity	ft./sec	Compute
V_m	Mean velocity (channel)	ft/sec	RAS
W	Channel width, or flow top width, whichever is smaller	ft.	RAS
W_{bf}	Bankfull width (width at top of channel banks)	ft.	RAS
Y	Depth from original streambed to bottom of armoring layer	ft.	Compute
Y_a	Thickness of armoring layer	ft.	Compute
Y_d	Depth from original streambed to top of armor layer (degradation)	ft.	Compute
Y_h	Hydraulic depth	ft.	RAS
Z	Side slope ratio (horizontal to vertical)	-	Field
Z_t	Total scour depth, excluding long-term degradation or aggradation	ft.	Compute
Z_{gs}	General scour depth	ft.	Compute
Z_a	Anti-dune trough depth	ft.	Compute

Table 5-1. Skunk Creek Watercourse Master Plan Hydraulic Variable List			
Symbol	**Variable Name**	**Units**	**Source**
Z_{ls}	Local scour depth	ft.	Compute
Z_{bs}	Bend scour depth	ft.	Compute
Z_{lft}	Low-flow thalweg depth	ft.	Compute

Constants

Constant	Value	Equation	Notes
γ_s	165.4 lb/ft^3	Shield Diagram Incipient Bed Movement (BUREC #5)	Specific weight of sediment particles
γ_w	62.4 lb/ft^3	Lane's Tractive Force (BUREC #4, 14)	Specific weight of water
Kn	0.02	Nikuradse's Sand Grain Roughness	See Chang, 1996, p. 43
K_{ac}	3.6	Ackers & Charlton Surface width	3.6 for straight streams 7.2 for meandering streams
K_{mpm}	0.19	MPM Bedload (BUREC #2)	
K_s	0.00174	Schoklitsch Stable Slope (BUREC #13)	
G	32.2	Shields Stable Slope (BUREC #15)	Gravitational Constant
υ	1.217x10^5	Shields Stable Slope (BUREC #15)	Kinematic viscosity H_2O @ 60°F – Chang, p. 414
π	3.1416	BUREC Stable Channel Size (MacBroom, p. 72)	Pi

Notes:
RAS = HEC-RAS output; Field = field estimate; Compute = calculated from other data
Hydro = Hydrologic modeling; Sieve = sieve analysis

HEC-2 Modifications

HEC-2 or HEC-RAS models prepared for Flood Insurance Studies (FIS) can be used to generate hydraulic data required for geomorphic assessments and channel stability studies. The primary objective of an FIS is to estimate the 100-year water surface elevation for a stream reach. Therefore, the other hydraulic data developed by a HEC-RAS model for a detailed FIS generally are not as thoroughly evaluated as the 100-year water surface elevation estimates. For example, the cross section division into channel and overbank sections for an FIS is performed to optimize the water surface elevation estimates, and may not accurately reflect other hydraulic characteristics of the channel and floodplain, particularly at flow rates other than the 100-year peak discharge. Therefore, prior to using an FIS HEC-2 or HEC-RAS model for a geomorphic analysis, the model must be evaluated and modified. The following types of data may require modification:

- Discharge
- Starting Water Surface Elevation
- Selection of N Values
- Number of Cross Section Points
- Section Limits beyond floodplain
- Cross Section Alignment
- Bank Station Definition
- Ineffective Flow Areas

Discharge. For most geomorphic studies, a number of recurrence intervals are evaluated over the entire hydrograph. Therefore, the parameterization of the HEC-RAS model must be applicable for the entire range of discharges, not just the peak of the 100-year flood. Where the model cannot be realistically modified for the full range of flows, the model should be optimized for flows approximating the bankfull discharge.

Starting Water Surface Elevation. To achieve conservative estimates of velocity at the downstream limit of the model, the starting water surface should be based on normal depth. Where significant backwater conditions can sometimes occur at the outfall due to downstream conditions, the potential for backwater-induced sedimentation should be analyzed separately. In addition, use of the normal depth method allows the full range of discharges to have the most appropriate starting elevations.

Selection of N Values. It is important to recognize that geomorphic analyses typically consider existing conditions and long-term future conditions. Over any reasonable planning horizon, channel vegetation changes and the channel itself evolves. Therefore, n values should be selected to reflect the uncertainty of the modeling effort; precision beyond two significant figures is not warranted. If the HEC-2 model is to be used as the input code for HEC-6 or another sediment continuity computer model, options such as NH (horizontal variation of n values by station) or NV (vertical variation of n values) records should not be used. N values should be selected based on bankfull conditions. Sensitivity analyses can be conducted to evaluate the effect of changing n values on key hydraulic variables like channel depth and velocity.

Number of Cross Section Points. If the HEC-2 model is to be converted to a HEC-6 model, the fewest number of points required to simulate the overall reach geometry should be used to make the channel and overbank hydraulics as computationally simple as possible. The number of points should correctly depict the wetted perimeter of the modeling reach. Unfiltered cross sections obtained directly from a digital terrain model (DTM) tend to have too many data points. In addition, the geometry should apply to the reaches between adjacent sections, rather than geometry along a single cross section line. Therefore, local irregularities should be eliminated. Over the time frame of a geomorphic analysis, sediment movement will result in scour and fill. Consequently, the accuracy implied by too many significant figures, decimal places, or cross section points is not realistic. In addition, HEC-2 output will generally be averaged for reaches that include a number of cross sections. Therefore, the unique minor characteristics of a single section are usually less important than the average shape of the reach. The channel geometry should be simplified, approaching (but generally not achieving) the simplicity of an eight point section.

Section Limits Beyond Floodplain. Cross section points that extend beyond the elevation of the largest expected discharge should be eliminated to improve plotting and facilitate comparison with adjacent cross sections.

Cross Section Alignment. Sections aligned perpendicular to the flow of the 100-year flood may be skewed relative to the primary flow direction of more frequent floods that occupy only the main channel. If sections are skewed to the low flow channel, the misalignment will cause the channel dimensions to be too large, resulting in erroneous estimates of channel capacity, topwidth, and area. The flow distribution at a range of discharges should be evaluated, particularly where divided flow occurs. For discharges less than the 100-year event, divided flow may occur. Flow in these divided paths must connect to the main channel both upstream and downstream. If no connection exists, the unused flow areas should be coded out of the model. The most active flow paths can be readily identified in the field or on aerial photographs. Unfortunately, current versions of HEC-RAS models do not allow such discharge-dependent coding of ineffective and divided flow conditions, and therefore could not be performed as part of the hydraulic analysis of this study.

Bank Station Definition. Definition of the left and right bank stations is critical to obtaining accurate hydraulic data for the following reasons:

- Bankfull discharge. Some elements of river stability assessments and many geomorphic principles are based on the concept of bankfull discharge. Therefore, it is necessary to accurately define the channel stations to distinguish channel and overbank characteristics and processes. In general, bank stations were defined to separate portions of the cross section that experience channel processes (bed load movement, scour, high velocities) from overbank processes (deposition, low velocities). A detailed discussion of bank station definition was provided in the *Upper Cave Creek/Apache Wash Watercourse Master Plan Lateral Stability Report* (JEF, 2000).

- Sediment movement. When using hydraulic models, it is necessary to distinguish areas where sediment moves primarily as bed-material load (i.e., channels, subject to both scour and deposition) from areas where sediment moves primarily as wash load or suspended load (i.e., overbanks, primarily subject to deposition). If portions of the overbank areas are included in the channel, the channel velocity and hydraulic depth will be underestimated, resulting in low estimates of sediment transport capacity and/or erosion potential.

Application to the Skunk Creek/Sonoran Wash Study Area

Three HEC-2 models and one HEC-RAS model for the study area were provided by the District and the project team for use in the Skunk Creek Watercourse Master Plan Study. The HEC-2 models were developed for the following floodplain delineation studies:

- Skunk Creek, CAP to New River Road (Montgomery Watson, 1996)
- Skunk Creek, CAP to Cloud Road (Hoskins Engineering Consultants, 1999)
- Skunk Creek, Desert Hills Drive to Honda Bow Road (Erie & Assoc., 1996)
- Sonoran Wash, CAP to 19th Avenue (Stantec, 2001)

The Skunk Creek HEC-2 models were combined and converted to HEC-RAS format by Stantec (2000) for the Skunk Creek Watercourse Master Plan project. The Sonoran Wash model prepared by Stantec for this study was performed using HEC-RAS. The HEC-RAS models were delivered to TTI and distributed to the project team.

The Skunk Creek HEC-2 models were developed for delineation of the 100-year floodplain and floodway. Therefore, the modifications described in the previous section were required prior to using the converted HEC-RAS model for the sedimentation and geomorphic analyses and evaluating the hydraulics of floods other than the 100-year event. The following paragraphs summarize the minor changes made by JEF staff to the converted HEC-RAS model for use in the lateral stability assessment. In addition, irregularities in the original HEC-2 model that could not be modified are noted.

Modifications to HEC-RAS Model. The original HEC-2 models were developed for the specific purpose of delineating the 100-year floodplain and floodway of Skunk Creek. For the geomorphic analysis, the HEC-RAS models will be used to estimate reach-averaged hydraulic characteristics for a wide range of discharges and recurrence intervals. To address the expected use of the model output, the following changes and observations were made with respect to the HEC-RAS models:

1. Model assumptions. It is likely that a number of the key assumptions of the HEC-RAS model are violated by its application to Skunk Creek. Specifically, one-dimensional, gradually-varied, steady flow probably does not occur during the 100-event simulated by the HEC-RAS model. However, despite these possible deficiencies, and given that HEC-RAS step-backwater modeling is the standard of practice for river engineering, the HEC-RAS model was used as the best available source of hydraulic data.

2. Discharge. The 2- and 10-year peak discharges for Skunk Creek estimated using the HEC-1 model do not compare favorably with either the published estimates at the USGS gauge on Skunk Creek (Pope et. al., 1999) or the USGS regional regression equations for central Arizona. Therefore, the 2-year discharge estimates obtained using the USGS regression equations will be used for the geomorphic analyses, as discussed in Chapter 2 of this report. The larger of the existing or future HEC-1 discharge was used for the geomorphic analyses, unless specifically stated otherwise.

3. Discharge continuity. The computed channel discharge (QCH) varies widely between adjacent cross sections (Figures 5-1 and 5-5). Figures 5-2, 5-3, 5-6, and 5-7 indicate that a significant portion, if not the majority of, the 100-year discharge on Skunk Creek and Sonoran Wash is conveyed in the overbanks, rather than in the channel. The computed distribution of flow from the left to right floodplain between adjacent cross sections in the 100-year event (Figure 5-4 and 5-8) is somewhat improbable in some reaches and probably reflects poor cross section alignment (Skunk Creek) as well as a two-dimensional element to flood flows on the floodplain. In general, the HEC-2 modeling results for Skunk Creek would have been improved by realigning cross sections, by using closer consistently-spaced cross sections, and by simplifying the cross section geometry.

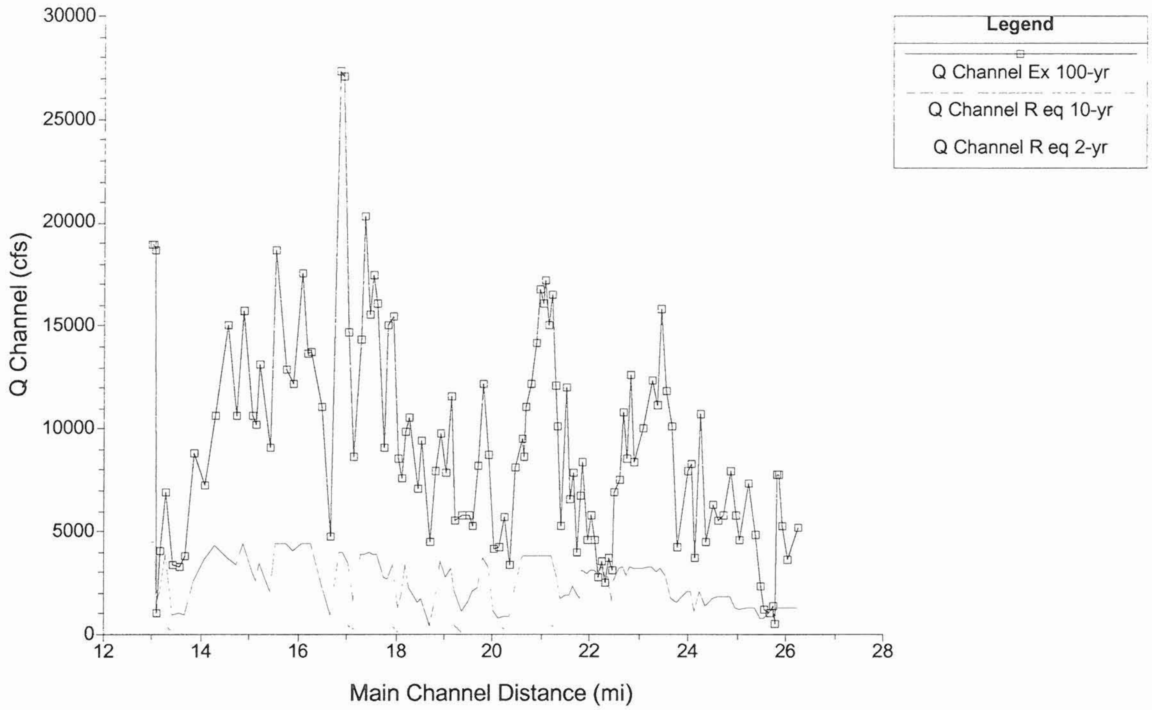


Figure 5-1. Skunk Creek Channel Discharge (QCH) vs. Distance.

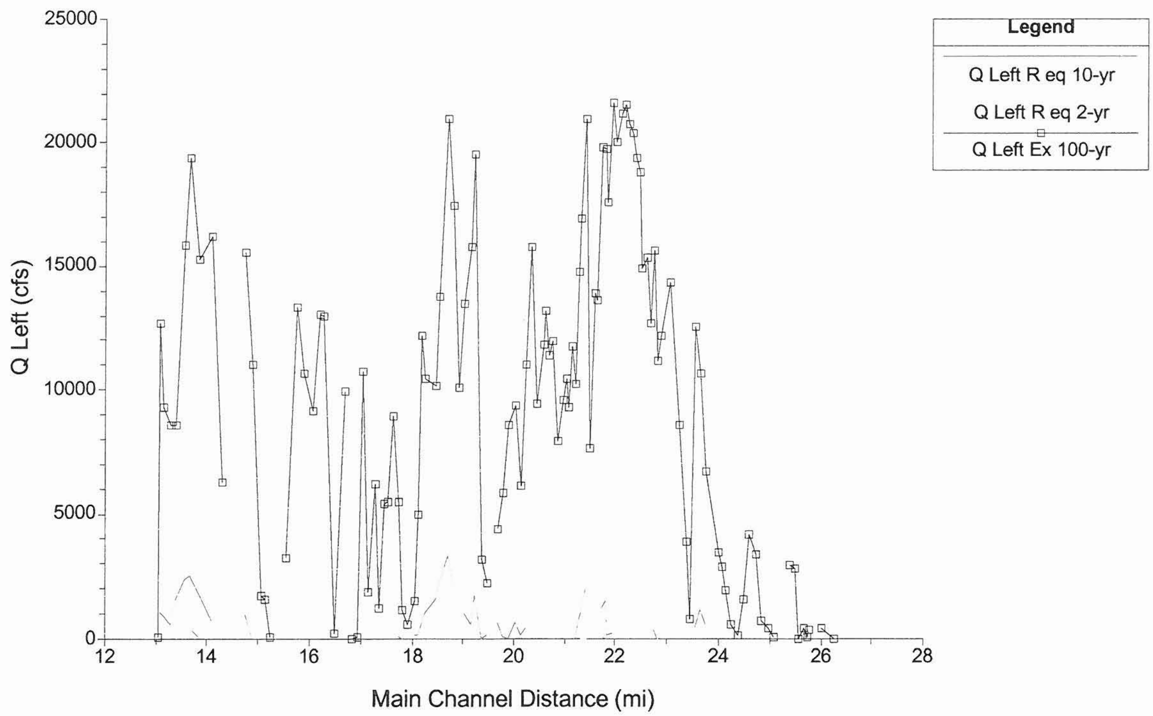


Figure 5-2. Skunk Creek Left Overbank Discharge vs. Distance. Gaps in Line Segments Indicate Cross Sections With No Overbank Discharge.

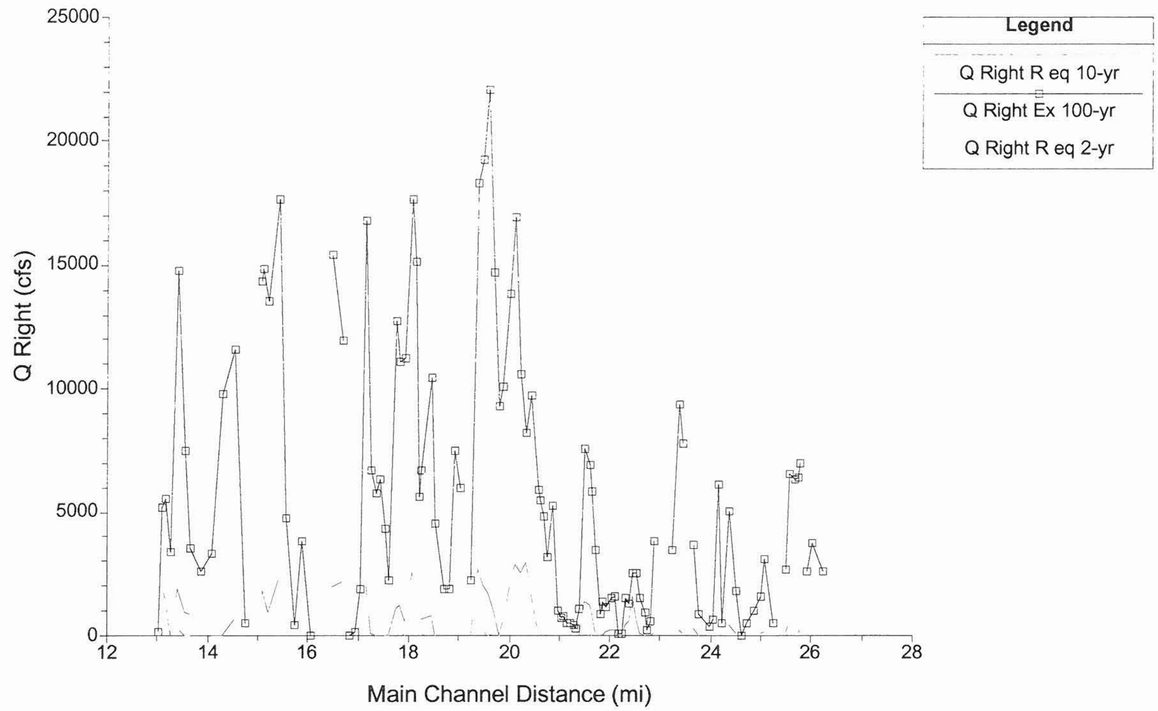


Figure 5-3. Skunk Creek Right Overbank Discharge vs. Distance. Gaps in Line Segments Indicate Cross Sections With No Overbank Discharge.

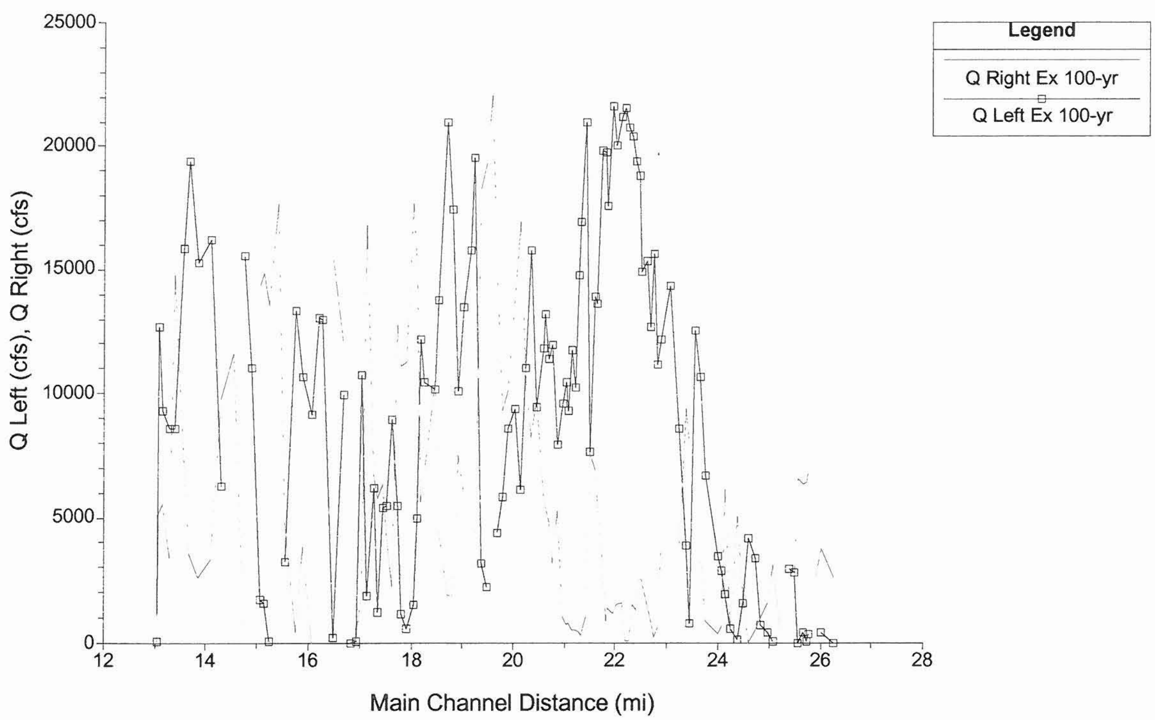


Figure 5-4. Skunk Creek Right and Left Overbank Discharge 100-Year Event. Gaps in Line Segments Indicate Cross Sections With No Overbank Discharge.

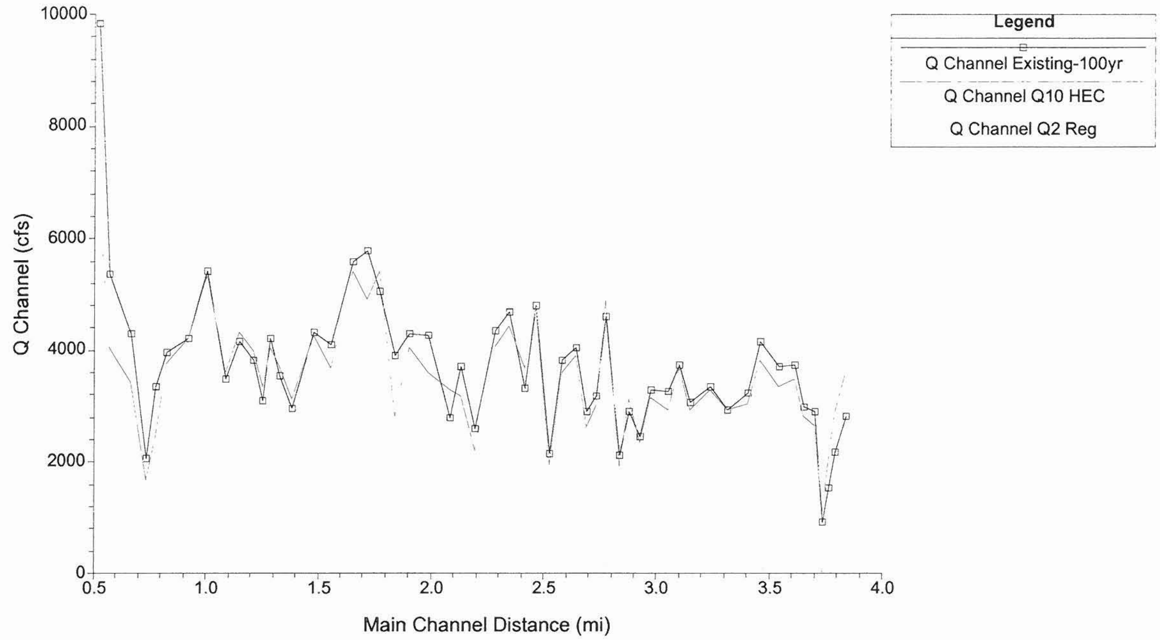


Figure 5-5. Sonoran Wash Channel Discharge (Qch) vs. Distance.

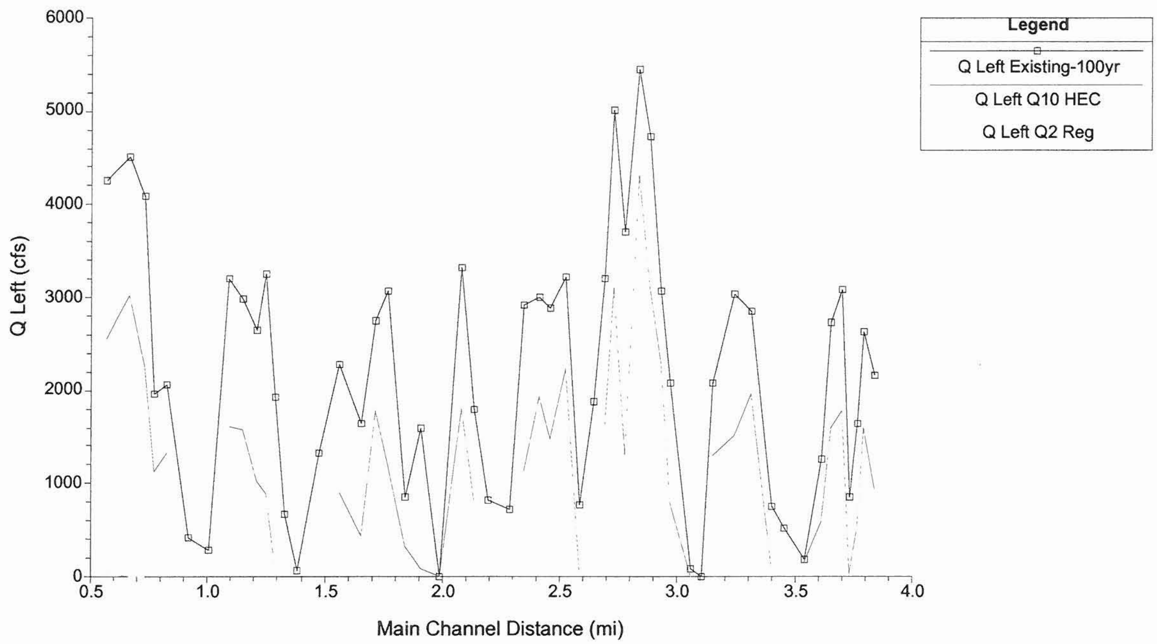


Figure 5-6. Sonoran Wash Left Overbank Discharge vs. Distance. Gaps in Line Segments Indicate Cross Sections With No Overbank Discharge.

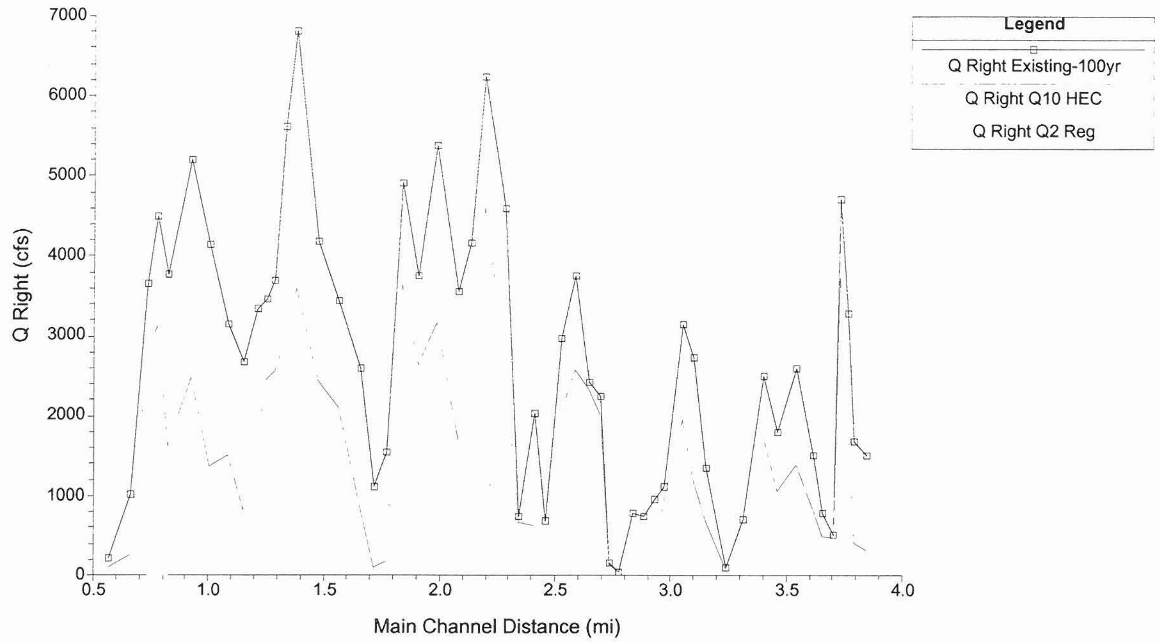


Figure 5-7. Sonoran Wash Right Overbank Discharge vs. Distance. Gaps in Line Segments Indicate Cross Sections With No Overbank Discharge.

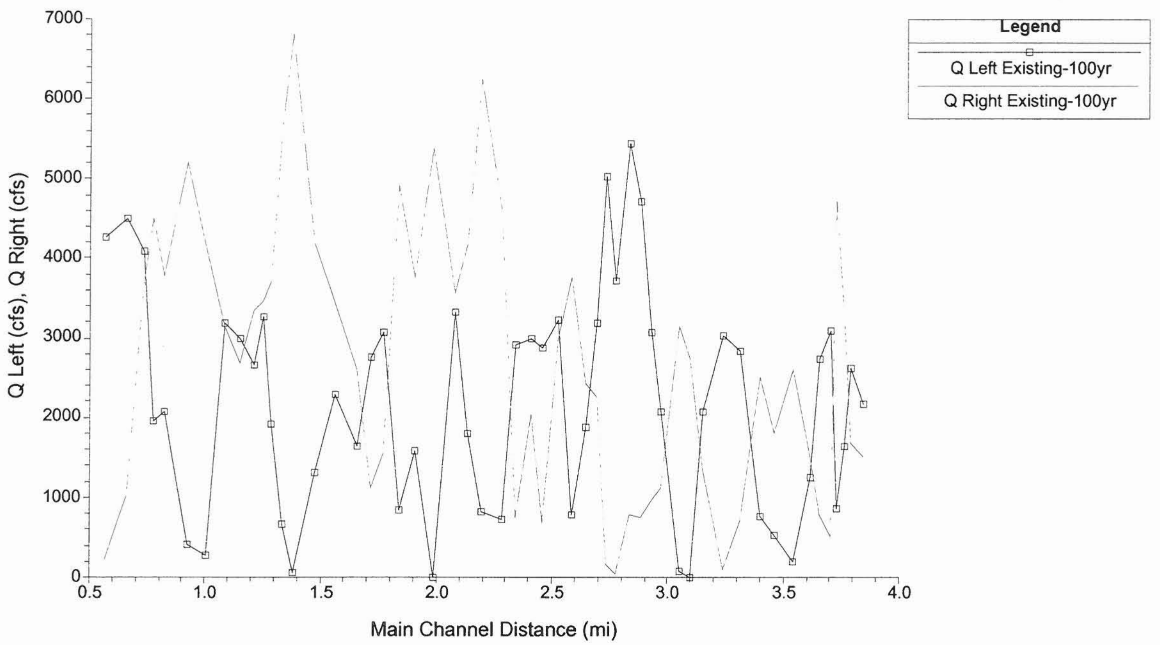


Figure 5-8. Sonoran Wash Left and Right Overbank Discharge 100-Year Event.

4. Discharge concentration points. The discharge change intended to match the HEC-1 concentration point near Rodgers Creek appears to have been located incorrectly in the FIS HEC-2 model of Skunk Creek, possibly due to misinterpreting the subwatershed code (16) on the watershed map as the concentration point with the same identifier. The discharge values were changed appropriately in the HEC-RAS model to better reflect the actual confluence of the

two streams. In addition, the actual point of confluence of Skunk Creek and Rodger Creek is a function of channel capacity and discharge. Therefore, the discharge change for the 100-year peak was modified to be upstream of the discharge change for the 2- and 10-year peaks. No modifications in concentration points were required for Sonoran Wash.

5. Channel depth. The maximum channel depth for Skunk Creek varies widely between adjacent cross sections (Figure 5-9). Depth varies by one to four feet between adjacent cross sections, only some of which can be attributed to the pool and riffle channel pattern observed along Skunk Creek. Channel hydraulic depth (Figure 5-10) is slightly less variable than maximum depth. For gradually varied flow, computed depths, channel areas, topwidths, and velocities should be relatively consistent between adjacent cross sections. Computed flow depths for Sonoran Wash are less variable than for Skunk Creek, as shown in Figures 5-11 and 5-12, and indicate that while the 2-year event is contained in the channel, the 10-year events inundates the floodplain.

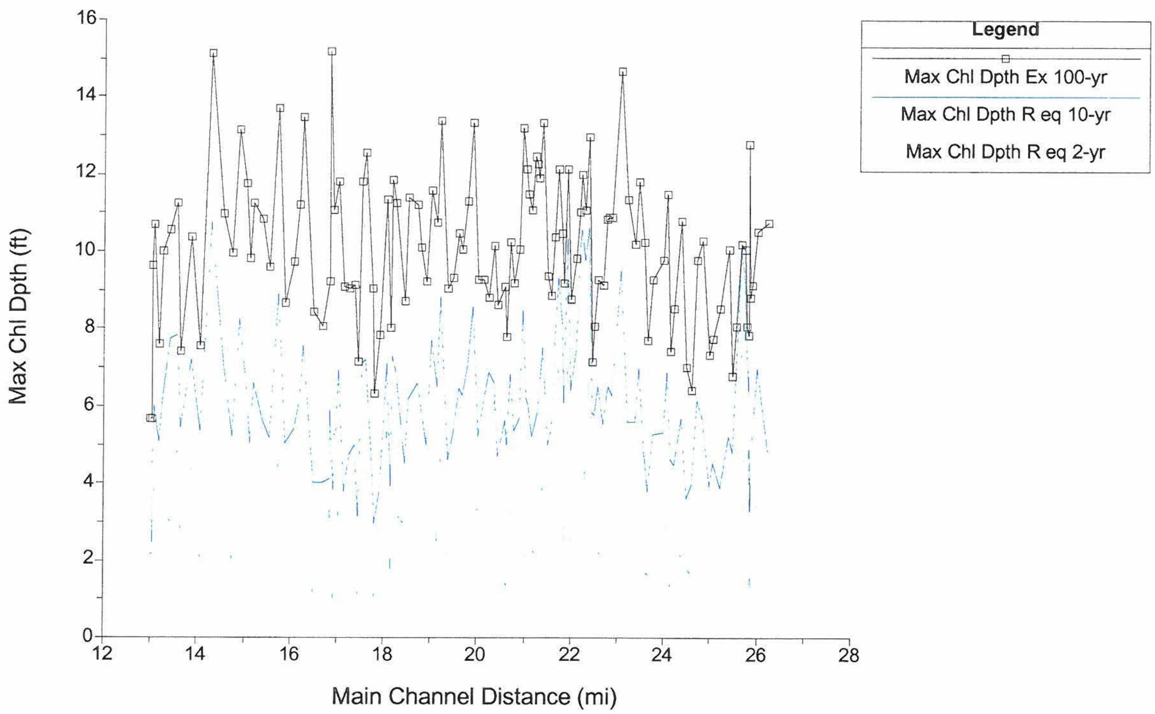


Figure 5-9. Skunk Creek Maximum Channel Depth vs. Channel Distance.

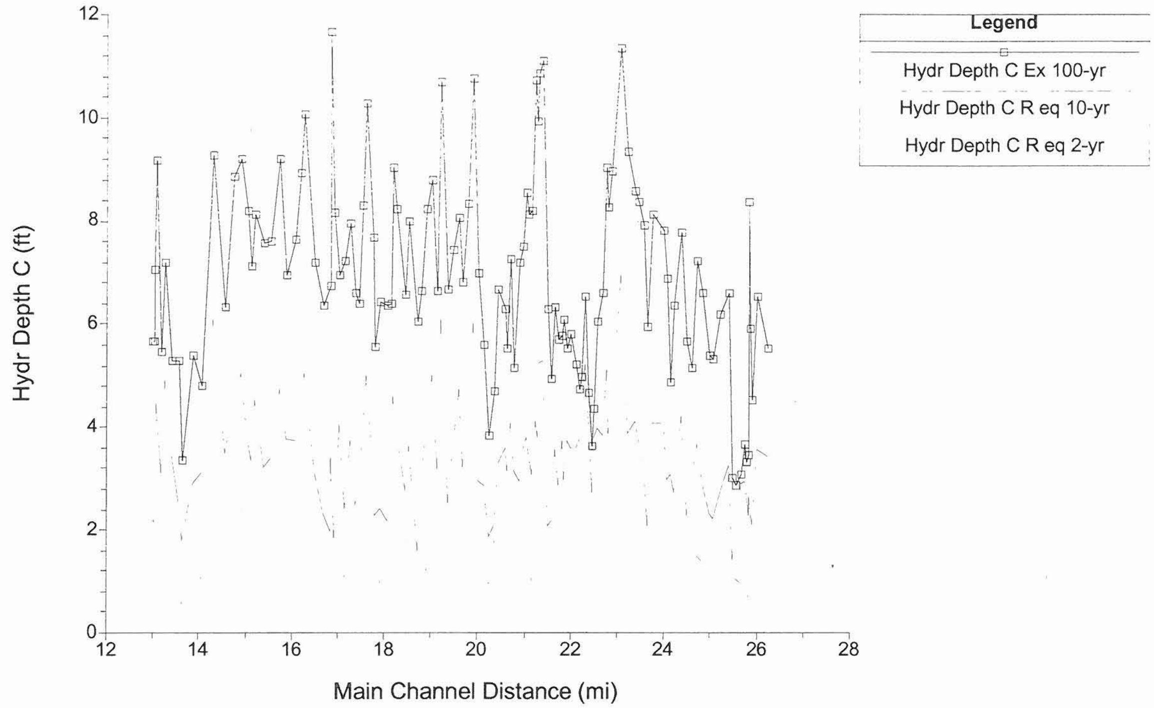


Figure 5-10. Skunk Creek Hydraulic Channel Depth vs. Channel Distance.

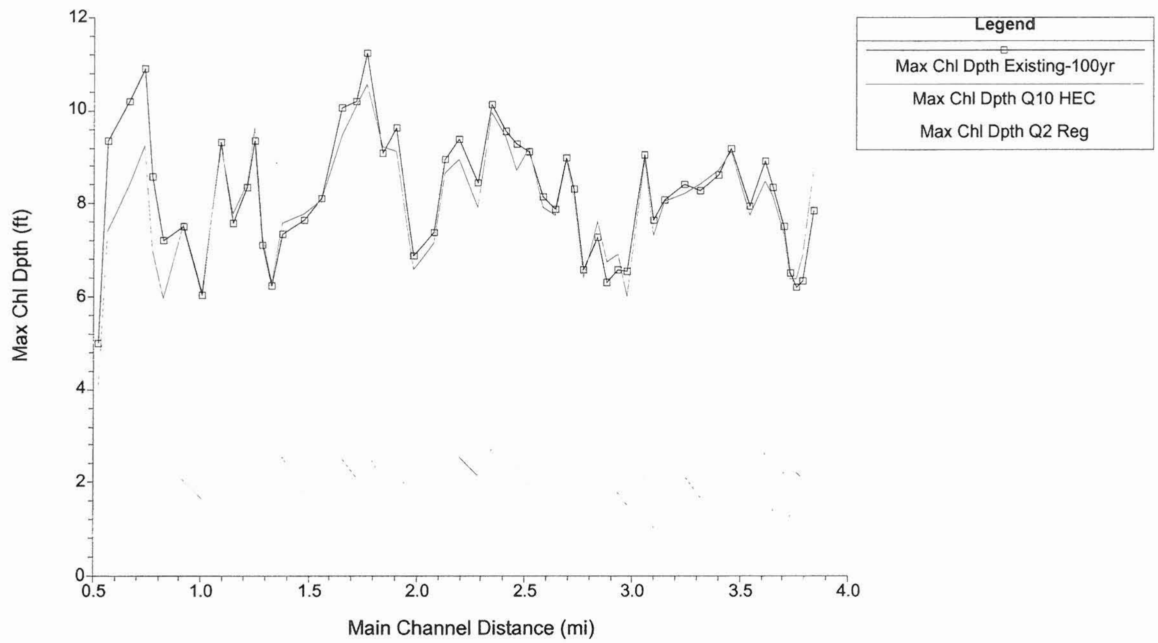


Figure 5-11. Sonoran Wash Maximum Channel Depth vs. Channel Distance.

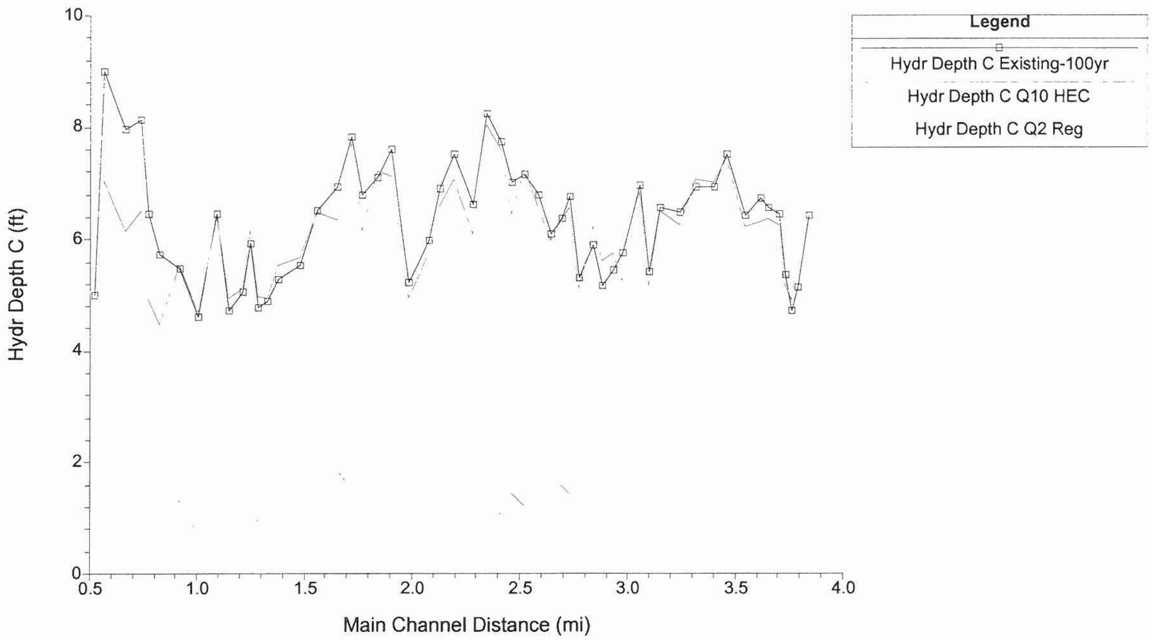


Figure 5-12. Sonoran Wash Channel Hydraulic Depth vs. Channel Distance.

6. Channel Area. Channel area on Skunk Creek (Figure 5-13) is slightly less variable than maximum channel depth, suggesting that some the variation in depth is due to variable channel width. For Sonoran Wash (Figure 5-14), the channel area generally decreases in the upstream direction. For gradually varied flow, computed channel area should be relatively consistent between adjacent sections.

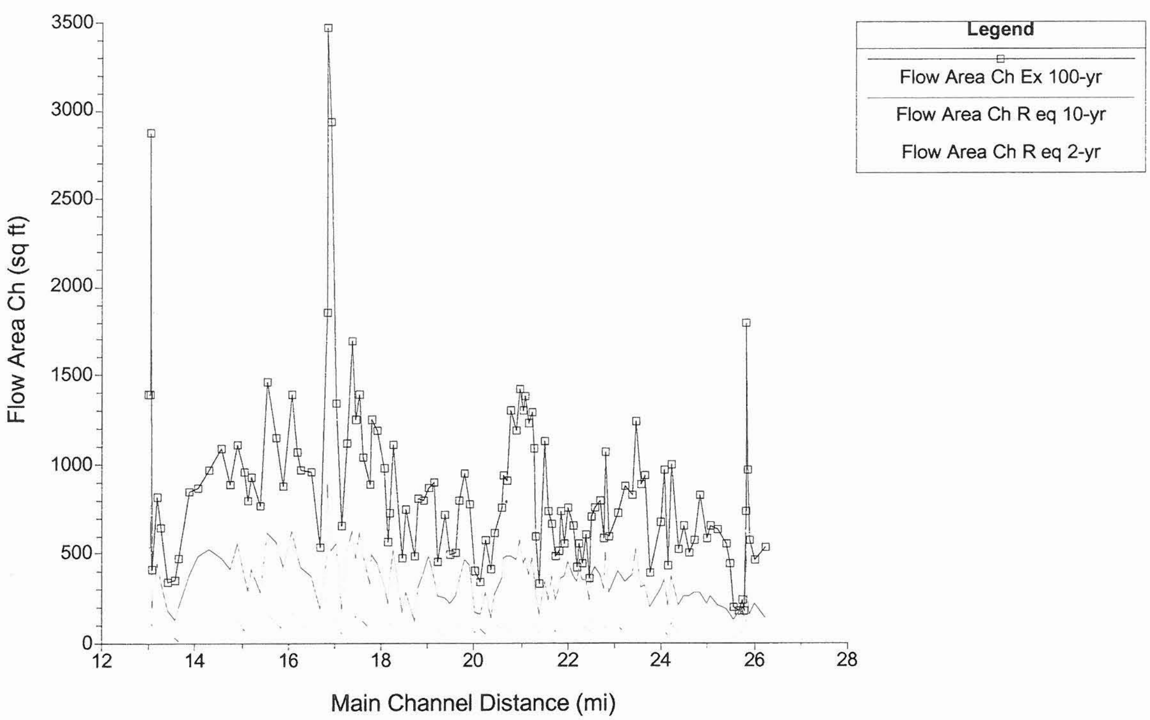


Figure 5-13. Skunk Creek Channel Flow Area vs. Channel Distance.

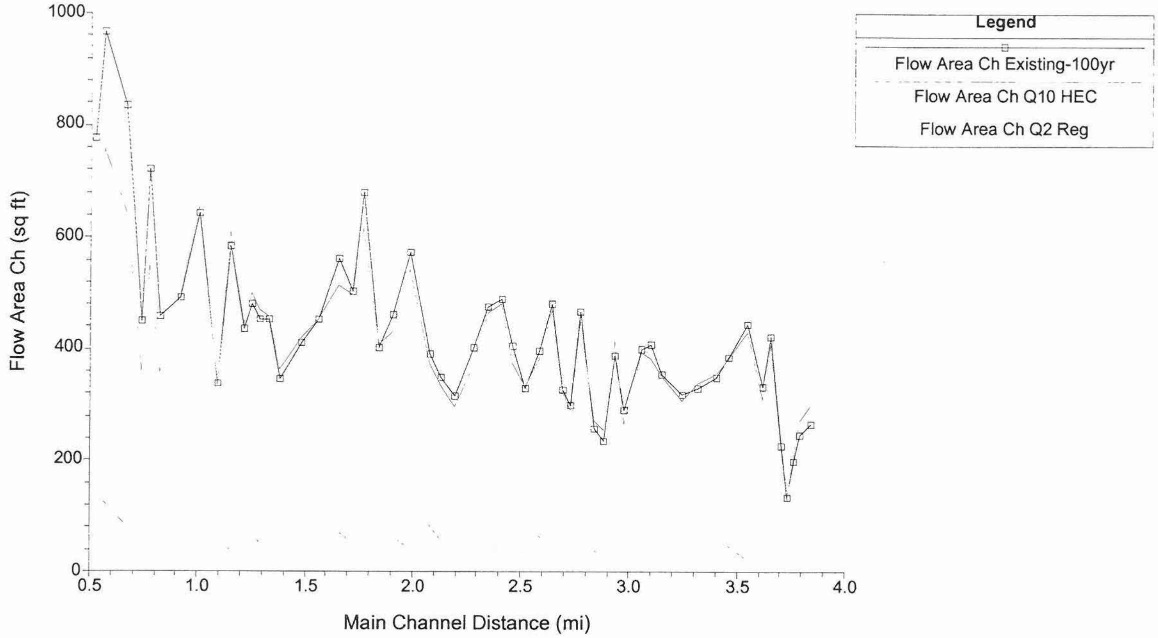


Figure 5-14. Sonoran Wash Channel Flow Area vs. Channel Distance.

7. Wetted Perimeter. Channel wetted perimeter for Skunk Creek varies significantly between adjacent cross sections. The 10- and 100-year wetted perimeter estimates are nearly identical, suggesting that the bankfull discharge may be close to the 10-year recurrence interval (Figure 5-15). The total wetted perimeter values (Figure 5-16) for the 2- and 10-year events are more similar to each other than to the 100-year values, indicating that the 2- and 10-year events are contained in the main channel of Skunk Creek. By contrast, the wetted perimeter data for Sonoran Wash shown in Figures 5-17 and 5-18 indicate that the 10-year event is not contained in the main channel, and that the channel dimensions decrease in the upstream direction.

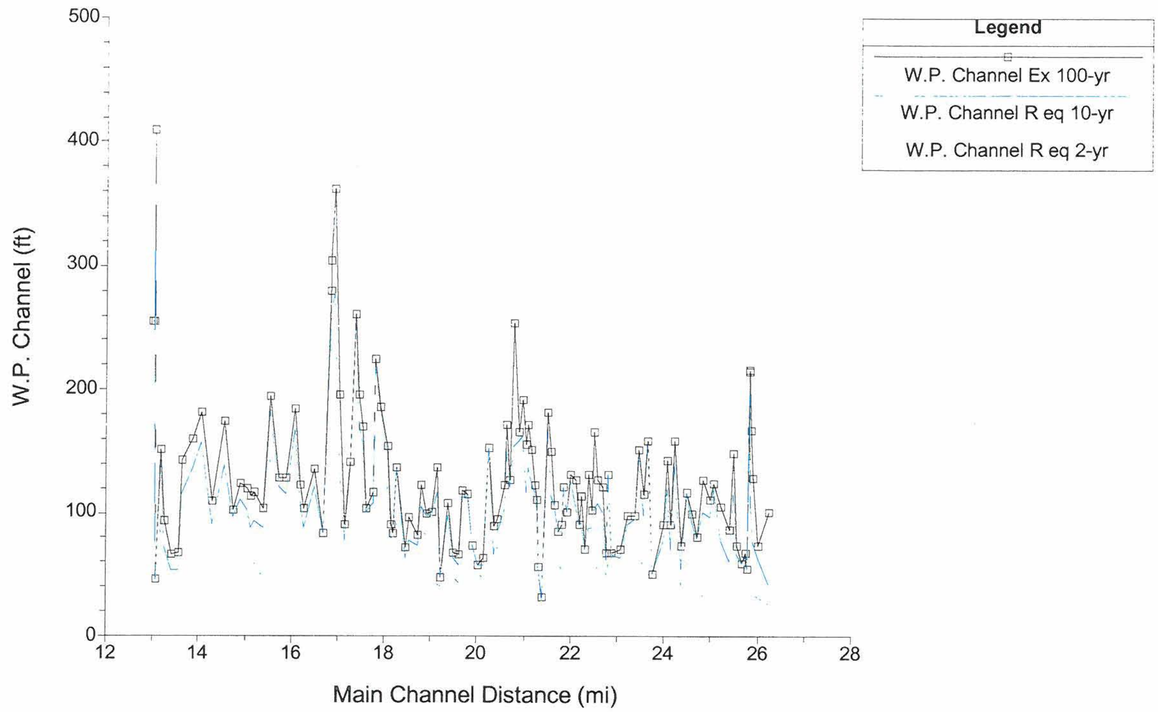


Figure 5-15. Skunk Creek Channel Wetted Perimeter vs. Channel Distance.

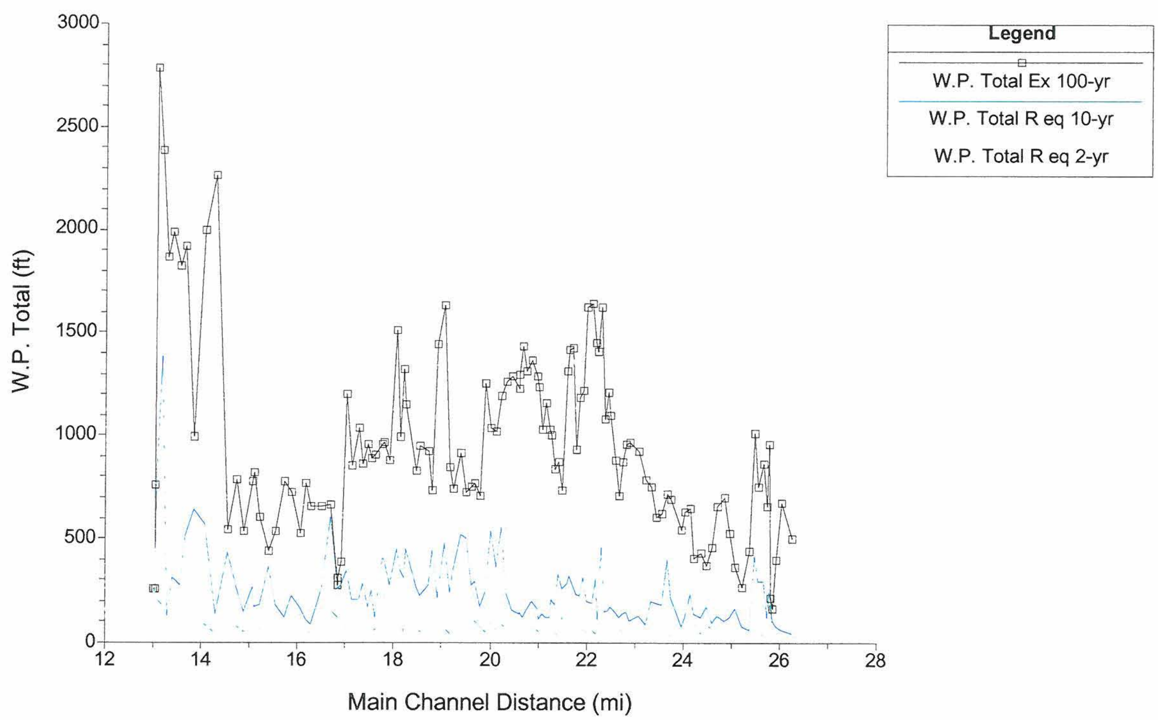


Figure 5-16. Skunk Creek Total Wetted Perimeter vs. Channel Distance. Gaps in Line Segments Indicate Cross Sections With No Overbank Discharge.

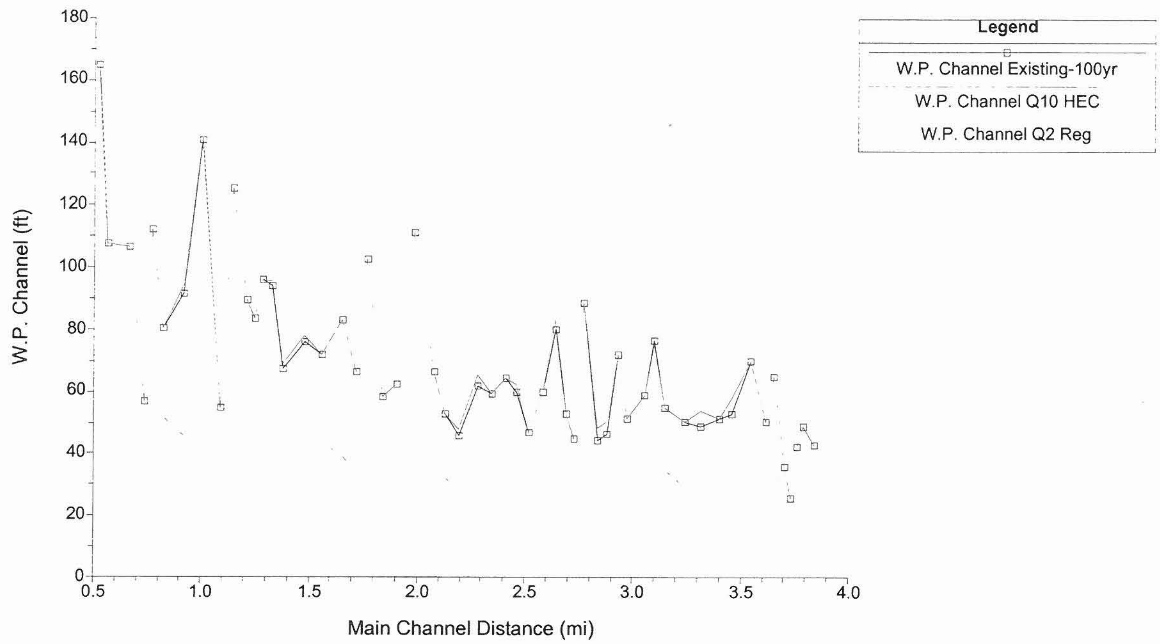


Figure 5-17. Sonoran Wash Channel Wetted Perimeter vs. Channel Distance.

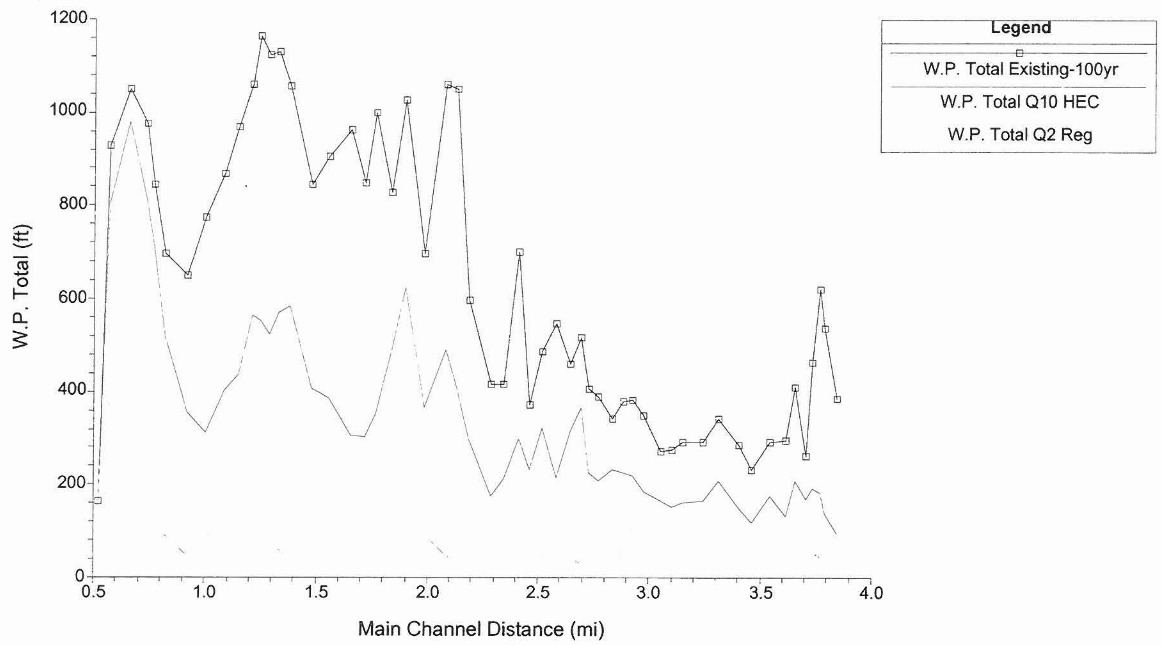


Figure 5-18. Sonoran Wash Total Wetted Perimeter vs. Channel Distance.

8. Velocity. Computed channel velocity for Skunk Creek is highly variable between adjacent cross sections. The 100-year velocities are lower than the 2- and 10-year velocities at some cross sections, probably due to use of the levee option to contain flows within the channel at poorly aligned cross sections (Figure 5-19). Levee options were required along Skunk Creek where multiple channels occurred, or where poor cross section alignments resulted in overbank areas lower than the main channel. For Sonoran Wash (Figure 5-20), velocity generally decreases in the downstream direction, especially in the backwater area upstream

of the CAP overchute. Channel velocities are highly variable between adjacent cross sections.

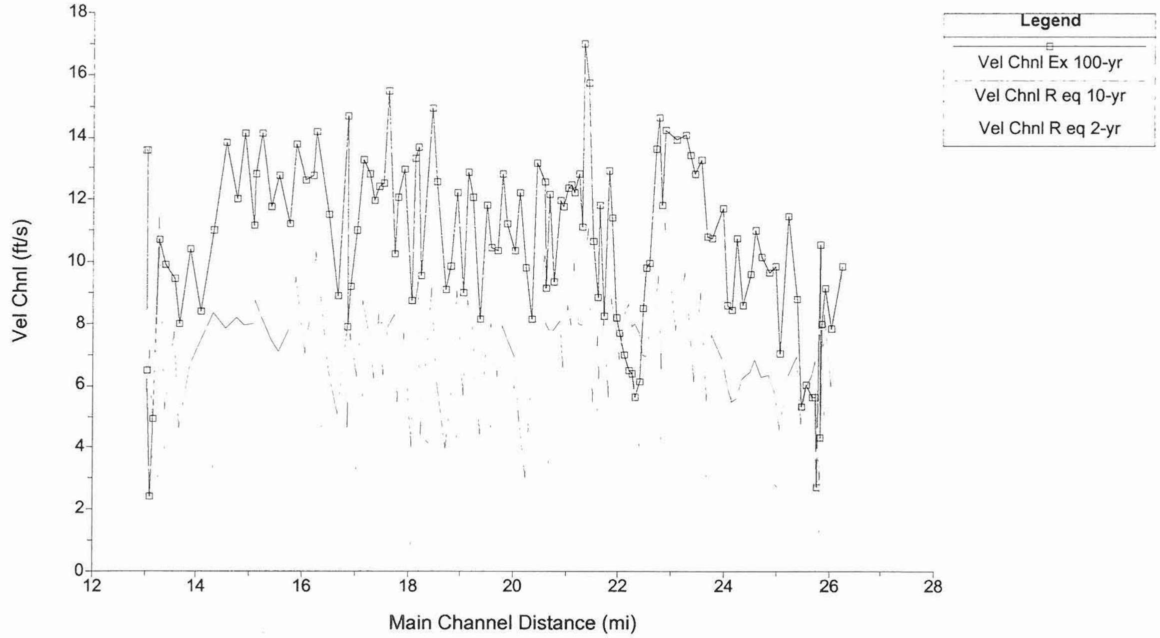


Figure 5-19. Skunk Creek Channel Velocity vs. Channel Distance.

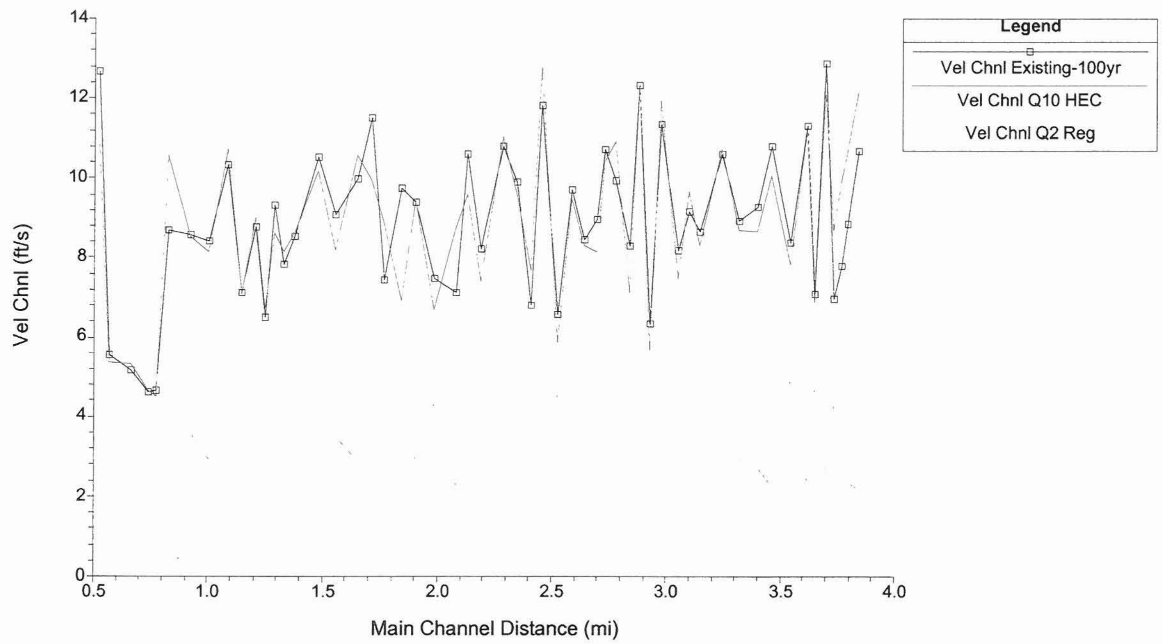


Figure 5-20. Sonoran Wash Channel Velocity vs. Channel Distance.

9. Energy Slope. The energy slopes for Skunk Creek is highly variable between adjacent cross sections, but the values at individual cross sections are similar for the 2-, 10-, and 100-year events (Figure 5-21), suggesting that the computed energy slope is driven by the channel slope and the excessive fall between the widely spaced cross sections. For Sonoran Wash, the energy slopes for the 2-year

event are more variable than for the 10- or 100-year events, suggesting that the slightly irregular channel slope caused by the pool and riffle sequence controls the energy slope at low discharges, but tends to be drown out at flows exceeding the bankfull discharge (Figure 5-22).

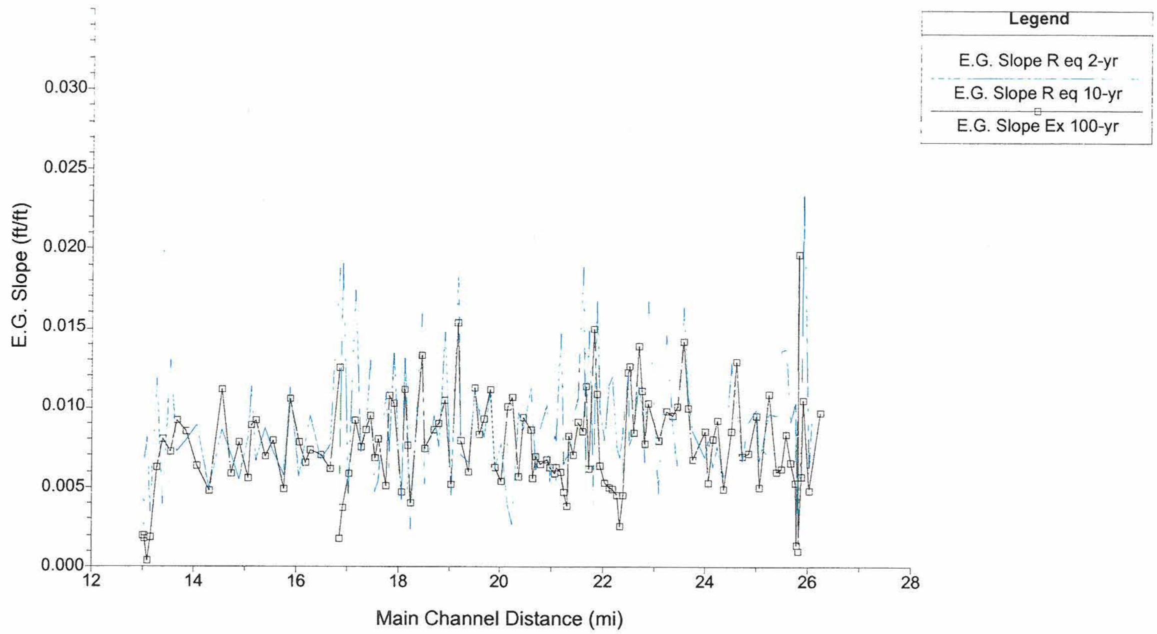


Figure 5-21. Skunk Creek Energy Grade Slope vs. Channel Distance.

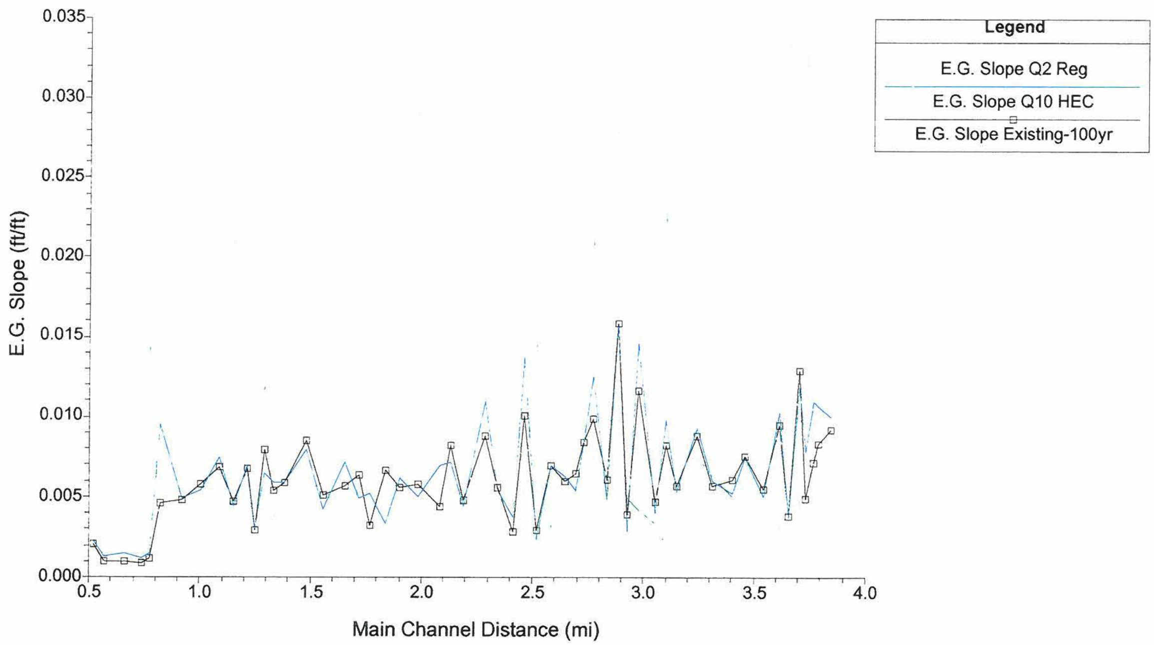


Figure 5-22. Sonoran Wash Energy Grade Slope vs. Channel Distance.

10. Cross Section Spacing. The distances between adjacent cross sections on Skunk Creek are not consistent (Figure 5-23), may be too long to assure gradually varied flow at most sections, and may lead to other modeling deficiencies as indicated by

the long list of errors, warnings, and notes printed in the RAS model output (Stantec, 2001). Cross section spacing for Sonoran Wash (Figure 5-24) is more consistent and does not exceed 500 feet.

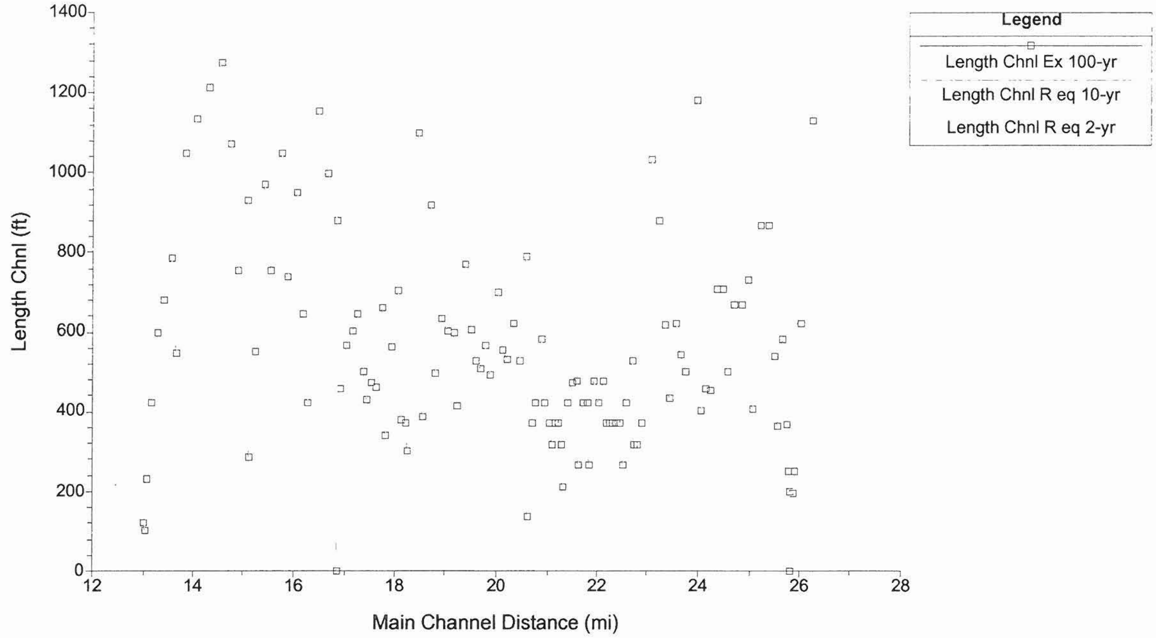


Figure 5-23. Skunk Creek Distance Between HEC-RAS Cross Sections (equal for each profile).

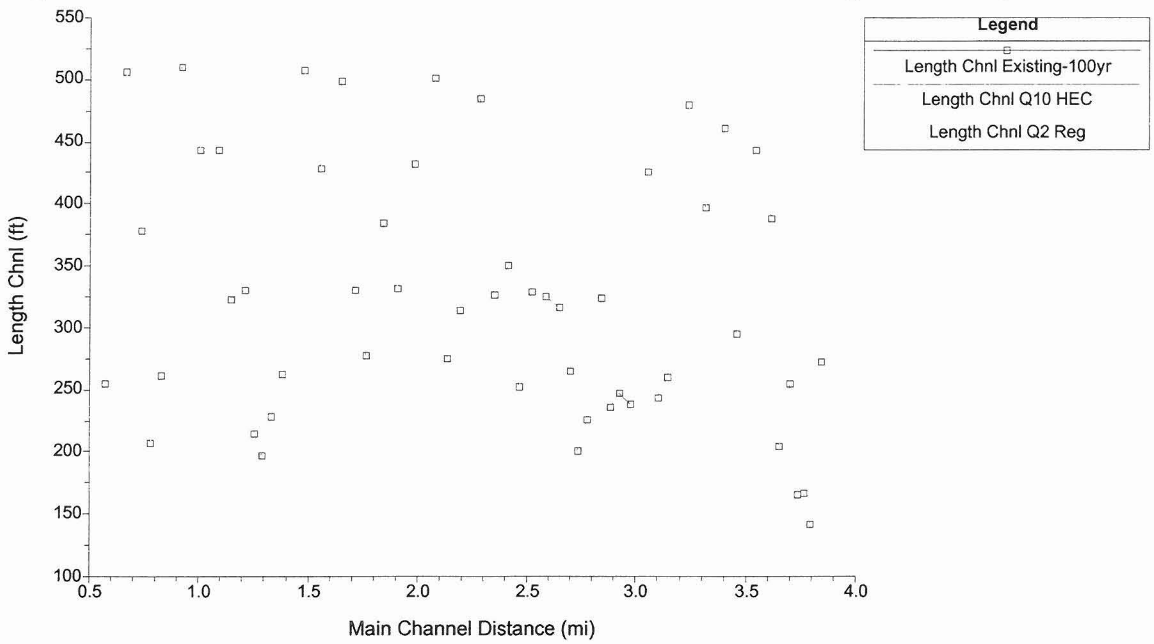


Figure 5-24. Sonoran Wash Distance Between HEC-RAS Cross Sections (equal for each profile).

11. N Values. Weighted Manning's n values for the channel of Skunk Creek are consistent in discrete reaches, (Figure 5-25) implying some level of consistency and uniformity of channel conditions. Weighted Manning's n values for the

overbanks are highly variable between adjacent cross sections, implying no continuity of conditions within the study reach. The weighted n values for the overbanks are lower than the weighted values for the channel in several reaches. In general, n values for the channel appear a bit high for the 100-year event. The excessive division of n value zones in the overbanks implies a level of precision that probably is not supported in reality. For Sonoran Wash (Figure 5-26), variation in channel and overbank n values more realistically depicts average conditions and the level of accuracy of the modeling effort.

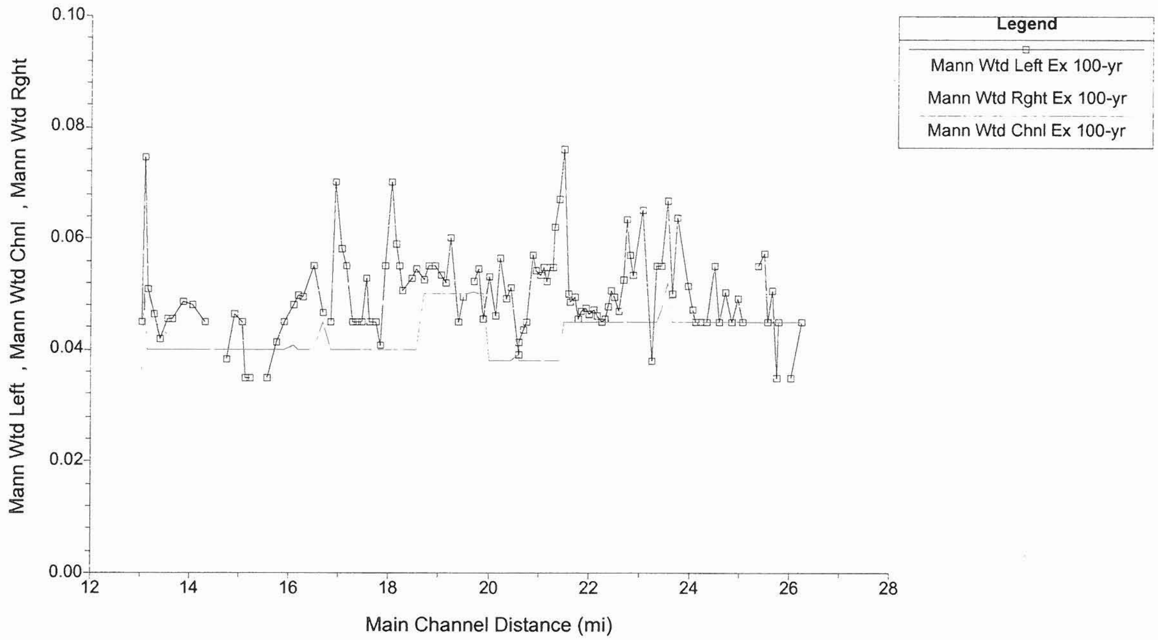


Figure 5-25. Skunk Creek Weighted Channel and Overbank Manning's n Values.

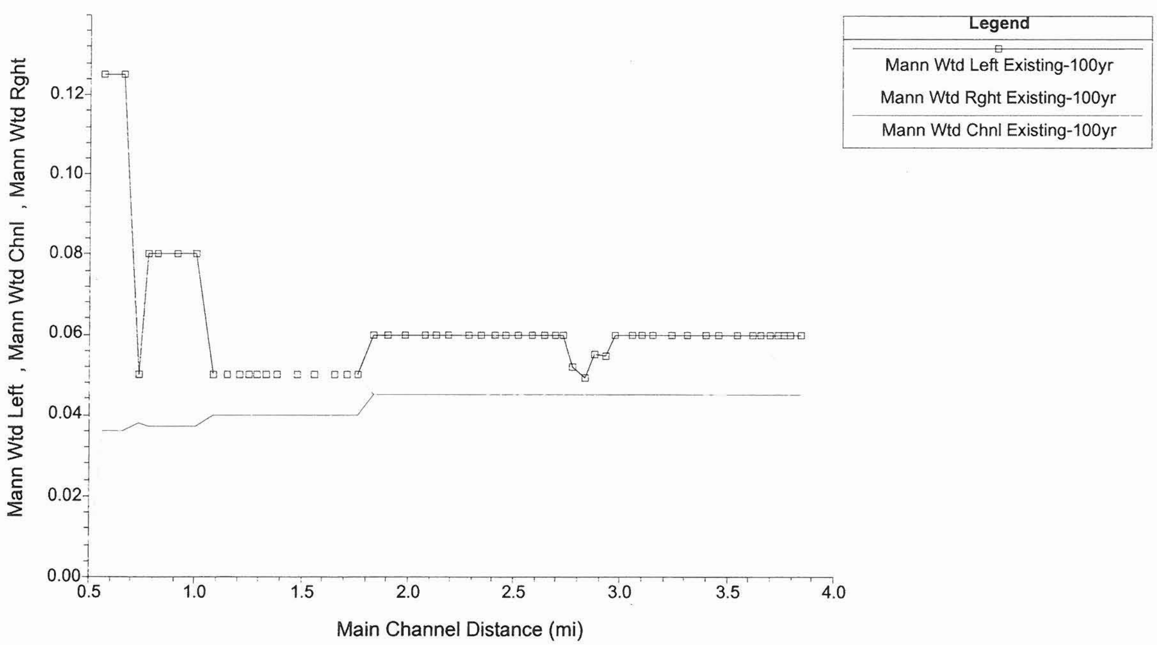


Figure 5-26. Sonoran Wash Weighted Channel and Overbank Manning's n Values.

12. Froude Number. The computed Froude number for the channel of Skunk Creek is generally subcritical and is moderately variable between adjacent cross sections (Figure 5-27). However, it is noted that a subcritical profile was mandated by the input code, and that error messages indicate that no valid subcritical solution was available at some cross sections. For Sonoran Wash, the channel Froude number is variable, but consistently subcritical (Figure 5-28).

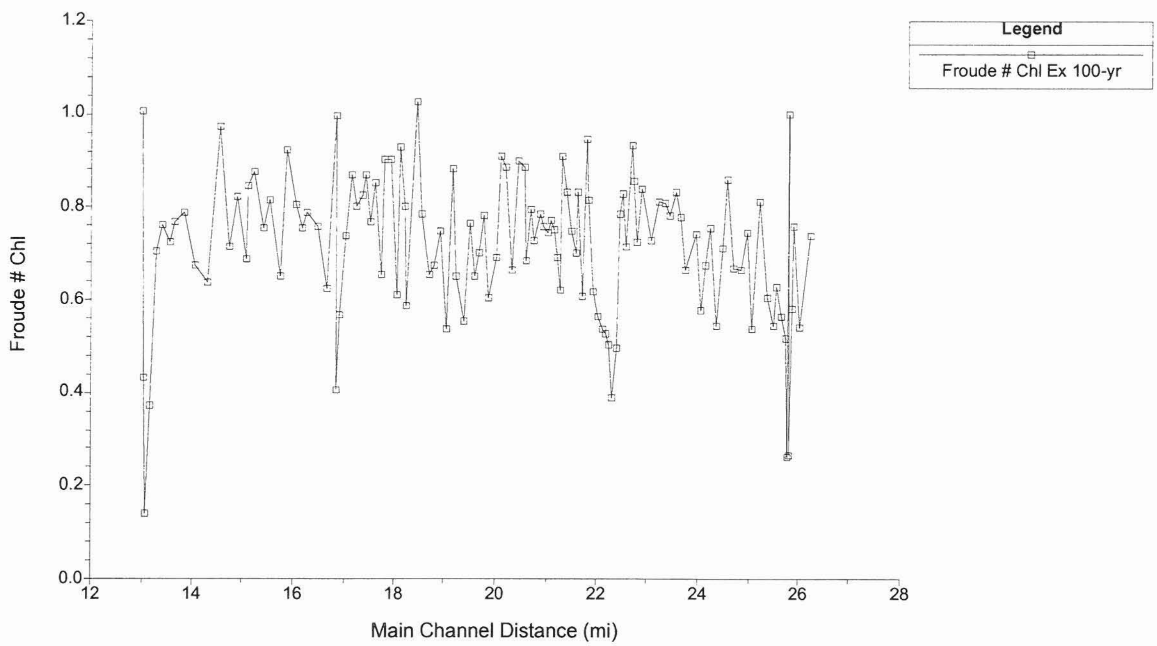


Figure 5-27. Skunk Creek Froude Number vs. Channel Distance.

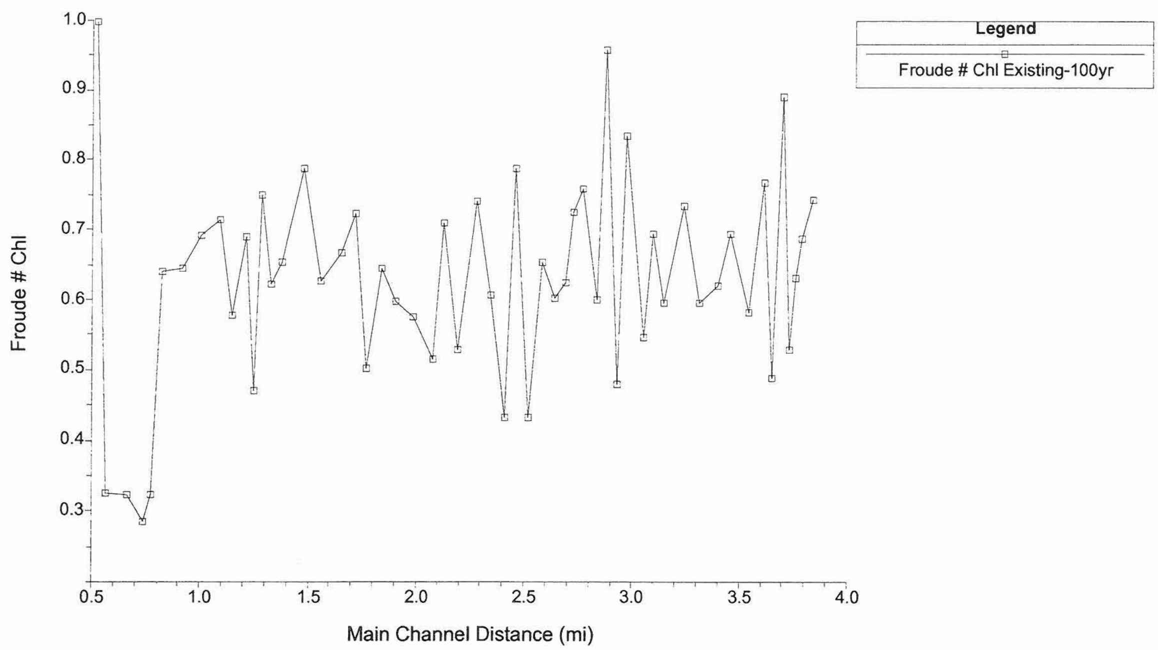


Figure 5-28. Sonoran Wash Froude Number vs. Channel Distance.

13. Head Loss. Head loss between adjacent cross sections along Skunk Creek varies from zero to 12 feet (Figure 5-29), probably due primarily to the excessive length between adjacent cross sections. Note that the head loss at individual cross sections is nearly equivalent for the 2-, 10-, and 100-year profiles, indicating that minimum backwater conditions were simulated by the HEC2 modeling. For Sonoran Wash (Figure 5-30), the computed head loss between sections is less than for Skunk Creek, and varies little by recurrence interval.

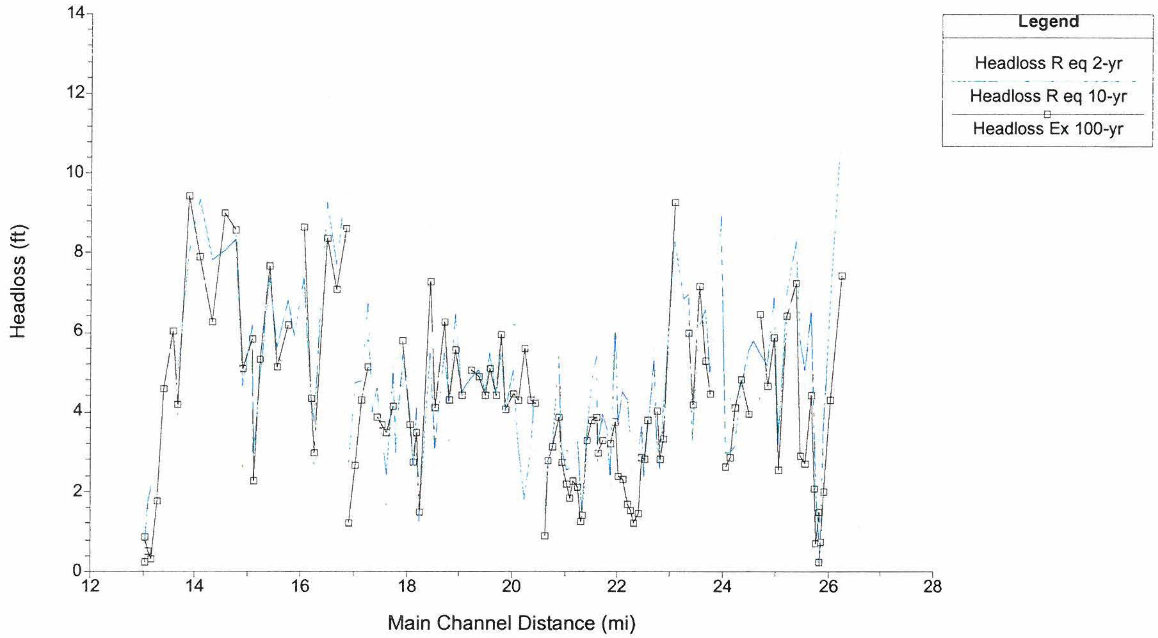


Figure 5-29. Skunk Creek Head Loss vs. Channel Distance.

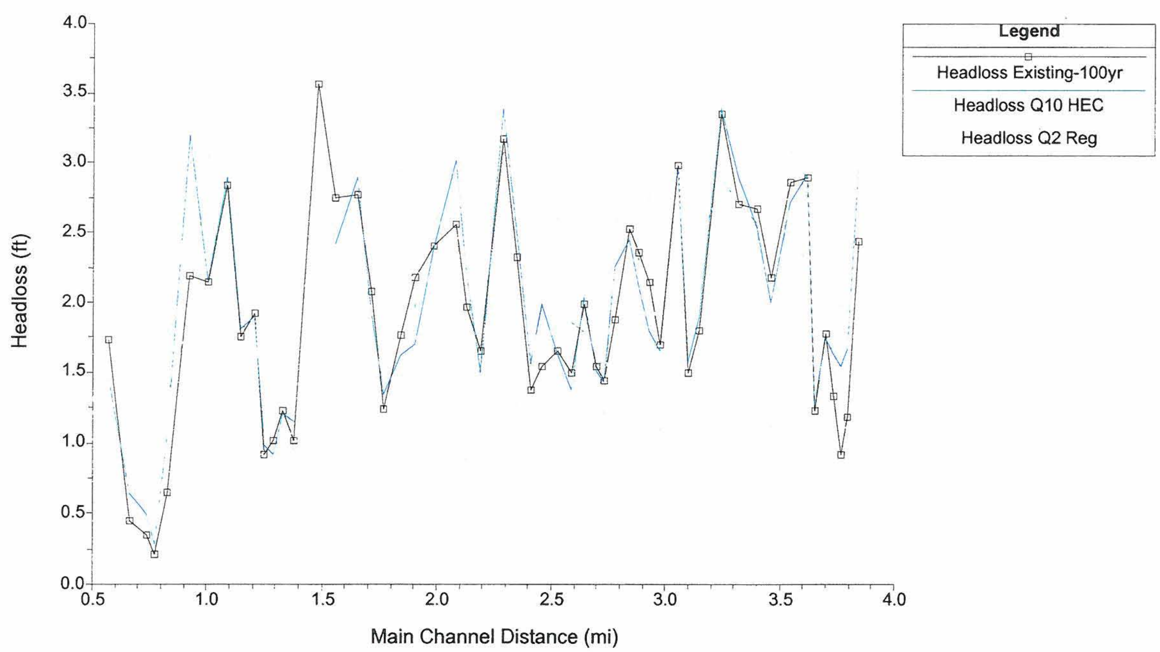


Figure 5-30. Sonoran Wash Head Loss vs. Channel Distance.

14. Topwidth. Channel topwidth for Skunk Creek varies significantly between adjacent cross sections (Figure 5-31), suggesting that the gradually varied flow assumption is not consistently supported. The data shown in Figure 5-31 indicate that the 2-year event does not typically fill the main channel, although the 10- and 100-year events do. The overall flow topwidth (Figure 5-32) indicates that the 2- and 10-year events are contained in or concentrated near the main channel, whereas the 100-year event inundates a significantly broader floodplain. Improbably large variations in floodplain width are indicated by the data shown in Figure 5-32. For Sonoran Wash, the data shown in Figure 5-33 indicate that the 2-year discharge does not fill the entire channel, but that the 10-year does. The total flow widths shown in Figure 5-34 vary more reasonably than the widths reported for Skunk Creek.

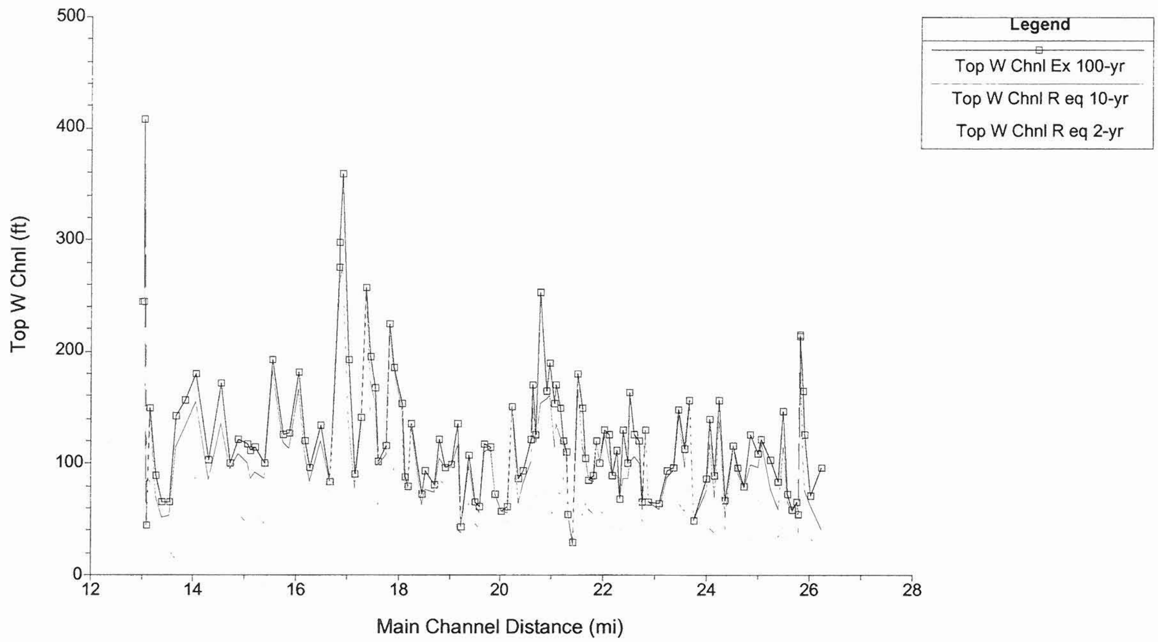


Figure 5-31. Skunk Creek Channel Topwidth vs. Channel Distance.

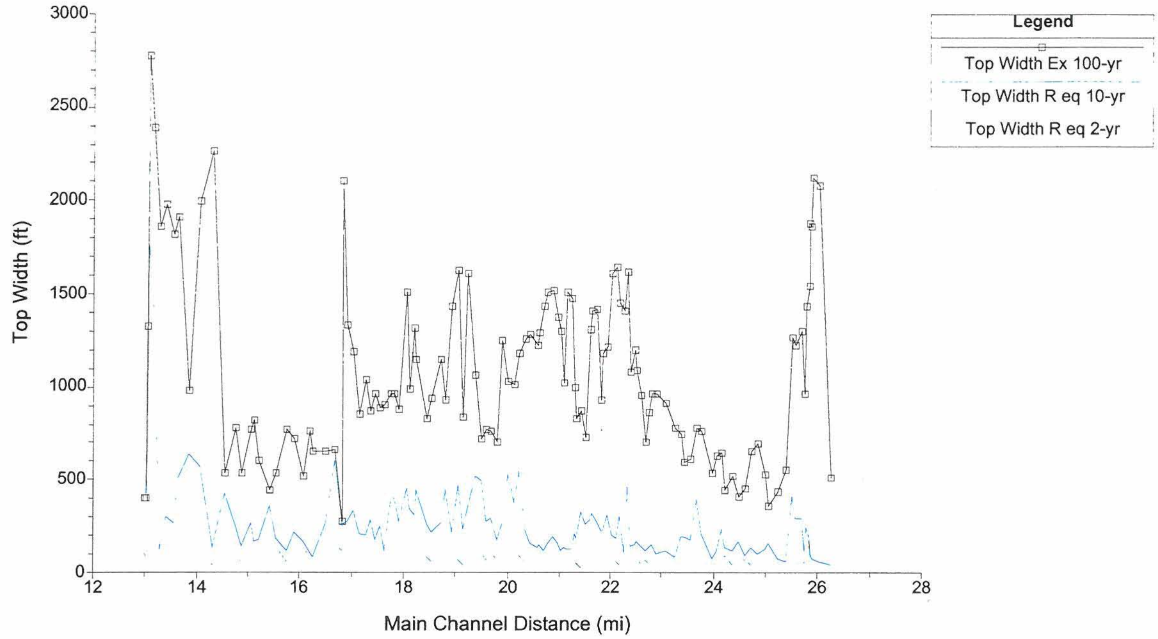


Figure 5-32. Skunk Creek Total Topwidth vs. Channel Distance.

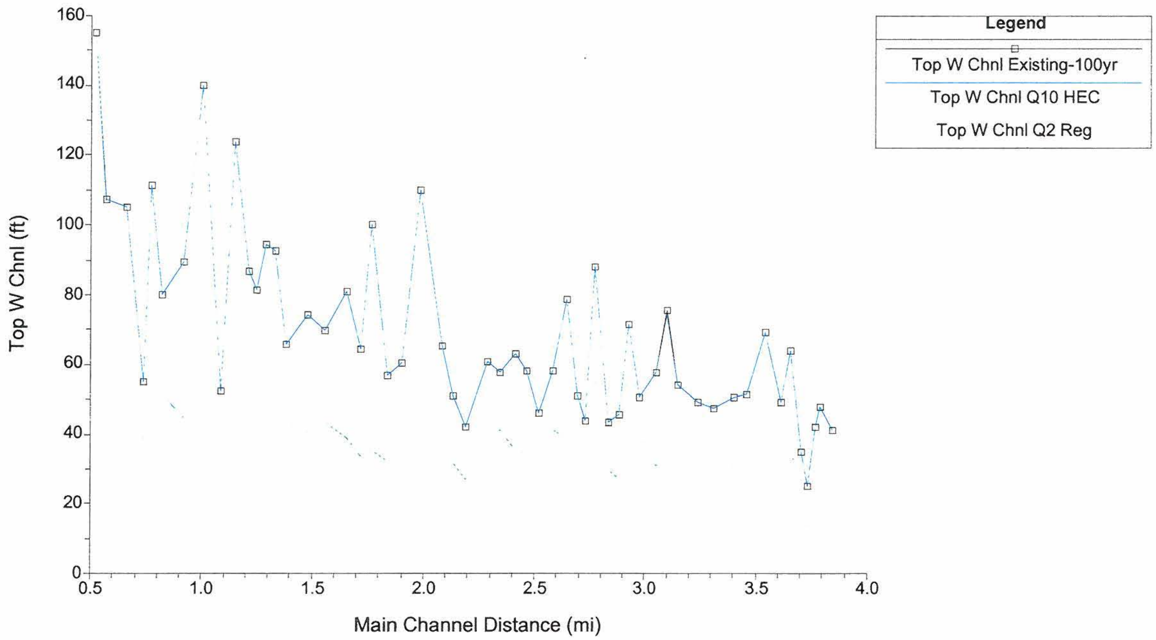


Figure 5-33. Sonoran Wash Channel Topwidth vs. Channel Distance.

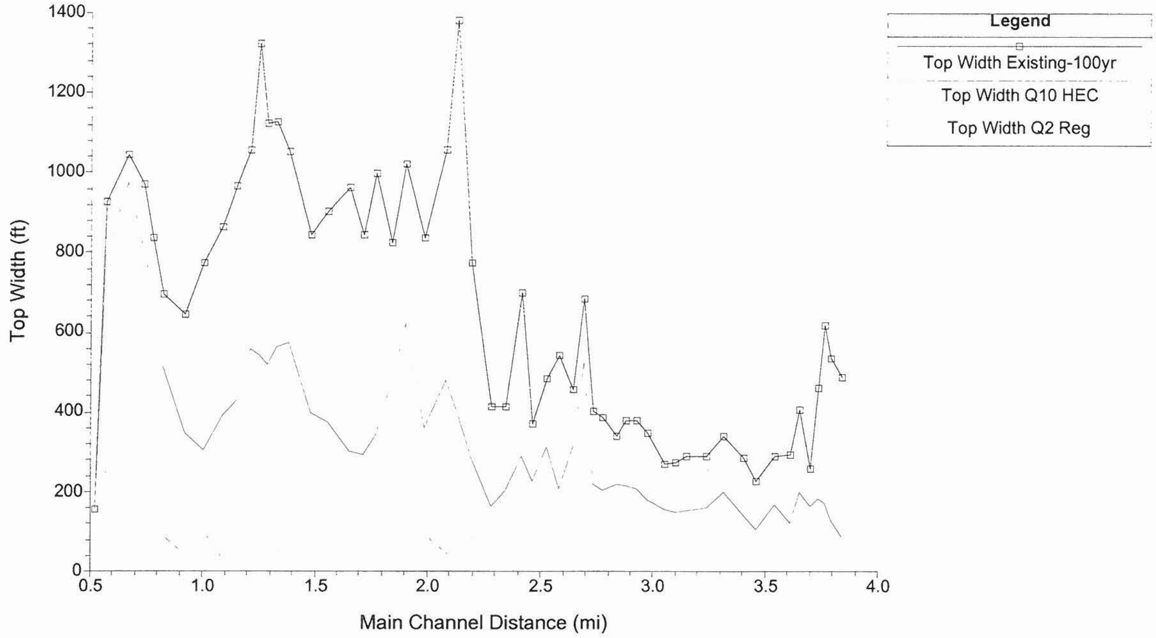


Figure 5-34. Sonoran Wash Total Topwidth vs. Channel Distance.

15. Channel Profile. Longitudinal profiles for Skunk Creek and Sonoran Wash based on the minimum elevation coded in the input file for each cross section in the HEC-RAS models are shown in Figures 5-35 and 5-36. The longitudinal profile of Skunk Creek has an irregular, but generally concave up shape, with no reaches of negative slope (Figure 5-35). The longitudinal profile of Sonoran Wash is slightly less irregular than the profile of Skunk Creek (Figure 5-36). The Sonoran Wash profile reflects a more strongly developed pool and riffle sequence and the adverse slope caused by the CAP overchute.

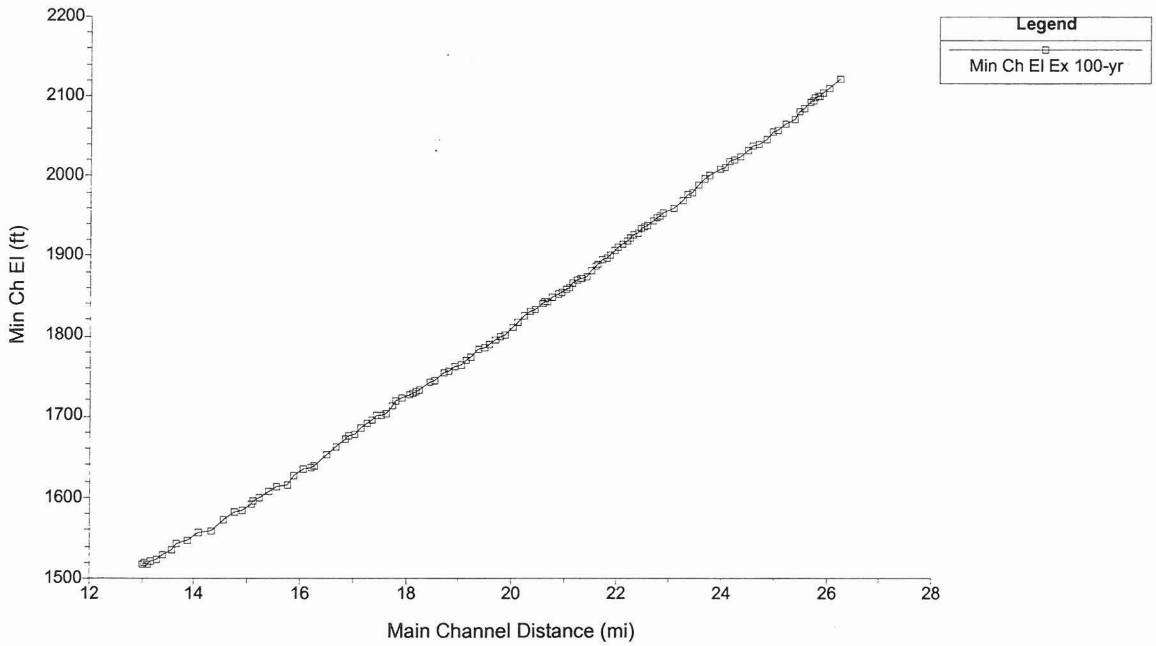


Figure 5-35. Skunk Creek Profile from HEC-RAS Minimum Elevations.

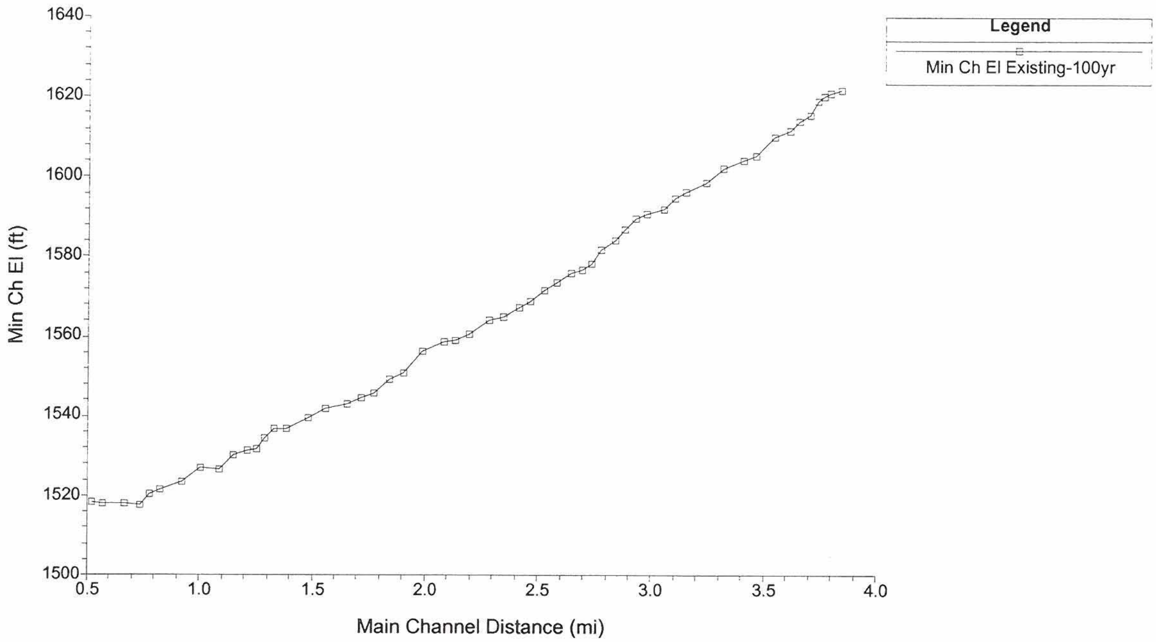


Figure 5-36. Sonoran Wash Profile from HEC-RAS Minimum Elevations.

16. Channel Width. Channel width, defined as the difference between RAS bank stations, is highly variable between adjacent cross sections on Skunk Creek, but generally decreases in the upstream direction (Figure 5-37). Channel width on Sonoran Wash is somewhat less variable than on Skunk Creek, and has a similar decreasing pattern in the upstream direction.

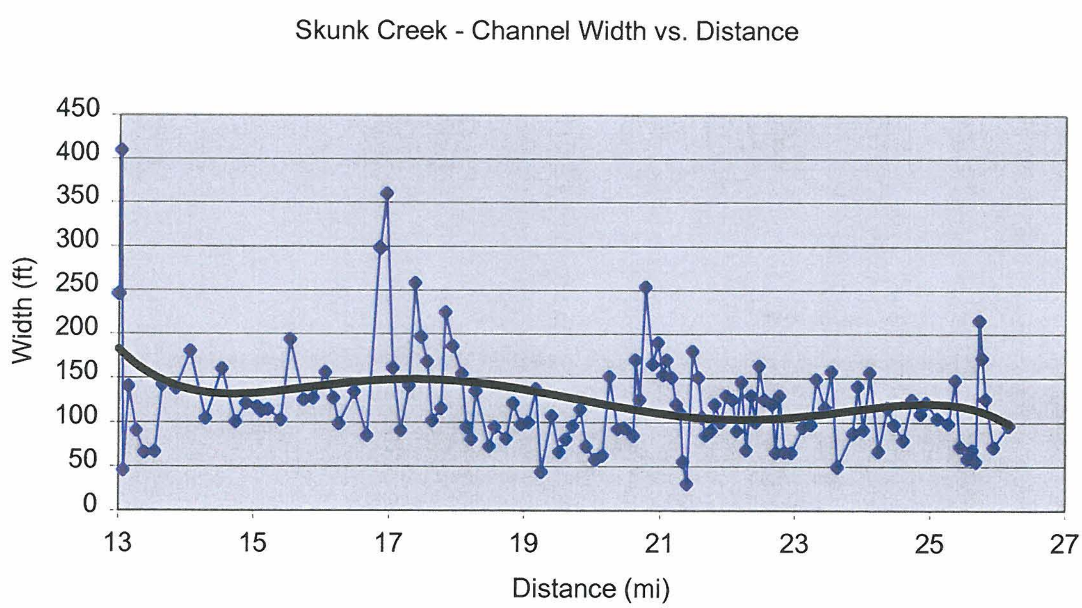


Figure 5-37. Skunk Creek Channel Width Defined by HEC-RAS Bank Stations (with 5-station moving average trend line shown in black).

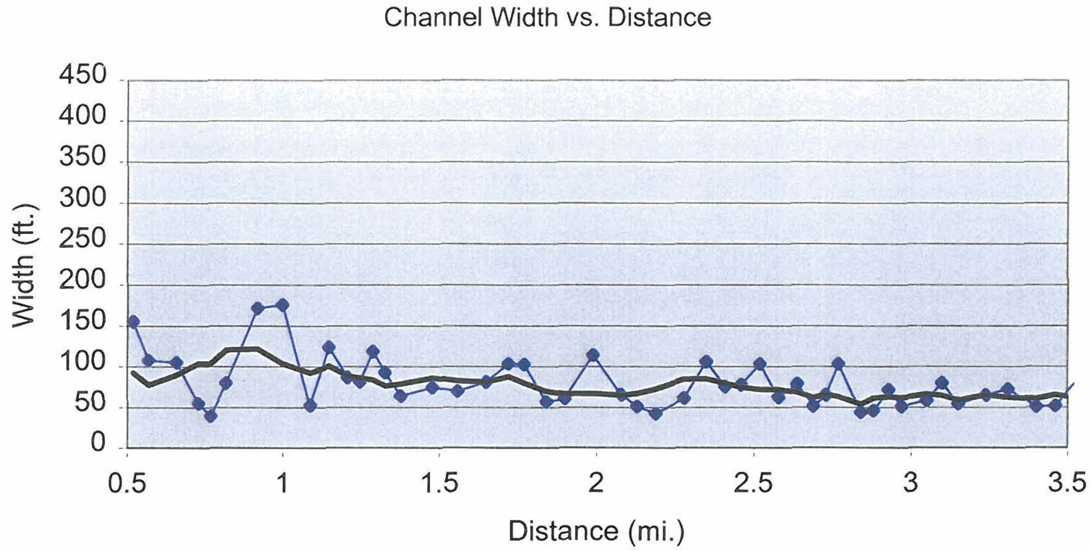


Figure 5-38. Sonoran Wash Channel Width Defined by HEC-RAS Bank Stations (with 5-station moving average trend line shown in black).

17. Bank Height. Bank heights are highly variable over the Skunk Creek study reach, with slight average increases near the downstream and upstream portions of the study area (Figure 5-39). Bank heights for Sonoran Wash are lower, less variable, and more consistent from left to right than for Skunk Creek (Figure 5-40).

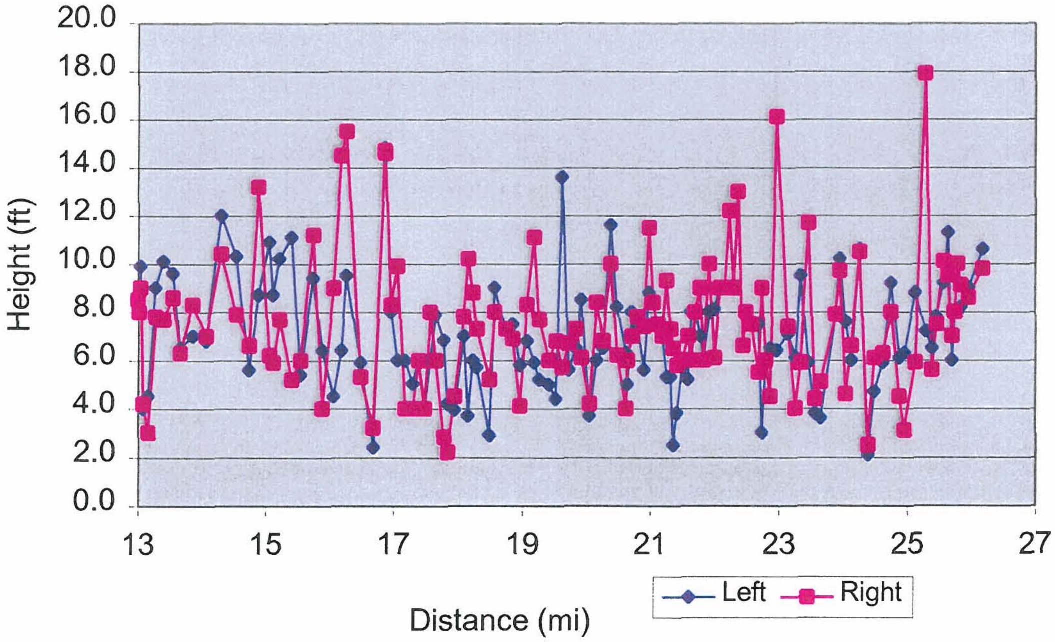


Figure 5-39. Skunk Creek Bank Height Defined by HEC-RAS Data.

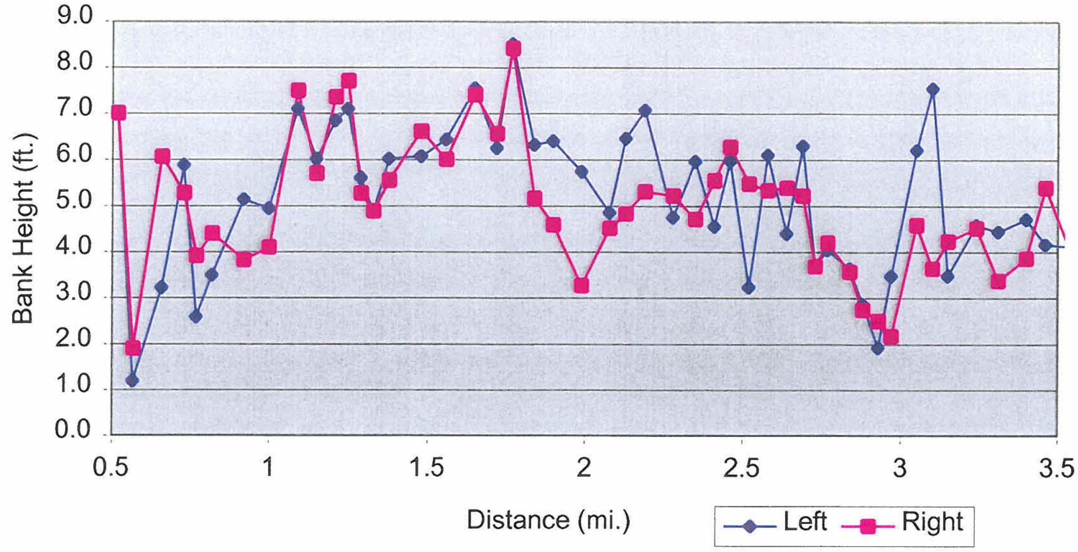


Figure 5-40. Sonoran Wash Bank Height Defined by HEC-RAS Data.

18. Bank Stations. Bank stations were adjusted to facilitate more accurate computation of the hydraulics of flow within the main channel, as described above.

19. Flow Regime. The HEC-RAS model was run in both subcritical and mixed flow regime to examine the extent and importance of supercritical flow within Skunk Creek. The differences in the computed water surface for the 2-, 10-, and 100-year existing conditions discharges are shown in Figures 5-41, 5-42, and 5-43. The results indicate that while short reaches probably are supercritical at flow rates exceeding the 10-year event, when averaged by reach the differences are minimally significant. The Sonoran Wash HEC-RAS model was consistently subcritical.

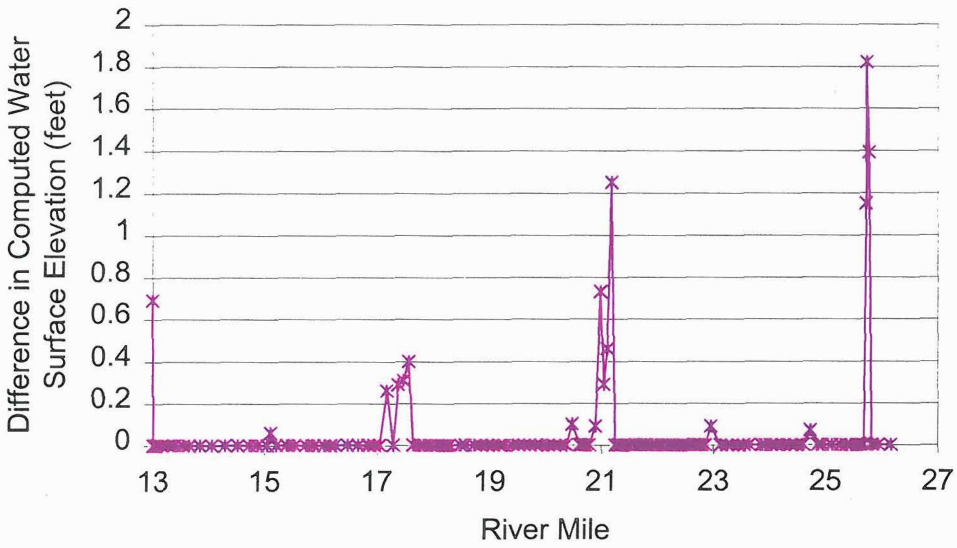


Figure 5-41. Difference in 100-year Computed Water Surface Elevation: Subcritical vs Mixed Flow Regime. Zero difference value indicates no difference between subcritical and mixed profile water surface elevations.

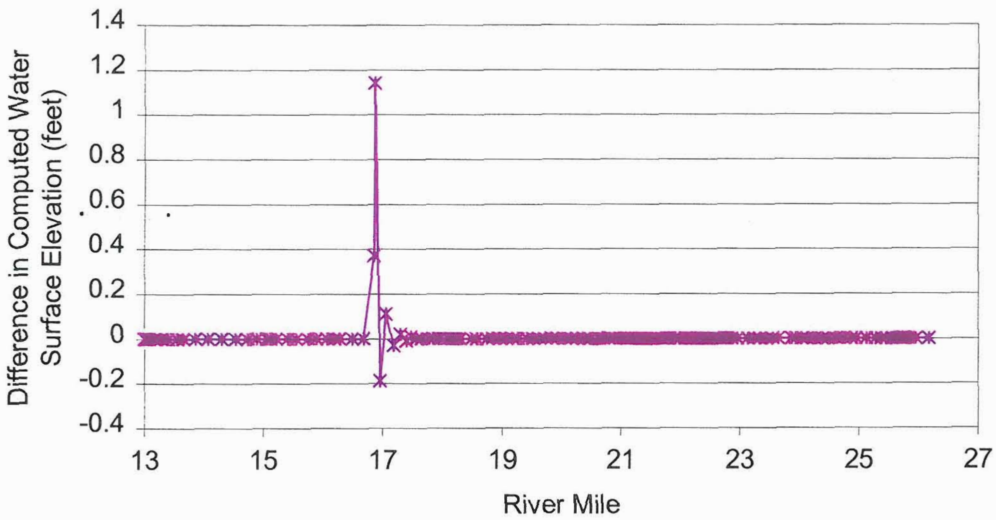


Figure 5-42. Difference in 10-year Computed Water Surface Elevation: Subcritical vs. Mixed Flow Regime. Zero difference value indicates no difference between subcritical and mixed profile water surface elevations.

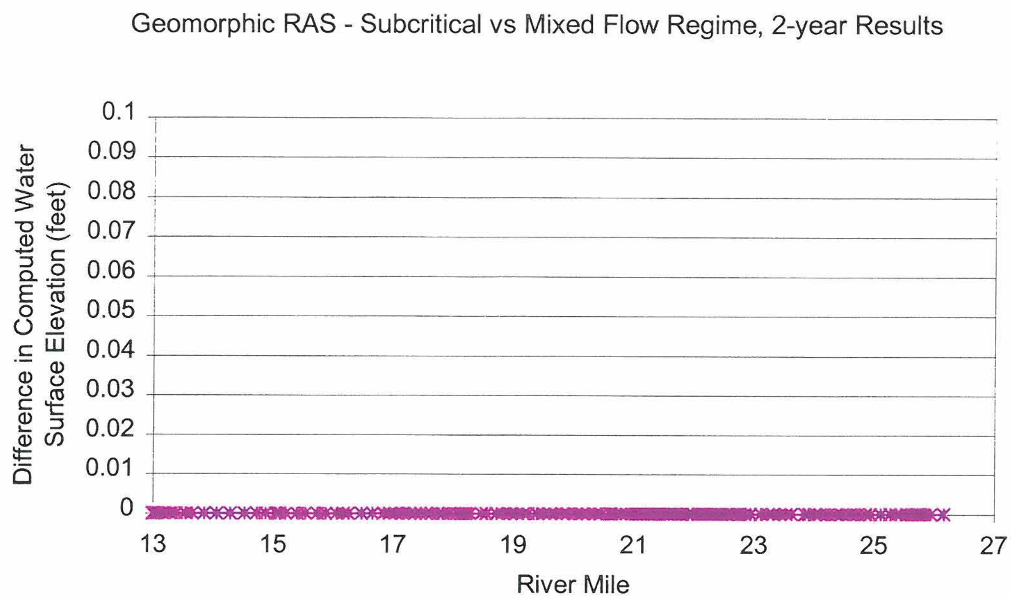


Figure 5-43. Difference in 2-year Computed Water Surface Elevation: Subcritical vs. Mixed Flow Regime. Zero difference value indicates no difference between subcritical and mixed profile water surface elevations.

For the 2-year discharge, no difference in computed water surface elevations was found between the subcritical and mixed flow regime models. For the 10-year discharges, differences were limited to one short reach at the Carefree Highway bridge. This reach is also in the area where the Tramonto development has modified the right overbank. This reach also showed higher subcritical water surface elevations in the 100-year profile. Five additional locations in the 100-year model showed differences, including a reach at the New River Road bridge. Another area with profile differences is location is at River Mile 21 near the upstream limit of a long, straight reach downstream of the Rodger Creek tributary junction.

Comparison of the subcritical and supercritical water surface profiles indicates that while the mixed flow regime model may be hydraulically more correct in a few short reaches, it is generally not very different from the modified FIS model used as the basis of the Skunk Creek Watercourse Master Plan. Therefore, to remain more consistent with the FEMA model results, the subcritical model was used for the geomorphic analyses.

Summary. The HEC-RAS modeling results could be improved by realigning cross sections, adding additional cross sections, and more carefully considering parameters that describe low flow hydraulics. However, it is noted that the converted HEC-RAS is the best available hydraulic model and that creation of a new HEC-RAS model was beyond the scope of the Watercourse Master Plan study. Therefore, for the purposes of the lateral stability assessment, it was assumed that a new HEC-RAS model would result in only minor changes to the reach-averaged hydraulic values. Such minor changes would probably be within the uncertainty of the available engineering data. That is, while the

HEC-RAS output for individual cross sections might change significantly, the reach-averaged changes will be less significant and thus will be acceptable for the intended purposes of this study.

HEC-RAS Modeling Objectives. The objectives of the HEC-RAS hydraulic analyses for the study area were to estimate the hydraulic characteristics of the study reach, to identify hydraulically similar subreaches within the study area, and to identify subreaches with limited conveyance capacity. Specific tasks included the following:

- Provide basic data for use in engineering and geomorphic analyses
- Identify hydraulically similar channel reaches
- Estimate existing channel capacity relative to return period

The basic data developed for use in the engineering and geomorphic analyses were described in the previous section of this Chapter. Channel capacity, or bankfull discharge capacity, was discussed in Chapter 4 of this report.

The HEC-RAS modeling results indicate that there is no clear hydraulic basis for identifying subreaches within the study area, as shown in Figures 5-1 to 5-39. While there are geomorphic, geographic, visual, jurisdictional and hydrologic changes along each of the four streams in the study area, these changes were not adequately expressed in the HEC-RAS output. The changes in flow depth, velocity, topwidth, energy slope, channel slope, conveyance capacity, and unit discharge could not be used to define continuous subreaches, or at least could not be tied to specific break points. Therefore, the streams were subdivided based on hydrologic, geomorphic, and geographic factors.

Sediment Data

Measurements of sediment sizes of bed, bank, and floodplain materials were obtained for use in the geomorphic and engineering analyses performed for the lateral stability assessment. This section describes the sediment sampling procedures and results.

Sediment Sampling Procedures

Sediment sampling procedures for the Watercourse Master Plan are based on the methodologies reported in the following publications:

- Wolman, M.G., 1954, "A Method of Sampling Coarse River-Bed Material," *Transactions American Geophysical Union*. December. Vol. 35, No. 6, p. 951-956.
- Kellerhals, R., 1967, "Stable Channels With Gravel-Paved Beds," Journal of the Waterways and Harbors Division, Proceedings of the American Society of Civil Engineers. February. Vol. 93, WW1, p. 63-83.
- Leopold, L.B., 1970, "An Improved Method for Size Distribution of Stream Bed Gravel," *Water Resources Research*. October. Vol. 6, No. 5, p. 1357-1366.
- Pemberton, E.L., and Lara, J.M., 1984, *Computing Degradation and Local Scour, Technical Guideline for Bureau of Reclamation*. Denver, Colorado. January.

Obtaining a representative sample of sediment material from coarse bed streams has numerous challenges. The bed material not only varies laterally within a single cross section, often with finer material at the margins of the active channel, it also varies longitudinally with distance along the channel, as well as vertically with depth below the stream bed. In pool and riffle streams such as Skunk Creek and Sonoran Wash, the longitudinal variation in grain size is not necessarily linear. In streams with bars, the bed material on the bars fines appreciably in the downstream direction, and is generally coarser than the bed material in the active channel outside the bar. Therefore, the sampling procedure selected is as much a function of the intended results of the study as of the stream type and bed material distribution. The following guidelines were used to obtain representative sediment samples:

Bed Material Size. For sand-bed stream segments (< 2.0 mm), bulk sampling and sieve analysis are recommended for samples excavated from exposed sand bars. Three samples from each cross section are recommended, which may then be combined before sampling. Bulk sampling sites should be located no more than 0.5 mile apart if the bed material is relatively uniform throughout the study reach, although right-of-entry and budget also control the sampling interval. For gravel-bed streams (> 2.0 mm), the sampling procedure depends on the study objectives. For sediment transport studies, the surface material should be sampled. For scour studies, the surface and subsurface material should be sampled.

Sieve Analysis. Sieve analyses are appropriate for small sediment sizes because the small samples can be readily transported to the laboratory for analysis. For streams like those in the study area which have coarse sediment sizes, representative sample volumes would likely exceed 300 pounds. Kellerhals (1967) reports a study where 90 tons of material were sampled for two short reaches. For sieve samples, a representative location within the section was selected for sampling. Where an armor layer was present on the channel bed, the alluvium under the armor layer was sampled.

Surface Count Sampling. Kellerhals (1967) reports the lower size limit for the surface count method at 0.5 inch, due to difficulties in estimating the diameters of the smallest sediment grains. However, use of an engineering rule and a sand grain sizing folder enables a field investigator to estimate sediment diameters accurately to the fine sand classification (< 1mm). The surface count procedure described below extends the surface count methodology to the lower limit of the range of sand clasts. If the sampling results are to be combined with sieve analysis results, a conversion from size to weight should be made, as described in Pemberton & Lara (1984). Grid sampling of a small area (e.g., 1 m^2) is acceptable unless the bed material is variable within the section.

Surface Count Procedure. The surface counting procedure used for (a.k.a. pebble counts) is summarized as follows:

1. Select the sampling location.
   a. The sampling locations should be equally spaced throughout the study reach, and should be representative of the channel characteristics. For example, on pool and

riffle streams where pools make up 75% of the stream length, about 75% of the samples should be from pools.

b. Disturbed reaches, such as active mining areas or bridge sections, should be avoided or should be distinguished from non-disturbed reaches.

c. Note that some initial field work or interpretation of aerial photographs is required.

2. Stretch a tape across the sampling section, or establish a grid by pacing. Set the sampling interval so that 75-100 measurements are taken at the section. The sampling interval should be larger than the visual estimate of the D_{50}.
3. Where the channel is too narrow to obtain 100 samples in a single section, multiple sections should be used. Each section should be located at least $5*D_{50}$ apart.
4. Measure the intermediate axis (b in Figure 5-44) of each clast located directly under the sampling interval. If the material under the sampling interval is fine-grained enough that it is difficult to tell which specific grain is under the interval marking, it is acceptable to pick up a handful of the material and estimate an average size by comparing the sediment with the grain size classifications shown in the sand sizing folder.

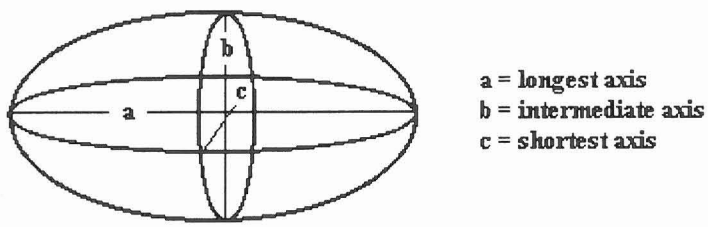


Figure 5-44. Three dimensions of a sediment grain.

For sediment grains too small to be reliably measured using the survey tape or other ruler, the sand grain sizing folder should be used. Material smaller than sand sizes should be classified as silt/clay.

5. A close-up photograph should be taken of the bed material, as well as a photograph showing the entire sampling location. Both photographs should include a scale.

Analysis of Results

1. Enter the data in a spreadsheet and use the Excel "@PERCENTILE" function to estimate the "percent-smaller" size fractions.
2. Plot the results on a frequency diagram. It is important to note that this plot is for percent of size grains, not percent by weight, as is reported for standard sieve analyses, or percent by volume.

Evaluation of Sampling Procedures. Some literature is available on the accuracy of sediment sampling techniques.

- Kellerhals (1967) reports an operator error factor that was significant at the 5% level when the pacing or stretched tape methods were used. The error presumably was due to local variability and subjectivity in determining which clast lies directly under the index mark.
- Kellerhals (1967) reports that the pacing method yields slightly coarser estimates for very coarse bed materials than the stretched tape method because the foot tends to

land on the larger grains because of their higher profile on the bed. The smaller clasts typically are visible beneath the stretched tape and are better recorded using the stretched tape method.

Results

Sediment samples were obtained for both Skunk Creek and Sonoran Wash. Sieve samples were collected at each of the channel soil pit locations. Boulder counts were completed at approximately 2,000-foot intervals at each of the channel field sections. The sediment distributions applicable to each reach were plotted on a standard sediment sampling data form and a best-fit distribution was selected by eye. The recommended sediment distributions shown in Table 5-2 were used for the engineering and geomorphic analyses presented in Chapters 4 and 5 of this report.

Table 5-2. Skunk Creek Watercourse Master Plan
Sediment Sampling Results

Reach	Mean (mm)	D90 (mm)	D84 (mm)	D50 (mm)	D16 (mm)	D10 (mm)	Max (mm)	Min (mm)
Skunk Creek								
1	28	82	58	5	0.5	0.4	213	0.2
2	30	108	66	6	0.8	0.5	225	0.1
CFR Hwy	31	128	65	6	0.4	0.2	317	0.1
3	37	109	59	6	0.6	0.4	443	0.2
4	32	93	64	9	1.2	0.9	312	0.2
5	36	92	62	9	1.7	1.5	366	0.4
6	40	118	73	16	1.4	0.7	409	0.2
NR Rd.	33	80	68	15	2.0	0.5	335	0.1
Supply	68	229	166	9	2.0	2.0	655	0.4
Sonoran Wash								
1	6	15	12	4	0.2	0.2	43	0.1
2	26	67	56	5	0.6	0.3	255	0.1
3	55	150	123	29	4.6	2.0	328	0.1
4	19	56	41	6	0.2	0.1	142	0.1
5	100	244	213	61	12.1	6.1	549	0.2
6	48	120	99	29	3.6	1.8	308	0.1
Entire	37	96	79	19	2.8	1.4	245	0.1

Notes:
1. Use entire reach average for Sonoran Wash subreaches 3, 4, 5, & 6 since samples didn't get both pools and riffles
2. CFR Hwy – Carefree Highway Bridge NR Rd. – New River Road Bridge

The plots of sediment size distribution shown in Figure 5-45 reveal several trends. First, there is a significant difference in size of the bed materials in riffles compared to the size of the bed materials in pools, as shown by the plots of the data from Skunk Creek. Therefore, sediment-related engineering analyses are highly dependent on whether bed samples are obtained from pools or riffles. Second, the data from Sonoran Wash indicate that mean sediment size varies by about an order of magnitude over the study length.

Sediment sampling data and additional plots of bed sediment distributions are provided in Figure 5-45 and in Appendix C.

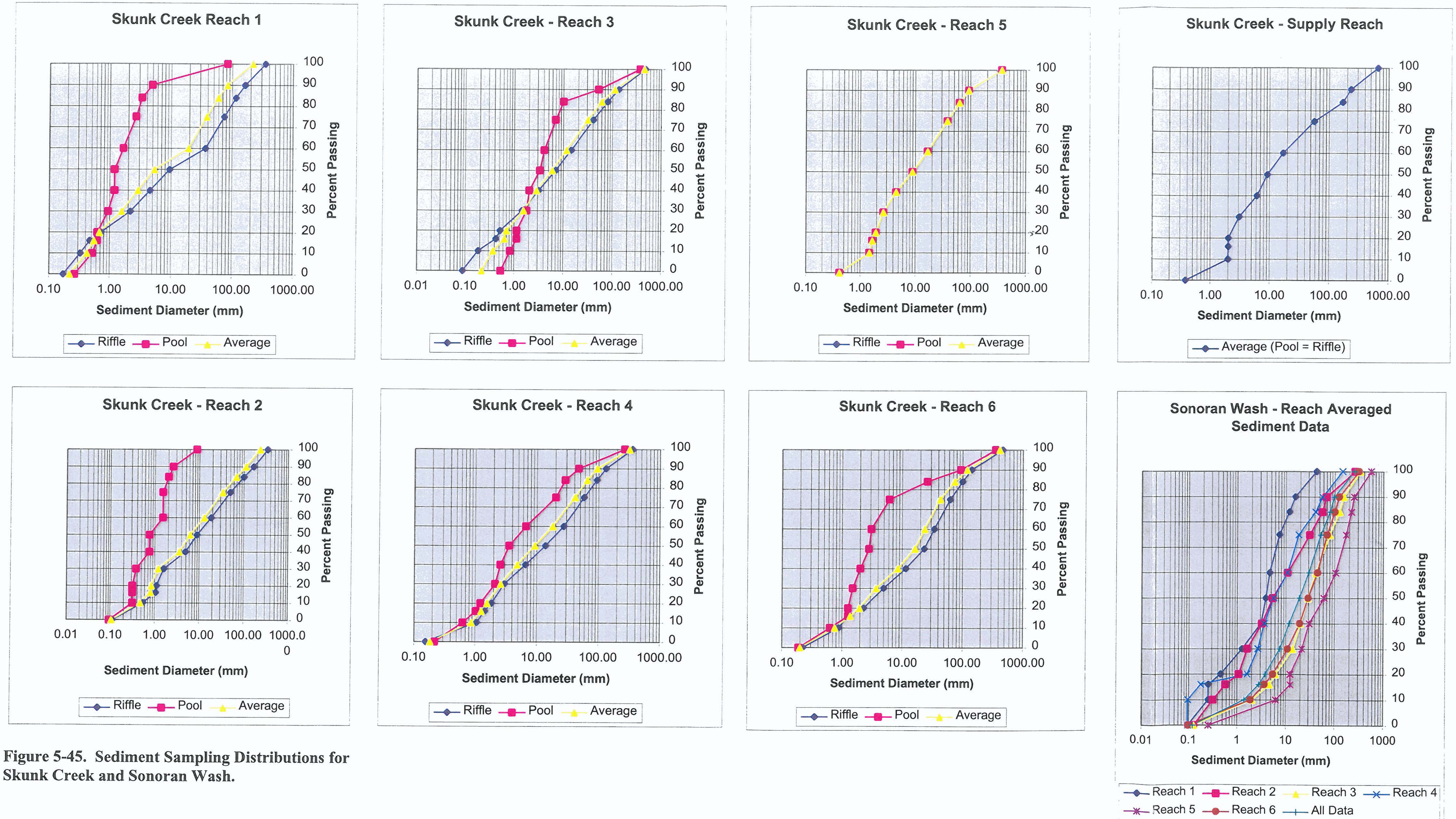


Figure 5-45. Sediment Sampling Distributions for Skunk Creek and Sonoran Wash.

Engineering Methodologies

Engineering methodologies for evaluating channel stability and estimating future bank erosion applied to the Skunk Creek/Sonoran Wash study area included the following:

- State Standard 5-96
- HEC-6 Modeling
- Allowable Velocity
- Equilibrium Slope
- Armoring
- General Scour
- Lane Relation
- AMAFCA Prudent Line

State Standard 5-96

State Standards for floodplain management have been adopted by the Arizona Department of Water Resources as the minimum required regulatory policies in the State of Arizona. State Standard 5-96 (ADWR, 1996), which was adopted in 1996, describes a methodology for estimating an erosion setback to account for lateral instability.

Limitations. The State Standard 5-96 Level 1 erosion setback methodology has the following limitations:

1. Drainage area. The Level 1 methodology is not intended to be used for streams with drainage areas larger than 30 square miles. Skunk Creek has a drainage area of about 65 square miles at CAP and 33 square miles at Cline Creek. Sonoran Wash has a drainage area of less than 30 square miles.
2. Historic channel movement. The Level 1 methodology is not to be used for streams where "massive shifting" has been observed in the past. No definition of "massive shifting" is provided in the State Standard. Comparison of historical aerial photographs and interpretation of geomorphic surfaces indicates that avulsive channel changes which could be considered massive have occurred on portions of Skunk Creek and Sonoran Wash.
3. Human impacts. The Level 1 methodology is not to be used for streams where local mining, channelization or other modifications could alter the anticipated flow direction. Some small in-stream mining occurred in at least two locations along Skunk Creek in the past, and two bridges that alter natural flow patterns have been constructed at Carefree Highway and New River Road. Except for illegal dumping of trash, several unpaved ranch road crossings, and historical grazing of the watershed, Sonoran Wash has been relatively undisturbed by human impacts.
4. Top of bank. No definition of the "top of bank" or description of how to identify the top of bank is provided in the State Standard. It is assumed that the top of bank refers to the primary bank of the main channel, rather to than the bank associated with the margin of the 100-year floodplain.

5. Aggradation. The methodology is not recommended for reaches undergoing a significant degree of channel filling (aggradation), although no guidelines are provided on how to define or determine whether this condition exists. Stantec (2000) concluded that the HEC-6 results indicate that portions of Skunk Creek are likely to aggrade. Significant aggradation has occurred on Skunk Creek at the New River Road bridge.
6. Unique site conditions. The results of the Level 1 methodology do not consider unique soil conditions or other geomorphic features, and hence could significantly underestimate or overestimate the actual erosion hazard.
7. Documentation. No supporting documentation, technical support, or useful literature citations for the recommended Level 1 equations are provided in the State Standard. There is no reason to suggest that the equations produce technically meaningful results for streams in central Arizona.

The Level 2 methodology for State Standard 5-96 does not include a procedure for estimating an erosion setback. Other limitations include the following:

1. Bank materials. Instructions for considering stratified bank materials are lacking.
2. Cohesive and vegetated bank materials. Instructions for assessing the stability of cohesive materials or well-vegetated channel banks are lacking.

Results. The results of applying the Level 1 methodology to Skunk Creek and Sonoran Wash are shown in Table 5-3. The Level 1 erosion hazard setbacks are included on Exhibit 2.

Table 5-3. Skunk Creek Watercourse Master Plan Level 1 Erosion Setback Estimates - Future & Existing Condition Hydrology							
		Q100 (cfs)	Setback (ft)		Q100 (cfs)	Setback (ft)	
		Existing Condition	Straight Channel	Curved Channel	Future Condition	Straight Channel	Curved Channel
Skunk Creek							
	S6C	7,840	89	221	8,811	94	235
	S10C	9,741	99	247	11,837	109	272
	S13C	11,811	109	272	12,587	112	280
	S14C	24,427	156	391	20,910	145	362
	S16C	27,332	165	413	23,669	154	385
	S21C2	27,733	167	416	24,642	157	392
	S22C	27,283	165	413	24,474	156	391
	S23C	26,513	163	407	24,126	155	388
Sonoran Wash							
	C002L	3,267	57	143	3,454	59	147
	C002	6,492	81	201	7,246	85	213
	C003L	6,303	79	198	5,695	75	189
	C003	8,359	91	229	6,861	83	207
	C007L	8,039	90	224	5,856	77	191
	C007	9,664	98	246	6,671	82	204
	C009	472	22	54	525	23	57
	C010L	9,203	96	240	5,889	77	192
	C010	9,825	99	248	6,098	78	195
Note: Concentration point locations (e.g. C400, 12T, etc) are described and illustrated in the Hydrology Report prepared for this study by Tetra Tech (2001).							

The results for the setback equation for straight channels are more applicable to Skunk Creek and Sonoran Wash and than the results for curved channels. Very few reaches in the study area have "obvious curvature," as defined in the State Standard. Therefore, the results of the straight channel erosion setback equation were plotted on the mapping.

Conclusions. The following conclusions can be drawn from the application of the State Standard erosion hazard methodology to Skunk Creek, Sonoran Wash, and other streams in Arizona:

- There is poor correspondence of Level 1 results to erosion hazard delineations made using the detailed (Level 3) procedures described elsewhere in this report.
- Differences in bank stability between the right and left banks of a channel are not recognized in the State Standard Level 1 methodology.
- The effects of small bends on erosion hazard are not considered in the State Standard methodology.
- The erosion hazard due to channel avulsions is not reflected in the Level 1 or 2 methodology of the State Standard.
- Geomorphic processes such as braiding or meandering that operate over extended time periods are not explicitly included in the State Standard methodology.

- The State Standard Level 1 methodology is difficult to apply in reaches with poorly defined banks or where compound banks make the bank station hard to identify.
- The State Standard Level 1 methodology does not reflect reaches with wider or narrower channels, where width adjustments are more or less likely.
- The State Standard Level 1 methodology assumes the erosion hazard is a function of only the 100-year discharge.

Because of the limitations listed above, the State Standard Level 1 and 2 methodologies are probably not applicable to Skunk Creek or Sonoran Wash, and was not considered in the definition of the erosion hazard zones described in Chapter 6 of this report. The basic Level 2 procedures, allowable velocity, tractive force, and tractive power analyses were applied to Skunk Creek and Sonoran Wash as part of the detailed geomorphic and engineering analysis of lateral stability described elsewhere in this report. However, since a more detailed Level 3 methodology was applied to the Skunk Creek/Sonoran Wash study area, the Level 1 setback results are provided only for comparison.

HEC-6 Modeling

HEC-6 models of the study area were prepared by Stantec as part of the scope of services for the Skunk Creek Watercourse Master Plan. The HEC-6 modeling effort is described in a separate report (Stantec, 2001), but is summarized here.

Overview of HEC-6 Modeling. HEC-6 was designed to simulate long-term trends of *scour* and/or deposition in a stream channel that result from changing the natural hydrology, channel geometry, or sediment supply. The U.S. Army Corps of Engineers describes the HEC-6 computer program as follows:

> *HEC-6 is a one-dimensional movable boundary open channel flow numerical model designed to simulate and predict changes in river profiles resulting from scour and deposition over moderate time periods. Continuous flow records may be partitioned into a series of steady flows of variable discharge and duration. For each flow, a water surface profile is calculated providing hydraulic data at each cross section. These hydraulic data, combined with the discharge and flow duration information, allow volumetric accounting of sediment within stream reaches. The amount of scour or deposition at each section may then be computed and the cross section bed elevation adjusted accordingly. Hydraulic data associated with the next discharge are then computed using the updated geometry, and the channel geometry is again updated. This process is repeated through the entire duration of flows. (paraphrased, p. 1, USACOE, 1993)*

HEC-6 Model Assumptions and Limitations. The HEC-6 computer model is based on the following explicit or implied assumptions:

- One Dimensional. Flow in the stream is one dimensional, i.e., the model does not account for secondary currents from meandering, eddying, or turbulence that cannot be addressed through the use of energy loss coefficients. Gradually-varied flow conditions usually are modeled adequately using a one-dimensional model (p. 5, USACOE, 1993).

- Steady Discharge. The HEC-6 model simulates passage of a flood or annual hydrograph (unsteady flow) as a series of discrete steady flows of known duration. HEC-6 is best suited to simulating channel changes from hydrographs that rise and fall gradually over a relatively long duration (p. 7, USACOE, 1993).

- Uniform Scour or Deposition. Any change in bed elevation resulting from *scour* or deposition is applied uniformly across the entire moveable portion of channel. That is, a uniform depth of sediment is added to, or subtracted from, each station (GR) point used to describe the geometry of the active channel. The formation of point or lateral bars, bend scour holes, and local scour are not simulated (p. 17, USACOE, 1993).

- Sediment Continuity. HEC-6 computes changes in bed elevation based on the principal of conservation of sediment volume, which can be summarized in the following equations:

  $$\text{Sediment}_{(in)} - \text{Sediment}_{(out)} = \text{Change in Sediment Volume}$$
  $$\text{Change in Bed Elevation} = \text{Change in Sediment Volume} \div \text{Reach Length}$$

- Initial Conditions. The initial concentration of suspended bed material is assumed to be negligible. That is, all bed material is contained in the sediment reservoir at the start of the computational interval and is returned to the sediment reservoir at the end of the interval (p. 16, USACOE, 1993)

- Time Scale. HEC-6 was developed "to predict changes in river profiles from scour and/or deposition over moderate time periods (typically years, although applications to single flood events are possible)." HEC-6 performs best for gradually changing hydraulic conditions, e.g. for large rivers with slow rising and falling hydrographs (p. 5, USACOE, 1993).

- Sediment Sources. The model assumes that there are only two sediment sources - inflowing water and the movable portion of the stream bed. HEC-6 does not consider lateral channel (bank) erosion - no sediment is supplied from the banks (p. 17, USACOE, 1993).

- Sediment Calculations. Several transport functions are coded into HEC-6, all of which apply the transport function by grain size (p. 41, USACOE, 1993).

- Equilibrium. The HEC-6 sediment transport function algorithms assume that sediment equilibrium conditions are reached during each time step of a single event, a condition which probably is not met for very short events. If equilibrium conditions are probably not established, then the modeling results should be interpreted in a qualitative manner (p. 5, USACOE, 1993).

- Time Step. Reach hydraulics and sediment transport potential are based on the channel geometry at the beginning of the time step. Therefore, the time step must be short enough that the computed change in bed elevation during a time step does not result in significant change in channel and reach geometry. Generally, a change in bed elevation of 1 foot, or 10 percent, of the flow depth is considered significant. In addition, the time step must be long enough that the flow would have sufficient time to travel through the longest stream segment[1] (p. 58, USACOE, 1993).

Table 5-4 lists these assumptions and indicates which assumptions may or may not be applicable to the study area. Given the assumptions and conditions that are not (or are marginally) valid for the study area, the HEC-6 modeling results are best suited to predicting relative trends of expected changes in the channel profiles, rather than calculating precise depths of channel scour and deposition at specific cross sections.

Table 5-4. Skunk Creek Watercourse Master Plan HEC-6 Modeling Assumptions and Limitations

Assumption/Limitation	Assumption Valid for Study Reach?
One Dimensional	No. RAS results suggest not gradually varied
Uniform Scour or Deposition	No. Braided system with bars and swales
No Bank Erosion	No. Banks unstable in design flood
Steady Flow Condition Modeled	No. Flash flood hydrograph
Sediment Continuity	Yes.
Initial Conditions for Suspended Sediment	Yes. Ephemeral stream
Time Scale of Hydrograph	No. Flash flood conditions
Sediment Sources	Yes. Bed is primary source of sediment
Sediment Calculations	Yes.
Equilibrium Achieved in Time Step	No. Short duration hydrograph
Time Step Length Adequate	Yes. Scour generally limited in time steps No. Inadequate travel time through model

Application of HEC-6 Results to Lateral Stability. The HEC-6 model does not explicitly consider bank erosion. However, HEC-6 is a sediment continuity model and computes the sediment deficit or surplus within each stream segment. The computed sediment deficit can be applied to the banks to estimate possible lateral erosion potential.

Methodology. The sediment deficit predicted by the HEC-6 models and integrated over the reach length was used to compute the volume of bank erosion required to satisfy the sediment deficit. The data required for this computation is shown in Table 5-5. Bank height was estimated from field and HEC-RAS data. The sediment deficit for each cross section and reach for the 10- and 100-event hydrographs[2] was obtained by using the $VOL record[3] in the HEC-6 input code. The deficit was applied to the left and right banks individually as if none of the deficit were satisfied from the opposite bank.

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[1] Stream segment as defined for HEC-6 is a reach with uniform discharge, no tributaries, or special conditions.

[2] The 25- and 100-year hydrographs were used for Sonoran Wash HEC-6 modeling.

[3] See USACOE (1993) for complete explanation of the $VOL record. The $VOL record controls the level and type of output from the HEC-6 model.

The sediment deficit and bank erosion distance was translated to average annual and long-term estimates using a probability weighting procedure based on equations and methodologies recommended or used in the following publications:

- FEMA, 1999, Riverine Erosion Hazard Area Study.
- Lagasse, P.F., and Schall, J.D., 1988, Delineation of Flooding and Erosion Buffer for a Southwestern Arroyo, ASFPM Conference on Arid West Floodplain Management Issues, Las Vegas, Nevada, October 19-21, 1988.
- Resource Consultants and Engineers, Inc., 1994, AMAFCA Sediment and Erosion Design Guide.

Probability weighting is typically computed using event specific values from the 2-, 5-, 10-, 25-, 50-, and 100-year events, or as many of these recurrence intervals for which data are available (ADWR, 1985). Since only the 10- and 100-year events were modeled using HEC-6 for this study, the probability weighting equation[4] was modified to the following:

$$X_{wtd} = 0.01\ X_{100} + 0.09\ (X_{100} + X_{10})/2 + 0.9\ (X_{10} + 0)/2$$

Where:
X_{wtd} = weighted average annual erosion distance
X_{100} = predicted erosion distance for the 100-year event
X_{10} = predicted erosion distance for the 10-year event

This equation can be reduced to the following form:

$$X_{wtd} = 0.055\ X_{100} + 0.495\ X_{10}$$

The expected long-term erosion distance for a 60 year period, the designated planning period for the Skunk Creek Watercourse Master Plan, can then be estimated using the following equation:

$$X_{tot} = 60 * X_{wtd}$$

The erosion distance was then estimated by averaging the predicted erosion distance for individual cross sections within each reach. Cross sections with an estimated sediment surplus were considered to have a zero bank erosion distance, and the reach-average value was used.

Results. The results of the HEC-6 based bank erosion estimates are shown in Table 5-5. In general, the HEC-6 results indicate that bank erosion can be expected throughout the study area during large floods, although the results also depict some of the difficulties of applying the HEC-6 model to Skunk Creek and Sonoran Wash. For example, greater

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[4] The probability weighting equation for Sonoran Wash, which was based on the 25- and 100-year events is $X_{wtd} = 0.01\ X_{100} + 0.03\ (X_{100} + X_{25})/2 + 0.96\ (X_{25} + 0)/2$, which can be reduced to $X_{wtd} = 0.025\ X_{100} + 0.495\ X_{25}$

Table 5-5. Skunk Creek Watercourse Master Plan
HEC-6 Sediment Deficit Translation to Bank Erosion Distance Estimates (ft)

Reach	Bank Height Left (ft)	Bank Height Right (ft)	Channel Reach Length (ft)	HEC6 Deficit Q100 TOTAL yd^3	HEC6 Deficit Q10 TOTAL yd^3	Deficit Applied to Bank (ft) Left Bank (ft) Q100 Total	Left Bank (ft) Q10 Total	Right Bank (ft) Q100 Total	Right Bank (ft) Q10 Total	Erosion Distance (ft) Average Annual Left	Average Annual Right	Project Planning Period 100-Year Event Left	100-Year Event Right	Long-Term Left	Long-Term Right
Skunk Creek															
Supply	8	8	668	28	-215	-3	-4	-3	-3	-2	-2	-3	-3	-130	-108
NR	5	5	253	354	180	-9	-12	-8	-11	-7	-6	-9	-8	-408	-376
6	7	7	638	-57	24	-4	-2	-5	-2	-1	-1	-4	-5	-79	-94
5	7	7	520	-38	-21	-9	-5	-9	-5	-3	-3	-9	-9	-182	-194
4	6	6	484	9	7	-9	-5	-7	-4	-3	-2	-9	-7	-182	-152
3	5	6	536	-493	-131	-21	-11	-22	-12	-7	-7	-21	-22	-429	-457
CFR	15	15	440	1351	544	0	0	0	0	0	0	0	0	0	0
2	8	8	785	310	56	-6	-4	-6	-3	-2	-2	-6	-6	-140	-128
1	8	7	710	132	158	-7	-1	-7	-2	-1	-1	-7	-7	-72	-74

Sonoran Wash

Reach	Bank Height Left (ft)	Bank Height Right (ft)	Channel Reach Length (ft)	HEC6 Deficit Q100 TOTAL yd^3	HEC6 Deficit Q25 TOTAL yd^3	Deficit Applied to Bank (ft) Left Bank (ft) Q100 Total	Left Bank (ft) Q25 Total	Right Bank (ft) Q100 Total	Right Bank (ft) Q25 Total	Erosion Distance (ft) Average Annual Left	Average Annual Right	Project Planning Period 100-Year Event Left	100-Year Event Right	Long-Term Left	Long-Term Right
6	3	4	227	-18	-8	-1	-2	-1	-2	-1	-1	-1	-1	-52	-49
5	4	4	349	-43	-39	-2	-2	-2	-2	-1	-1	-2	-2	-49	-49
4	5	5	286	26	9	-1	-1	-1	-1	-1	-1	-1	-1	-34	-31
3	6	5	370	5	5	-1	-1	-1	-1	0	0	-1	-1	-21	-24
2	6	6	332	-2	-3	-1	-2	-1	-2	-1	-1	-1	-1	-50	-50
1	5	5	375	41	39	-1	-1	-1	-1	-1	-1	-1	-1	-31	-31

erosion distances are predicted for the 10-year event than for the 100-year event in some reaches, probably due to the cross section alignment and geometry deficiencies of the FEMA HEC-2 models described above. Despite these difficulties, the HEC-6 results reasonably simulate the bank erosion distances observed in the study reach during the field visits. Therefore, the HEC-6 results can be used as one method to estimate expected lateral erosion, but probably represent no better than order-of-magnitude estimates. HEC-6 modeling results are also discussed in the *Skunk Creek Watercourse Master Plan Attachment 5 – Phase 1 Erosion and Sedimentation Technical Data Notebook* prepared by Stantec (2001).

Allowable Velocity

Allowable velocity criteria have long been used in channel design to estimate the velocity at which channel bed and bank sediments will begin to erode. A variety of allowable velocity data have been published by the Corps of Engineers (1970, 1990), the Soil Conservation Service (1977), and others (cf., Pemberton and Lara (BUREC), 1984).

Methodology. The following allowable velocity approaches were applied to the four major streams in the study area:

- Fortier & Scobey Table
- BUREC/Mavis & Laushey Equation
- Neill Equation
- USACOE Permissible Velocity Tables

Fortier & Scobey Table. Fortier and Scobey (1926) published one of the first tables of permissible velocity in 1926. Their data, based on records of seasoned stable canals, was later republished by a number of federal agencies and other organizations including the FHWA, ASCE, and Chow (MacBroom, 1981). The Fortier and Scobey data (Table 5-6) distinguish erosion hazards for clear water, silt-laden water, and water transporting sand and gravel (bedload). Their data presumably do not account for the stabilizing effect of bank vegetation.

Table 5-6. Skunk Creek Watercourse Master Plan
Fortier & Scobey Table of Permissible Canal Velocities (ft/s)

Bank Material	Clear Water	Silt-Laden	Sand/Gravel Bedload
Sandy Loam	1.75	2.50	2.00
Firm Loam	2.50	3.50	2.25
Fine Gravel	2.50	5.00	3.75
Stiff Clay	3.75	5.00	3.00
Coarse Gravel	4.00	5.50	6.50
Cobbles	5.00	5.50	6.50

BUREC/Mavis & Laushey Equation. The BUREC (1974) recommends that permissible velocity be estimated using a modification of the Mavis and Laushey equation (Jurnikis, 1971), which was developed by bridge engineers in Great Britain (MacBroom, 1981). The BUREC equation is a function of grain size, and is most applicable to bed material.

$V_b = 0.64\ D^{(4/9)}$ for $D < 6.0$ mm
$V_b = 0.5\ D^{1/2}$ for $D > 6.0$ mm

Where V_b = competent velocity (ft/sec)
D = particle diameter (mm)

Neill Equation. Neill (1975) developed equations that are a function of flow depth and grain size for permissible velocities on gravel and cobble bed streams, with a separate equation for cohesive soils.

$V_b = 3.15\ d^{(1/3)}\ D^{(2/3)}$ (non-cohesive soils)
$V_b = 7.5\ d^{(1/6)}\ \tau_c^{1/2}$ (for cohesive soils)

Where V_b = competent velocity (ft/sec)
d = flow depth (ft)
D = grain size (ft)
τ_c = critical shear stress (lb/ft^2)

USACOE Permissible Velocity. The Corps of Engineers (1970; 1995) has established suggested maximum velocities for design of non-scouring flood control channels, as shown in Table 5-7.

Table 5-7. Skunk Creek Watercourse Master Plan
Suggested Maximum Permissible Mean Channel Velocities (USACOE, 1995)

Channel Material	Mean Velocity (ft/sec)
Fine Sand	2.0
Fine Gravel	6.0
Grass-Lined Banks (< 5% Slope, Sandy Silt, Bermuda Grass)	8.0
Poor Rock (Sedimentary)	10.0
Good Rock (Igneous or Metamorphic)	20.0

The Corps of Engineers (1990) has also developed criteria relating flow depth and velocity to the beginning of movement of granular bed materials and erosion of cohesive bank materials, as summarized in Table 5-8.

Table 5-8. Skunk Creek Watercourse Master Plan
Corps of Engineers Erosive Velocity Data

Grain Size (mm)	Flow Depth (ft)	Velocity (ft/sec)	Cohesiveness	Flow Depth (ft)	Velocity (ft/sec)
1 (sand)	5 10	2.5 4.0	Very Soft	5 10	2.0 2.5
10 (gravel)	5 10	4.5 5.5	Average	5 10	3.5 4.0
100 (cobbles)	5 10	9.5 10.5	Very Stiff	5 10	5.5 6.0

Results. Using the 2-, 10-, and 100-year velocities, and bed sediment characteristics, the four methodologies described above were applied to the stream reaches on Skunk Creek and Sonoran Wash. Mean channel velocity for each stream reach is shown in Table 5-9.

Table 5-9. Skunk Creek Watercourse Master Plan
Reach-Averaged Channel Velocity (ft/s)

Reach	2-Year	10-Year	100-Year
Skunk Creek			
SR	4.7	10.1	9.8
NR B	2.5	4.9	6.5
6	3.8	7.5	9.3
5	4.3	7.1	10.4
4	4.4	9.5	10.5
3	3.8	9.7	11.8
CFR B	2.9	9.1	10.9
2	4.0	10.2	12.1
1	3.7	8.3	9.4
Sonoran Wash			
6	3.1	8.3	8.9
5	3.3	8.9	9.7
4	3.5	8.4	9.1
3	3.6	8.4	8.9
2	3.5	7.9	8.6
1	3.0	7.1	7.5

The reach-averaged velocities estimated from the HEC-RAS models for the 2-, 10-, and 100-year events were then compared to the allowable velocities determined by the methodologies described above, as shown in Tables 5-10 and 5-11. Where the allowable velocities are exceeded by the predicted HEC-RAS reach-averaged velocity, erosion (E) is expected. Where the allowable velocities are not exceeded, the channel is expected to be stable (S). The number listed after S or E in Tables 5-10 and 5-11 indicate the percent of the cross sections within the reach which exhibit the S or E trend.

Skunk Creek. Most of the methodologies used indicate that the banks of Skunk Creek are erodible throughout the entire study reach. However, Neill's equation for cohesive soils predicts that the banks will be stable up to the 100-year event, even though the 100-year channel velocities approach or exceed the USACOE values of erodibility for igneous bedrock (Table 5-10). Comparison of HEC-RAS channel velocities with the USACOE and Fortier & Scobey erosive velocity thresholds indicate that the channel banks are probably stable during the 2-year event, but erodible during flows that exceed the 100-year event.

Table 5-10. Skunk Creek Watercourse Master Plan Allowable Velocity Results – Skunk Creek							
Reach	Fortier & Scobey	BUREC	Neill: Non-Cohesive		Neill: Cohesive		USACOE
			Erosive?	Velocity	Erosive?	Velocity	
2-Year							
Supply	S 67	E 100	E 100	1.5	S 100	8.4	S 100
NR	S 100	E 60	E 60	1.9	S 100	4.4	S 100
6	S 94	E 100	E 100	2.2	S 100	6.8	S 100
5	S 81	E 100	E 100	1.5	S 100	7.6	S 100
4	S 72	E 100	E 100	1.6	S 100	7.5	S 97
3	S 88	E 94	E 94	1.1	S 100	6.0	S 100
CFR	S 100	E 100	E 100	1.0	S 100	4.6	S 100
2	S 92	E 100	E 100	1.2	S 100	6.5	S 100
1	S 93	E 100	E 100	1.0	S 86	5.4	S 100
10-Year							
Supply	E 100	E 100	E 100	2.3	S 100	18.2	E 100
NR	S 60	E 80	E 80	3.0	S 100	8.7	S 60
6	E 81	E 100	E 100	3.3	S 100	13.5	E 81
5	E 70	E 100	E 96	2.3	S 100	13.0	E 67
4	E 100	E 100	E 100	2.4	S 100	16.1	E 100
3	E 100	E 100	E 100	1.8	S 100	15.5	E 100
CFR	E 100	E 100	E 100	1.7	S 100	14.6	E 100
2	E 100	E 100	E 100	1.9	S 100	16.4	E 100
1	E 100	E 100	E 100	1.6	S 86	11.9	E 86
100-Year							
Supply	E 100	E 100	E 100	2.4	S 100	17.6	E 100
NR	E 60	E 100	E 100	3.3	S 100	11.9	E 60
6	E 100	E 100	E 100	3.6	S 100	16.7	E 94
5	E 94	E 100	E 100	2.5	S 100	19.0	E 67
4	E 100	E 100	E 100	2.6	S 100	18.1	E 100
3	E 100	E 100	E 100	2.0	S 100	18.8	E 100
CFR	E 100	E 100	E 100	2.0	S 100	17.5	E 100
2	E 100	E 100	E 100	2.1	S 100	19.5	E 100
1	E 93	E 100	E 100	1.7	S 86	13.1	E 86
Notes: E = allowable velocity exceeded; erosion expected S = allowable velocity not exceeded; erosion not expected E_{100} = 100 % of sections in reach have indicated erosive trend, E_{87} = 87 % of sections in reach, etc.							

Sonoran Wash. Most of the methodologies used indicate that the banks of Sonoran Wash are erodible throughout the entire study reach for events above the 2-year flood. However, Neill's equation for cohesive soils predicts that the banks will be stable up to the 100-year event, even though the 100-year channel velocities approach the USACOE values of erodibility for soft sedimentary bedrock. The results shown in Table 5-11 indicate that Sonoran Wash is subject to erosion at higher flow rates and that cohesion of the bank materials significantly affects erodibility.

Table 5-11. Skunk Creek Watercourse Master Plan Allowable Velocity (ft/s) Results –Sonoran Wash							
Reach	Fortier & Scobey	BUREC	Neill: Non-Cohesive		Neill: Cohesive		USACOE
			Erosive?	Velocity	Erosive?	Velocity	
2-Year							
6	S_{100}	E_{100}	E_{71}	2.4	S_{100}	5.5	S_{100}
5	S_{100}	E_{90}	E_{70}	2.4	S_{100}	5.9	S_{100}
4	S_{91}	E_{91}	E_{82}	2.4	S_{100}	6.4	S_{100}
3	S_{100}	E_{100}	E_{89}	2.6	S_{100}	6.3	S_{100}
2	S_{89}	E_{100}	E_{100}	1.1	S_{100}	5.5	S_{100}
1	S_{100}	E_{100}	E_{100}	0.8	S_{89}	4.0	S_{100}
10-Year							
6	E_{100}	E_{100}	E_{100}	4.0	S_{100}	17.6	E_{100}
5	E_{100}	E_{100}	E_{100}	4.2	S_{100}	16.9	E_{90}
4	E_{100}	E_{100}	E_{100}	4.1	S_{100}	16.1	E_{91}
3	E_{100}	E_{100}	E_{100}	4.1	S_{100}	15.2	E_{100}
2	E_{100}	E_{100}	E_{100}	1.7	S_{100}	13.6	E_{100}
1	E_{100}	E_{100}	E_{100}	1.3	S_{89}	10.2	E_{100}
100-Year							
6	E_{100}	E_{100}	E_{100}	4.3	S_{100}	19.3	E_{100}
5	E_{100}	E_{100}	E_{100}	4.4	S_{100}	18.7	E_{100}
4	E_{100}	E_{100}	E_{100}	4.3	S_{100}	17.5	E_{100}
3	E_{100}	E_{100}	E_{100}	4.3	S_{100}	16.7	E_{100}
2	E_{100}	E_{100}	E_{100}	1.8	S_{100}	15.2	E_{100}
1	E_{100}	E_{100}	E_{100}	1.4	E_{89}	10.8	E_{56}

Notes:
E = allowable velocity exceeded; erosion expected
S = allowable velocity not exceeded; erosion not expected
E_{100} = 100 % of sections in reach have indicated erosive trend, E_{87} = 87 % of sections in reach, etc.

Conclusions. Allowable velocity criteria provide general information on the likelihood of bank and channel erosion. However, accurate predictions of lateral stability based on allowable velocity criteria are difficult to achieve because of the effect of soil cohesiveness on erodibility. The range of allowable velocities indicated by the Neill equations illustrates the effect of cohesion on erodibility. Broadly interpreted, the allowable velocity data indicate that all of the channel banks in the study area will erode even in small floods if the banks are not cohesive, but will resist erosion if they are cohesive. Additional uncertainty in allowable velocity predictions is caused by the effects of bank vegetation (increase stability), stratified bank sediments (decrease stability), and other local variations ($CaCO_3$ content, piping, bed scour, etc.).

Equilibrium Slope

Equilibrium slope[5] is defined as the slope which causes the channel's sediment transport capacity to equal the incoming sediment supply (ADWR, 1985). If the slope is too steep, channel velocities will be high and net erosion will occur. If the slope is too flat, channel velocities will be low and net deposition will occur. The equilibrium slope is the slope that the undisturbed, natural channel will tend towards over the long term. While there

[5] Equilibrium slope is also referred to as stable slope or limiting slope.

are philosophical and practical problems with applying equilibrium slope concepts to small ephemeral streams with variable channel geometry and high flash flood potential, equilibrium slope equations provide a useful order-of-magnitude assessment of the likelihood of vertical channel adjustments.

Methodology. Reach-averaged data required for application of equilibrium slope equations to the study area were derived from the following sources:

- Hydraulic data - HEC-RAS modeling (Chapter 5)
- Hydrologic data - HEC-1 modeling and USGS gauge records (Chapter 2)
- Topographic data – Floodplain delineation studies (Chapter 5)

Most equilibrium slope equations are based on the mean annual flood, the "channel-forming," or "bankfull" discharge. On many alluvial streams, the mean annual flood and the channel-forming and bankfull discharges are nearly equivalent. However, on ungauged ephemeral streams where flow events are rare, the average annual discharge (Figure 2-5 to 2-7) is difficult to determine. Bankfull discharge estimates were described in Chapter 4, and ranged from the 10- to 30-year event for Skunk Creek (60- to 100-year for the bridge reaches; Table 4-5) and from the 4- to 8-year event for Sonoran Wash (Table 4-6). To account for the discrepancies in what flow rate is appropriate for equilibrium slope analyses, and to assess the trend of expected slope adjustments during floods, the 2-, 10-, and 100-year peaks were used in the equilibrium slope equations to assess the expected slope adjustment over a range of discharges. The 2-year event approximates the mean annual flood calculated on a weighted probability basis. The 10-year event better approximates bankfull conditions on the streams in the study area. The 100-year event represents possible channel responses during extreme flooding. The following equilibrium slope equations were applied to the study reach:

- Albuquerque Metropolitan Arroyo Flood Control Authority (AMAFCA) Equations
- BUREC Equation
- Bray Equation
- Henderson Equation
- Schoklitsch Equation
- Meyer-Peter Muller Equation
- Shield's Diagram Method
- Lane's Tractive Force Method

AMAFCA Equation. The AMAFCA (1994) equation for the maximum equilibrium slope is based on the sediment transport characteristics of the reach.

$$S_L = \left(\frac{a}{q_s}\right)^{\frac{10}{3(c-b)}} q^{\frac{2(2b+3c)}{3(c-b)}} \left(\frac{n}{1.49}\right)$$

Where S_L = channel slope (ft./ft.)

q_s = unit sediment transport (cfs/ft)
q = water discharge (cfs)
n = Manning's roughness
a, b, c = power function coefficients from sediment transport function

A simplified version of the AMAFCA Equation is written for wide, rectangular channels, similar to the those in the study area, based on the assumptions that steep, wide, rectangular alluvial streams flow at or close to critical depth and that sediment supply is transport limited.[6]

$$S_s = 18.28\, n^2\, F^{0.133}\, F_r^{2.133}\, Q_{dd}^{-0.133}$$

Where S_s = Stable slope (ft/ft)
n = Manning's roughness value for the channel
F = Width/depth ratio of the channel
F_r = Froude number for the channel
Q_{dd} = Dominant discharge (cfs)

BUREC Equation. The BUREC published an equation for stable slope based on theoretical considerations of sediment transport (MacBroom, 1981).

$$S_L = (0.00021\, D_{50}\, W_{bf} / Q)^{0.75}$$

Where S_L = Stable slope (ft/ft)
D_{50} = Bed sediment diameter (ft)
W_{bf} = Channel width (ft)
Q = Discharge (cfs)

Bray Equation. Bray's (1979) equation for equilibrium slope is based on regime analysis of perennial gravel bed streams in Alberta, Canada.

$$S_L = 0.965\, Q_2^{-0.344}\, D_{50}^{0.58}$$

Where S_L = Equilibrium slope (ft/ft)
D_{50} = Mean bed sediment diameter (ft)
Q_2 = 2-year discharge (cfs)

Henderson Equation. To generate an equation for the slope of stable channels, Henderson (1961) modified the Lane (1952) equations using a threshold theory of shear stress concept.

$$S_L = 0.44\, D_{90}^{1.15}\, Q^{-0.46}$$

Where S_L = Stable slope (ft/ft)

[6] Transport limited means that the sediment inflow equals or exceeds the reach transport capacity.

D_{90} = Bed sediment diameter for which 90 percent is smaller (ft)
Q = Discharge (cfs)

The BUREC (Pemberton and Lara, 1984) published a manual for computing scour and channel degradation downstream of dams or other structures that interrupt the natural sediment supply to the downstream channel. The BUREC manual describes the following four approaches for estimating equilibrium slope: (1) Schoklitsch Equation, (2) Meyer-Peter Muller Equation, (3) Shield's Diagram Method, and (4) Lane's Tractive Force Method. The approaches are based on the assumption of zero sediment transport. Therefore, these results represent a minimum probable slope for the streams in the study area, unless their watersheds become intensely urbanized and the sediment supply is drastically reduced.

Schoklitsch Equation. The Schoklitsch (Shulits, 1935) equation is based on the concept of zero bedload transport.

$$S_L = K_s\,(D\,W_{bf}/Q)^{3/4}$$

Where S_L = Stable slope (ft/ft)
K_s = 0.00174 (constant)
W_{bf} = Bankfull width (ft)
D = Mean bed sediment diameter (mm)
Q = Dominant discharge (cfs)

Meyer-Peter, Muller Equation. The Meyer-Peter, Muller (1948) equation is based on the incipient motion theory, or the point of initiation of sediment transport.

$$S_L = K_{mpm}\,(Q/Q_{bf})\,(n_s/D_{90}^{\;1/6})^{3/2}\,D\,/\,d$$

Where S_L = Stable slope (ft/ft)
K_{mpm} = 0.19 (constant)
Q = Total discharge
Q_{bf} = Dominant (bankfull) discharge (cfs); flow over the channel
n_s = Manning's n for the stream bed
D_{90} = Bed sediment diameter for which 90 percent is smaller (mm)
D = Mean sediment diameter (mm)
d = Channel depth (ft)

Shields Diagram Method. The Shields diagram (1936) for determining the boundary condition for no sediment transport can be used to define an equation for stable slope.

$$R_* = U_*\,D\,/\,\upsilon$$
$$U_* = (S_L\,R\,g)^{1/2}$$
$$T_* = \tau_c\,/\,((\gamma_s - \gamma_w)\,D\,)$$

Where S_L = Stable slope (ft/ft)

R_* = Boundary Reynold's number
U_* = Shear velocity = $(S_L\ R\ g)^{\wedge 0.5}$
D = Mean sediment diameter (mm)
υ = Kinematic velocity of water (ft/sec^2)
R = Hydraulic radius for wide channels (ft)
g = Gravitational constant = 32.2 ft/sec^2
T_* = Dimensionless shear stress
τ_c = Critical shear stress (lb/ft^2)
γ_s = Specific weight of sediment (lb/ft^3)
γ_w = Specific weight of water (lb/ft^3)

Lane's Tractive Force Method. Lane's equation (1952) for stable slope uses critical tractive force relationships.

$$S_L = (\tau_c/\gamma_w)\ d$$

Where S_L = Stable slope (ft/ft)
d = Mean flow depth (ft)
τ_c = Critical shear stress (lb/ft^2)
γ_w = Specific weight of water (lb/ft^3)

Results. The results of the equilibrium slope analyses are shown in Tables 5-12 and 5-13 on the following pages. Because the Schoklitsch, Meyer-Peter Muller, Shield's Diagram, and Lane's Tractive Force results represent minimum slopes, they are averaged separately than the results for the AMAFCA, BUREC, Bray, and Henderson equations. Long-term degradation (or aggradation) can be predicted by comparing the equilibrium slope and existing channel slopes for a given reach. If the predicted equilibrium slope is less than the existing channel slope, long-term degradation should be expected. Conversely, if the predicted equilibrium slope is greater than the existing channel slope, long-term aggradation should be expected. Where long-term degradation occurs, lateral instability occurs by undercutting the channel banks. Where long-term aggradation occurs, lateral instability occurs due to braiding and avulsions. The magnitude of long-term degradation or aggradation cannot be reliably predicted using the equilibrium slope equation, although the strength of the trend in either direction probably can. The strongest trends are predicted where the difference between the average equilibrium slope and the existing channel slope is greatest.

In general, the equilibrium slope equations indicate that long-term degradation will occur in the study area in response to large floods, with deposition during the smaller floods, which supports the conclusions of the bankfull discharge analysis (Chapter 4), as well as the armoring and scour calculations presented in this Chapter. Also, a greater degree of degradation is predicted when the 10- and 100-year peak discharges are used in the equilibrium slope equations than when the 2-year discharge is used. The difference in expected slope adjustment between large and small floods highlights the sensitivity of Skunk Creek to the flood series. That is, if a series of small floods occur over time without a significant major flood, less channel change may occur than if a series of very large events occur. Finally, the four equilibrium slope equations that assume no sediment inflow almost always predict long-term scour, which serves as a warning that watershed development guidelines should address sediment supply issues to assure channel stability.

Skunk Creek. The following trends are indicated by the predicted equilibrium slope values for each reach of Skunk Creek shown in Table 5-12:

- Supply Reach. The supply reach has the highest existing channel slope, and is most sensitive to alteration of the watershed sediment supply. Except during for the equilibrium slopes predicted using the 2-year discharge, long-term degradation is predicted, with much of the degradation likely to occur during the largest floods.

- New River Road Bridge (NRB) Reach. The New River Road bridge reach is the only reach in the study area where any of the zero sediment inflow equilibrium slope equations predict long-term aggradation. The Meyer-Peter Muller equation predicts aggradation even during the 100-year event. These results indicate how far out of equilibrium this reach became due to excavation of the main channel and floodplain during construction of the New River Road bridge, and confirms the observations of deposition made over the duration of this study (Chapter 2).

- Reach 6. Due to the high equilibrium slope values predicted by the Bray equation, aggradation is predicted for Reach 6, assuming that the watershed sediment supply remains unchanged. Nearly all the other equations predict long-term degradation, particularly during large floods.

- Reach 5. Long-term degradation is predicted for Reach 5. The tendency for long-term degradation in Reach 5 may be due to increased water supply downstream of the Cline Creek confluence. Alternatively, it is noted that the existing channel slope of Reach 5 is greater than the next upstream (Reach 6) and downstream (Reach 4) reaches, indicating that degradation must occur to achieve a more uniform concave up profile.

- Reaches 4 and 3. Net aggradation is predicted for Reaches 3 and 4 during small floods, with net long-term degradation during the largest floods.

- Carefree Highway Bridge (CFR) Reach. A stronger trend toward net long-term aggradation is predicted by the equilibrium slope equations for the Carefree Highway bridge reach, although not as strongly as for the New River bridge reach. Aggradation is likely during floods up to the 10-year event, with slight net scour occurring during the 100-year event, assuming the watershed sediment supply remains unchanged. Development at the Tramonto subdivision could reduce the local sediment supply and decrease the potential for aggradation at Carefree Highway. The predicted trend toward aggradation is primarily due to channel widening caused by bridge construction.

- Reach 2. Net long-term degradation is predicted for reach 2. The average equilibrium slope computed using the 2-year discharge is approximately equal to the existing channel slope, a result which indicates overall stability.

- Reach 1. Aggradation during small floods and degradation during large floods is predicted by the equilibrium slope equations for Reach 1. Note that the equilibrium slope equations do not explicitly consider the effects of backwater at the CAP overchute, which is likely to induce deposition during the largest events.

Sonoran Wash. As shown in Table 5-13, the predicted equilibrium slope trends for Sonoran Wash are generally consistent throughout all six study reaches. A strong trend toward aggradation during small and moderate floods is predicted, with a slightly less strong trend toward aggradation during the largest floods. The equilibrium slope equations which assume no sediment inflow uniformly predict long-term degradation, underscoring the importance of watershed management in maintaining channel stability.

Summary. The scour and deposition caused by the channel's adjustment to its equilibrium slope will be limited to a reach length sufficient for the channel to regain a sediment transport balance. In general, long-term aggradation is predicted for the periods dominated by small floods, with long-term degradation more likely to occur during periods dominated by large floods. The greatest amount of expected slope adjustments will occur in the reaches disturbed by bridge construction. In the bridge reaches, the equilibrium slope equations predict long-term aggradation. The actual magnitude of the expected bed elevation changes will be based in part on the potential for armoring, sediment supply, and the magnitude and frequency of the flows experienced in the future.

Table 5-12. Skunk Creek Watercourse Master Plan
Equilibrium Slope Analysis Results – Skunk Creek (ft/ft)

Method	Supply Reach			NRB Reach			Reach 6			Reach 5			Reach 4		
	Q2	Q10	Q100	Q2	Q10	Q100	Q2	Q10	Q100	Q2	Q10	Q100	Q2	Q10	Q100
Schoklitsch	0.0023	0.0005	0.0005	0.0082	0.0019	0.0012	0.0045	0.0012	0.0008	0.0023	0.0007	0.0004	0.0024	0.0005	0.0004
Meyer-Peter, Muller	0.0033	0.0010	0.0013	0.0093	0.0131	0.0127	0.0073	0.0053	0.0051	0.0042	0.0041	0.0037	0.0061	0.0025	0.0030
Shields	0.0021	0.0006	0.0005	0.0045	0.0012	0.0010	0.0038	0.0011	0.0009	0.0018	0.0005	0.0004	0.0018	0.0005	0.0004
Lane	0.0018	0.0005	0.0004	0.0039	0.0010	0.0009	0.0033	0.0010	0.0008	0.0016	0.0004	0.0004	0.0016	0.0004	0.0004
Average	0.0024	0.0007	0.0007	0.0065	0.0043	0.0039	0.0047	0.0021	0.0019	0.0024	0.0014	0.0012	0.0030	0.0010	0.0010
Bray	0.0215	0.0237	0.0237	0.0289	0.0319	0.0319	0.0274	0.0308	0.0308	0.0171	0.0173	0.0173	0.0165	0.0168	0.0169
Henderson	0.0276	0.0068	0.0062	0.0083	0.0035	0.0026	0.0117	0.0039	0.0030	0.0075	0.0028	0.0021	0.0073	0.0022	0.0019
BUREC	0.0053	0.0005	0.0005	0.0103	0.0020	0.0012	0.0073	0.0012	0.0008	0.0039	0.0008	0.0005	0.0037	0.0005	0.0004
AMAFCA	0.0145	0.0118	0.0085	0.0050	0.0045	0.0059	0.0089	0.0066	0.0072	0.0094	0.0059	0.0078	0.0085	0.0071	0.0071
Average	0.0172	0.0107	0.0097	0.0131	0.0105	0.0104	0.0138	0.0106	0.0104	0.0095	0.0067	0.0069	0.0090	0.0067	0.0066
Measured Slope	0.0130			0.0062			0.0093			0.0097			.0085		
Predicted Trend	Low flow aggradation High flow degradation			Aggradation			Aggradation			Degradation			Degradation		

Method	Reach 3			CFR Reach			Reach 2			Reach 1		
	Q2	Q10	Q100	Q2	Q10	Q100	Q2	Q10	Q100	Q2	Q10	Q100
Schoklitsch	0.0026	0.0004	0.0002	0.0034	0.0004	0.0002	0.0020	0.0003	0.0002	0.0023	0.0004	0.0003
Meyer-Peter, Muller	0.0041	0.0010	0.0009	0.0028	0.0005	0.0003	0.0028	0.0010	0.0010	0.0112	0.0019	0.0022
Shields	0.0015	0.0003	0.0002	0.0018	0.0003	0.0002	0.0013	0.0003	0.0002	0.0015	0.0003	0.0003
Lane	0.0013	0.0003	0.0002	0.0016	0.0003	0.0002	0.0012	0.0003	0.0002	0.0014	0.0003	0.0002
Average	0.0024	0.0005	0.0004	0.0024	0.0004	0.0002	0.0018	0.0005	0.0004	0.0041	0.0007	0.0008
Bray	0.0129	0.0129	0.0129	0.0125	0.0125	0.0125	0.0128	0.0128	0.0128	0.0117	0.0117	0.0117
Henderson	0.0094	0.0024	0.0019	0.0100	0.0022	0.0016	0.0086	0.0023	0.0019	0.0084	0.0021	0.0018
BUREC	0.0038	0.0004	0.0002	0.0048	0.0004	0.0002	0.0028	0.0003	0.0002	0.0048	0.0004	0.0003
AMAFCA	0.0080	0.0076	0.0074	0.0076	0.0084	0.0068	0.0076	0.0071	0.0070	0.0064	0.0049	0.0049
Average	0.0085	0.0058	0.0056	0.0087	0.0059	0.0053	0.0079	0.0056	0.0055	0.0078	0.0048	0.0047
Measured Slope	0.0082			0.0054			0.0080			0.0057		
Predicted Trend	Low flow aggradation High flow degradation			Low flow aggradation High flow degradation			Degradation			Low flow aggradation High flow degradation		

Table 5-13. Skunk Creek Watercourse Master Plan
Equilibrium Slope Analysis Results – Sonoran Wash (ft/ft)

Method	Reach 6			Reach 5			Reach 4			Reach 3			Reach 2		
	Q2	Q10	Q100	Q2	Q10	Q100	Q2	Q10	Q100	Q2	Q10	Q100	Q2	Q10	Q100
Schoklitsch	0.0064	0.0010	0.0009	0.0056	0.0008	0.0007	0.0053	0.0009	0.0008	0.0046	0.0009	0.0007	0.0020	0.0004	0.0003
Meyer-Peter, Muller	0.0161	0.0070	0.0066	0.0089	0.0036	0.0035	0.0096	0.0046	0.0045	0.0075	0.0038	0.0039	0.0021	0.0012	0.0013
Shields	0.0052	0.0012	0.0010	0.0045	0.0010	0.0009	0.0047	0.0011	0.0009	0.0040	0.0010	0.0009	0.0012	0.0003	0.0003
Lane	0.0044	0.0010	0.0009	0.0038	0.0008	0.0007	0.0040	0.0009	0.0008	0.0033	0.0008	0.0007	0.0010	0.0003	0.0003
Average	0.0080	0.0025	0.0023	0.0057	0.0015	0.0014	0.0059	0.0018	0.0018	0.0048	0.0016	0.0016	0.0016	0.0006	0.0005
Bray	0.0398	0.0398	0.0398	0.0398	0.0398	0.0398	0.0359	0.0359	0.0359	0.0332	0.0332	0.0332	0.0155	0.0155	0.0155
Henderson	0.0145	0.0037	0.0034	0.0118	0.0028	0.0026	0.0112	0.0030	0.0027	0.0103	0.0028	0.0026	0.0066	0.0019	0.0017
BUREC	0.0094	0.0010	0.0009	0.0083	0.0008	0.0007	0.0084	0.0009	0.0008	0.0073	0.0009	0.0007	0.0032	0.0004	0.0003
AMAFCA	0.0099	0.0070	0.0068	0.0084	0.0065	0.0066	0.0106	0.0071	0.0070	0.0074	0.0057	0.0055	0.0069	0.0054	0.0056
Average	0.0184	0.0129	0.0127	0.0171	0.0125	0.0124	0.0165	0.0117	0.0116	0.0146	0.0106	0.0105	0.0080	0.0058	0.0058
Measured Slope	.0084			.0069			.0074			.0060			.0060		
Predicted Trend	Aggradation			Aggradation			Aggradation			Aggradation			Low flow aggradation High flow degradation		

Method	Reach 1		
	Q2	Q10	Q100
Schoklitsch	0.0021	0.0003	0.0003
Meyer-Peter, Muller	0.0025	0.0012	0.0011
Shields	0.0012	0.0002	0.0002
Lane	0.0010	0.0002	0.0002
Average	0.0017	0.0005	0.0004
Bray	0.0127	0.0127	0.0127
Henderson	0.0013	0.0004	0.0003
BUREC	0.0029	0.0003	0.0003
AMAFCA	0.0054	0.0034	0.0029
Average	0.0056	0.0042	0.0041
Measured Slope	.0032		
Predicted Trend	Low flow aggradation High flow degradation		

Armoring

When the channel sediment transport capacity exceeds the upstream sediment supply, the balance of the sediment load may be eroded from the channel bed, causing the channel to degrade. Because fine sediments can be transported at more frequent lower discharges and velocities than coarse sediments, which may require large floods to be moved, fine sediment tends to be preferentially removed from the channel bed. Selective removal of fine sediments causes channel bed material to become progressively coarser over time, as long as the upstream sediment supply is limited. If this process continues over a long period, it ultimately creates a surficial layer of coarse channel sediments, called an armor layer, that the stream is incapable of transporting (Yang, 1996).

Methodology. The BUREC (Pemberton and Lara, 1984) recommends the following methodologies for estimating the minimum sediment size and depth of scour required to form an armor layer for a given flow rate:

- Meyer-Peter, Muller Bedload Transport Function
- Competent Bottom Velocity
- Shields Diagram
- Yang Incipient Motion

Meyer-Peter, Muller Bedload Transport Function. The Meyer-Peter, Muller (1948) bedload sediment transport function for the beginning of transport of individual grain sizes can be used to estimate the non-transportable sediment size.

$$D_c = d\ S\ /\ (K_{mpm}\ (n/D_{90}{}^{(1/6)})^{3/2})$$

Where D_c = Non-transportable sediment diameter (mm)
d = Average flow depth (ft)
S = Energy slope (ft/ft)
K_{mpm} = 0.19 (constant)
n = Manning's n for the stream bed
D_{90} = Particle size for which 90% of the bed material is finer (mm)

Competent Bottom Velocity. This methodology is based on the work of Mavis and Laushey (1948), who developed an equation for the beginning of sediment movement on a stream bed.

$$D_c = 1.88\ V_m{}^2$$

Where D_c = Armor size (mm)
V_m = Average channel velocity (ft/s)

Shields Diagram. The Shields (1936) diagram is a standard method used to define the initiation of motion for various channel bed sediment sizes. The method uses an iterative process to compute dimensionless shear stress (T_*) and the armor diagram from the Shields diagram.

$$T_* = \tau_c / ((\gamma_s - \gamma_w) D_c)$$

Where T_* = Dimensionless shear stress
D_c = Armor size (mm)
τ_c = Critical shear stress (lb/ft^2)
γ_s = Specific weight of water = 62.4 lb/ft^3
γ_w = Specific weight of sediment = 165 lb/ft^3

Note that for gravel sediment sizes and turbulence levels typical in natural streams:

$T_* = 0.05$ For sediment sizes greater than 1 mm and Boundary Reynold's Number (R_*) > 500

Yang Incipient Motion. Yang (1973) developed a relationship between dimensionless critical velocity (V_{cr}/w, where w = fall velocity, ft/s) and shear velocity Reynold's number R* at incipient motion. Under natural stream conditions for sediment sizes greater than 2 mm, Yang's equation can be written as follows:

$$D_c = 0.00659\ V_{cr}^2 \qquad \text{(For D > 2 mm)}$$

Where D_c = Armor size (ft)
V_{cr} = Critical average velocity at incipient motion (ft/s)

Depth to Armor Equation. Once the size of material (D_c) that will form an armor layer is estimated from one or more of the equations listed above, the depth of scour required to form a stable armor layer can be estimated from the sediment distribution of the channel bed material. The equation for the depth to armor is the following:

$$Y_d = y_a (1/\Delta p - 1)$$

Where Y_d = Depth from original streambed to the bottom of the armor layer (ft)
y_a = Thickness of the armor layer (ft)
Δp = Decimal percentage of the bed material larger than the armor size

Results. The results of the application of the BUREC methodologies to the study area are summarized in Tables 5-14 and 5-15. Channel sediment size distribution data for the study reach were reported in Table 5-2 for comparison with the critical armoring sediment diameter. The "Armor Layer Likely" column in Tables 5-14 and 5-15 was rated by comparing field and soil pit data with the predicted depth of scour required to form an armor layer. If the computed depth to armor is excessive, and no evidence of armoring was observed in nearby reaches during the field work, it was assumed that formation of an armor layer was unlikely. A comparison of the depth of scour required to form an armor layer with the computed general scour depths is presented in another section of this Chapter.

Skunk Creek. As shown in Table 5-14, the bed of Skunk Creek will experience general scour during most significant floods. The bed material is large enough to form an armor layer during a 2-year flood, although the actual depth of scour and duration of flow during a 2-year design flood may be insufficient to cause an armor layer to fully develop. The bed material is coarse enough for an armor layer to form in the Supply Reach and near the New River bridge during a 10- or 100-year flood, but is unlikely to form elsewhere along Skunk Creek during significant floods. It is noted that formation of an armor layer in the New River bridge reach is unlikely since the reach will probably experience deposition rather than scour during floods. Field evidence suggests that the boulder riffles are coarser than the reach-averaged sediment distribution and will be armored, at least for the 2- and 10-year floods.

Table 5-14. Skunk Creek Watercourse Master Plan Armoring Analysis Results – Skunk Creek								
Reach	Methodology – Critical Armor Diameter (mm)				Average Critical Diam. (mm)	Field D50 (mm)	Armor Layer Likely?	Depth to Armor (ft.)
	MPM	CBV	Yang	Shield				
100-Year Flood								
SR	112	180	192	175	165	9	Yes	2.6
NR	46	93	100	94	83	15	Yes	1.6
6	84	168	179	155	146	16	No	5.8
5	99	221	236	200	189	9	No	15.0
4	94	217	232	175	180	9	No	12.7
3	115	266	284	181	211	6	No	7.9
CFR	111	245	262	169	197	6	No	26.3
2	119	279	298	190	222	6	No	37.1
1	71	181	193	103	137	5	No	18.6
10-Year Flood								
SR	126	191	204	198	180	9	Yes	3.0
NR	30	56	60	60	51	15	Yes	1.0
6	62	115	123	115	104	16	Yes	3.9
5	57	116	124	113	102	9	No	5.3
4	81	176	188	147	148	9	No	8.8
3	87	180	192	137	149	6	No	6.0
CFR	86	164	175	131	139	6	No	5.3
2	93	201	215	148	164	6	No	15.2
1	58	137	147	87	107	5	No	7.1
2-Year Flood								
SR	42	42	45	66	49	9	Yes	1.2
NR	11	14	15	22	15	15	Yes	0.3
6	23	28	30	42	31	16	Yes	0.7
5	26	35	37	51	37	9	Yes	1.2
4	28	39	42	49	39	9	Yes	1.0
3	22	29	31	35	29	6	Yes	0.6
CFR	17	18	20	25	20	6	Yes	0.4
2	24	32	34	38	32	6	Yes	0.7
1	18	26	28	28	25	5	Yes	0.5
MPM = Meyer-Peter, Muller Yang = Yang's Incipient Motion			CBV = Competent Bottom Velocity Shield = Shield's Method					

Sonoran Wash. As shown in Table 5-15, an armor layer forms at a relatively shallow depth on the bed of Sonoran Wash during the 2-year flood. However, armor layers are unlikely to form during floods larger than the 2-year event. For the 10- and 100-year events the depth of scour and duration of flow required to form an armor layer is too great to be effective at limiting scour. However, field evidence suggests that some of the boulder riffles in Reaches 5 and 6 are coarser than the reach-averaged sediment distribution and will be armored, at least for the 10-year flood. Field evidence also indicates that much of the coarsest sediment observed on the bed of Sonoran Wash has been transported during past floods.

Table 5-15. Skunk Creek Watercourse Master Plan Armoring Analysis Results – Sonoran Wash								
Reach	Methodology – Critical Armor Diameter (mm)				Average Critical Diam. (mm)	Field D50 (mm)	Armor Layer Likely?	Depth to Armor (ft.)
	MPM	CBV	Yang	Shield				
100-Year Flood								
6	73	152	163	141	132	19	No	14.2
5	81	177	189	157	151	19	No	11.9
4	77	160	171	149	139	19	No	17.7
3	72	157	167	134	132	19	No	11.1
2	63	148	159	112	120	5	No	9.7
1	30	118	126	59	83	4	No	39.5
10-Year Flood								
6	66	133	142	129	118	19	No	7.7
5	71	150	161	139	130	19	No	8.0
4	69	138	148	134	122	19	No	10.5
3	65	138	147	123	118	19	No	5.9
2	54	122	131	96	101	5	No	15.2
1	29	105	112	58	76	4	No	42.1
2-Year Flood								
6	17	19	20	33	22	19	Yes	0.4
5	17	21	23	34	24	19	Yes	0.4
4	20	25	27	40	28	19	Yes	0.5
3	19	24	26	35	26	19	Yes	0.4
2	16	24	25	29	24	5	Yes	0.7
1	9	19	20	18	16	4	No	5.2
MPM = Meyer-Peter, Muller Yang = Yang's Incipient Motion			CBV = Competent Bottom Velocity Shield = Shield's Method					

Conclusions. The following conclusions can be drawn from the armoring analysis results summarized in Tables 5-14 and 5-15:

- The channel bed scour depth is probably limited by armoring during frequent flows and small floods, but the average bed material is too small to prevent scour during large flood events.
- The channel bed material is mobile, and will be transported during moderate to large flood events. Cobble and boulder transport should be considered in the sediment routing analysis.
- The depth of the inactive clay-rich layer of alluvium observed in the channel soil pits is generally shallower than the depth required to form an armor layer for the 10- and 100-year events. Therefore, scour is probably limited by factors other than formation of an armor layer.
- Soil profiles observed in the channel pits were not significantly more coarse-grained than the material exposed on the surface, although the finest grain sizes generally were not exposed directly on the surface. That is, effective armor layers were not observed in the field at the soil pits.

General Scour

Scour is defined as any lowering of the channel bed elevation that occurs as a result of flowing water. Scour can be caused by changes in the sediment transport capacity of a channel during the passage of a flood wave (general scour), by the formation of bed forms (dune, anti-dune, thalweg scour), by velocity currents around channel bends (bend scour), by local flow obstructions (local scour), or by gradual adjustments to changes in channel morphology (long-term scour).

Methodology. General scour for Skunk Creek and Sonoran Wash was estimated using procedures outlined in the City of Tucson's *Standards Manual for Drainage Design and Floodplain Management - Chapter VI - Erosion and Sedimentation* (1989; hereafter, "the COT Manual"). Depth of scour in a stream is given in the COT Manual:

$$Z_t = 1.3\ (Z_{gs} + \tfrac{1}{2}\, Z_a + Z_{ls} + Z_{bs} + Z_{lft})$$

where:

Z_t	= Design scour depth, excluding long-term degradation or aggradation (ft)
Z_{gs}	= General scour depth (ft)
Z_a	= Anti-dune trough depth (ft)
Z_{ls}	= Local scour depth (ft)
Z_{bs}	= Bend scour depth (ft)
Z_{lft}	= Low-flow thalweg depth (ft)
1.3	= Safety factor to account for nonuniform flow distribution

General scour, Z_{gs}, is the component of scour that represents the mobile portion of the bed-material of the channel bottom. General scour was estimated using the following equation:

$$Z_{gs} = Y_{max}\ [(0.0685\ V_m^{0.8})/(Y_h^{0.4}\ S_e^{0.3})-1]$$

where:

Z_{gs}	= General scour depth (ft)
V_m	= Average velocity of flow at design discharge (ft/sec)
Y_{max}	= Maximum depth of flow at design discharge (ft)
Y_h	= Hydraulic depth of flow at design discharge, (ft)
S_e	= Energy slope (ft/ft)

Where Z_{gs} was determined to be negative, the general scour component was assumed to be zero.

Anti-dune trough depth, Za, is the component of scour caused by movement of dune shaped bed forms along the bottom of the channel. The anti-dune trough depth was estimated using the following equation:

$$Z_a = 0.0137\ V^2_m$$

where:

V_m = Average velocity of flow at design discharge (ft/sec)

The anti-dune trough depth is limited to a maximum of ½ the flow depth. Anti-dunes were observed on portions of Skunk Creek during the small flood which occurred on July 15, 1999. Therefore, it was assumed that antidunes could form in any part of the study reach, except in riffles or in the reaches with the coarsest bed sediments.

Low-flow thalweg scour, Z_{lft}, occurs if a small channel forms to convey minor flows within the main channel of a stream. Typically, a low-flow thalweg forms on large streams with a high width to depth ratio and with mobile bed sediments. No physical evidence of formation of a distinct low flow thalweg was observed on Skunk Creek or Sonoran Wash, either during floods or in the channels between floods. However, to be conservative, the low-flow thalweg component of scour was assumed to be one foot for the purposes of the scour analysis.

Bend scour, Z_{bs}, occurs on the outside of bends in a stream channel, and is caused by spiral transverse currents. Bend scour was estimated using the following equation:

$$Z_{bs} = 0.0685\ Y_{max}\ V_m^{0.8}\ Y_h^{-0.4}\ S_e^{-0.3}\ \{2.1\ [\sin^2(\alpha/2)/\cos\alpha]^{0.2} - 1\}$$

where:

Z_{bs} = Bend-scour component of total scour depth (ft), and
= 0 when $r_c/T > 10.0$, or $\alpha < 17.8^o$
= computed value when $0.5 < r_c/T < 10.0$, or $17.8^o < \alpha < 60^o$
= computed value when $\alpha = 60^o$ when $r_c/T < 0.5$, or $\alpha > 60^o$

Y_{max} = Maximum depth of flow immediately upstream of the bend (ft)

V_m = Average velocity of flow immediately upstream of the bend (ft/sec)

Y_h = Hydraulic depth of flow immediately upstream of the bend (ft)

S_e = Energy slope immediately upstream of the bend (ft/ft)

α = Angle formed by the projection of the channel centerline from the point of curvature to a point which meets a line tangent to the outer bank of the channel (degrees)

r_c = radius of curvature along centerline of channel (ft)

T = channel topwidth (ft)

The reach-averaged bend angle was computed from the arccosine of the reciprocal of the sinuosity.

Local scour, Z_{ls}, occurs where there is an abrupt change in the direction of flow caused by obstructions such as bridge piers, abutments, or other structures. Local scour will occur at the Carefree Highway and New River Road bridges, as well as at new bridge crossings currently planned but not constructed south of the Carefree Highway. However, since local scour at these structures will be limited to the bridge section itself, the local scour component was not included in the estimate of total scour for the entire study reach. Local scour may also occur along the margin of the floodplain bank protection proposed for the Tramonto Subdivision which is currently under construction.

Long-term scour, or aggradation and degradation, is best evaluated from historical evidence and field data. Historical evidence of long-term changes in channel bed elevation was discussed in Chapters 3 and 4 of this report. Depending on the time scale considered, long-term scour can be the largest component of scour. For example, if sufficient time is allowed for the channel to achieve its equilibrium slope or to become armored, the long-term scour component could more than double the scour estimate. A practical rule of thumb for determining a reasonable maximum long-term estimate for undisturbed watersheds is to use the height of the floodplain above the channel bottom or the bank height (Table 5-5).

Results. Scour estimates for Skunk Creek and Sonoran Wash obtained from the City of Tucson scour equations are summarized in Tables 5-16 and 5-17. In general, the largest component of scour other than long-term scour is the bend scour. Given that the bed scour is limited to the outside of channel bends, the scour estimates listed in the first columns of Tables 5-21 to 5-24 are conservative when applied to an entire reach. However, given the potential for future channel movement within the stream corridor, consideration of bend scour at any point within the reach is prudent for design of any structure with an extended design life. In every reach within the study area, general scour was calculated as a negative value, which the COT Manual dictates should be interpreted as a zero depth of scour. Local scour was estimated as zero for the study, since reach-averaged values for a local condition could not be justified. Thalweg scour was also estimated as zero because a low flow thalweg was not observed in the study reaches.

Skunk Creek. Scour estimates for Skunk Creek are shown in Table 5-16. Neglecting the bend scour component, the total scour along Skunk Creek is less than one foot for the 2-year event, less than three feet for the 10-year event, and two to four feet for the 100-year event. In sinuous reaches, the bend scour component increases the total scour estimate by a factor of four to five. The 2- and 10-year scour depths[7] are most similar to the depth of the observed clay-rich layer in the excavated channel soil pits, indicating either that the channel has not experienced a recent extreme flood or that the 100-year scour depths are overestimated. The total scour depths shown in the first column of Table 5-16 are primarily due to the bend scour component, which itself is driven by the channel sinuosity. Therefore, the more sinuous reaches have the greatest total scour estimates. The similarity of the 10- and 100-year total scour estimates is due to marginal increase in channel discharge for flows greater than the 10-year event. That is, flows greater than the 10-year peak discharge tend to inundate the floodplain, and do not significantly increase the depth and velocity of flow in the main channel.

[7] Bend scour is neglected for this comparison since channel pits were excavated in straight reaches at mid-channel.

Table 5-16. Skunk Creek Watercourse Master Plan Scour Estimates – Skunk Creek (ft.)							
Reach	**Total Zt**	**General Zgs**	**Antidune Za**	**Bend Angle**	**Bend Zbs**	**Local Zls**	**Thalweg Zlft**
Q100							
SR	3.6	-1.3	2.8	19.4	0.4	0.0	1.0
NR	3.1	-2.1	2.2	19.4	0.3	0.0	1.0
6	3.7	-1.3	3.0	19.4	0.3	0.0	1.0
5	4.0	-1.4	3.4	19.4	0.4	0.0	1.0
4	4.0	-0.9	3.4	18.1	0.3	0.0	1.0
3	3.6	-0.2	3.5	11.4	0.0	0.0	1.0
CFR	4.2	-0.7	4.3	11.4	0.0	0.0	1.0
2	3.8	-0.3	3.8	15.9	0.0	0.0	1.0
1	4.7	-0.2	2.8	20.5	0.6	0.0	1.0
Q10							
SR	3.2	-1.1	2.4	19.4	0.3	0.0	1.0
NR	2.6	-2.2	1.5	19.4	0.2	0.0	1.0
6	3.1	-1.4	2.3	19.4	0.3	0.0	1.0
5	3.1	-1.9	2.3	19.4	0.3	0.0	1.0
4	3.5	-0.8	2.9	17.8	0.3	0.0	1.0
3	3.0	-0.5	2.6	11.4	0.0	0.0	1.0
CFR	2.9	-0.6	2.5	11.4	0.0	0.0	1.0
2	3.2	-0.5	3.0	15.9	0.0	0.0	1.0
1	4.1	-0.3	2.4	20.5	0.5	0.0	1.0
Q2							
SR	1.8	-0.7	0.6	19.4	0.1	0.0	1.0
NR	1.7	-1.6	0.4	19.4	0.1	0.0	1.0
6	1.8	-0.7	0.6	19.4	0.1	0.0	1.0
5	1.9	-0.9	0.8	19.4	0.1	0.0	1.0
4	1.9	-0.7	0.8	17.8	0.1	0.0	1.0
3	1.7	-0.6	0.6	11.4	0.0	0.0	1.0
CFR	1.6	-0.8	0.4	11.4	0.0	0.0	1.0
2	1.8	-0.6	0.7	15.9	0.0	0.0	1.0
1	2.0	-0.6	0.7	20.5	0.1	0.0	1.0
Note: Long-term and local scour not included in estimate of total scour.							

Sonoran Wash. Scour estimates for Sonoran Wash are shown in Table 5-17. The total scour depths are not significantly less than for Skunk Creek due to the generally lower width/depth ratio in Sonoran Wash, which results in higher unit discharge in the channel, flow depths, and velocities. Predicted scour depths for the 2-year event are about equal to the depth of the clay-rich sublayer observed in the excavated channel soil pits. No evidence for scour in the range of the estimated total scour depths for the 10- and 100-year events was observed in the field, indicating that the total scour depths in Table 5-17 are probably overestimated for the large floods or that bend scour has not been a significant component of the total scour in the past. The similarity of the 10- and 100-year total scour estimates is due to negligible increase in channel discharge for flows greater than the 10-year event. That is, flows greater than the 10-year peak discharge tend to inundate the floodplain, and do not significantly increase the depth and velocity of flow in the main channel.

Table 5-17. Skunk Creek Watercourse Master Plan
Scour Estimates - Sonoran Wash (ft.)

Reach	Total Zt	General Zgs	Antidune Za	Bend Angle	Bend Zbs	Local Zls	Thalweg Zlft
Q100							
6	3.8	-1.1	2.9	20.8	0.5	0.0	1.0
5	4.2	-1.1	3.4	20.8	0.6	0.0	1.0
4	4.0	-1.2	3.1	20.8	0.5	0.0	1.0
3	4.2	-1.2	3.4	20.8	0.6	0.0	1.0
2	3.8	-0.7	2.8	20.8	0.5	0.0	1.0
1	4.6	-0.3	3.0	20.8	0.6	0.0	1.0
Q10							
6	3.5	-1.1	2.6	20.8	0.4	0.0	1.0
5	3.9	-1.1	3.0	20.8	0.5	0.0	1.0
4	3.7	-1.2	2.7	20.8	0.5	0.0	1.0
3	3.9	-1.2	3.0	20.8	0.5	0.0	1.0
2	3.6	-0.8	2.5	20.8	0.5	0.0	1.0
1	4.0	-0.4	2.6	20.8	0.5	0.0	1.0
Q2							
6	1.8	-0.7	0.6	20.8	0.1	0.0	1.0
5	2.2	-0.6	0.7	20.8	0.4	0.0	1.0
4	1.9	-0.6	0.7	20.8	0.1	0.0	1.0
3	1.9	-0.6	0.8	20.8	0.1	0.0	1.0
2	1.9	-0.6	0.7	20.8	0.1	0.0	1.0
1	1.8	-0.5	0.5	20.8	0.1	0.0	1.0
Note: Long-term and local scour not included in estimate of total scour.							

Long-Term Scour. The long-term scour component is the progressive scour that occurs over long time periods, rather than in response to a single flow event. Long-term scour was estimated from the following types of data:

- Field estimates of recent scour
- Interpretation of longitudinal profiles
- Interpretation of historical maps and photographs
- Interpretation of the ages of geomorphic surfaces
- Comparison of equilibrium and existing channel slopes

The first of four of the types of data listed above were described in Chapters 3 and 4 of this report. Field data were described in Chapter 4, and consisted of qualitative estimates of whether the channel had recently scoured or filled, and the depth of recent long-term scour. Longitudinal profiles were described in Chapters 3 and 4, and were used to estimate whether the bed elevation had moved up or down during the period of record. Geomorphic mapping of stream terraces was used to establish the net channel bed adjustments over the past 10,000 to 700,000 years. A summary of these data is shown in Table 5-18.

Predictions of the magnitude of long-term degradation or aggradation can also be made by comparing the predicted equilibrium slope with the existing channel slope (Tables 5-12 and 5-13). The slope difference multiplied by a stream reach length is the amount of adjustment in bed elevation at the upstream end of the reach. Reach lengths of 1,000 and 5,000 feet were used for the predictions shown in Table 5-18. Typically, long-term scour estimated using equilibrium slope is measured from the closest point of permanent grade control. However, because the only permanent grade control in the study area is at the CAP overchutes, as the distance from the CAP increases the predicted long-term scour depth would become unreasonably large. Therefore, the estimates were based on reach lengths of 1,000 and 5,000 feet to illustrate the potential range of channel responses to long-term slope adjustment.

Summary. General and long-term scour estimates for the streams in the study area indicate that moderate scour should be expected for Skunk Creek, especially in channel bends. Somewhat lower scour depths should be expected for Sonoran Wash. When scour occurs, it undermines the channel banks and increases the rate of lateral erosion. Therefore, the greatest amount of scour-induced bank erosion in the study area should be expected at channel bends, near obstructions, or where the channel has been excavated. Estimated bank erosion distances should be adjusted upward where bed scour is significant.

Table 5-18. Skunk Creek Watercourse Master Plan Summary of Long-Term Degradation/Aggradation Data Sources										
Reach	**Field Assessment**	**Longitudinal Profile Comparison**	**Archaeological & Historic Data (ft/yr)**	**Geologic Mapping (ft/yr)**	**Equilibrium Slope Adjustment – Reach Length (ft)**					
					Q100		**Q10**		**Q2**	
					1000 ft	**5000 ft**	**1000 ft**	**5000 ft**	**1000 ft**	**5000 ft**
Skunk Creek										
SR	Degradation	Degradation	No information	< -0.0001	-3.3	-16.3	-2.3	-11.3	4.3	21.3
NR	Aggradation	Mixed	+ 4 ft. since 1996	< -0.0001	4.2	20.8	4.3	21.3	6.9	34.7
6	Mixed	Degradation	No information	< -0.0001	1.1	5.6	1.3	6.5	4.5	22.4
5	Aggradation	Mixed	No information	< -0.0001	-2.8	-13.8	-3.3	-16.5	-0.5	-2.6
4	Degradation	Mixed	No information	< -0.0001	-2.4	-12.0	-1.8	-9.2	0.5	2.6
3	Mixed	Mixed	No information	< -0.0001	-2.6	-12.9	-2.4	-11.9	0.4	1.8
CFR	Aggradation	Mixed	+ 3 ft since 1977	< -0.0001	-0.1	-0.6	0.5	2.3	3.3	16.6
2	Stable	Mixed	No information	< -0.0001	-2.5	-12.6	-2.3	-11.7	0.0	-0.1
1	Mixed	Mixed	No information	< -0.0001	-1.0	-4.8	-0.9	-4.3	2.2	10.9
Sonoran Wash										
6	Stable	Unclear	No information	< -0.0001	4.3	21.6	4.5	22.4	10.0	50.1
5	Stable	Unclear	No information	< -0.0001	5.6	27.8	5.6	28.2	10.2	51.1
4	Stable	Unclear	No information	< -0.0001	4.2	20.9	4.3	21.6	9.1	45.6
3	Stable	Unclear	No information	< -0.0001	4.5	22.5	4.6	23.2	8.5	42.7
2	Degradation	Unclear	No information	< -0.0001	-0.2	-1.0	-0.2	-1.0	2.0	10.2
1	Aggradation	Unclear	No information	< -0.0001	0.8	4.1	1.0	4.8	2.3	11.7
Source of Data	Chapter 4 Appendix A	Chapter 3 Fig. 3-15 to 19	Chapter 3	Chapter 4 Fig. 4-76	Values computed by the following equation: (equilibrium slope – existing channel slope) x reach length (ft.)					

Comparison of Armoring, Scour, and Equilibrium Slope Predictions.
Channel degradation can be prevented by armoring of the channel bed, by achieving a non-scouring stable slope, or by physical barriers to scour such as bedrock or artificial grade control. A comparison of the armoring, scour and equilibrium slope estimates described in the previous sections of this chapter is provided in Tables 5-19 and 5-20. The possible slope adjustment, or depth of long-term scour caused as the channel adjusts to stable slope, was estimated by multiplying the difference in the predicted (regime) and existing channel slopes by a specified reach length of 1,000 or 5,000 feet. The latter two distances were selected based on the length of typical pool and riffle sequence as well as on the reach lengths used for this study. The distances are intended to illustrate the order of magnitude of vertical change possible due to slope adjustments, rather than a specific prediction of long-term scour at any specific point in the study reach. Actually long-term changes will depend on a variety of site-specific variables.

The "Armor v. Scour" and "Armor v. Slope" columns in Tables 5-19 and 5-20 indicate whether total or long-term scour will be limited by armoring. That is, if the predicted depth of general scour (column 3 in Tables 5-19 and 5-20) is less than the depth of scour required to form an armor layer, scour will not be limited by armoring at that flow rate. Similarly, if the difference between the predicted and existing channel slope is too small to cause long-term scour greater than the depth of scour required to form an armor layer, long-term scour will not be limited by armoring. A "no" code indicates that scour will not be limited by armoring. A "yes" code indicates that scour will be limited by an armor layer.

Skunk Creek. As shown in Table 5-19, armoring generally will not prevent long-term degradation (last column) on Skunk Creek where it is predicted by the equilibrium slope analysis, except in the supply reach upstream of the New River Road bridge. Short-term or single event scour will be prevented by armoring in reach 1, and upstream of reach 3 during the 2- and 10-year events, and upstream of reaches 5 during the 100-year event. Bank stability will be most impacted by bed scour during the largest floods.

Table 5-19. Skunk Creek Watercourse Master Plan Comparison of Armoring, Scour, and Equilibrium Slope Estimates – Skunk Creek								
1	2	3	4		5		6	7
Reach	Depth to Armor (ft)	Scour Depth (ft)	Stable Slope		Slope Adjustments		Armor v. Scour	Armor v. Slope
			Regime	Actual	1000 ft.	5000 ft.		
Q100								
SR	2.6	13.3	0.0097	0.0130	-3.3	-16.3	Yes	Yes
NR	1.6	11.7	0.0104	0.0062	4.2	20.8	Yes	N/A
6	5.8	12.1	0.0104	0.0093	1.1	5.6	Yes	N/A
5	15.0	13.7	0.0069	0.0097	-2.8	-13.8	No	No
4	12.7	12.7	0.0066	0.0085	-2.4	-12	No	No
3	7.9	2.3	0.0056	0.0082	-2.6	-12.9	No	No
CFR	26.3	2.9	0.0053	0.0054	-0.1	-0.6	No	No
2	37.1	2.5	0.0055	0.0080	-2.5	-12.6	No	No
1	18.6	13.4	0.0047	0.0057	-1	-4.8	No	No
Q10								
SR	3.0	11.8	0.0107	0.0130	-2.3	-11.3	Yes	Yes
NR	1.0	8.8	0.0105	0.0062	4.3	21.3	Yes	N/A
6	3.9	9.6	0.0106	0.0093	1.3	6.5	Yes	N/A
5	5.3	10.8	0.0067	0.0100	-3.3	-16.5	Yes	N/A
4	8.8	10.2	0.0067	0.0085	-1.8	-9.2	Yes	No
3	6.0	1.7	0.0058	0.0082	-2.4	-11.9	No	No
CFR	5.3	1.6	0.0059	0.0054	0.5	2.3	No	N/A
2	15.2	1.9	0.0056	0.0080	-2.3	-11.7	No	No
1	7.1	11.3	0.0048	0.0057	-0.9	-4.3	Yes	No
Q2								
SR	1.2	3.2	0.0172	0.0130	4.3	21.3	Yes	N/A
NR	0.3	4.4	0.0131	0.0062	6.9	34.7	Yes	N/A
6	0.7	3.2	0.0138	0.0093	4.5	22.4	Yes	N/A
5	1.2	4.0	0.0095	0.0100	-0.5	-2.6	Yes	Yes
4	1.0	3.0	0.0090	0.0085	0.5	2.6	Yes	N/A
3	0.6	0.4	0.0085	0.0082	0.4	1.8	No	N/A
CFR	0.4	0.3	0.0087	0.0054	3.3	16.6	No	N/A
2	0.7	0.5	0.0079	0.0080	0.0	-0.1	No	N/A
1	0.5	3.2	0.0078	0.0057	2.2	10.9	Yes	N/A

Notes:
1. No = scour not limited by armoring
2. Yes = scour limited by formation of armor layer
3. N/A = not applicable, aggradation is predicted (no long-term scour)
4. Armor v. Scour: compare column 3 to 1, i.e. will scour will be limited by armoring?
5. Armor v. Slope: compare column 5 to 1, i.e. will long-term scour be limited by armoring?

Sonoran Wash. As shown in Table 5-20, armoring would have no impact on long-term slope adjustments since aggradation (last column) is predicted for most of Sonoran Wash. In reach 2, where some long-term degradation is predicted for the 10- and 100-year events, armoring would not prevent the possible long-term bed elevation change. Short term scour will be prevented by armoring in reaches 2 to 6 during a 2-year event, in reaches 3, 5 and 6 in the 10-year event, and in reaches 2, 3 and 5 during a 100-year event. The reaches of Sonoran Wash that cannot limit scour by armoring will be most susceptible to erosion caused by bed scour during floods.

Table 5-20. Skunk Creek Watercourse Master Plan
Comparison of Armoring, Scour, and Equilibrium Slope Estimates – Sonoran Wash

1	2	3	4		5		6	7
Reach	**Depth to Armor (ft)**	**Scour Depth (ft)**	**Stable Slope**		**Slope Adjustments**		**Armor v. Scour**	**Armor v. Slope**
			Regime	**Actual**	**1000 ft.**	**5000 ft.**		
Q100								
6	14.2	10.4	0.0127	0.0084	4.3	21.6	No	N/A
5	11.9	12.0	0.0124	0.0069	5.6	27.8	Yes	N/A
4	17.7	11.4	0.0116	0.0074	4.2	20.9	No	N/A
3	11.1	12.5	0.0105	0.0060	4.5	22.5	Yes	N/A
2	9.7	11.4	0.0058	0.0060	-0.2	-1.0	Yes	No
1	39.5	12.8	0.0041	0.0032	0.8	4.1	No	N/A
Q10								
6	7.7	9.3	0.0129	0.0084	4.5	22.4	Yes	N/A
5	8.0	10.8	0.0125	0.0069	5.6	28.2	Yes	N/A
4	10.5	10.1	0.0117	0.0074	4.3	21.6	No	N/A
3	5.9	11.3	0.0106	0.0060	4.6	23.2	Yes	N/A
2	15.2	10.3	0.0058	0.0060	-0.2	-1.0	No	No
1	42.1	10.7	0.0042	0.0032	1.0	4.8	No	N/A
Q2								
6	0.4	2.3	0.0184	0.0084	10.0	50.1	Yes	N/A
5	0.4	2.2	0.0171	0.0069	10.2	51.1	Yes	N/A
4	0.5	2.3	0.0165	0.0074	9.1	45.6	Yes	N/A
3	0.4	2.7	0.0146	0.0060	8.5	42.7	Yes	N/A
2	0.7	2.6	0.0080	0.0060	2.0	10.2	Yes	N/A
1	5.2	2.5	0.0056	0.0032	2.3	11.7	No	N/A

Notes:
1. No = scour not limited by armoring
2. Yes = scour limited by formation of armor layer
3. N/A = not applicable, aggradation is predicted (no long-term scour)
4. Armor v. Scour: compare column 3 to 1, i.e. will scour will be limited by armoring?
5. Armor v. Slope: compare column 5 to 1, i.e. will long-term scour be limited by armoring?

Conclusion. The engineering analyses described in the preceding sections predict mixed trends of aggradation and degradation for Skunk Creek and Sonoran Wash. These mixed trends indicate that the streams are subject to erosive conditions during floods, and will experience scour and slope adjustments best depicted by the type of erosion and deposition documented in the recent historical record.

Lane's Relation

Lane (1955) developed the following equation that expresses the delicate balance and adjustment between several key geomorphic variables:

$$Q_s\, d \propto Q\, S;$$

Where Q_s = sediment discharge (cfs)
d = sediment size (mm)
Q = water discharge (cfs)
S = slope (ft./ft.)

Lane's equation implies that a change in one variable requires a change in one or more of the other variables to maintain stability, and provides a means to evaluate the effects of historical changes in watershed and channel conditions, and to estimate future river responses to change.

For the study area, watershed conditions have not been significantly altered in the past 100 years, with the possible exception of (undocumented) over-grazing, according to some regional studies (e.g., Earl, 1983), and some recent urbanization in the lower watershed. Over-grazing is thought to increase water supply (Q) over the short-term by reducing the vegetative cover and increasing the percent of rainfall that becomes runoff. To balance the Lane equation in response to increased runoff, a stream would have to flatten its slope (S^-, degradation) and/or increase the sediment transport rate (Q_s^+, scour). Therefore, over-grazing could be a plausible explanation for historical degradation described in Chapter 3 of this report. However, grazing impacts cannot explain all the historical degradation since such degradation is also proposed as the cause of the demise of Hohokam farming on Skunk Creek below the Watercourse Master Plan study area, and because the scale of degradation on the Sonoran Wash system is much different than on Skunk Creek.

Alternatively, urbanization is thought to increase runoff volumes (Q^+) and decrease sediment supply (Q_s^-). Therefore, as the watersheds become more urbanized, Skunk Creek and Sonoran Wash will tend to decrease their slopes (S^-, degradation) and/or increase the bed material size (d^+, armoring). However, some of this expected response may be muted if retention policies are enforced, since HEC-1 modeling indicated that some future condition discharges decreased if retention volumes were considered. The exact impacts of retention policies on channel stability are not yet known.

AMAFCA Prudent Line Methodology

The AMAFCA prudent line methodology (RCE, 1994) was developed to estimate the amount of lateral erosion that could be expected with a 30-year planning period along arroyo stream systems common in the Albuquerque, New Mexico area.

The Level 3 prudent line methodology for the arroyos in the Albuquerque area depends in part on being able to define the hydraulic stability number, N_h, and the geotechnical stability number, N_g. The geotechnical stability number is the ratio of the actual bank height at a given angle to the critical bank height. The critical bank height is the height above which a bank is unstable, and is defined either computationally or observationally. The hydraulic stability number is the ratio of the expected sediment supply to the sediment transport capacity, which was not defined for Skunk Creek or Sonoran Wash. More importantly, no geotechnical data for the channel banks in the Skunk Creek Watercourse Master Plan study area were available from which to computationally define a stable bank height. Review of field data indicated that there was no statistically significant relationship between the height of stable and unstable banks on any of the four streams in the study area (Figures 5-46 and 5-47), probably due to carbonate cemented stratigraphic units in the bank sediments. Therefore, this key element of the prudent line approach described in the AMAFCA manual could not be applied.

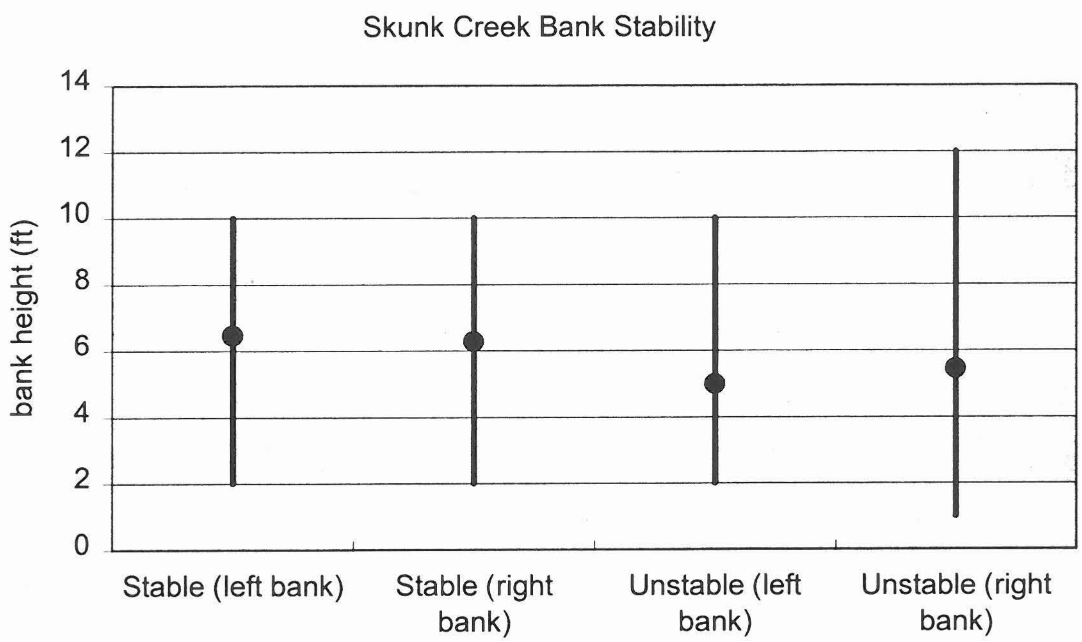

Figure 5-46. Height of stable banks vs. unstable banks observed on Skunk Creek.

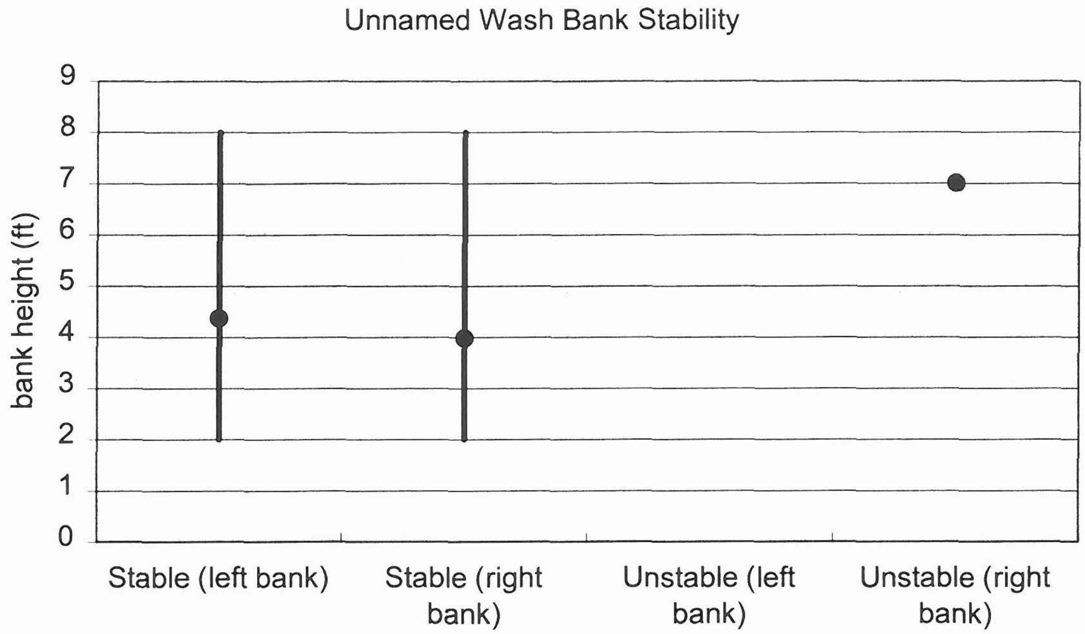

Figure 5-47. Height of stable banks vs. unstable banks observed on Sonoran Wash.

Despite the inability to define values for the geotechnical and hydraulic stability number, the overall AMAFCA approach is very similar to the approach used in this study. In particular, the use of probability-weighted erosion distances applied to a single channel bank (Chapter 6, HEC-6 discussion), the consideration of both long-term and single event lateral erosion processes in determining the safe setback, and the consideration of historical and field data in the stability study are key elements in both approaches.

Summary

Engineering methodologies were applied to the stream reaches in the study area to estimate the potential and magnitude of future bank erosion. Analysis of the HEC-RAS modeling indicated that the models could be improved by realigning cross sections, adding additional cross sections, and carefully selecting parameters that depict the hydraulics of low flows. However, it is recognized that the HEC-RAS models provide the best available data for the study reach. For the purposes of the lateral stability assessment, it is likely that new HEC-RAS modeling would have minor impacts on the reach-averaged hydraulic values, and that any differences would be well within the uncertainty of the available engineering data. The HEC-RAS modeling results indicate that there is no clear hydraulic basis for identifying subreaches within the study area. Therefore, the streams were subdivided based on hydrologic, geomorphic, and geographic factors.

Sediment data collected for use in the lateral stability assessment reveal two trends. First, there is a significant difference in the size of the bed materials in riffles compared to the size of the bed materials in pools. Therefore, the engineering analyses used in this study were dependent on whether bed samples were obtained from pools or riffles. Second, the data from Sonoran Wash indicate that mean sediment size varies by about an order of magnitude over the study length.

The specific engineering methodologies used to assess lateral stability indicate that Skunk Creek and Sonoran Wash are subject to bank erosion during floods. The State Standard Level 1 erosion hazard methodology was generally not applicable to the study area and had poor correlation to the Level 3 type analyses used in this study. HEC-6 sediment continuity modeling results were used to generate bank erosion estimates. These results indicate that bank erosion can be expected throughout the study area during large floods, although the results also depict some of the difficulties of applying the HEC-6 model to Skunk Creek and Sonoran Wash. Despite these difficulties, the HEC-6 results reasonably simulate the bank erosion distances observed in the study reach during the field visits. Allowable velocity criteria provide general information on the likelihood of bank and channel erosion. Broadly interpreted, the allowable velocity data indicate that all of the channel banks in the study area will erode even in small floods if the banks are not cohesive, but will resist erosion if they are cohesive. Additional uncertainty in allowable velocity predictions is caused by the effects of bank vegetation (increase stability), stratified bank sediments (decrease stability), and other local variations ($CaCO_3$ content, piping, bed scour, etc.).

The scour and deposition caused by the channel's adjustment to an equilibrium slope indicate that long-term aggradation is predicted for the periods dominated by small floods, with long-term degradation more likely to occur during periods dominated by large floods. The greatest amount of expected slope adjustments will occur in the reaches disturbed by bridge construction. In the bridge reaches, the equilibrium slope equations predict long-term aggradation. The actual magnitude of the expected bed elevation changes is based in part on the potential for armoring, sediment supply, and the magnitude and frequency of the flows experienced in the future. The armoring analyses indicate that channel bed scour depth is probably limited by armoring during frequent flows and small floods, but the average bed material is too small to prevent scour during large flood events. Other results of the armoring analysis include evidence that the channel bed material is mobile, and will be transported during moderate to large flood events. Effective armor layers were not observed in the field at the soil pits. General and long-term scour estimates for the streams in the study area indicate that moderate scour should be expected for Skunk Creek, especially in channel bends. Somewhat lower scour depths should be expected for Sonoran Wash. When scour occurs, it undermines the channel banks and increases the rate of lateral erosion. Therefore, the greatest amount of scour-induced bank erosion in the study area should be expected at channel bends, near obstructions, or where the channel has been excavated. Estimated bank erosion distances should be revised upward where bed scour is significant.

The engineering analyses described in this chapter predict mixed trends of aggradation and degradation for Skunk Creek and Sonoran Wash. These mixed trends indicate that the streams are subject to erosive conditions during floods, and will experience scour and slope adjustments best depicted by the types of erosion and deposition documented in the recent historical record.

Chapter 6
Definition of Erosion Hazard Zones

Introduction

Erosion hazard boundaries for Skunk Creek and Sonoran Wash were identified based on the results of the geomorphic, historical and engineering analyses of lateral stability. The geomorphic analysis included consideration of field data, analytical procedures, and sediment continuity routing of the existing and future condition 10- and 100-year floods. The methodology used to define the erosion hazard boundaries is presented in this chapter.

Methodology

The following types of information were considered in defining the erosion hazard boundaries, as described in Chapters 2 to 5 of this report:

- Field Data
- Stream Classification
- Historical Channel Changes
- Archaeological Data
- Mapping of Geomorphic Surfaces
- Longitudinal Profile Analysis
- Hydraulic Geometry/Regime Equations
- Expected Channel Pattern
- Allowable Velocity
- Equilibrium Channel Slope
- Armoring Potential
- Stable Bank Slope
- HEC-6 Modeling Results
- Expected Lateral Erosion Mechanism
- Impacts of Mining-Induced Entrenchment

A summary of the data types listed above was generated and plotted on a single work map so that the results of the various analyses could be collated and compared. The paragraphs below describe how those data were summarized into a single map element which was used to generate the erosion hazard zone maps.

Field Data
Collection of field data was described in Chapter 4. Detailed field inspections of the study reach were conducted in which cross sections were described at 1,000 foot intervals. At each field section, and at significant points between sections, the relative bank stability was assessed, evidence of past erosion was documented, and the likelihood

of future erosion was predicted. Field data were also used to identify reaches of historically recent scour and degradation, as well as to identify actively eroding areas outside the main channel. Based on the field observations, the right and left primary channel banks were classified as either stable or unstable, and mapped on a set of the orthorectified aerial photographs of the study reach.

Map Elements for Field Data:

- Channel Bank Location – Right and Left
- Evidence of Active Degradation or Aggradation
- Evidence of Active or Historical Lateral Erosion
- Miscellaneous Notes
- Stable/Unstable Bank Designation

Stream Classification

Stream classification data were described in Chapter 2, and the application of stream classification erosion hazard methodologies was presented in Chapter 5. Based on the stream classification methodologies, the right and left primary channel banks were classified as either stable or unstable, and mapped on the orthorectified aerial photographs of the study reach used as the base maps for the report exhibits.

Map Elements for Stream Classification Data:

- Channel and Floodplain Characteristics
- Stable/Unstable Bank Designation

Historical Channel Movement

Mapping of historical channel movement was described in Chapter 3. The maximum measured channel movement within the 40 to 60 year period of photographic record was used as a minimum predicted erosion distance. Figure 3-1 shows the thalweg position for the 37 years (1953 to 1999) of historical aerial coverage.[1] The maximum measured channel movement distance was plotted on the orthorectified aerial photograph base maps. Because the direction of future erosion cannot be predicted with 100 percent certainty, the maximum erosion distance was plotted as the lateral distance across the channel from each of the banks. That is, it was assumed future erosion could occur in either direction. Because Skunk Creek and Sonoran Wash are subject to channel avulsions, the maximum channel movement distance during the period of record was about 1,000 feet, equal to the width of the recent geologic floodplain.

Map Element for Historical Channel Movement:

- Former Channel Positions

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[1] Length of record equals 104 years if the 1894 GLO survey channel positions are considered. Partial coverage only for 1940 and 1953 photographs.

Historical Long-Term Scour
Historical long-term scour was described in Chapters 3 and 5. Historical long-term scour was identified using interpretation of channel thalweg profiles on topographic maps, historical stereo aerial photographs, field data, and archaeological evidence. Reaches that have experienced long-term scour are more vulnerable to bank erosion from undercutting, tensional failures, piping, and slumping. None of the Skunk Creek or Sonoran Wash reaches have been subject to severe long-term scour. Instead, the available data indicate that stream bed elevations have fluctuated in response to local condition around a net degradation trend that has average less than 10^{-4} over the past 10,000 years. Some historical data have been interpreted to indicate that some channel incision occurred after 1894 that resulted in narrowing and deepening of Skunk Creek and Sonoran Wash.

Map Element for Historical Long-Term Scour:
- Estimate of Historically Recent Degradation (<100 yrs)
- Estimate of Maximum Degradation in Recent Geologic Time (1,000-10,000 yrs)

Archaeological Data
Archaeological evidence of prehistorical channel change and scour was described in Chapter 3. Reaches of prehistoric irrigated agriculture sites and the implied depth of long-term scour were noted relative to the other information on the orthorectified photographs of the study area. In general, archaeological data suggest that climate fluctuations have played an important role in the long-term stability of Skunk Creek and Sonoran Wash. However, because of the lack of significant archaeological sites in the study area, few data were available for use in assessing future channel stability.

Map Element for Archaeological Data:
- Archaeological site locations were not plotted on maps prepared for this analysis, to comply with the Arizona Antiquities Act.

Mapping of Geomorphic Surfaces
The geomorphic mapping process was described in Chapter 4. Based on interpretation of stereo photographs, field investigations, surficial soil characteristics, channel and floodplain topography, published surficial mapping, and detailed soil profile descriptions of 44 soil pits located along the study reach, detailed geomorphic mapping was performed for the study reach. These data were used to estimate the age of the fluvial terraces in the study area, and to distinguish geologically recent geomorphic surfaces (0-10,000 years old) from older, more stable surfaces (10,000 – 700,000 years old.). Geomorphic age data were useful for distinguishing areas of active and inactive channel movement, and for constraining the maximum and minimum rates of channel evolution. The geomorphic surface map was overlaid on a set of the orthorectified photograph base maps for the study area.

Elements for Geomorphic Mapping:
- Geomorphic Surface Units and Relative Ages

Longitudinal Profile Analysis
The longitudinal profile analysis was presented in Chapter 4. Longitudinal profiles derived from recent and historical topographic maps were compared to identify reaches of historical degradation. The estimated long-term scour based on the comparison of profiles was plotted on the orthorectified photographs of the study area.

Elements for Geomorphic Mapping:
- Long-term Scour Estimate

Hydraulic Geometry/Regime Equations
Regime equations and hydraulic geometry relationships were described in Chapter 4. Regime relationships for channel width were applied to the study reach using the 2-, 10-, and 100-year peak discharges, as well as the estimated bankfull discharge, to estimate the expected direction and possible magnitude of channel adjustment to flood flows. Bankfull discharge recurrence intervals ranged from about 5 years for Sonoran Wash to about 100 years in the Skunk Creek bridge sections at Carefree Highway and New River Road. Also, a variety of equations based on empirical data were applied, and the average widths were plotted on the orthorectified aerial photograph base maps. Channel widening is expected where predicted widths were greater than existing widths. The widths plotted on the aerial photographs were measured first from one bank, then the other bank, assuming that the adjustment occurred on each side of the channel independently. The existing channel widths appear to be adjusted to about the 2- to 10-year predicted widths.

Map Element for Hydraulic Geometry/Regime Equations:
- Average Expected Width Based on the 100-Year Peak Discharge
- Average Expected Width Based on the 10-Year Peak Discharge
- Average Expected Width Based on the 2-Year Peak Discharge

Expected Channel Pattern
Channel pattern analysis was described in Chapter 4. Published data relating expected channel pattern (braided, meandering, straight, intermediate) to channel slope, mean annual discharge, and/or the mean annual flood were used to predict the equilibrium channel pattern at each cross section in the study reach. The existing channel pattern was then compared to the predicted channel pattern and the anomalies were noted on the orthorectified aerial photographs. In general, the expected channel pattern in the study area is a straight braided channel.

Map Elements for Expected Channel Pattern:
- Predicted Equilibrium Channel Pattern

Allowable Velocity
Allowable velocity analyses were described in Chapter 5. Published values of non-erosive velocities were compared to existing channel velocities computed by HEC-RAS modeling. Each cross section where the 2-, 10- or 100-year channel velocity exceeded the allowable velocity was plotted on the orthorectified aerial photograph base maps of the study area.

Map Elements for Allowable Velocity:

- Erosive Velocity by Recurrence Interval

Equilibrium Channel Slope

Equilibrium slope calculations were described in Chapter 5. The equilibrium channel slope was predicted based on channel hydraulics, bed sediment characteristics, empirical data, and flood discharges. Reaches expected to experience long-term degradation are more likely to experience lateral erosion due to undercutting. Aggrading reaches are more likely to experience avulsive channel changes. Reaches of expected long-term degradation or aggradation in response to expected slope adjustments were plotted on the orthorectified aerial photograph base maps of the study area.

Map Element for Equilibrium Slope:

- Expected Slope Adjustment (Degradation/Aggradation)

Armoring Potential

The channel bed armoring analysis was presented in Chapter 5. Bed armoring was computed using the sediment distribution of the bed material, HEC-RAS hydraulic data, and flood discharge estimates. Armoring can prevent general and long-term scour, and limit undercutting of the banks. However, armoring of the bed could lead to preferential erosion of the banks for reaches with a sediment deficit relative to the transport capacity. Cross sections likely to develop an armor layer were noted on the orthorectified aerial photograph base maps of the study area.

Map Element of Armoring:

- Recurrence Interval of Flow Likely to Develop Armor Layer

Stable Bank Slope

Field observations in the study reach and elsewhere in central Arizona indicate that vertical banks are inherently unstable, although the time scale over which instability is expressed varies with the degree of erosivity and resistance of the local bank characteristics. Evidence of lateral instability observed on vertical or oversteepened banks in the study reach included the following:

- Lack of Bank Vegetation
- Piles of Collapsed Bank Materials at the Base of the Banks
- Tipped Vegetation
- Exposed Roots
- Age of Vegetation
- Overhanging Banks
- Tensional cracks

The angle of repose[2] of typical unconsolidated alluvial soil materials is about 20°-40°, or about a 3:1 slope. Therefore, it was assumed that the minimum value for the magnitude of potential erosion would be estimated by measuring a 3:1 slope from the toe of the existing bank to the intercept of the existing floodplain. That is, if the toe of the bank were to experience no future erosion, what distance could the top of bank retreat before reaching a non-erosive (i.e., a 3:1) slope? The assumption that 3:1 bank slopes are stable along Skunk Creek and Sonoran Wash was verified using field data from the study reach, as presented in Chapter 4. The 3:1 intercept line was plotted on the orthorectified aerial photograph base maps as a minimum estimate of future bank erosion.

Map Element for Stable Bank Slope:

- 3:1 Offset From Existing Bank Toe

HEC-6 Modeling Results

Sediment continuity routing was performed by Stantec Consulting, Inc. for the 10- and 100-year future and existing condition hydrographs.[3] The computed total[4] sediment deficit (scour) or surplus (deposition) was divided by the average bank height and the reach length to estimate the amount of lateral erosion, assuming all of the bank erosion occurred on only one side of the channel. In addition, a distance equal to 6 times the 10-year erosion distance plus 1 times the 100-year bank retreat was plotted on the orthorectified aerial photograph base maps to simulate erosion over a 60 year period, the planning period adopted for the Watercourse Master Plan. For channel sections where aggradation or small amounts of degradation were predicted, the reach-averaged erosion distance was plotted.

Map Element for HEC-6 Results:

- 100-Year Erosion Line
- Long-Term Erosion Line

Expected Lateral Erosion Mechanism

The expected mechanism of lateral erosion for the study reach was defined based on interpretation of historical aerial photographs, field data, the geologic history of the study area, the relative age of stream terraces adjacent to the active channel, and general geomorphic principles. Gradual or episodic bank retreat (accretive erosion) by undercutting, tensional failures, and shear stress during periods of flow was demonstrated to occur more frequently, but at much slower rates and with less consequence for floodplain management and public safety. Accretive erosion has been the dominant form of lateral movement on Sonoran Wash in the past 40 years. The most significant type of lateral erosion in the study area over the long term is avulsive channel movement. During an avulsion, the channel experiences very rapid shifts in channel position (avulsive channel change) that leave islands of low terraces between active channel

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[2] The angle of repose is the maximum angle of slope at which alluvium will remain in place without sliding.

[3] The 25-year event was used in place of the 10-year event for Sonoran Wash.

[4] Total sediment deficit, not the cumulative sediment deficit reported in the HEC-6 output.

braids. In the reaches subject to avulsions, the active floodplain occupies the entire recent geologic floodplain, which is subject to future erosion.

Map Elements for Lateral Erosion Mechanism:

- Avulsion Potential is Reflected in the Width Erosion Hazard Boundaries

Measurements

All measurements of expected or predicted erosion were taken from the top of bank. Top of bank was identified on the aerial photograph base maps and FIS topographic mapping using the criteria outlined in Chapter 5, which included the following:

- Change in contour density (bank slope to floodplain)
- Field notes (bank profile sketches, descriptions)
- Field photographs
- Change in vegetative characteristics (riparian zone)

All of the information described above, once it was plotted on the orthorectified aerial photograph base maps for the study area, was used to define the lateral migration hazard for the four major streams.

Definition of Erosion Hazard Zones

Erosion hazard zones were defined for the Skunk Creek and Sonoran Wash corridors. The erosion hazard zones were defined based on the channel stability assessment methodologies described in Chapters 2, 3, 4, and 5 of this report, as well as on the information plotted on the orthorectified aerial photograph base maps for the study area as summarized above. The following three erosion hazard zones were defined:

- Severe Erosion Hazard Zone
- Lateral Migration Erosion Hazard Zone
- Long-Term Erosion Hazard Zone

Uncertainty

The use of erosion hazard zones rather than erosion hazard lines reflects the inherent uncertainty in predicting future channel changes such as lateral migration. Stream morphology and behavior are governed by a large number of variables, few of which can be predicted with certainty (Table 6-1). Therefore, prediction of future channel change and future lateral movement is subject to similar uncertainty. The uncertainty and/or measurement error associated with each of the specific methodologies used to assess channel stability was described in the previous chapters of this report. Even if the uncertainties associated with the methodologies used and the variables listed in Table 6-1 were eliminated, the sequence, timing, and magnitude of future floods cannot be predicted. Therefore, future erosion cannot be known with a high degree of certainty.

Floodplain Management

The erosion hazard zones are a distinct management tool for protecting the health, safety and welfare of landowners and users of the river corridors in the study area. Although

<table>
<tr><th colspan="3">Table 6-1. Skunk Creek Watercourse Master Plan
Some Variables Affecting River Behavior and River Characteristics That Can Change With Time</th></tr>
<tr><th>Variable</th><th>Variable Subgroup</th><th>River Characteristics</th></tr>
<tr><td>Hydrology</td><td>Dominant Discharge
Mean Annual Discharge
Flow Duration Statistics
Variation with Season
Diversions and Storage
Flow Source</td><td rowspan="8">Channel Width
Channel Depth
Bank Height
Bank Slope
Bank Materials
Bank Stratification
Stream Pattern
Bed Forms
Meander Amplitude
Meander Wavelength
Sinuosity
Floodplain Width
Depth of Floodplain Flow
Stream Terraces
Channel Slope
Aggradation
Degradation
Local Scour
Bed Sediment
Bar Sediment
Pool & Riffle Sequence
Armoring
Bedrock Outcrop & Control
Human Modifications
Bank Protection
Grade Control
Roadway Crossings
Utility Crossings</td></tr>
<tr><td>Flow</td><td>Width
Depth
Hydraulic Radius
Friction Factor
Velocity
Topwidth
Turbulence
Temperature
Transmission Losses</td></tr>
<tr><td>Flood Characteristics</td><td>Magnitude (peak)
Duration (flashy?)
Ratio of Peak to Base Flow
Ratio of Rare to Frequent Floods
Channel Capacity
Losses
Reservoirs/Flood Storage</td></tr>
<tr><td>Streambed and Bank Sediment</td><td>Mean Diameter
Size Distribution
Armoring Potential
Cohesion
Stratigraphy</td></tr>
<tr><td>Climate</td><td>Precipitation Type (snow?)
Precipitation Intensity
Precipitation Duration
Seasonal Distribution
Temperature/Evaporation</td></tr>
<tr><td>Time Scale</td><td>Engineering (short-term)
Geologic (long-term)</td></tr>
<tr><td>Channel Vegetation</td><td>Vegetation Type
Root Depth
Root Density
Branch/Foliage Density
Trunk Pliability
Growth Rate
Germination Cycle
Grazing Practices</td></tr>
<tr><td>Watershed Characteristics</td><td>Vegetation Cover
Slope
Drainage Area
Elevation
Geology
Valley Slope
Sediment yield
Human Impacts – Urbanization
Grazing Practices</td></tr>
</table>

they are based on the same hydraulic data, the erosion hazard zones are independent of the FEMA 100-year floodplain and floodway limits. That is, the severe or lateral migration erosion hazard zones are not coincident with the 100-year floodway, nor is the long-term erosion hazard zone coincident with the 100-year floodplain. The FEMA floodplain boundaries are primarily intended to prevent damage from flood inundation. The erosion hazard zones are intended to prevent damage from erosion during flooding, whether or not the property is located within the 100-year floodplain.

Severe Erosion Hazard Zone

The severe erosion hazard zone is comprised of the active stream channels and the channel margin areas likely to be eroded during a single 100-year flood, or the area likely to be removed if the bank angle were to be reduced to the natural angle of repose. The basis of mapping for the severe erosion hazard zone included the following:

- Bank retreat equivalent to the 100-Year HEC-6 future conditions sediment deficit
- Bank retreat resulting from a 3:1 bank slope
- 2- or 10-year regime channel width, if wider than the existing active channel
- Areas within the bed and banks of existing active channels

In addition, areas within the limits of existing sand & gravel mining operations were considered to be in the severe erosion hazard zone, since no engineering erosion protection was observed near the mines during field visits.

Lateral Migration Erosion Hazard Zone

The lateral migration erosion hazard zone consists of the channel margin area likely to be eroded by a "typical" series of floods over a sixty year period, plus the erosion that would be caused by a 100-year flood. The lateral migration erosion hazard zone also includes the natural channel movement due to geomorphic processes such as meander migration or channel avulsion. The basis of mapping for the lateral migration erosion hazard zone included the following:

- Probability-weighted bank erosion distance equivalent to the HEC-6 future conditions sediment deficit applied over a 60 year planning period, plus the 100-year HEC-6 future conditions sediment deficit.
- 2-, 10-, or 100-year regime channel width, if wider than the existing active channel
- Limits of historical channel movement and geologically recent channel avulsions

The limits of the lateral migration erosion hazard zone were widened in reaches where the field assessment indicated a high potential for future erosion, where evidence of ongoing erosion was observed, and in reaches where accelerated erosion was expected due to channel bends or oversteepened banks. In general, the lateral migration erosion hazard zone included areas outside, but adjacent to the active channels of Skunk Creek and Sonoran Wash.

Long-Term Erosion Hazard Zone

The long-term erosion hazard zone consists of the channel margin area defined by geologic evidence of channel movement over the past 100 to 1,000 years, and represents expected or potential channel movement over the next 60 to 1,000 years in the future.

The boundary of the expected long-term erosion hazard zone envelopes the results of all the predictive methods used to assess channel stability, in addition to application of engineering judgment and interpretation of the site geomorphology. The basis of mapping will be the following:

- Geomorphic mapping
- Channel pattern development
- "Meander" migration trend
- Interpretation of potential impact from human activities

Portions of areas mapped as older geomorphic surfaces, but adjacent to active channels and floodplains, were generally included in the long-term erosion hazard zone.

Summary

The recommended erosion hazard zones for the Skunk Creek Watercourse Master Plan study area developed using the criteria outlined above are shown in Exhibit 2. Management recommendations for these erosion hazard zones are discussed in Chapter 7.

Chapter 7
Summary and Recommendations

Summary of Lateral Stability Analysis

A variety of analyses were performed to assess the potential for future lateral migration of Skunk Creek and Sonoran Wash. In Chapter 2, base data on the watershed, geology, hydrology, and geomorphology of the study reaches were provided to set the context for the stability assessment and to define stream reaches. The watershed for the study area has not yet been subject to dense urbanization, although future development is likely to increase runoff in the study area. The geologic record indicates that Skunk Creek and Sonoran Wash have experienced net degradation over the past 500,000 years as the area transformed from an aggrading alluvial fan to a continuous river system. Entrenchment during recent geologic time has created a series of older, stable terraces that confines lateral channel movement within a well-defined corridor. Stream classification data indicate that the streams in the study area are subject to rapid bank erosion rates, except where the banks are stabilized by carbonate-cemented soils or bedrock. Hydrologic data for the study area indicate that climatic variability as expressed in annual and seasonal flow volume, flood peaks, and flow duration has led to changes in stream characteristics and erodibility rates.

Historical information summarized in Chapter 3 illustrates the types of channel changes that have occurred in the study area during the past, and suggests the types of channel change that can be expected in the future. Archaeological records imply that channel erosion has affected Skunk Creek for at least 10,000 years. That is, lateral erosion is not caused solely by human impacts on the channel and watershed. Natural cycles of stream degradation, local aggradation, lateral migration, and climate change must be accounted for in development of the erosion hazard zones and the watercourse management plan. Climate changes have been significant factors in long-term lateral erosion and channel development. Direct human impacts on Skunk Creek have been limited to construction of bridge and at-grade road crossings, construction of the CAP, and several small sand and gravel excavations. Direct human impacts on Sonoran Wash have been limited to construction of the CAP and several at-grade ranch road crossings. Indirect human impacts on Skunk Creek and Sonoran Wash include construction of stock ponds, moderate urbanization of the watershed, and cattle grazing. Human impacts tend to destabilize stream channels and lead to increased rates of lateral erosion. Because the degree of watershed urbanization is accelerating, Skunk Creek and Sonoran Wash are likely to be less stable in the future than they have been over the past 40 years.

The types of channel changes observed on historical aerial photographs included channel avulsions, bank failure, channelization, channel width changes, formation of multiple channels, braiding, sediment deposition, and movement of splays. Historical channel width and channel position have changed significantly during the past 100 years. The maximum recorded channel movement was more than 400 feet on Skunk Creek and nearly 300 feet on Sonoran Wash. Avulsions are the primary mechanisms of channel movement in the study area, and are responsible for the largest changes in channel position. The average long-term rate of lateral channel movement in the study area is about 1 foot per year over the past 100 years, but the maximum recorded rate of lateral movement during any discrete time interval was 18 feet per year. Large changes in channel width were recorded someplace in the study area during every time period evaluated. Therefore, significant erosion should be expected somewhere on Skunk Creek and Sonoran Wash during any sizable flood. The observed rate of channel degradation ($\approx$0.1 ft/yr) during the period of historical record exceeded the implied long-term geologic rate ($\approx 10^{-4}$ ft/yr) by several orders of magnitude. Since aggradation was recorded in some reaches, it is likely that channel bed elevations will not only degrade, but will also fluctuate around a slight long-term degradational trend.

The geomorphic analyses described in Chapter 4 used field observations, interpretation of the surficial geology, and application of empirical and theoretical data to evaluate the lateral stability of Skunk Creek and Sonoran Wash. Field observations made in the study area indicate that the study reaches are subject to lateral erosion, channel avulsions, scour, and have experienced some historical channel degradation. Sonoran Wash appears more laterally stable than Skunk Creek, primarily because of a higher frequency of channel avulsions on Skunk Creek. The ages and relative heights of the geomorphic surfaces along Skunk Creek and Sonoran Wash indicate that the study area has been dominated by erosional processes for the past 500,000 years, and that the floodplains have been subject to channel avulsion for at least 10,000 years. The scale of lateral channel change observed in the recent geologic record was not significantly different than the scale of historical changes documented in Chapter 3. The rates of lateral movement have been fastest on the youngest, less indurated surfaces and slowest along the margins of the older, more well indurated surfaces. The older terrace margins serve as a practical limit for predicted future rapid channel change, although the older terraces are also subject to (slower) lateral erosion where abutted by the main channel.

The longitudinal profiles of Skunk Creek and Sonoran Wash indicate that the streams have probably adjusted to an equilibrium slope, and that future lateral movement will be related to depositional processes in the downstream reaches, avulsions in reaches of irregular slope, and local scour throughout the study area. Bankfull discharge data indicate that channel geometry is controlled by large floods. Small floods (recurrence interval less than 5 years) do not fill the channels or flow against the banks, and thus cannot perform significant geomorphic work. Poor continuity in bankfull discharge between adjacent cross sections indicates that the streams recover slowly from local erosion. That is, local perturbations such as bank failures that lead to channel widening tend to persist over long periods of time. Rosgen method bank erodibility assessment techniques indicated that Skunk Creek has moderate to high erosion potential, and Sonoran Wash has low to moderate erosion potential. These results are consistent with field observations of greater bank stability along Sonoran Wash compared to Skunk Creek.

Channel pattern analyses indicate that Skunk Creek is likely to remain braided, but that because Sonoran Wash is close to the threshold for braiding, changes in watershed or channel characteristics could cause major changes in the channel pattern. Channel geometry equations indicate the main channel width of Skunk Creek appears to be adjusted to the 2-year event. Therefore, at flow rates exceeding the 10-year recurrence interval, the channel will tend to widen. The existing channel width in the bridge sections at New River Road and the Carefree Highway are wider than the 100-year expected width. Therefore, most floods will tend to narrow the channel section by depositing sediment, resulting in loss of conveyance through the bridge section. Predicted channel depths are greater than computed depths. Therefore, degradation should be expected in future floods. Predicted channel slopes are flatter than existing channel slopes. Therefore, long-term degradation should be expected. Predicted velocities are lower than the modeled velocities. Therefore, scour and high rates of sediment transport should be expected.

The engineering methodologies described in Chapter 5 were applied to the stream reaches in the study area to estimate the potential and magnitude of future bank erosion. These methodologies uniformly indicate that Skunk Creek and Sonoran Wash are subject to bank erosion during floods. Allowable velocity data indicate that all of the channel banks in the study area will erode even in small floods if the banks are not cohesive, but will resist erosion if they are cohesive. Equilibrium slope equations predict that some long-term aggradation will occur during periods dominated by small floods, but that long-term degradation will occur during periods dominated by large floods. The greatest number of expected slope adjustments will occur in the reaches disturbed by bridge construction. Armoring analyses indicate that channel bed scour depth is probably limited by armoring during frequent flows and small floods, but the average bed material is too small to prevent scour during large flood events. General and long-term scour estimates for the streams in the study area indicate that moderate scour depth will occur along Skunk Creek, especially in channel bends. Somewhat lower scour depths should be expected for Sonoran Wash. When scour occurs, it undermines the channel banks and causes increases the rate of lateral erosion. Therefore, the greatest amount of scour-induced bank erosion in the study area should be expected at channel bends, near obstructions, or where the channel has been excavated.

The methodologies used to determine the limits of three erosion hazard zones were described in Chapter 6. The three zones are the severe erosion hazard zone, the lateral migration erosion hazard zone, and the long-term erosion hazard zone. The lateral migration erosion hazard zone is recommended for adoption as the regulatory erosion zone for the watercourse master plan. Management recommendations for Skunk Creek and Sonoran Wash are described below.

Recommended Management Practices

Society is never more vulnerable to climatic-related crises than after a period of exponential population growth during a relatively favorable climatic period.[1]

The quotation printed above is as true today as it was for the Anasazi people it describes who lived a thousand years ago. The historic and geologic records indicate that Skunk Creek and Sonoran Wash are vulnerable to extreme rates of lateral channel movement. During the past 30 years, few large floods have occurred which demonstrate the catastrophic erosion potential that exists in the study area. However, population growth in the north Phoenix corridor has increased the pressure to develop flood and erosion prone lands along the major stream corridors. We have had our "favorable" climatic period. We are now facing exponential population growth. A watercourse management plan is required to prevent flood damages and preserve the natural function of the streams. The analyses summarized in the previous chapters have shown that bank erosion is not a new phenomenon in the Skunk Creek Watercourse Master Plan study area. The recommended management alternatives are intended to promote safe development of river corridors in the future.

General Recommendations

The following general recommendations are intended for management of both the Skunk Creek and Sonoran Wash corridors:

1. Adopt the recommended lateral migration erosion hazard zone for floodplain management purposes.

2. Amend the regional master plan to avoid structural improvements such as bank stabilization within the erosion hazard boundary limits, except to protect existing structures needed for public safety such as bridges or utility crossings, or where the channel threatens to move outside of the established erosion corridor.

3. Regulate all new development within the severe and lateral migration erosion hazard zones by requiring a special use permit. To obtain a permit, the development within the corridor must do the following:

    - Meet the National Flood Insurance Program (NFIP) requirements for development within a floodplain.
    - Provide an engineering and geomorphic study certifying that the proposed development will not be affected by erosion over a 60-year planning period.
    - Demonstrate that any proposed bank stabilization will not deleteriously affect reaches or development upstream and downstream.

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[1] Statement in reference to abandonment of Anasazi culture river corridor occupation sites circa 1150 a.d. after a period of extended drought. (Larson & Michaelson, 1990)

- Demonstrate the stability of any proposed bank stabilization. Local scour, long-term degradation, channel movement, and bank erosion shall be explicitly addressed in the design reports for any proposed bank protection.
- Hold the City of Phoenix, the Flood Control District of Maricopa County, and Maricopa County harmless from any and all claims resulting from erosion or any other flood related damage to development within the erosion corridor.
- Provide for perpetual maintenance of bank stabilization at no cost to any public agency. Provide for maintenance and access easement adjacent to any bank stabilization.
- Obtain necessary floodplain, wetlands (404), and water quality (401) permits or approvals for any construction activities at no cost to any public agency.

4. Regulate all new development within the long-term erosion hazard zone by requiring a special use permit. Permit requirements should include the following:

   - Include a note on the plat indicating that the homes or structures are built within an area subject to potential erosion.
   - Demonstrate that any proposed bank stabilization will not deleteriously affect reaches or development upstream and downstream.
   - Demonstrate the stability of any proposed bank stabilization. Local scour, long-term degradation, channel movement, and bank erosion shall be explicitly addressed in the proposed bank protection design.
   - Hold the City of Phoenix and Flood Control District harmless from any and all claims resulting from erosion or any other flood related damage to development within the erosion corridor.
   - Provide for perpetual maintenance of any bank stabilization at no cost to any public agency. Provide for maintenance and access easement adjacent to any bank stabilization.
   - Obtain necessary floodplain, wetlands (404), and water quality (401) permits or approvals for any construction activities at no cost to any public agency.

5. Vegetation Management. Within any of the erosion hazard zones, the following requirements are recommended for all future development:

   - Establish a no-build zone close to banks. Habitable structures should be set back a minimum distance from the top of the bank.
   - Vegetation on and near banks should not be disturbed, or should be replaced where disturbed by construction activities.
   - Where vegetation is disturbed, provisions for temporary bank stabilization should be made that protect the bank from erosion and allow for re-establishment of vegetation.
   - Any proposed modifications of the floodway and active channel should include a detailed geomorphic and engineering study of the potential impacts on adjacent reaches.

- The channel should be allowed the freedom to erode it banks and move within the floodplain.
- Fill should not be placed in the entrenched portion of the channel.

6. Regulation of In-Stream Sand & Gravel Mining. Sand and gravel mining is likely to result in channel degradation and increase bank erosion if it is not properly engineered and managed. The following minimum requirements should be fulfilled:

   - A mining reclamation plan should be established prior to the initiation of mining or leasing of land.
   - An assessment of potential upstream and downstream impacts should be prepared that certifies that no adverse impacts will occur under normal and extreme flow conditions. The assessment should include detailed consideration of the full range of possible discharges (normal low flow to 100-year flood), application of the types of geomorphic analyses summarized in this report, and mathematical modeling of sediment transport, headcut progression, and scour. The assessment should also include consideration of cumulative impacts that could be caused if similar mining were allowed everywhere on the watercourse.
   - In-stream mining or other excavation that intercepts, blocks or diverts the main channel should be prohibited. Excavation within the 100-year floodplain or lateral migration erosion hazard zone should be avoided, and should include engineered bank stabilization and grade control were permitted.

7. Future Monitoring. Channel stability should be monitored periodically to assess impacts of floods, to determine whether erosion hazard zones should be updated, and to document continued channel change for application to other stream systems in Maricopa County. The monitoring effort should include the following:

   - Install stream gauges on Sonoran Wash and Rodger Creek.
   - Establish monitoring stations at the field sections established for this study. Cross sections should be inspected and photo-documented during the fall of every year, and immediately after any flood that exceeds the 5-year recurrence interval.
   - Controlled aerial photography should be collected every other year or after any flood that exceeds the 10-year recurrence interval.

Chapter 8
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Chapter 9
Glossary

Agglomerate – Sedimentary rock type formed of detrital volcanic material explosively ejected from a volcanic vent, with clasts larger than 32 millimeters.
Alluvial Fan - A fan-shaped deposit of sediment located where a stream issues from a narrow valley of high slope onto a plane or broad valley of low slope.
Alluvium – Deposits of clay, silt, sand, gravel, or other particulate material in a streambed , on a floodplain or delta, or at the base of a mountain.
Altithermal – A period of time within the Holocene epoch characterized by higher than average temperatures and/or decreased precipitation.
Anabranching – A river channel pattern in which the width of islands is more than three times the river width at average discharge.
Anastomosing – A stream pattern charcterized by a net-like or interwoven channel pattern, with individual flow paths better defined or permanent than braided channel flow paths.
Andesite – A volcanic rock type mostly composed of plagioclase and other mafic materials.
Angle of Repose – The maximum angle of a slope that can be maintained by an accumulation of material before sliding or failing.
Argillic – Descriptive of a detrital sedimentary rock with particles less than 4 mm in diameter.
Arkosic – Rock type, generally sandstone, composed of more than 25 percent silica-feldspar minerals.
Armor – A natural layer of particles, usually gravel and cobble sizes, that may cover the surface of the streambed as a coarse residue after erosion of the finer bed materials. The layer, often just one to three particles thick, inhibits the erosion of underlying particles.
Avulsion – The sudden relocation of a stream away from its original flow path, usually due to catastrophic sediment deposition in the original flow path.
Bajada – A piedmont comprised of coalescing alluvial fans.
Bankfull Elevation – The elevation on the bank where flooding begins. Bankfull discharge is defined as the flow rate which fills the active channel just prior to inundating the floodplain.
Bed Load – The portion of sediment in a stream which is transported by rolling, bouncing, or sliding on the stream bed.
Bifurcation – The division of a stream into two or more channels in the downstream direction.
Bioturbation – The disruption of sediments mainly by the burrowing activities of organisms.
Boundary Shear Stress – A frictional resistance at the marginal area of a flow which results in a decrease in velocity at the boundary areas.
Breccia – A rock unit composed of coarse highly angular fragments.
Calcareous – Calcium-rich.
Caliche – Calcium Carbonate ($CaCO_3$) deposited and illuviated in arid region soils cemented into a petrocalcic horizon; often as Stage IV carbonate.

Carbonate Stage – Stage I carbonate is loose disseminated $CaCO_3$ in the soil matrix. State II carbonate is thin, discontinuous coatings of $CaCO_3$ on the bottoms of coarse clasts in the soil matrix. Stage III carbonate is continuous coatings of $CaCO_3$ on the majority of coarse clasts in the soil matrix. Stage IV carbonate is replacement of the original soil matrix by a thick, well-cemented layer of $CaCO_3$. Stage V carbonate has strongly expressed laminar and/or platey structure.
Clastic – Rock fragments or other material which has been transported.
Contraction Scour – A form of scour frequently occurring in rivers at bridge crossings where stream width rapidly contracts causing an increase in stream velocity and/or turbulence.
Crenulation Index – The ratio of the topographic contour length to the straight line distance along the arc of the contour. A low crenulation index indicates low relief and a uniform surface.
Critical Shear Stress – The component of shear stress parallel to a slip plane in a slip system which controls the activity along that plane.
Cut Bank – The outside bank of a channel bend, often eroding and on the opposite side of the stream from a point bar.
Dendritic Drainage Pattern – A drainage system with tributaries which join at all angles, similar to the branching pattern of a tree. The number of flow paths decrease in the downstream direction.
Desert Pavement – A layer of tightly packed coarse sediment found on the surface of desert soils formed by winnowing away finer sediment by wind, rainfall, or local runoff. Degree of pavement development is related to the intensity of the formative processes.
Desert Varnish – A dark stain substance with a glistening luster, composed of manganese or iron oxide, found on the exposed surfaces of coarse rock material in arid climates. Desert varnish is formed as microbiotic organisms fix eolian cations with oxygen during infrequent wetting by rain.
Discharge – The volume of water passing through a channel during a given time, usually measured in cubic feet per second.
Dynamic Equilibrium – A natural state of regular, expected channel change with time where stream characteristics naturally adjust to the physical conditions of the environment.
Embayment – Fault-bounded mountain ranges have highly linear mountain fronts upon formation. Headward erosion along stream forms canyons. With time, these canyons cause the mountain front to be increasingly non-linear or "embayed".
Entrenchment Ratio – A computed index value which is used to describe the degree of vertical containment of a river channel (width of the flood-prone area at an elevation twice the maximum bankfull depth/bankfull width).
Ephemeral Stream – A stream that only experiences flow in times of heavy runoff and precipitation. An ephemeral stream does not have a base flow, as the channel is always above groundwater.
Evaporites – Sedimentary rock types formed by evaporation of water; for example, halite and gypsum.
Facies – A grouping of sediments, rocks, or soils with a common or related origin.

Fanglomerate – Rock and soil material originally deposited as an alluvial fan which has since been transformed into bedrock. Fanglomerates are characterized by a wide range of grain sizes and bedding types.
Felsic – A term applied to K-feldspar and silica rich rock types.
Fluvial – Of or pertaining to rivers and stream flow.
Froude Number – A number describing the ratio of inertial to gravitational forces in flowing water. A Froude number greater than one indicates supercritical flow.
Geomorphology – The study of the shape and form of the Earth's surface.
Graywacke – A type of sandstone characterized by detrital sand grains in a clay matrix. A dirty hard sandstone.
Headcutting – Channel degradation associated with abrupt changes in the bed elevation (headcut) that migrate in an upstream direction.
Holocene – Recent; that period of geologic history (an epoch) since the last ice age in North America (the past 10,000 years); also the series of strata deposited during that epoch.
Hydraulic Geometry – The description of the graphical relations between plot points of the hydraulic characteristics of a stream, typically width, depth, velocity and discharge.
Illuviation – The downward transport of mineral or other material in a soil layer, usually the B or C soil horizon.
Imbrication – Overlapping alignment of pebbles and cobbles due to transport in water. The tail of one clast overlies the head of the next clast downstream.
Incised Channel – A channel that cuts vertically downward, below the level at which it originally formed.
Inselbergs – Isolated remnants of bedrock exposed as small hills or buttes in the alluvial plain or pediment.
Intermittent Streams – A stream or part of a stream that flows only in direct response to precipitation, receiving little or no water from springs, snowmelt or other sources. It may be dry for a large part of the year, generally more than three months. Its course may be marked by an eroded channel, sediment deposits, scour, or transport of leaf litter or soil.
Interrupted Stream – A stream which has short perennial segments with intervening ephemeral or intermittent segments.
Interfluves – The area between braided flow channels. The area is usually vegetated in contrast to the sandy channel beds.
Normal Fault – A fault in which the hanging-wall block moved down relative to the footwall block.
Paleoflood – any flood that occurred prior to, or without, human records.
Patina – a coating or layer of corrosion formed by oxidation. Desert varnish forms a patina on the surface of rocks.
Pediment – A gently sloped erosion surface composed of bedrock with a thin veneer of alluvium, often formed by mountain front planation.
Pedogenic Clay – Clay that forms as a result of in place weathering within a soil column.
Perennial Streams – A stream that normally has water in its channel at all times.
Petrocalcic – Calcium-rich rock material
Piedmont – A general term for the sloping land area adjacent to a mountain front.
Planform – The form or pattern contour of an object as viewed from above; map view.
Pool – A section of the river with relatively deep water and low flow velocities.

Relict – a feature formed in a previous climatic or geologic condition.
Riffle – A relatively shallow section of a river with high-velocity, turbulent flow.
Riparian – Pertaining to anything connected with or adjacent to the banks of a river or stream.
Riprap – Rock material placed on stream banks to protect a structure or embankment from erosion.
Runoff – That part of precipitation that appears in surface-water bodies. It is the same as streamflow unaffected by artificial diversions, storage or other human works in or on the stream channels.
Scour – lowering of the channel bed elevation due to flowing water.
Sediment Yield – The total sediment outflow from a watershed or a drainage area at a point of reference and in a specified period of time. This is equal to the sediment discharge from the drainage area.
Sherds – Broken pieces of pottery or ceramic ware.
Sinuous – The "curviness" of planform of a river channel, the degree of meandering.
Slackwater – A low-energy zone in a stream characterized by near-zero velocity and sediment deposition.
Strath Terrace - A stream terrace formed by erosion, rather than deposition.
Stratigraphy – The study of layered sedimentary or metamorphic rock, especially their relative ages and correlation between different areas.
Stream Order – A geomorphic parameter used to describe the complexity of a drainage system. A first order stream has no tributaries. A second order stream is formed by the confluence of two first order streams. A third order stream is formed by the confluence of two second order streams. No stream order system exists specifically for alluvial fans.
Stream Power – A technical term relating shear stress and velocity. The units signify power per unit area of stream bed.
Supply Reach. The reach located upstream of the reach studied in detail. Since water flows downstream, sediment and water are supplied from reaches upstream.
Suspended Load – The part of the total sediment load that moves above the bed load. The weight of the suspended sediment is totally supported by the fluid.
Swale – A small channel, ditch, or depression.
Tensional Cracks – Cracks that are elongate and that form as forces work to pull apart a soil or rock unit.
Thalweg – An imaginary line along the length of the river connecting the deepest points.
Torrifluvents – A type of soil characterized by stream deposits of gravelly, sandy material, and lack of significant soil horizon development.
Tuff – A rock type formed of compacted volcanic fragments and ash.
Watershed – An area confined by drainage divides, usually having only one streamflow outlet.