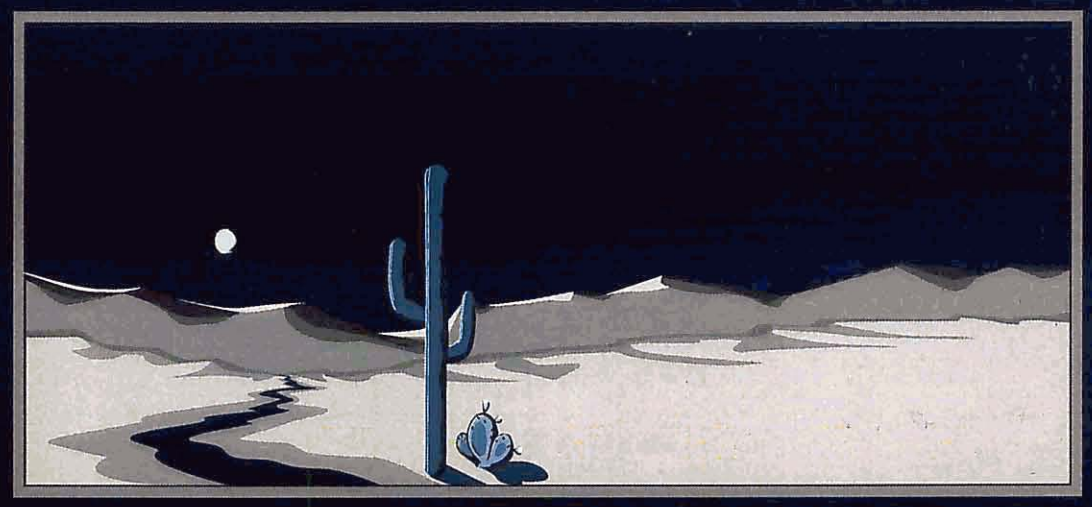
UPPER CAVE CREEK/APACHE WASH



Watercourse Master Plan

Attachment 5:Lateral Stability Assessment Report

Flood Control District of Maricopa County

April 2001

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Upper Cave Creek/Apache Wash Watercourse Master Plan Report

Attachment 5: Lateral Stability Assessment

December, 2000

Prepared for: **Flood Control District of Maricopa County & Tetra Tech, Inc. Infrastructure Southwest Group**

Prepared by: **JE Fuller/ Hydrology & Geomorphology, Inc. Tempe, AZ**

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Chapter 1
Introduction

The Flood Control District of Maricopa County (FCDMC) is preparing a watercourse master plan for Upper Cave Creek and three of its tributaries located between Cave Buttes Dam and the Carefree Highway. The watercourse master plan was prepared by a team of consultants led by ASL Consulting Engineers, Inc. (ASL), 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 Cave Creek/ Apache Wash study area is located in north-central Maricopa County, within the corporate limits of the City of Phoenix (Figure 1-1). The Upper Cave Creek/ Apache Wash Watercourse Master Plan includes the following reaches of four streams:

- Cave Creek - Carefree Highway to Cave Buttes Dam (6.5 miles)
- Apache Wash - Carefree Highway to Cave Buttes Dam (4.8 miles)
- Paradise Wash - Carefree Highway to the Apache Wash confluence (1.9 miles)
- Desert Hills Wash - Phoenix corporate boundary to Apache Wash (0.5 miles)

In addition, a qualitative analysis of Apache Wash from the Carefree Highway north to the Town of Cave Creek Corporate Boundary (3.0 miles) was included in the study.

Objectives

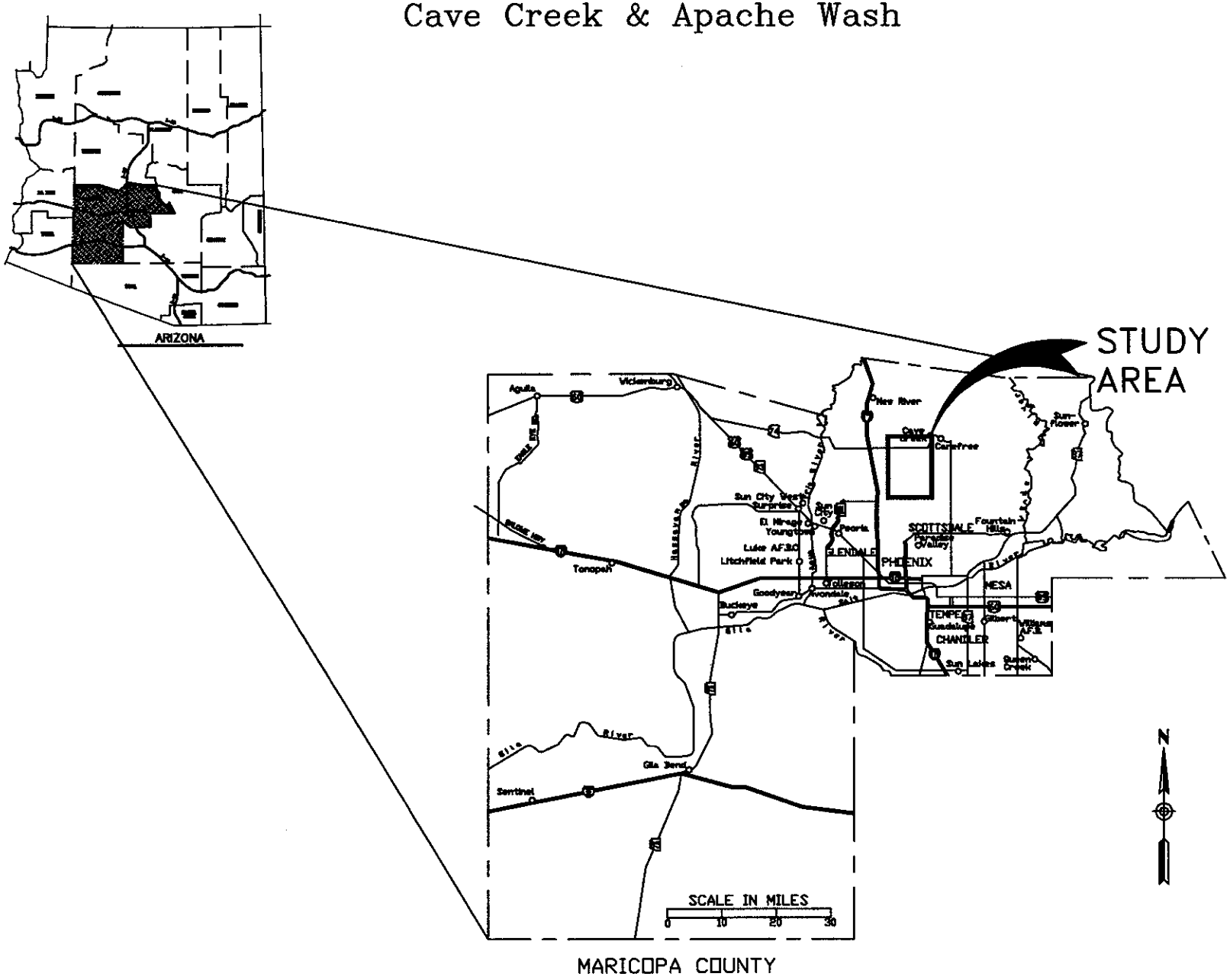
The primary objectives of the Upper Cave Creek and Apache Wash Watercourse Master Plan Lateral Stability Assessment were to determine the potential for lateral migration of the Upper Cave Creek and its three principal tributaries, and to determine the benefits of and opportunities for non-structural 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:

- City of Phoenix (COP)

Figure 1-1. Location Map
Cave Creek & Apache Wash



- Flood Control District of Maricopa County (FCDMC)
- Maricopa Department of Transportation (MCDOT)
- Salt River Project – Historical Archives (SRP)
- Arizona Department of Transportation (ADOT)
- Arizona Geological Survey (AZGS)
- Arizona State Land Department (ASLD)
- Arizona State University – Geology Department (ASU)
- Federal Emergency Management Agency (FEMA)
- 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 four 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 Upper Cave Creek and Apache Wash 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 will improve the accuracy of the hydrologic and geomorphic analyses.
- Hydrologic Data. No streamflow gauging data were available for Apache Wash, Paradise Wash, or Desert Hills 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 would improve the accuracy of the lateral stability assessment.
- Hydraulic Modeling. HEC-2 models were prepared by others for the purpose of delineating the 100-year floodplain and floodway (Willdan, 1996; George V. Sabol Consulting Engineers, Inc. (GVSCE), 1996, Jerry R. Jones, 1991). As described in Chapter 5, some modifications of the input code were required prior to use 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.
- Topographic Mapping. Detailed topographic mapping was provided from previous projects completed by others (Willdan, 1996; GVSCE, 1996, Jerry R. Jones, 1991). The most recent detailed topographic mapping was prepared in 1995, prior to development of the Wheeler sand & gravel mine on Cave Creek and construction of the new eastbound lanes on Carefree Highway. Therefore, HEC-2 model for Cave Creek does not reflect the channel excavations at the Wheeler mine (Willdan, 1996). The HEC-2 models for Apache Wash, Paradise Wash, and Desert Hills Wash do not reflect any erosion or deposition that occurred during the 1993 or 1995 floods.
- Sediment Continuity Modeling. Sediment modeling was performed for the Upper Cave Creek/Apache Wash Watercourse Master Plan by others using the HEC-6 model, 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. More accurate predictions of lateral stability could be made with extensive geotechnical investigations along the channel banks.
- Scale of Analysis. This study considered approximately 14 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, stable slope, *scour*, sediment continuity modeling (HEC-6), Albuquerque Metropolitan Arroyo Flood Control Authority (AMAFCA) Methodology, Lane Relation, and Arizona Department of Water Resources (ADWR) State Standard 5-95.
- 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. Term included in the glossary are shown in italics in the text of the report.

Chapter 2
Study Area Description

The study area for the Upper Cave Creek/Apache Wash Watercourse Master Plan includes four streams located between the Carefree Highway and Cave Buttes Dam. This chapter provides the basic information about the following characteristics of the 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. This information can then be used to define specific stream reaches for more detailed analyses.

Watershed Description

The lateral stability of the streams of the Cave 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

Cave Creek and its principal tributaries form a moderately large stream system (142 mi.^{2}) that heads in the New River Mountains north of the Town of Cave Creek 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 unnamed watercourses, the significant tributaries of Cave Creek Wash upstream of Carefree Highway include the following:

- Seven Springs Wash (10.6 mi^2)
- Bronco Creek (4.8 mi^2)
- Big Maggie Way Wash (1.8 mi^2)
- Skunk Tank Wash (1.3 mi^2)
- Grays Gulch (3.4 mi^2)
- Mattys Fork (3.8 mi^2)
- Cottonwood Creek (10.4 mi^2)

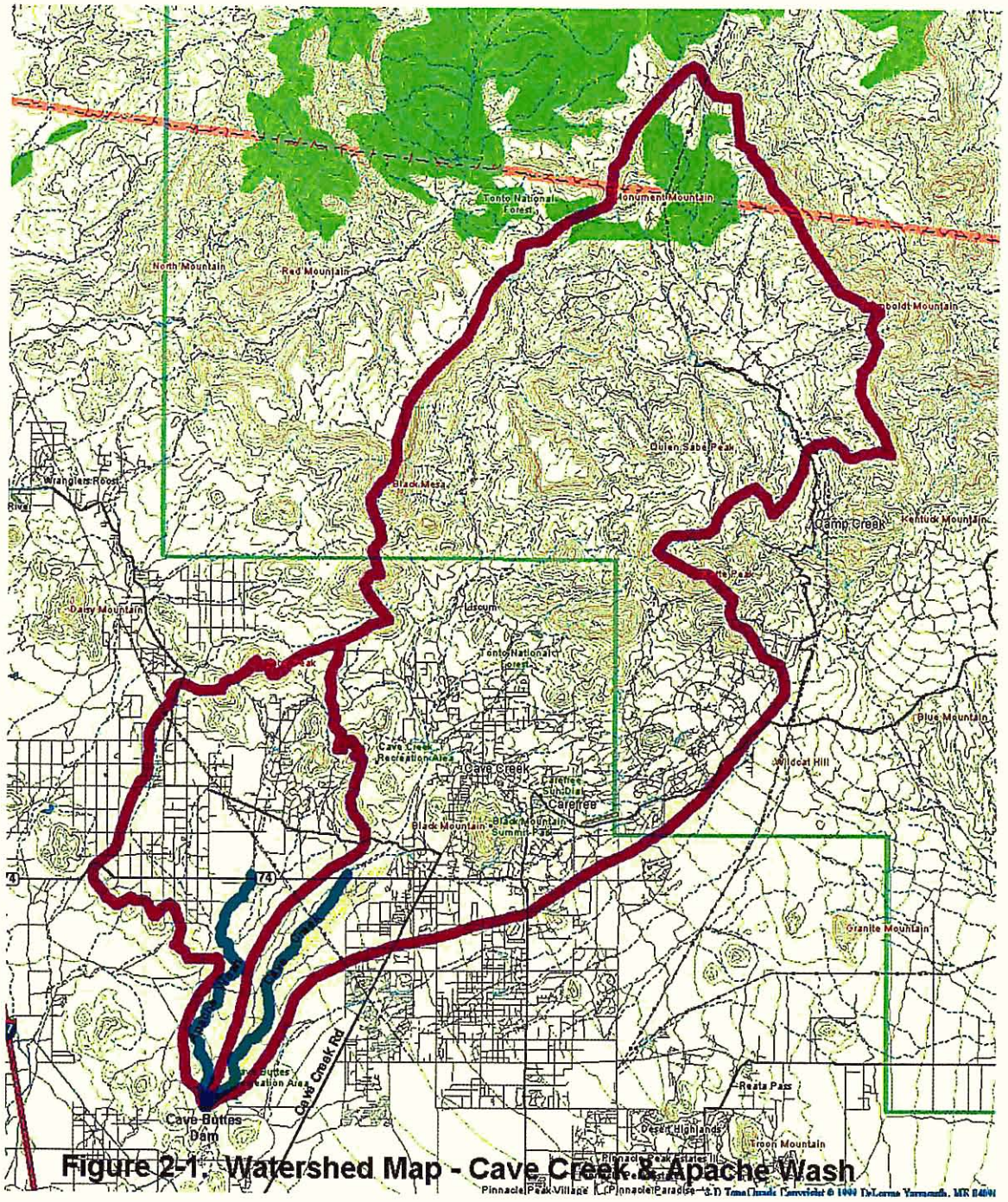
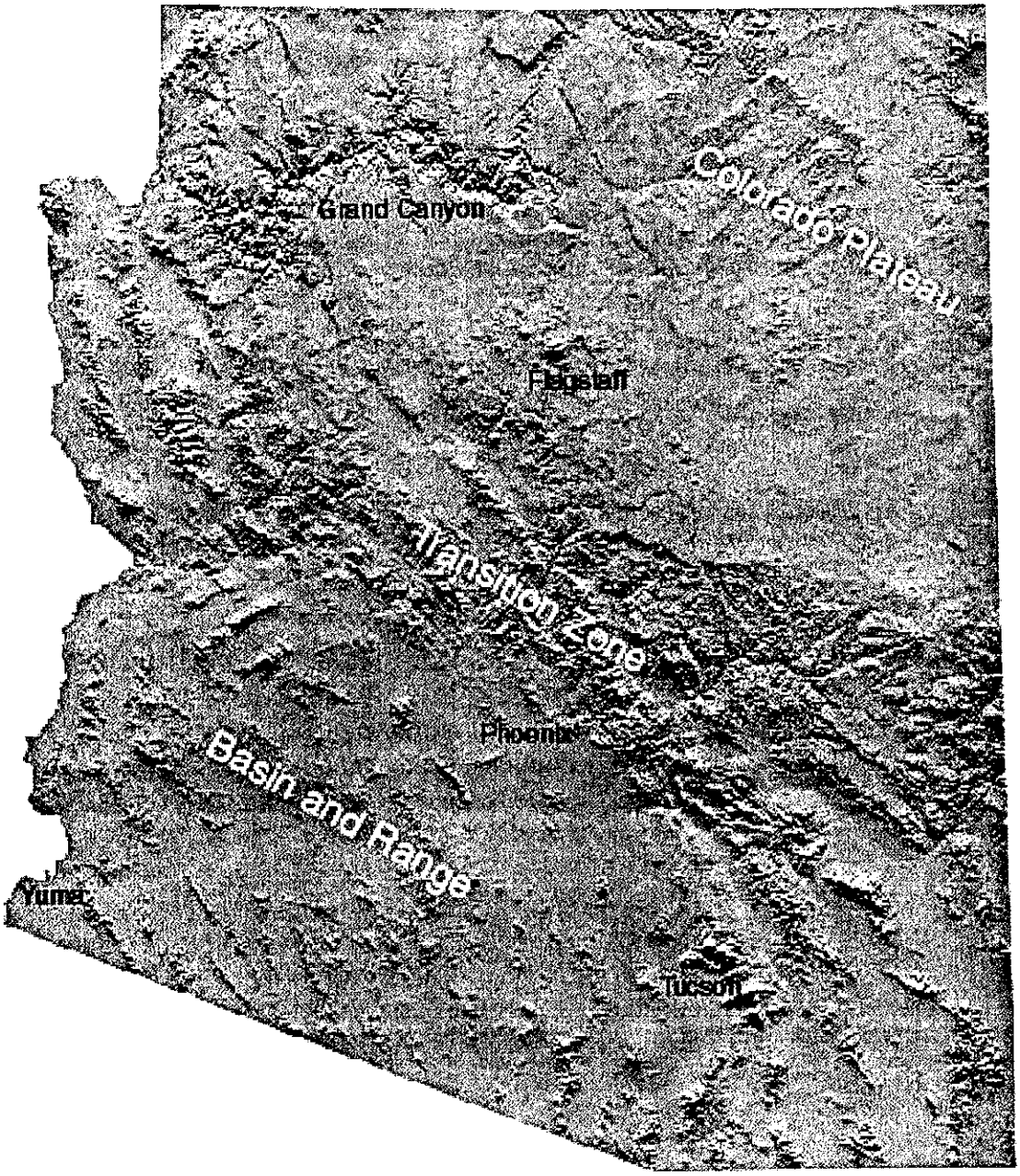


Figure 2-1 Watershed Map - Cave Creek & Apache Wash

Figure 2-2. Physiographic Provinces of Arizona



Willow Springs Wash (5.9 mi^2)

- Grapevine Wash (20.8 mi^2)
- Galloway Wash (7.6 mi^2)
- Andora Hills Wash (2.8 mi^2)

The following unnamed tributaries drain the distal portions of the northern part of the McDowell Mountain *piedmont* and join Cave Creek from the east within the study limits (Figure 2-1):

- Unnamed Tributary #1 (a.k.a. "Effluent Wash"; mi^2)
- Unnamed Tributary #2 (a.k.a. "Black Tank Wash; mi^2)
- Unnamed Tributary #3 (a.k.a. "Carefree Highway Wash; mi^2)

No significant tributaries join Cave Creek within the study limits from the west side of the *watershed*. However, flow concentrating in the right (west) geologic floodplain has formed a defined channel which eventually joins the main channel upstream of Cave Buttes Dam. Apache Wash and Mesquite Tank Wash flow into the Cave Buttes Dam impoundment area before joining Cave Creek.

Apache Wash drains a 27 square mile watershed located between the Union Hills and the foothills of the New River Mountains west of the Town of Cave Creek (Figure 2-1). Apache Wash has two major tributaries, Desert Hills Wash and Paradise Wash, both of which join Apache Wash within the study limits and are included within the Watercourse Master Plan. The most significant tributary of Paradise Wash is Ranieri Tank Wash (1.9 mi^2). Desert Hills Wash has two major tributaries, Jonathan Wash (a.k.a. "Desert Lake Wash", 5.0 mi^2) and the West Branch of Desert Hills Wash (a.k.a. "East Fork Wash, 1.2 mi^2), both of which are located upstream of the study limits. The area between the Cave Creek *watershed* and the Apache Wash watershed is drained by Mesquite Tank Wash (1.1 mi^2), which flows directly into the Cave Buttes impoundment area.

Table 2-1. Upper Cave Creek/Apache Wash 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)
Cave Creek			
@ Carefree Highway	124.4	1,800	33,800
@ Cave Buttes Dam	142.5	1,900	38,100
Apache Wash			
@ Carefree Highway	6.5	130	7,200
Above Desert Hills Wash	7.7	150	7,500
Above Paradise Wash	20.3	270	13,500
@ Cave Buttes Dam	27.0	330	17,100
Paradise Wash			
Below Carefree Highway	4.7	110	5,200
@ Apache Wash Confluence	5.6	120	5,800
Desert Hills Wash			
Above City of Phoenix Boundary	12.1	200	10,300

Urbanization

The Cave Creek and Apache Wash watersheds encompass portions of the City of Phoenix, the City of Scottsdale, the Town of Cave Creek, the Town of Carefree, unincorporated Maricopa County, and the Tonto National Forest. Most of the *watershed* is comprised of undeveloped desert mountain terrain or desert upland foothills with low density suburban ranch development. Cave Creek south of Cave Buttes Dam is heavily urbanized. Some suburban ranch and commercial development has occurred along Cave Creek within the Town of Cave Creek upstream of the study reach. Rural development has occurred along the portions of Apache Wash, Paradise Wash, and Desert Hills Wash upstream of Carefree Highway within unincorporated Maricopa County. The reaches of the Cave Creek/Apache Wash system located between Cave Buttes Dam and Carefree Highway consist of State Trust land and are currently undeveloped, although the land has been leased for sand and gravel mining and for cattle grazing. The northern Phoenix metropolitan area is experiencing rapid population growth and urbanization. Therefore, future development within and upstream of the study area is expected in the near future.

Physiographic Setting

The headwaters of the Cave Creek watershed are located in the rugged Transition Zone Physiographic Province of central Arizona. Cave Creek flows southwestward from the Transition Zone to the margins of the Basin and Range Physiographic Province, across the northern edge of the Paradise Valley,[1] and into the Cave Buttes Reservoir. Paradise Valley is drained by Apache Wash and its tributaries. Desert Hills Wash is the axial stream for Paradise Valley, forming the low point divide. Prior to construction of Cave Creek Dam in 1923 and Cave Buttes Dam in 1986, Cave Creek flowed through the Union Hills and around the western end of the Phoenix Mountains. Today, Cave Creek terminates at the Arizona Canal Diversion Channel (ACDC). Prior to historical development of the Phoenix area and construction of the ACDC, Cave Creek continued generally southward through what is now the west side of the City of Phoenix to join the Salt River. However, even topographic maps dating to the early 1900's do not show a distinct channel or course for the lowermost part of Cave Creek (USGS, 1914). *Runoff* from Cave Creek probably reached the Salt River system only during rare long-duration, high-volume floods.

Elevations in the watershed range from about 5,340 feet at Blackjack Point in the Tonto National Forest to about 1,600 feet near Cave Buttes Dam. Elevations, average channel slopes, and stream lengths for the channels within the study reach are shown in Table 2-2.

---

[1] Not the Town of Paradise Valley. Paradise Valley is the geographic name of the northwest-southeast trending valley lying between the Union Hills and the New River Mountains, as shown on the New River SE, Arizona topographic quadrangle map (USGS, 1981).

Table 2-2. Upper Cave Creek/Apache Wash Watercourse Master Plan Stream Physiographic Characteristics				
Stream Name	Elevation (ft.)		Average Channel Slope (ft./ft.)	Stream Length (mi.)
	Upstream Limit	Downstream Limit		
Cave Creek	1854	1622	0.008	5.1
Apache Wash	1800	1646	0.007	4.4
Desert Hills Wash	1742	1736	0.002	0.6
Paradise Wash	1814	1726	0.009	2.0

All of the streams within the study limits are *ephemeral*, although *perennial* springs and stream reaches occur near the headwaters of Cave Creek, and nearly permanent water exists in stock ponds along some of the tributaries. The average annual rainfall for the *watershed* above the USGS stream gauge downstream of Carefree Highway is reported as 15.7 inches per year (Pope et. al., 1998). About three percent (3%) of the annual rainfall over the *watershed* becomes *runoff* within the study reach downstream of Carefree Highway.

More detailed descriptions of specific watershed characteristics are provided in the Hydrologic Modeling Section of the Upper Cave Creek/Apache Wash Watercourse Master Plan Final Report (ASL, 1999).

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 Basin and Range and Transition Zone Physiographic Provinces (Figure 2-2) have a long, complex history of geologic activity. The most recent major geologic activity involved crustal extension and *normal faulting* during the late Tertiary Period (Table 2-3) which helped to form the modern Basin and Range - Transition Zone boundary. The alluvial deposits associated with Cave Creek and its principal tributaries provide evidence of the evolution of this *fluvial* system in response to geologic activity over the past several million years.

The highest and oldest deposits of Cave Creek are found about two miles northwest of the town of Cave Creek, north of the study area (Gorey, 1990; Doorn and Pewe, 1991; Leighty et al., 1997). These high, old alluvial deposits were formed about 2 to 3 million years ago (Gorey, 1990). At that time, the bed of Cave Creek was about 300 feet higher than it is now, and it probably exited the mountains well to the west of its current course (Leighty et al., 1997). Flow of Cave Creek changed direction toward the south to its modern course, sometime between about 2 million and 750,000 years ago. When Cave

Creek established this southerly course between Black Mountain and Go John Mountain, it cut down through Tertiary-aged basin fill deposits into Precambrian bedrock and deposited a large *alluvial fan* complex to the south in the Paradise Valley (Leighty et al., 1997). The study reaches are located within the Pleistocene-aged alluvial fan complex in the Paradise Valley.

Table 2-3. Upper Cave Creek/Apache Wash 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

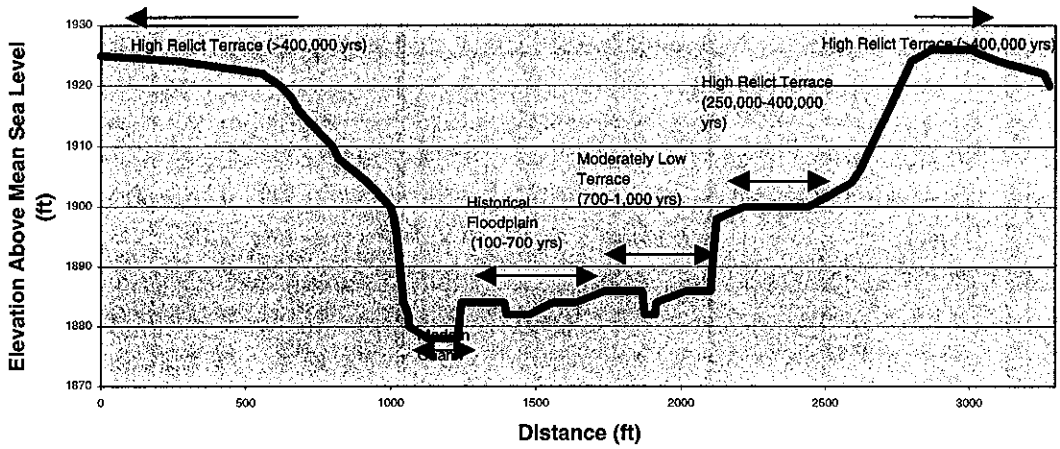
Notes:
1. ma = million years

Cave Creek. The depositional record of Cave Creek along its modern course in northwestern Paradise Valley begins with the deposition of the major *alluvial fan* complex between Black Mountain and Cave Buttes Dam during the middle Pleistocene (400,000 to 750,000 years ago). The apex of this relict fan is located downstream of the bedrock valley between Black Mountain and Go John Mountain (Figure 2-1). The width of the relict fan rapidly widens to about 2 miles in the vicinity of Carefree Highway, and remains approximately that wide through the study area (Gorey, 1990; Leighty et al., 1997; Holloway and Leighty, 1998; Leighty and Holloway, 1998).

In the past four hundred thousand years since deposition of this large relict fan, Cave Creek and its tributaries have incised, leaving behind a series of stream terrace deposits above the modern channel. The surfaces of the relict middle Pleistocene alluvial fan complex now are about 25 to 35 feet above the modern channel, and the younger middle Pleistocene terraces are about 15 to 20 feet above the channel (from Gorey, 1990; Leighty et al., 1997). The height of these relict surfaces above the modern channel generally decreases downstream (Gorey, 1990). Younger terraces of late Pleistocene and *Holocene*

age stand about 8 to 15 feet, and 1 to 8 feet above the current channel bottom, respectively. A cross section of the stream channel and the associated deposits at the Carefree Highway shows a flight of terraces inset into the highest relict fan surface (Figure 2-3). The inset landforms become progressively younger as elevation decreases.

Figure 2-3. Geomorphic Surfaces - Cave Creek At Carefree Highway



Interpretation of the geologic setting indicates that the long-term trend of Cave Creek during the past few million years has been one of downcutting and incision into older stream deposits and bedrock. In the vicinity of the town of Cave Creek, Cave Creek has *incised* about 300 feet since the late Pliocene. Although the presence of terrace deposits of many ages shows that significant deposition also must have occurred during certain time periods, the overall long-term trend has clearly been toward downcutting and channel incision upstream of Cave Buttes Dam. Since the middle-Pleistocene, when the one to two mile-wide surfaces of the alluvial fan complex in northern Paradise Valley became entrenched and no longer received deposition of river *alluvium*, the main channel of Cave Creek has remained within the same broad corridor now *incised* into the relict fan. In the study reach, this corridor is defined by a swath of *Holocene*-aged deposits produced by lateral migration and shifting of the active channel over the past ten thousand years. The width of this corridor of Holocene-aged deposits averages about 1,300 feet wide, but ranges from about 770 to 2,510 feet within the study reach. Along portions of the Cave Creek study reach characterized by a single active channel today, channel width averages about 100 feet. The channel width averages about 350 feet in multiple and braided reaches where numerous islands and bars divide the channel.

Apache Wash System. The geologic history of Apache Wash, Paradise Wash, and Desert Hills Wash is less well known. The smaller *watersheds* of these streams do not extend as far north as the Cave Creek watershed into the Transition Zone, although they have been shaped by much of the same geologic history. Downstream of their confluence, Paradise Wash and Apache Wash drain the western margin of the middle

Pleistocene *alluvial fan* complex formed by Cave Creek, and have terrace surfaces analogous to Cave Creek. The presence of analogous terraces on these reaches of Apache and Paradise Washes suggests a direct connection to the main channel of Cave Creek and its source water during the formative period for the middle Pleistocene alluvial fan, perhaps as linked distributary channels on a alluvial fan.

The depth of incision (or height of the terraces) decreases dramatically to the west across the Paradise Valley. Apache Wash upstream of the Paradise Wash confluence lacks well developed late *Holocene* and Holocene/late Pleistocene terraces found on Cave Creek and the Paradise-Apache stream corridors. Further west, the terrace height progressively decreases and the surfaces adjacent to the stream channels become progressively younger. Desert Hills Wash drains the axis of the valley located between the Precambrian-aged rock outcrops of the Union Hills and the middle Pleistocene alluvial fan complex. The geomorphic surfaces surrounding the Desert Hills Wash floodplain are mapped as late Pleistocene aged by the Arizona Geological Survey (Leighty & Holloway, 1998).

The width of the corridor of active channel and Holocene-aged terraces also vary with the distance from Cave Creek and proximity to the valley axis, as demonstrated by the following measurements of corridor width:

- Apache Wash. The geologically recent corridor along Apache Wash averages 535 feet, but ranges from 100 to 970 feet within the study reach. The corridor width narrows significantly upstream of the Desert Hills Wash confluence, with an average width of 395 feet and 650 feet, downstream and upstream of the confluence, respectively.

- Paradise Wash. The geologically recent corridor along Paradise Wash is fairly constant in width, with an average width of 750 feet, and ranges from 600 to 860 feet within the study reach. Upstream of Carefree Highway, the corridor width narrows gradually toward the headwaters.

- Desert Hills Wash. The geologically recent corridor along Apache Wash averages 870 feet, but ranges from 530 to 1,100 feet within the study reach, gradually narrowing in the upstream direction.

Summary

Within the study area, the existing channels of Cave Creek and its tributaries have experienced net degradation over the past 700,000 years. 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 Cave Creek and its tributaries is provided in the geomorphic mapping discussion in Chapter 4 of this report.

Hydrology

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

Data Sources

Hydrologic data for Cave Creek and its tributaries 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 (GVSCE, 1995; Willdan, 1997; Jerry R. Jones & Associates, 1992) and for this study (ASL Consulting, 1999), and from application of USGS regression equations for peak *discharge* (Thomas et. al. 1994). USGS stream-gaging stations on or near Cave Creek are listed in Table 2-4.

Table 2-4. Upper Cave Creek/Apache Wash Watercourse Master Plan USGS Stream Gauge Stations

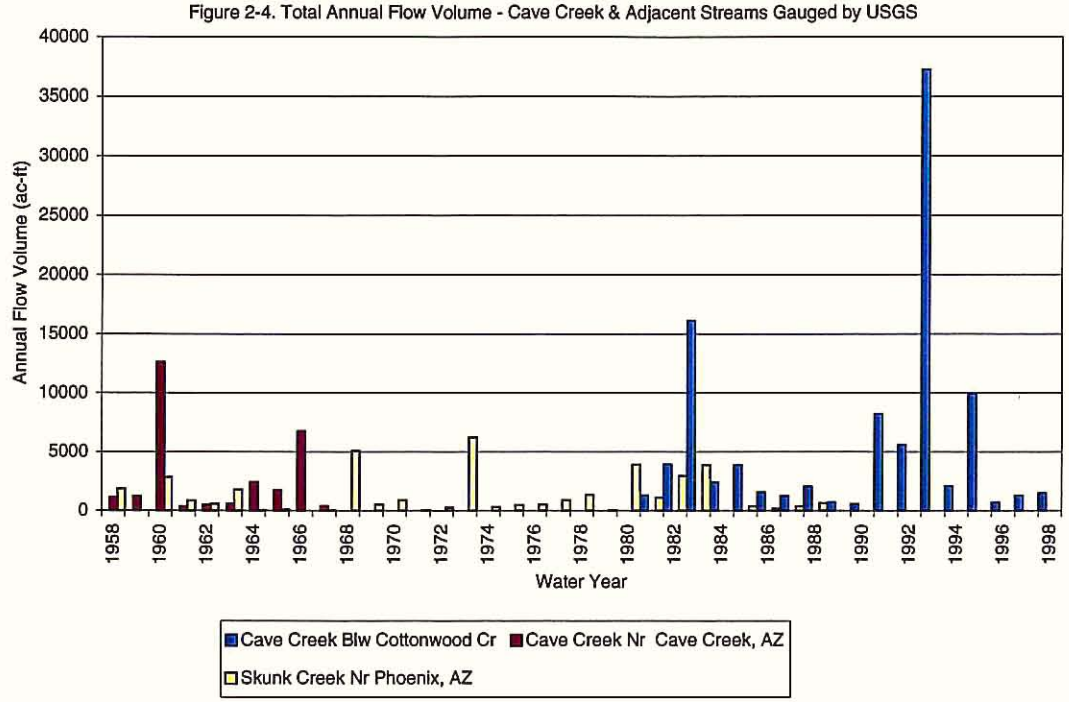
Name	Station #	Period of Record	Drainage Area (mi^2)
Cave Creek below Cottonwood Ck.	09512280	1981-1999	82.7
Cave Creek near Cave Creek, AZ[1,2]	09512300	1958-1999	121
Cave Creek near Phoenix, AZ[3]	09512400	1957-1990	252
Skunk Creek near Phoenix, AZ	09513860	1968-1999	64.9
New River near Rock Springs, AZ	09513780	1966-1999	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 is located downstream of Cave Buttes Dam.

No stream gauging stations exist on Apache Wash or its tributaries. 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 Apache Wash system.

Annual Flow

Lateral channel movement is strongly related to volume of flow. In addition to the effects on stability of saturating the bank materials, 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 2-4 shows the gauged flow volumes for Cave Creek and nearby streams. Flow data from nearby Skunk Creek are provided to cover the gap in Cave Creek gauge records between 1967 and 1981.



The following conclusions may be drawn from the annual flow volume data shown in Figure 2-4:

- 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.

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 Cave Creek gauges are summarized in Figure 2-5.

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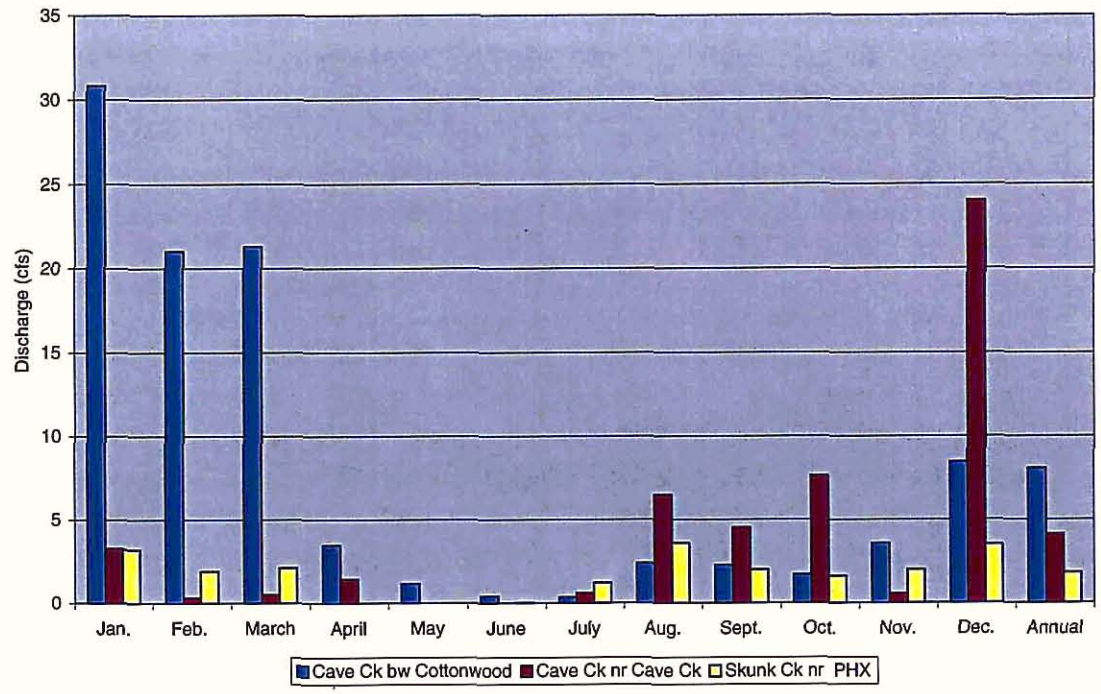
[2] 10 acre-feet, Skunk Creek, 1977.

[3] 37,262 acre-feet, Cave Creek near Cottonwood Creek, 1993.

Figure 2-5. Monthly Average Flow Rate at Nearby USGS Gauges



The following conclusions can be drawn from the monthly flow data summarized in Figure 2-5:

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

- Location. Average monthly flow rates vary significantly within the *watershed.* With the exception of the month of December, the Cave Creek near Cottonwood Creek gauge near the headwaters experiences winter flow rates about four to five times the magnitude of the average flow rates at the Cave Creek near Cave Creek gauge for the same period. However, the summer peaks at the Cave Creek near Cave Creek gauge are about double the peaks at Cave Creek below Cottonwood Creek gauge.

- Drainage Area. Monthly flow rate is not consistently related to drainage area at the two Cave Creek stations.

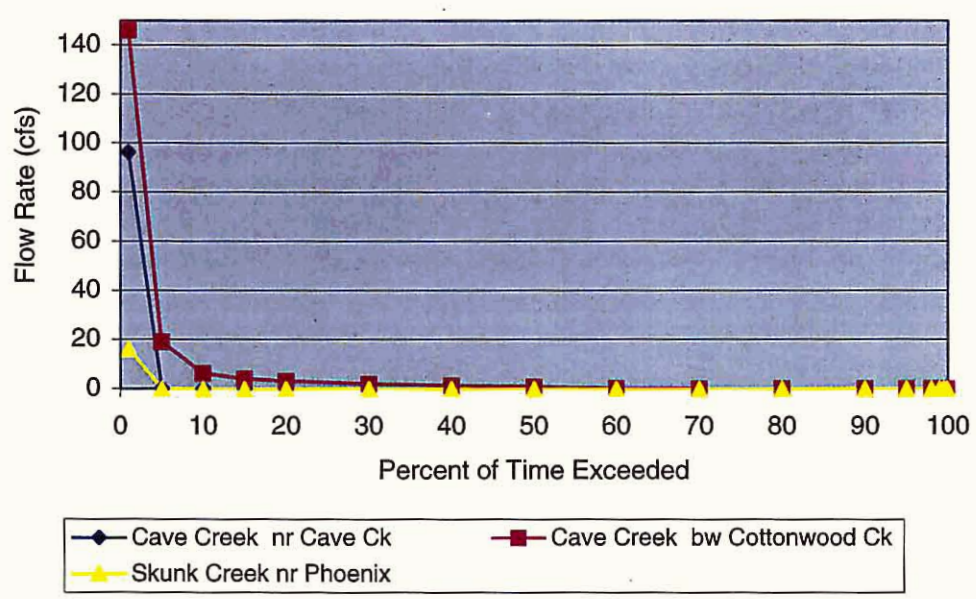
- Erosion. Within the study area, seasonal channel change can be expected in response to late summer monsoon flooding, and during early winter floods.

- Similarity to Skunk Creek. The Skunk Creek flow data are most similar to the data from Cave Creek near Cave Creek USGS station.

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 low 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 flash floods. Comparison of flow duration and average flow data help identify streams subject to flash floods. Flow duration statistics for Cave Creek and Skunk Creek are shown in Figure 2-6.

Figure 2-6. Flow Duration Statistics for Cave Creek



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

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

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

Precipitation Records

For *ephemeral* streams like those in the study area, *runoff* is directly related to precipitation. Precipitation records can be used to identify wet/dry cycles, climatic

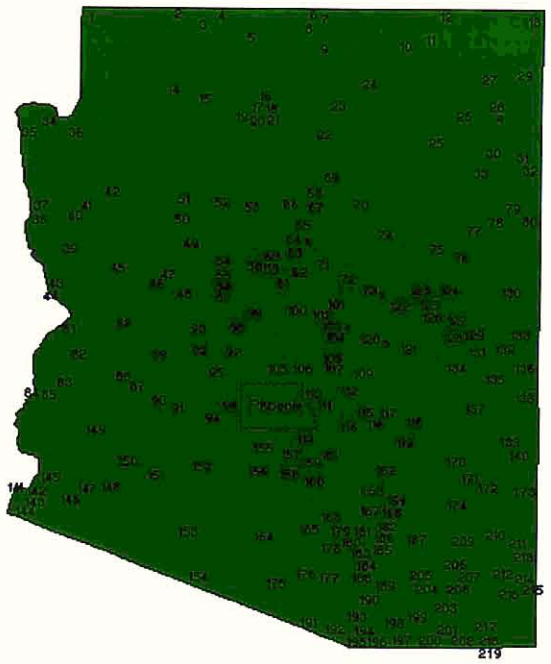
variation, and other trends that may affect stream stability or explain historical channel change. For streams like Apache Wash and its tributaries which lack any systematic gauge record, precipitation data can be used to identify potential flood years or periods of frequent sustained flow. Also, precipitation records are available dating back to the late 1800's, whereas streamflow records on Cave Creek date only to 1958.

Long-term precipitation data were obtained for the Phoenix metropolitan region and for the Cave 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 and long-term average and seasonal precipitation data are shown in Figures 2-7 and 2-9. Average annual runoff computed as a percent of the long-term regional average precipitation is shown in Figure 2-8.

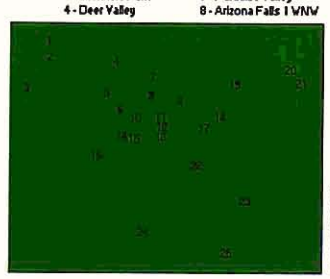
Table 2-5. Upper Cave Creek/Apache Wash Watercourse Master Plan Regional Long-Term Precipitation Stations

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.



INSET for Metro Phoenix Area



1 - Marinette
2 - Youngtown
3 - Litchfield Park
4 - Deer Valley
5 - Alhambra
6 - Phoenix City
7 - Paradise Valley
8 - Arizona Falls 1 WNW
9 - Scottsdale
10 - Phoenix WSFO Airport
11 - Tempe
12 - Tempe ASU
13 - Tempe 3S
14 - South Phoenix
15 - Goulds Ranch
16 - Laveen 3 SSE
17 - Mesa
18 - Falcon Field
19 - Granite Reef Dam
20 - Stewart Mountain
21 - Mormon Flat
22 - Chandler
23 - Chandler Heights
24 - Maricopa 4 N
25 - Sacaton

94 - Buckeye
105 – Carefree
106 – Bartlett Dam

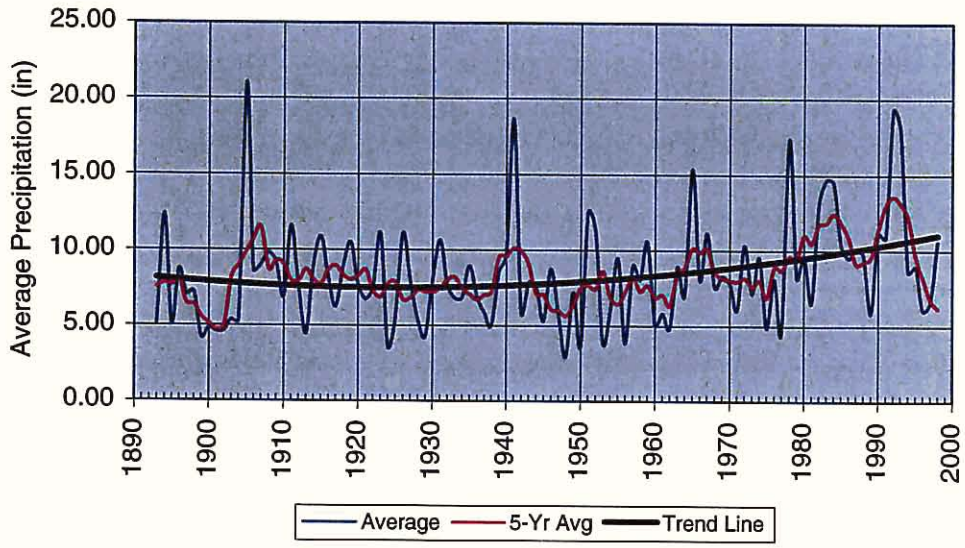


Figure 2-7. Precipitation Measurement Stations & Annual Precipitation Trends for Station Located near Phoenix, Arizona. (See Table 2-5 for the listed of stations used to estimate long-term trends.)

Figure 2-8. Runoff as Percent of Regional Average Precipitation

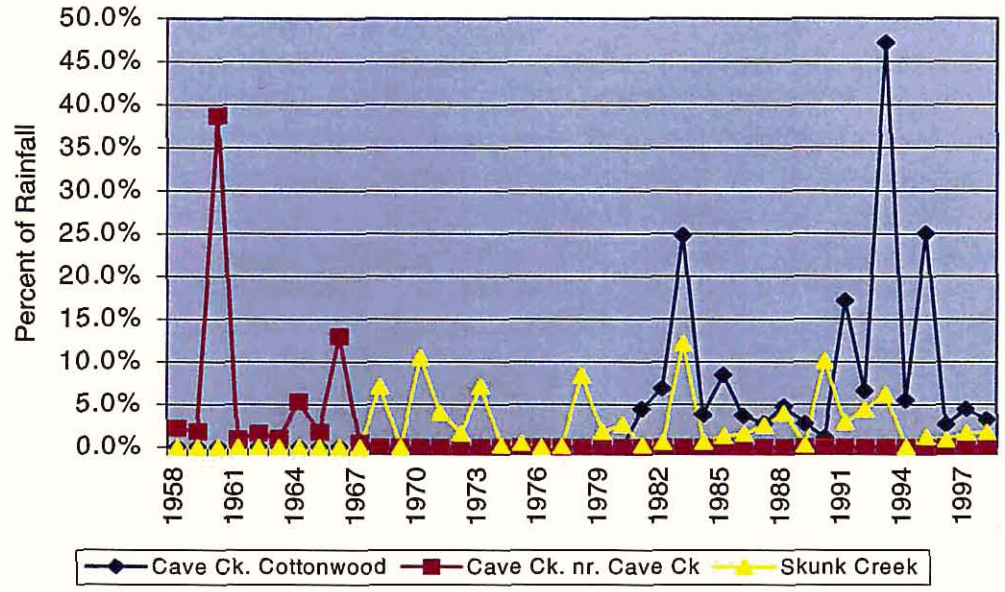
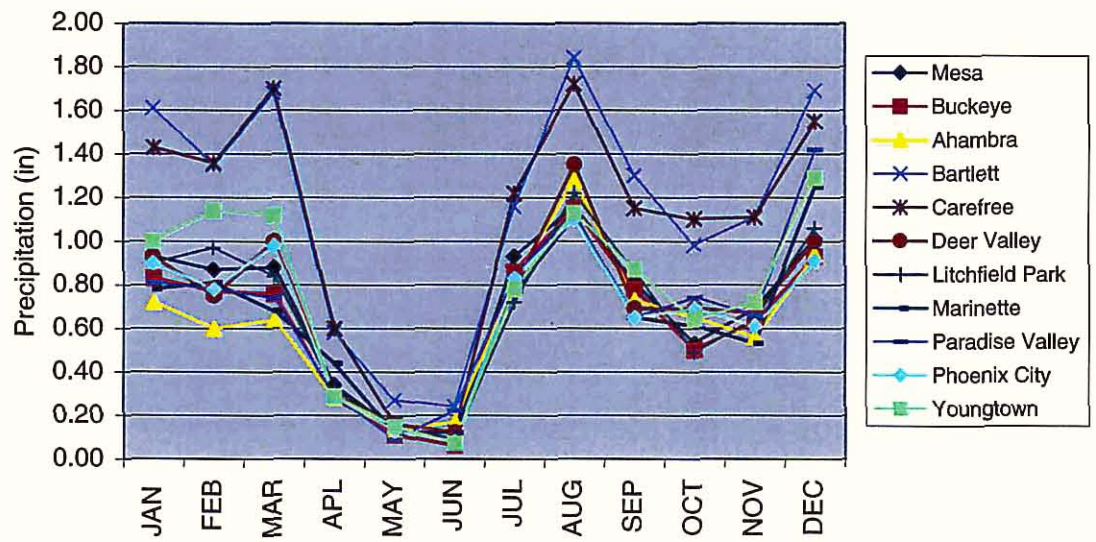


Figure 2-9. Long-Term Average Monthly Precipitation



From the data presented in Table 2-5 and Figures 2-7 to 2-9, the following conclusions can be drawn:

- Long-Term Trends. Figure 2-7 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

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

line indicates that annual precipitation volume has increased during this century, increasing the likelihood of runoff and 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 higher precipitation and runoff, particularly when these wetter periods immediately follow periods of sustained drought.

- Wet Years. Years of unusually high annual precipitation occurred in 1905, 1941, 1965, 1978, and 1993. Interestingly, the percent of rainfall that became runoff typically spiked in the year after these wet years, rather than during the wet year itself, according to the data presented in Figure 2-7.

- Floods. The occurrence of floods during wet years or wet cycles is discussed in the following section of this chapter. A comparison of Figure 2-7 and 2-8 indicates that years of high annual precipitation correlates 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 2-9. These seasonal variations in precipitation are expressed more strongly in the precipitation records of the stations closest to the Cave Creek watershed (Carefree & Bartlett) than in stations located elsewhere in the Phoenix area.

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.

Flooding

Much of the geomorphic work of channel change occurs during the largest floods. Flood data were obtained primarily from USGS streamflow records. No anecdotal records of flooding in Cave Creek or its tributaries were obtained during the data collection or public involvement phases of the study. No suitable sites for *paleoflood* reconstruction of the pre-gage flood

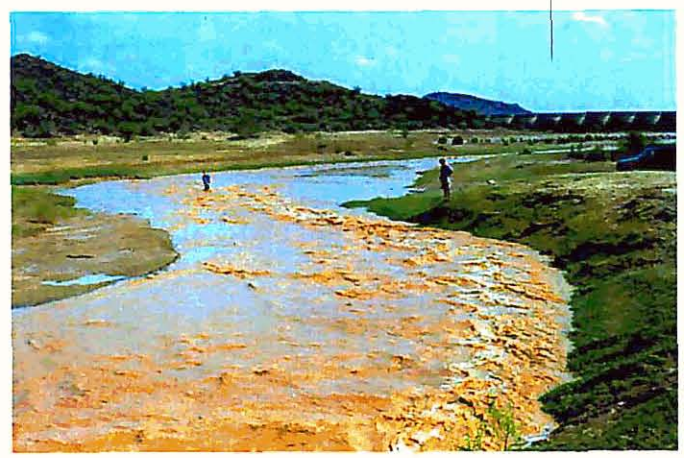


Figure 2-10. July 15, 1999 Flood on Cave Creek upstream of Cave Creek Dam.

history were found within the study area.[6]

Historical Floods. Historical records of floods on Cave 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 Table 2-6.

Table 2-6. Upper Cave Creek/Apache Wash Watercourse Master Plan Historical Floods on Cave Creek

Date	Details	Source	Location
1905 February	Major flood	Selected water resource abstracts	FCD (899.135) FCD (690.704)
1916 September	Minor flood	USACOE Report (1971)	FCD (690.704)
1919 November	Minor flood	USACOE Report (1971)	FCD (690.704)
1921 8/21/21	...flood of serious proportions...	Arizona Climate The First 100 Years	Sellers (1981)
	Flooded Phoenix, heavy rainstorm (4"), *discharge* of 20-25,000 cfs (source of estimate unknown)	Cave Creek Dam Report (Carollo, 1969)	FCD (690.904)
	flooding mentioned with no reference	Floods of October 1977 in Southern Arizona...	FCD (802.041)
1922 January	Minor flood	USACOE Report (1971)	FCD (690.704)
1935	Minor flood	USACOE Report (1972)	FCD (802.025)
1943 8/3/43	No information given	Untitled report	FCD (690.702)
	Flood report	Desert Flood of August 3, 1943	FCD (802.010)
	Largest since completion of Cave Creek Dam, flooded State Capitol, and reached Salt River. Flow est. at 9,000 cfs @ Peoria Ave.	USACOE Report (1971)	FCD (690.704)
1949	Minor flood	USACOE Report (1972)	FCD (802.025)
1951 8/3/51	Flooding	Phoenix Gazette	FCD (802.053)
1952	Minor flood	USACOE Report (1972)	FCD (802.025)
1956 10/23/56	Flood waters...poured into a gravel pit and buried a crushing plant under 30 feet of water.	Arizona Climate The First 100 Years	Sellers (1981)
1957	Minor flood	USACOE Report (1972)	FCD (802.025)
1959 10/31/59	General flooding	Arizona Republic	FCD (007.114)
1967 12/21/67	"Cave Creek does Jekyl and Hyde Routine" – story and pictures	Arizona Republic	FCD (007.114)
	12/19 peak@ 4,080 @ Peoria Ave.	USACOE Report (1971)	FCD (690.704)

[6] Slackwater deposits observed on Cave Creek downstream of Carefree Highway were trenched, but were found to consist of poorly-stratified, moderately coarse, probably recent flood sediments that would not be suitable for paleoflood investigation. The project team was prevented from looking for paleoflood sites upstream of the project limits due to right-of-entry concerns.

Table 2-6. Upper Cave Creek/Apache Wash Watercourse Master Plan Historical Floods on Cave Creek			
Date	**Details**	**Source**	**Location**
1968 7/22/68	Flooding	Phoenix Gazette	FCD (007.114)
1972 June	12,400 cfs @ Cave Ck. gauge	USACOE Report (1972)	FCD (802.025)
1977-1978	Flooding	Floods of October 1977 in Southern Arizona	FCD (802.017) p. 59
1978 March	7,000 AF water, within 6" of crest, overtopped Arizona Canal. Damaged Carefree Hwy crossing.	Untitled report	FCD (690.702)
	Pictures of Cave Creek Dam	Flooding Events 1978-1980	FCD (802.046)
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 Apache Wash system were identified. Field evidence suggests that at least one event exceeded the *bankfull discharge* and inundated the floodplains of Apache, Paradise, and Desert Hills Washes within the past 20 years. Also, photographic interpretation indicates that a large flood occurred on these streams prior to the 1960 aerial photographs (See Chapter 3).
2. References listed with FCD (##) codes in this Table are on file at the FCDMC Library.

Table 2-7. Upper Cave Creek/Apache Wash 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. Of the four stream segments in the study area, a gauge record exists only for Cave Creek. The Cave Creek record extends back to 1958. The annual flood series for Cave Creek and Skunk Creek is shown in Figure 2-11. A depiction of the distribution of flood occurrence by month is shown in Figure 2-12. A list of significant floods over 3,000 cfs is provided in Table 2-8.

Figure 2-11. Annual Peak Discharges @ USGS Gauge Stations

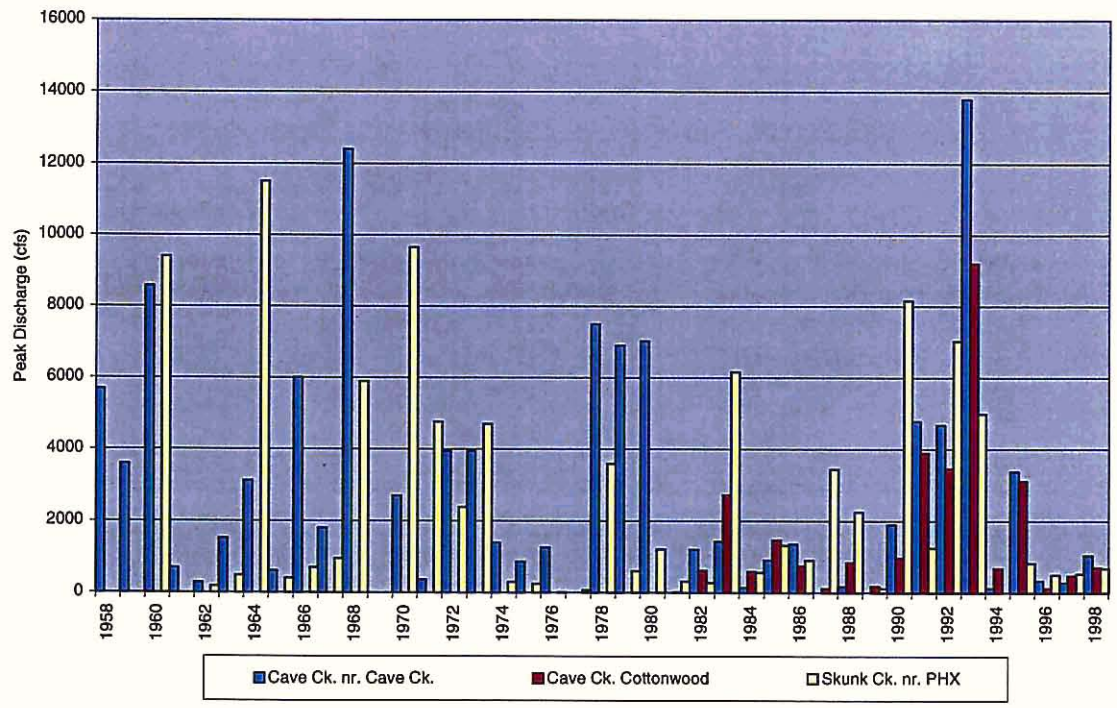


Figure 2-12. Season Distribution of Gauged Annual Peak Floods

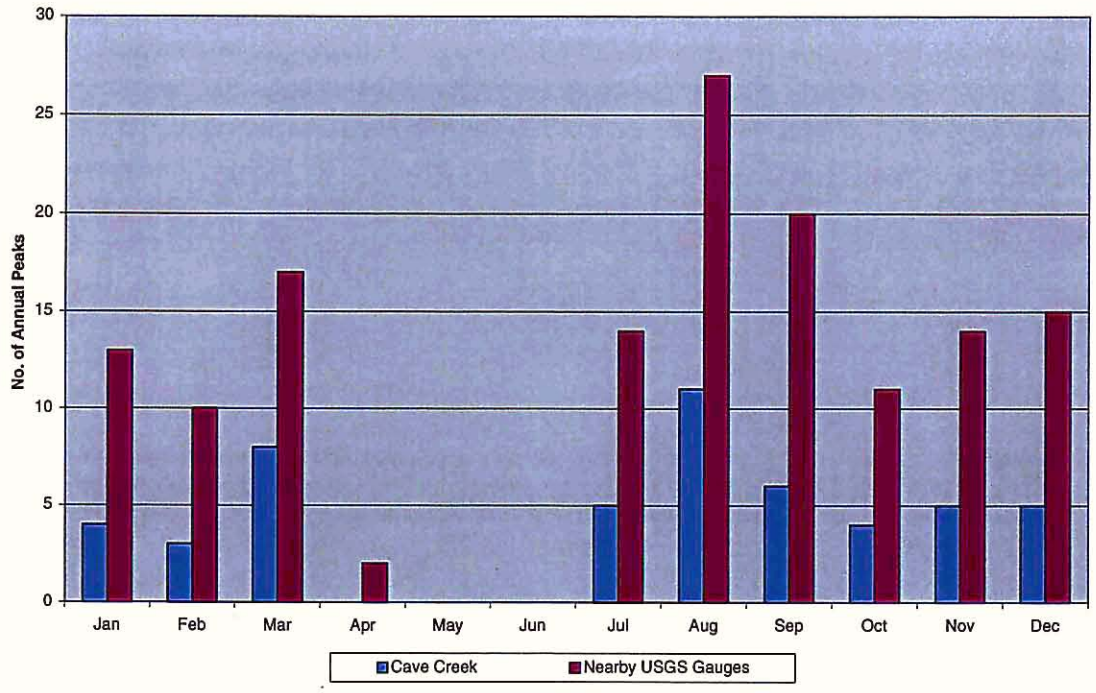


Table 2-8. Upper Cave Creek/Apache Wash Watercourse Master Plan Significant gauged Floods on Cave Creek and Flood Peaks on Adjacent Streams (cfs)					
	USGS Streamflow Station				
Date Of Flood	Cave Creek @ Cave Ck.	Cave Creek Below Cottonwood Ck.	Skunk Creek	New River Rock Springs	Deadman Wash Nr. New River
1960 (10-29-59)	8,570	-	9,400	-	1,850
1968 (12-19-67)	12,400	-	5,900	10,600	950
1978 (3-2-78)	7,500	-	3,590	13,600	1,400
1979 (12-18-78)	6,900	-	600	6,530	88
1980 (2-20-80)	7,020	-	1,210	9,350	-
1993 (1-8-93)	13,800	9,200	4,990	12,600	729

The following conclusions may be drawn from the flood data shown in Figures 2-11 and 2-12, and Tables 2-7 and 2-8:

- Drainage Area. Peak *discharge* increases in the downstream direction, or as a function of drainage area, for the largest floods during the period of record for Cave Creek.

- Seasonality. Most (51%) of the annual floods during the period of record occurred during the late summer monsoon. However, all but one of the six largest floods on Cave Creek (Table 2-8) occurred during winter, between December and March.

Flood Frequency. Estimates of flood frequency were obtained from the work of others, including the USGS (Pope et. al., 1998) and ASL Consulting (1999). The HEC-1 modeling methodology used to estimate flood magnitude and frequency for the Upper Cave Creek/Apache Wash Watercourse Master Plan is presented in a companion volume prepared by ASL Consulting (1999). Peak *discharge* and volume estimates accepted by the FCDMC for use in the Watercourse Master Plan and the geomorphic analyses are shown in Table 2-9. Estimates of peak discharge obtained by statistical analysis of USGS streamflow records are shown for comparison in Table 2-10, and USGS regression equation results are shown in Table 2-11.

TABLE 2-9. Upper Cave Creek/Apache Wash Watercourse Master Plan Summary of Accepted 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
Cave Creek							
31.91	C400R	1,700	2,300	7,400	8,300	31,400	33,500
30.85	C400	2,000	2,500	8,100	9,100	33,800	36,000
29.012	C410	1,800	2,300	7,800	8,800	33,800	35,800
26.845	C518	1,900	2,600	8,600	9,800	36,700	39,700
25.233	C528	1,900	2,600	8,800	10,100	38,100	41,400
Apache Wash							
6.09	23T	130	146	1,130	1,187	5,706	7,408
3.86	22T	130	143	1,210	1,262	7,213	7,403
2.97	20T	150	161	1,370	1,482	7,534	7,727
2.73	20MT	270	290	2,710	3,085	13,541	13,890
0.20	ET	330	386	3,280	3,573	17,136	17,944
---	DT	350	410	3,560	3,891	18,413	19,252
Desert Hills Wash							
0.31	F5T	200	240	1,990	2,140	10,259	10,761
0.22	20MT	270	290	2,710	3,085	13,541	13,890
Paradise Wash							
2.23	12T	90	99	800	837	4,049	4,152
1.65	11T	110	125	1,010	1,075	5,232	5,401
0.04	10T	120	134	1,150	1,219	5,763	5,992

Note: HEC-1 concentration point locations are provided in the Hydrology Report (ASL, 1999).

TABLE 2-10. Upper Cave Creek/Apache Wash Watercourse Master Plan USGS Flood Frequency Estimates For Cave Creek								
Station	Area (mi^2)	Mean Elev. (ft)	Recurrence Interval (yrs)					
			2	5	10	25	50	100
Cave Creek nr. Cave Creek	121	3,470	1,780	4,580	7,360	12,000	16,400	21,500
Cave Creek nr. Cottonwood Creek	82.7	-	840	2,940	5,350	9,710	14,000	19,000

TABLE 2-11. Upper Cave Creek/Apache Wash Watercourse Master Plan USGS Regression Equation Discharge Estimates for Apache Wash, Paradise Wash and Desert Hills 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
Apache Wash									
6.09	23T	6.03	2274	130	610	1,130	2,130	3,900	6,100
3.86	22T	6.54	2205	130	650	1,210	2,270	4,200	6,500
2.97	20T	7.73	2124	150	740	1,370	2,560	4,700	7,400
2.73	20MT	20.30	1900	270	1,500	2,710	4,910	9,100	14,000
0.2	ET	27.02	1899	330	1,820	3,280	5,880	10,800	16,500
---	DT	30.64	1899	350	1,990	3,560	6,360	11,600	17,700
Desert Hills Wash									
0.31	F5T	12.08	1754	200	1,080	1,990	3,650	6,900	10,700
0.22	20MT	20.30	1900	270	1,500	2,710	4,910	9,100	14,000
Paradise Wash									
2.23	12T	3.29	2023	90	420	800	1,520	2,700	4,300
1.65	11T	4.65	1965	110	540	1,010	1,920	3,500	5,500
0.04	10T	5.61	1928	120	620	1,150	2,170	4,000	6,300
Note: HEC-1 concentration point locations are provided in the Hydrology Report (ASL, 1999).									

The following conclusions can be drawn from the data summarized in Tables 2-9 to 2-11:

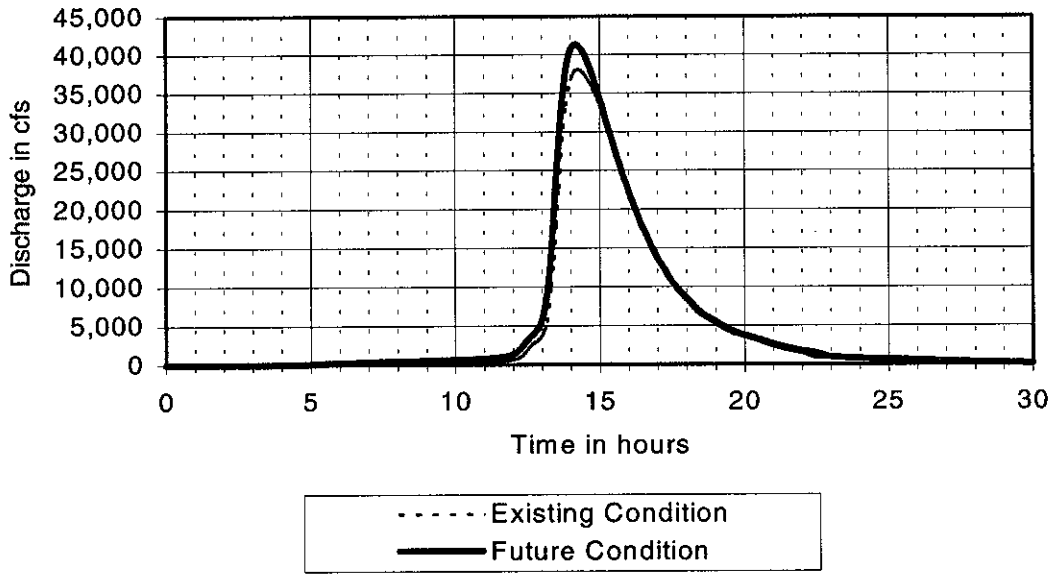
- Recurrence Interval. The largest flood on Cave Creek which occurred during the period of record, the January 1993 event, had a recurrence interval of about a 30-year event at the Cave Creek near Cave Creek station, and a recurrence interval of about a 20-year event at the Cave Creek near Cottonwood station. The 1968 flood had a recurrence interval of about a 25-year event. All other gauged floods had recurrence intervals of less than 15 years. The study reaches probably have not experienced a 100-year flood during the period of record.

- Peak Discharge Estimates. Comparison of the USGS flood frequency results and the HEC-1 modeling results shown in Tables 2-9 to 2-11 indicate 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).

Hydrologic Modeling

Design hydrographs for existing conditions and future conditions were generated from the HEC-1 modeling results (ASL, 1999). For the purposes of this study, the future condition was defined as full build-out to the existing zoning plan. The HEC-1 peak *discharge* estimates for existing and future conditions were listed in Table 2-9 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 2-13. Cave Creek Design Hydrographs - HEC-1 Results



An example hydrograph for 100-year event at the downstream study limit of Cave Creek is shown in Figure 2-13. A complete description of the hydrographs for each of the stream segments within the study area is provided in the ASL Hydrology Report (1999).

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 Upper Cave Creek/Apache Wash study area: (1) a descriptive classification system based on the Brice system, and (2) the 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 Upper Cave Creek/Apache Wash 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 2-12). 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 2-12. Upper Cave Creek/Apache Wash Watercourse Master Plan Brice Classification System

Stream Characteristic	Cave Creek	Apache Wash	Paradise Wash	Desert Hills Wash
Stream Size	Medium (<500 ft) 290 ft.	Medium (<500 ft) 120 ft.	Small (<100 ft) 60 ft	Small (<100 ft) 34 ft.
Flow Habit	Ephemeral Flashy	Ephemeral Flashy	Ephemeral Flashy	Ephemeral Flashy
Bed Material	Gravel	Gravel	Gravel	Gravel
Valley Setting	Relict alluvial fan (low relief)	Relict alluvial fan (low relief)	Relict alluvial fan (low relief)	Valley axis wash Low relief valley
Floodplain	Narrow (2-10x chl width)	Narrow (2-10x chl width)	Narrow (2-10x chl width)	Wide (> 10x chl width)
Natural Levees	Little or none	Little or none	Little or none	Little or none
Apparent Incision	Incised6-15 ft.	Incised0-4 ft.	Incised0-4 ft.	Incised0-6 ft.
Channel Boundaries/ Bank Materials	Alluvial	Alluvial Local bedrock	Alluvial	Alluvial
Bank Vegetative Cover	< 50 percent	50-90 percent	50-90 percent	50-90 percent
Sinuosity	Sinuous (1.08)	Sinuous (1.07)	Sinuous (1.08)	Sinuous (1.12)
Braiding	Braided low flow Reach 5 braided	Local braiding	Local braiding	Not braided
Anabranching	Portion anabranched	Not anabranched	Not anabranched	Not anabranched
Width Variability Bar Development	Random variation Irregular pt. bars	Wider at bends Irregular pt. Bars	Random variation Irregular pt. Bars	Random variation Irregular pt. bars

Highlighted fields indicate highest potential for lateral erosion in classification category.

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 B. Definitions of key terms are provided in the Glossary (Chapter 9).

1. Stream Size. The potential for, and scale of, lateral erosion increases with stream size. Cave Creek has the largest active channel (290 feet) of the four streams studied, and thus has the largest potential for lateral channel movement based on its size alone. Desert Hills Wash has the smallest active channel (34 ft.) of the four streams studied, and has the lowest predicted magnitude of lateral erosion during floods.
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 may be highly erosive. Cave Creek and its tributaries in the study area are ephemeral, but all four streams experience flash floods, and are subject to lateral movement and long-term fluctuations in bed elevation.
3. Bed Material. The streams in the study area have bimodal bed sediment distributions, with clast sizes ranging from fine sands to boulders. The median bed sediment diameters range from 5.0 to 19.0 mm. in the study reach, all within the gravel size classification. Bed and bank materials typically are stratified with sizes varying widely with depth and distance. Stratified sediments may be more vulnerable to *scour* and bank erosion 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. All of the streams except Desert Hills Wash are formed within the entrenched terraces of a relict middle Pleistocene-aged *alluvial fan* complex, which cannot be readily fit into the Brice valley setting categories. Desert Hills Wash is formed along a broad floodplain of the alluvial valley axis of low relief.
5. Floodplains. Channels with wide floodplains (> 10 times channel width) typically experience more lateral channel movement than channels with narrow floodplains (2 to 10 times channel width). All of the streams in the study area had historically wider floodplains, except for Desert Hills Wash which has retained its wide floodplain throughout the historical period. However, historic and prehistoric channel entrenchment has left the historic floodplains perched above the main channel, effectively narrowing the active floodplain and increasing channel capacity.
6. Natural Levees. Streams with natural levees tend to have low rates of lateral migration. Cave Creek, Paradise Wash, Desert Hills Wash, and the upper portions of Apache Wash do not have natural levees. On Apache Wash near the Cave Buttes impoundment, small irregular levees have formed due to deposition of fine sediment within the ineffective flow zones created by dense bank vegetation.
7. Apparent Incision. Streams with vertical *cut banks* are generally unstable. Cave Creek has *incised* about 6 to 15 feet within the project reach during the past 800 years, leaving many reaches with near vertical cut banks. Field evidence suggests that incision on the Apache Wash system is considerably less recent and of lower magnitude than incision on Cave Creek. Channel banks along the Apache Wash systems are generally flatter and better vegetated.
8. Channel Boundaries and Bank Materials. Alluvial streams are more susceptible to lateral erosion than non-alluvial streams. Bedrock crops out on the right bank of

Apache Wash downstream of Bosco Tank and near the Cave Buttes impoundment. Streams in the remainder of the study area are formed in *alluvium*. However, where the channel intersects geomorphic surfaces of late Pleistocene age or older, 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. Vegetation slows velocities along the banks, and can even redirect flow away from the banks. Roots can also stabilize the banks, providing a solid structure that holds the bank materials together. Deeper and denser root networks provide greater stability than shallow, less dense roots. In general, field evidence indicates that the banks of Cave Creek are poorly vegetated, with perched or shallow-rooting species. Apache and Paradise Washes were observed to have 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 meander geometry and meander movement cannot be accurately predicted by most of the published meander geometry relationships.[7]
11. Degree of Braiding. Braided streams tend to be laterally unstable. Cave Creek is braided at very low flows because the channel geometry is adjusted to lower frequency events, except in the reach above the Cave Buttes impoundment where a highly braided, multiple channel pattern exists. Apache Wash and Paradise Wash have local areas of braiding, where high flows leave the main channel at incipient or relict *avulsion* points. Desert Hills Wash is not braided. All of the streams in the study area may have been more braided prior to pre-historic channel incision.
12. Degree of *Anabranching*. The channels in the study area are not anabranched, except for the portion of Cave Creek between the abandoned Tanner sand and gravel mines and the Cave Buttes Dam impoundment area. 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. Except for Desert Hills Wash, the streams in the study reach 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, the project reaches score the highest rating for susceptibility to erosion in five of the thirteen the categories for Apache Wash, Paradise Wash, and Desert Hills Wash, and eight of the thirteen categories for Cave Creek. These broad stream characteristics indicate potential for frequent bank erosion and rapid lateral channel movement, especially on the downstream reaches of Cave Creek.

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

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 throughout 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 Cave Creek, Apache Wash, and Paradise Wash stream segments in the study area appear to best match Rosgen's D4 (Table 2-13) category, although there are a few significant differences from Rosgen's criteria. The streams clearly have gravel beds, with slopes between 0.006 and 0.010 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, the cut off for Rosgen's D4 category.[8] However, the streams are not truly braided during flows that impact its banks, except for the reaches of Cave Creek downstream of the Wheeler mine. 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 is the most applicable. The Rosgen entrenchment ratio parameter indicates only moderate entrenchment (1.4 – 2.2), although historical data (Chapters 3 and 4) indicates that entrenchment of about five to ten feet has occurred in the past 800 years on Cave Creek. Field evidence (Chapter 4) suggests that two to ten feet of degradation may have occurred throughout the study area in the past 100 years. The Desert Hills Wash segment best fits the Rosgen D4c category due to the lower channel slope than the other stream segments.

[8] The Rosgen categories with lower width/depth ratios have much higher sinuosity and lower entrenchment ratios, and are therefore, a worse fit than the D4 category selected.

Table 2-13. Upper Cave Creek/Apache Wash Watercourse Master Plan Rosgen Classification Data

	Reach #						
Cave Creek	SR	1	2	3	4	5	6
Rosgen Classification	D4	D4	D4	D4	D4	D4	D4
Entrenchment Ratio	1.9	2.1	2.5	2.1	2.2	1.7	>2.0
Width/Depth Ratio	36	48	35	54	41	32	>40
Sinuosity	1.10	1.02	1.03	1.03	1.10	1.18	>1.1
Channel Slope	0.010	0.010	0.009	0.010	0.008	0.006	<0.006
Channel Materials (D50)	19 mm CG	19 mm CG	12 mm MG	5 mm FG	5 mm FG	8 mm FG	<5mm VFG
Channel Pattern	B	S&B	S	DIST	DIST	B, MC	B
Apache Wash	SR	1	2	3	4	5	6
Rosgen Classification	D4	D4	D4	D4	D4	D4	D4
Entrenchment Ratio	1.9	2.7	1.7	11.0	1.6	1.7	>1.7
Width/Depth Ratio	35	21	20	45	42	33	>40
Sinuosity	1.07	1.07	1.07	1.07	1.07	1.07	>1.1
Channel Slope	0.010	0.009	0.008	0.006	0.006	0.005	<0.005
Channel Materials	7 mm FG	7 mm FG	13 mm MG	10 mm MG	7 mm FG	4 mm VFG	<4 mm VFG
Channel Pattern	Single channel, with local braided and braiding at high flows						
Paradise Wash	SR	1	Desert Hills Wash			SR	1
Rosgen Classification	D4	D4				D4c	D4c
Entrenchment Ratio	1.7	1.9				1.3	1.2
Width/Depth Ratio	55	44				11	15
Sinuosity	1.08	1.08				1.12	1.12
Channel Slope	0.010	0.008				0.004	0.001
Channel Materials	9 mm MG	14 mm MG				12 mm MG	8 mm MG
Channel Pattern	Single channel; local braiding					Single channel	

Notes:
1. Sinuosity – measured on 1996 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)

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[9]. 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 streams segments in the Cave Creek/Apache Wash system and Rosgen's D4 category, as described above include the following:

- Distributary channel pattern. Except for the reach of Cave Creek immediately upstream of the Cave Buttes impoundment area and other highly localized areas, the streams in the study area do not exhibit a distributary channel pattern expected for the Rosgen classification.
- Depositional environment. The streams in the study area have experienced net degradation during the past 700 years, as opposed to the net aggradation defined by Rosgen.
- Bed material. Cobbles and boulders material comprise a significant percentage of the bed material, rather than a small percentage as described by Rosgen.
- 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. The streams in the study area generally have width/depth ratios less than 40, as described above.
- Highly active bank erosion. Except in the reach of Cave Creek above the Cave Buttes Impoundment, 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.

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

- Pool and riffle. Portions of Cave Creek, Apache Wash, and Paradise 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:

- Historical disturbance of the channels by sand and gravel mining, grazing, or regional entrenchment during the late 1800's and early 1900's.
- Adjustment of the stream channel to entrenched conditions over the past 40 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 Cave 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 Cave Creek and its tributaries have many characteristics typical of braided, ephemeral streams, although the channel pattern itself is not braided, except for the reach of Cave Creek below the Wheeler sand and gravel mine. This anomaly may reflect historical disturbance of the streams, the infrequency of flow, and/or the stabilizing effects of bank vegetation and carbonate accumulation. More detailed discussion of specific channel characteristics will be provided in Chapter 4 of this report. Regardless, 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 four streams in the study area, such as those used to perform the stream classification, were not sufficient to define boundaries between adjacent reaches. Hydraulic modeling results (Chapter 5) also indicated no consistent trends or significant distinctions in variables such as flow width, depth, velocity, or channel capacity. Therefore, stream reaches were defined based primarily on geographic features such as the following:

- Tributary confluences or HEC-1 model concentration points
- Bridge or culvert crossings
- Areas of disturbance by active or historical sand and gravel mining

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 Upper Cave Creek/Apache Wash Watercourse Master Plan are listed in Table 2-14 and illustrated in Figure 2-14 and Exhibit 1. Field photographs of each of the study reaches are shown in Figures 2-15 to 2-30.

Table 2-14. Upper Cave Creek/Apache Wash Watercourse Master Plan Stream Reach Designation

Reach Code	HEC-RAS Section D/S End	HEC-RAS Section U/S End	Description	Comment
Cave Creek				
Supply reach (SR)	30.960	30.850	Model limit to Carefree Hwy	Change in HEC-1 discharge
Bridge	29.663	29.850	Carefree Hwy Bridge	Bridge reach
1	28.657	29.601	Carefree Hwy to gauge	
2	27.604	28.555	Gage to Tanner mining area	Area of historic disturbance
3	26.775	27.502	Tanner to Tributary #2	Area of Tanner S&G mine
4	25.326	26.695	Trib #2 to Effluent Wash	Area of Wheeler S&G mine
5	24.525	25.233	Effluent Wash to Pool Area	End HEC-RAS data
6			Cave Buttes Impoundment	Not modeled in detail
Apache Wash				
SR	4.740	5.640	Cloud Rd to Carefree Hwy	Upstream supply reach
Culvert	4.560	4.650	Carefree Hwy Crossing	Culvert reach
1	3.860	4.490	Carefree Hwy to tributary	
2	3.070	3.780	Tributary to Desert Hills Wash	
3	2.730	2.970	Apache from DHW to PW	
4	1.660	2.600	Paradise Wash to Hill	
5	0.200	1.600	Hill to start of RAS	End HEC-RAS data
6	AW-19K	0.200	Cave Buttes Impoundment	Not modeled in detail
Paradise Wash				
SR	1.650	2.230	Upstream of Ranieri Wash	Supply reach
1	0.040	1.540	Ranieri Wash to Apache Wash	CF Hwy culvert not modeled
Desert Hills Wash				
SR	0.640	1.100	End of RAS to COP Boundary	Supply reach
1	0.386	0.560	COP Boundary to Apache Wash	Split flow from Apache Wash

Abbreviations:
PW = Paradise Wash DHW = Desert Hills Wash CF = Carefree
S&G = Sand and gravel COP = City of Phoenix

The reaches designated in Table 2-14 will be used throughout the remainder of this report.

Reach Photographs.

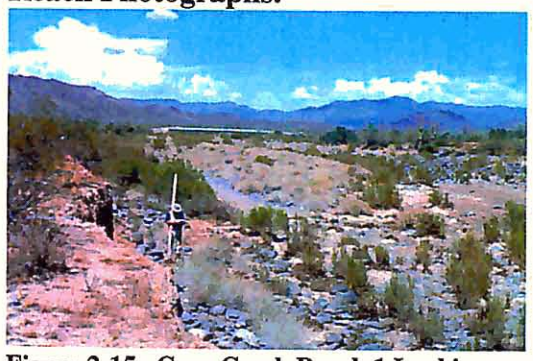


Figure 2-15. Cave Creek Reach 1 Looking Upstream at Carefree Highway.

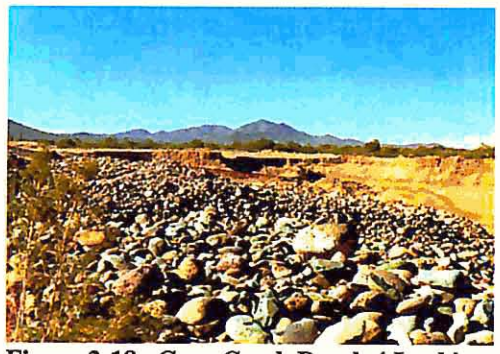


Figure 2-18. Cave Creek Reach 4 Looking Downstream at Wheeler Sand & Gravel Mine.

Figure 2-16. Cave Creek Reach 2 Downstream of USGS Gage

Figure 2-19. Cave Creek Reach 5 Upstream of Cave Buttes Impoundment Area.

Figure 2-17. Cave Creek Reach 3 Looking Upstream from Dumped Mining Debris.

Figure 2-20. Apache Wash Reach 1 Looking at Cut Bank With Exposed Roots.

Figure 2-21. Apache Wash Reach 2 Looking Downstream at Flow Split.

Figure 2-22. Apache Wash Reach 3 Between Paradise and Desert Hills Wash Confluences.

Figure 2-23. Apache Wash Reach 4 Looking Downstream.

Figure 2-24. Apache Wash Reach 5 Looking Downstream Above Riffle.

Figure 2-25. Apache Wash Reach 6 Looking at Headcut in Cave Buttes Impoundment.

Figure 2-26. Apache Wash Supply reach Above Carefree Highway

Figure 2-27. Paradise Wash Reach 1 Above Apache Wash Confluence.

Figure 2-29. Desert Hills Wash Reach 1 Above Bosco Tank.

Figure 2-28. Paradise Wash Supply reach Near Carefree Highway.

Figure 2-30. Desert Hills Wash Supply reach Above City of Phoenix Boundary.

Summary

Understanding the watershed characteristics, regional geologic setting, and hydrologic inputs are 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 Upper Cave Creek/Apache Wash 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 the streams in the study area.

The primary data sources for the evaluation of the historical *geomorphology* of Cave 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 Cave 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 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 archaeology of Cave Creek is moderately well known due to studies by Arizona State University (Dittert, 1974) and investigations completed in conjunction with construction of Cave Buttes Dam (Rodgers, 1974) and the Wheeler sand and gravel mine (Phillips, 1998). No specific information on the archaeology of Apache Wash, Paradise Wash, and Desert Hills 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, 1998). The following publications were used to develop the summary of archaeological information presented below:[1]

[1] See bibliography for full references.

- Class I Inventory of Cultural Resources along Upper Cave Creek, Maricopa County, Arizona. Douglas, D.L., 1998.
- An Archaeological Inventory in the Southern Part of the Upper Cave Creek Watercourse Master Plan Study Area of Phoenix and Cave Creek, Arizona. Rodgers, J.B., 1998.
- Prehistoric Floodwater Agriculture Along Middle Cave Creek, Maricopa County, Arizona. Phillips, B.G., 1998.
- An Archaeological Survey in the Gila River Basin, New River and Phoenix City Streams, Arizona Project Area. Dittert, A.E., Editor, 1974.

Overview

Hohokam farming in central Arizona began as early as 300 B.C. in the Salt/Gila River valleys downstream of the study area. Sherd fragments and radiocarbon dates of material found in or below the soil units farmed by the Hohokam indicate that permanent occupation and farming along Cave Creek began about 900 A.D. (Phillips, 1998). Estimates of the time of abandonment of these Hohokam farms range from about 1200 A.D. (Phillips, 1998) to 1400 A.D. (Douglas, 1998), although Rodgers (1998) estimates that the period of occupation was much shorter. During the 300 to 400 year period of occupation, the Hohokam constructed canals to irrigate crops such as corn, squash, and cotton (Phillips, 1998). Evidence of the Hohokam farm systems includes rock alignments, field borders, canals, check dams, and dwelling structures.

At least four significant farm sites were located along Cave Creek within the study limits, three of which are located on the west side of Cave Creek between Carefree Highway and the Cave Buttes impoundment area. The fourth was originally located on the east side of Cave Creek near the abandoned Tanner sand and gravel operation, but now is found on an island between two channels. These four sites were described by Phillips (1998) as follows:

- T:4:29 – This site consisted of a large field with two canal segments and numerous rock alignments. The irrigation canals headed at Cave Creek and diverted *runoff* a short distance to the fields where the water was then spread by rock diversion features. This site, which was obliterated by the Wheeler sand & gravel operation, was located in Reach 4.

- T:4:92 – This site consisted of a 25.8 acre field with a complex array of water control features. A canal brought water to the fields from the northeast, presumably heading at Cave Creek downstream of the current power line crossing in Reach 1.

- T:4:93 – This site consisted of a small 4.6 acre field with a canal that heads just downstream of the current Carefree Highway bridge (Reach 1). Archaeological features located closest to Cave Creek have been interpreted to indicate that the stream had begun to incise and erode its banks during the period of Hohokam occupation.

- T:4:32 – This site is currently located on an "island" in Cave Creek near the confluence of Tributary #2. At the time the site was farmed, it was contiguous with the left floodplain terrace, but an avulsive channel change thought to have been initiated by a stream capture (pirating) left the site as an island. Archaeological features indicate that bank erosion also impacted the site during the period of Hohokam occupation.

In addition, several prehistoric farm sites with irrigation canals were identified downstream of Cave Creek Dam, below the study reach (Dittert, 1974). Numerous archaeological sites not associated with irrigation agriculture were also identified throughout the study area. No significant (i.e., irrigated) sites were identified on Apache Wash or its tributaries.

The Hohokam abandoned the Cave Creek farm systems between 1200 A.D. and 1400 A.D. due to declining conditions. The reasons for the abandonment suggested by archaeologists 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 the Cave Creek systems provides several lines of evidence with implications for the channel stability assessment. These lines of evidence include the following:

- Pre-Hohokam channel conditions
- Climate change
- Prehistoric lateral channel instability
- Prehistoric channel conditions
- Prehistoric vegetation cover
- Evidence of prehistoric channel incision

Pre-Hohokam Channel Conditions

Pre-Hohokam channel conditions have been inferred from stratigraphic interpretation of the soils surrounding the geologic floodplain (Phillips, 1998; Earl, 1983). This geologic evidence indicates that high magnitude flows during the Pleistocene and mid-*Holocene* created a coarse, high-relief floodplain. The high flows left numerous gravel bars and multiple channels spread over a wide area that now comprises the modern geologic floodplain of Cave Creek. Following the erosional *altithermal* period during the mid-Holocene, internal drainage factors initiated a change in stream regimen, augmented by cooler temperatures. Cool temperatures during the altithermal increased the effective precipitation and ground cover, slowing net *runoff* and erosion. Then, rising water tables increased and sustained channel flow, helping to transform Cave Creek from a wide, braided, active stream to a single-channel, narrower meandering stream, with deposition of fine-grained overbank sediments on a low floodplain. Overbank flooding probably occurred about every 2 years, more frequently than it does today, and *intermittent* flow in the main channel typically lasted from January to April. Summer flow was restricted by high evaporation rates, although the channel probably held water for a short time after

local convective thunderstorms. These stream conditions lasted until the period when the Hohoham first occupied Cave Creek around 800 A.D.

Climate Change

Based on interpretation of cultural and environmental data, a model of prehistoric climate change for the Cave Creek area was developed by Phillips (1998), and is summarized the following paragraphs.

> In the 800's (A.D.), 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 along Cave Creek due to favorable local conditions.
>
> Precipitation decreased during the 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 the 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 Cave Creek floodplain 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 channel of Cave Creek, the timing and degree of incision can only be inferred from indirect evidence, such as land use information preserved in the archaeological record.
>
> The 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 Cave Creek 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 of Cave Creek. However, it is clear that by the 15th century, channel incision was widespread and Cave Creek had become an *ephemeral* stream.

Prehistoric Lateral Channel Instability

Cultural features at two archaeological sites in the study area 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.

Prehistoric Channel Conditions

Because of the scale of modern erosion of the Cave Creek channel, little physical evidence of the channel characteristics present during the period of Hohokam occupation remains. Channel conditions along Cave Creek, however, can be inferred from studies of the prehistoric *geomorphology* of Skunk Creek (Earl, 1983) and New River (Rankin and Katzer, 1989). Earl's model of channel evolution for Skunk Creek is summarized in the next paragraph.

> Around 4500 b.p.[2], Skunk Creek shifted from an *ephemeral*, braided stream to an *intermittent*, meandering stream with frequent overbank floods that deposited fine sedimentary layers on the shallow floodplain. This condition lasted until the late 19th century, when the stream reverted back to an *incised* channel. Earl (1983) assigned the cause of modern *entrenchment* to over-grazing. During the period of Hohokam occupation, Skunk Creek flowed most years from late winter through mid-spring. The prehistoric (pre-entrenchment) channel capacity on Skunk Creek was about 10 percent of current channel capacity, and the average channel section had about 15 percent of the current area. The bed materials were finer-grained, reducing infiltration losses and allowing winter flows to be sustained from January to April in average years, depending on precipitation. Overbank flooding occurred with a 2-year recurrence interval.

Archaeologists have applied Earl's model of Skunk Creek conditions to Cave Creek based on similarities in the stratigraphic record at excavated cultural sites (Phillips, 1998). The applicability of Earl's model to Cave Creek is also supported by a functional

[2] B.p. indicates years before present.

analysis of the Cave Creek irrigation systems. Given that the primary water source for irrigation was Cave Creek, it is inferred that the main channel of Cave Creek must have been higher relative to the floodplain. Diversion from the main channel to the floodplain would have been impractical in the current entrenched channel conditions. With a higher channel bed, overbank floods occurred more frequently, leading to the deposition of the fine-grained soils farmed by the Hohokam. By applying the ratio of the estimated prehistoric channel capacity to current channel capacity on Skunk Creek to Cave Creek, archaeologists have estimated a pre-entrenchment *bankfull discharge* for Cave Creek of 3,380 cfs and a channel area of 302 ft^2. According to the USGS (Pope et. al., 1999), 3,380 cfs is equivalent to about a 3- to 4-year event on Cave Creek in the study area, indicating that overbank floods occurred every three to four years, on average.[3] Given the *watershed* characteristics and larger drainage area, *intermittent* flows probably lasted longer in Cave Creek than in Skunk Creek.

Prehistoric Vegetative Cover

Inferences can also be made from archaeological data regarding vegetation changes along Cave Creek (Phillips, 1998). 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, 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. Prehistoric riparian species in the study area included willow, cottonwood, cattail, and sedge, even in areas located away from the main channel of Cave Creek, increasing the probability that these plants grew locally and that the pollen was not simply transported from upstream channel localities.

The pollen signals obtained from the 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 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*, not *ephemeral*, streams.

Prehistoric Channel Incision

The environmental models described above support a conclusion that channel incision was one of the reasons for abandonment of the Hohokam farming systems. Other evidence of prehistoric incision includes the presence of unburied Hohokam artifacts on the floodplain. If the floodplain were frequently inundated every three to four years since abandonment, then these artifacts would have been buried by deposition long ago. That

[3] The 3- to 4-year recurrence interval corresponds to the bankfull capacity for the relatively undisturbed reaches of Desert Hills Wash and Paradise Wash (Chapter 4).

is, incision has left the floodplain perched well above the active channel. In addition, the canal bottoms are also perched well above the active channel. In order for the canals to have headed in the channel at its current elevation, their diversion points would have had to have been up to 1,000 feet upstream of the existing head points. This scenario is impractical due to the length of the required canal, and impossible where the much higher mid-Pleistocene terraces impinge on the main channel. The total depth of incision since the period of Hohokam occupation probably does not exceed 15 feet on Cave Creek, and locally includes up to 10 feet of modern incision initiated by in-stream sand and gravel mining.

Summary

Archaeological records imply that channel erosion has affected the Cave Creek stream corridor for more than 1,000 years. Therefore, erosion is not simply the result of human impacts on the channel and *watershed*. Natural cycles of stream degradation and lateral migration must be accounted for in 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. A chronology for each of the four streams in the study area is summarized in Tables 3-2 to 3-5. Discussions and analyses of the changes documented in Tables 3-2 to 3-5 are provided in other sections of this chapter.

Table 3-1. Upper Cave Creek/Apache Wash Watercourse Master Plan Summary of Historical Records Used			
Year	**Scale**	**Type of Record**	**Description/Source**
1867	n/a	GLO Survey	General Land Office (BLM) original survey notes
1894	n/a	GLO Survey	General Land Office (BLM) original notes for J.H. Mantineau survey
1919	n/a	GLO Survey	General Land Office (BLM) original notes for S.E. Blout 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 (23 photos) 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.
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. Upper Cave Creek/Apache Wash Watercourse Master Plan Cave Creek Chronology Based on Aerial Photograph Interpretation		
Date	**Description**	**Source Info.**
1940	No man-made development, improvements, or structures upstream of Cave Creek Dam are visible in the 1940 photographs. Black Tank is visible on small tributary to Cave Creek. Very active channel movement recently (and historically) occurred in the lower half of the study reach, as shown by abandoned channels, multiple channels and flow paths through low overbank terraces. Human impacts limited to cattle grazing of *watershed* Channel pattern is braided downstream of tributary #2. Evidence of more active floodplain processes in 1940 indicates post-1940 *entrenchment.* Perched braids upstream of tributary #2 indicate recent historic *entrenchment* prior to 1940, as shown by downstream end of perched channel that has not yet downcut, and is perched at the Hohokam canal head. Comparison of 1940 and 1999 photographs indicate the following: • Impoundment area was significantly excavated after 1940. The sharp point of the older surface near the 19CHL and 19LOB1 soil pits did not exist in 1940; it was formed by excavating material for construction of Cave Buttes Dam. • The two main channels above the dam are well defined, with *cut banks* & bank vegetation well into the impoundment area to about the location of 20CHL. Channels are now buried by reservoir sedimentation and grading for Cave Buttes Dam construction. • The main channel has *incised* throughout the study reach, except in impoundment area.	B&W aerial Partial stereo coverage Partial photo coverage
1953	Powerline and powerline road built across channel. No sand and gravel mining in study reach or upstream. Interfluve areas do not appear as active as in 1940 (may be photo scale and/or quality), but compared to 1996 photographs, active channel movement only occurs immediately downstream of Carefree Highway, and in lower half of study area near impoundment. Channels in the impoundment area have partially filled and are less well defined. The braided channel pattern begins approx. 2,000 feet upstream of tributary #2. Channel is also strongly braided upstream of Carefree Highway, but is single channel in between. Moderate sized tributary enters CC upstream of future Carefree Highway alignment. Recent floods have occurred on Tributaries #1 and #2 making the bed appear whiter.	B&W aerial Full stereo coverage Good regional perspective
1960	Carefree Highway has been graded, with at-grade crossing at Cave Creek. No sand and gravel mining exists in or near study reach. Channels in the Cave Creek Dam impoundment have shifted and filled since 1953, resulting in a delta-like pattern and form. Berms of Hohokam canal head are visible in what was a low overbank area downstream of Carefree Highway.	B&W aerial Partial stereo coverage Full photo coverage
1962	Small area is graded in LOB with short access road from Carefree Highway, probably the beginning of the sand & gravel mining/processing operation there. No significant excavation is visible in photo. An access road follows Cave Creek bed from Carefree Highway, then is cut into left bank of the channel. Moderate sized tributary at Carefree Highway crosses new road twice before entering CC. Vegetative cover in Cave Creek Dam impoundment has increased, obscuring recent channel change.	B&W aerial Partial photo coverage
1971	Carefree Highway improved, with at-grade crossing of Cave Creek. Moderate sized tributary at Carefree Highway was re-routed and diverted along north side of Highway. Sand & gravel mining operation in progress downstream of Carefree Highway. Mining area in shallow pit includes main channel and left side of active floodplain. Processing and storage on left bank floodplain. Powerline crossing road may have been elevated or re-graded.	False color aerial Full stereo coverage Full photo coverage
1978	Sand & gravel mining operation at Carefree Highway expanded. Upstream of highway, mostly processing occurs with moderate sized pit at tributary mouth. Downstream has excavation and some processing. Downstream pit is now on left side of active floodplain – *thalweg* is located in right braid. *Thalweg* has entrenched by several feet near Carefree Highway. Carefree Highway crossing (at-grade?) is completely washed out by very recent flood.	B&W aerial Partial photo coverage
1984	Sand & gravel mine continues upstream and downstream of Carefree Highway. Carefree Highway crossing (at-grade?) appears to be completely washed out by recent flood. Road built to future Tanner sand & gravel mine location, but no active mining yet. Cave Buttes Dam is under construction, but borrow area near 19LOB1 has not yet been excavated. Large overbank and channel-filling flood has recently occurred. Right braid located along right margin of Qm surface above impoundment carried significant flow. Stream may be flowing in photo – compare bed color of CC to its tributaries.	False color aerial Full stereo coverage
1985	Cave Buttes Dam and levees are constructed. Cave Buttes Dam impoundment area has been heavily excavated for borrow material.	B&W aerial Partial stereo coverage

Table 3-2. Upper Cave Creek/Apache Wash Watercourse Master Plan Cave Creek Chronology Based on Aerial Photograph Interpretation		
Date	**Description**	**Source Info.**
	Sand & gravel mining in process at Tanner site, with new haul road constructed from Cave Creek Road. Mining excavation includes moderately deep circular pit located at the nose of the fan shaped terrace at the principal pit access point. Processed material and boulder waste is stored along left bank forming the boulder levee still present in 1999. Left braid of the channel is mined, leaving the right braid somewhat perched. Sand & gravel mining area at Carefree Highway appears dormant – tributary has cut through graded area to re-join main channel.	Full photo coverage
1996	Wheeler sand & gravel mining excavation has begun along CC in the ROB area between the Black Tank Wash and Tributary #1 confluences. Excavation is moderately shallow, and includes sand dike along perimeter. The main channel is not significantly excavated in 1996, except by haul road crossing, but has been recently bladed. Wheeler excavation also includes mining of left side of active floodplain. Processing is done outside floodplain on high left bank terrace. *Tanner sand & gravel mine is inactive in 1996, but was extended upstream and downstream* from 1985, for total length of about 5,000 feet. Mining appears to have been limited to the main channel and younger terraces near the active channel, with processing and storage on the flooodplain. The 1993 and 1995 floods obscured most of the direct evidence of mining in the main channel, possibly filling pits and moving material downstream. Access road crossing channel is still elevated above channel invert, and main channel has been bladed, indicating post-1995 activity at Tanner site. Channel has shifted to re-occupy the left braid downstream of Carefree Highway in the former mining area. Channel has shifted and entrenched near CC-16k leaving the former *thalweg* (1960) perched in ROB by 6-10 feet, at and upstream of the former Tanner pit location. Further upstream, the perched braid observed in 1940 and 1953 photos is now higher relative to bed.	B&W aerial Full stereo coverage
1999	New bridge constructed at Carefree Highway Wheeler sand & gravel mine has been extensively expanded, and is much larger than any previous excavation on the Cave Creek system in the study area: • Main channel of CC is not continuous through the mined area (goes thru ponding area). • Several pits are very deep, well below the channel invert elevation. • Pit is nearly contiguous with upstream Tanner operation. Tanner sand & gravel operation is not active. Channel pattern is identical to 1996 pattern. More channel vegetation is present, and erosion of bed is less fresh – evidence of no recent large floods since 1996.	B&W aerial Full stereo coverage

Notes:
1. LOB = left overbank; ROB = right overbank
2. PW = Paradise Wash; AW = Apache Wash; DHW = Desert Hills Wash
3. See Exhibit 1 for place names and field section locations, e.g. CC-16k, 19LOB1
4. Abbreviations: B&W = Black and white; CC = Cave Creek; AW = Apache Wash; PW = Paradise Wash; DHW = Desert Hills Wash.

Table 3-3. Upper Cave Creek/Apache Wash Watercourse Master Plan Apache Wash Chronology Based on Aerial Photograph Interpretation		
Date	**Description**	**Source Info.**
1940	No man-made development upstream of Cave Creek Dam is visible in photos. Silt/fine sediment deposits ring channel and floodplain at Cave Creek Dam impoundment limit. Sediment "ring" located downstream of Stn. AW-20k. Overbank floodplain channels (near Stn. AW-LOB1, AW-3k to AW-5k, and AW-0k to AW-2k) are less well defined than in 1999, but have been recently used to convey flow. The lowest terraces appear more active than in 1999 with less vegetation, evidence of recent floodplain flow, and sediment deposited in splay patterns. Water is ponded behind irrigation diversion dam downstream of Cave Creek dam. No water observed in Cave Creek impoundment area.	B&W aerial No stereo coverage Partial photo coverage
1953	Stock ponds built at: (1) Tin Can Tank – AW tributary, (2) Bosco Tank – DHW, (3) several others in upper *watershed*. 4-wheel drive roads and cattle tracks built on interfluve uplands leading to stock tanks and holding pens. Transmission line has been constructed upstream of study reach. Fence lines built over main channel upstream of Paradise Wash confluence. Silt/fine sediment deposits ring channel and floodplain at Cave Creek Dam impoundment limit. "Ring" has progressed upstream since 1940, to about Stn. AW-20k. Evidence of a large ROB flow in overflow channel between Stn. AW-7k and AW-10k includes bank erosion at upstream end and increased distributary character at downstream end. Low terraces are better vegetated than in 1940. Multiple channel pattern at future Carefree Highway alignment – main channel appears to be the right braid, unlike 1999 condition in which large box culvert is located on the left braid.	B&W aerial Full stereo coverage Good regional perspective
1960	Carefree Highway graded out and possibly paved, with at-grade crossing on AW. Silt/fine sediment deposits ring channel and floodplain at Cave Creek Dam impoundment limit. "Ring" has progressed about 1,000 ft. upstream since 1953, to about Stn. AW-19k. Upper portions of the (DHW) *watershed* have been platted for quarter-section development. Main access road to future west levee of Cave Buttes Dam has been constructed. May have been large scale tree cutting from banks of wash, making banks more visible. Fence line construction scars from 1953 have faded due to vegetation re-growth. Impoundment area has heavy grazing and recreational activity. ROB channels from Stn. AW-11k to AW-12k, AW-7k to AW-10k, AW-3k to AW-5k, AW-5k to AW-6k appear to have been eroded and widened. Also new channel was *scoured* around north spillway of Bosco Tank on DHW.	B&W aerial Full stereo coverage
1962	No significant change from 1960.	B&W aerial Partial photo coverage
1971	Sedimentation ring in Cave Creek dam impoundment extended upstream to Stn. AW-17k, with active sediment deposition extending to AW-19k.	False color aerial Partial stereo coverage Full photo coverage
1984	Sedimentation ring in Cave Creek dam impoundment extended upstream to Stn. AW-15k, with active sediment deposition extending to AW-18k. New culvert crossing constructed at Carefree Highway. More roads constructed on uplands near study reach and in upper *watershed*. False color interpretation indicates that the overbank channels between AW-9k to AW-10k and AW-3k to AW-5k are the most active of the overbank channels in the study reach. Both braids of multiple channel at Carefree Highway are geologically active.	False color aerial Full photo coverage
1985	24th Street constructed upstream of Carefree Highway in center of floodplain. New box culvert is under construction at Carefree Highway crossing. Dirt road and wash crossing constructed along State Land boundary. West levee road improved and widened. Extensive sedimentation has occurred in Cave Creek Dam impoundment. Stereo comparison of photographs indicates no measurable changes in channel position from 1962 to 1985. Overbank channels appear more active than in 1962.	B&W aerial Full photo coverage
1999	Development increased in upper *watershed* above Carefree Highway. Stereo comparison of photographs indicate no measurable changes in channel position from 1991 to 1995, at scale of photo coverage.	B&W aerial Full stereo coverage

Notes:
1. LOB = left overbank; ROB = right overbank
2. PW = Paradise Wash; AW = Apache Wash; DHW = Desert Hills Wash
3. See Exhibit 1 for place names and field section locations, e.g. CC-16k, 19LOB1
4. Abbreviations: B&W = Black and white; CC = Cave Creek; AW = Apache Wash; PW = Paradise Wash; DHW = Desert Hills Wash.

Table 3-4. Upper Cave Creek/Apache Wash Watercourse Master Plan Paradise Wash Chronology Based on Aerial Photograph Interpretation		
Date	**Description**	**Source Info.**
1940	No man-made development visible in photos. Multiple channel, braided character of wash is evident at reach above AW confluence. By 1999, both flow paths are still visible, but one has entrenched and the other is perched and probably is used only during large overbank flows. Channel banks and uplands are poorly vegetated.	B&W aerial No stereo coverage Partial photo coverage
1953	4-wheel drive roads and cattle tracks built leading to stock tanks. *Transmission line has been constructed upstream of study reach.* Fence lines built over main channel upstream of Apache Wash confluence. No stock ponds constructed on Paradise Wash or its tributaries. Overbank channels appear less active. Reach has more single channel character. PW has sequence of several terraces along study reach (more than DHW or AW), and appears to be geologically linked to formation of Cave Creek. Terraces of Ranieri Tank tributary upstream of study reach head at margin of geologic floodplain of Cave Creek.	B&W aerial Full stereo coverage Good regional perspective
1960	Carefree Highway graded out and possibly paved. Culvert crossing was constructed over the West Branch of PW, with at-grade crossing on main channel of PW. No stock ponds constructed on Paradise Wash or its tributaries. Possible increase in depth of *entrenchment* of main channel upstream of AW confluence. Bank vegetative density is lower than AW or DHW. Evidence of a recent large flood since 1953 is not as strongly expressed as on DHW. Tributaries appear to join main channel at grade.	B&W aerial Full stereo coverage
1962	Photo's at same scale as 1960 – stereo comparison indicates no measurable channel changes	B&W aerial Partial photo coverage
1971	Photo quality is poor near PW. No visible changes in character of reach.	False color aerial Partial stereo coverage Full photo coverage
1984	*Stock tank built on Ranieri Wash upstream of study reach.* New culvert crossing constructed at Carefree Highway. False color interpretation indicates a narrow active floodplain, with a thin veneer of recent sedimentation from shallow overbank flooding.	*False color aerial* Full photo coverage
1985	New crossing at Carefree Highway is under construction – channel reach several hundred meters downstream of new construction was cleared and straightened. Dirt road and wash crossing constructed along State Land boundary. Secondary overbank channel at AW confluence is nearly abandoned due to lowered bed elevation of main channel. Continued decrease in multiple channel character of reach. Stereo comparison of photographs indicates no measurable changes in channel position from 1962 to 1985.	B&W aerial Full photo coverage
1999	Channel banks better vegetated than at beginning of photographic record. Main channel may have *incised* since 1940 – banks appear higher, and reach is less braided and narrower.	B&W aerial Full stereo coverage

Notes:
1. LOB = left overbank; ROB = right overbank
2. PW = Desert Hills Wash; AW = Apache Wash; DHW = Desert Hills Wash
3. See Exhibit 1 for place names and field section locations, e.g. CC-16k, 19LOB1
4. Abbreviations: B&W = Black and white; CC = Cave Creek; AW = Apache Wash; PW = Paradise Wash; DHW = Desert Hills Wash.

Table 3-5. Upper Cave Creek/Apache Wash Watercourse Master Plan Desert Hills Wash Chronology Based on Aerial Photograph Interpretation		
Date	**Description**	**Source Info.**
1940	No man-made development visible in photos. Channel is moderately *sinuous*. Bank vegetative cover is good throughout reach, densest cover near Apache Wash confluence. Possible remnant of avulsive channel change in LOB downstream of DHW Tributary #1. Floodplain corridor is defined by slightly flatter terrain and increased vegetative density than uplands. May be less floodplain and upland vegetative cover in 1940 than later years, esp. after 1980.	B&W aerial No stereo coverage Full photo coverage
1953	Two stock tanks built upstream of study reach on tributaries. Tanks have ponded water and locally increased vegetative cover. Bosco Tank recently constructed to intercept entire main channel of DHW upstream of AW confluence. Double spillways – one north, one south. Spillways not vegetated. No water ponded in tank. Minimal increase in vegetation near tank. 4-wheel drive roads and cattle tracks built leading to stock tanks. Transmission line has been constructed upstream of study reach. Remnant of pre-historic avulsive channel change visible at margin of floodplain near Stn+6K. Minimal terrace formation within study reach. Terracing increases above Carefree Highway.	B&W aerial Full stereo coverage
1960	*Watershed* area upstream of study reach was platted with graded dirt quarter section roads. Vegetative density at and upstream of Bosco Tank and its south spillway increased since 1953. Evidence of recent large flood since 1953: • Water ponded in Bosco Tank. • North spillway of Bosco Tank is destroyed, and channel downstream is highly *scoured*, with new very *sinuous* channel pattern. Channel has relocated to the north along the former spillway alignment. • Visual evidence of recent flow on floodplains – deposited sediment and local *scour*. Bed elevation may have dropped upstream of Bosco Tank – several minor tributaries have entrenched into DHW floodplain and lost some bank vegetation.	B&W aerial Full stereo coverage
1962	Bank vegetation density increased at Bosco Tank. Photos at same scale as 1960 – stereo comparison indicates no measurable channel changes.	B&W aerial Full stereo coverage
1971	Flow path along abandoned north spillway of Bosco Tank is now well-defined main channel.	False color aerial Full stereo coverage
1984	Suburban ranch development (<1 RAC) of *watershed* areas formerly platted. Additional *scour* of *sinuous* channel reach downstream of Bosco Tank.	False color aerial Full photo coverage
1985	Dirt road and wash crossing constructed along State Land boundary. Extent of *watershed* urbanization continued to increase. Some development encroaches on the floodplain upstream of Carefree Highway above the study reach. *Watershed*, floodplain, and bank vegetative density have increased measurably since 1962. Vegetative density at Bosco Tank has increased, making healthy Mesquite bosque area. Secondary channels formed in overbank floodplains have become more defined, possibly due to recent floodplain flows.	B&W aerial Full photo coverage
1999	Marked increase in bank and floodplain vegetative density upstream of the State Land boundary, probably due to limited grazing of reach upstream of State Land. Evidence of recent large flood since 1985: • Visual evidence of fine sediment deposition and local *scour* on the floodplain. • Additional *scour* of very *sinuous* channel reach downstream of Bosco Tank. • Dirt road crossing at State Land boundary is washed out. Minor tributaries entrenched circa 1960 have flatter bank slopes, and more bank vegetation.	B&W aerial Full stereo coverage

Notes:
1. LOB = left overbank; ROB = right overbank
2. DHW = Desert Hills Wash; AW = Apache Wash
3. See Exhibit 1 for place names and field section locations, e.g. CC-16k, 19LOB1
4. Abbreviations: B&W = Black and white; CC = Cave Creek; AW = Apache Wash; PW = Paradise Wash; DHW = Desert Hills Wash; RAC = Residences per acre.

Scanned and reprinted copies of key portions of the aerial photographs listed in Tables 3-1 to 3-5 above are include in Appendix B. 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 Cave Creek/Apache Wash system:

- Lateral channel change
- Vertical channel change
- Change in channel geometry
- Change in channel pattern

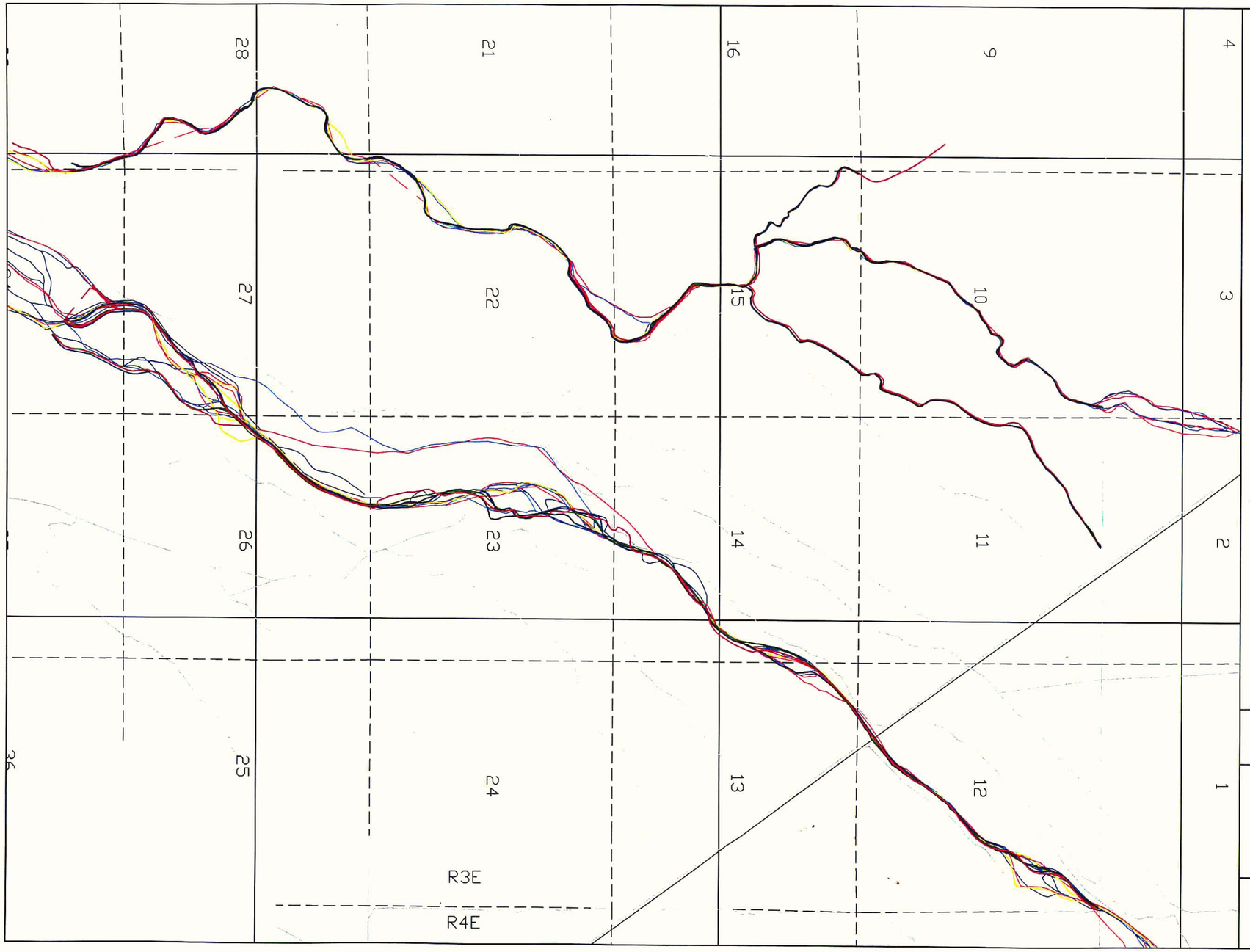
Lateral channel movement is defined as any change in the horizontal position of the stream, and includes gradual bank erosion or sudden *avulsions*. Vertical channel change is defined as change in the elevation of the stream bed, and includes local *scour*, long-term (degradation), and deposition (aggradation). Channel geometry changes may be the result of lateral or vertical adjustments, and are measured by adjustments of the total width or depth of the main channel. Change in channel pattern includes adjustments of sinuosity, or shifts from a braided to a single 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. A plot of channel position from each of the years of photographic and map coverage is shown in Figure 3-1.

Lateral Channel Movement

Long-Term Changes. Long-term channel changes were evaluated by comparing channel positions mapped 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 46 to 73 years beyond the oldest aerial photographs. It is noted that the GLO survey data and the USGS mapping is spatially less accurate than the aerial photography.

Methodology. Locations where a watercourse crosses Township/Range section lines can be used to provide information on long-term lateral stability. Historical data were gathered from original field notes produced by United States GLO surveyors J.H. Martineau (1894) and S.E. Blout (1919), and from USGS 7.5-minute topographic maps (1981). The USGS 7.5 minute topographic maps were originally created in 1965 from 1962 aerial photographs, and were photo-revised in 1981. The GLO land surveys described the stream position only along the section lines, although sketches of channel locations between section lines were sometimes provided in the field notes and on plat maps. To facilitate comparison of the channel position, measurements were taken from the topographic map section corners on the same heading as the original survey.

The original GLO surveys were measured in Gunter's Chains (= 66 feet), and were reported to two decimal places. Therefore, the accuracy of measurements using the GLO survey notes can be no better than ± 0.7 feet. The accuracy of measurements from the USGS topographic maps is limited to 1/60 of an inch (the smallest increment on an



FLOOD CONTROL DISTRICT OF MARICOPA COUNTY

CAVE CREEK/APACHE WASH
WATERCOURSE MASTER PLAN
LATERAL STABILITY ASSESSMENT

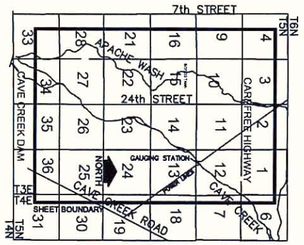
FCD 97-45

DECEMBER, 2000

LEGEND

- 1940
- 1950
- 1953
- 1962
- 1971
- 1978
- 1984
- 1991
- 1993
- 1994
- 1995
- 1996
- 1998
- GLO
- USGS

INDEX MAP



SCALE IN FEET

1000' 0' 2000'

ASL Consulting Engineers

IN ASSOCIATION WITH

JE FULLER
HYDROLOGY & GEOMORPHOLOGY, INC.

FIGURE 3-1

HISTORICAL CHANNEL POSITION

engineering scale), or ± 33.33 ft., given the 1:24,000 map scale. For the purposes of this analysis, any measured change in channel position less than 33.33 ft. was considered as an estimate of stability. The stream course marked on the map is considered to be the center of the channel for the purpose of comparison with historical survey measurements. The channel centerline for the GLO data was estimated as the midpoint of the bank stations indicated on the GLO survey notes.

Results. The results of the comparisons of estimated channel centerline position for each of the four major streams in the study area are summarized below.

Cave Creek. The following data summarized in Table 3-6 reflect the location of Cave Creek in Township 5 North, Range 3 East, between Cave Creek Dam and Carefree Highway. Discussion of specific channel reaches is provided in the following paragraphs.

Table 3-6. Upper Cave Creek/Apache Wash Watercourse Master Plan
Measurements of Long-Term Channel Movement on Cave Creek, 1894-1981

REACH 5: EFFLUENT WASH to POOL

Between sections 27 and 34, from corner of sections 26, 27, 34, and 35, heading west

1894	1981
Left Bank.....1023 ft	West Channel Center.....2417 ft
Center of Channel...1122 ft (17.0 chains, 3.0 chains wide)	Average.....2400 ft
Right Bank.....1221 ft	East Channel Center.....2383 ft

Summary of movement: ***moved west 1278 feet (river right)***

REACH 4: TRIBUTARY #2 to EFFLUENT WASH

Between sections 26 and 27, from corner of sections 26, 27, 34, and 35, heading north

1894	1981
Left Bank.....1835 ft (27.8 chains)	
Center of Channel...1997 ft	Center of Channel.....2583 ft
Right Bank.....2158 ft (32.7 chains)	

Summary of movement: ***moved north 587 feet (river right)***

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

1894	1981
Left Bank.....3326 ft (50.4 chains)	
Center of Channel...3363 ft	Center of Channel.....3367 ft
Right Bank.....3399 ft (51.5 chains)	

Summary of movement: ***moved west 4 feet (river right)***

REACH 3: TANNER to TRIBUTARY #2

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

1894	1981
Left Bank.....2396 ft (36.3 chains)	
Center of Channel...2485 ft	Center of Channel.....2567 ft
Right Bank.....2574 ft (39.0 chains)	

Summary of movement: ***moved west 82 feet (river right)***

REACH 2: USGS Gauge to TANNER

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

1894	1981
Left Bank.....3478 ft (52.7 chains)	East Branch, split flow.....3029 ft
Center of Channel...follows section line	
Right Bank.....4323 ft (65.5 chains)	West Branch, split flow.....4200 ft

***Section line follows the bed of Cave Creek in 1894 resulting in unusually wide apparent measurement.**

***Cave Creek was drawn as a single channel in this location on the section map of 1894.**

***On the 1981 topographic map Cave Creek is depicted as split flow around an island. The island still exists on 1996 aerial photos.**

Best comparison of lateral movement is from Right Bank, 1894, to East Branch, 1981. This comparison indicates that the channel has *moved south at least 449 feet (river left).

Between sections 12 and 13, from corner of sections 12 & 13 (T5N R3E) and 7 & 18 (T6N R3E), heading west

1894	1981
Left bank.....4092 ft (62.0 chains)	
Center of Channel...4158 ft	Center of Channel.....4203 ft
Right Bank.....4224 ft (64.0 chains)	

Summary of movement: moved west 45 feet (river right)

REACH 1: CAREFREE HIGHWAY to gauge

No Data

Table 3-6 (Continued). Upper Cave Creek/Apache Wash Watercourse Master Plan
Measurements of Long-Term Channel Movement on Cave Creek, 1894-1981

BRIDGE REACH: CAREFREE HIGHWAY BRIDGE

Between sections 1 and 12, from corner of sections 1 & 12 (T5N R3E) and 6 & 7 (T6N R3E), heading west

1894	1981
Left bank.....0.0 ft (0.0 chains)	
Center of Channel...79.2 ft	Center of Channel.....100 ft
Right Bank.....158 ft (2.4 chains)	

Summary of movement: moved west 21 feet (river right)

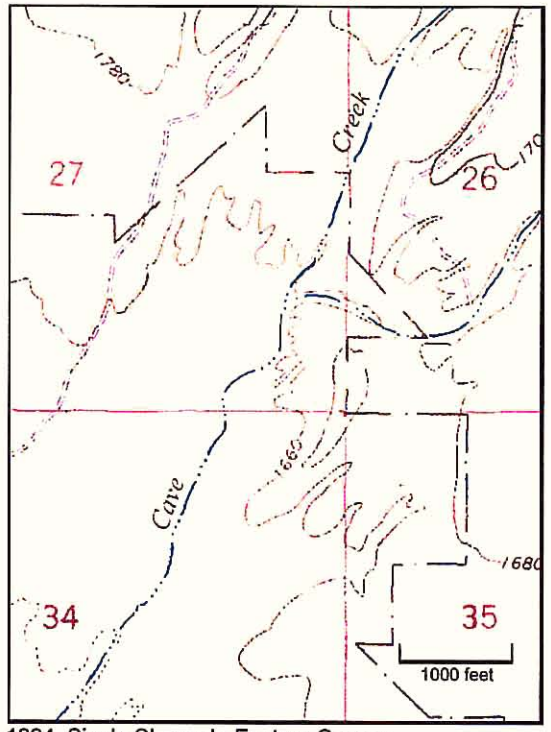
Between sections 1 (T5N R3E) and 6(T6N R3E), from corner of sections 1 & 12 (T5N R3E) and 6 & 7 (T6N R3E), heading north

1894	1981
Left bank.....0.0 ft (0.0 chains)	
Center of Channel...145 ft	Center of Channel.....167 ft
Right Bank.....290 ft (4.4 chains)	

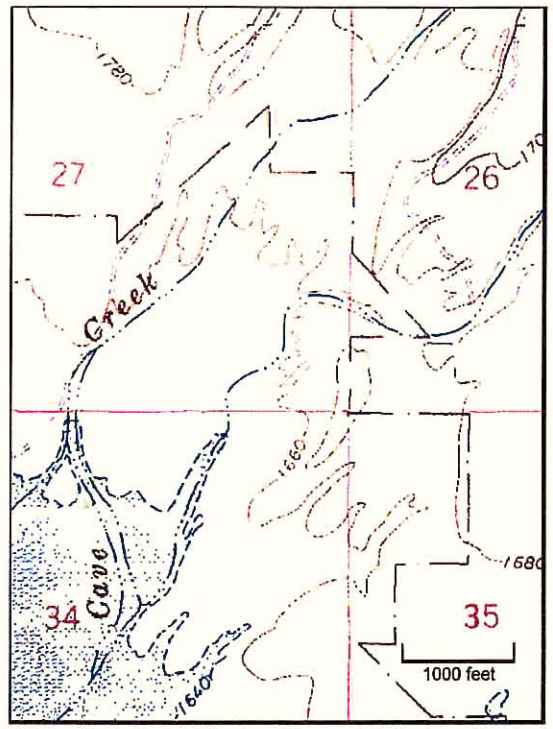
Summary of movement: moved north 21 feet (river right)

Cave Creek generally moved towards the west and north, or river right, between 1894 and 1981, with varying degrees of magnitude. The greatest lateral movement occurred in the downstream reaches, in Reaches 4 and 5. An apparent channel *avulsion* moved the main channel between 587 and 1,278 feet to the north and west. Upstream of this avulsion the channel location has remained relatively stable, with lateral moves ranging from 4 to 82 feet. The only exception to the northwest trend is in Reach 2 where the flow has changed from a single channel to a split flow condition, and the channel moved generally towards the south.

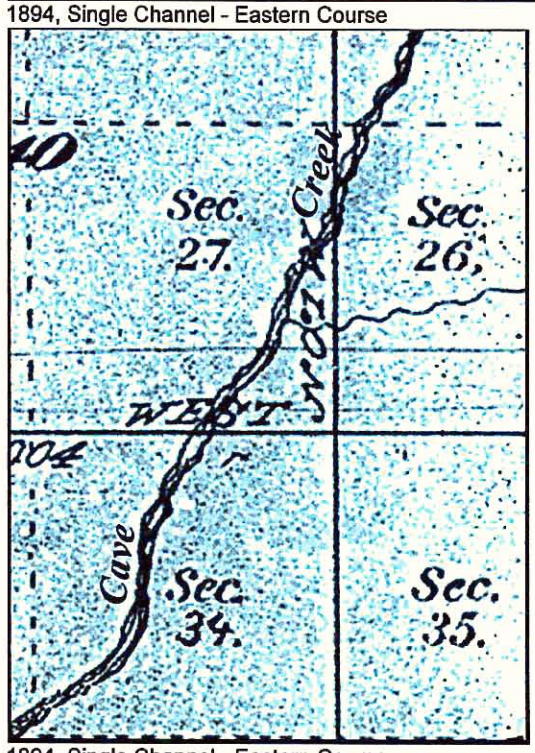
Cave Creek, Reach 5 (Section 27/34). The 1981 photo-revised topographic maps indicate the presence of two channels along the section line between sections 27 and 34 (Figure 3-2). The eastern channel lies adjacent to the "kidney bean" shaped hill located the left overbank floodplain. The USGS maps label the western channel as the main channel of Cave Creek. In 1894 the surveyors made no record of two flow paths along the section line. They recorded the location of the Cave Creek channel at the approximate location of the eastern channel on the 1981 topographic map. The 1940 and 1996 aerial photos (Figure 3-2, Appendix E) also show two channels that match the position of the flow paths indicated on the 1981 USGS topographic map. The positions of these two channels was relatively consistent from 1940 to 1996. Aerial photos from the 1940s do not show typical channel migration scars, or meander scars, that would be expected if the channel moved by the more gradual erosional process of accretion. This suggests that an avulsion occurred sometime between 1894 and 1940, shifting the course of Cave Creek approximately 1,280 feet to the west, as measured along the line between sections 27 and 34. The less active eastern channel of Cave Creek has since been captured by Tributary #1 ("Effluent Wash").



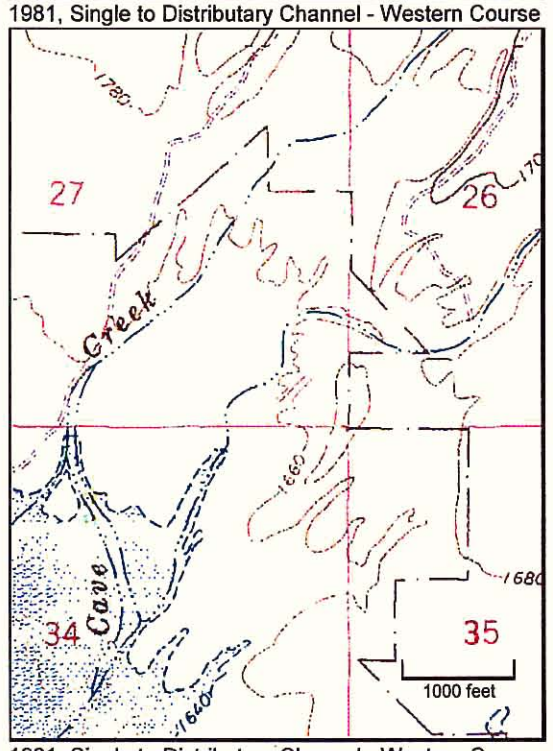
1894, Single Channel - Eastern Course



1981, Single to Distributary Channel - Western Course



1894, Single Channel - Eastern Course



1981, Single to Distributary Channel - Western Course

Figure 3-2. Historical Channel Change – Cave Creek, Reach 5. Drawings on the left are from the 1894 GLO Plat Map superimposed on the 1981 USGS topographic map.

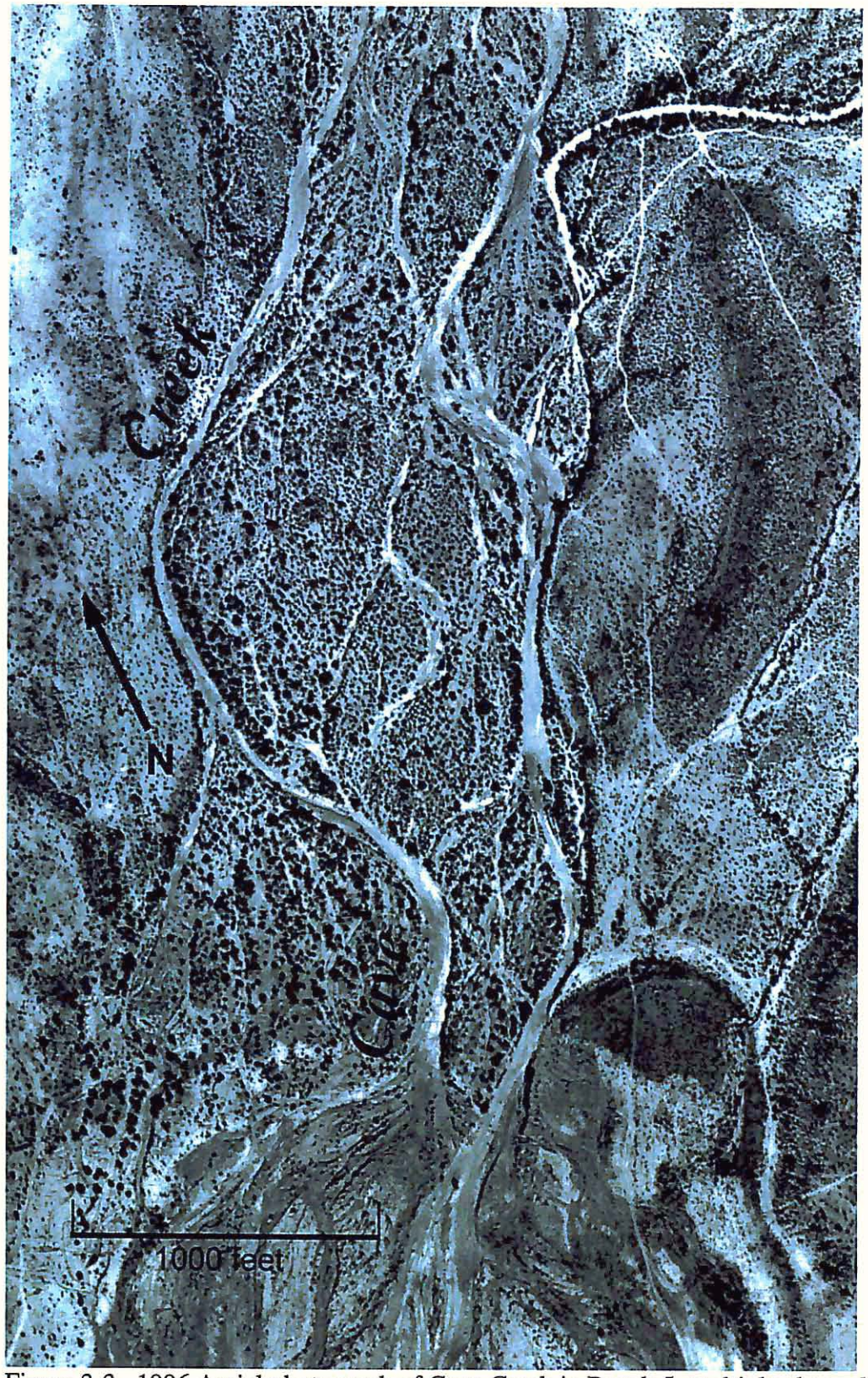
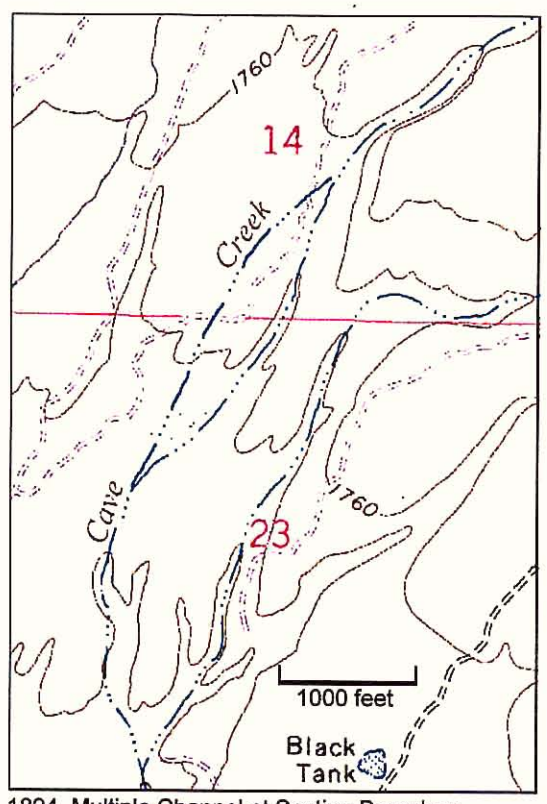


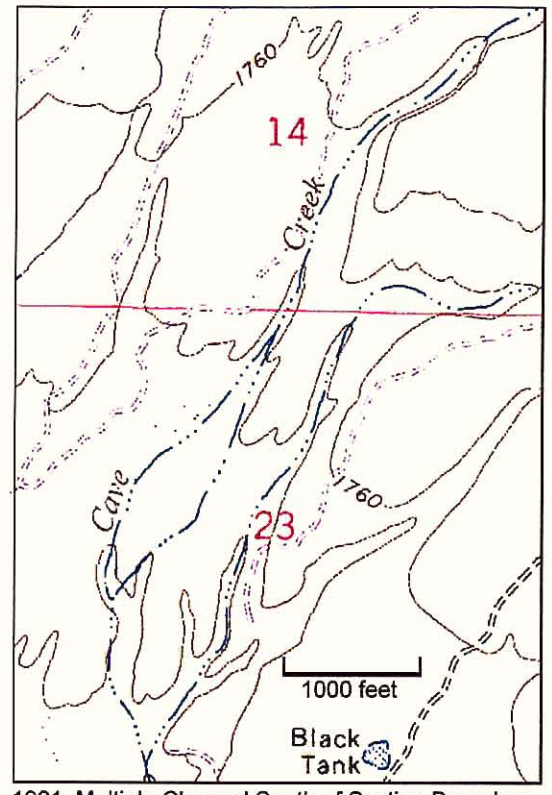
Figure 3-3. 1996 Aerial photograph of Cave Creek in Reach 5, multiple channel reach above Cave Buttes impoundment area. Match to Figure 3-2.

Besides the apparent avulsive change described above, Reach 5 of Cave Creek apparently has undergone a change from a single channel configuration to a multiple channel system. The 1894 GLO survey describes a definite center of a 3.0 chains (198 feet) wide channel. The 1940 aerial photos show only two channels clearly, Cave Creek and the channel captured by the eastern tributary. By 1996, however, the area between Cave Creek and its tributary has been cut by various channels that resemble a classic braided channel configuration. Faint indications of multiple channels are visible on air photos from 1953, and by 1985 the multiple channels are fairly conspicuous. In 1996 the width of the multiple channel area from its western edge at the main channel of Cave Creek to its eastern edge at the tributary is nearly 1600 feet.

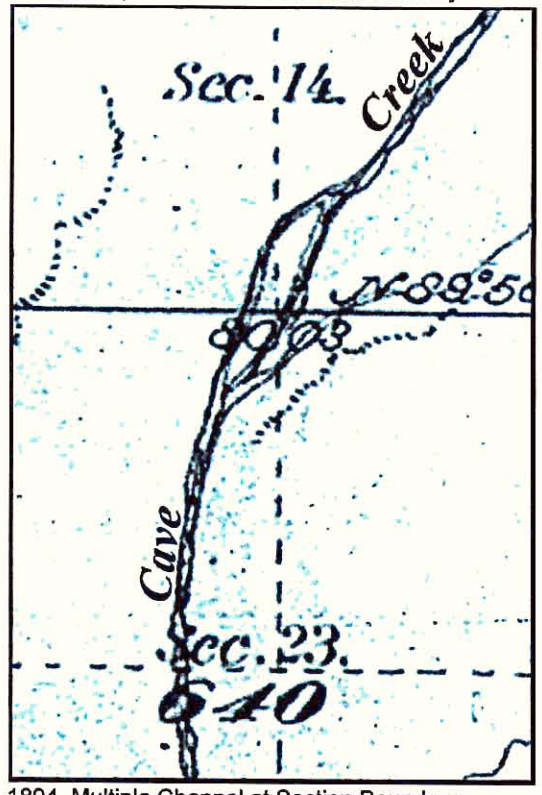
Cave Creek, Reach 3 (Section 14/23). Two other areas of significant channel change along Cave Creek involve island migration and island formation. First, in Reach 3, at the section line between sections 14 and 23, a second wash to the east of Cave Creek's main channel is drawn on the 1894 Township map as a channel around an island (Figure 3-4). By 1981 the island had migrated southward and was no longer located on the section line. The island has since become ill-defined; in 1996 photos Cave Creek has apparently consolidated its flow on the west side of the remnants of the island.



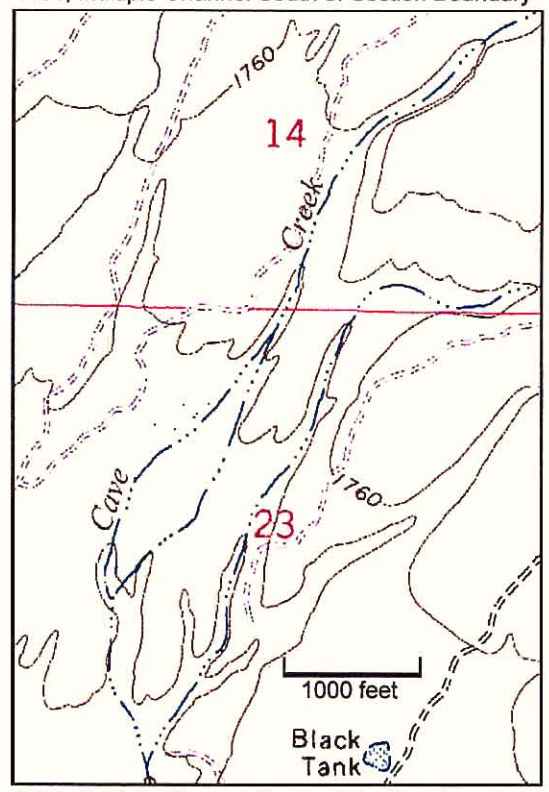
1894, Multiple Channel at Section Boundary



1981, Multiple Channel South of Section Boundary



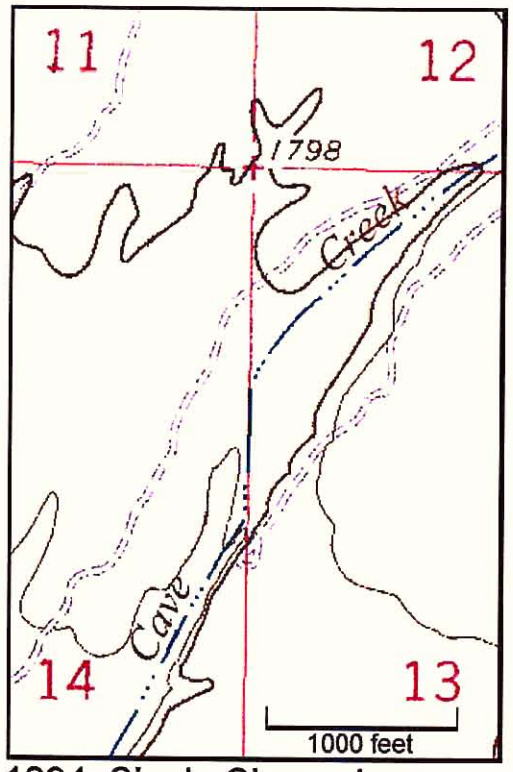
1894, Multiple Channel at Section Boundary



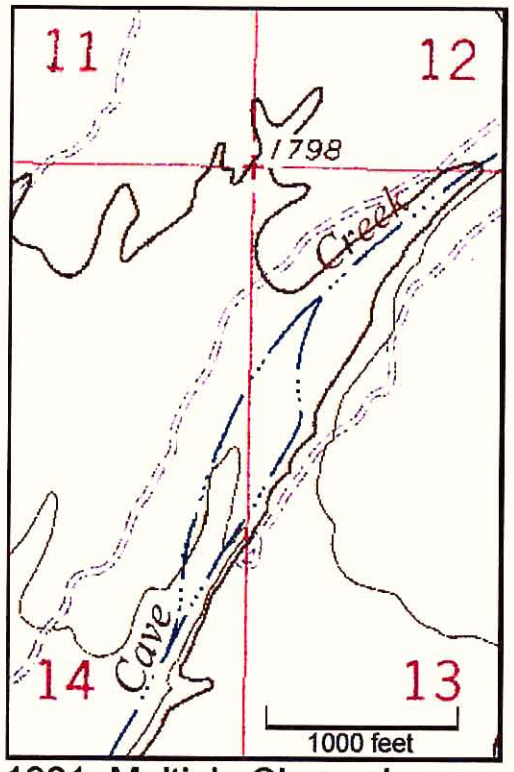
1981, Multiple Channel South of Section Boundary

Figure 3-4. Historical Channel Change – Cave Creek, Reach 3. Drawings on the left are from the 1894 GLO Plat Map superimposed on the 1981 USGS topographic map.

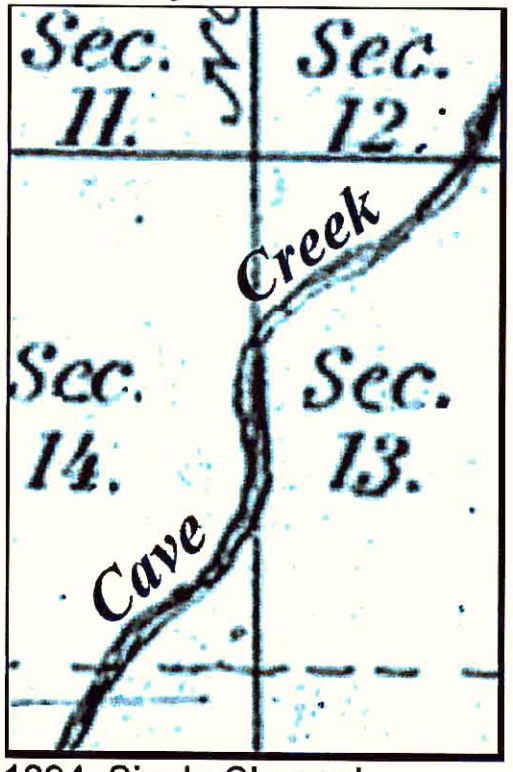
Cave Creek, Reach 2 (Section 13/14). Second, in Reach 2, the 1894 surveys indicate that Cave Creek's course flowed along the north-south section line between sections 13 and 14 (Figure 3-5). Aerial photo coverage from 1940 does not extend to this section of Cave Creek, although 1953 photos show an island in the channel that remains stable through the 1996 photos. Thus we can assume that the island formed sometime between 1894 and 1953, and has remained relatively stable since its formation.



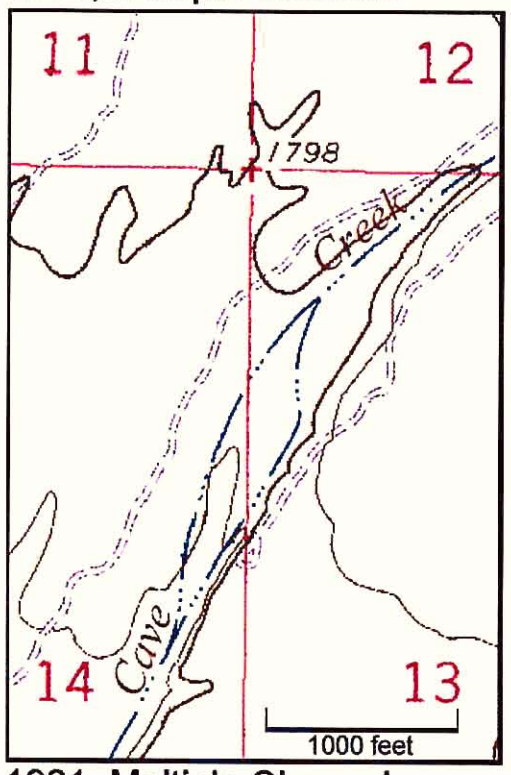
1894, Single Channel



1981, Multiple Channel



1894, Single Channel



1981, Multiple Channel

Figure 3-5. Historical Channel Change – Cave Creek, Reach 2. Drawings on the left are from the 1894 GLO Plat Map superimposed on the 1981 USGS topographic map.

Apache Wash/Paradise Wash/Desert Hills Wash. The following data summarized in Tables 3-7 to 3-9 reflect the location of Apache Wash, Paradise Wash, and Desert Hills Wash in Township 5 North, Range 3 East, between the Cave Creek Dam and Carefree Highway. The GLO survey field notes do not name any of the washes in the study area except Cave Creek. Instead, the smaller streams are simply referred to as a dry wash or an arroyo. For this analysis, to allow comparison with modern records, the washes described in the original survey notes were identified with the wash names that best fit the location. Therefore, there is some uncertainty regarding the identity of the feature described in the GLO survey notes. In the northern portion of the study area, where all three streams cross a given section line, the appropriate wash identity was determined by the position of the closest present-day wash. Although there are few large washes in the study area except for the named streams, the measurements in this area have this additional potential source of error.

Table 3-7. Upper Cave Creek/Apache Wash Watercourse Master Plan
Measurements of Long-Term Channel Movement on Apache Wash, 1867-1981

APACHE WASH, REACH 6

Between sections 33(T5N,R3E) and 4(T4N,R3E), from corner of sections 3, 4, 33, and 34, heading east

1867	1894
Arroyo.....924 ft (14.0 chains, 13.2 ft wide)	Dry Wash.....990 ft (15.0 chains)
Arroyo.....2376 ft (36.0 chains, 66.0 ft wide)	
Arroyo.....2508 ft (38.0 chains)	Dry Wash.....3630 ft (55.0 chains, 52.8 ft wide)
Apache Wash.....4686 ft (71.0 chains, 105.6 ft wide)	Apache Wash.....4778 ft (72.4 chains, 66 ft wide)

1981

Ephemeral Wash....867 ft
Same Eph. Wash...1750 ft
Apache Wash.....4933 ft

Summary of movement: ***Apache Wash moved east 92 feet (river left), 1867-1894***
Apache Wash moved east 155 feet (river left), 1894-1981

Between sections 33 and 34, from corner of sections 3, 4, 33, and 34, heading north

1894	1981
Dense Brush..... 2970-5280 ft (45.0-80.0 chains)	Apache Wash.....3300 ft
Apache Wash.....no record	Apache Wash.....4417 ft

Summary of movement: ***Apache Wash meandered eastward across the section line into dense brush noted in 1894***

Between sections 28 and 33, from corner of sections 27, 28, 33, and 34, heading west

1894	1981
Apache Wash 323 ft (4.9 chains, 26 ft wide)	Apache Wash..... 267 ft

Summary of movement: ***Apache Wash moved east 57 feet (river left)***

APACHE WASH, REACH 5

Between sections 21 and 28, from corner of sections 21, 22, 27, and 28, heading west

1894	1981
Apache Wash.....924 ft (14.0 chains)	Apache Wash.....300 ft

Summary of movement: ***Apache Wash moved east 624 feet (river left)***
****Within section 28 Apache Wash may have meandered westward, closer to hill; based on comparison of 1894 GLO map and 1981 topographic map.***

Between sections 21 and 22, from corner of sections 21, 22, 27, and 28, heading north

1894	1981
Dense Brush.....0-4620 ft (0-70.0 chains)	
Apache Wash.....799 ft (12.1 chains)	Apache Wash..... 767 ft

Summary of movement: ***Apache Wash moved south 32 feet (river left)***

APACHE WASH, REACH 4

Between sections 15 and 22, from corner of sections 14, 15, 22, and 23, heading west

1894	1981
Left bank.....1663 ft (25.2 chains)	
Center of Channel...1756 ft	Apache Wash..... 1700 ft
Right Bank.....1848 ft (28.0 chains)	

Summary of movement: ***Apache Wash moved east 56 feet (river left)***

APACHE WASH, REACH 2

Between sections 10 and 15, from corner of sections 10, 11, 14, and 15, heading west

1894	1981
Paradise Wash..... no record	Paradise Wash.....967 ft
Apache Wash.....3597 ft (54.5 chains)	Apache Wash..... 3600 ft
Desert Hills Wash...5247 ft (79.5 chains)	Desert Hills Wash..... 5217 ft

Summary of movement: ***Apache Wash moved east 3 feet (river left)***
Desert Hills Wash moved east 30 ft (river left) – meander amplitudes increasing

APACHE WASH, *SUPPLY REACH*

Between sections 3 and 10, from corner of sections 2, 3, 10, and 11, heading west

1894	1981
Apache Wash.....no record	East Channel, Apache Wash..233 ft
	West Channel, Apache Wash.433 ft
	Upstream Tributary.....2567 ft

Summary of movement: ***Can't make conclusion due to lack of 1894 records***

Table 3-8. Upper Cave Creek/Apache Wash Watercourse Master Plan
Measurements of Long-Term Channel Movement on Paradise Wash, 1894-1981

PARADISE WASH, REACH 1
Between sections 10 and 11, from corner of sections 10, 11, 14, and 15, heading north

1894	1981
Paradise Wash.....2323 ft (35.2 chains)	Paradise Wash.....2433 ft

Summary of movement: ***Paradise Wash moved north 110 feet (river right)***

PARADISE WASH, *SUPPLY REACH*
Between sections 2 and 11, from corner of sections 1, 2, 11, and 12, heading west

1894	1981
Paradise Wash..... 2475 ft (37.5 chains)	Paradise Wash.....2400 ft
West Branch, (PW).4231 ft (64.1 chains)	West Branch, Paradise Wash.4167 ft

Summary of movement: ***Paradise Wash moved west 75 feet (river left)***
West Branch, Paradise Wash, moved east 64 feet (river right)

Table 3-9. Upper Cave Creek/Apache Wash Watercourse Master Plan
Measurements of Long-Term Channel Movement on Desert Hills Wash, 1894-1981

DESERT HILLS WASH, REACH 1 & *SUPPLY REACH*
Between sections 15 and 16, from corner of sections 15, 16, 21, and 22, heading west

1894	1981
Desert Hills Wash...4838 ft (73.3 chains)	Desert Hills Wash.....4800 ft
Desert Hills Wash...5122 ft (77.6 chains)	Desert Hills Wash.....5167 ft

Summary of movement: ***Desert Hills Wash meander moved west into the cutbank 38-45 feet (river right)***

DESERT HILLS WASH, *SUPPLY REACH*
Between sections 10 and 15, from corner of sections 10, 11, 14, and 15, heading west

1894	1981
Paradise Wash..... no record	Paradise Wash.....967 ft
Apache Wash.....3597 ft (54.5 chains)	Apache Wash.....3600 ft
Desert Hills Wash...5247 ft (79.5 chains)	Desert Hills Wash.....5217 ft

Summary of movement: ***Apache Wash moved east 3 feet (river left)***
Desert Hills Wash moved east 30 ft (river left) – meander amplitudes increasing

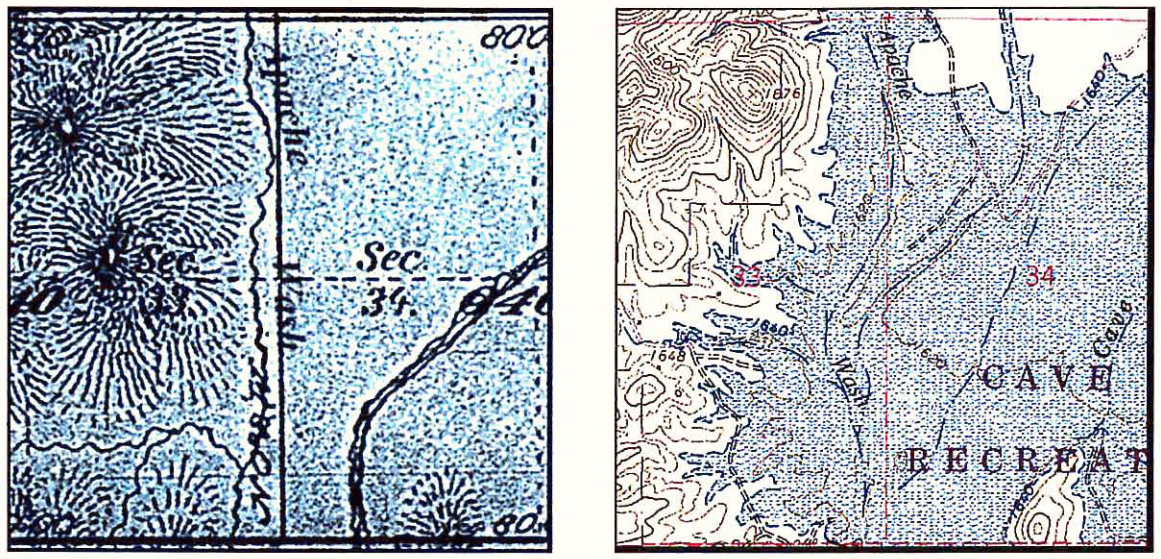
DESERT HILLS WASH, *SUPPLY REACH*
Between sections 9 and 10, from corner of sections 9, 10, 15, and 16, heading north

1894	1981
Desert Hills Wash...no record	Desert Hills Wash.....800 ft

Summary of movement: ***Desert Hills Wash moved west (river right)***

The results of the comparison of historical channel position at specific locations along the Apache Wash system are summarized in the following paragraphs.

Apache Wash, Reach 6 (Section 33/34). Comparison of the 1894 surveys, 1940 aerial photos, and 1981 topographic map indicate that Apache Wash moved eastward across the section 33/34 boundary line sometime between 1894 and 1940 (Figure 3-6). The 1894 survey makes no mention of Apache Wash crossing the section line, but reports dense brush in the area that probably represents riparian vegetation along the nearby bank line to the west. Because the wash did not cross the section line boundary in 1894, only a minimum distance can be determined based on the distance between the section and wash in 1981. Based on these data, Apache Wash moved a minimum of 67 feet to the east.



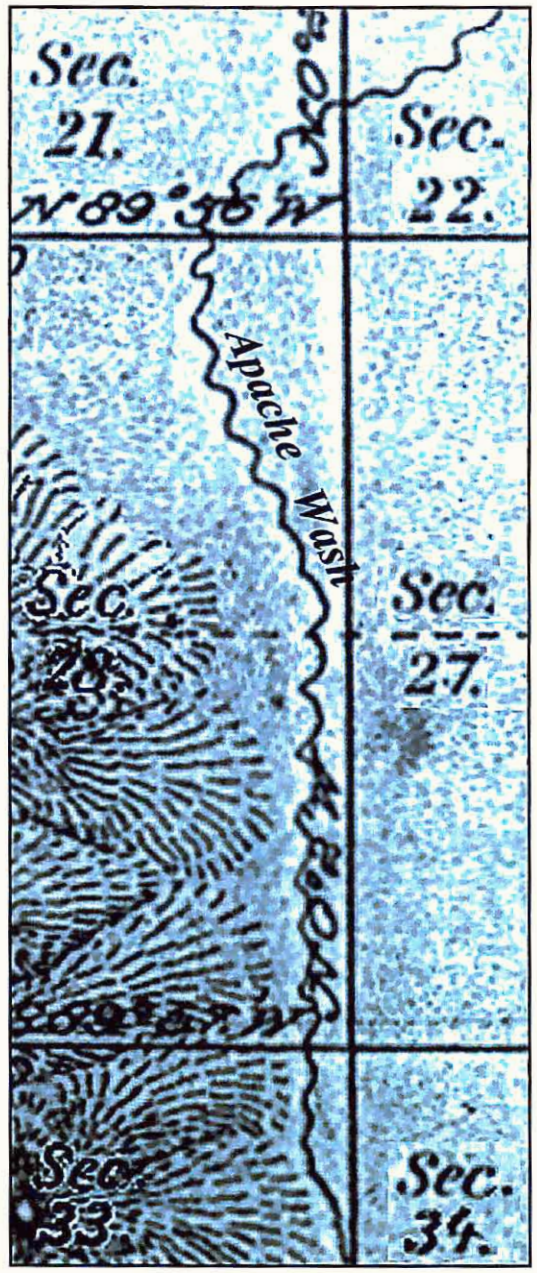
1894, Single Channel (1895 GLO Township Map) 1981, Single Channel 1981 USGS Topographic Map)

Figure 3-6. Historical Channel Change – Apache Wash, Reach 6. Drawings on the left are from the 1894 GLO Plat Map superimposed on the 1981 USGS topographic map.

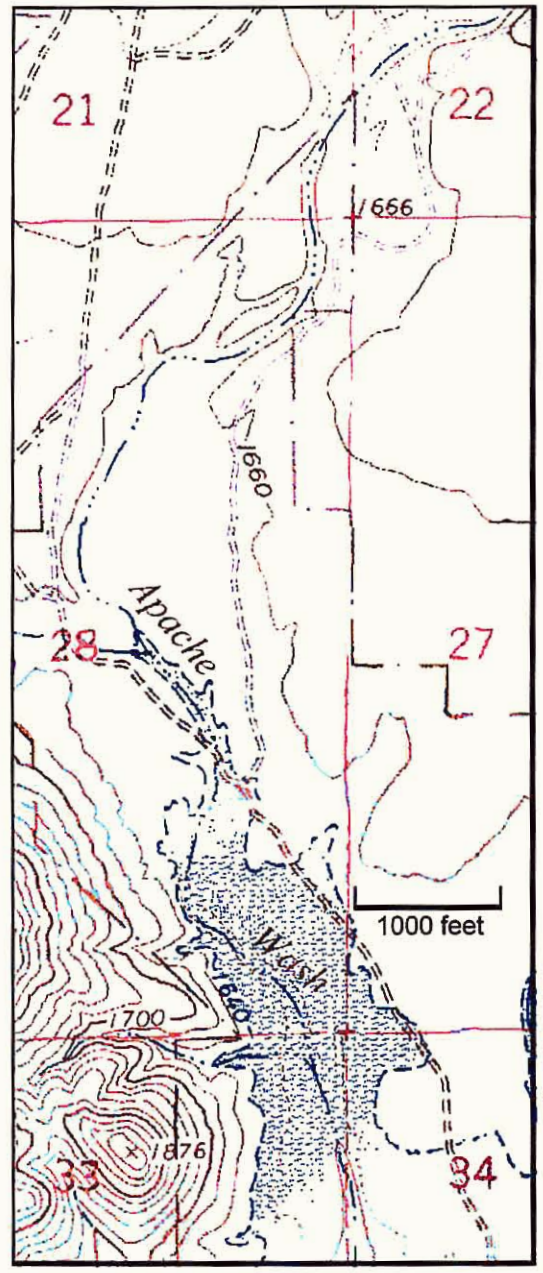
Apache Wash Reach 6 (Section 28/33) & Apache Wash, Reach 5 (Sections 21/28). Comparison of data from the 1894 survey and 1981 topographic map and later aerial photos indicates the following shifts in channel position (Figure 3-6 and 3-7):

- 21/28 section line – channel moved 624 feet east
- 28/33 section line – channel moved 57 feet east

These two section line surveys provide the only specific data about the position of Apache Wash in this area. Comparison of the 1987 topographic maps and 1940 aerial photographs shows that Apache Wash was in the same basic position during both time periods. The position of the channel drawn on the 1894 plat map, when compared to later location data, implies a significant change in channel location between 1894 and 1940 (Figure 3-6). The 1894 Township map shows Apache Wash flowing adjacent to the terrace scarp that bounds the eastern margin of the geologic floodplain. This scarp is clearly visible in aerial photos of the wash, although evidence of an abandoned channel at this location appears to have been largely obscured by vegetation and sediment deposition. The maximum shift in channel location would have been about 1,400 feet.



1894, Single Channel
(1895 GLO Township Map)



1981, Single Channel
(1981 USGS Topographic Map)

Figure 3-7. Historical Channel Change – Apache Wash, Reach 5. Drawings on the left are from the 1894 GLO Plat Map superimposed on the 1981 USGS topographic map.

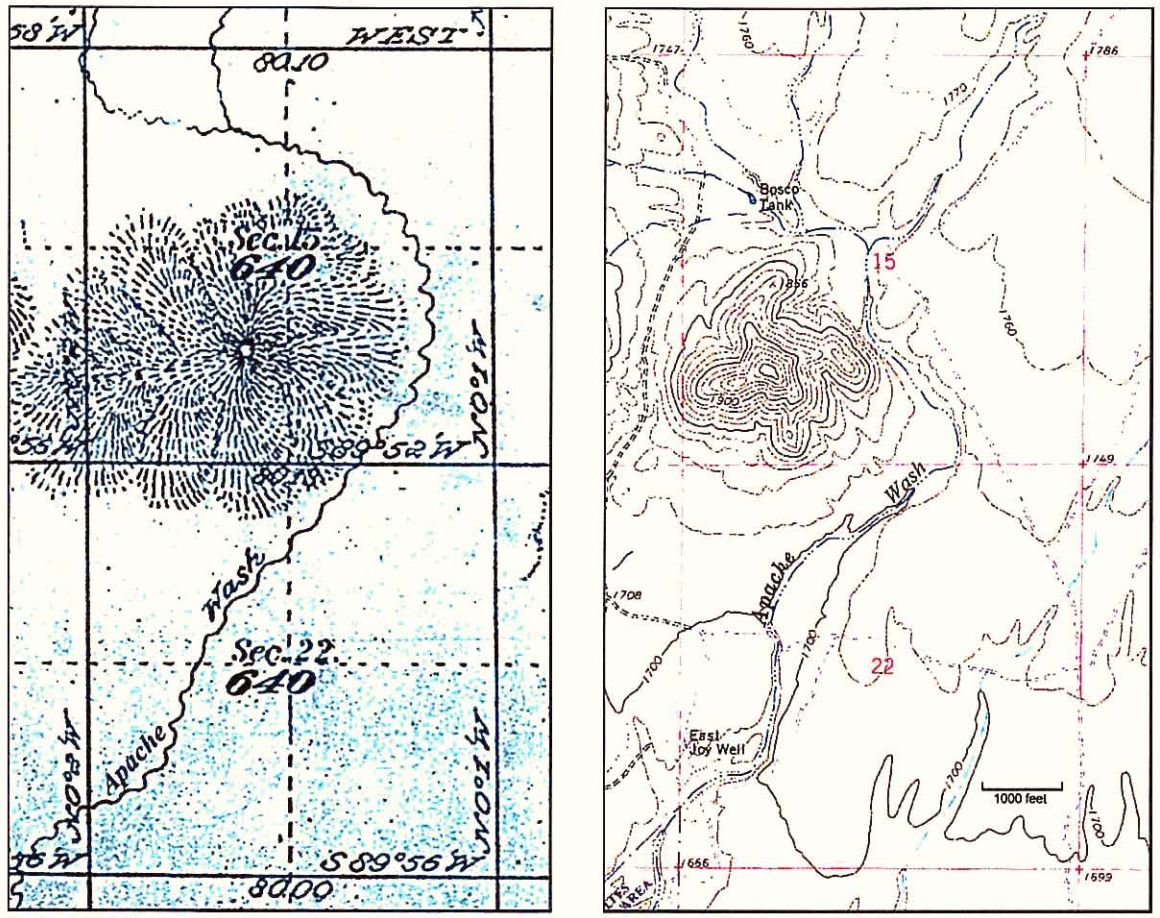
The accuracy of GLO survey records has been questioned in other studies of historical channel movement (c.f. Jones & Harper, 1998). Therefore, it is reasonable to question whether Apache Wash actually moved the large distance indicated by the GLO survey data. The topography of the geologic floodplain suggests that such movement is possible,

although it implies that incision of Apache Wash may have occurred after 1894.[4] The 1894 channel position was located along the eastern side of the floodplain at the margin of the middle Pleistocene terrace. The modern aerial photographs show only minimal surficial evidence that could indicate the presence of an abandoned channel, such as linear patterns of large trees that might once have defined a stream bank. The only large trees in the floodplain grow around the present-day channel. The lack of meander scars suggests that if the channel shift did occur, it had to have been a fairly abrupt, avulsive change. By 1940, fairly large trees are established along the banks of Apache Wash.

The eastward shift of 624 feet that occurred along the section 21/28 line speaks to the fact that the channel was capable of changing its position in large increments in the past. This evidence of large lateral migrations between 1894 and 1940 serves as a warning of the potential for future changes. Since 1940 the channel has been relatively stable at this location.

Apache Wash, Reach 4 (Section 15/22). The inaccuracy of the plotted 1894 channel location for Apache Wash at this location casts doubt on the accuracy of the GLO plat map for section 15. Apache Wash is shown too far to the northeast on the GLO plat map (Figure 3-8), well outside the geologic floodplain within the limits of the middle Pleistocene terrace. Topographic maps and aerial photos produced after 1940 indicate that Apache Wash could not have occupied the position shown on the 1894 map. The eastern bank of the wash in 1940 is a steep cliff separating the streambed from the upper land surface by approximately 30 feet. In addition, there is no evidence on the aerial photos, such as abandoned channels or meander scars, that indicate Apache Wash ever flowed east of its present position.

[4] Coincident with the timing of Skunk Creek incision hypothesized by Earl (1983).



1894, Single Channel (1895 GLO Township Map) 1981, Single Channel (1981 USGS Topographic Map)

Figure 3-8. Historical Channel Change – Apache Wash, Reach 4. Drawings on the left are from the 1894 GLO Plat Map superimposed on the 1981 USGS topographic map.

Although the channel position on the GLO plat map within the center of Section 22 is suspect, the position of Apache Wash along the section lines conforms closely to the present day position of Apache Wash and indicates a reasonable amount of channel movement. Based on the centerline of the stream, Apache Wash moved about 56 feet to the east along the section 15/22 line (Figure 3-8). Movement of 55 feet is within the boundaries of the banks established in 1894, indicating that Apache Wash is fairly stable within its established floodplain at this location.

Apache Wash, Reach 2 (Sections 10/15). Surveyors recorded the position of Apache Wash along the section line between sections 10 and 15 at essentially the same position as that marked on the 1981 topographic map. There is a difference of only 3.0 feet indicating that Apache Wash was very stable at this location between 1894 and 1981.[5]

Apache Wash, Reach 1 (Section 3/10 – Carefree Highway Alignment). At the section 3/10 boundary, the GLO surveyors made no record of crossing Apache Wash. It is possible that Apache Wash, which currently has a shallow multiple channel pattern at this

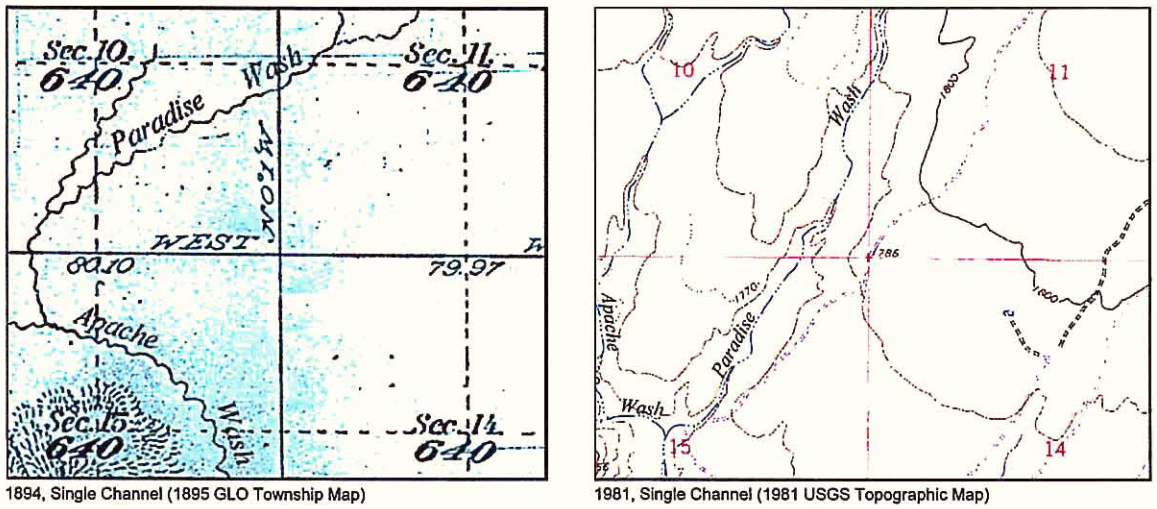
[5] No figure provided – no measurable change.

location, may have been so indistinct that the surveyors did not recognize it as a major stream crossing. If incision occurred after 1894, as implied by the discussion of the Section 28 GLO notes, then the channel may have been even less well defined in the 19th century. By 1953, the channel did not look significantly different from the channel at the section 10/15 crossing downstream. However, given that the main objective of the GLO survey was not to identify wash corridors, it is possible that the surveyors simply neglected to record the position of Apache Wash at this section line. (See also the discussion of the Paradise Wash section 10/15 crossing below.)[6]

Paradise Wash, Reach 1 (Sections 10/11 & 10/15). Comparisons of Paradise Wash locations between the 1894 GLO survey and 1981 topographic map show significant movement at some locations.

- 10/15 section line – no record of channel in 1894
- 10/11 section line – channel moved 110 feet northward

The lack of record in 1894 between sections 10 and 15 is more likely due to carelessness by the GLO cartographers than to a large shift in the course of Paradise Wash. The 1894 GLO Township map (Figure 3-9) shows what is most likely Paradise Wash flowing into Apache Wash north of the southern boundary of section 10. The current confluence of Paradise and Apache Wash is located near the center of section 15. There are no abandoned channels or any other evidence to suggest a lateral shift of that magnitude. Thus the position of Paradise Wash as drawn on the 1894 map is most likely an interpretive error by the GLO surveyors due to incomplete field data.



1894, Single Channel (1895 GLO Township Map)

1981, Single Channel (1981 USGS Topographic Map)

Figure 3-9. Historical Channel Change – Paradise Wash, Reach 1. Drawings on the left are from the 1894 GLO Plat Map superimposed on the 1981 USGS topographic map.

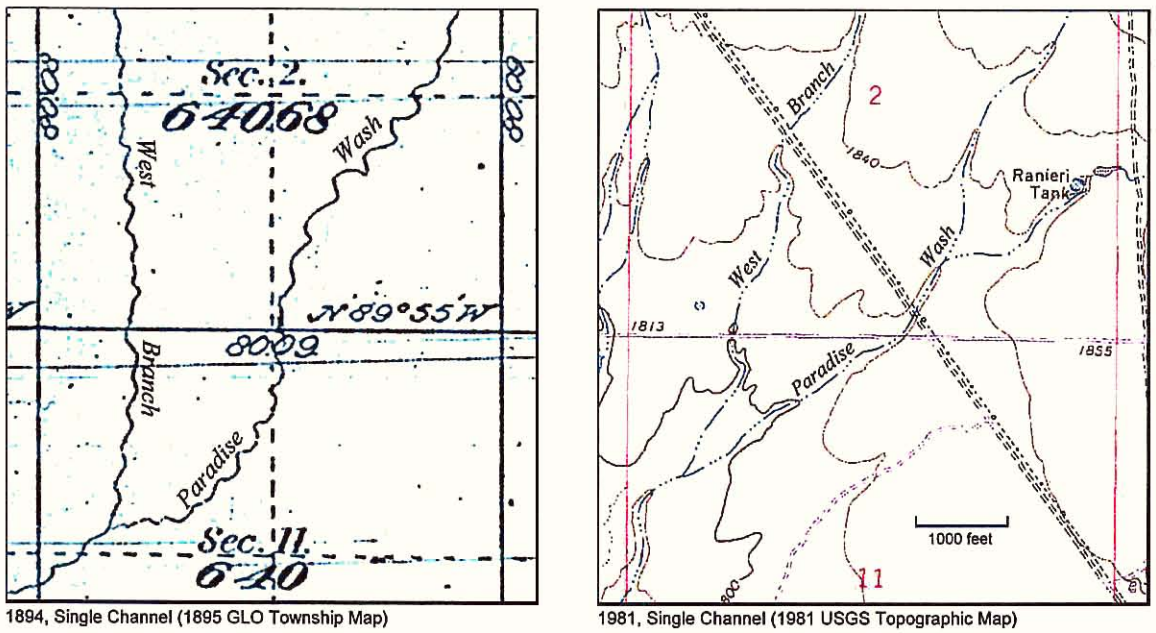
Analysis of the current floodplain topography (Willdan, 1996) and photographic record for Paradise Wash indicates that the implied channel movement of 110 feet along the section 10/11 boundary is reasonable.

[6] No figure provided – GLO plat map does not show Apache Wash at this crossing.

Paradise Wash, *Supply reach* (Section 2/11) & West Branch Paradise Wash (Section 2/11). Comparisons of Paradise Wash locations between the 1894 GLO survey and 1981 topographic map show significant movement at some locations (Figure 3-10).

- Paradise Wash 2/11 section line – channel moved 75 feet west
- West Branch Paradise Wash 2/11 section line – channel moved 64 feet east

The current topography and photographic record for both Paradise Wash and the West Branch Paradise Wash indicate that the implied channel movements along the section 2/11 boundary are reasonable.



1894, Single Channel (1895 GLO Township Map)

1981, Single Channel (1981 USGS Topographic Map)

Figure 3-10. Historical Channel Change – Paradise Wash, *Supply reach*. Drawings on the left are from the 1894 GLO Plat Map drawn on the 1981 USGS topographic map.

Desert Hills Wash (Sections 9/10, 10/15, 15/16). Comparison of Desert Hills Wash locations between 1894 and 1981 indicate that the meanders just upstream of the confluence with Apache Wash increased in amplitude on the order of 30-45 feet. These values are only slightly higher than the measurement error associated with the USGS topographic map. Therefore, it was assumed that the implied change may have occurred, and are not the result of measurement or recording errors. The channel changes along Desert Hills Wash are summarized in the following bullets and in Figures 3-11 and 3-12.

- 15/16 section line, northern crossing – channel moved 38 feet south
- 15/16 section line, southern crossing – channel moved 45 feet north
- 9/10 section line - channel moved 30 feet east

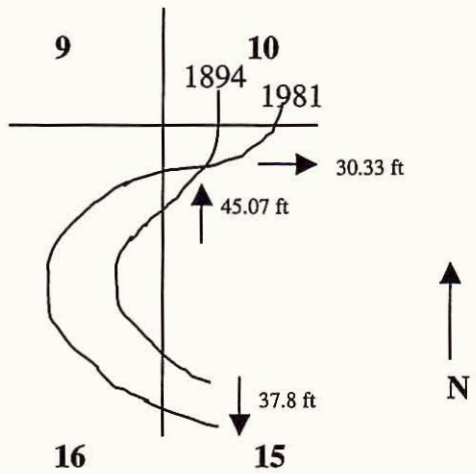
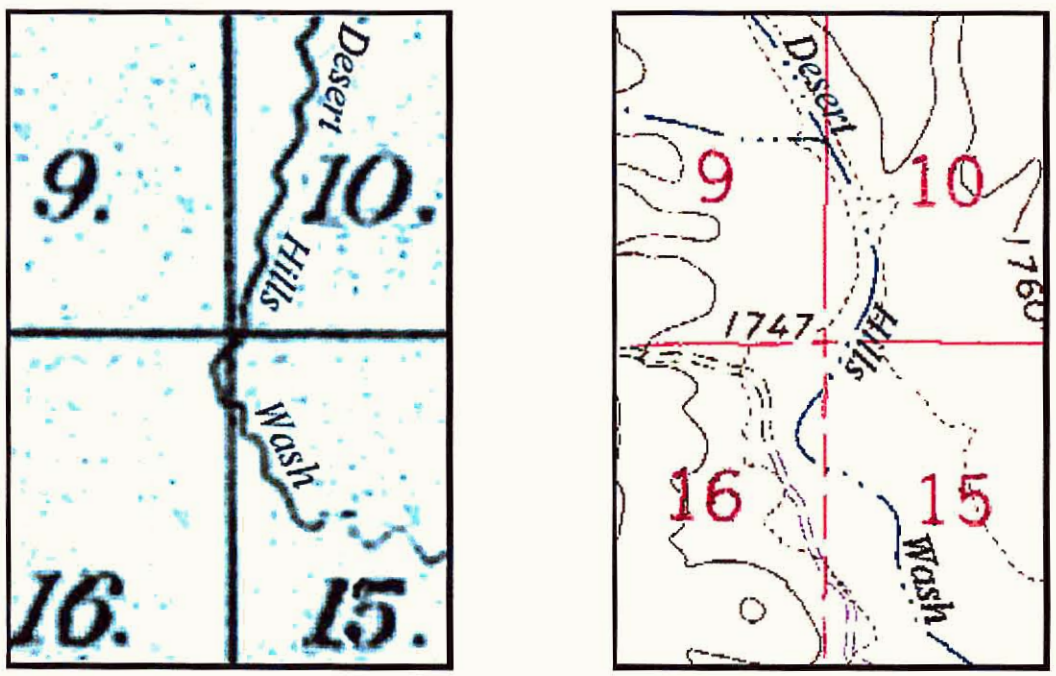


Figure 3-11. Measured Channel Change - Desert Hills Wash at Upstream Study Limit

There is no record of Desert Hills Wash crossing the boundary between sections 9 and 10 in 1894. As with some sections of Paradise and Apache Washes, this is most likely due to carelessness by the original surveyors and does not reflect a real change in the course of Desert Hills Wash.



1894, Single Channel
(1895 GLO Township Map)

1981, Single Channel
(1981 USGS Topographic Map)

Figure 3-12. Historical Channel Change – Desert Hills Wash. Drawings on the left are from the 1894 GLO Plat Map superimposed on the 1981 USGS topographic map.

Summary. Analysis of the 1894 survey data for reliability and subsequent comparison of the 1894 channel positions with 1981 channel positions produces the following conclusions.

- Cave Creek. Measurable long-term channel movement occurred throughout the study area. At least two types of channel movement occurred:
  1. Gradual bank erosion – the rate of lateral erosion averaged less than one foot per year in most of the study area during the period of record. The single channel reaches (1 and 2) tended to be the most stable.
  2. Avulsive channel change – *avulsions* caused shifts in channel location of more than 1,200 feet at one place within the study area, with avulsions of several hundred feet elsewhere. In addition, avulsions caused the stream to change from a single to multiple channel pattern. Avulsions were more common in Reaches 4 and 5, downstream of Tributary #2. One avulsion created an island in Reach 2.

- Apache Wash. Measurable long-term channel movement occurred in several places. Two types of movement occurred:
  1. Gradual bank erosion – the rate of lateral erosion averaged less than one foot per year, and the channel remained in essentially the same position (e.g., Section 10/15).
  2. Avulsive channel change – the magnitudes of avulsive shifts were several hundred feet or more, and the channel rapidly shifted to the other side of the floodplain (e.g., Section 21/28 boundary and section 28 interior).

  The magnitude of channel movement appeared to increase in the downstream direction, perhaps reflecting the lower slope, sediment deposition near the Cave Butte impoundment, and increased flood magnitudes.

- Paradise Wash. Measurable channel movement occurred at most points of comparison, although the reliability of the 1894 survey data was poor. The measured change at the section 10/11 boundary is significant, and may represent a small channel avulsion.

- Desert Hills Wash. Measured channel movement was interpreted to be meander development at a scale within the range of measurement error.

Lateral Channel Movement

Single Event Changes. Many *ephemeral* streams in central Arizona are subject to rapid lateral migration during floods. Bank erosion of several hundred feet during a single storm has been reported on some streams (c.f. Kresan, 1988). To test the susceptibility of Cave Creek and its tributaries to erosion during a single event, the position of the channel banks and *thalweg* were digitized using partially rectified aerial photographs (Landis, 1991, 1993, 1994, 1995) from before and after the January 1993 flood, which was the largest *runoff* event gauged by the USGS. Flood data for the floods that occurred between 1991 and 1995 are shown in Table 3-10.

Table 3-10. Upper Cave Creek/Apache Wash Watercourse Master Plan Single Event Channel Change – Floods Between 1991 and 1995				
Date	**Peak Discharge**	**Storm Volume**	**Recurrence Interval**	**Notes**
August 22, 1992	4,680 cfs	1170 AF	≈ 5 year	2nd largest summer peak in record
January 8, 1993	13,800 cfs	13021 AF	≈ 25 year	Largest gauged peak in record; highest recorded annual flow volume
October 7, 1993	132 cfs	241 AF	<< 2 year	
January 5, 1995	3,110 cfs	2600 AF	≈ 3 year	Moderately high volume

Notes:
1. Peak flow data obtained from the USGS gauging Station Cave Creek near Cave Creek (09512300).
2. Flow volume data obtained from the USGS gauging Station Cave Creek below Cottonwood Creek (09512280).

The January 1993 flood was clearly the largest event during the period between 1991 and 1995, and was one of the largest floods ever recorded on Cave Creek. Both the volume and the peak of the January 1993 flood were large. The *runoff* volume from January 6th to the 10th accounted for about 35 percent of the total annual flow volume for 1993, and was more than twice the long-term average annual volume. The runoff volume for the entire month of January 1993 was about 22,689 acre-feet, or 61 percent of the total volume of runoff for 1993.[7] Given the disparity in storm peak and volume during the four years of record, the greatest amount of channel change is expected for the period bracketing the January 1993 flood.

Methodology. Aerial photos for the four years of record were digitized using AutoCAD LT 97 software to allow direct comparison of the channel bank and thalweg positions for Cave Creek Wash, Apache Wash, Desert Hills Wash and Paradise Wash over a four-year period which included the largest gauged flood in the 40 years of record.[8] Semi-rectified composite aerial photos were obtained from Landiscorp, Inc at a scale of 1:12,000. The dates of the aerial photography were

- November 5, 1991 – Base condition.
- January 4, 1993 –Pre-flood condition, one day before flood of record.[9]
- February 15, 1994 – Post 1993 flood condition.
- January 18, 1995 – Post 1995 flood condition.

The main channel banks were identified by characteristics such as the color contrast between the bed and bank soil materials, increased vegetative density along the banks, and the topographic break in slope at the top of bank. The top of the main channel banks, thalweg, split flow areas and islands were digitized in addition to the limits of active sand and gravel mining areas. All digitized features were located on separate AutoCAD layers by year and feature type.

[7] Runoff volumes reported are for the Cave Creek below Cottonwood Creek station, and probably underestimate the actual storm volume in the study reach.
[8] The 1921 flood was probably the largest flood in the last century (25,000 cfs, Carollo, 1969), but it pre-dates the gauge record, which begins in 1958. The 1978 flood probably had a larger volume than the 1993 event since it reached a higher stage in the Cave Creek impoundment area, but the peak was significantly lower.
[9] Average daily discharge on photo date was 10 cfs at the Cave Creek below Cottonwood Creek gauge.

The aerial photos were then referenced to the Arizona Central State Plane Coordinate System using points common to the photos and USGS quad sheets, which cover the area. Common match points included road intersections, small stock ponds, and well-defined topographic features. Once a grid of known points was established, the photos were "rubber-sheeted" using a projective transformation based on at least four points with known state plane coordinates. In some cases, mostly in the areas surrounding Apache Wash, Desert Hills Wash and Paradise Wash, no reliable landmarks common to both USGS maps and the aerial photos were visible. In these cases, features such as distinctive trees or intersections of roads and trails not shown on USGS maps were digitized in the perimeters of the areas with adequate known points common to both USGS and the photos. These points were then cross-referenced to the areas with less established points.

Minor corrections were necessary to correctly position certain stream reaches of Apache Wash, Desert Hills Wash and Paradise Wash. These minor corrections were required because of a lack of sufficient match points to adequately cross reference between the USGS maps and the photos in the areas surrounding these washes. Such corrections were not possible for a portion of the January 4, 1993 coverage, which was provided as a spliced photo product. Therefore, part of the 1993 coverage of Apache Wash Reach 3 was not digitized (Figure 3-13). The digitization covering Cave Creek required only minimal smoothing from one grid section to another. The digitization was done as individual grids and then joined because the photos were larger than the digitizing board. The results of the Cave Creek Wash digitization are considered very good because of the dense grid of known cross-reference points.

Error Analysis. Several types of potential error may result from the methodology used to determine the bank movement from 1991 to 1995. Measurement error was probably within the range of ± 20 feet, given the 1:12,000 scale of the aerial photographs. A second source of error was caused by the "rubber sheeting" process described above. The latter source of error is more difficult to quantify, but is readily distinguished by examining the offset channel boundaries in non-eroding reaches in Figures 3-13.1 to 3-13.6. A more problematic form of error was caused by the inability to distinguish new channels on the aerial photographs due to their quality. In several cases, what are shown as *avulsions* on Figures 3-13.1 to 3-13.6 are instances where overbank flow concentrated in previously existing low areas and resulted in *scour*, deposition, and removal of vegetation. The scoured areas were then more visible on the aerial photographs for the next year and were digitized as active channels. To overcome this potential source of error the plots shown in Figures 3-13.1 to 3-13.6 were reviewed in more detail prior to developing the information summarized in Tables 3-12 to 3-13.

Results. Plots of the digitized channel boundaries from the 1991, 1993, 1994, and 1995 aerial photographs are shown in Figures 3-13.1 to 3-13.6. Based on the comparison of bank position from 1991 to 1995, as shown in Tables 3-11 to 3-12, the following conclusions were drawn:

- Avulsions. Several *avulsion*s occurred in the study area between 1991 and 1995 (Table 3-11), despite the fact that none of the flow events exceeded the 25-year recurrence interval. The largest avulsions occurred on Cave Creek, with a maximum channel movement distance of more than 400 feet. Avulsions on the Apache Wash system tended to be small and involved formation of a new cutoff channel or exploitation of a previously existing overbank flow path. No avulsions occurred during the low flow years between 1994 and 1995. The largest number of avulsion occurred between 1993 and 1994, the period of greatest flooding. As expected, the avulsions were contained within the recent geologic floodplain.

- Non-avulsive lateral erosion. The average non-avulsive erosion distances reported in Table 3-12 are not corrected for measurement or plotting errors. Therefore, some interpretation is required. Positive values indicate net erosion or channel widening. Negative values indicate net deposition or channel narrowing, relative to the previous year recorded. In general, the reported average values are less than the accuracy of the methodology used, which should be interpreted as no change. Interestingly, the average bank erosion reported during the 1991 to 1993 period was greater than the erosion during the period which included the 1993 event, the flood of record. The least amount of bank erosion was recorded during the 1994 to 1995 period.

- Narrowing. Net channel narrowing may be inferred during periods where the negative non-avulsive distances are reported, or where the negative value exceeds the positive value for the opposite bank. Cave Creek widened between 1993 and 1994, but narrowed during the other time periods sampled. Apache Wash experienced net narrowing during each of the three time periods, although bank retreat was observed in some reaches. Paradise Wash and Desert Hills Wash experienced net widening during the two driest periods, and net narrowing during the period of highest flow (1993-1994). Narrowing is best interpreted as encroachment by bank vegetation which obscures the bank stations and affects the measurement.

- Cave Creek. Cave Creek was subject to avulsions and accretive bank erosion, although the magnitude of avulsive changes far exceeds the rate of accretive erosion. The scale of erosion on Cave Creek exceeds the scale of erosion on the Apache Wash system.

- Apache Wash. Apache Wash was subject to several small *avulsion*s, but on average experienced little measurable accretive erosion.

- Paradise Wash. Paradise Wash experienced greater accretive erosion than Apache Wash, but had fewer discernable avulsions.

- Desert Hills Wash. Desert Hills Wash was not subject to avulsions between 1991 and 1995, but experienced some accretive channel change, particularly in the reach of historical disturbance downstream of the failed Bosco Tank spillway.

Table 3-11. Upper Cave Creek/Apache Wash Watercourse Master Plan Number of Channel Avulsions – 1991-1995						
Reach	**1991-1993**		**1993-1994**		**1994-1995**	
	#	**Maximum Distance (ft)**	**#**	**Maximum Distance (ft)**	**#**	**Maximum Distance (ft)**
Cave Creek	1	320	3	410	0	-
Apache Wash	1	72	2	140	0	-
Paradise Wash	0	-	1	98	0	-
Desert Hills Wash	0	-	0	-	0	-

Table 3-12. Upper Cave Creek/Apache Wash Watercourse Master Plan Reach-Averaged Non-Avulsive Bank Erosion Distances (ft): 1991-1995						
Reach	**1991-1993**		**1993-1994**		**1994-1995**	
	Reach Average		**Reach Average**		**Reach Average**	
	Left	**Right**	**Left**	**Right**	**Left**	**Right**
Cave Creek						
1	2	-17	-15	18	-21	-5
2	38	-59	-67	91	1	-12
3	67	-40	-52	51	-36	-45
4	-37	-18	26	-7	-6	-1
5	65	-66	4	5	62	10
Entire	16	-37	-17	28	-6	-9
Apache Wash						
1	1	1	0	1	8	-2
2	-3	-19	-6	7	-2	-9
3	2	6	10	-19	5	2
4	6	-5	8	-13	-3	2
5	-10	5	13	-11	7	-10
Entire	-4	2	7	-9	2	-4
Paradise Wash						
1	-26	33	26	-29	5	5
Desert Hills Wash						
1	25	-22	22	-30	14	-3

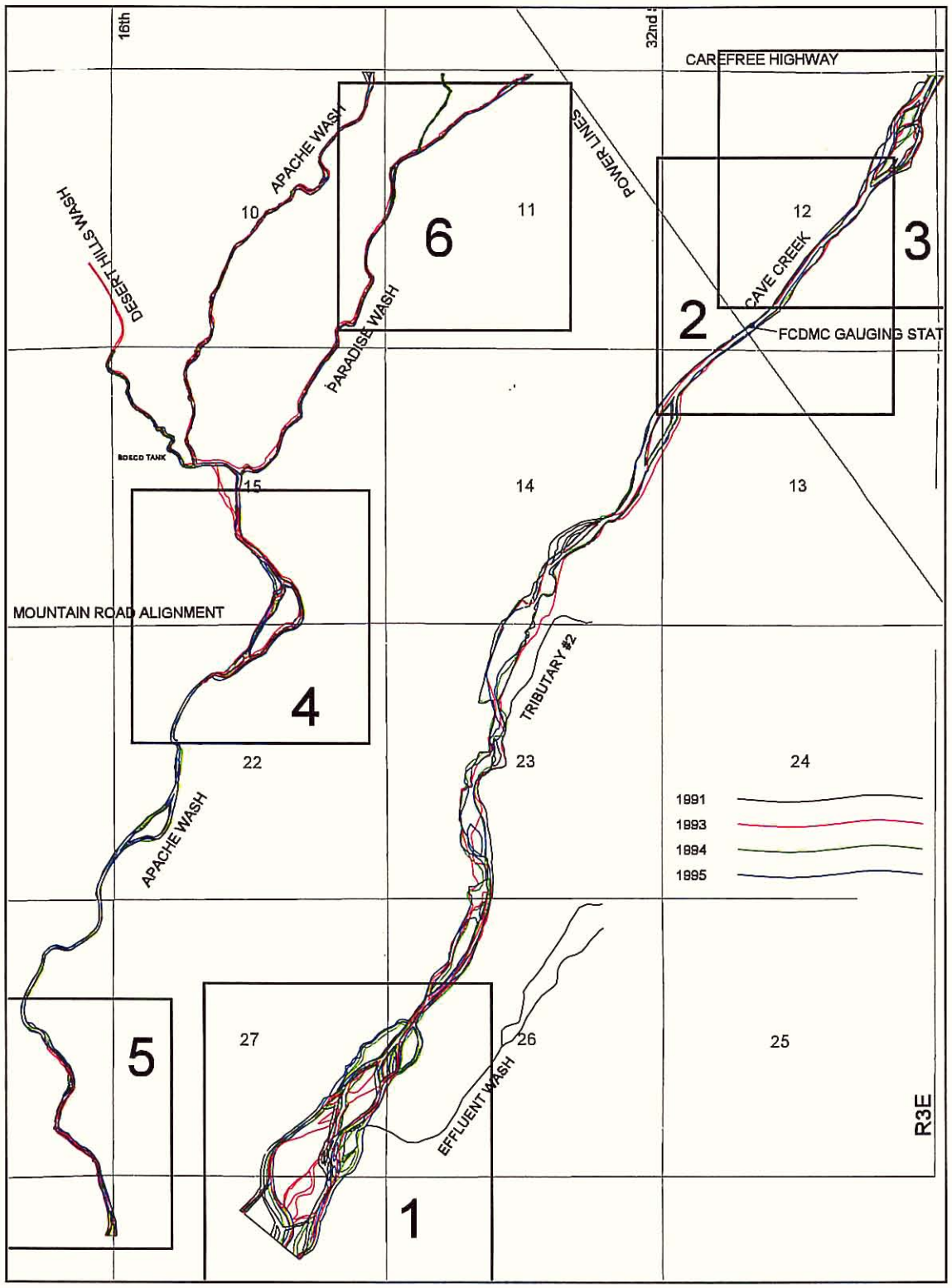


Figure 3-13. Map Key for Figures 3-13.1 to 3-13.6 - 1991 to 1995 Channel Change Plots in the Upper Cave Creek/Apache Wash Watercourse Master Plan Study Area. Digitized Channel Bank Positions for 1991, 1993, 1994, and 1995.

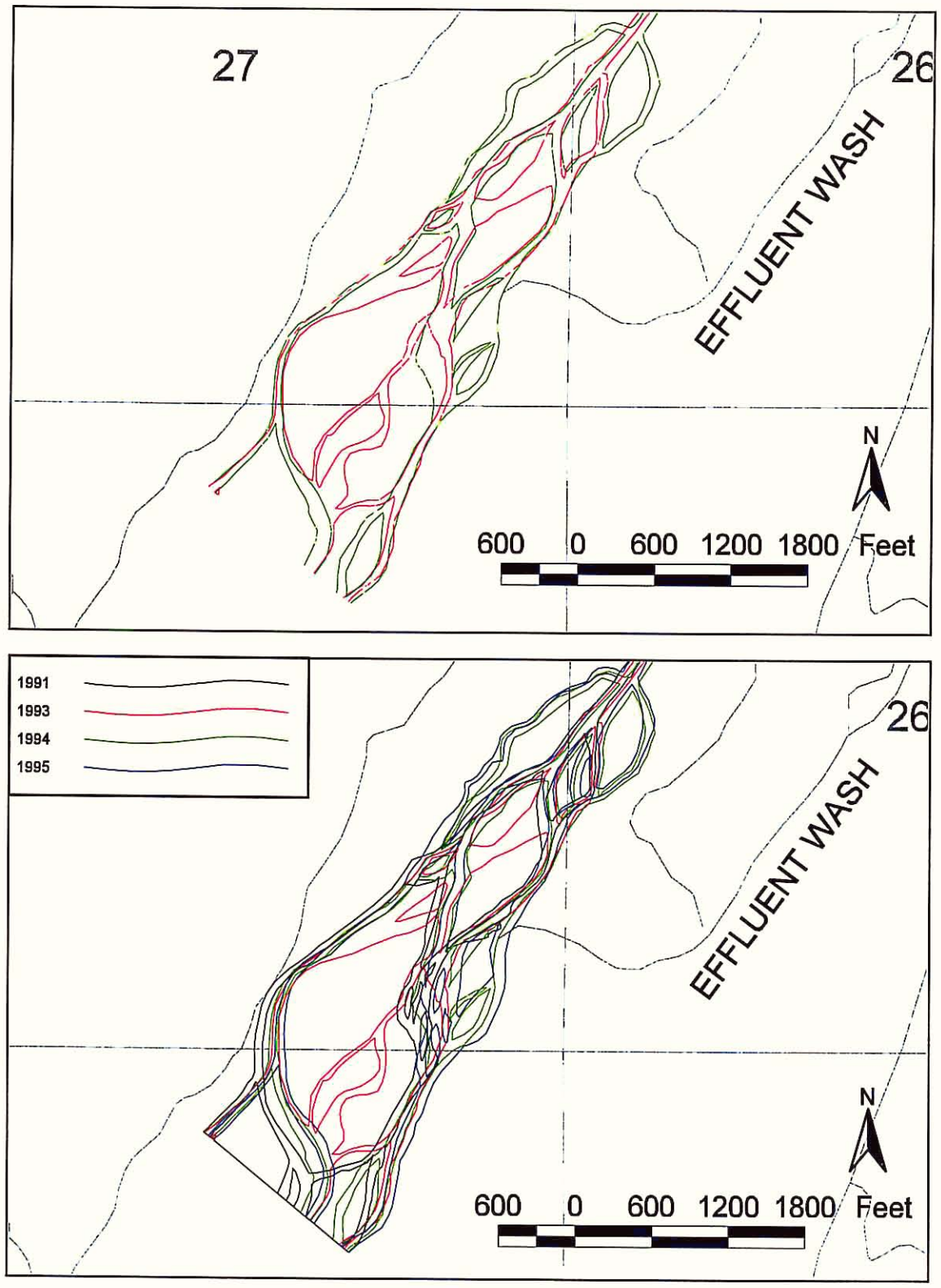


Figure 3-13.1. Digitized Channel Bank Positions on Cave Creek in Reach 5, 1991 to 1995 (bottom) and 1993 to 1994 (top).

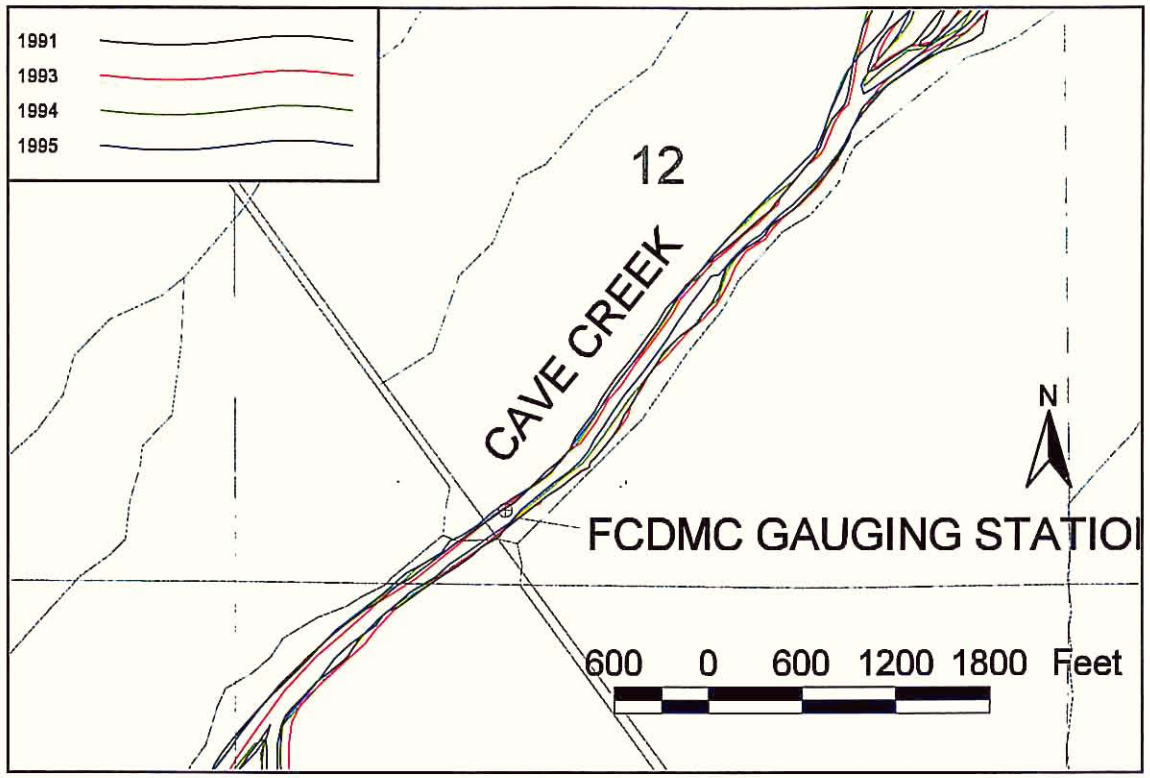


Figure 3-13.2. Digitized Channel Bank Positions on Cave Creek in Reach 2, 1991 to 1995.

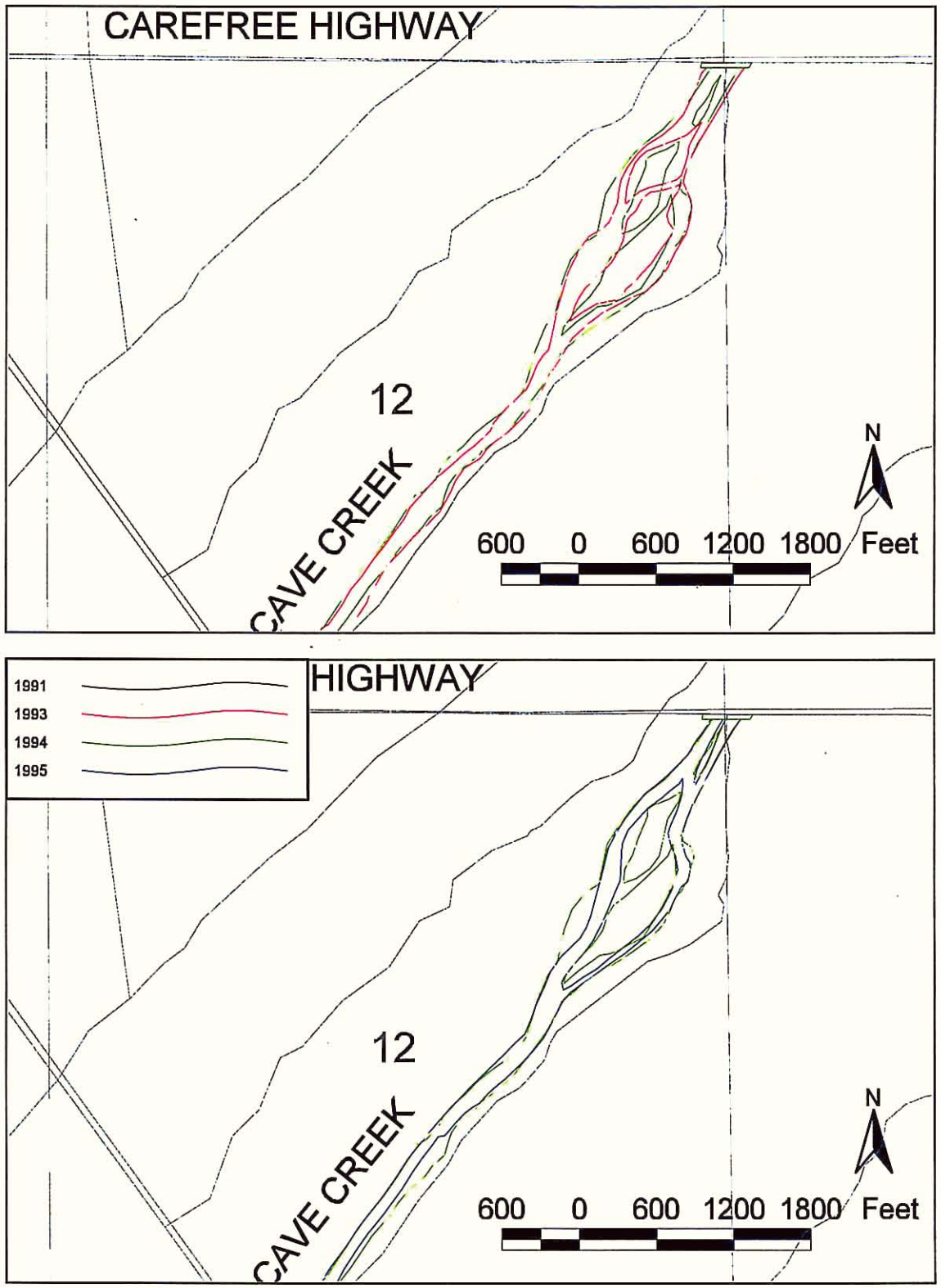
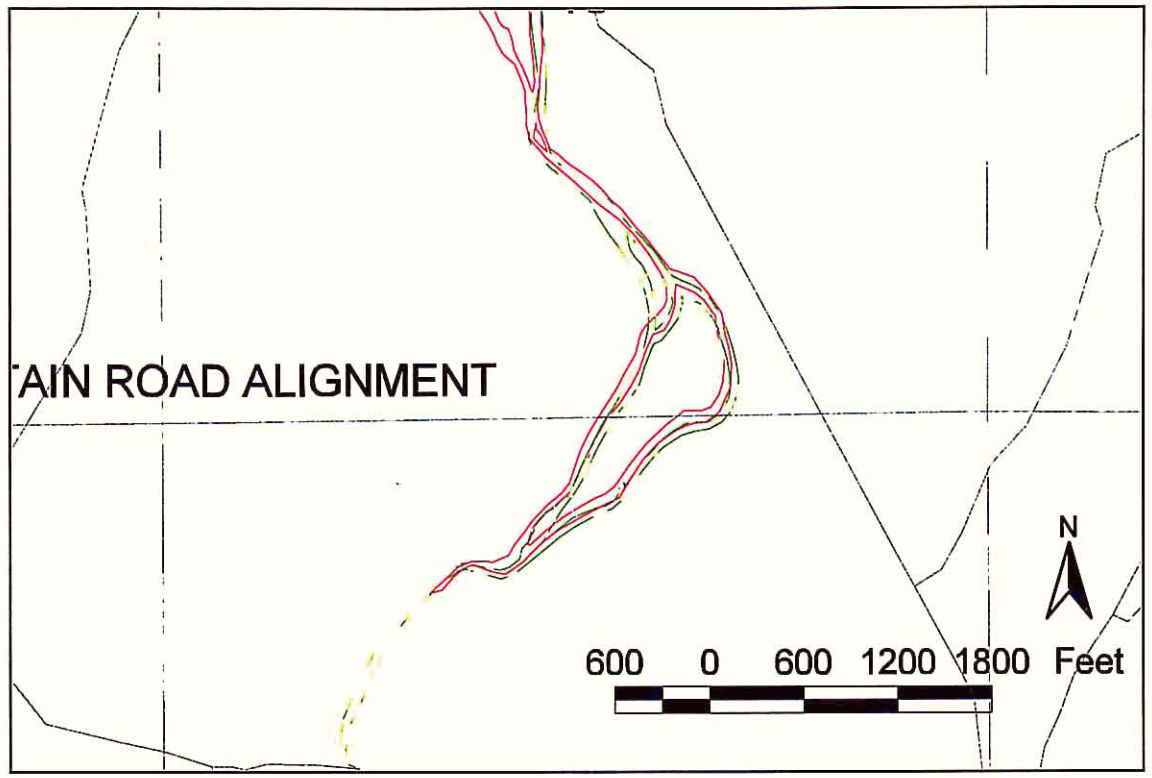


Figure 3-13.3. Digitized Channel Bank Positions on Cave Creek in Reach 1, 1991 to 1995 (bottom) and 1993 to 1994 (top).



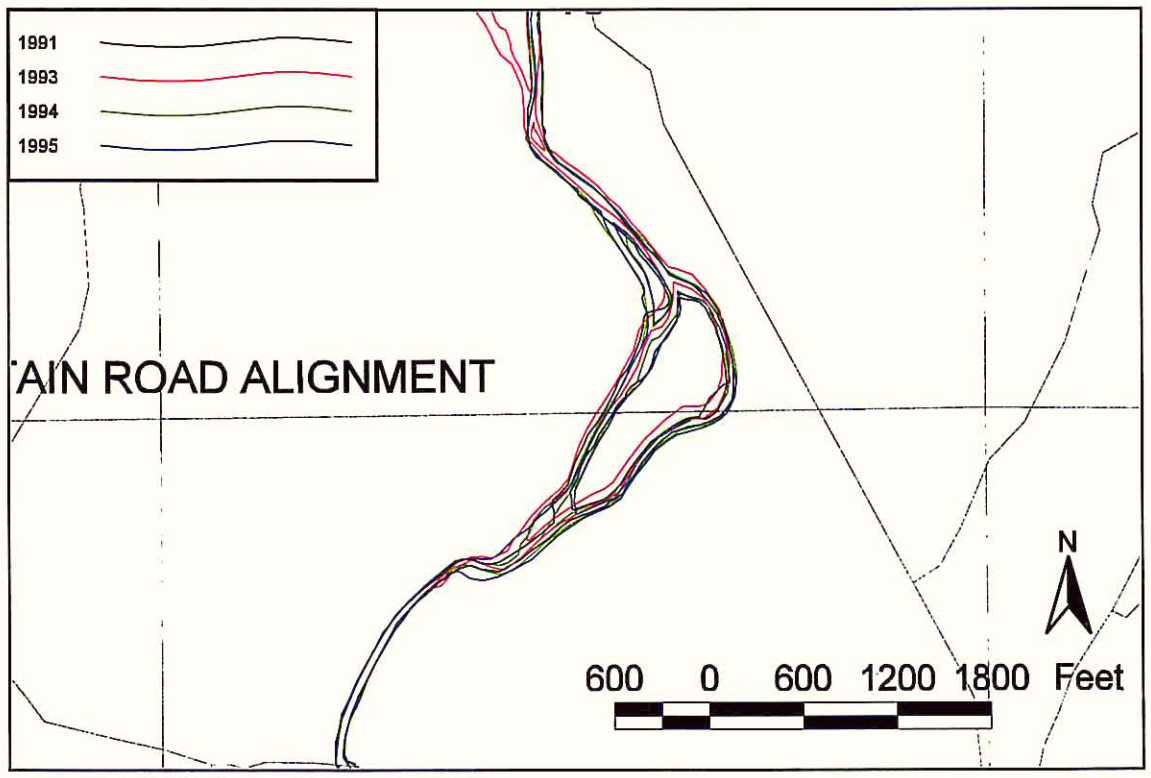


Figure 3-13.4. Digitized Channel Bank Positions on Apache Wash in Reach 4, 1991 to 1995 (bottom) and 1993 to 1994 (top).

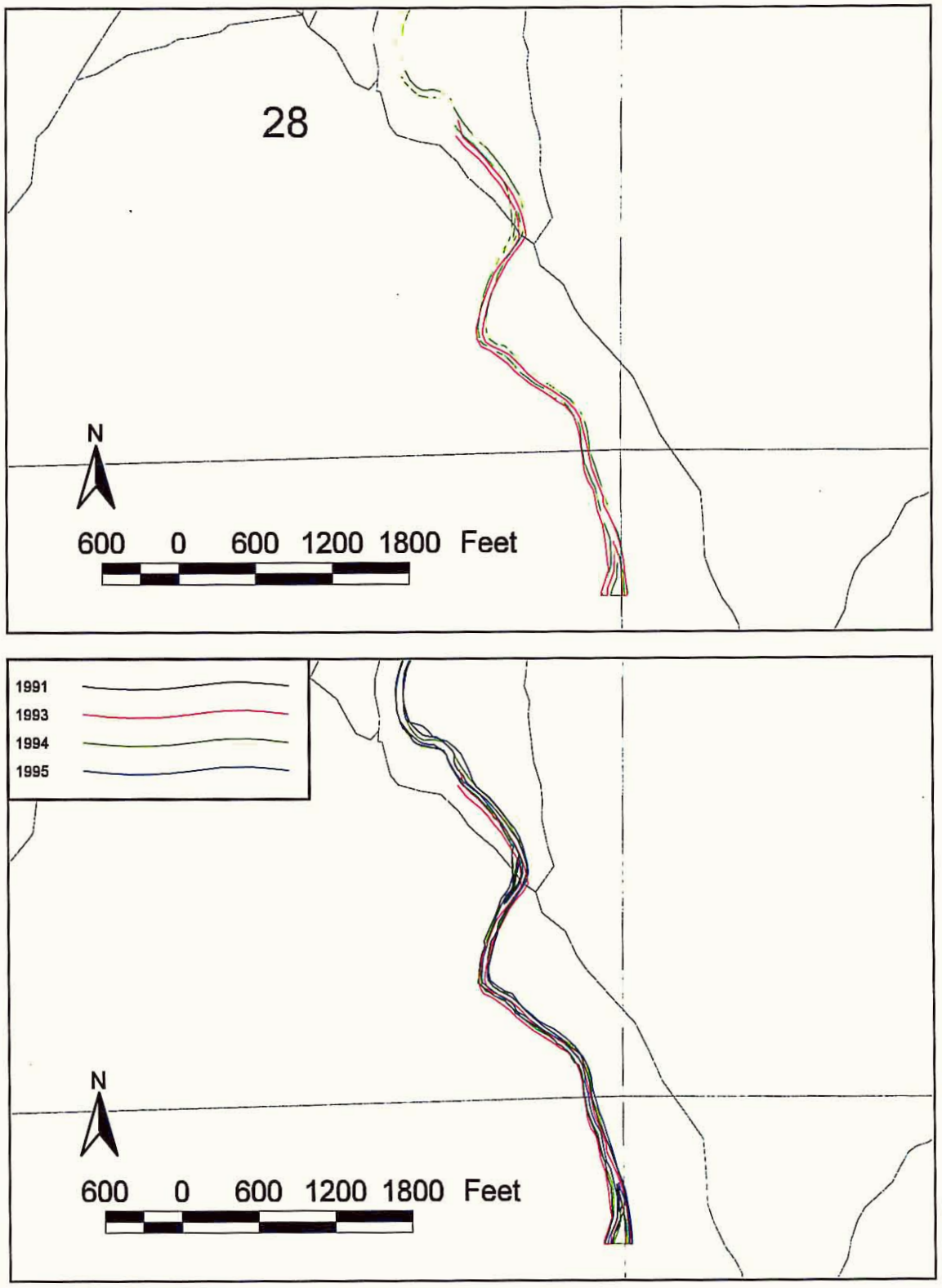


Figure 3-13.5. Digitized Channel Bank Positions on Apache Wash in Reach 5 and 6, 1991 to 1995 (bottom) and 1993 to 1994 (top).

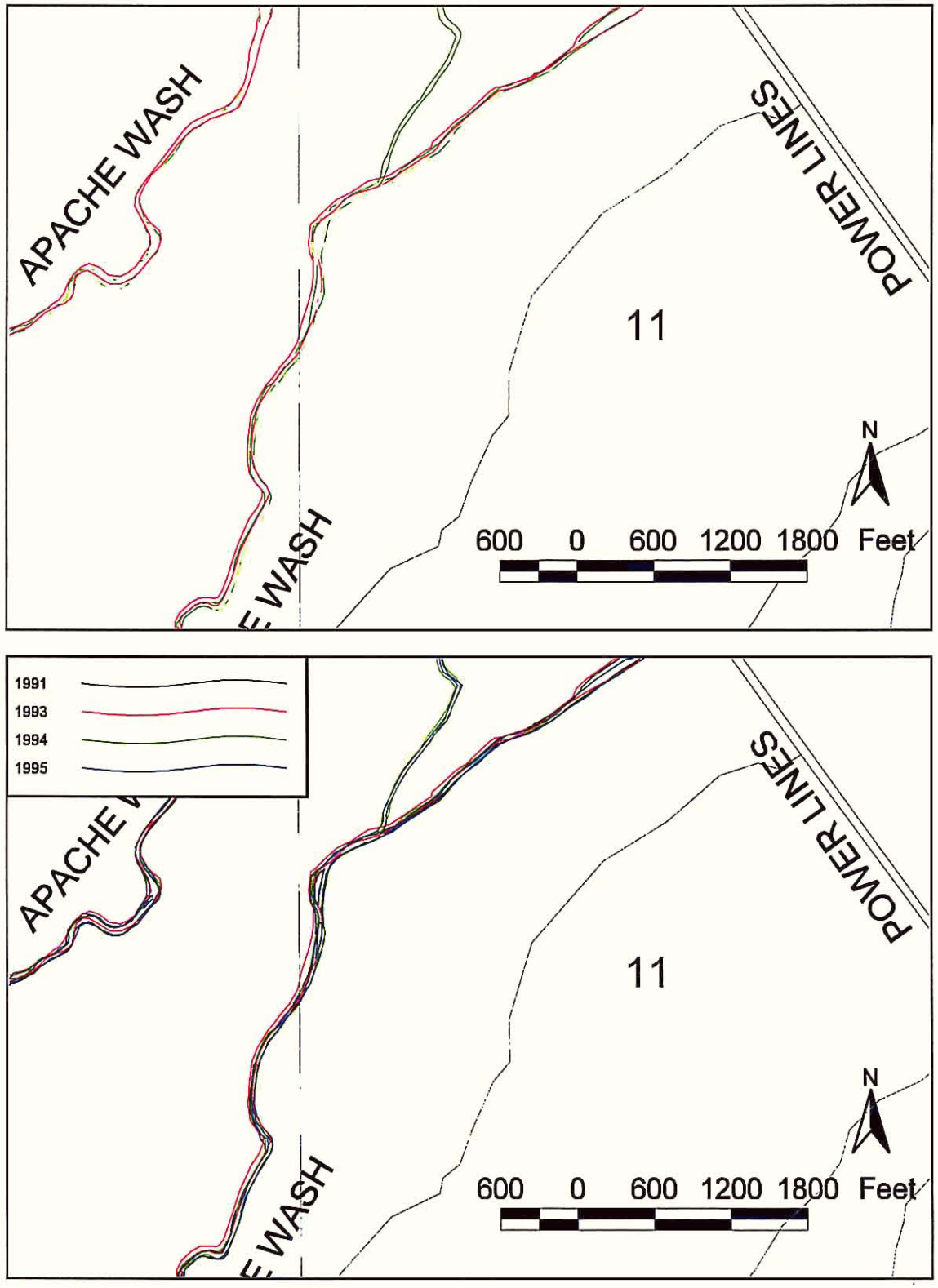


Figure 3-13.6. Digitized Channel Bank Positions on Paradise in the *Supply reach* and Reach 1, 1991 to 1995 (bottom) and 1993 to 1994 (top).

Vertical Channel Movement

Long-Term Changes. Vertical changes in the bed elevations of the streams in the Upper Cave Creek/Apache Wash Watercourse Master Plan study area were estimated using the following methods:

- Comparison of topographic mapping – longitudinal profile
- Interpretation of historical stereo photographs – bank height estimates
- Interpretation of archaeological features (Cave Creek only) – canal head elevation

Data Sources. The sources of aerial photographs and topographic information used in the vertical channel movement analysis are shown in Table 3-13. Although older historical aerial photographs were available for the study reach (Table 3-1), the older coverage did not have sufficient stereo overlap to allow elevation data to be extracted.

Table 3-13. Upper Cave Creek/Apache Wash Watercourse Master Plan Source of Channel Elevation Data, 1960-1999

Date	Description	Source	Scale	Contour Interval	Range of Coverage
1960	Stereo Aerial Photographs	USGS	1:24,000	n/a	Entire Reach
1962	Topographic Map	USGS	1:24,000	20 ft	Entire Reach
1979	Topographic Map	Harris-Toups	1:4,800	2 ft.	Upstream End
1981	As-Built Plans	MCDOT	1:360	1 ft.	Carefree Hwy
1990	Topographic Map (Apache)	FCDMC/J.R.Jones	1:2,400	2 ft.	Apache Wash
1996	Topographic Map (Cave)	FCDMC/Willdan	1:4,800	2 ft.	Entire Reach
1997	Engineering Drawings	MCDOT	1:600	1 ft.	Carefree Hwy
1999	Stereo Aerial Photographs	ASL	1:9600	n/a	Entire Reach

The data used provide coverage of the entire study reach include two time periods: pre-development (1960 or 1962) and modern (1990 or 1999). Engineering drawings for the Carefree Highway bridge (1981 & 1997) and the Harris-Toups FIS mapping (1979) provide data only for the upper reach of Cave Creek. The Harris-Toups FIS mapping extends from about 3,500 feet downstream of the Carefree Highway to above the New River Road alignment.

Methodology. Comparison of Topographic Mapping. The topographic information obtained from the sources listed in Table 3-13 were used to develop a history of aggradation and/or degradation for the washes of the Upper Cave Creek/Apache Wash Watercourse Master Plan study area. All data except for the 1962 USGS topographic map were at similar scales and levels of detail. The small scale and large contour interval of the USGS map may contribute an additional source of error when evaluating changes between 1962 and 1996.

Error Analysis. Comparison of the elevations listed on the 1997 MCDOT engineering drawing for the Carefree Highway bridge expansion with the 1996 FCDMC Floodplain Delineation Study (FDS) work map topography (Willdan, 1996) revealed different elevations for the Carefree Highway grade. Because it is unlikely that the Carefree

Highway changed elevations during a one year period, elevations obtained from the engineering drawings were adjusted to facilitate comparison with the FDS topography. The differences in elevations are summarized below.

Table 3-14. Upper Cave Creek/Apache Wash Watercourse Master Plan Elevation Adjustment for 1997 MCDOT Plans & 1996 FDS Topography			
Location	**1996 FDS**	**1997 MCDOT**	**Difference**
West Approach – point of highest elevation	1876 ft.	5723 m (1877 ft.)	+1.6 ft.
East Approach – 280 ft. east of bridge abutment	1874 ft.	5715 m (1875 ft.)	+1.0 ft.
RECOMMENDED AVERAGE ADJUSTMENT			-1.5 ft.

Elevations on the 1997 Engineering Drawings are 1.0 to 1.6 ft higher than elevations at the same location reported on the 1996 FCDMC FDS topographic map. This difference may be partly due to use of a different datum, although the difference was not consistent within the coverage area, as shown in Table 3-14. To adjust for the difference, based on engineering judgment, 1.5 feet was subtracted from elevations on the 1997 MCDOT engineering drawings. This gross elevation adjustment is not a true datum adjustment and may result in additional measurement error, although the magnitude of the error is small relative to the historical elevation changes.

Other potential sources of error for the topographic comparison include the following:

- Interpolation error – the accuracy is typically estimated as half the contour interval where elevations are read between contours.
- Grading elevations – proposed bed elevations shown on engineering drawings do not necessarily reflect a natural channel bed. If improperly designed or maintained, channel grading typically does not persist after the first significant flow.

Methodology. Interpretation of Aerial Photographs. Bank heights were extracted from stereo aerial photographs of the study area to provide an indication of the longitudinal distribution of aggradation and degradation during the period of record. Change in bank height can be used to indicate the direction and magnitude of vertical channel change. Two-foot contour interval topographic maps of the study reach (Willdan, 1996) were used to verify the methodology used to photo-extract bank height. The procedure for estimating bank heights from stereo photographs is described below.

1. The standard procedures for using a stereometer (a.k.a., a parallax bar) was followed to measure differences in heights, as outlined in the Instruction Manual for the TopCon Mirror Stereoscope MS-3 (TopCon, 1999, p. 6-7). Instead of calibrating the stereometer to the lowest point on the photo, the stereometer was calibrated to the lowest point in the field of vision. This field vision low point was the lowest point in the streambed, i.e., the minimum channel elevation.
2. The equation $h=(H/b)p$ (Equation 1, p. 7, Topcon, 1999) was used to determine the difference between the low point of the streambed and the bank, where h is the bank height, H is the camera altitude, b is the distance between principle points of the stereo pair, and p is the stereometer measurement of difference in parallax.

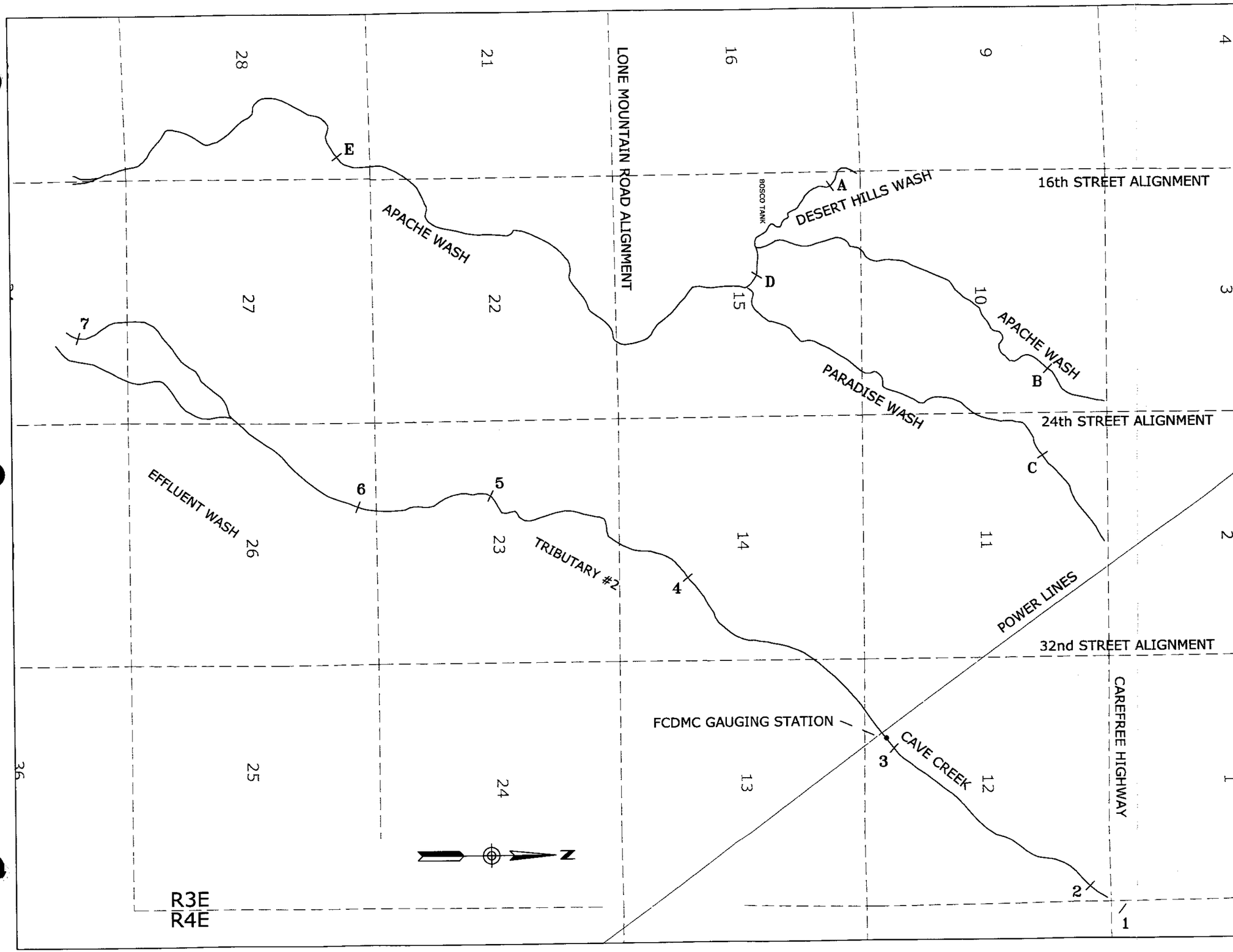
3. The camera altitude of each photo set was calculated based on the photo scale and camera focal length. The principle points of each photo in the stereo pair were then located and the photo distance (mm) between the two points was measured.
4. The left bank and right bank parallax on the 1999 photos were measured, the equation to determine bank heights was solved, and the measurements were compared to the bank heights indicated on the detailed topographic mapping. The comparison of two measurements gives an indication of photo measurement accuracy.
5. The left bank and right bank parallax of the corresponding cross section on the 1960 photos were then measured, the equation to determine bank heights solved, and those measurements were compared to the 1999 bank heights.
6. A summary of photo measurements, calculated bank heights, differences between photo-extracted bank heights and topographic map bank heights, and bank height change between 1960 and 1999 is shown in Table 3-15.

The location of the points of bank height estimates on Cave Creek (7 sections), Apache Wash (3 sections), Paradise Wash (1 section), and Desert Hills Wash (1 section) are shown in Figure 3-14.

Error Analysis. The detection of real change in bank heights is limited by the potential error of measurement associated with the photo extraction methods. This error must be considered when analyzing the bank height change. In most cases the photo-extracted heights were within three feet of the topographic map bank heights. There were two instances in which the difference between the topographic data and the photo-extracted measurement was almost six feet, and one instance in which the difference was greater than seven feet (Table 3-15). The results were used cautiously where the difference between the 1960 and 1999 bank heights was less than the associated error at that cross section.

Difference in scale between the 1960 and 1999 aerial photographs is another potential source for error. The 1999 photos were a larger scale (1:9,600) than the 1960 photos (1:24,000). Therefore, measurements made from the 1960 photographs have greater potential error.

Results. The results of measurements obtained from comparison of topographic mapping and from interpretation of aerial photographs are summarized in Table 3-15.



FLOOD CONTROL DISTRICT OF MARICOPA COUNTY

CAVE CREEK/APACHE WASH WATERCOURSE MASTER PLAN LATERAL STABILITY ASSESSMENT

FCD 97-45

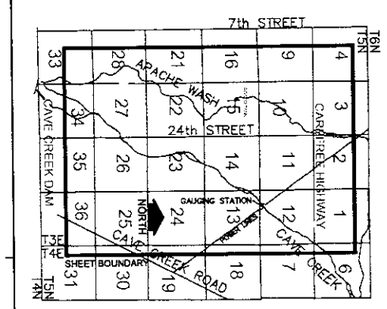
DECEMBER, 2000

LEGEND

1995 THALWEG

BANK HEIGHT ESTIMATE POINT B

INDEX MAP



SCALE IN FEET

1000' 0' 2000'

ASL Consulting Engineers

IN ASSOCIATION WITH

JE FULLER HYDROLOGY & GEOMORPHOLOGY, INC.

FIGURE 3-14

BANK HEIGHT ESTIMATE LOCATIONS

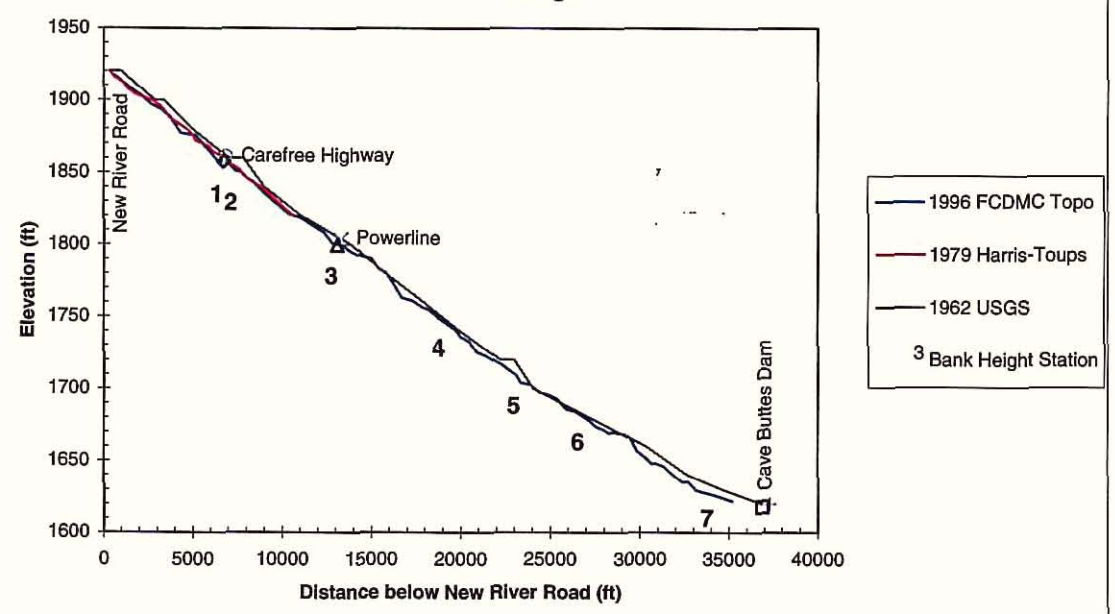
Table 3-15. Upper Cave Creek/Apache Wash Watercourse Master Plan. Stereo Photograph Extracted Bank Height Data, 1960-1999

Cross-Section	1999 Photo Measurements						1999 Bank Elevations (Photos)				1999 Photo / Topo Comparison			
	Scale RF	Focal Length (mm)	H (m)	B (mm)	Left Bank p (mm)	Right Bank p (mm)	Bank Height (m)		Bank Height (ft)		Left Bank Topo. Ht. (ft)[1]	Right Bank Topo. Ht. (ft)[1]	Left Bank Error (ft)[2]	Right Bank Error (ft)[2]
							Left	Right	Left	Right				
1	9600	153.025	1469	93.35	0.290	0.350	4.56	5.51	14.97	18.07	12	20	2.97	-1.93
2	9600	153.025	1469	93.35	0.200	0.510	3.15	8.03	10.33	26.33	9	19	1.33	7.33
3	9600	153.025	1469	90.42	0.650	0.180	10.56	2.92	34.65	9.59	36	11	-1.35	-0.91
4	9600	153.025	1469	99.06	0.440	0.180	6.53	2.67	21.41	8.76	24	12	-2.59	-3.24
5	9600	153.025	1469	93.47	0.170	0.390	2.67	6.13	8.77	20.11	10	14	-1.23	6.11
6	9600	153.025	1469	92.96	0.760	0.175	12.01	2.77	39.40	9.07	34	8	5.40	1.07
7	9600	153.025	1469	92.08	0.260	---	4.15	---	13.61	---	12	---	1.61	---
A	9600	153.025	1469	91.95	0.065	0.080	1.04	1.28	3.41	4.19	3	3	0.41	1.19
B	9600	153.025	1469	92.71	0.080	0.090	1.27	1.43	4.16	4.68	4	4	0.16	0.68
C	9600	153.025	1469	92.71	0.075	0.040	1.19	0.63	3.90	2.08	4	2	-0.10	0.08
D	9600	153.025	1469	91.95	0.080	0.080	1.28	1.28	4.19	4.19	4	4	0.19	0.19
E	9600	153.025	1469	93.73	0.100	0.060	1.57	0.94	5.14	3.09	6	4	-0.86	-0.91
Cross Section	**1960 Photo Measurements**						**1960 Bank Elevations (Photos)**				**Bank Height Change (1960 - 1999)[3]**			
	Scale RF	Focal Length (mm)	H (m)	B (mm)	Left Bank p (mm)	Right Bank p (mm)	Bank Height (m)		Bank Height (ft)		Left Bank Change (m)	Right Bank Change (m)	Left Bank Change (ft)	Right Bank Change (ft)
							Left	Right	Left	Right				
1	24000	153.63	3687	93.98	0.050	0.100	1.96	3.92	6.44	12.87	-2.60	-1.58	-8.54	-5.20
2	24000	153.63	3687	93.98	0.080	0.200	3.14	7.85	10.30	25.74	-0.01	-0.18	-0.03	-0.59
3	24000	153.63	3687	88.90	0.210	0.050	8.71	2.07	28.58	6.80	-1.85	-0.85	-6.07	-2.79
4	24000	153.63	3687	88.39	0.180	0.060	7.51	2.50	24.63	8.21	0.98	-0.17	3.23	-0.55
5_1[4]	24000	153.63	3687	94.74	0.100	0.100	3.89	3.89	12.77	12.77	*	-2.24	*	-7.34
5_2[4]	24000	153.63	3687	94.74	0.040	0.090	1.56	3.50	5.11	11.49				
6	24000	153.63	3687	94.74	0.300	0.060	11.68	2.34	38.31	7.66	-0.33	-0.43	-1.10	-1.41
7	24000	153.63	3687	94.74	0.140	---	5.45	---	17.88	---	1.30	---	4.27	---
A	24000	153.63	3687	91.69	0.050	0.040	2.01	1.61	6.60	5.28	0.97	0.33	3.19	1.08
B	24000	153.63	3687	88.39	0.025	0.030	1.04	1.25	3.42	4.11	-0.22	-0.17	-0.74	-0.57
C	24000	153.63	3687	88.39	0.030	0.025	1.25	1.04	4.11	3.42	0.06	0.41	0.21	1.34
D	24000	153.63	3687	91.69	0.050	0.045	2.01	1.81	6.60	5.94	0.73	0.53	2.40	1.74
E	24000	153.63	3687	90.42	0.050	0.025	2.04	1.02	6.69	3.34	0.47	0.08	1.55	0.26

1) Bank heights were extracted from HEC-RAS cross sections for Cave Creek FIS (Willdan), and topographic maps for study area (1995 FIS Mapping).
2) A positive value indicates the photo-extracted bank height was greater than the bank height on the topographic map. A negative value indicates the photo-extracted bank height was less than the bank height on the topographic map.
3) A positive value indicates a rise in stream bed elevation relative to the bank elevation (aggradation). A negative value indicates a drop in stream bed elevation relative to the bank elevations (degradation).
4) 4. 5_1,5_2. 5_1 refers to the main channel in 1960. 5_2 is a high flow channel in 1960 that corresponds to the main channel in 1999. See attached figures.

Cave Creek – Overview. Based on the bank height estimates shown in Table 3-15, and the comparison of reach topographic mapping summarized below, Cave Creek exhibited a trend toward net degradation from 1960 to 1999. Comparison of the data sets for the upper reaches of the Cave Creek study area allows better refinement of the chronology of vertical channel change. These data indicate that total degradation of up to 10 feet occurred between 1962 and 1996 in portions of the study area. However, because the 1979 elevations are closer to the 1996 data than they are to the 1962 data, it is assumed that degradation occurred at a much faster rate during the 18 year span from 1962 to 1979 than during the 17 year span from 1980 to 1996 (Table 3-15). Two reaches of Cave Creek above Carefree Highway experienced aggradation between 1980 and 1996. A graphical depiction of these data for Cave Creek is shown in Figure 3-15.

Figure 3-15. Location of Cave Creek Bank Height Estimate Points vs. Stream Length



Cave Creek at Carefree Highway. Detailed examination of available elevation data for Cave Creek at Carefree Highway reveals a sequence of streambed elevation changes summarized in Table 3-16.

Table 3-16. Upper Cave Creek/Apache Wash Watercourse Master Plan Vertical Channel Change – Cave Creek @ Carefree Highway Bridge, 1962-1997

Date	Source	Channel Elevation	Change (ft)	Comments
1962	USGS topographic map	1860	-	Interpolated between contours
1979	Harris-Toups FIS Worksheet	1856	-4 ft	Average degradation rate: 0.22 ft/year
1981	ADOT Engineering Drawings	1856	No change	Specified graded bed elevation
1996	FCDMC topographic map	1855	-1 ft	Average degradation rate: 0.06 ft/year
1997	ADOT Engineering Drawings	1854.3	- 0.7 ft	Degradation rate: 0.7 ft/year

The sequence of degradation documented in Table 3-16 supports the conclusion that degradation occurred at a faster rate prior to 1979. There are at least two probable causes of accelerated degradation prior to 1979: (1) a period of above-average flooding prior to 1979, and (2) in-stream sand and gravel mining at Carefree Highway. The USGS gauge Cave Creek near Cave Creek (#09512300) collected instantaneous *discharge* data from 1958 to 1967, and 1994 to 1999, and annual peaks from 1958 to 1999. Annual peak discharges can give some indication of the largest discharges that occurred in Cave Creek during the two time periods from 1962 to 1979 and from 1980 to 1996. Unfortunately, flow volume information cannot be extracted from the gauge record after 1967.

A ranking of the annual peak discharges from 1962-1996 reveals that of the 14 annual peak discharges greater than the 2-year recurrence interval (1780 cfs), nine occurred between 1962 and 1979. Five occurred between 1980 and 1996. Of the 20 annual peak discharges less than the 2-yr recurrence interval, nine occurred during the 1962 to 1979 period, and 11 occurred during 1980 to 1996. Five years between 1962 to 1996 saw no measured flows in Cave Creek; three of these years occurred during the 1980 to 1996 period, while two occurred during the 1962 to 1979 period. No data were collected during the 1980 water year.

Table 3-17. Upper Cave Creek/Apache Wash Watercourse Master Plan Cave Creek Flooding Relative to Period of Topographic Record

Distribution of Floods	1962-1979	1980-1996
Number of Annual Peak Q Events > 2-yr Q	9	5
Number of Annual Peak Q Events < 2-yr Q	9	11
% of Annual Peak Q Events > 2-yr Q occurring during period	64% (9 of 14)	36% (5 of 14)
% of Annual Peak Q Events < 2-yr Q occurring during period	45% (9 of 20)	55% (11 of 20)
% of Annual Peak Q Events during period > 2-yr Q	50% (9 of 18)	31% (5 of 16)
% of Annual Peak Q Events during period < 2-yr Q	50% (9 of 18)	69% (11 of 16)

As shown in Table 3-17, larger annual peak discharges tended to occur more often prior to 1980 on Cave Creek than after 1980. However, as summarized in Chapter 2 of this report, regional annual flow volumes (Figure 2-4) and annual precipitation totals (Figure 2-7) collected from nearby streamflow gauges and weather monitoring stations were generally higher from 1980 to 1996 than from 1960 to 1980. It is noted that data specific to the Cave Creek *watershed* is incomplete with respect to flow duration and frequency, two factors that likely affect channel changing processes. However, it is known that the 1978 flood had sufficient volume to pond water to within six inches of the top of Cave Creek dam, a condition that has not been repeated during its life span, even during the largest gauged peak and annual flow volume in 1993.

Human influence should not be dismissed as a cause of the accelerated long-term degradation during the 1962 to1979 period. In-stream mining activity by the Maricopa County Highway Department and Cave Creek Sand & Rock, Inc. (Stantec, 1999) immediately downstream of Carefree Highway that began in about 1962 and continued through 1984 could also account for the differences in measured degradation rate. Active in-stream mining near Carefree Highway stopped after 1984, although material continues to be stored in the overbank upstream of Carefree Highway. Around 1981, the bed of

Cave Creek was graded in conjunction with Carefree Highway bridge construction. Since 1981, the streambed elevation has remained fairly constant. A likely scenario is that the channel bed was lower due to in-stream sand and gravel mining, a trend which was exacerbated by the large floods of the 1970's. Extensive degradation caused the channel to partially *armor* itself, limiting further degradation. Cessation of mining activities has allowed the bed elevations to rebound or stabilize since the mid-1980's.

Downstream of Carefree Highway. Changes in the bed elevation between 1962 and 1996 also indicate net degradation, as shown in Table 3-16, although the data indicate that net aggradation occurred at the following three locations:

- Reach 2 – central part of the reach in a mildly braided section.
- Reach 3 – downstream of the abandoned Tanner sand and gravel mine.
- Reach 5 – downstream of the active Wheeler sand and gravel mine.

The cause of local aggradation in these reaches is not certain, but is probably related to channel widening, either artificially from in-stream mining, or from influx of tributary sediments from Cave Creek tributaries draining the distal portions of the McDowell Mountain piedmont.

Bank Height Estimates. Additional information to support the longitudinal profile data consists of bank height changes extracted from stereo aerial photos taken in 1960 and 1999. Seven locations along Cave Creek were analyzed for changes in bank heights (Figure 3-14 and 3-15). The average of the change in left bank height and right bank height is reported in Table 3-18. The results of the bank height analysis relative to the changes measured from topographic mapping are shown in Table 3-18.

Table 3-18. Upper Cave Creek/Apache Wash Watercourse Master Plan Cave Creek Bank Height Changes, 1960-1999

Site	Reach	HECRAS Section	1960-1999 Photo Change	1962-1996 Topo Change	Comments
1	SR	29.850	-6.9 ft	-7.8 ft	Agrees
2	1	29.710	-0.3 ft	-9.2 ft	Topo change much greater
3	1/2	28.657	-4.4 ft	-6.9 ft	General agreement
4	2	27.502	Left: +3.2 ft Right: -0.6 ft	-2.3 ft	Disagrees, opposite direction for left bank
5	3	26.695	-7.2 ft	-7.9 ft	Agrees
6	4	26.044	-1.3 ft	-1.7 ft	Agrees
7	5	26.646	+4.3 ft	-6.9 ft	Disagrees, opposite direction

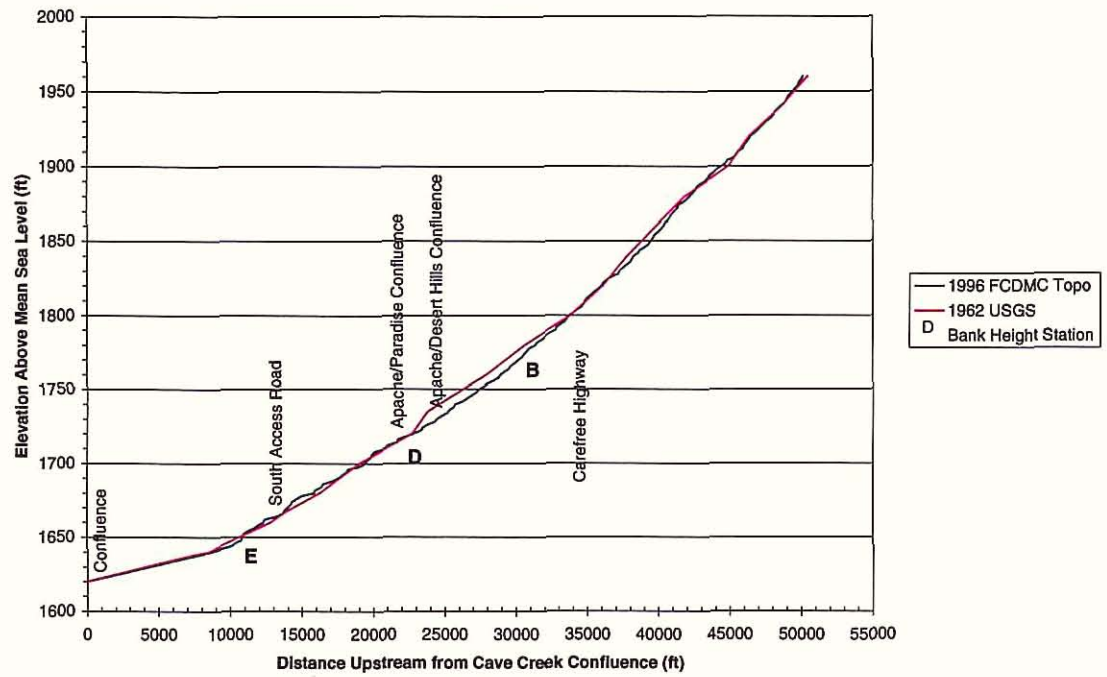
To use changes in bank heights to provide information on aggradation and degradation assumes that the upper bank elevation remains constant while the streambed moves up or down in elevation. To assure that the assumption that the upper bank level remained constant was reasonable, the bank heights were measured as the distance from the streambed to a surface that was interpreted as the lowest inactive terrace. In general, the results based on the photo and topographic data agree, with the topographic maps providing a slightly greater magnitude of degradation. Exceptions to the general

agreement include sites 2, 4, and 7. Sites 2 and 7 are located in areas of braiding or multiple channels. No definite cause for these discrepancies was identified, although possible causes could include the difference in record length, *scour* or fill occurring during floods not within the period of record of the topographic mapping, or simply the measurement error related to map or photograph scale and contour interval.

Archaeological Data. An irrigation canal dated to 1150 A.D. (Rodgers, 1998) is located on a terrace approximately 1,440 feet downstream of the Carefree Highway Bridge. The geomorphic surface in which the canal is cut is at an elevation of 1852 feet. The canal is cut approximately two feet into the surface, according to field observations, making the elevation for the canal bottom 1850 feet. Interpolation between contours on the 1996 topographic map places the streambed elevation near the canal head at 1843 feet. Based on these data, the streambed has dropped about 7 feet in 850 years, providing an annual average degradation of 0.008 feet/year. This average value may be misleading since degradation usually does not occur in regular annual increments, but rather in "pulses" during large flow events, periods of sustained high flows, or multiple years of above-average *discharge*. Archaeologists have theorized that such a pulse of channel degradation may have led to abandonment of the Cave Creek irrigated farm systems.

Apache Wash - Overview. Longitudinal profiles along Apache Wash from 1962 USGS topographic maps and 1990 FCDMC Floodplain Delineation Study (Jerry R. Jones, 1990; 1992) topographic maps (Figure 3-16) reveal mixed trends of degradation and aggradation. Upstream of Carefree Highway, net degradation occurred from 1960 to 1990. Degradation also occurred between Carefree Highway and the confluence with Paradise Wash and Desert Hills Wash, with the magnitude of degradation in this reach increasing in the downstream direction. According to the topographic mapping, the bed elevation dropped about 9.5 feet from 1962 to 1990 just upstream of the Apache Wash/Desert Hills Wash confluence, which translates to a *maximum* annual degradation rate of about 0.3 feet/year. This amount of total degradation is not supported by field evidence, although the field data do suggest a lower amount of total degradation (See Chapter 4 for a more complete discussion of field data).

Figure 3-16. Location of Bank Height Estimates vs. Stream Length



The average degradation rate from 1960 to 1990 for the entire reach was lower than for the reach above the Paradise Wash confluence. An average annual degradation rate for the entire wash was calculated by estimating elevation change along the longitudinal profile at 5,000 ft intervals through the study reach. Calculations indicate that the average elevation change was 1.23 feet of degradation, or an average annual degradation rate for Apache Wash of 0.04 ft/yr. over the 28 year period of record (1962-1990). However, it is noted that although the average rate indicates degradation, the actual measurements included five sampling points that experienced aggradation, five that experienced degradation, and one that had no change. An average value indicating degradation does, however, point out that the overall magnitude of degradation is greater than the overall magnitude of aggradation.

Net degradation has caused the longitudinal profile from the Apache Wash /Desert Hills Wash confluence to the Carefree Highway to develop a more concave form.[10] The topographic data indicate that the elevation of Apache Wash has remained relatively stable downstream of the Paradise Wash confluence in Reach 4. In Reach 5, the topographic data indicate that aggradation has occurred.

Apache Wash at Carefree Highway. The streambed at the Carefree Highway remained at a constant elevation from 1962 to 1997 (Table 3-19). Both the 1962 and 1990 topographic maps show the elevation at Carefree Highway to be approximately 1803 feet. ADOT engineering drawings dated 1997 show a streambed elevation of 549.7 m (1803.5

[10] A more detailed discussion of the longitudinal profile is provided in Chapter 4 of this report.

ft) at the Carefree Highway crossing. Taking into account the aforementioned 1.5 foot datum difference, the adjusted elevation would be approximately 1802 feet, although the actual required adjustment is uncertain.

Table 3-19. Upper Cave Creek/Apache Wash Watercourse Master Plan
Apache Wash – Measured Elevation Change at Carefree Highway

Date	Data Source	Elevation(ft)	Change	Comments
1962	USGS topographic map	≈ 1803		Interpolated between contours
1996	FCDMC topographic ma p	1803	No change	Long-term stability (34 years)
1997	ADOT Engineering Drawings	1802 (adj)	Degrade 1 ft	Uncertain datum

Whether the elevation did actually drop by approximately 1.0 feet in a one-year period is unlikely, given that grade control has been provided by a box culvert under Carefree Highway since 1984, and since the elevation did not appear to change in the previous 28 years.

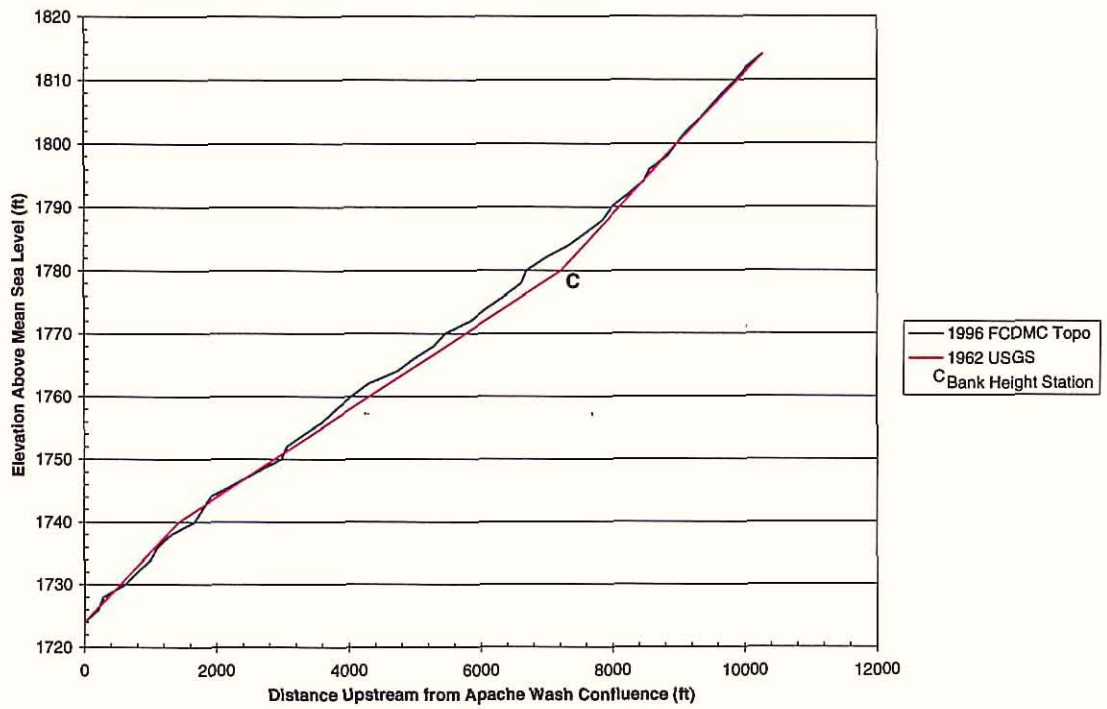
Bank Height Estimates. Bank height information was collected for three locations along Apache Wash, as shown in Table 3-20. The locations of the bank height estimates are shown in Figure 3-16. The elevation estimates obtained from the topographic maps tend to be larger than those extracted from the aerial photos. Location D is in a transition area where the channel changed from net degradation to net aggradation. Disagreement at location D may be due to local changes or the slightly different period of record. Field evidence suggests that the reach near location D has experienced recent degradation of one to four feet.

Table 3-20. Upper Cave Creek/Apache Wash Watercourse Master Plan
Apache Wash –Bed Elevation Change Estimated from Bank Height

Location	HEC-RAS Section	1960-1999 Photo Changes	1962-1996 Topo Changes	Comments
B	4.311	-0.7 ft	-4.0 ft	Topo indicates greater degradation
D	2.730	+2.1 ft	-2.0 ft	Disagree
E	0.430	+0.9 ft	+1.0 ft	Agree

Paradise Wash - Overview. Unlike Cave Creek and Apache Wash, topographic data show that Paradise Wash experienced slight aggradation or no significant change between 1962 and 1990 (Figure 3-17). The 1962 and 1990 topographic mapping indicates that approximately 2,000 feet upstream from the confluence with Apache Wash the stream aggraded. The maximum estimated aggradation was about 3.7 feet, at a point about 6,150 feet upstream of the Apache Wash confluence. These data result in a maximum aggradation rate of 0.1 feet/year. Downstream of the 2,000 feet mark, the stream has generally lowered its elevation.

Figure 3-17. Longitudinal Profile - Paradise Wash



Paradise Wash at Carefree Highway. Channel bed elevations near Carefree Highway remained fairly constant between 1962 and 1990, due in part to grade control provided by the box culvert constructed in 1984 (Table 3-21). Both the 1962 and 1990 topographic map data yield an elevation of 1814 feet at the Carefree Highway. Engineering drawings from 1997 report an elevation of 553.8 m (1816.9 ft). Taking into account the aforementioned datum change, the elevation in 1997 is adjusted to 1815.4 feet. It is unlikely that the bed elevation actually rose by about 1.5 feet from 1990 to 1997 given the presence of the concrete box culvert and the fact that the elevation apparently did not change in the previous 28 years.[11] At minimum, the data indicate a long-term trend of stability, with the potential for short-term fluctuations.

Table 3-21. Upper Cave Creek/Apache Wash Watercourse Master Plan
Paradise Wash – Elevation Data at Carefree Highway

Date	Data Source	Elevation	Change	Comments
1962	USGS Topographic Map	1814 ft		Elev'n interpolated betw. Contours
1990	FCDMC Topographic Map	1814 ft	No change	Long-term stability
1997	MCDOT Engineering Drawings	1815.4 ft (adjusted)	+1.4 ft	Possible survey or datum error?

Bank Height Estimates. Changes in bank heights at location C (Figure 3-17, Table 3-22) indicate that Paradise Wash aggraded about 0.8 feet between 1960 and 1999, somewhat less than the 3.0 feet indicated by the topographic data. However, the estimated change is

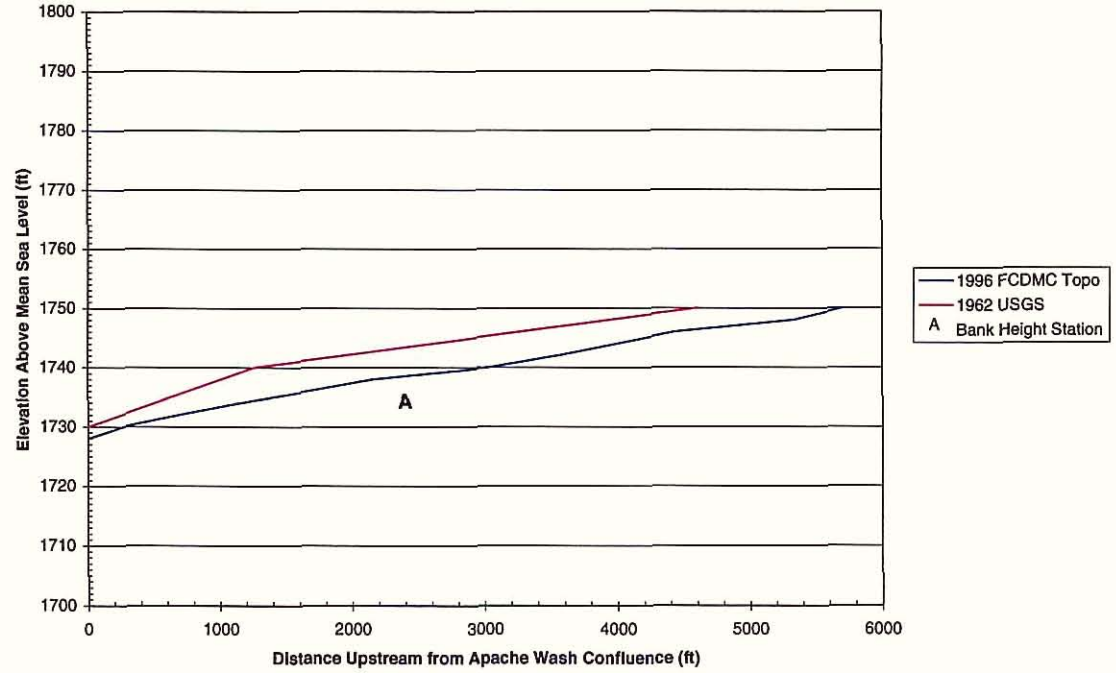
[11] Sediment deposition of about 0.5 ft. was observed in the upstream end of the Carefree Highway box culverts during the field visits.

in the same direction as the topographic data, is within the margin of expected error, and parallels the trend seen in Cave Creek and Apache Wash where the estimated bank height differences are less than mapping differences.

Table 3-22. Upper Cave Creek/Apache Wash Watercourse Master Plan Paradise Wash –Bed Elevation Change Estimated from Bank Height				
Location	**HEC-RAS Section**	**1960-1999 Photo Changes**	**1962-1990 Topo Changes**	**Comments**
C	1.46	+0.8 ft	+3.0 ft	Topo indicates greater degradation

Desert Hills Wash - Overview. Based on 1962 and 1990 topographic data, Desert Hills Wash has experienced degradation throughout its course within the study limits. Estimated degradation ranged from 2 feet near the Apache Wash confluence to about 5.8 feet at a point about 1,200 feet upstream of the confluence. Degradation of 5.8 feet over 28 years yields an average annual degradation rate of 0.2 feet/year. This rate is slightly lower than the rate experienced by Cave Creek at the Carefree Highway in the 17 year period between 1962 and 1979. If Desert Hills Wash has remained fairly stable (like Cave Creek) over the past 17 years and the degradation was concentrated between 1962 and 1979, then the average degradation rate increases to 0.3 feet/year, slightly higher than that experienced by Cave Creek.

Figure 3-18. Longitudinal Profile - Desert Hills



Bank Height Estimates. Changes in bank heights derived from aerial photographs at Location A (Figure 3-18, Table 3-23) indicated that the wash aggraded approximately 2 feet between 1960 and 1999. The bank height estimate based on aerial photographs

contradicts the data extracted from the topographic mapping. The difference in the estimates may be due to the different period of record, measurement errors associated with map scale and contour interval, or potential measurement error in stereoscopic air photo interpretation. Field evidence suggests that Desert Hills Wash has been subject to net degradation over the past 100 years.

Table 3-23. Upper Cave Creek/Apache Wash Watercourse Master Plan Desert Hills Wash –Bed Elevation Change Estimated from Bank Height

Location	HEC-RAS Section	1960-1999 Photo Changes	1962-1990 Topo Changes	Comments
A	0.480	+2.1 ft	-4.8 ft	Disagree

Vertical Channel Movement

Single Event Changes. No data were available from which to accurately quantify estimates of vertical channel change due to a single flow event. However, qualitative estimates of vertical changes could be made from field evidence and from interpretation of the 1991 to 1995 sequence of aerial photographs. The following types of information were observed:

- Scour holes. *Scour* holes ranging from 0.5 feet to more than 5 feet were observed in Cave Creek, Apache Wash, and Desert Hills Wash at sharp channel bends, at points where bedrock impinges on the main channel (Figure 3-19), and at the upstream noses of islands. Presumably, these scour holes formed during individual events, although they may form repeatedly in the same locations due to persistent hydraulic conditions.

Figure 3-19. Scour Hole in Reach 4 of Apache Wash.

- Deposition. Approximately two to three feet of deposition occurred in Cave Creek downstream of the mouth of Tributary #2 (Effluent Wash) after the August 17, 1998 event. The source of the material was the Tributary #2 *watershed*. The abrupt transition in channel pattern from a single channel to a multiple channel near the Tributary #2 confluence suggests that deposition has occurred continuously over recent geologic time.

- General Degradation. Interpretation of the 1993 to 1994 aerial photographs indicated that the right overbank flow path of Apache Wash at the Paradise Wash confluence was abandoned during the 1993 flood. The abandonment was interpreted to mean

that the left (main) channel deepened so that it could contain most of the 1993 flood *discharge* without spilling onto the floodplain.

- Clay Layer Depth. A clay-rich layer was observed in most of the soil test pits excavated in the main channels of all four streams in the study area (Figure 3-20). 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 a few inches in Desert Hills Wash to more than six feet in Cave Creek. Generally, the depth of the clay-rich layer increased in the upstream direction.

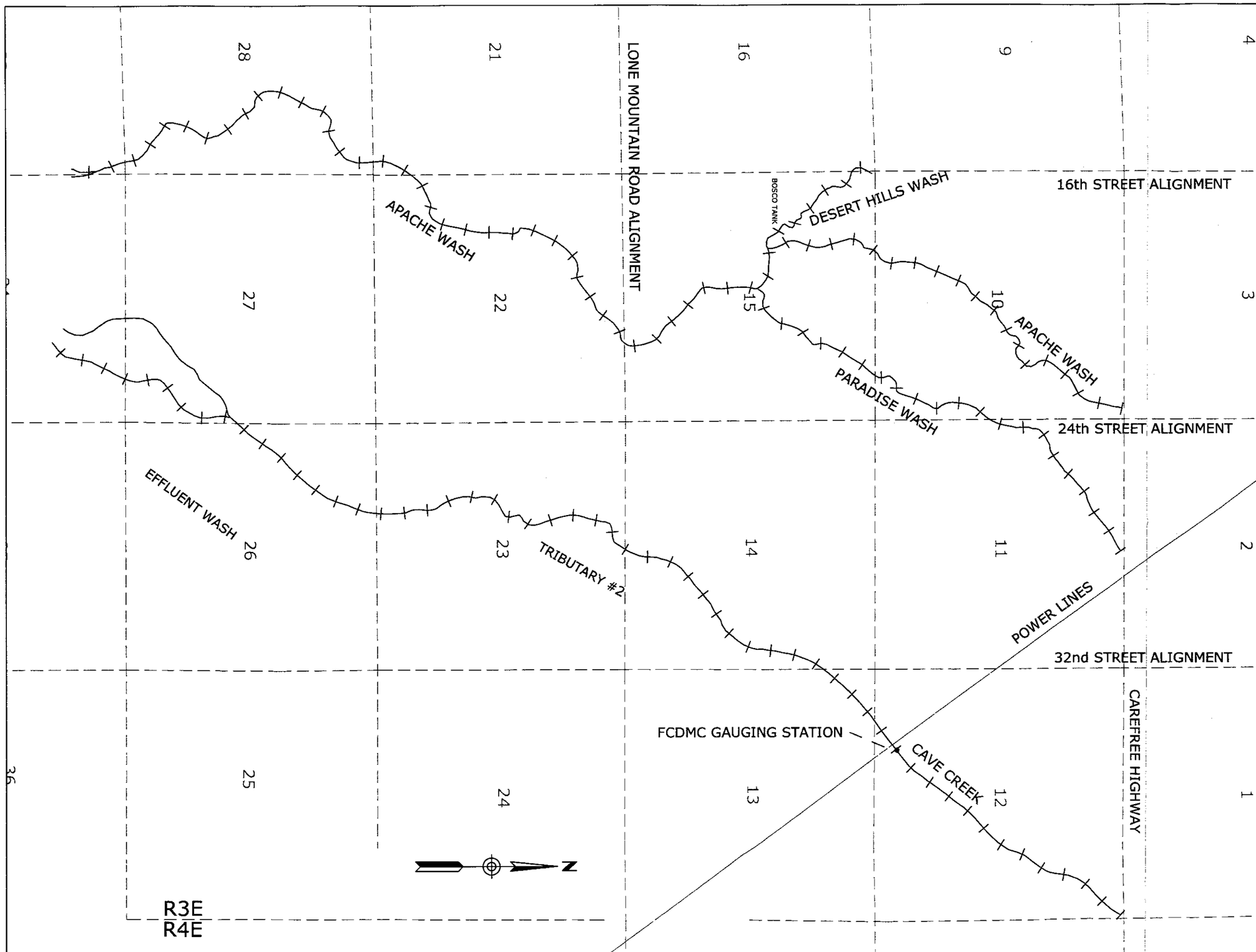
Figure 3-20. Subsurface Clay-Rich Layer

Channel Geometry

The geometry of a stream channel is defined by its width, depth, and overall shape. Historical changes in channel width and depth were measured from aerial photographs and topographic mapping. Changes in channel depth correspond to measured historical aggradation and degradation, and were presented in the previous section on bank height, longitudinal profile, and topographic mapping.

Channel Width. The channel width is defined as the distance between the primary stream banks. Channel widths measured on 1940, 1960, and 1999 aerial photographs of Cave Creek, Apache Wash, Paradise Wash, and Desert Hills Wash were used to estimate the amount of channel widening and/or narrowing during the period of record. In addition, channel widths recorded by GLO surveyors are presented, although the GLO data are not continuous and were available only where the streams crossed Township, Range, or section lines.

Methodology. The change in width between years of coverage was estimated by subtracting the channel width measured on the most recent photograph from the channel width measured on the older photograph. Thus, if the reported change was negative, the channel width decreased. If the change was positive, the channel width increased. To facilitate accurate comparison, measurements were taken at identical locations along the channel for each year of coverage. Measurements were taken in 500 foot increments along Cave Creek, and in 1,000 foot increments along Apache Wash, Paradise Wash, and Desert Hills Wash. The widths reported are the maximum channel widths, which include any islands or low floodplains located between major active channels. The width measurement sampling locations are shown on Figure 3-21.



FLOOD CONTROL DISTRICT OF MARICOPA COUNTY

CAVE CREEK/APACHE WASH
WATERCOURSE MASTER PLAN
LATERAL STABILITY ASSESSMENT

FCD 97-45

DECEMBER, 2000

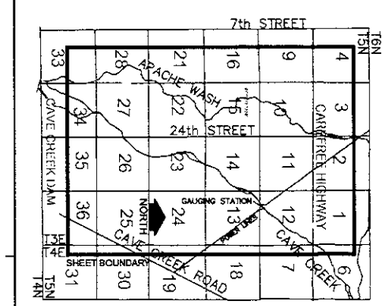
LEGEND

1995 THALWEG

WIDTH MEASUREMENT POINTS

Note: The location of the channel width measurment points shown on this figure are approximate; the actual locations may vary.

INDEX MAP



SCALE IN FEET

1000' 0' 2000'

ASL Consulting Engineers

IN ASSOCIATION WITH

JE FULLER HYDROLOGY & GEOMORPHOLOGY, INC.

FIGURE 3-21

WIDTH MEASUREMENT POINTS

Error Analysis. The smallest scale increment available for measuring the stream widths was 0.02 inches. For example, if the bank width was between increments 0.02 and 0.04 inches, the width could be estimated with confidence at 0.03 inches, greater than 0.03 but less than 0.04 inches, or less than 0.03 but greater than 0.02 inches. That works out to an accuracy of within 0.01 inches of the true width on a aerial photograph. The resulting measurement error, assuming that the aerial photographs are actually at their reported scale, is shown in Table 3-24. The largest error of two scales was used when comparing two different years of coverage. Thus, the maximum accuracy for the comparison was ±13 feet, the error of measurement from the 1940 photographs.

Table 3-24. Upper Cave Creek/Apache Wash Watercourse Master Plan Channel Width Change: Photo Dates Used and Measurement Error

Photo Date	Stream	Photo Scale	Estimated Measurement Error
1940	AW, PW, DHW	1:32000	± 27 ft.
1953	CC	1:28800	± 24 ft.
1960	AW, PW, DHW	1:24000	± 20 ft.
1962	CC	1:12000	± 10 ft.
1971	CC	1:28800	± 24 ft.
1984	CC	1:31680	± 26 ft.
1996	CC	1:12000	± 10 ft.
1999	AW, PW, DHW	1:9600	± 16 ft.

Notes:
AW = Apache Wash; PW = Paradise Wash; DHW = Desert Hills Wash; CC = Cave Creek

Bank vegetation occasionally obscured the tops of the banks on the aerial photographs, making it difficult to accurately measure the channel widths, introducing an additional source of error into the measurements. In such instances, the bank position was interpolated between open bank areas upstream and downstream of the delineated cross section.

Results. Historical changes in channel width estimated from aerial photographs are a useful way to calibrate predictions of future channel movement. Where the photographic record indicates that channels have been stable or have narrowed, mathematical models that predict excessive widening for similar flow conditions should be interpreted cautiously. Conversely, where historical data indicate that the channel banks have been susceptible to erosion, future erosion may be expected unless some condition exists that provides increased stability.

Cave Creek. Measurements of historical channel width for Cave Creek are summarized in Table 3-25, and are illustrated in Figure 3-22. In general, the average channel width in the study area increased from 1894 to 1996, with a slight decrease from 1984 to 1996. Within the study reach, the channel width tends to increase in the downstream direction, although this trend became more pronounced after 1971.

Table 3-25. Upper Cave Creek/Apache Wash Watercourse Master Plan Reach-Averaged Channel Width Measurements from Historical Aerial Photographs Cave Creek (ft)						
Reach	**Year of Coverage**					
	1894	**1953**	**1962**	**1971**	**1984**	**1996**
Supply	-	524	461	201	144	278
1	224	220	247	150	79	227
2	132	119	153	182	147	159
3	178	139	83	190	299	303
4	198	113	114	1046	1267	219
5	198	504	577	262	776	800
Reach Average	186	270	272	338	452	331
Note: 1894 data obtained from GLO survey notes - may represent only a single measurement, and may be significantly skewed from perpendicular width.						

Reach specific trends included the following:

- Reach 1 – Narrowing. Despite a regional trend toward channel widening, Reach 1 narrowed by a factor of about three from 1894 to 1984. Most of the narrowing occurred after 1962, when the reach was being mined for sand and gravel. After 1984, when in-stream mining ceased, the channel recovered almost all of its pre-mined width. The trend of narrowing is often paired with channel incision, which was observed in Reach 1, as described in a previous section of this Chapter.

- Reach 2 – Stability. The total range of measured historical channel widths is about the same as the estimated error of measurement. Field observations and estimates of long-term vertical change support the width data that indicates stability.

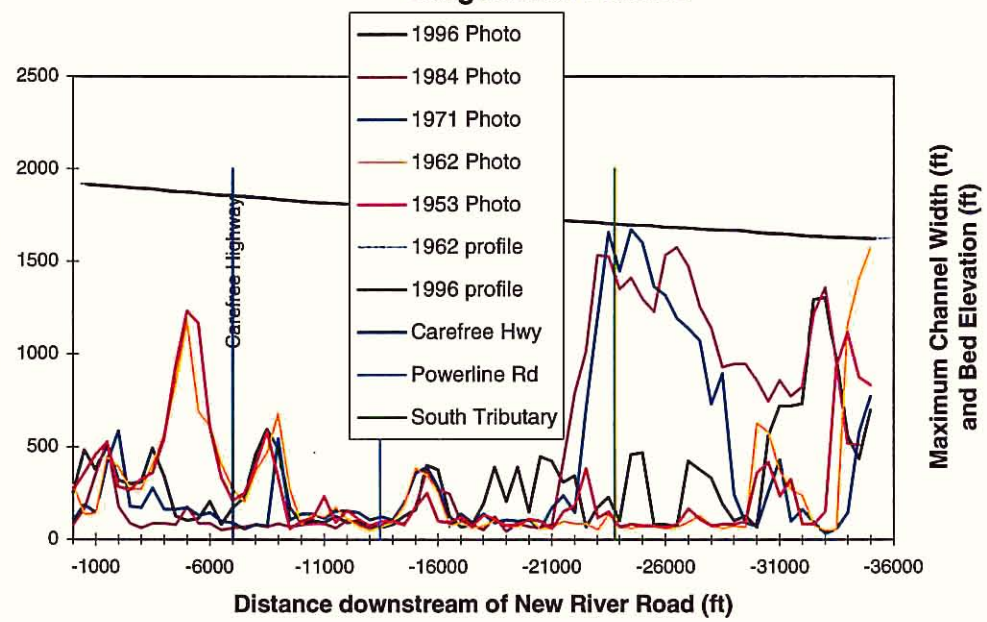
- Reach 3 – Net Widening. Despite an apparent trend toward narrowing in Reach 3 from 1894 to 1962, widening from 1962 to 1996 created a net increase in channel width. The 1996 width is almost four times the 1962 channel width. Reach 3 was artificially widened by in-stream sand and gravel mining, although mining cannot explain widening that occurred prior to 1984. Relict features observed on the floodplain in Reach 3 indicate that in prehistoric times, a multiple channel pattern similar to Reach 5 existed in Reach 3 that probably left it susceptible to formation of split channels which extended over a greater portion of the floodplain.

- Reach 4 – Extreme Widening. The width of Reach 4 increased by an order of magnitude between 1953 and 1984 due to the development of a multiple channel pattern that occupied most of the geologic floodplain. The multiple channel pattern is probably due in part to excessive sediment deposition from Tributaries #1 and #2. After 1984, the channel was narrowed artificially due to construction of a bypass channel around the Wheeler sand and gravel mine in 1996.

- Reach 5 – Widening. Reach 5 has had the widest channel area in the study reach during the entire period of record. The large width is due primarily to the distance

between the numerous flow paths in the multiple channel area. The width of the multiple channel corridor has increased by about 50 percent since 1953. GLO survey data may indicate that this multiple channel pattern did not exist or was less strongly developed prior to 1900.

Figure 3-22. Cave Creek Maximum Channel Width and Longitudinal Profiles



Apache Wash System. Measurements of historical channel width for Apache Wash, Paradise Wash, and Desert Hills Wash are summarized in Table 3-26, and are illustrated in Figures 3-23 to 3-25. In general, the average channel width in these three streams decreased from 1940 to 1999. Within the study reach, the width of Apache Wash increases slightly in the downstream direction. The widths of Paradise Wash and Desert Hills Wash are essentially unchanged with stream length. The average measured width changes are well within the limits of the measurement error for the aerial photographs. Therefore, no definitive conclusions regarding trends of channel change can be drawn from any apparent historical changes in width. Overall, the record indicates that the average widths of the three streams has been very stable for the past 60 years.

Table 3-26. Upper Cave Creek/Apache Wash Watercourse Master Plan Reach-Averaged Channel Width Measurements from Historical Aerial Photographs Apache Wash, Paradise Wash, Desert Hills Wash (ft)				
Reach	**Year of Coverage**			
	1894	**1940**	**1960**	**1999**
Apache Wash				
1	-	-	47	33
2	-	33	30	23
3	-	44	40	35
4	211	56	80	56
5	-	50	48	35
6	165	50	68	73
Average	-	47	52	43
Paradise Wash				
PW – SR	-	-	30	36
1	-	36	38	29
Average	-	36	34	33
Desert Hills Wash				
DHW – SR	284	22	19	17
1	284	24	24	24
Average	-	23	21	21

Notes:
1. Apache Wash, Reach 6 also surveyed in 1867 at 106 ft. wide
2. 1894 data obtained from GLO survey notes - may represent only a single measurement, and may be significantly skewed from perpendicular width.

Figure 3-23. Apache Wash - Change in Historical Channel Width, 1940-1999

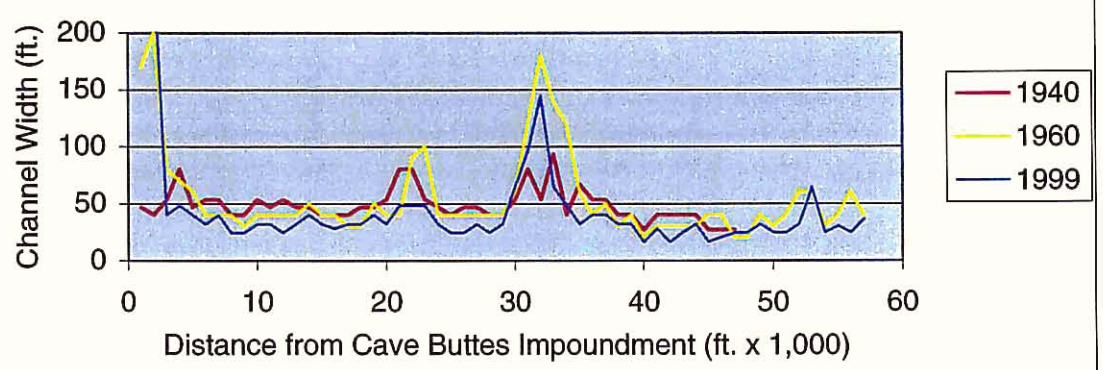


Figure 3-24. Paradise Wash - Change in Historical Channel Width, 1940-1999

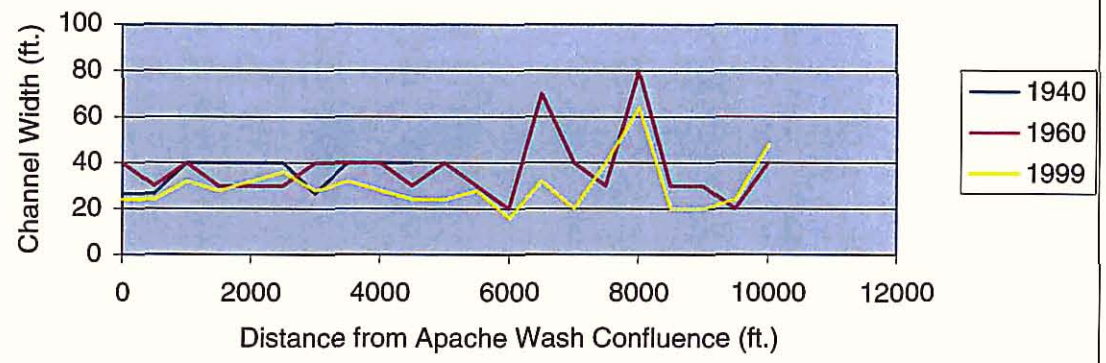
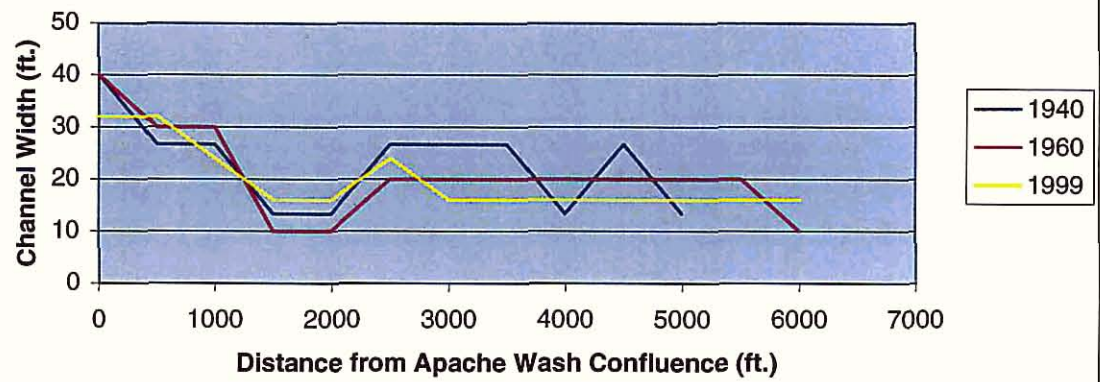


Figure 3-25. Desert Hills Wash - Change in Historical Channel Width, 1940-1999



Width measurements for individual cross sections are provided in Appendix C. These data indicate that width adjustments occurred at specific areas such as sharp channel bends, where *avulsions* redirected floodwater, and where new channels formed. The areas of greatest width changes (instability) were at the split flow areas that look like low islands in the aerial photographs. A second area of increasing channel width was near the Cave Buttes impoundment area, where deposition has decreased channel capacity.

Channel Depth. Changes in channel depth were summarized in the discussion on long-term vertical channel changes (Tables 3-19 to 3-23). In general, the main channels of Cave Creek and its tributaries have become deeper throughout the study area. The combination of greater channel width and depth have increased the channel capacity significantly during the period of record. The implications of the increased channel capacity will be discussed in more detail in Chapter 4 of this report.

Channel Planform

Channel *planform* includes the physical characteristics of a stream when observed in a map view. Historical changes in channel planform were documented by comparing historical maps and aerial photographs. Two characteristics of channel planform were measured, sinuosity and channel pattern.

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 3-27. Measurements of sinuosity for Cave Creek for each of the periods of photographic record are shown in Table 3-28.

Table 3-27. Upper Cave Creek/Apache 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 3-28, most of Cave Creek is straight and has been since at least 1940. Any changes in sinuosity implied by the data in Table 3-28 are not discernable when the data are reduced to two significant figures. There has been no consistent trend in the value of the channel sinuosity since 1940. The sinuosity of Cave Creek increases slightly in the downstream direction, although measures of sinuosity are not typically applied to the braided and multiple channel patterns present in Reaches 4 and 5.

Table 3-28. Upper Cave Creek/Apache Wash Watercourse Master Plan Historical Change in Channel Sinuosity – Cave Creek

Reach	1940	1953	1962	1971	1984	1991	1993	1994	1995	1996
1	-	1.02	1.06	1.02	1.02	1.04	1.04	1.02	1.02	1.02
2	-	1.02	1.02	1.02	1.03	1.03	1.04	1.02	1.03	1.03
3	1.07	1.01	1.03	1.00	1.00	1.00	1.09	1.01	1.06	1.03
4	1.03	1.08	1.09	1.09	1.08	1.09	1.09	1.07	1.09	1.10
5	1.22	1.23	1.33	1.21	-	-	-	-	-	1.18

No significant variations in the sinuosity of Apache Wash or its tributaries were observed in the historical records. Plots of historical channel position and channel width shown in the figures presented in this chapter (cf Figures 3-1 and 3-12) indicate minimal measurable change in channel pattern. Therefore, only the average sinuosity values are listed in Table 3-29.

Table 3-29. Upper Cave Creek/Apache Wash Watercourse Master Plan Sinuosity of Apache Wash, Paradise Wash, & Desert Hills Wash	
Stream	**Sinuosity**
Apache Wash	1.07
Paradise Wash	1.08
Desert Hills Wash	1.12

Channel Pattern. Plots of channel position are shown in Figure 3-13 as discussed previously. These plots of channel position indicate that the overall channel pattern has not changed within the period of historical aerial photographs and maps. GLO survey notes could be interpreted to indicate that Cave Creek shifted from a single channel pattern to a multiple channel pattern in Reaches 4 and 5 sometime between 1894 and 1940. Archaeological data have been interpreted to indicate that the Reaches 1, 2 and 3 of Cave Creek may have changed from a shallow, single channel with frequent overbank flooding to a more *incised* channel pattern with rare floodplain flows, although no change in the channel pattern is required to allow such a change.

Field Evidence of Historical Channel Change

A record of historical channel change is sometimes preserved in the physical characteristics of the 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:

- Degradation. Field evidence of historical channel degradation included archaeological artifacts dating to circa 1100 A.D. unburied on the floodplain (Figure 3-26), undercut and vertical channel banks, impassable farm road crossings, perched abandoned channels, and young floodplain soil units.

Figure 3-26. Hohokam Field Borders Along Cave Creek.

- Channel Pattern. Field evidence suggests that the channel pattern has not changed significantly during the historical period, with the exception of the mined areas of Reaches 3 and 4 of Cave Creek. Topographic features and soil conditions in the floodplain adjacent to the main channel in Reaches 3 and 4 suggest that an avulsive multiple channel pattern used to exist prior to sand and gravel mining. The floodplain

features are distinctly different than the overbank features in Reaches 1 and 2 of Cave Creek, but are very similar to the floodplain characteristics of Reach 5.

- Sand and Gravel Mining. Evidence of historical sand and gravel mining was observed in Cave Creek, but not in Apache Wash or its tributaries. The most prevalent evidence of historical mining included the numerous piles of mining by-products, especially boulders, stored along the channel banks or on the floodplain (Figure 2-17). Other evidence of mining included the excavations themselves, artificially widened stream reaches, access roads, and abandoned equipment or structures (Figure 3-27 and 3-28). A soil pit excavated in a former in-stream pit exposed uniform layers of coarse gravel that was unlike any of the material in any other soil pit in the study area, and probably represented post-excavation flood infill (Compare Figure 3-29 and 3-30).

Figure 3-27. Historical Mining Debris on Cave Creek near Carefree Highway.

Figure 3-28. Wheeler Excavation During Summer of 1998.

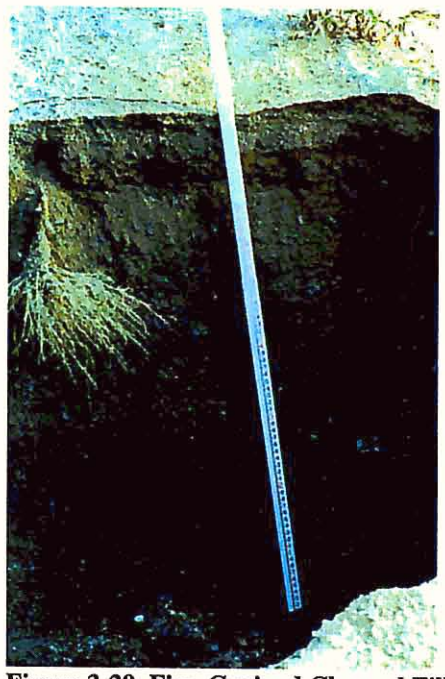


Figure 3-29. Fine-Grained Channel Fill in Cave Creek Channel Pit in Reach 3.

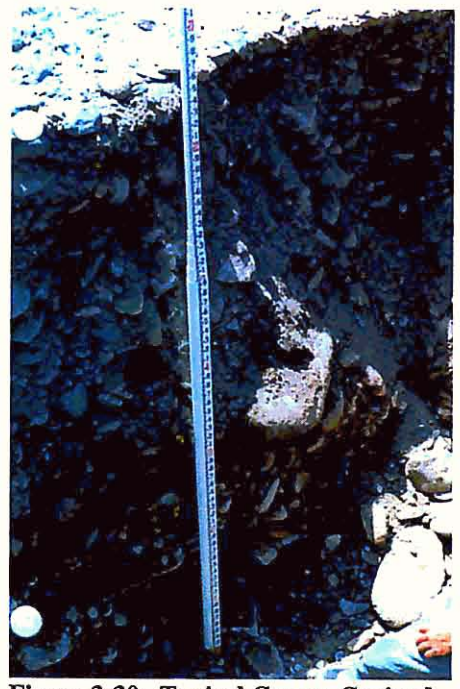


Figure 3-30. Typical Coarse-Grained Channel Fill in Cave Creek.

- Bank Erosion. Bank erosion occurred throughout the period of historical and prehistoric record. Field evidence of bank erosion (Figure 3-31 and 3-32) included a fence post hanging from the eroded cliff along Cave Creek, exposed roots of trees growing along the banks of all the streams, unstable fresh *cut banks*, and impassable farm road crossings. Field observations by archaeologists indicate the Hohokam also battled lateral channel movement during their period of occupation.

Figure 3-31. Hanging Fence Post on Cave Creek Cliff Bank in Reach 4.

Figure 3-32. Tree Roots Exposed by Lateral Erosion on Apache Wash.

- 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. More recently, portions of the Desert Hills Wash watershed upstream of the State Trust Land boundary have been converted to residential and suburban use with

no grazing. The contrast in channel conditions illustrated in Figures 3-33 and 3-34 indicates the type of channel impacts from grazing observed in the study area. Ungrazed banks are better vegetated and have lower side slopes with fewer *cut banks*.

Figure 3-33. Desert Hills Wash in Stream Reach Subject to Grazing.

Figure 3-34. Desert Hills Wash in Stream Reach Not Subject to Grazing.

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

Historical Descriptions of Channel Conditions

Few descriptions of Cave Creek and its tributaries were found in the literature search and data collection phase of the project. This lack of data probably reflects the lack of water in the study area during the last 100 years, since the early history of central Arizona is concentrated around reliable water sources.

Field notes from the 19th century surveys by the General Land Office (GLO; Martineau, 1894) provided the only historical descriptions of channel conditions in the study area, and those notes include very few descriptions of the channel compared to GLO survey notes for other Arizona streams. The few descriptions found are summarized as follows:

- "Dry wash" – This term was used at all the crossings of every stream within the study area. No flowing water was encountered. A GLO survey conducted during the month of February 1916 listed several springs, as well as flowing water in Cave Creek upstream of New River Road.
- "Left bank 35 foot perpendicular bank" – This phrase was used to describe Cave Creek at the Section 23/26 boundary in 1894. This cliff is still present today in Reach 4 of the study area.
- "Deep wash" – This phrase was used to describe Apache Wash at the Section 15/22 boundary (Reach 3) in 1894. The existing bank at this location is approximately 20 feet high.
- "Dense brush" – This phrase was used to describe Apache Wash at Sections 21/22, 27/28, 33/34 in 1894. Dense catclaw and hackberry characterized the banks of Apache Wash in Reaches 5 and 6 today.

These descriptions are not very revealing, but indicate that overall channel conditions were not significantly different than channel conditions today, except in areas of obvious human disturbance.

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 in the study area occurred in Reaches 1, 3, and 4 of Cave Creek, as well as in the *Supply reach* for Cave Creek upstream of Carefree Highway. The typical response to in-stream sand and gravel mining is channel degradation and increased lateral instability (ADOT, 1985).

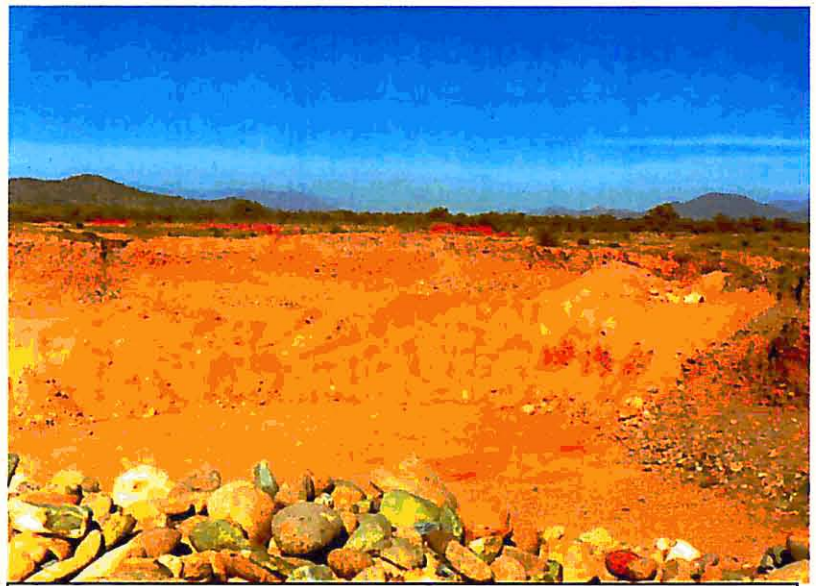


Figure 3-35. Wheeler Sand & Gravel Mine on Cave Creek.

- Cattle Grazing. The entire study area was been 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 (c.f., Hereford, 1984), ranging from no measurable impact to a significant increase in erosion hazard. Grazing impacts observed in the study area included minor hoof damage to stream banks (Figure 3-36), cutting trails on bank slopes, construction of fences across channels, and removal of floodplain and bank vegetation.

Figure 3-36. Channel Banks Damaged by Cattle. Right Bank of Apache Wash in Reach 4. Similar Evidence of Hoof Damage Observed Throughout Study Area.

- Road & Bridge Construction. The Carefree Highway, which forms the upstream limit of the study area, is the only paved road near or in the study area. Carefree Highway was not paved until about 1960. Improved drainage crossings over Apache Wash and Paradise Wash were not constructed until about 1984. Therefore, the impact of the Carefree Highway was probably minimal prior to 1980. Since 1980, no significant long-term impacts due to the road crossings were observed, except for minor sedimentation upstream of the undersized culvert crossings on Apache Wash and Paradise Wash at the Carefree Highway.

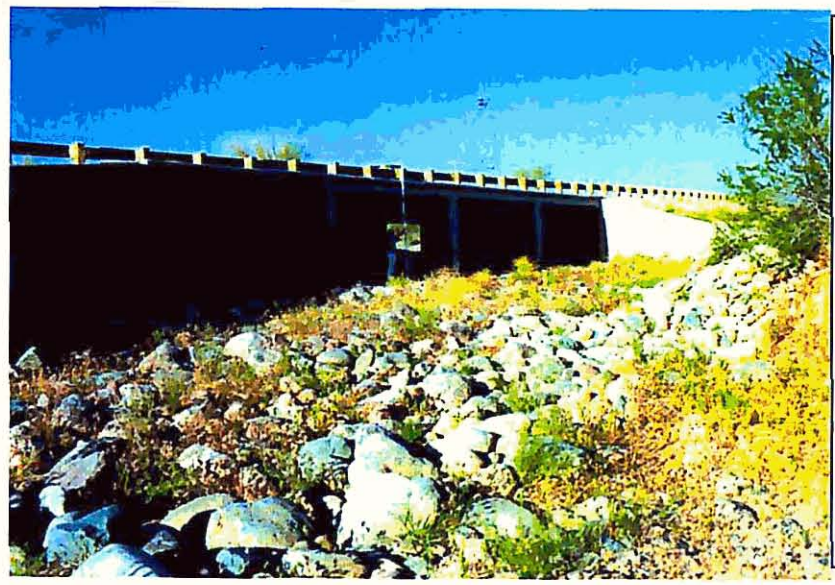


Figure 3-37. Looking Upstream at Box Culvert on Paradise Wash at Carefree Highway and Dumped Rip Rap Scour Protection.

- Dam Construction. Cave Creek Dam was constructed in 1923. Cave Buttes Dam was constructed in 1979. These dams store significant volumes of flood water and trap most of the sediment supplied through the study reach. The impact of this sedimentation has been limited to aggradation in the impoundment area (Reach 6 of

Apache Wash and Cave Creek). Excavation of borrow material for Cave Buttes Dam changed the channel boundaries of Cave Creek in Reach 6.

- Stock Tanks. Bosco Tank, which was constructed prior to 1953, is the only on-line stock tank in the study limits. The north spillway for Bosco Tank was destroyed by 1960, resulting in a realignment of Desert Hills Wash. Numerous other stock tanks were constructed within the watershed. 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 located within National Forest land. The remainder of the watershed is either suburban ranch land or low-density residential. 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 100 years, and suggests the types of channel change that can be expected in the future. Archaeological data collected along Cave Creek imply that channel erosion has affected the Cave Creek stream corridor for more than 1,000 years. During the period of Hohokam occupation, Cave Creek changed from an *intermittent* channel with frequent shallow overbank flooding to an *incised* braided stream that rarely inundated its floodplain. These data indicate that the erosion documented during the historical period is not simply the result of recent human impacts on the channel and *watershed*. Natural cycles of stream degradation and lateral migration must be accounted for in the watercourse management plan.

The earliest historical records, GLO survey notes and plat maps, indicate that Cave Creek generally moved towards the west and north between 1894 and 1981, with varying degrees of magnitude. The greatest magnitudes of lateral movement on Cave Creek occurred in the downstream parts of the study reach. The GLO data document apparent channel *avulsions* on Cave Creek and Apache Wash in which the channel moved up to 1,278 feet across the floodplain. The magnitude of accretive erosion on Cave Creek and Apache Wash was significantly less, with lateral moves ranging from 4 to 82 feet between 1894 and 1981. The evidence of large lateral avulsions in the past serves as a warning of the potential for future changes.

Comparison of historical maps and aerial photographs indicate that Cave Creek has been subject to both accretive and avulsive lateral movement during the past 50 years. Gradual accretive erosion averaged less than one foot per year in the study area, but avulsions caused shifts of more than 1,000 feet. Paradise Wash and Desert Hills Wash were more stable laterally than Cave Creek or Apache Wash during the period of record. Comparison of digitized channel positions before and after the 1993 flood, indicated avulsions can occur during a flood with a 25-year recurrence interval. Accretive erosion during the 1993 was minimal in most of the study reach, although field evidence suggests

that local bank failures occurred at channel bends or along unvegetated banks throughout the study reach.

Comparison of channel elevations obtained from topographic mapping and aerial photographs indicates that Cave Creek exhibited a trend toward net degradation from 1960 to 1999. Total degradation of up to 10 feet occurred between 1962 and 1996 in portions of the study area, primarily in areas of in-stream sand and gravel mining. Degradation occurred at a much faster rate during the 18 year span from 1962 to 1979 than during the 17 year span from 1980 to 1996. Mixed trends of degradation and aggradation occurred along Apache Wash, with an estimated maximum annual degradation rate of about 0.3 feet/year. Topographic data show that Paradise Wash generally experienced slight aggradation or no significant change between 1962 and 1990, with a maximum aggradation rate of 0.1 feet/year. Desert Hills Wash has experienced degradation at an average rate of about 0.2 feet/year within the study limits.

The average channel width of Cave Creek in the study area increased from 1894 to 1996, with a slight decrease from 1984 to 1996. Within the study reach, the channel width tends to increase in the downstream direction, although this trend became more pronounced after 1971. The average channel width in Apache Wash, Paradise Wash and Desert Hills Wash decreased slightly from 1940 to 1999, although overall the record indicates that the average widths of the three streams has been stable for the past 60 years. No significant change in channel sinuosity was noted on any of the streams in the study area during the period of historical record. Plots of historical channel position indicate that the overall channel pattern has not changed within the period of historical aerial photographs and maps, although GLO survey notes could be interpreted to indicate that Cave Creek shifted from a single channel pattern to a multiple channel pattern in Reaches 4 and 5 sometime between 1894 and 1940.

Historical descriptions of the streams obtained from GLO survey notes indicate that overall channel conditions were not significantly different than channel conditions today, except in areas of obvious human disturbance.

Chapter 4
Lateral Stability Assessment: Geomorphology

Introduction

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

- Field assessment techniques
- Geomorphic mapping
- Geomorphic assessment techniques

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 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. These personnel represented the various state and local agencies participating in the project, as well as the firms that comprised the consultant team.

- Detailed field investigations. These trips were conducted by the JEF project 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 1,000-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 4-1. Copies of the field notes and photographs, a log of field photographs, and a summary of field data are provided in Appendix B.

- Detailed soil investigations. These trips were also conducted by the JEF project geomorphologists, and consisted of examination and description of 44 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 B.

- Follow-up trips. Several additional field tours were conducted to present field findings to the rest of the project team.

- Flood visits. A series of moderately large summer thunderstorms caused a small flood on Cave Creek and its tributaries on July 15, 1999. JEF, Inc. staff visited the study area during the flood to document and observe channel conditions during this rare flow event. Some of the photographs from this field trip are shown in Figures 4-2 to 4-5. The entire photograph log from the trip is provided in Appendix B.

Figure 4-2. July 15, 1999 Flood on Apache Wash, Reach 4.

Figure 4-3. July 15, 1999 Flood at Apache/Paradise Confluence.

Figure 4-4. July 15, 1999 Flood on Desert Hills Wash Downstream of Bosco Tank.

Figure 4-5. July 15, 1999 Flood – Cave Creek Reach 4 at Wheeler Access Road.

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 4-1 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 B. Locations of field cross section (e.g., P-9K, AW-1000), soil test pits (e.g., 19LOB1, AW-CHL), and other field features are shown on Exhibit 1.

CAVE CREEK WATERCOURSE MASTER PLAN
FIELD CHECK LIST - GEOMORPHOLOGY
CHANNEL CHARACTERISTICS

CHANNEL LOCATION:	
DATE:	TIME: (BEGIN/END)
FIELD CREW:	
RECORDS CHECK BY: (NAME, DATE)	

NOTE: EVERY GEOMORPHIC CHARACTERISTIC NOTED ON FORMS SHOULD BE PHOTOGRAPHED

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

NOTES: ***INCLUDE SCALE IN ALL PHOTOGRAPHS***
PLOT PHOTO LOCATION AND ASPECT ON TOPO

DATA TYPE	STILL PHOTOGRAPH	CAMCORDER
LEFT BANK (SURVEY ROD FOR SCALE) LOOKING DIRECTLY AT BANK LOOKING UPSTREAM ALONG BANK LOOKING DOWNSTREAM ALONG BANK		
LEFT BANK BLOW COUNT		
RIGHT BANK (SURVEY ROD FOR SCALE) LOOKING DIRECTLY AT BANK LOOKING UPSTREAM ALONG BANK LOOKING DOWNSTREAM ALONG BANK		
RIGHT BANK BLOW COUNT		
INTERMEDIATE BANKS		
INTERMEDIATE BANKS		
BED MATERIAL - CLOSE UP		
BED MATERIAL - ENTIRE CHANNEL		
NOTABLE FEATURES: (LIST)		

3. PLOT CROSS SECTION LOCATION

☐ ON USGS QUADRANGLE _____(NAME)

☐ ON RECENT AERIAL PHOTOGRAPH _____(NUMBER)

☐ ON FCDMC TOPOGRAPHY _____(SHEET #)

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

2. DESCRIPTION OF CROSS SECTION CHARACTERISTICS		
☐ BANK VEGETATION		☐ PHOTOGRAPH
ROOT MAT		
CANOPY (HEIGHT, DENSITY)		
PERCENT OF BANK COVER		
APPROXIMATE AGE		
☐ CHANNEL VEGETATION (TYPE & PERCENT COVER)		☐ PHOTOGRAPH
☐ *ARMORING* POTENTIAL		
☐ VISUAL ESTIMATE OF D50 D90 _____ D10_____		☐ PHOTOGRAPH
☐ SEDIMENT SHAPE (DOMINANT CLASTS – ROUND, OBLONG, FLAT, ANGULAR, SUBANGULAR)		
☐ BANK EROSION SIGNS (PLOT LOCATION ON CROSS SECTION SKETCH, PHOTOGRAPH, EXTENT)		
	LEFT BANK	RIGHT BANK
CUT BANKS	☐	☐
VERTICAL BANKS	☐	☐
UNDERCUT BANKS	☐	☐
TENSION CRACKS	☐	☐
EXPOSED ROOTS	☐	☐
VEGETATION REMOVED FROM BANKS	☐	☐
VEGETATION TIPPED	☐	☐
PILES OF DIRT AT BANKS	☐	☐
POINT BAR UNDER BRIDGE	☐	☐
PIPING	☐	☐
RILLING OF BANKS	☐	☐
ISLANDS OR BARS (U/S-D/S)	☐	☐
CRITICAL BANK HEIGHT (HG)	☐	☐
SUMMARY (STABLE/UNSTABLE)	☐	☐
☐ BANK MATERIAL: COHESIVE? NON-COHESIVE? COMPOSITE? WEAK/STRONG?		
☐ BANK FAILURE MECHANISM: GRAIN-BY-GRAIN EROSION? MASS-WASTING? SKETCH:		
☐ CHANNEL PATTERN		☐ PHOTOGRAPH
☐ TRIBUTARIES NEARBY?		☐ PHOTOGRAPH
☐ BANKFULL CHARACTERISTICS (VELOCITY, DEPTH, TOPWIDTH)		☐ PHOTOGRAPH
☐ FLOW CHARACTERISTICS (VELOCITY, DEPTH, TOPWIDTH)		☐ PHOTOGRAPH
☐ HIGH WATERMARKS (PHOTOGRAPH & PLOT ON AERIAL/MAP)		☐ PHOTOGRAPH
TYPE AND STAGE (FEET) FLOTSAM *SLACKWATER* EROSION SCAR TREE SCAR GRUS LINE OTHER		

Figure 4-1. Field Data Collection Form (Sheet 2 of 4)

☐ DEPTH TO BEDROCK (FT., UNKNOWN)	
BEDROCK EXPOSED?	☐ PHOTOGRAPH
GRADE CONTROL? (TYPE, PHOTO)	☐ PHOTOGRAPH
☐ BEDFORMS (DUNES/RIPPLES/ARMOR/PLAIN)	☐ PHOTOGRAPH
☐ FENCES (PLOT LOCATION, PHOTO)	☐ PHOTOGRAPH
OBSTRUCT FLOW?	
☐ LONG-TERM *SCOUR* EVIDENCE (PLOT LOCATION, EXTENT, PHOTOGRAPH)	
HANGING TRIBUTARIES	☐ PHOTOGRAPH ☐ PLOT LOCATION
STREAM TERRACES	☐ PHOTOGRAPH ☐ PLOT LOCATION
OVERSTEEPENED BANKS (SIDE SLOPE)	☐ PHOTOGRAPH ☐ PLOT LOCATION
BRIDGE DATA (PIER CAPS, ABUTMENTS, ETC)	☐ PHOTOGRAPH ☐ PLOT LOCATION
HEADCUTS	☐ PHOTOGRAPH ☐ PLOT LOCATION
SLOPE BREAKS	☐ PHOTOGRAPH ☐ PLOT LOCATION
RECENT INCISION	☐ PHOTOGRAPH ☐ PLOT LOCATION
GRAVEL MINING (DISTANCE, EXTENT)	☐ PHOTOGRAPH ☐ PLOT LOCATION
SUMMARY – ESTIMATE OF LONG-TERM SCOUR DEPTH: _____ FEET/ _____ YEARS	
☐ HUMAN IMPACTS ON CHANNEL (STRAIGHTENING, BANK PROTECTION, ETC)	
☐ SKETCH CHANNEL CROSS SECTION (LOOKING DOWNSTREAM)	

SHOW THE FOLLOWING:

☐ VEGETATION	☐ MAIN CHANNEL/ OVERFLOW CHANNEL
☐ MANNING'S N VALUES	☐ ACTIVE CHANNEL LIMITS
☐ BARS	☐ ISLANDS
☐ FLOODPLAIN/ TERRACES	☐ ROSGEN BANKFULL ELEVATION
☐ DIMENSIONS	☐ EROSION BANKFULL ELEVATION

Figure 4-1. Field Data Collection Form (Sheet 3 of 4).

3. BANK PROFILE

☐ DRAW REPRESENTATIVE BANK PROFILE — NOTE THE FOLLOWING FOR EACH UNIT:

STRATIGRAPHY	☐ PHOTOGRAPH
GRAIN SIZE	☐ PHOTOGRAPH
COLOR	☐ PHOTOGRAPH
CROSS BEDDING	☐ PHOTOGRAPH
CARBONATE CONTENT	☐ PHOTOGRAPH
SOIL STRUCTURE	☐ PHOTOGRAPH
SOIL HORIZONS	☐ PHOTOGRAPH

LEFT BANK	RIGHT BANK

SHOW THE FOLLOWING IN THE SKETCHES:

☐ BANK HEIGHT	☐ RELATIVE HARDNESS (HAMMER TEST)	☐ STRATIFICATION
☐ CRITICAL BANK HEIGHT	☐ BANK MATERIAL SIZE	☐ FAILURE MECHANISMS
☐ VERTICAL CUTS	☐ BANK SLOPE	☐ BASAL ENDPOINT
☐ ROOTING LAYER DEPTH	☐ ROSGEN BANKFULL EVIDENCE/ OHM	☐

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

Cave Creek

- Artifacts. Hohokam artifacts were observed scattered on the surfaces of the left overbank floodplain throughout Reaches 1, 2 and 3, indicating that these surfaces have not been significantly flooded for at least 600 years. The Hohokam artifacts were important for correctly evaluating the flood potential on these surfaces because FEMA mapping shows the areas as within the 100-year floodplain, and because the fine grained surface material is typical of surfaces inundated by infrequent shallow flooding. The Hohokam evidence indicates that the extent of the FEMA 100-year floodplain may be overestimated or incorrectly delineated.

Figure 4-6. Hohokam Field Borders

- Armoring. Portions of the bed are covered by very coarse sediment that *armor* the channel during small floods. The bed material in Reaches 1, 2, and 3 was generally not in motion during the July 15, 1999 field visit, although large volumes of bed material on Tributaries #1 and #2 and in Reach 5 had been moved. Field data described below indicate that the channel is not armored during the largest floods.

Figure 4-7. Partially Armored Boulder Riffle

- Avulsions. The channel pattern in Reaches 3, 4, and 5 suggest that Cave Creek is subject to avulsive channel changes. However, direct evidence of such changes is difficult to obtain. Clay and carbonate layers exposed in the bed of the current active channel between field sections P-9K and P-11K are evidence that the existing channel cut through a former bank by an avulsive change (Figure 4-8). The abandoned former channel bed is still visible to the west, is several feet higher than the new channel, and now conveys flows only during large floods. This *avulsion* left an archaeological site as an isolated island in the middle of the channel corridor, as described in Chapter 3.

Figure 4-8. Bank of Cave Creek Breached by Avulsion. CaCO3 and Clay Material Now Exposed in Bed Was Formerly Basal Unit of Soil. Avulsion Cut Off the Hohokam Irrigated Field Described in Chapter 3.

- Boulder riffles. *Riffles* of very coarse boulders and cobbles were unevenly spaced in the study area (Figure 4-9). The length and spacing of the *pool* and riffle sequence is illustrated in Figures 4-10 to 4-12 and Table 4-1. In general, the channel slope through the riffles on Cave Creek appears to be steeper than the riffle slopes on Apache Wash and Paradise Wash.

Table 4-1. Upper Cave Creek/Apache Wash Watercourse Master Plan Pool and Riffle Sequence – Length and Ratio

Stream	Pool Length (ft)	Riffle Length (ft)	Ratio (Pool/Riffle)
Cave Creek	291	250	1.16
Apache Wash	176	185	0.95
Paradise Wash	136	183	0.75
Note: Desert Hills Wash does not have a pool and riffle pattern.			

Figure 4-9. Boulder Riffle on Apache Wash, Reach 5. Adjacent Downstream Pool is Visible in Distance.

Figure 4-10. Cave Creek Pool & Riffle Measurements

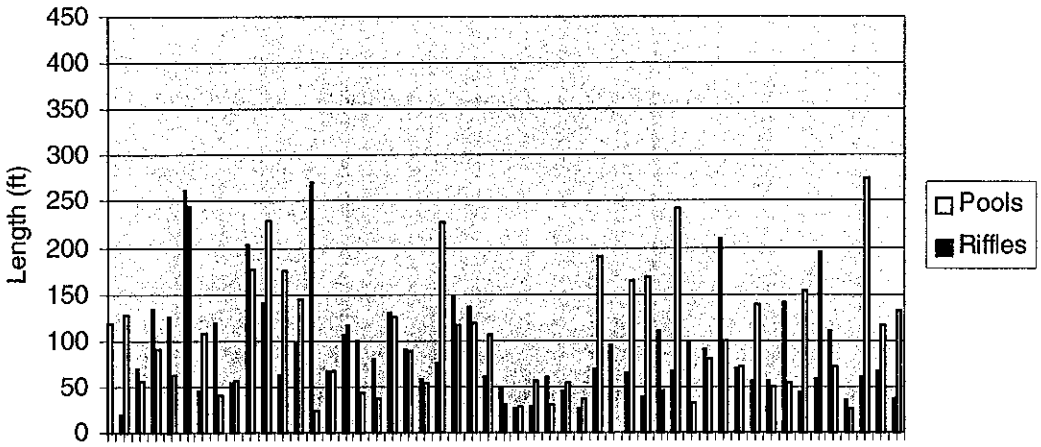


Figure 4-11. Apache Wash Pool & Riffle Measurements

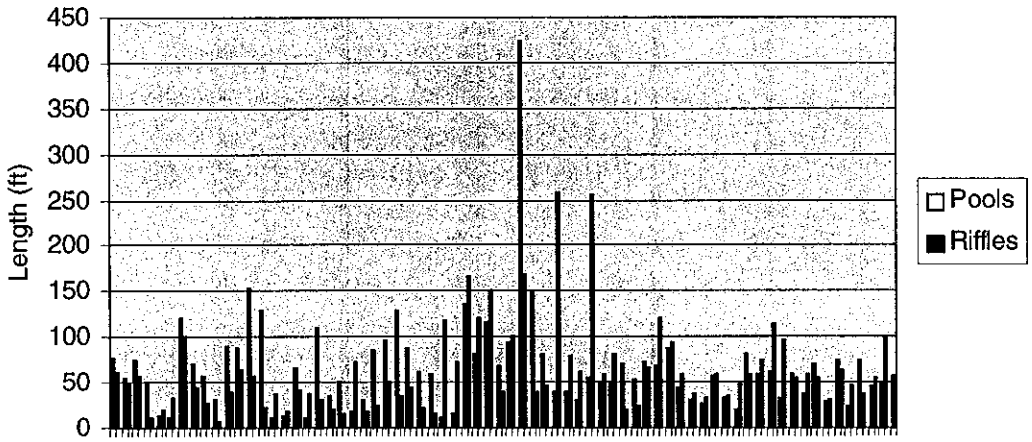
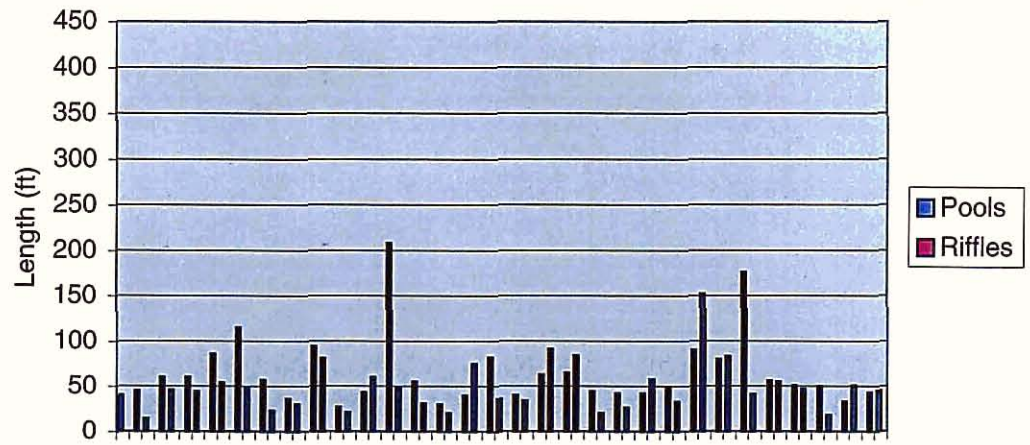


Figure 4-12. Paradise Wash Pool & Riffle Measurements



- Carefree Highway Bridge. No evidence of recent lateral migration was observed in the field near the bridge abutments or approaches. Cave Creek has *incised* about eight feet immediately downstream of the bridge, and appears to have shifted from its historical multiple channel pattern to an entrenched single channel upstream of the bridge.

- Cliffs. A 25 to 30 foot tall cliff is present along the east bank of Cave Creek in Reaches 1, 2, 3, and 4. 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. In other locations, a talus slope forms where the vertical cliff has collapsed but the fallen material has not yet been removed by the stream. Elsewhere, where the stream is not flowing directly at its base, the cliff has relaxed to a 2:1 slope and is well vegetated.

Figure 4-13. Erosion of Carbonate-Rich Cliffs Along Cave Creek, Reach 3.

Figure 4-14. Tall Cliffs With Basal Talus Pile in Cave Creek Reach 3.

Figure 4-15. Vertical Cliffs Along Cave Creek, Reach 3.

Figure 4-16. Overhanging Cliffs Along Cave Creek, Reach 2.

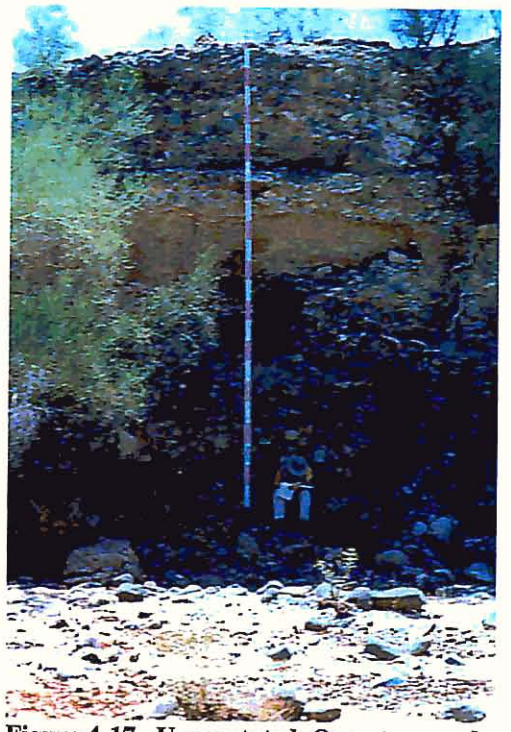


Figure 4-17. Unvegetated, Oversteepened Cliff on Cave Creek.

Figure 4-18. Vegetated, Sloped Bank of Equal Height as Figure 4-17.

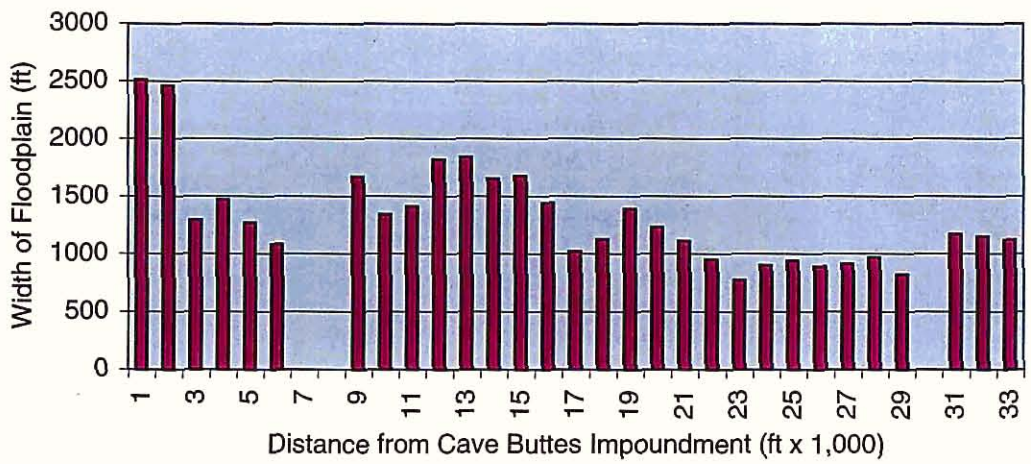
- Cliff Stratigraphy. The tall cliffs which form the left bank in most of Reaches 1, 2, 3, and 4 have very resistant layers that allow the 30-foot tall banks to stand at a vertical slope. However, there are weaker, more erodible layers that apparently fail where the stream directly impinges on the bank. These erodible layers are also removed by piping, by dissolving the carbonate matrix (Figure 4-13), or by slope processes (Figure 4-18).

- Cut banks. Actively eroding banks were observed throughout the Cave Creek study reach. The most stable appearing banks were in Reach 2. Banks that lacked vegetative cover were generally cut to vertical slopes (Figure 4-19). Banks with good vegetative cover had more gently sloped banks (Figure 4-18 above).

- Geologic floodplain width. The width of the geologic floodplain increases by a factor of about two at the Tributary #2 confluence (Figure 4-20). A similar increase in floodplain width occurs at the mouth of Tributary #3 at the Carefree Highway. The increased floodplain width is probably due to deposition of tributary sediments in the Cave Creek floodplain.

Figure 4-19. Cut Bank

Figure 4-20. Cave Creek Geologic Floodplain Width



- 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. Some of the flotsam consists of cottonwood tree trunks that were transported from well upstream of the study area. Elsewhere, trimlines defined by

older, more permanent vegetation marked the elevation of the highest recent flood.

Figure 4-21. Flood Debris at Bankfull Depth Wrapped on Mesquite Tree – Cave Creek, Reach 2.

Figure 4-22. Two-Foot Diameter Cottonwood Trunk on Low Island in Cave Creek Reach 2.

Figure 4-23. Trimline on Left Bank of Cave Creek Indicating Recent (ca. 1993) Scour. Arrows Point to Trimline Location on Bank.

- Imbrication. The largest boulders on the channel bed and in riffles, up to two feet in diameter, are imbricated in the direction of flow. *Imbrication* is a streamlined alignment of the coarse sediment on a stream bed which indicates that the bed material is transported by floods (Figure 4-24).

Figure 4-24. Imbrication of Boulders in Riffle on Cave Creek. Imbrication is a downstream Alignment of Sediment on a Stream Bed. Note that the Boulders in the Photograph are Aligned So That They Lean to the Upper Left in the Photograph.

- Incision. Field evidence of historically recent channel degradation observed in the field included perched, abandoned channels, over-steepened vertical *cut banks*, small terrace remnants along the channel margins, *headcut* tributaries (e.g., Tributary #2), and hanging tributaries.

Figure 4-25. Perched Tributary Entering Cave Creek From Right Overbank Floodplain.

Figure 4-26. Perched Abandoned Channel at Former Avulsion Site Shown in Figure 4-22.

- Mining. Evidence of historical in-stream sand and gravel mining of Cave Creek in the 1970's and 1980's is still visible in Reaches 1 and 3. Aside from the excavations, evidence of past mining includes abandoned mining equipment, piles of unused rock products, graded and devegetated areas, concrete structures, and roads. The channel excavations in the Tanner mining area appear to have filled during the floods of the 1990's. Active in-stream mining is ongoing in Reach 4 of Cave Creek.

- Perched channels. An abandoned perched channel and hanging tributaries that were probably portions of the main channel less than 100 years ago were observed near field sections P-6K and P-9K. Channels become perched due to long-term degradation and *scour*, as shown in Figures 4-25 and 4-26 above.

- Sub-channel clay layer. A red clay layer was observed in the channel pits at variable depths up to six feet below the surface. This clay layer was assumed to be the maximum limit of scour (Figures 3-20, 4-27, and 4-28). The layer probably formed by infiltration of floodwater that drove fine sediment into the coarse channel bed matrix. The clay layer was not observed at channel pit #16CHL, which was located at the upstream end of Reach 3, near the abandoned Tanner mine. Instead, the pit was filled with stratified sand and gravel which were most likely deposited as the in-stream pit filled during a flood (Figures 3-29 and 3-30).

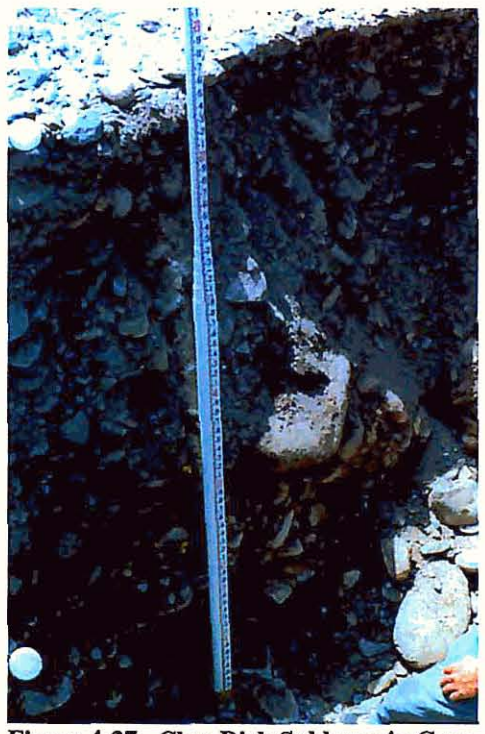


Figure 4-27. Clay-Rich Sublayer in Cave Creek.

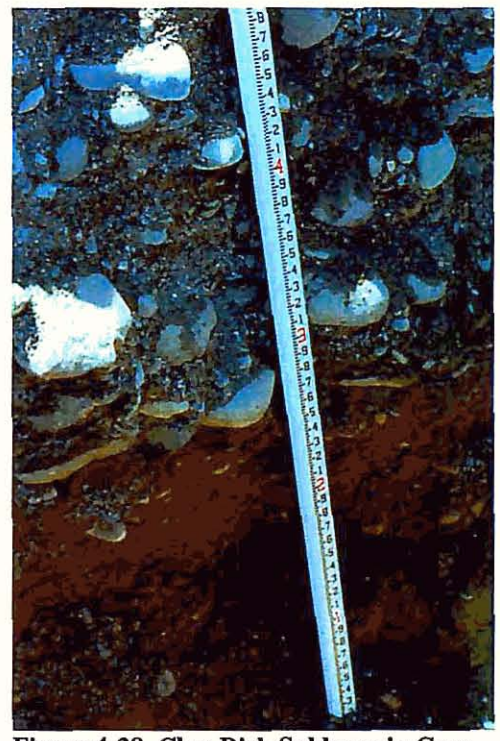


Figure 4-28. Clay-Rich Sublayer in Cave Creek.

- Tributary sedimentation. During the August 17, 1998 flood, a large slug of granitic gravelly sediment was deposited on the bed of Cave Creek at the mouth of Tributary #1 (Effluent Wash). The deposit covered about ½ acre and was up to three feet thick. A similar volume of sediment was deposited on Tributary #1 at the Wheeler access road during the July 15, 1999 event.

- Variable Bank Stratigraphy. The variation of the bank materials did not just consists of the variable *stratigraphy* at any given cross section, but also by the variation over the length of the stream. The variation in bank composition mimics the variability of the composition of the channel bed and bars (See Figures 4-13 to 4-17).

- 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 (See Figures 4-14 and 4-15).

- Wildlife. The wildlife observed in the study area included a gila monster, two foxes, numerous rattlesnakes, coyotes, hawks, owls, javalina, and scorpions. Scat and the den belonging to a large cat (e.g., mountain lion or bobcat) were also found. The number of wildlife sitings was higher along Apache Wash and its tributaries than along Cave Creek, but the diversity of mammal species observed was greater along Cave Creek.

Figure 4-29. Gila Monster near Cave Creek

Figure 4-30. Rattlesnake in Cave Creek

Apache Wash/Paradise Wash. Apache Wash and Paradise Wash have very similar field characteristics and will be discussed together.

- Bank vegetation. The bank vegetation was much denser on Apache Wash and its tributaries than on Cave Creek. The denser vegetation typically covered the entire bank profile, from the toe to the top of the bank. Banks that lacked vegetation were more likely to show evidence of recent erosion. The photograph in Figure 4-31 shows a vegetated bank on Apache Wash. Note that the grassy vegetation has been cropped by cattle.

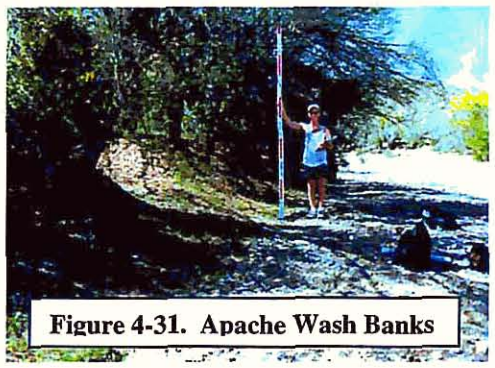


Figure 4-31. Apache Wash Banks

- Cattle damage on banks. The bank vegetation showed the effects of grazing. Cattle paths were cut into otherwise undisturbed banks. Elsewhere, the banks were scraped by hoofs where it appeared that cattle had tried to climb the banks, or had tried to reach plants growing on the upper banks (See Figure 3-36).

- Cliffs. Cliffs were observed in several reaches on Apache Wash and Paradise Wash where the main channel intersected the oldest geomorphic surfaces. In general, the cliffs were not as tall as the cliffs on Cave Creek.

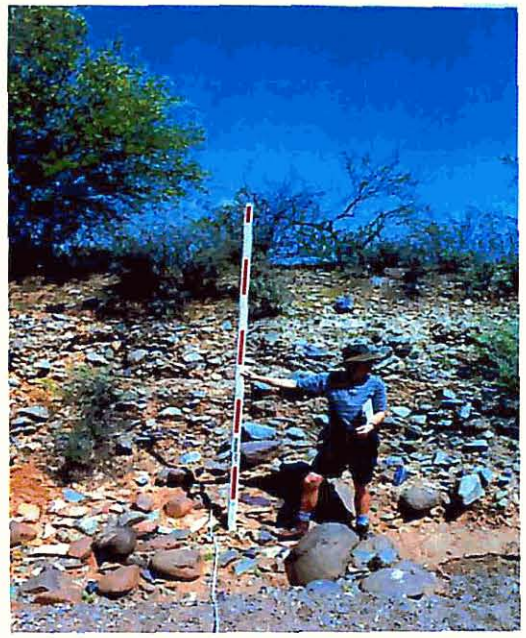


Figure 4-32 (Above). Ten Foot Cliff Face With Overhanging Vegetation on Apache Wash.

Figure 4-33 (Left). Ten Foot Cliff Face Composed of Cemented Cobbles on Paradise Wash.

- Overbank channels. Overflow channels that appeared to convey overbank floodwaters in a straight path exist at most of the channel bends. The overbank channels may be incipient avulsive channels or remnants of past *avulsions*. The photograph at the right shows an overbank flow path in Reach 4 of Apache Wash. Note that the bed material is finer, and that the bank height is lower than the main channel.

Figure 4-34. Overbank Flow Channel.

- Pool/Riffle Sequence. *Pool* and *riffle* data are shown in Figures 4-10 and 4-11 and Table 4-1. The riffles were relatively longer in Paradise Wash and Apache Wash than in Cave Creek. The pools were shorter in Paradise Wash than in Apache Wash.

- Subchannel clay layer. The subchannel clay rich layer was observed at a depth of only 6 to 24 inches, with the depth generally decreasing in the upstream direction.

Desert Hills Wash

- Bosco Tank disturbance. The *sinuous* sandy channel downstream of the historical Bosco Tank spillway failure is drastically different than the gravelly straight channel upstream of the Tank.

Figure 4-37. Dense Mesquite Bosque in Sinuous Channel Downstream of the Historical Bosco Tank Spillway Failure.

- Grazing impacts. Immediately upstream of the fence dividing State Trust Land from unincorporated Maricopa County, the amount of grass and brush cover on the banks increases dramatically. The only observed difference between the two reaches was that State Trust Land is leased for cattle grazing. (See Figures 3-33 and 3-34 for comparison of grazed and non-grazed reaches of Desert Hills Wash.)

Summary. In general, field observations made along Cave Creek indicate that study reach is subject to lateral erosion and channel *avulsions*, has experienced historical degradation, and has been extensively impacted by human activities. Field observations made along Apache Wash, Paradise Wash, and Desert Hills Wash indicate that the study reaches are more laterally stable than Cave Creek and have not experienced significant long-term degradation or human impacts. Field data suggest that the frequency of channel avulsions on Cave Creek (Reaches 3, 4, and 5) is greater than on Apache Wash or Paradise Wash.

Geomorphic Mapping

Alluvial deposits and soils associated with stream terraces along Cave Creek, Apache Wash, Paradise Wash, and Desert Hills Wash from the Carefree Highway to the Cave Buttes Dam were analyzed to assess the lateral stability of Cave Creek. 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 Cave Creek drawn from these estimates are described below.

- Terraces. The FEMA Flood Insurance Rate Maps (FIRM) imply that several terraces of late Pleistocene age are inundated by the 100-year flood. These old terraces have moderately well-developed *desert pavement*, varnished surface materials, and soil development, all of which are signs that the surfaces have been undisturbed by significant flooding for thousands of years. The surfaces lack a cap of recently deposited fine grained silts and sands that would be expected if they were in the 100-year floodplain. This evidence indicates that the 100-year *discharge* estimate for Apache Wash may be overestimated, or that the floodplain boundaries are incorrectly plotted on the FIRM.

Figure 4-35. Terrace Scarp and Floodplain Vegetation

- Upstream 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 4-36). The upstream laminations were interpreted to mean that the boulders had remained unmoved over the duration of a great number of floods.

Figure 4-36. Upstream Lamination of Cobbles on Bed of Paradise Wash. Lamination is Interpretation as Evidence of Non-Movement During Most If Not All Floods.

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 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 4-38, a minimum rate of lateral erosion for any surface can be estimated (X/Z), as well as the total magnitude of lateral migration and vertical change, by mapping the geomorphic surfaces at a given location.

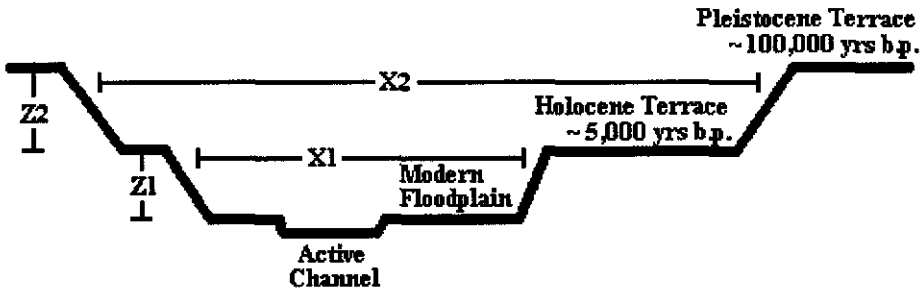


Figure 4-38. Idealized Sketch of Riverine Terraces & Ages

- 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 B.

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. Forty-four 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 4-39. 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 (Table 4-3). 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	Toughness of Fines	Cement-ation	Fines Symbol	Name	Round-ing	Sort-ing	Strat-ification Size	$CaCO_3$ Coat, Size, Contin
	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									

Figure 4-39. 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 data
- 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:

- 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 4-40. Soil Profile Showing B Horizon Development – Clay and CaCO3 Accumulation.

A Horizon. 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 is 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. 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 4-41. Subangular Blocky Soil Texture Developed in Clay-Rich B Horizon in Soil Profile from Cave Creek.

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 4-42. Soil Profile Showing CaCO3 Accumulation at Depth Indicated by Hard Whitish Layers.

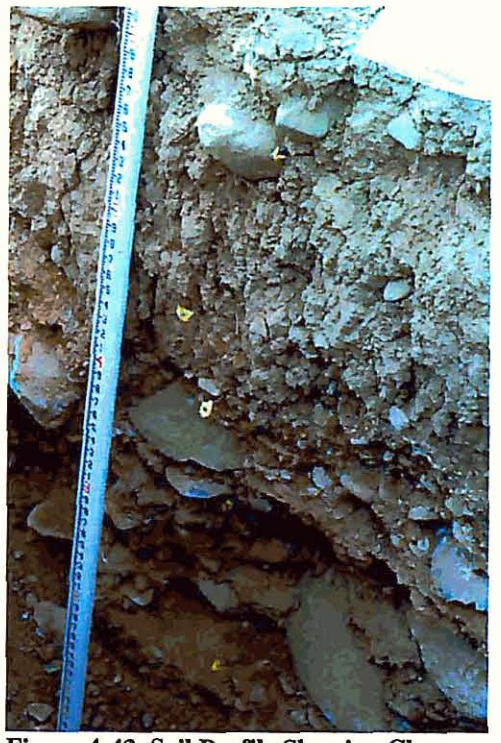


Figure 4-43. Soil Profile Showing Clay Accumulation and Reddening With Depth.

B Horizon – Carbonate Accumulation. 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. 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 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, the lack of a pavement does not necessarily imply a young surface.

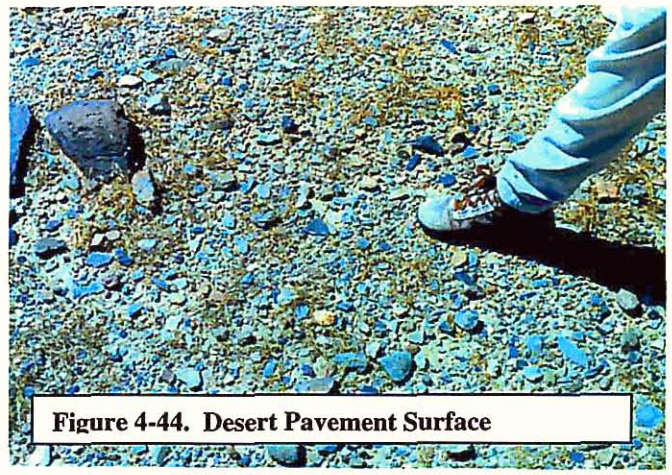


Figure 4-44. Desert Pavement Surface

Desert Varnish. Desert varnish, 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, and the varnish coating thickens over time (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. Therefore, the

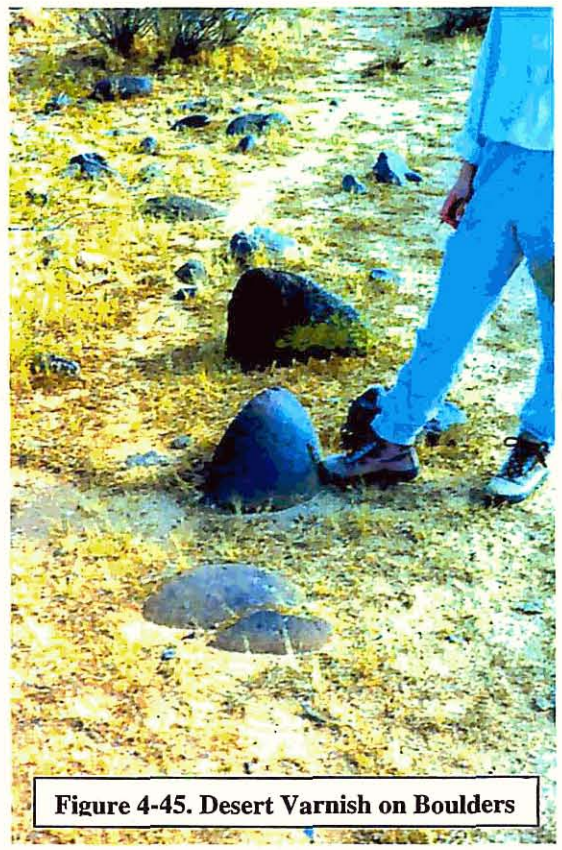


Figure 4-45. Desert Varnish on Boulders

presence of well-varnished clasts are 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. The Hohokam people of central Arizona farmed the terraces along Cave Creek in the study area, as described in Chapter 3 of this report. The most extensive occupation occurred from 900 to 1150 A.D. (Doyel and Elson, 1985). Hohokam artifacts such as rock alignments, lithic flakes, ground stones, pot *sherds*, and fire-cracked rocks are present at the surface of many of the terraces examined in this study (Douglas, 1998). The rock alignments are particularly useful for determining a minimum surface age. Rock alignments are cobbles and boulders placed in a line on a surface as agricultural field borders or as part of debris-dams, to retain surface water for farming (Doyel and Elson, 1985). The top of the rocks that made up the alignments along Cave Creek are coated with a poor to moderately developed black desert varnish. The varnish and the intact alignments of the rocks show that they have not been displaced by flood waters or substantially buried by stream deposits since they were constructed. Hohokam pottery sherds date the artifact sites from 1100 to about 700 years ago, indicating that the surfaces containing the sites have not been subject to substantial flooding for at least 700 years (Doyel and Elson, 1985).

Terraces containing Hohokam rock alignments were probably not very high above the active Cave Creek channel at the time the terrace was being farmed. In order for the rock lines to have been useful as retainers of flood water overbank flow, the terraces needed to be low enough in elevation to receive overbank flow, but high enough from the active channel to prevent reworking of the surface and seed/plant removal during most floods. Even if the rock alignments were not used to retain flood waters and maintain agriculture, the farmed terrace needed to be of the appropriate height above the active channel to receive overbank flow during floods (Doyel and Elson, 1985). The terraces are now 6 to 10 feet above the active channel, evidence that Cave Creek has cut down a total of about three to seven feet over the last 700-1100 years.

Not all terraces with Hohokam artifacts are of Hohokam age. Terraces older than those farmed by the Hohokam may also contain artifacts at the surface. But the highest concentrations of artifacts are on the low and middle surfaces, probably where most of the Hohokam activity was centered due to the proximity to a water source and to the fields. Therefore, the presence of Hohokam artifacts was interpreted as evidence of a minimum age of the surface on which the artifacts were found.

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.

Vegetative Characteristics. Local vegetation 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. The alluvial terraces of Cave Creek tend to have more shrubs, especially creosote, and fewer trees and cacti than the higher older terraces. Areas of prehistoric Hohokam agriculture typically have little or no vegetation. 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 are shown in Exhibit 2. Descriptions for each of the geomorphic surfaces mapped in Exhibit 2 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 six landform-based classifications, with a total of eight subunits:

- High Relict *Alluvial fan* Terraces – Map units Q_{m1} and Q_{m2}
- Intermediate Terraces – Map units Q_{l1} and Q_{l2}
- Moderately Low Terraces – Map units Q_{y1} and Q_{y1}
- Historical Floodplains and Low Terraces – Map unit Q_{y2}
- Active Channels – Map unit Q_{yc}
- Disturbed Areas

Areas extensively modified by historical human activities were also mapped, and are shown as disturbed areas on Exhibit 2. 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), Holloway and Leighty (1998), and Leighty and Holloway (1998).

High Relict Alluvial Fan Terraces. Two relict alluvial fan terrace units were mapped in the study area, Q_{m1} and Q_{m2}. Q_{m1} surfaces were distinguished from Q_{m2} surfaces based primarily on the following characteristics:

- Height above the active channel
- Strength of *argillic* and calcic horizon development
- Degree of *desert pavement* and varnish development

<u>Q_{m1} – 400,000 to 700,000 years old</u>. The soil profile associated with the older of the two alluvial fan terrace units, a relict middle 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 B horizon can frequently be broken into the zone of clay accumulation and the zone of carbonate accumulation. The clay-rich horizon, about 20 to 50 inches thick, is commonly red and shows moderately to well developed columnar or prismatic structure, although angular blocky structure is also observed. At a depth of 40 to 60 inches, a typical high terrace contains a well-cemented carbonate horizon. 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_{m1} terrace soils are classified as Calciortids, Paleorthids, and Paleargids. The Q_{m1} 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) and plants (e.g., plant heave when a plant falls over) 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. Hohokam lithic flakes were found around one soil pit on this very old surface.

<u>Q_{m2} – 250,000 to 400,000 years old</u>. The profile for the younger of the two relict *alluvial fan* units, a more dissected Middle Pleistocene alluvial fan terrace, consists of moderately to strongly developed soils, with surfaces ranging in color from strong brown to reddish brown. The Q_{m2} terraces are typically about 15 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_{m2} soils generally do not have cemented *petrocalcic* horizons (*caliche*). These soils are classified as Calciorthids and Haplargids. Q_{m2} 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_{m2} surfaces have typically been eroded into shallow valleys and low ridges; original depositional surfaces may be preserved along ridge crests. A ground stone and a pot sherd were found on one surface of moderate height.

Intermediate Terraces. Three intermediate terrace units were mapped in the study area, Q_{I1}, Q_{I2}, and Q_{yl}. The three surfaces were distinguished from each other based primarily on the following characteristics:

- Height above the active channel

- Height relative to the other intermediate terraces
- Slight differences in the strength of *argillic* and calcic horizon development

Q_{I1} – 50,000 to 250,000 years old. The oldest of the three mapped intermediate terraces is of late Pleistocene age and is comprised of former *alluvial fan* surfaces and 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_{I1} 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_{I1} soils typically have Stage II-III calcium carbonate development. Q_{I1} soils are more strongly developed than Q_y soils. Q_{I1} soils are classified as Haplargids, Camborthids, and Calciorthids.

Q_{I1} terrace surfaces range from about 6 to 15 feet above the modern channel. Q_{I1} 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_y surfaces. Q_I surfaces are generally not prone to flooding, except immediately adjacent to active washes. This surface is roughly equivalent to the Cahava Ranch terrace of Doorn and Pewe (1991).

Q_{I2} – 10,000 to 50,000 years old. The Q_{I2} surface consists of stream terraces, estimated at latest Pleistocene age, and are characterized by weak structure and thin, continuous carbonate coatings on clasts. Surfaces of this age have not had time to accumulate and translocate much clay, and they show weak subangular blocky structure. Typically, at a depth of 30 to 60 inches, the zone of maximum carbonate accumulation commonly shows clasts with thin (<1 mm thick) coatings of calcium carbonate that are continuous around the clast.

Desert pavement development on the Q_{I2} surface is typically poor to moderate on surfaces of intermediate height. A thin, dull black varnish on occasional surface gravels is representative of the middle terraces. Hohokam pot *sherds* and possible fire-cracked rocks were found on late Pleistocene terrace surfaces, although this surface was not used for irrigated agriculture by the Hohokam.

Q_{yI} – 1,000 to 50,000 years old. The youngest of the intermediate terrace surfaces is of latest Pleistocene or *Holocene* age, and bears characteristics of both the Q_{yI} and Q_{I2} surfaces. Q_{yI} soils are minimally developed, but typically contain slight texturally or structurally modified B (cambic) horizons, weak calcic horizons (Stage II or less), and are noticeably reddened. Some of the older soils may contain weakly developed *argillic* horizons. Surface colors are light brown to yellowish brown, with a slight reddening with depth due to oxidation. Q_{yI} soils are classified as *Torrifluvents*, Torriorthents, Camborthids, and Calciorthids. Because surface soils are not indurated with clay or calcium carbonate, Q_y surfaces have relatively high permeability and porosity. All areas mapped as Q_{I1} may be subject to inundation during very large floods.

The Q_{yl} surface lacks desert pavement or significant desert varnish, although varnish was observed on some of the larger boulders. Portions of the Q_{yl} surface along Cave Creek were extensively occupied by the Hohokam, and are immediately adjacent to the Q_{yl} surfaces used for irrigated agriculture, but tend to be somewhat coarser.

Moderately Low Terraces: Q_{y1} – 700 to 10,000 years old. Low terraces, estimated to be *Holocene* in age (700 to 10,000 yrs old), were distinguished by their weak structural development and thin to very thin, discontinuous carbonate coatings on clasts. The soils of the moderately low terraces exhibit similar structural development to the intermediate terraces, primarily weak subangular blocks. However, the low terraces contain clasts with thin, discontinuous carbonate coatings, usually coating only the bottoms of clasts. Along Cave Creek, the typical soil profile is capped by finer-grained sand and silt units deposited prior to the regional channel incision responsible for formation of the terrace.

Desert pavement has typically not formed on the low terraces. A minimal concentration of gravel at the surface of open areas is sometimes observed. A slight black tint to the tops of surface gravels is the only suggestion of desert varnish development. Hohokam pot sherds and rock alignments are relatively common on the low surfaces, indicating that the surfaces were already formed at the time that the Hohokam people lived in the area.

Historic Floodplains and Low Terraces: Q_{y2} – 100 to 700 years old. 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 eight feet above the modern channel, but minor channels are common locally. 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_{y2} terrace soils are *Torrifluvents* and Camborthids. Because surface soils are not indurated with clay or calcium carbonate, Q_{y2} surfaces have relatively high permeability and porosity. Portions of Q_{y2} 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_{y2} soils were distinguished from Q_{yc} soils primarily on the bases of topography (higher) and frequency of inundation (less frequent). Q_{y2} surfaces were distinguished from Q_{yl} surfaces primarily by the degree of soil development (less), grain size (coarser), and elevation (lower). Historical channel incision due to sand and gravel mining or other human impacts have perched some of the Q_{y2} surfaces above the 100-year floodplain.

Hohokam artifacts were not observed on the surfaces. A metal can, with crimped edges of the kind made roughly 50 years ago, was found at a depth of about 15 inches in one soil pit (Figure 4-46). The presence of the buried historical can indicates that the terrace was flooded historically, and the top ~15 inches of material was deposited in the past 50 years. The lack of Hohokam artifacts on the low terraces suggests that the maximum age is after the Hohokam abandoned the area, or less than 700 years old.

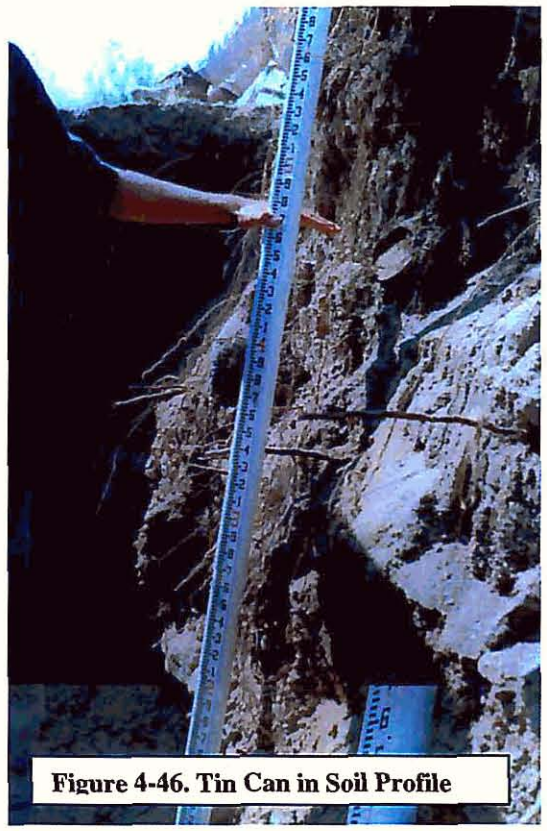


Figure 4-46. Tin Can in Soil Profile

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 Cave 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*.

Disturbed Areas. Soil units within areas of known historical disturbance were generally not mapped for this project. Known historical disturbances included sand and gravel mining (Cave Creek – Wheeler Mine, Tanner Mine, Carefree Highway Mines), construction of on-line stock ponds (Desert Hills Wash – Bosco Tank), and other graded areas (Cave Creek/Apache Wash – Cave Buttes Dam borrow areas, Carefree Highway grade).

Table 4-2. Upper Cave Creek/Apache 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	Upper Cave Creek/Apache Wash WMP Mapping		
Symbol	**Name**	**Symbol**	**Name**		**Symbol**	**Description**	**Age**
Qycr	Active Channel Deposits	Qyc	Active Channel Deposits	0-1ka	Qyc	Active Channel Deposits	0-100 yrs
Qyr	*Holocene* River Terrace Deposits	Qy	*Holocene Alluvium*	0-10ka	Qy2	Low Terraces & Hist. FP	0.1-0.7 ka
					Qy1	Moderately Low Terraces	0.7-1 ka
		Qylf	*Holocene* To Late Pleistocene Fine-Grained *Alluvium*	1-250 ka	Qyl	Intermediate Terraces	1-50 ka
					Ql2	Intermediate Terraces	10-50 ka
					Ql1	Intermediate Terraces	50-250 ka
Qlr	Late Pleistocene River Terrace Deposits	Ql	Late Pleistocene *Alluvium*	10-250ka			
Qmr	Middle Pleistocene River Terrace Deposits	Qm	Middle Pleistocene *Alluvium*	250-750ka	Qm2	High Relict Fan Terraces	250-400 ka
		Qmm	Middle Pleistocene metamorphic *alluvium*	250-750ka	Qm1	High Relict Fan Terraces	400-750 ka
Qor	Early Pleistocene River Terrace Deposits	Qo	Early Pleistocene *Alluvium*	750ka-1.6ma		Not mapped	
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. Upper Cave Creek/Apache Wash Watercourse Master Plan
Soil Pit Test Results

Pit #:	11ROB1	Relative Age: M1			Pearthree Age: >1 ka				Artifacts found: rock alignments			
Depth (in)	Bound-ary	Munsell Color		Soil Structure	Gravel %	Consistence		Texture	Clay Films	Carbonate	Other	Hammer Test
		Moist	Dry			Wet	Dry					
1.5	c,w	10YR4/2	10YR6/3	2,m,pl	10	ss,ps	sh	fSL	few	e2		so
7	c,w	10YR4/3	10YR5/3	1,f-m,sbk	10	ss,ps	so-sh	fSC	few	e2, vf fil		so
23.5	c,w	10YR4/2	10YR5/3	1,f-m,sbk	10	ss,ps	so-sh	mSL	v few	e2,vf fil, tn con		so
29	c,w	10YR4/4	10YR5/3	1,f-m,sbk	25-50	so,ps	so-sh	L	v few	e2, vf fil, vtn con		so
54	c,i	10YR4/3	10YR6/3	1,m,sbk	25	so,po	so-sh	LfS	v few	e2, com fil, sparse vtn dis		so
66.5	c,w	10YR4/3	10YR6/4	sg	50	so,po	so-sh	LS	none	e3, com fil, vtn con, I+/II		mh
72		10YR4/3	10YR5/3	sg	75	so,po	lo	LcS	none	e2,f fil	gypsum rinds	so

Pit #:	12LOB1	Relative Age: O1			Pearthree Age: several 100s of k.yrs.				Artifacts found: none			
Depth (in)	Bound-ary	Munsell Color		Soil Structure	Gravel %	Consistence		Texture	Clay Films	Carbonate	Other	Hammer Test
		Moist	Dry			Wet	Dry					
2.5	c.w	7.5YR4/2	10YR6/4	2,f-m,pl	10	ss,ps-p	Sh	SiCL	com	e0		lo
9	c.w	7.5YR5/4	7.5YR5/4	2,c.sbk	<10	ss,ps-p	H	CL	few-com	e1, f fil, sparse vtn dis		so
29	c,i	7.5YR4/3	7.5YR6/4	c,abk	25	s,p	sh-h	SiCL	abund	e2, com fil, vtn dis		mh
38.5	c.w	7.5YR5/4	7.5YR5/4	2,m,abk	<10	ss,ps-p	H	CL	com	e2, com fil, vtn dis	gypsum rinds	mh
47.5	c.w	7.5YR5/4	7.5YR6/4	1,f,abk	50	s,p	so-sh	mSC	few	e3, abun fil, tn con		h
57	c.w	7.5YR6/3	7.5YR7/2	m to 1,f,sbk	25	ss,ps-p	Eh	SL	v few	e3, strongly cem, III		vh
71		7.5YR6/4	7.5YR7/3	1,vf,sbk	25-50	ss,ps-p	Sh	mSCL	few	e2, moderately cem		h

Table 4-3. Upper Cave Creek/Apache Wash Watercourse Master Plan
Soil Pit Test Results (Continued)

Pit #:	12ROB1	Relative Age: M2/Y			Pearthree Age: <1300 yrs, probably <700 yrs (sherd in pit)				Artifacts found: sherd in pit, 15" down			
Depth (in)	Boundary	Munsell Color Moist	Munsell Color Dry	Soil Structure	Gravel %	Consistence Wet	Consistence Dry	Texture	Clay Films	Carbonate	Other	Hammer Test
2	c,w	7.5YR4/2	10YR6/3	2,f-m,pl	<10	so,ps	so	SiL	v few	e0-1		lo
14	c,w	7.5YR4/2	10YR6/3	1-2,m,sbk	10	so,ps	so	SiL	v few	e2,vf fil, sparse vtn dis		so
43	c,i	7.5YR4/2	10YR6/3	1,gr	25	so,ps	so	SiL	v few	e2,vf fil, sparse vtn dis		so
69		7.5YR4/2	10YR6/3	sg	75	so,ps	lo	fSL	none	e2,vf fil, sparse vtn dis		so

Pit #:	12ROB2	Relative Age: M1/M2			Pearthree Age: maybe mid-late Holocene soil over latest Pleistocene soil (?)				Artifacts found: none			
Depth (in)	Boundary	Munsell Color Moist	Munsell Color Dry	Soil Structure	Gravel %	Consistence Wet	Consistence Dry	Texture	Clay Films	Carbonate	Other	Hammer Test
1.5	c,w	10YR4/3	10YR5/4	2,f-m,pl	10	ss,ps	so-sh	SiL	com	e0		so
4	c,w	10YR4/3	10YR6/4	m-c,sbk	<10	ss,ps	sh-h	SiL	few	e0		so
13	c,w	10YR4/3	10YR6/3	1,c,sbk	10	ss,ps	h	SiL	few	e1		so
28.5	c,w	10YR4/3	10YR6/3	1,m,sbk	10	ss,ps	sh-h	SiL	v few	e1, f fil, sparse vtn dis		so
40	c,w	7.5YR4/3	10YR6/3	1,f,sbk	10	ss,ps	so-sh	SiL	few-com	e2, f fil, vtn dis, I		so
51	g,w	10YR4/3	10YR5/4	2,f,sbk	50	ss,ps	sh	SiL	com-abun	e2,com fil, tn con, II	gypsum, buried soil	so-mh
65		7.5YR4/4	7.5YR5/4	2,c,abk	50		eh	SCL	abun	e2,com fil,vtn dis		mh

Pit #:	12ROB3	Relative Age: 01			Pearthree Age: none				Artifacts found: none			
Depth (in)	Boundary	Munsell Color Moist	Munsell Color Dry	Soil Structure	Gravel %	Consistence Wet	Consistence Dry	Texture	Clay Films	Carbonate	Other	Hammer Test
1.5	c,w	7.5YR4/2	10YR5/4	2,m,pl	10	ss,ps	so-sh	SiCL	few-com	e0		so
7	c,w	7.5YR4/4	7.5YR4/4	2,c,sbk	<10	s,p	h	SiC		e0		mh

Table 4-3. Upper Cave Creek/Apache Wash Watercourse Master Plan
Soil Pit Test Results (Continued)

20.5	c,w	7.5YR4/4	7.5YR5/3	3,c,cpr	<10	vs,vp	h	SiC	abun	e1,f fil,vtn dis		mh
27	a,i	7.5YR4/4	7.5YR4/2	2,c,abk	25	ss,ps	vh	SiL	com	e2,com fil,tn dis, I		mh
42.5	c,w	5YR5/6	5YR5/6	2,f,sbk	50	s,p	sh	mSC	abun	e2,tn dis, I	gypsum	mh
62	c,w	7.5YR4/4	7.5YR5/4	1,f,sbk	75	ss,ps	sh	L	com	e1,sparse vtn dis	gypsum	h
68		7.5YR4/4	7.5YR5/4	1,f,sbk	75	so,po	so	LS		e0-1, few fil	indurated	h

Pit #:	13ISLAN	**Relative Age: Y**			**Pearthree Age: none**				**Artifacts found: none, suface flooded recently – flood-related debris**			
Depth (in)	**Bound-ary**	**Munsell Color**		**Soil Structure**	**Gravel %**	**Consistence**		**Texture**	**Clay Films**	**Carbonate**	**Other**	**Hammer Test**
		Moist	**Dry**			**Wet**	**Dry**					
2	c,w	10YR4/2	10YR6/2	m	10	so,po	so	LfS	none	e1	silt laminations	lo
63		7.5YR5/1	7.5YR7/2	sg	75	so,po	lo	LS	none	e1	thin alternat-ing c, f beds	so

Pit #:	13ROB1	**Relative Age: M2**			**Pearthree Age: none**				**Artifacts found: sherds, rock alignments, high density of artifacts**			
Depth (in)	**Bound-ary**	**Munsell Color**		**Soil Structure**	**Gravel %**	**Consistence**		**Texture**	**Clay Films**	**Carbonate**	**Other**	**Hammer Test**
		Moist	**Dry**			**Wet**	**Dry**					
1.5	c,w	10YR4/2	10YR6/4	2,vc,abk	<10	ss,ps	so-sh	SiL	v few	e1		lo
5	c,w	10YR4/2	10YR6/3	f,sbk	<10	ss,ps	so	SiL	v few	e1,vf fil		so
9	c,w	10YR4/2	10YR6/3	2,f,abk	<10	ss,ps	sh	SiL	few	e1,vf fil		so
24.5	c,w	10YR4/3	10YR5/3	2,c,sbk	<10	ss,p	so	CL	few	e1,vf fil		so
51	a,w	10YR4/3	10YR5/3	1,f-m,sbk	<10	so,ps	sh	L	none	e1,com fil		so
81		10YR4/3	10YR7/2	1,f,sbk	75	so,po	so	S	v few	e1,tn con, tk bot, I+/II-		so

Pit #:	14ROB1	**Relative Age: Y**			**Pearthree Age: none**				**Artifacts found: historical metal can in pit, ~15 in depth**			
Depth (in)	**Bound-ary**	**Munsell Color**		**Soil Structure**	**Gravel %**	**Consistence**		**Texture**	**Clay Films**	**Carbonate**	**Other**	**Hammer Test**
		Moist	**Dry**			**Wet**	**Dry**					
1.5	c,w	10YR4/2	10YR5/2	sg	<10	so,po	lo	fSL	none	e1		lo
11	c,w	10YR4/3	10YR5/3	1,f-m,sbk	<10	so,po	so	mSL	none	e1		so

Table 4-3. Upper Cave Creek/Apache Wash Watercourse Master Plan
Soil Pit Test Results (Continued)

29.5	a,w	10YR4/2	10YR5/2	1,f-m,sbk	50	so,po	so	mSL	none	e1, few fil, vtn dis		so
35	c,w	10YR4/3	10YR5/3	2,m-c,abk	<10	so,po	so-sh	L	none	e1-e2, com fil		so
70		10YR3/2	10YR5/3	sg	75	so,po	lo	LcS	none	e2, few fil, sparse vtn dis, I		so

Pit #:	14ROB2	Relative Age: M2			Pearthree Age: Holocene, maybe slightly older than other similar surfaces' pits				Artifacts found: sherds, agricultural area			
Depth (in)	Bound-ary	Munsell Color		Soil Structure	Gravel %	Consistence		Texture	Clay Films	Carbonate	Other	Hammer Test
		Moist	Dry			Wet	Dry					
1.5	c,w	10YR4/2	10YR6/4	2,m,pl	25	so,po	so-sh	fSL	v few	e0-e1		lo
4	c,w	10YR3/2	7.5YR5/3	2,m,sbk	<10	so,po	so	fSL	none	e0-e1, rare vtn dis		so
9.5		10YR4/3	10YR6/3	1,c,abk	10	so,po	sh	fSL		e1,sparse tn dis		so
36	c,w	10YR4/2	10YR6/3	1,m,sbk	25	so,po	so	mSL	none	e2, vtn dis, I		so
66		10YR3/2	10YR5/3	1,f,sbk	75	so,po	so	mSL	none	e2, vf fil, sparse tn dis	gypsum	so

Pit #:	14ROB3	Relative Age: 01			Pearthree Age: >300 ka				Artifacts found: none			
Depth (in)	Bound-ary	Munsell Color		Soil Structure	Gravel %	Consistence		Texture	Clay Films	Carbonate	Other	Hammer Test
		Moist	Dry			Wet	Dry					
2	c,w	7.5YR4/3	7.5YR5/4	2,c,sbk	10	ss,ps	sh-h	fSL	few	e0		lo
8	c,w	7.5YR5/4	7.5YR4/4	2,m-c,sbk	10	s,p	sh-h	SCL	few	e0		so
19.5	c,i	7.5YR5/4	7.5YR5/3	3,c,pr	25	s,p	h	SiC	abun	e1, f fil, vtn dis		so
26.5	c,w	7.5YR5/4	7.5YR5/4	2,f-m,sbk	75	ss,ps	sh-h	SiCL	com	e2, abun fil, vtn dis		so
30.5	c,i	7.5YR5/4	7.5YR5/4	1,f,sbk	50	s,p	sh	cSC	few	e1, f fil, vtn dis		mh

Pit #:	15ROB1	Relative Age: M2			Pearthree Age: late Holocene				Artifacts found: none			
Depth (in)	Bound-ary	Munsell Color		Soil Structure	Gravel %	Consistence		Texture	Clay Films	Carbonate	Other	Hammer Test
		Moist	Dry			Wet	Dry					
2.5	c,w	10YR3/4	10YR5/4	2,m,pl	<10	so,po	sh	fSL	v few	e1		so
4.5	c,i	7.5YR4/4	10YR5/4	1,f-m,sbk	25	so,po	so	mSL	few	e1		so
9.5	c,w	7.5YR4/4	7.5YR5/3	1,f,gr	50	so,po	so	mLS	v few	e1		mh

Table 4-3. Upper Cave Creek/Apache Wash Watercourse Master Plan
Soil Pit Test Results (Continued)

23.5	c,w	7.5YR5/3	7.5YR5/3	1,f,gr	75	so,po	so	LcS	v few	e1, abun fil, vtn dis, I		so
32	c,w	10YR3/3	7.5YR5/3	sg	>75	so,po	lo	S	none	e1, com fil, vtn dis		so
40.5	c,w	10YR3/2	10YR5/2	sg	>75	so,po	lo	LcS	none	e1, f fil, vtn dis		so
52	a,w	10YR4/4	10YR6/3	sg	>75	so,po	lo	S	none	e1,f fil, vtn dis		so
63	a,i	7.5YR4/6	10YR5/4	1,m,sbk	<10	so,po	so	LS	none	e1, com fil, vtn dis		so
66		10YR4/4	10YR6/4	sg	<10	so,po	so	LS	none	e2, f fil, tn dis		mh

Pit #:	16ROB1	Relative Age: M2			Pearthree Age: none				Artifacts found: sherds, cores, rock alignments, lithics			
Depth (in)	Boundary	Munsell Color		Soil Structure	Gravel %	Consistence		Texture	Clay Films	Carbonate	Other	Hammer Test
		Moist	Dry			Wet	Dry					
3	c,w	10YR3/4	10YR5/4	1,m,sbk	<10	ss,ps	so	SL	none	e0		so
12	c,w	10YR3/4	10YR5/4	m,sbk	<10	ss,po	so	LfS	none	e2, vf fil,vtn dis		so
21.5	c,w	10YR3/3	7.5YR5/4	1,f-m,sbk	25	so,po	so	LcS	v few	e2, f fil,vtn dis		so
34.5	c,w	7.5YR4/6	7.5YR5/4	1,f-m,gr	50	so,po	so	SL	v few	e2,f fil, tn dis		so-lo
44.5	c,w	7.5YR4/6	7.5YR5/4	1,f,gr	50	so,po	so	LcS	none	e2, f fil,tn dis		so-lo
58	c,w	7.5YR3/4	7.5YR6/4	2,c,sbk	50	so,po	sh-h	LS	few-com	e2-3, vf fil, tn dis, I		mh
67		7.5YR4/4	7.5YR5/3	1,f,sbk	75	so,po	so	LmS	few	e2-e3, f fil, vtn dis		mh

Pit #:	16ROB2	Relative Age: M1			Pearthree Age: none				Artifacts found: sherds, fire-cracked rock			
Depth (in)	Boundary	Munsell Color		Soil Structure	Gravel %	Consistence		Texture	Clay Films	Carbonate	Other	Hammer Test
		Moist	Dry			Wet	Dry					
3.5	c,w	7.5YR4/6	10YR5/4	2,m,sbk	10	vss,vps	sh	fSL	v few	e1,vf fil, sparse vtn dis		so-lo
7.5	c,w	7.5YR4/4	7.5YR5/4	1,f-m,sbk	10	so,po	so	fSL	v few	e2, f fil, vtn dis		so
13	c,w	10YR4/3	10YR5/4	1,f,sbk	10	so,po	so-sh	fSC	v few	e2, f fil, vtn dis		so
21	c,w	7.5YR4/4	10YR5/4	1,f-m,sbk	10	vss,vps	so	L	v few	e2, f fil, sparse vtn dis		so
30	c,w	7.5YR4/4	7.5YR5/4	1,f-m,sbk	25	so,po	so	fSL	v few	e2,f fil, com tn con		so-lo
46	g,i	7.5YR4/4	7.5YR5/4	2,m,sbk	<10	so,po	so	SL	none	e2, f fil, com tn con		so
70		7.5YR4/6	7.5YR5/4	3,c,abk	25-50	s,p	vh	SCL	abun	e2, com fil, tn con,		mh

Table 4-3. Upper Cave Creek/Apache Wash Watercourse Master Plan
Soil Pit Test Results (Continued)

Pit #:	16ROB3	Relative Age: 01			Pearthree Age: mid Pleist at least, maybe 500 ka				Artifacts found: none			
Depth (in)	Bound-ary	Munsell Color		Soil Structure	Gravel %	Consistence		Texture	Clay Films	Carbonate	Other	Hammer Test
		Moist	Dry			Wet	Dry					
2.5	c,w	7.5YR4/6	7.5YR5/8	2,f-m,pl	25	s,p	sh-h	CL	com	e0		so-lo
5	c,w	7.5YR4/6	7.5YR4/8	2,c,abk	25	s,p	sh-h	CL	com	e0		so
19	g,w	5YR4/8	5YR4/8	3,c-vc,pr	10	vs,p	vh	SiCL	abun	e0-1,f fil,vtn dis		so
31	g,i	5YR4/6	7.5YR5/6	2,m,sbk	75	s,ps	h	SCL	com	e2, vtn con, patchy moderate cem		mh
56	c,w	5YR5/3	5YR7/3	2,m,sbk	50	ss,po	vh	SL	none	e3, laminated, IV		eh
68	c,w	7.5YR3/2	7.5YR6/3	sg	75	ss,po	lo	SL	none	e2, abun fil,vtn dis,patchy cem		so
78		7.5YR3/3	7.5YR6/3	1,f,gr	50	ss,po	sh	SL	none	gypsum, e1, com fil, vtn dis		so

Pit #:	18LOB1	Relative Age: M2			Pearthree Age: Holocene – latest Pleistocene				Artifacts found: none			
Depth (in)	Bound-ary	Munsell Color		Soil Structure	Gravel %	Consistence		Texture	Clay Films	Carbonate	Other	Hammer Test
		Moist	Dry			Wet	Dry					
1.5	c,w	7.5YR4/4	7.5YR5/4	1,f-m,sbk	25	so,po	so	mSL	v few	e0-1		so-lo
4.5	c,w	7.5YR4/4	7.5YR5/6	1,f,gr	25	so,po	so	mSL	v few	e1,vf fil		so
11	g,i	7.5YR4/6	7.5YR5/6	1,f-m,gr	25	so,ps	so	L	v few	e1,vf fil, vtn dis		so
69		7.5YR4/4	7.5YR6/4	1,f,gr	50	so,ps	so	SL	v few	e2,vf fil, vtn dis, I-II		so

Pit #:	18LOB2	Relative Age: 02			Pearthree Age: ~100 ka, late Pleistocene				Artifacts found: ground stones, sherds			
Depth (in)	Bound-ary	Munsell Color		Soil Structure	Gravel %	Consistence		Texture	Clay Films	Carbonate	Other	Hammer Test
		Moist	Dry			Wet	Dry					
2	c,w	7.5YR4/6	7.5YR6/6	1,f-m,sbk	10	ss,ps	so	SCL	v few	e1		so-lo
9	g,w	7.5YR4/6	7.5YR5/6	1,f-m,gr	25	ss,p	so	mSC	few	e0		so-lo
21.5	g,w	7.5YR5/6	7.5YR5/6	2,m,pr	25	ss,vp	sh-h	C with fS	com	e0		so
34.5	g,w	7.5YR5/4	7.5YR5/6	2,f-m,sbk	25	ss,ps	h	L	abun	e2,com fil,tn dis		h

Table 4-3. Upper Cave Creek/Apache Wash Watercourse Master Plan
Soil Pit Test Results (Continued)

47	g,w	7.5YR5/6	7.5YR5/6	1,f,gr	50	ss,ps	sh-h	L	com	e2,com fil,vtn dis		h
55.5	c,i	7.5YR4/6	7.5YR6/4	1,f,gr	75	ss,ps	sh-h	L	few	e1,f fil,vtn dis		mh
63		7.5YR5/6	7.5YR7/2	m	75	so,po	h	LS	v few	e3, strongly? cem, III		h

Pit #:	18LOB3	Relative Age: 01			Pearthree Age: ~500 ka				Artifacts found: lithics			
Depth (in)	Bound-ary	Munsell Color		Soil Structure	Gravel %	Consistence		Texture	Clay Films	Carbonate	Other	Hammer Test
		Moist	Dry			Wet	Dry					
1.5	c,w	7.5YR5/6	7.5YR6/4	1,f,sbk	25	ss,ps	so	SiCL	few	e1		so
3.5	c,w	7.5YR4/6	5YR6/4	2,f-m,sbk	<10	ss,ps	sh	SiCL	com	e1		so
7.5	c,i	7.5YR4/6	7.5YR6/6	2,m,gr	25	ss,ps	so-sh	cSCL	few	e2,vtn dis		so
32.5	c,w	7.5YR8/2	2.5YR8/1	1,f-m,sbk, m	50	so,po	eh	CcSL	none	e3,stongly cem, IV		h
50.5	g,w	7.5YR7/3	7.5YR8/2	sg - m	50-75	so,po	eh	LcS	none	e3,stongly cem		h
57.5	c,w	7.5YR4/4	7.5YR6/3	sg	75	so,po	lo	LcS	none	e2,tk dis	gypsum	so
65		10YR3/2	10YR4/2	sg	>75	so,po	lo	LcS	none	e0		lo

Pit #:	18ROB1	Relative Age: Y			Pearthree Age: late Holocene				Artifacts found: none			
Depth (in)	Bound-ary	Munsell Color		Soil Structure	Gravel %	Consistence		Texture	Clay Films	Carbonate	Other	Hammer Test
		Moist	Dry			Wet	Dry					
1.5	a,w	7.5YR4/3	7.5YR5/3	1,f-m,pl	<10	so,po	so-sh	LfS	none	e1		lo
5	c,w	7.5YR3/3	10YR5/3	1,m,sbk	<10	so,po	so	fSL	none	e1		so
9.5	c,w	7.5YR4/3	7.5YR5/3	1,m,sbk	10	so,po	so	LmS	v few	e1,com fil,vtn dis		so
19	c,i	7.5YR4/3	7.5YR5/3	1,f-m,sbk	10	so,po	so	fSL	none	e1,f fil,vtn dis		lo
30	g,i	7.5YR4/4	7.5YR5/3	1,f-m,gr	75	so,po	so	LcS	v few	e2,com fil,tn dis	gypsum	mh
51	g,w	7.5YR3/3	7.5YR5/2	sg	>75	so,po	lo	LmS	none	e2,f fil,vtn dis	gypsum	mh
67		7.5YR4/4	7.5YR5/4	sg	75	so,po	lo	LcS	none	e1,f fil,vtn dis	gypsum	so

Table 4-3. Upper Cave Creek/Apache Wash Watercourse Master Plan
Soil Pit Test Results (Continued)

Pit #:	18ROB2	Relative Age: M2			Pearthree Age: none				Artifacts found: none			
Depth (in)	Boundary	Munsell Color		Soil Structure	Gravel %	Consistence		Texture	Clay Films	Carbonate	Other	Hammer Test
		Moist	Dry			Wet	Dry					
1.5	c,w	10YR3/4	10YR5/3	1,m-c,pl	10	so,po	so	SL	v few	e0		so
7	c,w	10YR3/4	10YR5/3	1,f,sbk	10-25	ss,ps	so	LfS	v few	e0-1, sparse vtn dis		so
21.5	c,w	7.5YR3/3	7.5YR5/3	1,f,sbk	75	ss,po	so	SL	none	e1, vf fil,vtn dis		lo
42		7.5YR3/3	7.5YR5/2	sg	50	so,po	lo	LS	none	e1,vf fil, sparse vtn dis		lo

Pit #:	19LOB1	Relative Age: M2/Y			Pearthree Age: late Pleistocene + poss. '78 flood deposit				Artifacts found: possible old backhoe blade-made boulder alignments			
Depth (in)	Boundary	Munsell Color		Soil Structure	Gravel %	Consistence		Texture	Clay Films	Carbonate	Other	Hammer Test
		Moist	Dry			Wet	Dry					
1	a,s-w	7.5YR4/4	10YR4/4	sg	25	ss,ps	lo	mSCL	v few	e0	75%wood-flood debris	lo
3	c,w	7.5YR4/6	7.5YR6/4	1-2,f-m,pl	50	ss,ps	so-sh	mSCL	few	e2,com fil, vtn dis		so
5	c,w	7.5YR4/6	7.5YR5/6	1,f-m,sbk	25	ss,ps	sh	SCL	com	e2,com fil, vtn dis		so
8.25	c-g,i	7.5YR4/6	7.5YR4/6	1,f-m,sbk	75	so,ps	h	SCL	com	e2,com fil, tn dis		mh
25.5	g,i	7.5YR4/4	7.5YR8/1	1,f-m,sbk	75	ss,po	vh	LcS	v few	e2,tn dis, weakly cem, III		h
38.5	g,w	7.5YR4/4	7.5YR5/4	2,f-m,sbk	>75	so,po	h	LcS	v few	e2,vtn dis, weakly cem		h
57		7.5YR4/6	5YR6/4	1,f-m,sbk	75	so,po	so	LS	v few	e1,com fil, vtn dis		

Pit #:	19LOB2	Relative Age: 02			Pearthree Age: mid Pleistocene				Artifacts found: none			
Depth (in)	Boundary	Munsell Color		Soil Structure	Gravel %	Consistence		Texture	Clay Films	Carbonate	Other	Hammer Test
		Moist	Dry			Wet	Dry					
2	c,w	7.5YR4/4	7.5YR5/6	1,f-m,sbk	<10	ss,p	so-sh	mSCL	v few	e1		lo
4.5	c,w	7.5YR4/4	7.5YR6/4	1,m-c,sbk	<10	so,ps	so-sh	SCL	few	e1		so
15	c,w	7.5YR4/6	7.5YR5/4	2,m-c,gr	10	ss,ps	h	SCL	abun	e0		so
24	g,w	7.5YR4/6	7.5YR5/6	2,f-m,gr	0	s,p	h	CL	abun	e1,abun fil		mh
36.5	c,w	7.5YR4/6	7.5YR5/6	2,f-m,sbk	0	ss,ps	h	SCL	com	e1,f fil		mh

Table 4-3. Upper Cave Creek/Apache Wash Watercourse Master Plan
Soil Pit Test Results (Continued)

50	g,w	7.5YR6/4	7.5YR7/2	2,m,sbk - m	0	ss,ps	sh	mSL	few	e2-3,cem,III		h
56	c,w	7.5YR4/4	7.5YR7/3	2,c,sbk	0	so,ps	vh	SL	v few	e2,weakly cem		h
60.5	c,w	7.5YR5/3	7.5YR6/3	2,m-c,sbk	50	ss,ps	so-sh	mSL	v few	e2,vtn dis		mh
66.5		7.5YR4/4	7.5YR5/4	sg	50	so,po	lo	LcS	none	e1,com fil, vtn dis		mh

Pit #:	20ROB1	**Relative Age: Y**			**Pearthree Age: none**				**Artifacts found: possible ground stone tools, possibly fire cracked rocks**			
Depth (in)	**Bound-ary**	**Munsell Color**		**Soil Structure**	**Gravel %**	**Consistence**		**Texture**	**Clay Films**	**Carbonate**	**Other**	**Hammer Test**
		Moist	**Dry**			**Wet**	**Dry**					
1.25	a,s	10YR4/3	10YR7/3	1,f-m,pl	0	s,p	sh-h	SiC	none	e2		
4.5	a,w	10YR4/3	10YR7/3	2,m-c,pl	0	ss,ps	sh-h	SiCL	none	e2		
7.25	a,s	10YR6/3	10YR7/3	1,f-m,sbk	0		sh	SiC	few	e2		
8.25	a,s	10YR3/4	10YR6/3	1,f,pl	0	s,p	sh	SiC	few	e2		
10	a,s	10YR3/4	10YR6/4	1,f-m,sbk	0	ss,ps	so	SiCL	none	e2		
12.75	c,w	10YR4/3	10YR6/4	1,f-m,sbk	0	ss,ps	sh	SiCL	none	e2		
15	a,s	10YR3/3	10YR5/4	1,f,pl	0	so,po	sh-h	Si	none	e1	micaceous, x-beds	
17.25	a,s	10YR3/4	10YR6/4	1,f-m,pl	0	so,po	h-vh	Si	few	e2	less micaceous	
22	a,w	10YR4/3	10YR7/3 clasts, 10YR6/4 matrix	m	0	ss,ps	h-vh	SiCL	none	e2	35% clay rip-up clasts	
28	a,w	10YR3/4	10YR6/4	m	0	ss,ps	sh-h	SiCL	none	e2	5-10% clay rip-up clasts	
36	a,s	10YR3/4	10YR5/3 sand, 10YR6/4 silt	m	0	ss,ps	sh-h	cS-SiCL	none	e2	laminated cS grades to Si	
41.5	a,s	10YR4/3	10YR6/2 sand, 10YR7/3 silt	m	0	ss,ps	sh-h	cS-SiCL	none	e2	laminated cS grades to Si	
50.5	a,s	10YR4/3	10YR5/4	1,vf-f,sbk	0	s,p	sh-h	SiC	none	e2		
68.5	a,w	10YR6/4	10YR7/3	1,f,sbk	0	so,po	so-sh	fSL	none	e2	micaceous	
82.5	a,w	10YR4/4	10YR5/4 silt, 7.5YR4/3	m	0	ss,sp	sh	cS-SiCL	none	e2	micaceous	

Table 4-3. Upper Cave Creek/Apache Wash Watercourse Master Plan
Soil Pit Test Results (Continued)

			gravel									
89		10YR3/3	10YR5/4	m	0	so,po		fSL-cS	none	e2	Si cap over cS and gravel	

Pit #:	AW1LOB1	Relative Age: none			Pearthree Age: none				Artifacts found: none			
Depth (in)	Boundary	Munsell Color Moist	Munsell Color Dry	Soil Structure	Gravel %	Consistence Wet	Consistence Dry	Texture	Clay Films	Carbonate	Other	Hammer Test
0.6	a,s	7.5YR 4/3	7.5YR 6/4	1,m,pl	<10	so-po, vfr	lo	LS	none	no CO3, slight eff.		soft
3.6	c,w	7.5YR 4/6	7.5YR 6/4	3,m,c,sbk	<10	so-ps, fr	so	SL	none	ves.,no CO3,slight eff		soft
7.2	a,I	7.5YR 5/4	7.5YR 6/4	2,m,sbk	<10	so-ps, fr	so	L	none	isolated CO3 flecks, strong eff.		soft
15.6	c,I	7.5YR 5/4	7.5YR 8/2	2,m,sbk	25	so-po, vfr	h	SL	1,f	ves., CO3 nod., violently eff.		hard
12	c,w	7.5YR 5/4	7.5YR 7/2	1,vf,sbk	50	so-po, vfr	vh	LS	v1	ves., thck/cont. rind, viol eff.		hard-extr.
43.2	none	7.5YR 6/4	7.5YR 7/2	sg,vf	75	so-po, vfr	sh	LS	v1,f	strong eff., CO3 in matrix but horiz. not indurated		hard-extr.

Pit #:	AW2LOB1	Relative Age: none			Pearthree Age: none				Artifacts found: none			
Depth (in)	Boundary	Munsell Color Moist	Munsell Color Dry	Soil Structure	Gravel %	Consistence Wet	Consistence Dry	Texture	Clay Films	Carbonate	Other	Hammer Test
1.2	a,s	7.5YR 5/6	7.5YR 5/6	2,f,pl	10	s-fi	so	SiCL	none	eff.		none
22.8	c,w	7.5YR 5/6	7.5YR 5/4	2,m,sbk	<10	ss,p-fr	vh	SiCL	1,2,f	strong eff.		soft
33.6	c,s	7.5YR 5/6	7.5YR 5/4	2,m,abk	<10	s,p-fr	vh	SiC	v1,f	flecks, nodules, thin, discont., strong eff.		hard
53.4	c,w	7.5YR 6/4	7.5YR 6/4	2,f,abk	<10	ss,p-fr	sh	SiL	v1,f	thin/discont. CO3 w/ nod., viol. eff.		hard
78	none	7.5YR 6/4	7.5YR 7/2	2,m,sbk	<10	ss,p-fr	sh	SiL	v1,f	thin/disc/small nod., slight vesic., viol eff.		hard

Table 4-3. Upper Cave Creek/Apache Wash Watercourse Master Plan
Soil Pit Test Results (Continued)

Pit #:	AW2ROB1	Relative Age: none			Pearthree Age: none				Artifacts found: none			
Depth (in)	Bound-ary	Munsell Color Moist	Munsell Color Dry	Soil Structure	Gravel %	Consistence Wet	Consistence Dry	Texture	Clay Films	Carbonate	Other	Hammer Test
1	c,w	10YR 4/6	7.5YR 6/4	2,m,pl	10	ss,ps-fr	so	L	none	ves., no CO3, no eff.		none
9	a,I	7.5YR 5/6	7.5YR 6/6	2,m,abk	25	ss,p-fr	sh	L	none	no CO3, no eff.		soft
25	a,s	7.5YR 6/6	7.5YR 5/6	f,sbk	50	ss,p-fr	sh	SL	2,f	CO3 fila. In finer matrix, thin/disc CO3, clasts, strong eff.	clay film increase with depth and locally	soft
66+	none	7.5YR 7/4	7.5YR 8/2	m,sbk	50,25	so,po-vfr	h,sh	LS	1,f,none	ves., CO3 in matrix, thin/disc coat, viol eff., mod laminations		very hard

Pit #:	AW2ROB2	Relative Age: none			Pearthree Age: none				Artifacts found: none			
Depth (in)	Bound-ary	Munsell Color Moist	Munsell Color Dry	Soil Structure	Gravel %	Consistence Wet	Consistence Dry	Texture	Clay Films	Carbonate	Other	Hammer Test
0.7874	a,s	7.5YR 4/4	7.5YR 5/4	f,pl	<10	s,p-fr	sh	SiCL/SiL	v1	none	surface gravels scattered as part of pavement	none
7.874	sharp,w	10YR 4/4	7.5YR 5/6	2,m,sbk	25	ss,vp-fr	h	SiCL	1,f	none	few clay films	none
26.772	a,w	7.5YR 4/6	7.5YR 5/6	2,c,abk	10,25	ss,vp-fi	vh	SiCL	1,f	none	few clay films	mod. Hard
39.764	a,w	10 YR 4/4	10YR 4/6	c,abk	10	s,vp-fi,vfi	vh	SiC	1,f	few CF, eff.		hard
47.244	a,w	7.5 YR 4/6	7.5YR 5/6	2,f,sbk	50	s/vs,vp-fi	so	SiC	2,d	many CF, thin/disc CO3 on clasts, strong eff.		hard
55.118	c,w	7.5YR 6/6	7.5YR 6/6	m	50	ss,vp-fi	h/vh	SCL	2,f	common CF, disc. CO3 on clasts, matrix, viol eff.		hard
70.866+	c,s	7.5YR 6/4	7.5YR 6/8	m	50,75	ss,vp-fi	vh/eh	SCL	1,f	CO3 cementing agent, disc. Coatings on clasts, violent eff.		extr. Hard

Table 4-3. Upper Cave Creek/Apache Wash Watercourse Master Plan
Soil Pit Test Results (Continued)

Pit #:	AW3 ROB1	Relative Age: none			Pearthree Age: none				Artifacts found: none			
Depth (in)	Bound-ary	Munsell Color Moist	Munsell Color Dry	Soil Structure	Gravel %	Consistence Wet	Consistence Dry	Texture	Clay Films	Carbonate	Other	Hammer Test
9.6	c,w	7.5YR 4/4	7.5YR 5/4	sg	25-50	so/ss, po	lo	LS	none	str. eff., no visible CO3		soft
13.2	c,w	7.5YR 4/3	7.5YR 6/4	m,*	<10	ss,ps-fr	sh	LS	none	eff., occ v. thin/disc. CO3	breaks to 1 m sbk	soft
24	g,w	7.5YR 4/3	7.5YR 6/4	m,*	<10	ss,po	sh	SL	none	str. eff. thin/disc CO3	*breaks to 2 med sbk	mod hard
49.2	d,I	7.5YR 5/4	7.5YR 6/4	m,*	<10	so,po	so	LS	none	str. eff., thin/disc CO3	breaks to 1m sbk	soft-mod hard
82.8	none	7.5YR 4/4	7.5YR 5/4	m	50	so,po	so	LS	none	viol. eff., thin/disc. CO3		mod hard

Pit #:	AW5 ROB1	Relative Age: none			Pearthree Age: none				Artifacts found: none			
Depth (in)	Bound-ary	Munsell Color Moist	Munsell Color Dry	Soil Structure	Gravel %	Consistence Wet	Consistence Dry	Texture	Clay Films	Carbonate	Other	Hammer Test
2.4	a,w	7.5YR 3/4	7.5YR 5/4	1,c,sbk	25-50	ss,ps	h	L	none	no eff., no carb.		ex soft
14.4	c,w	7.5YR 4/4	7.5YR 5/6	1,c/m,sbk	36458	ss,ps	sh	L	1,f	no eff., no carb.		soft
28.8	a,w	7.5YR 4/4	7.5YR 4/4	1,m,sbk	25	s,p	so	CL	1,f	eff., thin/disc on pebbles		soft
33.6	a,w	10YR 8/4	10YR 8/2	m	10	none	sh,eh	none	none	viol eff., ~95% CO3		hard
48	c,I	10YR 4/4	10YR 6/3	2,m,sbk	36458	ss,ps	sh,vh	SL	none	strong eff., CO3 whitens matrix, nod. and vert. concret. several cm across		hard
64.8	c,w	7.5YR 4/6	7.5YR 5/6	1,m,sbk	25	ss,ps	so,sh	L	none	strong eff., disc. CO3 fims on peb.		mod. Hard
76.8	none	7.5YR 4/6	7.5YR 5/3	m	75	so,po	lo	LS	none	viol eff., many clasts w/ cont. CO3 (local), some with well-dev'd pendnts		hard to ex.

Table 4-3. Upper Cave Creek/Apache Wash Watercourse Master Plan
Soil Pit Test Results (Continued)

Pit #:	DHW ROB1	Relative Age: none			Pearthree Age: none				Artifacts found: none			
Depth (in)	Bound-ary	Munsell Color		Soil Structure	Gravel %	Consistence		Texture	Clay Films	Carbonate	Other	Hammer Test
		Moist	Dry			Wet	Dry					
11.5	a,s	7.5YR 4/6	7.5YR 5/6	1,c,pl/sbk	<10	ss,ps-fr	so	L	none	No vis CO3, slight to strong eff.		soft
23.5	a,w	10YR 4/6	10YR 5/8	1,m,sbk	10	ss,p-fr	sh	SCL	none	very thin/disc CO3 coat on clasts, strong eff.		soft
53.5	a,w	7.5YR 5/6	7.5YR 6/6	1,c,sbk	<10	s,p-fr	sh	SiCL	v1,f	disc. Flecks , very thin CO3 coat on clasts, strong eff.		soft
76.5	none	7.5YR 5/6	7.5YR 5/6	sg,vf	50	so,po-vfr	lo	LS	2,f	some disc. Films, viol eff.		very soft

Pit #:	PWLOB1	Relative Age: none			Pearthree Age: none				Artifacts found: none			
Depth (in)	Bound-ary	Munsell Color		Soil Structure	Gravel %	Consistence		Texture	Clay Films	Carbonate	Other	Hammer Test
		Moist	Dry			Wet	Dry					
11	a,l	7.5YR 4/4	7.5YR 6/6	1,c,sbk	25	so,po-vfr	sh	SiCL	v1,f	no eff.		soft
27	a,w	7.5YR 4/6	7.5YR 5/6	1,vf,sbk	50	so,po-vfr	h	LS	v1,f	thin/disc, strong eff.		soft/mod har
55	g,w	7.5YR 5/6	7.5YR 6/4	2/sg,f,abk	75	ss,ps-vfr	lo	L	v1,f	viol eff., disc to nearly cont./thin coat on clasts	sg structure some more fg	hard
75	none	5YR 4/8	5YR 5/6	2/sg, f,sbk	75	ss,ps-vfr	lo	LS	2,d	none to thin/disc., strong eff.	clay binds gravel	hard

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 indicates the potential for future flooding. In addition, mapping these surfaces constrains 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_m) were deposited by the channels of a very large, Pleistocene-aged *alluvial fan* that was the predecessor of Cave 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 processes. The geologic record also indicates that portions of Cave Creek, Apache Wash and Paradise Wash have been subject to channel *avulsion*s for at least the past 10,000 years. All of the streams in the study area have experienced net degradation over the last 700,000 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 rate 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, but within the range of long-term geologic rates of incision.

  Lateral change. Channel movement recorded in historical aerial photographs is not significantly different in rate or scale than the rate suggested by interpretation of the geomorphic surficial mapping. 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.

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

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

  Cave Creek and its major tributaries 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 (slower) lateral erosion.

- Channel processes. Geologic information often provides information on types of stream and geomorphic processes active in the study reach that are currently obscured by historical or human interference along the stream corridor.

  Entrenchment near the Wheeler and Tanner sand and gravel operations on Cave Creek has increased the capacity of the main channel. Geologic evidence preserved in the soils and surficial characteristics indicate that this reach of Cave Creek was subject to channel avulsions and had a multiple channel pattern prior to incision. If this reach were to recover from the human-induced incision, it would probably be subject once again to avulsions and rapid bank erosion.

- 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_l 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_l and Q_{yl}) and moderate (Q_{yl}) heights above the active channel generally have minimal potential for significant flood inundation. However, because the deposits associated with the lower set of these terraces (Q_{yl}) 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 Analysis Techniques

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 geomorphology approaches are applicable to the stream types in the study area, and were applied using the data described previously. The following quantitative geomorphic analyses are presented in this section:

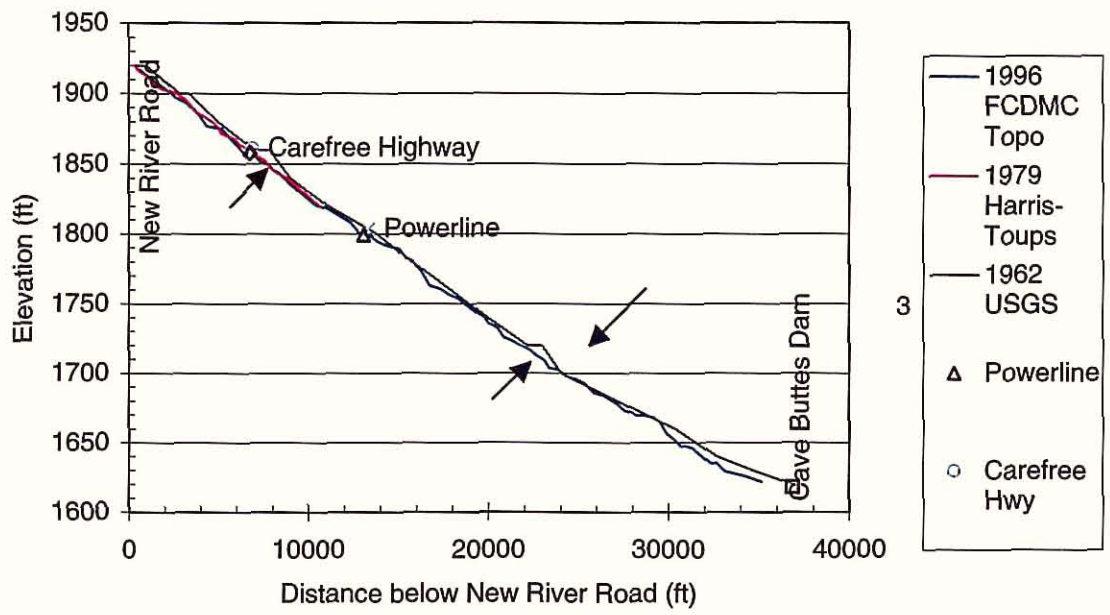
- Longitudinal Profile
- Bankfull Discharge
- River Classification Methods
- Hydraulic Geometry/Regime Equation Methods

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. The longitudinal profile provides some information on expected lateral stability. Reaches with lower slopes than adjacent reaches will experience net deposition, and bank erosion associated with braiding and *avulsions*. Where sequential profiles indicate channel incision has occurred, bank erosion due to undercutting and bank collapse may be expected.

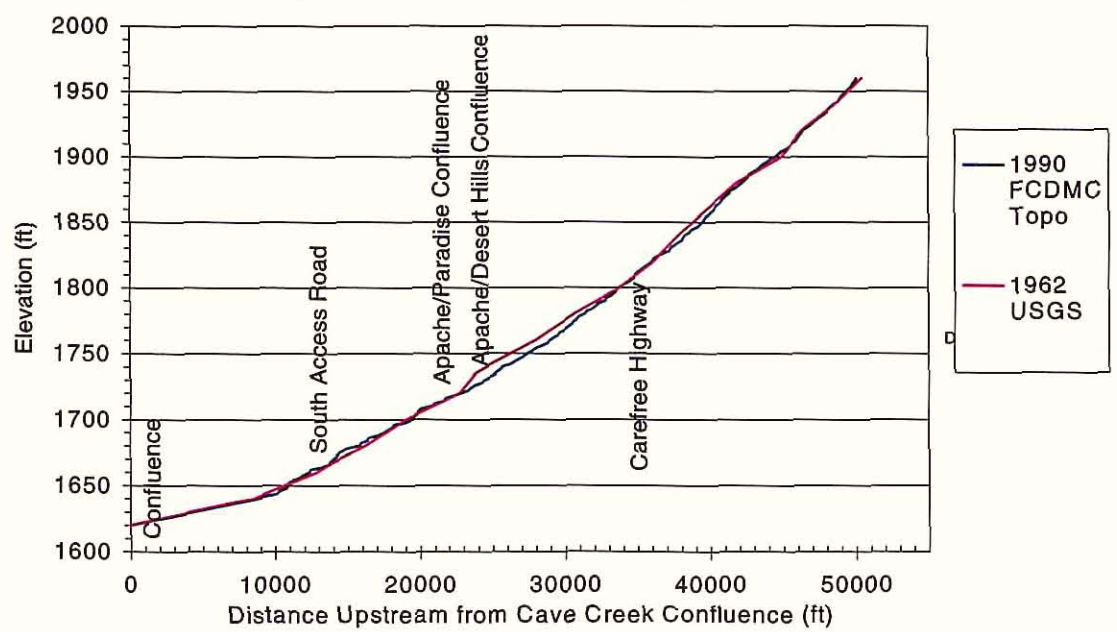
Cave Creek. The longitudinal profile based on the available topographic mapping for the Cave Creek study reach is shown in Figure 4-47. Overall, the profile exhibits the expected concave upward shape. However, both the 1962 and 1996 profiles are somewhat irregular. Two prominent upward bulges in the 1962 profile, indicated by upward pointing arrows on Figure 4-47, are probably due to sediment deposition at the mouths of tributaries that have high sediment loads. The greater number of irregularities in the 1996 profile relative to the 1962 mapping are mostly due to the smaller contour interval, but may also reflect local slope adjustments to in-stream mining. The moderate flattening of the channel profile upstream of Cave Buttes Dam indicates that the stream experienced net deposition in what became the impoundment area long before construction of the dams. Note that the transition from the single channel to the multiple channel avulsive reach, indicated by the downward pointing arrow on Figure 4-47, occurs where the slope begins to decrease.

Figure 4-47. Cave Creek Longitudinal Profile



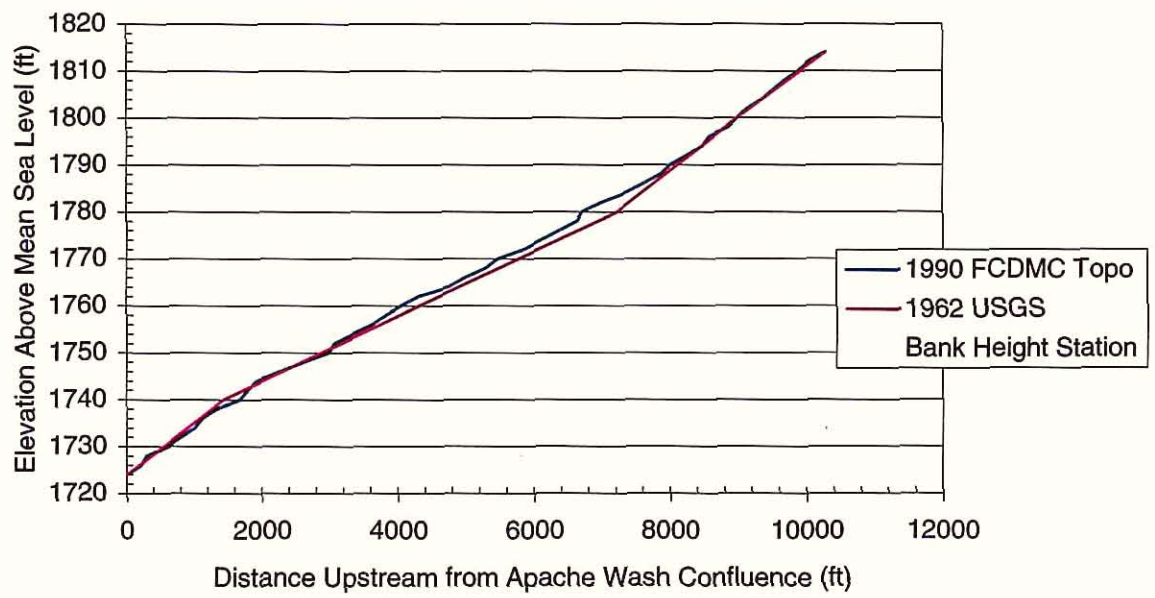
Apache Wash. The longitudinal profile based on the available topographic mapping for the Apache Wash study reach is shown in Figure 4-48. Overall, the profile exhibits the expected concave upward shape. The more irregular 1990 profile relative to the 1962 profile is due primarily to the smaller contour interval which better depicts the *pool* and *riffle* topography, local *scour* holes, and areas of localized deposition. The flattening of the channel profile upstream of Cave Buttes Dam is more pronounced than the slope adjustment for Cave Creek due to the smaller drainage area, the steeper slope upstream, and the control of slope provided by Cave Creek below the confluence.

Figure 4-48. Longitudinal Profile - Apache Wash



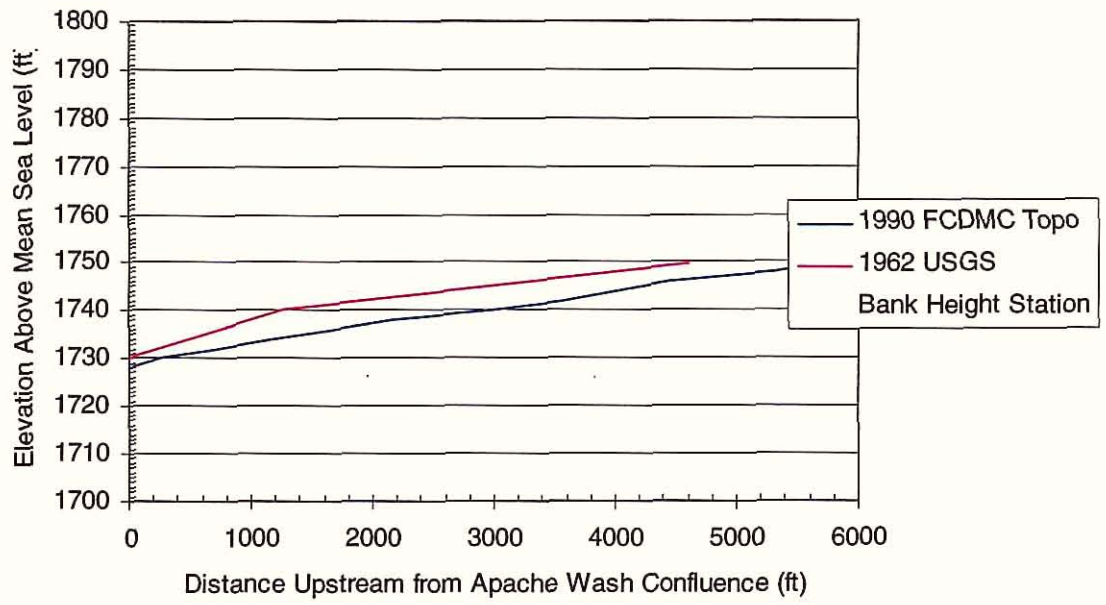
Paradise Wash. The longitudinal profile based on the available topographic mapping for the Paradise Wash study reach is shown in Figure 4-49. Unlike Cave Creek and Apache Wash profiles, the profile of Paradise Wash exhibits a compound "S" shape. The upstream portion of the profile has the expected concave upward shape. However, near the Apache Wash confluence the slope steepens, creating a convex shape in both the 1962 and 1990 profiles. The steeper slope near the confluence is best interpreted as an adjustment to past *entrenchment* along Apache Wash. Given that no major degradation was observed in the historical record for Paradise Wash (Chapter 3), the entrenchment of Apache Wash probably occurred prior to 1900, and possibly much earlier. Furthermore, since the slope adjustment has only affected the profile of Paradise Wash over about a 2,000 feet long reach, it can be concluded that Paradise Wash is relatively resistant to vertical adjustments and long-term *scour*, and/or that the slope adjustment was initiated in recent geologic time. The more irregular 1990 profile relative to the 1962 profile is mostly due to the smaller contour interval which better depicts the pool and riffle topography, local scour holes, and areas of localized deposition.

Figure 4-49. Longitudinal Profile - Paradise Wash



Desert Hills Wash. The profile of Desert Hills Wash is too short to draw any meaningful conclusions regarding the channel morphology or long-term trends. A slight increase in slope near the Apache Wash confluence could point to an adjustment to prehistoric entrenchment of Apache Wash, as indicated on the Paradise Wash profile. However, the fact that the 1990 profile is lower than the 1962 profile indicates a historical slope adjustment has also occurred on this system.

Figure 4-50. Longitudinal Profile - Desert Hills



Summary. Longitudinal profile analyses of Cave Creek and its three tributaries in the study area indicate that there has been historical degradation, although some local reaches have experienced net aggradation in the past 40 years. No natural grade control was observed in the beds of the stream channels. Bedrock crops out in the banks of Apache Wash in Reaches 3 and 4, but scour holes in those reaches indicate that bedrock does not significantly affect bed elevations, at least in the short term. Grade control is provided by the concrete box culverts on Apache Wash and Paradise Wash at the Carefree Highway, although no evidence of progressive long-term degradation was observed at the downstream sides of these structures since 1984.

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; that is, 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). Because many geomorphic analyses are based on the bankfull discharge, an evaluation of the flow rate and frequency of bankfull discharge for Cave Creek and its tributaries was performed.

Methodology. Bankfull discharges were estimated using a combination of field and HEC-RAS data. HEC-RAS models were developed for this study from HEC-2 models prepared for Floodplain Delineation Studies of Cave Creek (GVSCE, 1996; Willdan, 1996) and its tributaries (Jerry R. Jones, 1992) 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.[2] 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 2-9).

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 geometry values indicate the capacity of the channel and how the 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 velocity and the bankfull width/depth ratio are provided for each of the four major streams analyzed (Figures 4-51 to 4-62).[3] 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).

Cave Creek. A plot of estimated bankfull *discharge* for each HEC-RAS cross section is shown in Figure 4-51. Table 4-4 shows the reach-averaged hydraulic values associated with bankfull discharge, as well as an estimate of the recurrence interval of the bankfull discharge.

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[2] 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.

[3] In Figures 4-51 to 4-62, the gaps in the discontinuous lines connecting values for each cross section denote the beginning and end of the reaches defined in Chapter 2 and used throughout the report.

Figure 4-51. Cave Creek Estimated Bankfull Discharge (cfs)

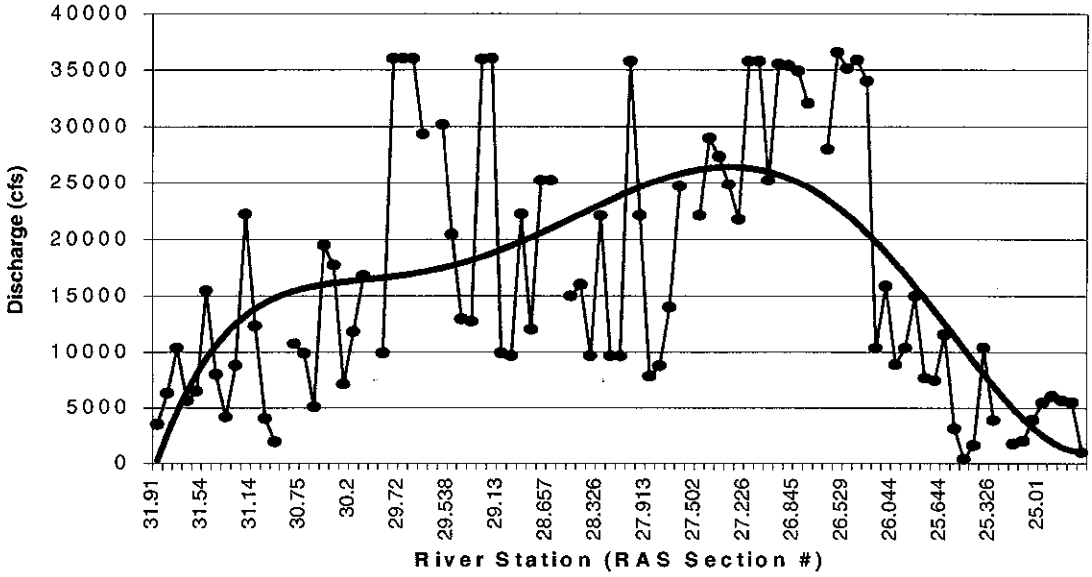


Table 4-4. Upper Cave Creek/Apache Wash Watercourse Master Plan Reach-Average Bankfull Discharge Hydraulic Variables – Cave Creek							
Reach	**Recurrence Interval (yrs)**	**Channel Discharge (cfs)**	**Total Discharge (cfs)**	**Top Width Channel (ft)**	**Maximum Channel Depth (ft)**	**Hydraulic Radius Channel (ft)**	**Mean Channel Velocity (ft/s)**
SR	45	13,100	18,800	270	9.8	5.6	9.5
1	55	21,600	22,100	319	11.0	6.8	11.5
2	35	16,100	16,500	227	10.9	6.3	11.5
3	94	30,200	32,600	355	11.5	7.4	12.3
4	65	16,600	25,100	263	10.0	5.7	9.5
5	13	4,500	7,600	180	7.3	4.1	7.0

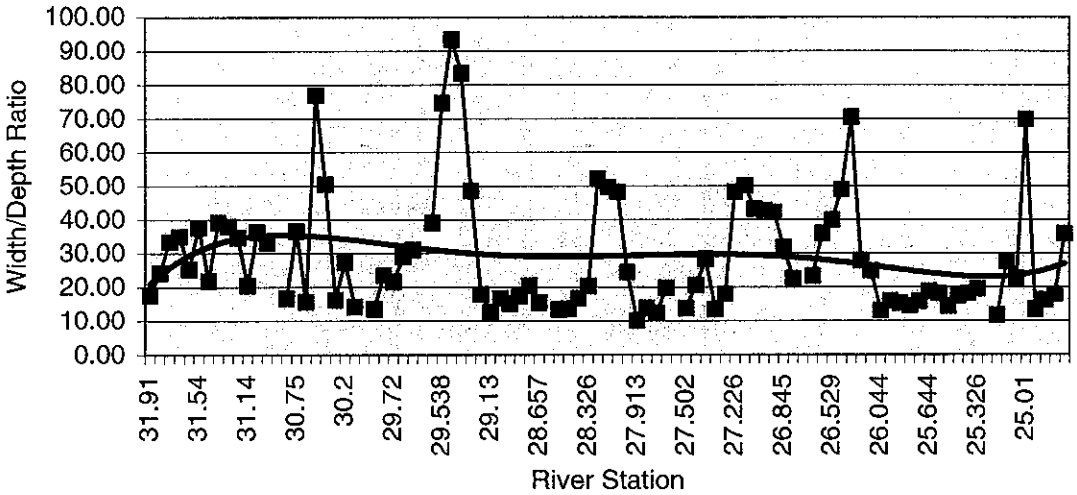
Note: Channel *discharge* is the flow contained in the main channel when the *bankfull elevation* is reached. The total *discharge* indicates the flow contained in the entire cross section including low overbank areas when the *bankfull elevation* is reached.

As shown by the five-station trend line in Figure 4-51, the magnitude and recurrence interval of the bankfull discharge varies widely over the length of the study reach. In addition, there is little continuity in the values between adjacent cross sections. In general, bankfull capacity increases in the downstream direction from Carefree Highway to just below the Tributary #2 confluence (HEC-RAS section #26.3), and then markedly decreases in Reach 5. The values of bankfull discharge in Reach 5 are very similar to the values in the upper portion of the *supply reach*. The highest estimates of bankfull discharge occur in Reach 3, the section of channel that was mined in the 1980's by the Tanner sand and gravel operation.[4]

[4] The Wheeler mine had not yet opened when the topography used for the HEC-RAS was prepared.

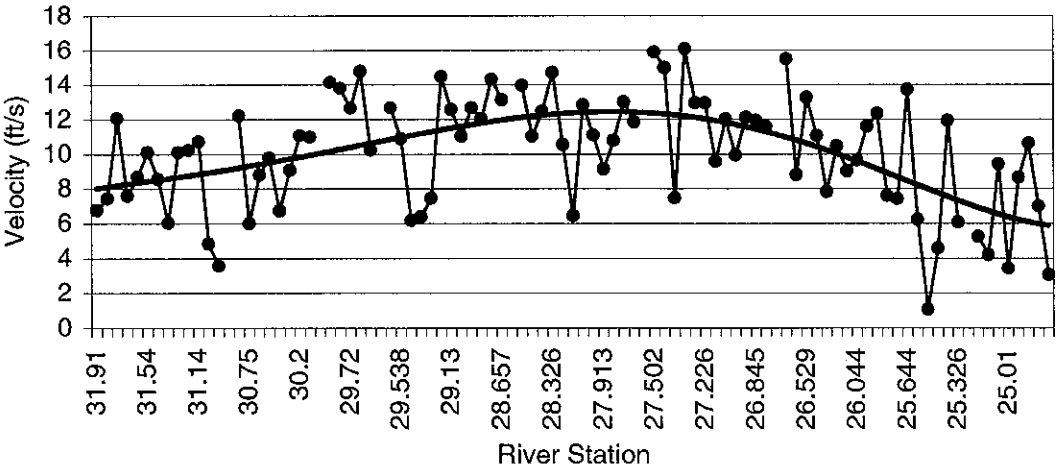
Bankfull width/depth ratios are not significantly different over the length of the study reach, despite the variation between adjacent cross sections shown in Figure 4-52. The highest individual values of width/depth ratio occur in historically mined reaches. Interestingly, the width/depth ratios in the multiple channel reach are not significantly different than the width/depth ratios in the single channel reaches.

Figure 4-52. Cave Creek Bankfull Width/Depth Ratio



Bankfull velocities for Cave Creek shown in Figure 4-53 reflect the increased channel capacity in Reaches 3 and 4 (Table 4-4). Velocity generally increases with discharge, resulting in an increase where channel capacity is large.

Figure 4-53. Cave Creek Bankfull Channel Velocity (ft/s)



Apache Wash. A plot of bankfull discharge for each HEC-RAS cross section for Apache Wash is shown in Figure 4-54. 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.

Like Cave Creek, bankfull discharge in Apache Wash (Figure 4-54) varies over the length of the study reach, although the magnitude of the differences between adjacent cross sections is less than for Cave Creek. The five-station trend line in Figure 4-54 indicates that bankfull capacity generally increases in the downstream direction within the study reach. A slight decrease in bankfull capacity occurs in the multiple channel reach near Carefree Highway where the floodplain has been modified by construction of 24th Street. The sharp increase in capacity near the Cave Buttes Impoundment area (Reach 6) is somewhat anomalous; a decrease analogous to the decrease seen in Cave Creek was expected due to sediment deposition and net aggradation in the impoundment area.

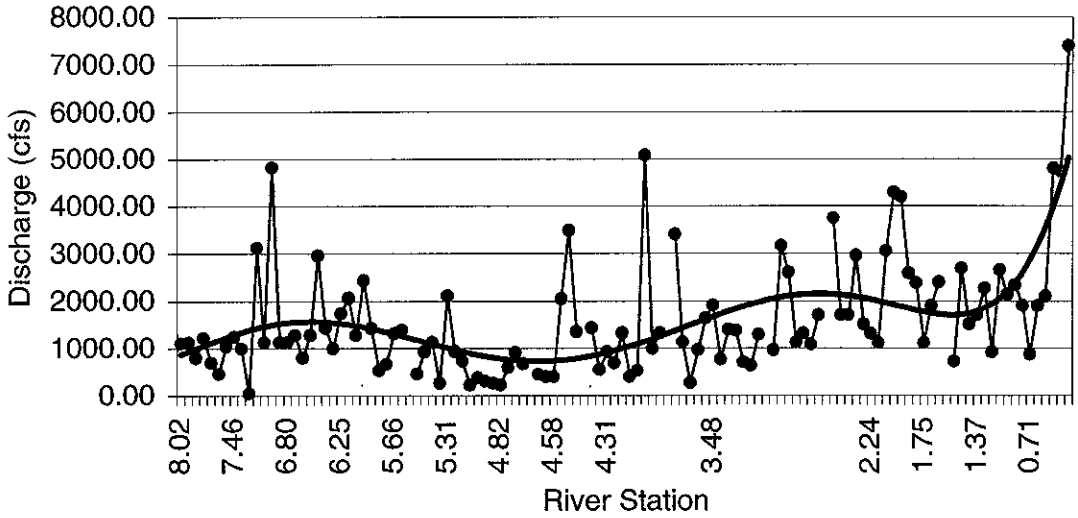
The recurrence intervals of bankfull discharges on Apache Wash are significantly less than the recurrence intervals of bankfull discharges on Cave Creek. This difference was interpreted to indicate that a greater degree of historical disturbance has affected Cave Creek, and that Apache Wash has been a more stable stream system.

Table 4-5. Upper Cave Creek/Apache Wash Watercourse Master Plan Reach-Average Bankfull Discharge Hydraulic Variables – Apache 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)
SR	9	759	1,029	61	3.5	2.0	6.7
1	14	1,500	1,779	70	4.2	2.4	7.7
2	10	1,182	1,380	48	4.3	3.0	8.1
3	6	1,365	1,425	175	4.6	2.5	4.2
4	9	2,384	3,051	94	4.3	3.1	8.1
5	9	2,371	3,151	78	4.6	3.5	8.6

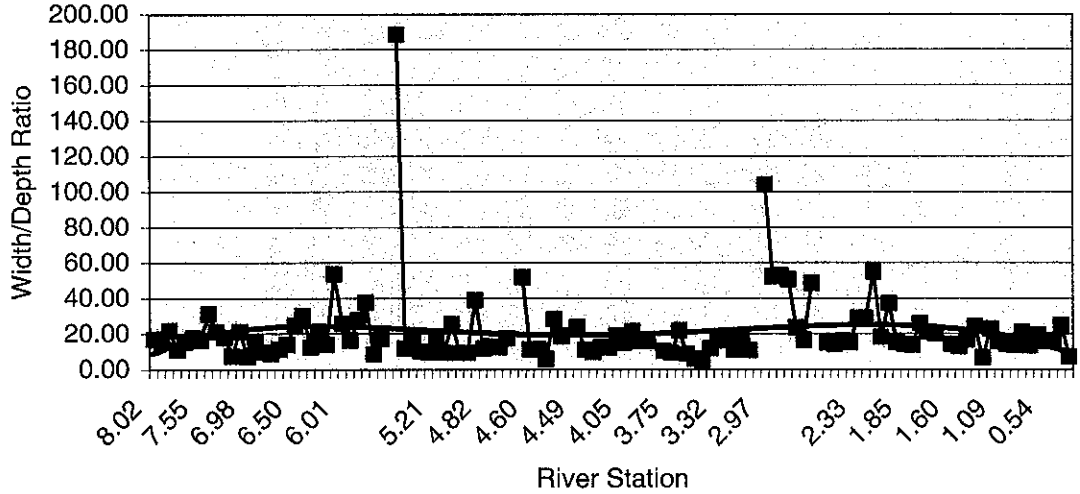
Note: Channel discharge is the flow contained in the main channel when the bankfull elevation is reached. The total discharge indicates the flow contained in the entire cross section including low overbank areas when the bankfull elevation is reached.

Figure 4-54. Apache Wash Bankfull Discharge (cfs)



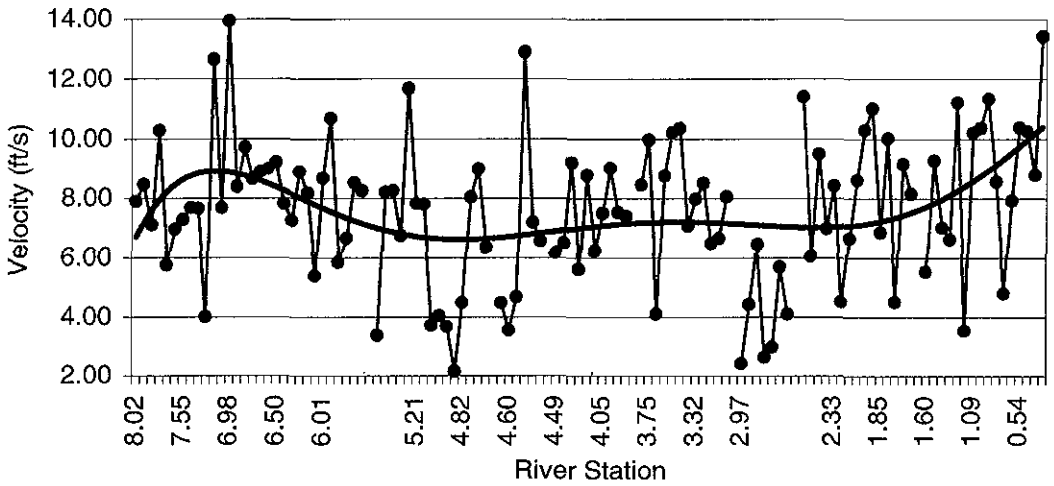
Bankfull width/depth ratios are relatively uniform over the length of the Apache Wash study reach, as shown in Figure 4-55. Variations in width/depth ratio between adjacent sections are probably due to the *pool* and *riffle* channel pattern, and alternating reaches of single channels and multiple channels.

Figure 4-55. Apache Wash Bankfull Width/Depth Ratio



Bankfull velocities vary significantly between adjacent cross sections, although the five-station trend line shown in Figure 4-56 is relatively uniform throughout the study area. Variation between adjacent cross sections was attributed to the pool and riffle sequence.

Figure 4-56. Apache Wash Bankfull Channel Velocity (ft/s)



Paradise Wash. A plot of estimated bankfull discharge for each HEC-RAS cross section for Paradise Wash is shown in Figure 4-57. 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.

As with Cave Creek and Apache Wash, bankfull discharge in Paradise Wash is highly variable within the study reach, although the magnitude of the differences between adjacent cross sections is less than for Cave Creek. The five-station trend line in Figure 4-57 indicates a net increases in bankfull discharge in the upper part of the study reach, followed by a gradual decrease near the Apache Wash confluence. Given the increase in slope indicated on the longitudinal profile of Paradise Wash near the Apache Wash confluence, the decrease in bankfull capacity is best explained as incision of a narrower main channel into a formerly broader braided or multiple channel cross section.

The recurrence intervals of bankfull discharges on Paradise Wash are somewhat higher than the recurrence intervals of bankfull discharges on Apache Wash, although they are generally lower than the values for Cave Creek. The difference from Apache Wash may be due to historical incision, as indicated by the longitudinal profile analysis summarized above.

Figure 4-57. Paradise Wash Bankfull Discharge (cfs)

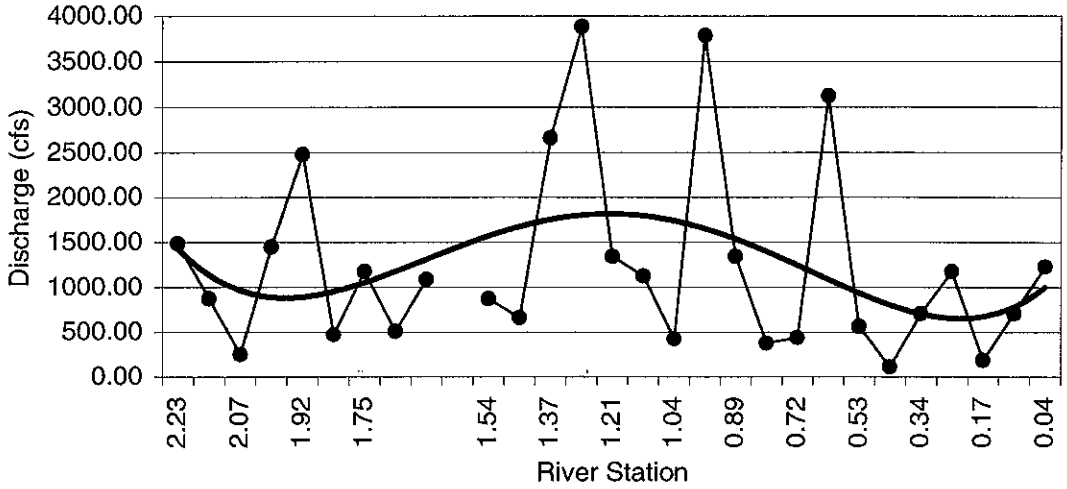
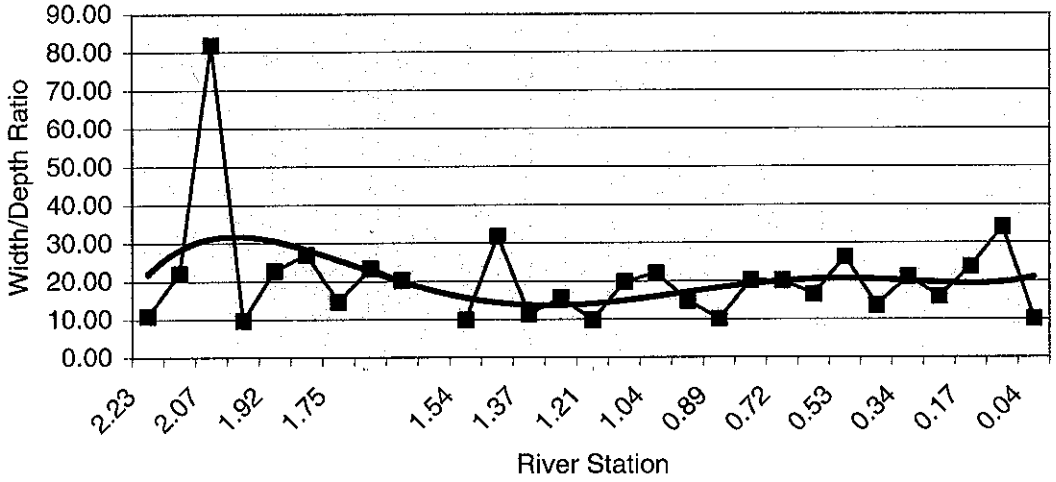


Table 4-6. Upper Cave Creek/Apache Wash Watercourse Master Plan Reach-Average Bankfull Discharge Hydraulic Variables – Paradise Wash							
Reach	**Recurrence Interval (yrs)**	**Channel Discharge (cfs)**	**Total Discharge (cfs)**	**Top Width Channel (ft)**	**Maximum Channel Depth (ft)**	**Hydraulic Radius Channel (ft)**	**Mean Channel Velocity (ft/s)**
SR	18	1,104	1,284	58	3.0	2.3	8.0
1	17	1,255	1,699	53	3.2	2.4	8.0
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.							

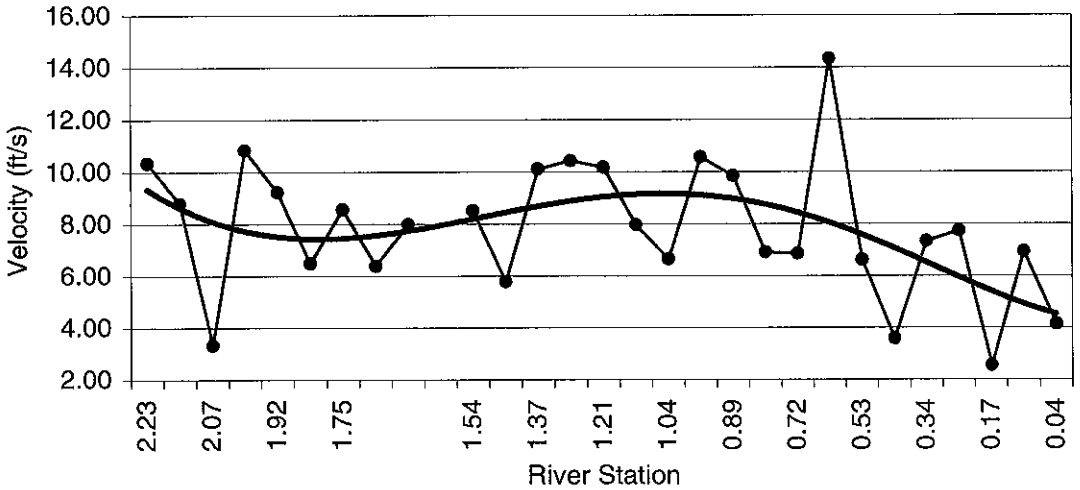
Bankfull width/depth ratios are relatively uniform over the length of the Paradise Wash study reach, as shown in Figure 4-58. Variations in width/depth ratio between adjacent sections are probably due to the pool and riffle channel pattern, and alternating reaches of single channels and multiple channels.

Figure 4-58. Paradise Wash Bankfull Discharge Width/Depth Ratio



Bankfull velocities vary somewhat between adjacent cross sections, and the five-station trend line shown in Figure 4-59 indicates an overall decrease in channel velocity in the downstream direction. Variation between adjacent cross sections was attributed to the pool and riffle sequence.

Figure 4-59. Paradise Wash Bankfull Channel Velocity (ft/s)



Desert Hills Wash. A plot of estimated bankfull discharge for each HEC-RAS cross section for Desert Hills Wash is shown in Figure 4-60. Table 4-7 shows the reach-averaged hydraulic values associated with bankfull discharge, as well as an estimate of the recurrence interval of the bankfull discharge.

As with the other streams in the study area, bankfull discharge in Desert Hills Wash varies within the study reach, although the magnitude of the differences between adjacent

cross sections is much less than for the other streams. The five-station trend line in Figure 4-60 indicates that overall the bankfull discharge has no significant trend within the study reach. Although the Desert Hills Wash study reach is too short to experience significant changes, field observations support a conclusion of uniformity.

The recurrence interval of bankfull discharge on Desert Hills Wash is the lowest of the four streams in the study area. It is noted that field evidence does not suggest that the banks of Desert Hills Wash are overtopped as frequently as every four years, indicating that the magnitudes of the more frequent floods (Tables 2-1 and 2-9) may be overestimated.

Figure 4-60. Desert Hills Wash Bankfull Discharge (cfs)

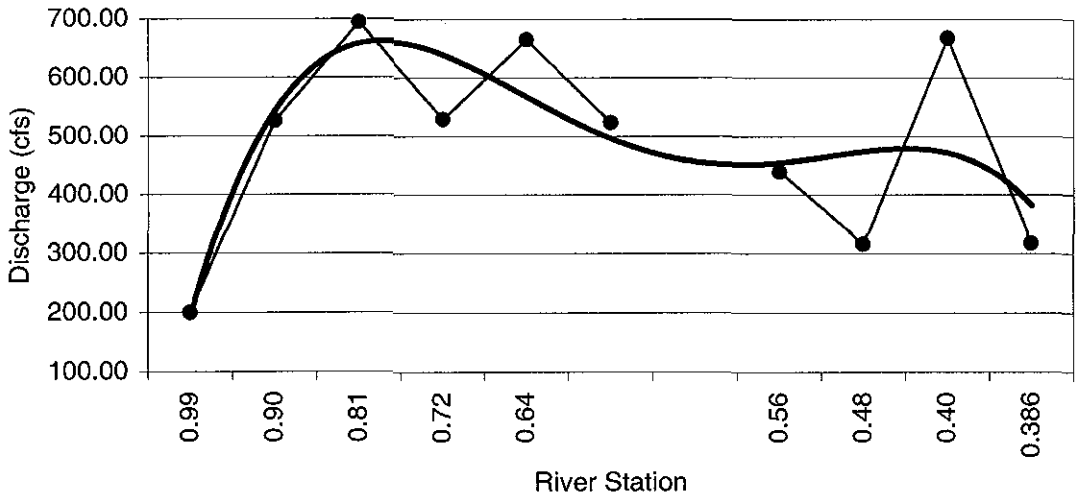


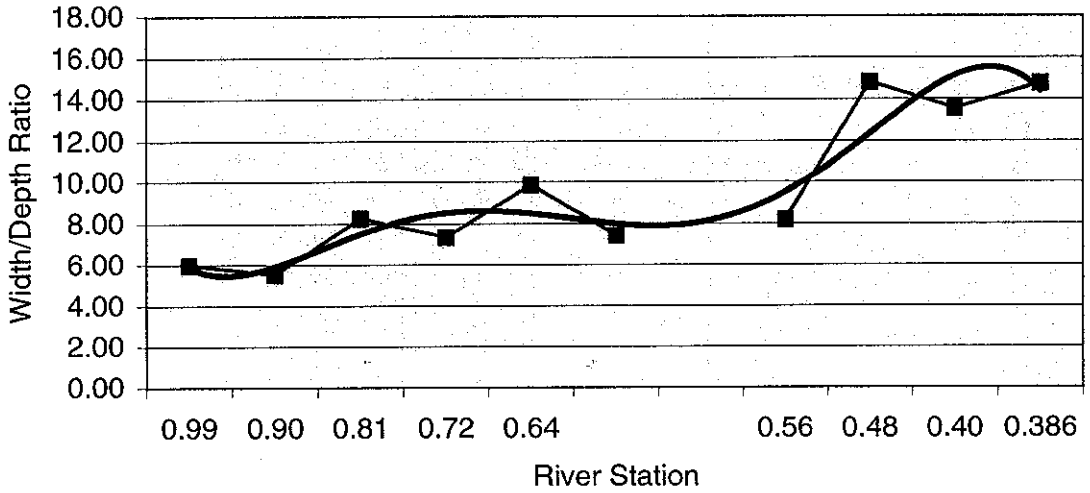
Table 4-7. Upper Cave Creek/Apache Wash Watercourse Master Plan Reach-Average Bankfull Discharge Hydraulic Variables – Desert Hills Wash

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)
SR	4	519	697	30	4.0	2.8	5.8
1	3	401	403	35	3.2	2.3	4.9

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.

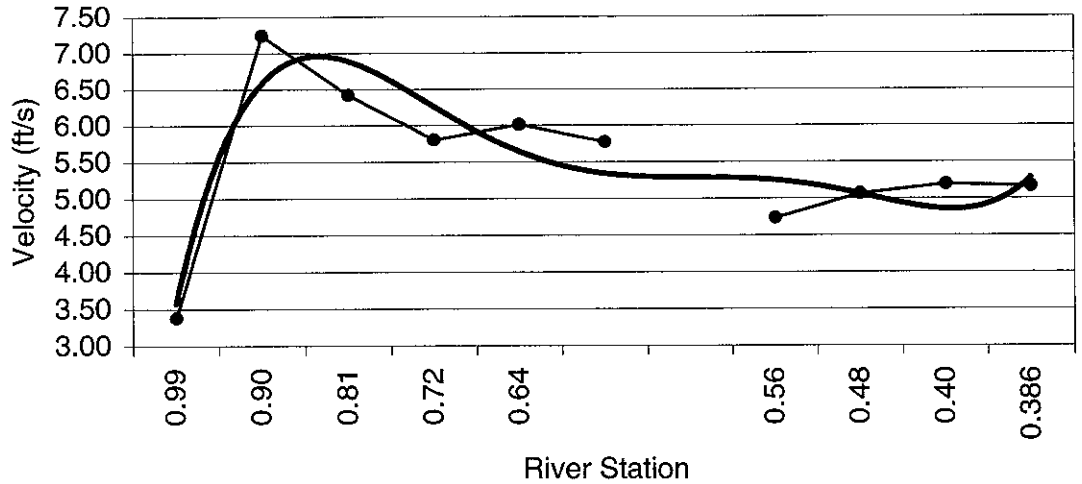
Bankfull width/depth ratios increase in the downstream direction within the Desert Hills Wash study reach, as shown in Figure 4-61. A wider, shallower channel has formed in the reach that formed after the circa 1960 failure of the northern spillway of Bosco Tank. Slight variations in width/depth ratio between adjacent sections are probably due to slow channel response and recovery to past local erosion.

Figure 4-61. Desert Hills Wash Bankfull Width/Depth Ratio



Bankfull velocities gradually decrease between adjacent cross sections in the downstream direction, except for the sharp increase at the upstream end of the model, as shown in Figure 4-62. The decrease may be due to backwater conditions in the HEC-RAS model from Apache Wash.

Figure 4-62. Desert Hills Wash Bankfull Channel Velocity (ft/s)



Summary. The following conclusions can be drawn from the bankfull *discharge* analysis:

- Bankfull recurrence interval. The recurrence interval of the bankfull discharge varies widely for the streams in the study area, with little continuity in the values between adjacent cross sections.
- Slow channel recovery. The poor continuity in bankfull discharge magnitude and frequency between 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 are shaped primarily by the largest floods. Small floods 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 indicates that stream stability is influenced more by the large floods, rather than the small annual floods. Therefore, the stability analyses should focus on the affects of the largest floods.
- Cave Creek. Bankfull capacity increases in the downstream direction from Carefree Highway through Reach 3, and then decreases in Reach 5. The highest estimates of bankfull discharge occurred in the sections of channel that were mined for sand and gravel.
- Apache Wash. Bankfull capacity increases in the downstream direction within the study reach. High bankfull capacity relative to Paradise Wash may indicate prehistoric incision increased the capacity of Apache Wash. Lower capacity relative to Cave Creek probably indicates less human disturbance has occurred on Apache Wash.
- Paradise Wash. Bankfull discharge increases in the upper part of the study reach, followed by a gradual decrease near the Apache Wash confluence. The recurrence intervals of bankfull discharges on Paradise Wash are somewhat higher than the recurrence intervals of bankfull discharges on Apache Wash and Desert Hills Wash, although they are generally lower than the very high values for Cave Creek.

River Classification Methods

Stream classification data were presented in Chapter 2 of this report. The objective of stream classification is to group stream types so that their behavior can be predicted. The stability predictions associated with the modified Brice classification scheme was shown in Table 2-11, and indicated that the streams in the study area are susceptible to rapid lateral migration and bank erosion.

Similarly, the Rosgen classification indicates 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,[5] (2) root depth/bank height, (3) root density,

[5] 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.

(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 4-8. While quantitative measurements of these parameters such as root density were not readily available for the study area, visual estimates of these parameters were used to apply the Rosgen erosion matrix to each of the four streams in the study area, as summarized in Table 4-8. Given the level of disturbance and on-going manmade changes to Reach 4 of Cave Creek, the point total for Reach 3 was applied to Reach 4 in Table 4-8.

According to the Rosgen bank erosion evaluation matrix, all of the streams in the study area are subject to at least moderate erosion hazard. The disturbed reaches of Cave Creek are rated as subject to extreme erosion hazards, with very high erosion hazards in the reaches adjacent to the historically mined reaches. Apache Wash generally was rated as having only moderate erosion hazards, primarily due to good vegetative cover on the banks. The presence of bedrock along the right bank in reaches 3 and 4 of Apache Wash partially accounts for the moderate rating. The Rosgen ratings generally correspond to the visual assessments of bank stability made during the field investigations.

Table 4-8. Upper Cave Creek/Apache 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 (°)	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

Boulders: Bank erosion potential low

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

Sand: Adjust values up by 10 points

Silt/Clay: No adjustment

Stratification: 5-10 points upward depending on position of unstable layers in relation to bankfull stage.

	Cave Creek Reach #					Apache Wash Reach #						Paradise Wash	Desert Hills Wash
Criteria	**1**	**2**	**3**	**4**	**5**	**1**	**2**	**3**	**4**	**5**	**6**	**1**	**1**
Bank Ht./Bankfull Ht.	10	10	10	-	10	10	10	10	10	10	10	10	10
Root Depth/Bank Ht.	3.6	3.9	6.1	-	2.2	1.5	1.0	1.0	1.0	1.2	1.3	1.2	1.5
Root Density (%)	7.1	7.8	8.9	-	7.2	7.6	7.5	6.8	7.7	5.9	6.1	7.4	6.5
Bank Angle (°)	3.6	4.5	4.1	-	2.3	2.9	2.4	2.2	2.4	2.6	2.3	2.5	3.0
Surface Protection (%)	5.0	4.2	9.0	-	5.1	5.7	5.5	4.7	4.5	3.4	3.7	5.3	4.4
TOTALS	29.3	30.4	38.1	38	26.8	27.7	26.4	24.7	25.6	23.1	23.4	26.4	25.4
Adjustments													
Bank Materials	+0	+5	+7	+7	+8	+0	+5	+0	+0	+5	+6	+0	+8
Stratification	+5	+7	+7	+7	+9	+5	+5	+0	+0	+0	+0	+5	+0
TOTAL	34.3	42.4	52.1	52	43.8	32.7	36.4	24.7	25.6	28.1	29.4	31.4	33.4
EROSION RATING	High	Very High	Ex-Treme	Ex-treme	Very High	Mod-erate	High	Mod-erate	Mod-erate	Mod-erate	Mod-erate	High	High

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-*scour*ing and non-silting stable alluvial canals (cf. Kennedy, 1895), and has been extended to a wide variety of stream types (cf., 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 (cf., Leopold & Maddock, 1953) published the most widely used hydraulic geometry data.

Regime equation and hydraulic geometry analyses were applied to the stream reaches in the study area to evaluate the following aspects of the channel morphology:

- Predictions of channel pattern
- Predictions of channel geometry
- Hydraulic geometry regression equations

Lateral stability was evaluated by comparing predicted channel characteristics from one or more of these methodologies to observed channel 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.

Regime equations and hydraulic geometry relationships are empirically derived from data sets of very specific stream types (e.g., sand-bed rivers, canals, etc.). Even among similar stream types, these data typically still have a large amount of scatter. The equations selected for this study were chosen to reflect the stream characteristics in the study area, although it is noted that *ephemeral* streams in central Arizona are unique. Therefore, the results obtained by applying these approaches to streams with different characteristics than the data sets from which they were derived must be interpreted cautiously. In general, the results are best interpreted as order-of-magnitude estimates of the direction of expected change, rather than exact predictions of the magnitude of future channel adjustments. A wide variety of applicable equations were selected, rather than the few equations that predicted results that were expected based on qualitative analyses, to illustrate the inherent uncertainty of river behavior, as well as the potential for a range of reasonable outcomes.

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 Cave 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 tried to establish a threshold slope between braided and meandering stream patterns using empirical data, flume studies, and theoretical relationships. 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 Cave Creek was estimated from USGS gauge records from the Cave Creek near Cave Creek station (Table 2-4). Mean annual discharge for Apache Wash, Paradise Wash, and Desert Hills 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).

$S_o > 0.0015\ Q_m^{0.12}$ (Braided 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 Tables 2-9 and 4-4). 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 counts as described in Chapter 5.

Results. Application of the four channel pattern equations to the study area are shown in Table 4-9. According to empirical data, the expected channel pattern for Cave Creek, Apache Wash, and Paradise Wash is braided. Field observations indicate that during the most frequent flows at low discharges, the channel pattern could be considered weakly braided, but at bankfull discharge a single channel is the most common pattern in most reaches. The *supply reaches* of Cave Creek and Apache Wash are braided, as is Reach 5 of Cave Creek. The remaining reaches are locally braided. The expected channel pattern for Desert Hills Wash is not braided.

Table 4-9. Upper Cave Creek/Apache Wash Watercourse Master Plan Channel Pattern Relationships: Threshold Slope for Braided Channels

Name	Equation	Threshold Slope for Braided Channel (ft/ft)			
		Cave Creek	Apache Wash	Paradise Wash	Desert Hills Wash
Lane	$S_o > 0.01\ Q_m^{-0.25}$	0.007	0.011	0.016	0.013
Ackers & Charlton	$S_o > 0.0015\ Q_m^{0.12}$	0.002	0.001	0.001	0.001
Leopold & Wolman	$S_o > 0.06\ Q_{maf}^{-0.44}$	0.002	0.005	0.008	0.006
Henderson	$S_o > 0.64\ d_{50}^{1.14}\ Q_{maf}^{-0.44}$	0.0005	0.0008	0.002	0.001
Average		0.003	0.004	0.007	0.005
	Measured Channel Slope	0.009	0.007	0.009	0.003
	Predicted Pattern	Braided	Braided	Braided	Not Braided

Notes: S_o = Slope for braided channel Q_{maf} = Bankfull discharge Qm = Average annual discharge

The channel pattern equations were also applied on a reach by reach basis for each of the four major streams in the study area (Tables 4-10 to 4-12). 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 4-10 to 4-12 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.

Cave Creek. As shown in Table 4-10, the channel pattern equations predict a straight braided channel pattern for Cave Creek, with no clear trend with increasing discharge. The coarse bed material in Cave Creek Reaches 1 to 4 probably inhibits the expression of the classic braided channel characteristics. Based on the data shown in Table 4-10, increased braiding is expected along Cave Creek in the future, especially in Reaches 2 and 3.

Table 4-10. Upper Cave Creek/Apache Wash Watercourse Master Plan Predicted Channel Pattern Relationships for Cave Creek

Name	Predicted Channel Pattern									
	1		2		3		4		5	
	Q2	Q10	Q2	Q10	Q2	Q10	Q2	Q10	Q2	Q10
Lane	B	B/I	B/I	B/I	B/I	B/I	B/I	B/I	I	B/I
Ackers & Charlton	S	S	S	S	S	S	S	S	S	S
Leopold & Wolman	B	B	B	B	B	B	B	B	B	B
Henderson	B	B	B	B	B	B	B	B	B	B
Observed Channel Pattern	B		S/B		S		B		B	

Notes: S = Straight Channel I = Intermediate Form B = Braided M = Meandering

Apache Wash. As shown in Table 4-11, the channel pattern equations predict less strongly braided conditions for Apache Wash than for Cave Creek. This prediction generally conforms to field observations of a relatively narrow single channel that is braided at flow expansions, at the heads of *riffles*, and where overflow channels form. Based on the data shown in Table 4-11, increased braiding is expected along Apache Wash in the future.

Table 4-11. Upper Cave Creek/Apache Wash Watercourse Master Plan Predicted Channel Pattern Relationships for Apache Wash

Name	Predicted Channel Pattern									
	1		2		3		4		5	
	Q2	Q10	Q2	Q10	Q2	Q10	Q2	Q10	Q2	Q10
Lane	I	I	I	I	I	IBM	I	I	I	I
Ackers & Charlton	S	S	S	S	S	S	S	S	S	S
Leopold & Wolman	B	B/M	B/M	B/M	B/M	B/M	B/M	B/M	B/M	B/M
Henderson	B	B	B	B	B	B	B	B	B	B
Observed Channel Pattern	S/B		S/B		S/B		S/B		S/B	

Notes: S = Straight Channel I = Intermediate Form B = Braided M = Meandering

Paradise Wash. As shown in Table 4-12, the channel pattern equations predict less strongly braided conditions for Paradise Wash than for Cave Creek. This prediction

generally conforms to field observations of a relatively narrow single channel that is braided at flow expansions, at the heads of riffles, and where overflow channels form. Based on the data shown in Table 4-12, a slight increase in braiding is expected along Paradise Wash in future.

Table 4-12. Upper Cave Creek/Apache Wash Watercourse Master Plan Predicted Channel Pattern Relationships for Paradise Wash & Desert Hills Wash

Name	Predicted Channel Pattern							
	Paradise Wash				Desert Hills Wash			
	1		2		1		2	
	Q2	Q10	Q2	Q10	Q2	Q10	Q2	Q10
Lane	I	I	I	I	I	I	M	M/I
Ackers & Charlton	S	S	S	S	S	S	S/M	M/S
Leopold & Wolman	B/M	B/M	B/M	B/M	M	M	M	M
Henderson	B	B	B	B	B	B	B/M	M/B
Observed Channel Pattern	S/B		S/B		I		M	

Notes: S = Straight Channel I = Intermediate Form B = Braided M = Meandering

Desert Hills Wash. As shown in Table 4-12, the channel pattern equations generally predict a meandering channel pattern for Desert Hills Wash. Downstream of the Bosco Tank spillway failure, the channel pattern is meandering, with point bars and sharp bends. Upstream of Bosco Tank, the channel pattern is only slightly *sinuous* with broad channel bends. Based on the data shown in Table 4-12, no significant change in channel pattern is expected along Desert Hills Wash.

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 the bankfull channel width, depth, and velocity to a specific *discharge* rate, such as the average annual flow or the dominant discharge. Some of these equations were applied to the streams in the study area to assess the expected direction of future channel change.

Bray Equation. 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.)

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)
$Q_* = 0.039\ V_m\ d^{-1}\ D_{50} / ((\rho_s-1)/\rho)\ g\ d)^{1/2})$ (dimensionless)
D_{50} = mean sediment diameter (ft.)
d = average channel depth (ft)
S_e = energy slope (ft./ft.)

Ackers & Charlton Equation.[6] 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 the *FLUVIAL*-12 sediment transport model, which attempt 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.)

[6] The results of the Ackers & Charlton and the Lacey equations are presented on the same line in Tables 4-13 to 4-16 to reduce the length of the tables.

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 Cave Creek/Apache 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.

Kellerhalls (1967) Equations. Kellerhals developed equations for the equilibrium channel width and depth in gravel bed rivers. The Kellerhals equations are 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 results, and are not specifically reported in Tables 4-13 to 4-16. Schumm results are included in Appendix C.

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.

$$W = 0.5\ F^{0.6}\ Fr^{-0.4}\ Q^{0.4}$$
$$S = 18.28\ n^2\ F^{0.133}\ Fr^{2.133}\ Q^{-0.133}$$

Where W = width of channel (ft.)
F = width/depth ratio
Fr = *Froude number* in channel
Q = discharge (cfs.)
S_o = channel slope (ft./ft.)
n = Manning's n value for channel

Results. The results of applying the channel geometry equations to the four streams in the study area are shown in Tables 4-13 to Table 4-16. The 2-, 10-, and 100-year discharges were substituted for the discharge variable used in the 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 predicted width is less than the HEC-RAS modeled width, the channel is assumed to be laterally stable, or subject to deposition along the banks at that flow rate. Where the predicted width is greater than the HEC-RAS modeled width, the channel is expected to erode its banks to achieve the greater width during future floods.

- Depth. Where predicted depth is less than the HEC-RAS modeled depth, the channel is expected to aggrade (deposit sediment) to reach the equilibrium state. Where the predicted depth is greater than the HEC-RAS modeled depth, the channel is expected to erode its bed (degrade) to achieve the equilibrium depth during future floods.

- Slope. Where the predicted slope is less than the existing slope, the channel is expected to decrease (*scour*) its slope to achieve a more stable form. In all cases in the study area, the predicted slope was flatter than the existing channel slope.

- 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 cases in the study area, 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 each of the four streams considered are summarized below.

Table 4-13. Upper Cave Creek/Apache Wash Watercourse Master Plan
Observed and Expected Channel Characteristics – Cave Creek

Equation	Channel Width (ft)			Flow Depth (ft)			Channel Slope (ft/ft)			Channel Velocity (ft/s)		
	Q2	Q10	Q100	Q2	Q10	Q100	Q2	Q10	Q100	Q2	Q10	Q100
Reach 1												
Bray	126	271	546	3.2	5.2	8.0	-	-	-	4.1	5.5	6.6
Parker	142	294	571	2.8	5.2	9.0	0.00133	0.00073	0.00042	-	-	-
Ackers & Charlton/Lacey	85	157	274	-	-	-	-	-	-	2.8	3.6	4.5
Chang	99	240	497	2.2	2.9	4.1	0.00055	0.00035	0.00017	-	-	-
Kellerhals	78	161	313	5.4	9.7	16.4	-	-	-	-	-	-
AMAFCA	120	196	272	-	-	-	0.00894	0.00870	0.00680	-	-	-
Average	110	216	395	3.8	6.7	11.1	0.00514	0.00472	0.00361	3.5	4.6	5.6
HEC-RAS Data	186	302	360	4.1	7.2	12.9		0.00915		5.7	8.5	12.2
Bankfull *Discharge* Data		319			11.0			0.00915			11.5	
Expected Behavior	Stable	Stable	Erosion	Fill	Fill	Fill	*Scour*	*Scour*	*Scour*	*Scour*	*Scour*	*Scour*
Reach 2												
Bray	124	268	529	3.2	5.1	7.8	-	-	-	4.1	5.3	6.4
Parker	158	329	629	2.8	5.2	8.9	0.00080	0.00044	0.00026	-	-	-
Ackers & Charlton/Lacey	84	155	267	-	-	-	-	-	-	2.8	3.6	4.4
Chang	118	284	567	1.6	2.0	2.5	0.00031	0.00017	0.00010	-	-	-
Kellerhals	76	159	304	5.3	9.6	16.1	-	-	-	-	-	-
AMAFCA	93	135	202	-	-	-	0.00970	0.00850	0.00630	-	-	-
Average	107	209	386	3.8	6.6	10.9	0.00525	0.00447	0.00328	3.5	4.5	5.4
HEC-RAS Data	121	178	266	4.1	7.8	14.2		0.00908		6.6	10.0	13.0
Bankfull *Discharge* Data		227			10.9			0.00908			11.5	
Expected Behavior	Stable	Erosion	Erosion	Fill	Fill	Fill	*Scour*	*Scour*	*Scour*	*Scour*	*Scour*	*Scour*
Reach 3												
Bray	124	269	536	3.2	5.1	7.9	-	-	-	4.1	5.5	6.6
Parker	196	407	783	2.9	5.4	9.3	0.00034	0.00019	0.00011	-	-	-
Ackers & Charlton/Lacey	84	156	270	-	-	-	-	-	-	2.8	3.6	4.4
Chang	168	408	844	0.6	0.1	*	0.00012	0.00007	0.00004	-	-	-
Kellerhals	77	159	307	5.3	9.6	16.2	-	-	-	-	-	-
AMAFCA	128	210	274	-	-	-	0.00920	0.00910	0.00730	-	-	-

Table 4-13. Upper Cave Creek/Apache Wash Watercourse Master Plan
Observed and Expected Channel Characteristics – Cave Creek

Equation	Channel Width (ft)			Flow Depth (ft)			Channel Slope (ft/ft)			Channel Velocity (ft/s)		
	Q2	Q10	Q100	Q2	Q10	Q100	Q2	Q10	Q100	Q2	Q10	Q100
Average	122	240	434	3.8	6.7	11.1	0.00477	0.00465	0.00371	3.5	4.6	5.5
HEC-RAS Data	199	303	348	4.0	6.8	12.0	0.00837			5.4	8.0	11.3
Bankfull *Discharge* Data	355			11.5			0.00837			12.3		
Expected Behavior	Stable	Stable	Erosion	Fill	Fill	Fill	Scour	Scour	Scour	Scour	Scour	Scour
Reach 4												
Bray	122	224	410	3.1	4.5	6.6	-	-	-	3.8	4.8	6.1
Parker	198	351	623	2.9	4.7	7.5	0.00032	0.00020	0.00013	-	-	-
Ackers & Charlton/Lacey	83	134	217	-	-	-	-	-	-	2.8	3.4	4.1
Chang	161	326	666	0.8	0.4	*	0.00011	0.00007	0.00004	-	-	-
Kellerhals	75	134	238	5.3	8.3	13.1	-	-	-	-	-	-
AMAFCA	111	150	195	-	-	-	0.00870	0.00760	0.00780	-	-	-
Average	118	199	337	3.8	5.8	9.1	0.00451	0.00390	0.00397	3.3	4.1	5.1
HEC-RAS Data	168	213	258	5.1	7.5	11.3	0.00799			5.4	7.6	10.9
Bankfull *Discharge* Data	263			10.0			0.00799			9.5		
Expected Behavior	Stable	Erosion	Erosion	Fill	Fill	Fill	Scour	Scour	Scour	Scour	Scour	Scour
Reach 5												
Bray	124	204	350	3.2	4.3	6.0	-	-	-	3.8	4.6	5.6
Parker	173	278	465	2.9	4.3	6.5	0.00055	0.00038	0.00025	-	-	-
Ackers & Charlton/Lacey	84	125	192	-	-	-	-	-	-	2.8	3.3	3.9
Chang	125	226	426	1.5	1.6	1.4	0.00021	0.00014	0.00009	-	-	-
Kellerhals	76	123	205	5.3	7.8	11.7	-	-	-	-	-	-
AMAFCA	96	127	153	-	-	-	0.00810	0.00780	0.00770	-	-	-
Average	111	171	273	3.8	5.5	8.1	0.00433	0.00409	0.00398	3.3	4.0	4.8
HEC-RAS Data	125	170	191	4.8	7.2	10.7	0.00551			5.8	7.5	10.5
Bankfull *Discharge* Data	180			7.3			0.00551			7.0		
Expected Behavior	Stable	Erosion	Erosion	Fill	Fill	Fill	Scour	Scour	Scour	Scour	Scour	Scour

Table 4-14. Upper Cave Creek/Apache Wash Watercourse Master Plan
Observed and Expected Channel Characteristics – Apache Wash

Equation	Channel Width (ft)			Flow Depth (ft)			Channel Slope (ft/ft)			Channel Velocity (ft/s)		
	Q2	Q10	Q100	Q2	Q10	Q100	Q2	Q10	Q100	Q2	Q10	Q100
Reach 1												
Bray	31	90	181	1.3	2.6	4.0	-	-	-	2.3	3.3	4.2
Parker	49	134	260	1.0	2.3	3.9	0.00135	0.00059	0.00035	-	-	-
Ackers & Charlton/Lacey	28	65	113	-	-	-	-	-	-	1.9	2.5	3.1
Chang	28	91	2002	0.7	1.2	1.4	0.00051	0.00022	0.00013	-	-	-
Kellerhals	21	57	110	1.9	4.2	7.1	-	-	-	-	-	-
AMAFCA	24	44	59	-	-	-	0.00803	0.00625	0.00614	-	-	-
Average	31	78	145	1.4	3.0	5.0	0.00469	0.00342	0.00325	2.1	2.9	3.7
HEC-RAS Data	29	61	76	1.5	4.0	6.9		0.00855		4.5	7.2	11.3
Bankfull Discharge Data		70			4.2			0.00855			7.7	
Expected Behavior	Erosion	Erosion	Erosion	Fill	Fill	Fill	Scour	Scour	Scour	Scour	Scour	Scour
Reach 2												
Bray	31	97	173	1.2	2.7	3.9	-	-	-	2.3	3.4	3.8
Parker	41	121	212	0.9	2.3	3.7	0.00268	0.00110	0.00070	-	-	-
Ackers & Charlton/Lacey	28	69	110	-	-	-	-	-	-	1.8	2.6	3.1
Chang	22	75	131	1.0	1.8	2.8	0.00109	0.00044	0.00028	-	-	-
Kellerhals	21	61	105	1.9	4.4	6.9	-	-	-	-	-	-
AMAFCA	24	37	43	-	-	-	0.00736	0.00624	0.00438	-	-	-
Average	29	77	129	1.3	3.1	4.8	0.00502	0.00367	0.00254	2.1	3.0	3.5
HEC-RAS Data	29	46	49	1.6	4.3	7.9		0.00754		4.3	8.3	11.3
Bankfull Discharge Data		48			4.3			0.00754			8.1	
Expected Behavior	Stable	Erosion	Erosion	Fill	Fill	Fill	Scour	Scour	Scour	Scour	Scour	Scour
Reach 3												
Bray	3.5	113	234	1.4	3.0	4.7	-	-	-	2.4	3.2	3.0
Parker	51	152	304	1.1	2.7	4.7	0.00176	0.00072	0.00041	-	-	-
Ackers & Charlton/Lacey	31	78	139	-	-	-	-	-	-	1.9	2.7	3.4
Chang	27	90	159	1.0	2.1	4.8	0.00069	0.00028	0.00015	-	-	-

Table 4-14. Upper Cave Creek/Apache Wash Watercourse Master Plan
Observed and Expected Channel Characteristics – Apache Wash

Equation	Channel Width (ft)			Flow Depth (ft)			Channel Slope (ft/ft)			Channel Velocity (ft/s)		
	Q2	Q10	Q100	Q2	Q10	Q100	Q2	Q10	Q100	Q2	Q10	Q100
Kellerhals	23	70	140	2.1	5.3	8.6	-	-	-	-	-	-
AMAFCA	47	123	307	-	-	-	0.00854	0.00528	0.00175	-	-	-
Average	31	107	225	1.5	3.7	6.0	0.00515	0.00300	0.00108	2.2	3.0	3.2
HEC-RAS Data	54	212	501	1.4	4.7	9.2		0.00591		3.1	4.4	4.6
Bankfull Discharge Data		175			4.6			0.00591			4.2	
Expected Behavior	Stable	Stable	Stable	Stable	Fill	Fill	Scour	Scour	Scour	Scour	Scour	Scour
Reach 4												
Bray	49	158	306	1.8	3.7	5.6	-	-	-	2.6	3.8	4.7
Parker	74	226	424	1.4	3.5	5.9	0.00100	0.00040	0.00024	-	-	-
Ackers & Charlton/Lacey	40	102	173	-	-	-	-	-	-	2.1	3.0	3.7
Chang	45	156	329	1.0	1.7	2.0	0.00038	0.00015	0.00009	-	-	-
Kellerhals	32	96	181	2.6	6.4	10.6	-	-	-	-	-	-
AMAFCA	52	76	84	-	-	-	0.00794	0.00525	0.00477	-	-	-
Average	49	132	234	1.9	4.5	7.4	0.00447	0.00283	0.00251	2.4	3.4	4.2
HEC-RAS Data	63	88	91	1.7	5.0	9.7		0.00619		4.5	8.7	13.6
Bankfull Discharge Data		94			4.3			0.00619			8.1	
Expected Behavior	Stable	Erosion	Erosion	Stable	Fill	Fill	Scour	Scour	Scour	Scour	Scour	Scour
Reach 5												
Bray	49	155	283	1.8	3.6	5.3	-	-	-	2.5	3.7	4.5
Parker	89	264	468	1.4	3.5	5.7	0.00049	0.00020	0.00013	-	-	-
Ackers & Charlton/Lacey	40	100	162	-	-	-	-	-	-	2.1	3.0	3.6
Chang	55	202	394	0.7	0.8	0.6	0.00017	0.00007	0.00004	-	-	-
Kellerhals	32	95	168	2.6	6.3	10.0	-	-	-	-	-	-
AMAFCA	46	63	70	-	-	-	0.00652	0.00506	0.00447	-	-	-
Average	51	135	230	1.9	4.5	7.0	0.00351	0.00263	0.00230	2.3	3.4	4.1
HEC-RAS Data	52	73	76	1.8	5.5	10.0		0.00584		4.6	9.2	13.7
Bankfull Discharge Data		78			4.6			0.00584			8.6	
Expected Behavior	Stable	Erosion	Erosion	Fill	Fill	Fill	Scour	Scour	Scour	Scour	Scour	Scour

Table 4-15. Upper Cave Creek/Apache Wash Watercourse Master Plan
Observed and Expected Channel Characteristics – Paradise Wash

Equation	Channel Width (ft)			Flow Depth (ft)			Channel Slope (ft/ft)			Channel Velocity (ft/s)		
	Q2	Q10	Q100	Q2	Q10	Q100	Q2	Q10	Q100	Q2	Q10	Q100
Supply reach												
Bray	25	74	135	1.2	2.3	3.3	-	-	-	2.3	3.2	3.7
Parker	37	102	180	0.8	1.9	3.0	0.00226	0.00098	0.00062	-	-	-
Ackers & Charlton/Lacey	24	56	90	-	-	-	-	-	-	1.7	2.4	2.9
Chang	21	66	120	0.7	1.2	1.8	0.00089	0.00036	0.00024	-	-	-
Kellerhals	17	47	83	1.6	3.6	5.7	-	-	-	-	-	-
AMAFCA	35	48	54	-	-	-	0.00992	0.00764	0.00636	-	-	-
Average	28	65	108	1.2	2.6	4.0	0.00609	0.00431	0.00349	2.0	2.8	3.3
HEC-RAS Data	40	56	59	0.9	2.5	4.8		0.01010		3.7	6.7	9.5
Bankfull Discharge Data		58			3.0			0.01010			8.0	
Expected Behavior	Stable	Erosion	Erosion	Scour	Fill	Fill	Scour	Scour	Scour	Scour	Scour	Scour
Reach 1												
Bray	24	73	140	1.1	2.3	3.4	-	-	-	2.1	3.0	3.7
Parker	33	92	171	0.8	1.9	3.1	0.00339	0.00146	0.00089	-	-	-
Ackers & Charlton/Lacey	23	55	92	-	-	-	-	-	-	1.7	2.4	2.9
Chang	18	53	108	0.9	1.7	2.4	0.00140	0.00059	0.00036	-	-	-
Kellerhals	16	46	86	1.6	3.6	5.8	-	-	-	-	-	-
AMAFCA	31	44	50	-	-	-	0.00952	0.00648	0.00583	-	-	-
Average	25	62	108	1.2	2.6	4.1	0.00646	0.00397	0.00336	1.9	2.7	3.3
HEC-RAS Data	34	52	56	0.9	2.8	5.4		0.00864		3.5	6.3	9.6
Bankfull Discharge Data		53			3.2			0.00864			8.0	
Expected Behavior	Stable	Erosion	Erosion	Scour	Fill	Fill	Scour	Scour	Scour	Scour	Scour	Scour

Table 4-16. Upper Cave Creek/Apache Wash Watercourse Master Plan
Observed and Expected Channel Characteristics – Desert Hills Wash

Equation	Channel Width (ft)			Flow Depth (ft)			Channel Slope (ft/ft)			Channel Velocity (ft/s)		
	Q2	Q10	Q100	Q2	Q10	Q100	Q2	Q10	Q100	Q2	Q10	Q100
Supply reach												
Bray	39	88	135	1.5	2.5	3.3	-	-	-	2.1	2.8	3.4
Parker	52	112	170	1.1	2.2	3.0	0.00210	0.00112	0.00080	-	-	-
Ackers & Charlton/Lacey	33	64	90	-	-	-	-	-	-	1.9	2.5	2.9
Chang	25	59	99	1.3	2.0	2.4	0.00089	0.00045	0.00032	-	-	-
Kellerhals	25	55	83	2.2	4.1	5.7	-	-	-	-	-	-
AMAFCA	21	26	27	-	-	-	0.00416	0.00361	0.00395	-	-	-
Average	34	69	101	1.6	2.9	4.0	0.00313	0.00237	0.00238	2.0	2.7	3.2
HEC-RAS Data	24	30	30	2.4	5.2	7.8		0.00359		4.6	7.7	11.0
Bankfull Discharge Data		30			4.0			0.00359			5.8	
Expected Behavior	Erosion	Erosion	Erosion	Fill	Fill	Fill	Scour	Scour	Scour	Scour	Scour	Scour
Reach 1												
Bray	39	91	146	1.5	2.6	3.5	-	-	-	1.9	2.7	3.3
Parker	58	130	203	1.2	2.3	3.3	0.00137	0.00070	0.00049	-	-	-
Ackers & Charlton/Lacey	33	66	96	-	-	-	-	-	-	1.9	2.5	2.9
Chang	26	68	121	1.3	1.9	2.2	0.00052	0.00027	0.00018	-	-	-
Kellerhals	25	57	90	2.2	4.2	6.0	-	-	-	-	-	-
AMAFCA	27	34	35	-	-	-	0.00313	0.00315	0.00359	-	-	-
Average	36	76	114	1.6	3.0	4.3	0.00225	0.00193	0.00204	1.9	2.6	3.1
HEC-RAS Data	32	38	38	2.2	4.8	7.4		0.00175		3.8	7.0	10.2
Bankfull Discharge Data		35			3.2			0.00175			4.9	
Expected Behavior	Erosion	Erosion	Erosion	Fill	Fill	Fill	Scour	Scour	Scour	Scour	Scour	Scour

Cave Creek. The channel geometry information for Cave Creek summarized in Table 4-13 indicates that during the 2-year event, the existing average channel width is wider than the regime width predicted by the channel geometry equations. Therefore, any bank erosion that occurs during a 2-year event is probably due to local conditions, rather than a system-wide equilibrium response. At flow rates that exceed the 10-year flood, the regime width exceeds the existing channel width, and system-wide expansion of channel width is expected. The channel width would be increased by bank erosion. Therefore, general widening and bank erosion should be expected during the largest future floods.

The predicted flow depths are less than the existing channel depths for the 2-, 10-, and 100-year events throughout the study reach, except in Reach 3, indicating that the channel is *incised* and would need to aggrade to achieve the regime geometry. Reach 3 is already incised due to historical mining. However, the predicted channel slope and velocity indicate that *scouring* conditions are expected for the 2-, 10-, and 100-year events. The higher than average velocities are due to the incised channel and above average channel slope.

Of the five reaches evaluated on Cave Creek, the geometry of Reach 5 is closest to the predicted channel geometry for all for variables considered.

The predicted channel geometry values were compared to the estimated bankfull geometry values are described elsewhere in this chapter (Table 4-4). 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 (Table 4-17) between data points.

Table 4-17. Upper Cave Creek/Apache Wash Watercourse Master Plan Approximate Recurrence Interval of Bankfull Discharge Geometry Estimated from Channel Geometry Equations – Cave Creek (yrs)

Reach	Width	Depth	Velocity
1	33 yrs	> 100 yrs	> 100 yrs
2	14 yrs	> 100 yrs	> 100 yrs
3	25 yrs	> 100 yrs	> 100 yrs
4	20 yrs	> 100 yrs	> 100 yrs
5	10 yrs	> 100 yrs	> 100 yrs

Apache Wash. The channel geometry information for Apache Wash summarized in Table 4-14 indicates that during the 2-year event, the existing average channel width is wider than the regime width predicted by the channel geometry equations, except in Reaches 1 and 2. Therefore, any erosion that occurs during a 2-year event is probably due to local conditions, rather than to a system wide response. At flow rates that exceed the 10-year flood, the regime width exceeds the existing channel width, and system-wide expansion of channel width is expected, except in Reach 3. The channel width would be increased by bank erosion. 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 flow depths are less than the existing channel depths for the 10-, and 100-year events throughout the study reach, indicating that the channel is moderately *incised* and would need to aggrade to achieve the regime geometry. For the 2-year event, the predicted flow depths in Reaches 3, 4, and 5are approximately equal to the bankfull depths computed from the HEC-RAS modeling. The predicted channel slope and velocity indicate that scouring conditions are expected for the 2-, 10-, and 100-year events throughout the entire study reach. The higher than average velocities are due to the above average channel slope.

Of the five reaches evaluated on Apache Wash, the geometries of Reaches 1 and 2 are closest to the predicted channel geometry over the range of variables considered.

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 (Table 4-18) between data points.

Table 4-18. Upper Cave Creek/Apache Wash Watercourse Master Plan Approximate Recurrence Interval of Bankfull Discharge Geometry Estimated from Channel Geometry Equations –Apache Wash (yrs)

Reach	Width	Depth	Velocity
1	7 yrs	> 100 yrs	> 100 yrs
2	5 yrs	100 yrs	> 100 yrs
3	33 yrs	33 yrs	> 100 yrs
4	6 yrs	17 yrs	> 100 yrs
5	3 yrs	33 yrs	> 100 yrs

Paradise Wash. The channel geometry information for Paradise Wash summarized in Table 4-15 indicates that during the 2-year event, the existing average channel width is wider than the regime width predicted by the channel geometry equations. Therefore, any erosion that occurs during a 2-year event is probably due to local conditions, rather than a system wide response. At flow rates that exceed the 2-year flood, the regime width exceeds the existing channel width, and system-wide expansion of channel width is expected. The channel width would be increased by bank erosion.

Throughout the study reach, the predicted flow depths are less than the existing channel depths for flows that exceed the 10-year event, indicating that the channel is slightly *incised* and would need to aggrade to achieve the regime geometry. For the 2-year event, the predicted flow depths are greater than the bankfull depths computed from the HEC-RAS modeling, indicating a tendency to *scour* to achieve the regime geometry during the 2-year event. The predicted channel slope and velocity indicate that scouring conditions are expected for the 2-, 10-, and 100-year events throughout the entire study reach. The higher than average velocities are due to the above average channel slope.

The predicted channel geometry values 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 (Table 4-19) between data points.

Table 4-19. Upper Cave Creek/Apache Wash Watercourse Master Plan Approximate Recurrence Interval of Bankfull Discharge Geometry Estimated from Channel Geometry Equations –Paradise Wash (yrs)

Reach	Width	Depth	Velocity
SR	11 yrs	33 yrs	> 100 yrs
1	10 yrs	33 yrs	> 100 yrs

Desert Hills Wash. The channel geometry information for Desert Hills Wash summarized in Table 4-16 indicates that the existing average channel width is narrower than the regime width predicted by the channel geometry equations for the 2-, 10-, and 100-year event. Therefore, a general tendency toward bank erosion and channel widening is expected during any flood. Throughout the study reach, the predicted flow depths are less than the existing channel depths for the 2-, 10-, and 100-year events, indicating that the channel is *incised* and would need to aggrade to achieve the regime geometry. The predicted channel slope and velocity indicate that scouring conditions are expected for the 2-, 10-, and 100-year events throughout the entire study reach. The higher than average velocities are due to the above average channel depth and slope.

The predicted channel geometry values were compared to the estimated bankfull geometry values described elsewhere in this chapter (Table 4-7). 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 (Table 4-20) between data points.

Table 4-20. Upper Cave Creek/Apache Wash Watercourse Master Plan Approximate Recurrence Interval of Bankfull Discharge Geometry Estimated from Channel Geometry Equations –Desert Hills Wash (yrs)

Reach	Width	Depth	Velocity
SR	1.3 yrs	> 100 yrs	> 100 yrs
1	2 yrs	20 yrs	> 100 yrs

Hydraulic Geometry Regression Equations. Hydraulic data for the streams in the study area were used to develop reach-average regression equations for hydraulic geometry. No data base of hydraulic geometry regression equations currently exists for central Arizona. The data presented in this section were compared to other data sets from the arid west, but are also presented as the beginning of a data collection effort for the unique types of streams found in Maricopa County. Following additional data collection and completion of geomorphic analyses for other watercourse master plans in Maricopa County, the data base may provide important information on the stable (or unstable) geometry of local watercourses.

Methodology. Hydraulic data were obtained from the HEC-RAS models for Cave Creek and its tributaries. These data were used to develop reach-averaged regression equations in form the of the classic hydraulic geometry equations for the four streams in the study

area. The following four regression equations were developed for each reach, using the conventions for variable and exponent names established in Leopold and Maddock (1953).

- $W \propto aQ^b$
- $d \propto cQ^f$ and $R \propto cQ^f$
- $v \propto kQ^m$

Where W = width
Q = *discharge*
d = depth
R = hydraulic radius
v = velocity
a, c, k = coefficients
b, f, m = exponents

The exponents and coefficients were based on the relationships between *discharge* and top width, discharge and maximum depth, discharge and hydraulic depth, and discharge and velocity. Plots of each of the regression relationships, and a summary of the intercept, slopes, R Squares, and resulting equations are provided in Appendix C.

The coefficients in the regression equations relating change of depth, width, and velocity to change in discharge should equal one when multiplied together ($a \times c \times k = 1$). The exponents within the equations also should have a sum of one ($b + f + m = 1$). These expectations were met in all instances. Note that in this discussion, the terms velocity (m), depth (f), or width (b) refer to the rate of change of each of the variables as discharge increases. A larger value indicates a faster rate of change; a smaller value indicates a slower rate of change.

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. 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 value of 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 In general, the analyses were focused on the reach-averaged conditions, but individual cross sections in a single reach and the total stream average were also considered to test the variation in results over a variety of reach lengths and data sets. No significant differences in results were found, as reported in the following paragraphs.

Table 4-21. Upper Cave Creek/Apache Wash Watercourse Master Plan Hydraulic Geometry Equations Results

Reach	Maximum Depth (ft)	Hydraulic Depth (ft)	Top Width (ft)	Velocity Channel (ft/s)	b + f + m	a x c x k
Cave Creek						
SR	$Dmax = .283\ Qchl^{.366}$	$Dhydr = .089\ Qchl^{.431}$	$TW = 14.028\ Qchl^{.307}$	$Vchl = .802\ Qchl^{.263}$	1.001	1.005
1	$Dmax = .188\ Qchl^{.405}$	$Dhydr = .093\ Qchl^{.419}$	$TW = 14.388\ Qchl^{.314}$	$Vchl = .743\ Qchl^{.266}$	0.999	0.998
2	$Dmax = .163\ Qchl^{.427}$	$Dhydr = .084\ Qchl^{.449}$	$TW = 16.032\ Qchl^{.268}$	$Vchl = .745\ Qchl^{.283}$	1.000	1.002
3	$Dmax = .206\ Qchl^{.391}$	$Dhydr = .093\ Qchl^{.415}$	$TW = 14.223\ Qchl^{.327}$	$Vchl = .752\ Qchl^{.259}$	1.001	0.998
4	$Dmax = .287\ Qchl^{.374}$	$Dhydr = .095\ Qchl^{.437}$	$TW = 19.454\ Qchl^{.263}$	$Vchl = .542\ Qchl^{.300}$	1.000	1.000
5	$Dmax = .189\ Qchl^{.425}$	$Dhydr = .119\ Qchl^{.426}$	$TW = 17.498\ Qchl^{.251}$	$Vchl = .482\ Qchl^{.323}$	1.000	1.000
Apache Wash						
SR	$Dmax = .236\ Qchl^{.407}$	$Dhydr = .141\ Qchl^{.419}$	$TW = 8.995\ Qchl^{.252}$	$Vchl = .791\ Qchl^{.329}$	1.000	0.999
1	$Dmax = .136\ Qchl^{.483}$	$Dhydr = .104\ Qchl^{.462}$	$TW = 9.333\ Qchl^{.251}$	$Vchl = 1.026\ Qchl^{.288}$	1.001	0.992
2	$Dmax = .133\ Qchl^{.500}$	$Dhydr = .091\ Qchl^{.514}$	$TW = 11.912\ Qchl^{.180}$	$Vchl = .929\ Qchl^{.306}$	0.999	1.007
3	$Dmax = .072\ Qchl^{.560}$	$Dhydr = .083\ Qchl^{.455}$	$TW = 11.940\ Qchl^{.375}$	$Vchl = 1.000\ Qchl^{.170}$	1.001	0.992
4	$Dmax = .084\ Qchl^{.514}$	$Dhydr = .058\ Qchl^{.531}$	$TW = 25.586\ Qchl^{.145}$	$Vchl = .670\ Qchl^{.323}$	1.000	1.000
5	$Dmax = .072\ Qchl^{.544}$	$Dhydr = .066\ Qchl^{.533}$	$TW = 26.607\ Qchl^{.117}$	$Vchl = .575\ Qchl^{.350}$	0.999	1.004
Paradise Wash						
SR	$Dmax = .065\ Qchl^{.557}$	$Dhydr = .059\ Qchl^{.541}$	$TW = 21.038\ Qchl^{.137}$	$Vchl = .809\ Qchl^{.322}$	1.000	1.002
1	$Dmax = .069\ Qchl^{.564}$	$Dhydr = .065\ Qchl^{.540}$	$TW = 18.967\ Qchl^{.143}$	$Vchl = .802\ Qchl^{.318}$	1.001	0.995
Desert Hills Wash						
SR	$Dmax = .131\ Qchl^{.536}$	$Dhydr = .119\ Qchl^{.522}$	$TW = 12.246\ Qchl^{.121}$	$Vchl = .684\ Qchl^{.358}$	1.000	0.997
1	$Dmax = .716\ Qchl^{.507}$	$Dhydr = .126\ Qchl^{.499}$	$TW = 16.866\ Qchl^{.110}$	$Vchl = .472\ Qchl^{.391}$	1.000	1.002

Table 4-22. Upper Cave Creek/Apache Wash Watercourse Master Plan
Comparison of Stream Averages for Cave Creek/Apache Wash Hydraulic Geometry with Semiarid U.S. Averages

Reach	Range	Average	Average Semiarid U.S.	Difference CC Avg – U.S. Avg	Explanation
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
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
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

Results. Values for the *m/f* ratio for each stream in the study area are summarized in Table 4-23.

Table 4-23. Upper Cave Creek/Apache Wash Watercourse Master Plan Stream Average m/f Ratio Values

Stream	Mean	Minimum	Maximum	Median
Cave Creek	.674	.610	.758	.661
Apache Wash	.591	.374	.785	.602
Paradise Wash	.592	.588	.596	.592
Desert Hills Wash	.734	.686	.783	.734

The data in Table 4-23 indicate the following trends for the four streams in the study area:

- The values for *m/f* ratio sediment transport rate for Cave Creek/Apache 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.
- Values for *m/f* ratio are much more variable in Apache Wash than in the other three streams, .374 to .785. Sediment transport will thus be more variable.
- Values for *m/f* ratio are highest in Cave Creek and Desert Hills Wash. As discharge increases, these streams will transport more sediment than the other streams in the study area.
- The lowest value for *m/f* ratio is for Reach 3 on Apache Wash (0.374). See also the low velocity values (low slope?) and large width values on longitudinal plots of bankfull Q.

At the individual cross-section level, the most striking characteristic is the degree of variation between adjacent cross-sections within a reach. The data for *Supply reach* 2 of Cave Creek is presented as an example of this characteristic (Table 4-24). Depth (*m*) varies the least of the three variables, ranging from values of 0.3088 to 0.5623. Velocity (*f*) varies the most (0.1371 to 0.4793), probably due partly to the wide variations in width (*b*), 0.1157 to 0.4223. Variations in both velocity (*m*) and depth (*f*) cause the variations in the *m/f* ratio.

Table 4-24. Upper Cave Creek/Apache Wash Watercourse Master Plan Coefficient and Exponent Variations within Supply reach 2, Cave Creek									
	Velocity		Depth		Width		Relationships		
HECRAS Section #	Slope m	Intercept Log k	Slope f	Intercept log c	Slope b	Intercept log a	(b+f+m)	(a x c x k)	m/f
31.91	0.45	-0.81	0.42	-0.77	0.13	1.58	1.00	1.00	1.07
31.87	0.41	-0.67	0.47	-1.09	0.12	1.76	1.00	0.99	0.87
31.82	0.36	-0.43	0.49	-1.31	0.14	1.73	0.99	1.00	0.73
31.75	0.18	0.28	0.45	-1.13	0.37	0.86	1.00	1.00	0.40
31.63	0.43	-0.76	0.35	-0.64	0.22	1.40	1.00	1.01	1.25
31.54	0.23	0.05	0.56	-1.64	0.22	1.58	1.00	0.97	0.40
31.45	0.48	-0.94	0.31	-0.51	0.20	1.49	0.98	1.13	1.55
31.34	0.15	0.28	0.49	-1.31	0.35	1.03	1.00	1.00	0.31
31.25	0.34	-0.36	0.36	-0.82	0.30	1.18	1.00	1.00	0.96
31.17	0.14	0.33	0.44	-1.17	0.42	0.84	1.00	1.00	0.31
31.14	0.42	-0.66	0.34	-0.59	0.25	1.24	1.00	1.00	1.23
31.05	0.24	-0.01	0.48	-1.26	0.29	1.26	1.00	1.00	0.50
30.96	0.32	-0.34	0.42	-0.96	0.26	1.30	1.00	1.01	0.75
Mean:	0.32	-0.31	0.43	-1.01	0.25	1.33	1.00	1.01	0.80
Min:	0.14	-0.94	0.31	-1.64	0.12	0.84	0.98	0.97	0.31
Max:	0.48	0.33	0.56	-0.51	0.42	1.76	1.00	1.13	1.55
Range:	0.34	1.26	0.25	1.13	0.31	0.92	0.02	0.15	1.24

In some cross sections, the rate of sediment transport increases much more slowly than average, indicating less efficiency in transporting sediment, i.e., deposition. The low *m/f* value within Supply reach 2 on Cave Creek is 0.31, compared to an average of 0.94 for streams located elsewhere in the semi-arid United States (Leopold, Wolman, and Miller 1964). The highest *m/f* value in the reach is 1.55, much higher than the average, indicating a more efficient transport of sediment and possible erosion. The average *m/f* ratio calculates to 0.80, below average for ephemeral streams in the semiarid United States. The wide variation in rates of sediment transport within a reach, indicating that reaches of high erosion may be close to reaches of significant deposition. The rate of sediment transport through the reach, or the amount coming out of the downstream end, increases at a slower rate than what could be expected for an average ephemeral stream.

At the reach scale, all the *m/f* ratios for the study area are below average, as shown in Table 4-24. There are several possible explanations for the below-average *m/f* ratios. Examination of the *m, f,* and *b* values for Cave Creek, Apache Wash, Paradise Wash, and Desert Hills Wash reveals that for all but Desert Hills Wash the velocity increases at a slower rate than average (Table 4-22). At the same time the depths of the washes are increasing 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. The exception to these trends is the reach on Apache Wash from Desert Hills Wash to Paradise Wash. Width increases much faster than average, indicating a wide relatively shallow channel with low velocities where deposition is most likely occurring ($m/f = 0.375$, well below average).

There is less variation between reach-averaged values on a single stream than within the individual cross section values within a single reach. The average values for each stream as a whole reflect the same conditions apparent in each reach. The exception once again is Apache Wash from Desert Hills Wash to Paradise Wash (Reach 3). The consistently degrading Desert Hills Wash had the highest m/f ratio values for the Cave Creek WCMP, meaning that rates of sediment transport in Desert Hills Wash increase the fastest as discharge increases. Desert Hills Wash may be the most efficient stream in the area at transporting sediment through and out of the system, leading to more consistent erosion and degradation along its course.

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 the four major streams in the study area. In general, field observations made along Cave Creek indicate that study reach is subject to lateral erosion and channel *avulsions*, has experienced historical degradation, and has been extensively impacted by human activities. Field observations made along Apache Wash, Paradise Wash, and Desert Hills Wash indicate that the study reaches are more laterally stable than Cave Creek and have not experienced significant long-term degradation or human impacts. Field data suggest that the frequency of channel avulsions on Cave Creek (Reaches 3, 4, and 5) is greater than on Apache Wash or Paradise Wash. The stability predictions associated with the modified Brice and Rosgen classification schemes also indicated that the streams in the study area are susceptible to rapid lateral migration and bank erosion.

The ages and relative heights of the geomorphic surfaces in the study area provide information on how recently they have been flooded or subject to lateral erosion. The geologic record indicates that portions of Cave Creek, Apache Wash and Paradise 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 700,000 years. Except in reaches affected by channel avulsions, geologic evidence preserved in the soils record indicates that the long-term rate of net channel change has been slow (< 1ft/yr

laterally, <0.01 ft/year vertically). 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, except where the streams are disturbed by human activities. The rate of net degradation since the middle Pleistocene and early *Holocene* was 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.; somewhat faster, but within the range of long-term geologic rates of incision.

Channel movement measured by comparison of historical aerial photographs is not significantly different in rate or scale than the rate suggested by interpretation of the geomorphic surficial mapping. 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. Cave Creek and its major tributaries 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 (slower) lateral erosion. Geologic evidence preserved in the soils and surficial characteristics indicate that Reaches 3 and 4 of Cave Creek were subject to channel avulsions and had a multiple channel pattern prior to the incision caused by in-stream mining. If this reach were to recover from the human-induced incision, it would probably be subject once again to avulsions.

Longitudinal profile analyses of Cave Creek and its three tributaries in the study area indicate that there has been historical degradation, although some localized areas have experienced net aggradation in the past 40 years. No natural grade control exists in the beds of the stream channels. Grade control is provided by the concrete box culverts on Apache Wash and Paradise Wash at the Carefree Highway at the upstream end of the study limits. No evidence of progressive long-term degradation was observed at the downstream sides of these structures.

The magnitude and recurrence interval of the bankfull *discharge* varies widely for the streams in the study area, with little continuity in the values between adjacent cross sections. On Cave Creek, bankfull capacity increases in the downstream direction from Carefree Highway through Reach 3, and then decreases in Reach 5. The highest estimates of bankfull discharge occurred in the sand and gravel mining reach on Cave Creek. Along Apache Wash, bankfull capacity increases in the downstream direction within the study reach. For Paradise Wash, bankfull discharge increases in the upper part of the study reach, followed by a gradual decrease near the Apache Wash confluence. The poor continuity in bankfull discharge magnitude and frequency between 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. This slow response is expected in streams whose geometry is formed primarily by large, infrequent floods.

The recurrence intervals of bankfull discharges on Paradise Wash are somewhat higher than the recurrence intervals of bankfull discharges on Apache Wash and Desert Hills

Wash, although they are generally lower than the very high values for Cave Creek. The difference in bankfull recurrence interval are primarily due to historical incision and disturbance by sand and gravel mining. The high recurrence interval of bankfull discharge for the streams in the study area indicates that stream stability is influenced more by the large floods, rather than the small annual floods. Therefore, the stability analyses should focus on the affects of the largest floods.

Channel pattern equations predict a straight braided channel pattern for Cave Creek, with less strongly expressed braiding expected on Apache Wash and Paradise Wash. Desert Hills Wash is likely to maintain its existing slightly *sinuous* to weakly meandering channel pattern in the future. 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. Cave Creek will tend to erode its banks during floods that exceed the 10-year event, but will experience only localized bank erosion during the 2-year flood. Likewise, Apache Wash and Paradise Wash will experience only local bank erosion during 2-year floods, but will tend to widen during the largest floods. The reach-averaged existing and predicted widths for Apache Wash differ by a factor of two to three for the 100-year event, indicating a strong tendency for lateral erosion during extreme floods. Desert Hills Wash has a tendency to widen and erode its banks during any flood, according to the hydraulic geometry equations. The channel geometry analysis indicates that almost all of the stream reaches in the study area are oversteepened and *incised*, and experience erosive velocities during most flows.

The hydraulic geometry regression equation results indicate that the study reaches are more incised than the average ephemeral wash in the semiarid United States, with the exception of Reach 3 of Apache Wash. The slower increase in width as discharge increased implies that the channels have well-consolidated banks, which constrain lateral erosion while concentrating erosive work on the bed of the channel. Desert Hills Wash may be the most efficient stream in the area at transporting sediment through and out of the system, leading to more consistent erosion and degradation along its course than along the other streams.

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. The HEC-RAS were developed from HEC-2 models prepared by others for floodplain delineation studies previously completed for the District (GVSCE, 1996; Willdan, 1996; Jerry R. Jones, 1992). 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, a large number of 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 Tables 5-1.

Table 5-1. Upper Cave Creek/Apache Wash 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)	°	Field
ϕ	*Angle of repose* of bank material	°	Look up
θ	Angle of channel bank	°	Field
τ_b	*Boundary shear stress*	lb/ft^2	Compute
τ_c	Critical tractive force *Critical shear stress*	lb/ft^2	Compute
τ_o	Average tractive force Average shear stress	lb/ft^2	Compute
ω	Terminal fall velocity	ft/sec	Compute
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
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

Table 5-1. Upper Cave Creek/Apache Wash Watercourse Master Plan Hydraulic Variable List

Symbol	Variable Name	Units	Source
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
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	1.217×10^5	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-RAS models prepared for Flood Insurance Studies can be used to generate hydraulic data for use in geomorphic assessments and channel stability studies. The primary objective of a Flood Insurance Study 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 floodplain delineation study generally are not as thoroughly evaluated as the 100-year water surface elevation estimates. Furthermore, the cross section division into channel and overbank sections is performed to optimize the water surface elevation estimates, and may not accurately reflect other hydraulic characteristics of the channel and floodplain. Therefore, prior to using a HEC-RAS model developed for a floodplain delineation study for a geomorphic analysis, the HEC-RAS model must be evaluated and modified. The following types of modifications are addressed:

- 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 are present at the outfall, 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-RAS 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-RAS 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 far too many 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-RAS 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. Then a specific terrace or geomorphic surface can be used as the limit of mapping to facilitate comparison of discharge capacity versus geomorphic age.

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.

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.

- 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.

Physical Characteristics of Channel Banks. Channel bank stations can be identified using the following procedures.

Ordinary High-Water Mark. The Corps of Engineers, in identifying the bank station associated with the ordinary high-water mark, uses the following three characteristics:

- Vegetation. A change from terrestrial to aquatic vegetation, or the onset of terrestrial vegetation often occurs at the ordinary high-water mark.
- Soils. A change in soil characteristics from undifferentiated, poorly developed soils to more well-developed soils with distinct profiles often occurs at the ordinary high-water mark. This change is caused by frequent *scour* and fill that prevents soil formation.
- Topography. A break in slope often occurs at the ordinary high-water mark.

The ordinary high-water mark, as defined by the Corps of Engineers, is analogous to a geomorphic definition of the top of the channel bank. Therefore, the Corps' definition can be applied to help define the location of the channel stations used for HEC-RAS modeling. However, the following modifications are required to apply these definitions to streams in Arizona and the arid west:

- Vegetation. On *ephemeral* and *intermittent* streams, vegetation in the channels may not be significantly different from vegetation growing in or above the floodplain. However, the following guidelines are suggested:
  1. Areas swept clean of vegetation. The areas of highest velocity occur in the main channel, and will be periodically swept clear of vegetation during high flows. Therefore, the channel will either lack vegetation, or will be populated with very young, fast growing vegetation. An inspection of the stream's flood history, either from gauge records or field evidence, should be made to determine whether high flows have occurred in the recent past. If no large flows have occurred in the recent past, vegetation may have encroached on the main channel and may obscure the banks.
  2. Bank vegetation. A swath of dense vegetation often lines the banks of ephemeral and intermittent channels. In southern and central Arizona, this vegetation generally consists of Mesquite, Palo Verde, Ironwood, and brushy plants, but may also include cactus species such as Sahauro. This vegetation is usually distinguished by species and/or density from both the vegetation on the channel bottom and the vegetation in the floodplain.
  3. Age of vegetation. The relative age of the bank vegetation can be used to assess the frequency and/or the age of the most recent channel changes. Older bank vegetation indicates infrequent channel movement in the past, and a stable bank. Young, intermittent vegetation may indicate the bank of an erodible inset terrace, rather than the primary channel bank.

- Avulsions. If the main channel location is subject to avulsive channel changes, the bank stations required for geomorphic assessment may be well outside the area defined by existing bank vegetation. The potential for avulsive channel changes can be assessed by a field inspection and by comparison of historical aerial photographs. The presence of multiple channels often is evidence of historical channel *avulsions*. Definition of channel bank stations in reaches subject to avulsive changes is complex. In general, the main channel should be defined at the margins of the portion of the floodplain subject to the most frequent flow and bedload sediment transport.

- Soils. Soil characteristics can be used to distinguish the main channel from less frequently inundated areas.
  1. Sediment size. Overbank areas primarily are subject to deposition, and thus generally are composed of accretive layers of fine grained sediment, or have a mantle of more recently deposited fine grained materials. Areas subject to channel processes typically are underlain by coarser sediments.

2. Imbrication. Coarse channel sediments are often *imbricated* in the direction of movement. However, caution should be used when examining areas of recent entrenchment where historical active sediment transport occurred, leaving imbricated sediments in areas that are now perched above the main channel.
3. Profile development. Areas outside the channel generally have remained undisturbed for longer periods of time, and hence have had time to develop soil horizons, surface pavements, and other features of soil development. Surface characteristics that may indicate subsurface soil profile development include *desert varnish*, *desert pavement*, and reddening of surface layers.
4. Bank cuts. Soil profiles can often be observed in *cut banks*. Features that indicate soil profile development that can be observed in cut banks include carbonate layers (*caliche*), clay accumulation (soil texture), reddening of soil layers, and soil structure (ped formation).

- Topography. Most large stream systems consist of compound channels with one or more terraces that reflect different levels of flooding and inundation. Inundation of these terraces corresponds to different flow frequencies – larger floods are required to inundate the highest terraces. Therefore, to some degree, definition of the main channel depends on the frequency of the flow event under consideration.

Flood Frequency. Use of a predetermined recurrence interval for *bankfull discharge* based on published reports (such as the 1.65-year flood) is not recommended for estimating the bankfull limits. This practice begs the question of how can the channel-forming discharge be determined unless the channel hydraulics are first estimated. To estimate channel hydraulics, one needs to define the bank stations. The following bank definition criteria relating to flood frequency information are noted:

1. Sediment size. If the channel is *armor*ed, and the banks are resistant to lateral erosion, it is unlikely the channel forming discharge is a frequent event (Q2 or less). In these cases, the channel geometry probably is the result of the largest flows (Q25 or greater).
2. Bankfull discharge. Definitions of bankfull discharge recommended by some publications (cf., Rosgen, 1996) are practically irrelevant for lateral stability studies in Arizona. Bankfull discharges that refer to a 1.5-year or more frequent discharge may be relevant for a micro-channel formed within a compound channel, or for fish habitat studies on perennial streams, but have little impact on river stability assessments in central and southern Arizona. Limiting the scope of analysis to this low flow micro-channel ignores the important role of floods on shaping channels and in causing lateral movement and bank erosion. For entrenched river systems, or for erosion hazard assessments, bankfull refers to the well-defined banks subject to erosion during floods. That is, the banks that if eroded, would be of concern to adjacent property owners.

3. Bank Station. The flood frequency should be high enough to reach an erosive velocity (> 3-5 ft/sec), and high enough to flow against the banks.

Bank Definitions for Specific Channel Types. Figures 5-1 to 5-6 illustrate selection of bank stations for a variety of stream types.

Single Channels. Bank stations are most easily identified for single channel reaches.

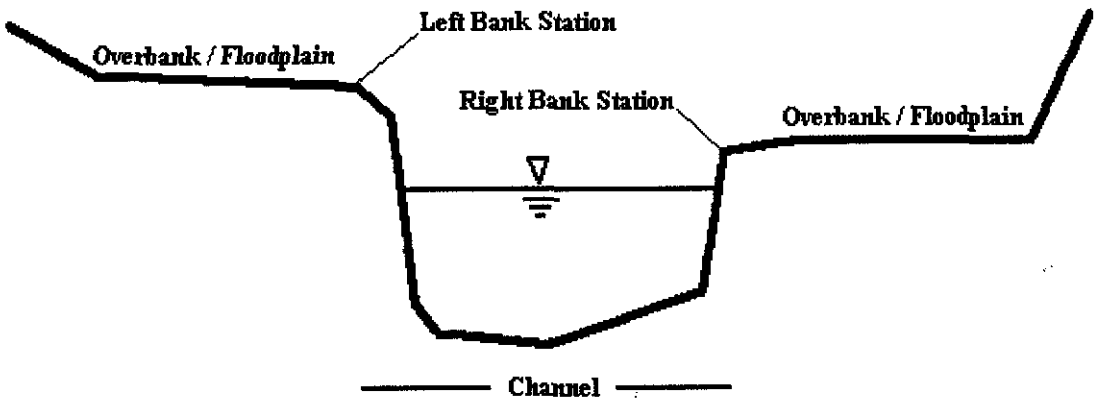


Figure 5-1. Recommended bank stationing for single channel cross sections.

Multiple Channels. Several types of multiple channel conditions exist. Judgment regarding the study objectives must be used to define the bank stations on multiple channel reaches.

Scenario #1 – Multiple Channel Where Islands Inundated by Flows

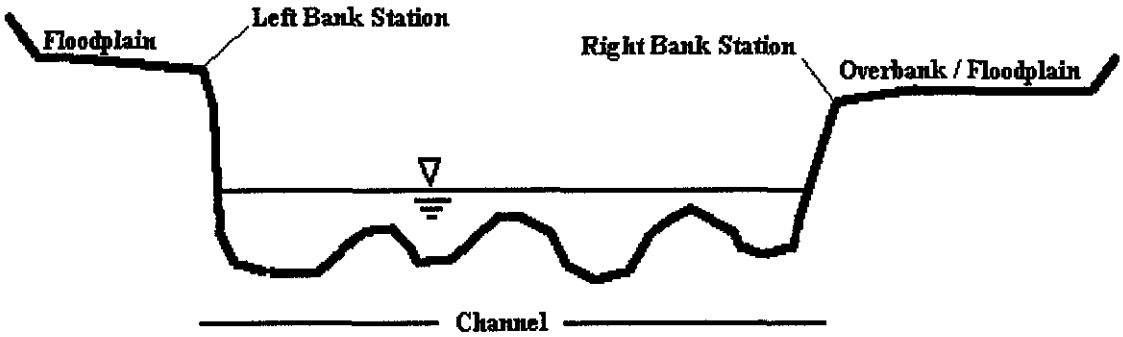


Figure 5-2. Recommended bank stationing for multiple channels with shallow islands.

Scenario #2a – Multiple Channel Where Islands Not Inundated by Flows: Small Islands

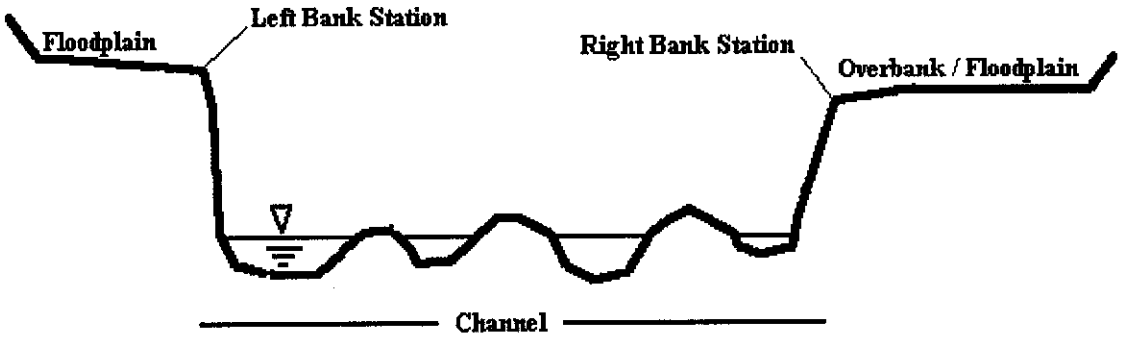


Figure 5-3. Recommended bank stationing for multiple channels with shallow, insignificant or small islands.

Scenario #2b - Multiple Channel Where Islands Not Inundated by Flows: Large Islands

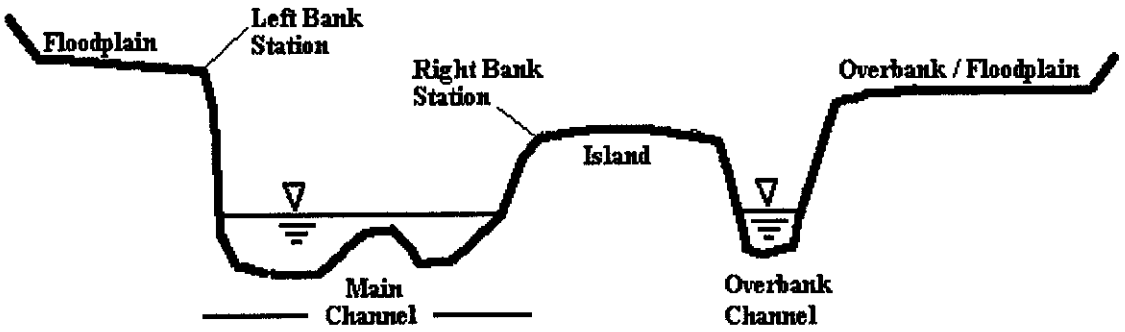


Figure 5-4. Recommended bank stationing for multiple channels with exposed islands of significant size.

Perched Channels. Perched channels are typically overbank conveyance corridors that are hydraulically disconnected from the main channel at a specific section. The bank stations should be selected to reflect the geometry of the main channel.

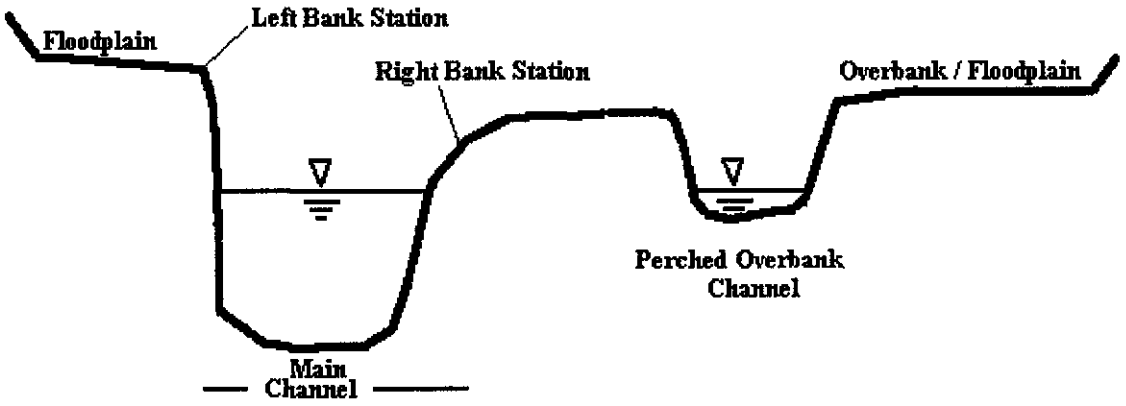


Figure 5-5. Recommended bank stationing for perched overbank channels.

Channels With Poorly Defined Banks. In some cases, a clearly defined bank station cannot be defined solely on geomorphic characteristics. Where the banks are poorly defined, the bank station can be selected using hydraulic criteria (e.g., $d*v^2>18$; where d=flow depth, ft. and v=flow velocity, ft./s.) or by comparison with the channel widths of upstream and downstream sections.

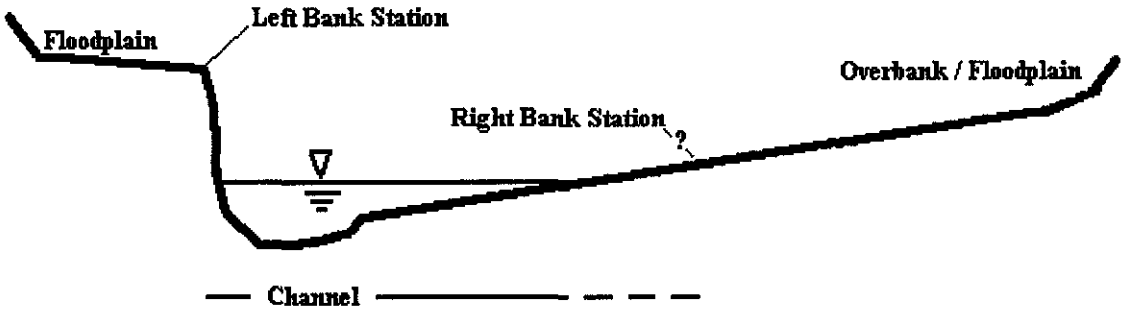


Figure 5-6. Recommended bank stationing for channels with poorly defined banks

Ineffective Flow Areas. The ineffective flow areas defined in the model should be appropriate for the full range of discharges. If this is not possible, optimize the ineffective flow areas for bankfull discharge.

Other Guidelines. The following other modeling guidelines are suggested:

- Consistency between cross sections. Large fluctuations in channel width, as defined by the bank stations, should be avoided unless dictated by actual changes in channel width documented in the field. Channel characteristics generally change gradually on stable, natural streams.
- Level of accuracy. HEC-2 is a one-dimensional, gradually varied flow model. It assumes a horizontal water surface, with no waves or no superelevation on bends, and no sediment movement or bank erosion during the passage of the flood. There is uncertainty in the discharge estimate, the channel geometry, and the hydraulic modeling coefficients. The actual accuracy of the predicted water surface probably is not known within one foot. Results should be interpreted accordingly.

Application to the Upper Cave Creek/Apache Wash Study Area
Three HEC-2 models for the study area were provided by the District for use in the Cave Creek Watercourse Master Plan Study. The HEC-2 models were developed for the following floodplain delineation studies:

- Cave Creek, Cave Buttes Dam to Carefree Highway (Willdan, 1996)
- Cave Creek, Upstream of Carefree Highway (GVSCE, 1996)
- Apache Wash, Paradise Wash, Desert Hills Wash (Jerry R. Jones, 1992)

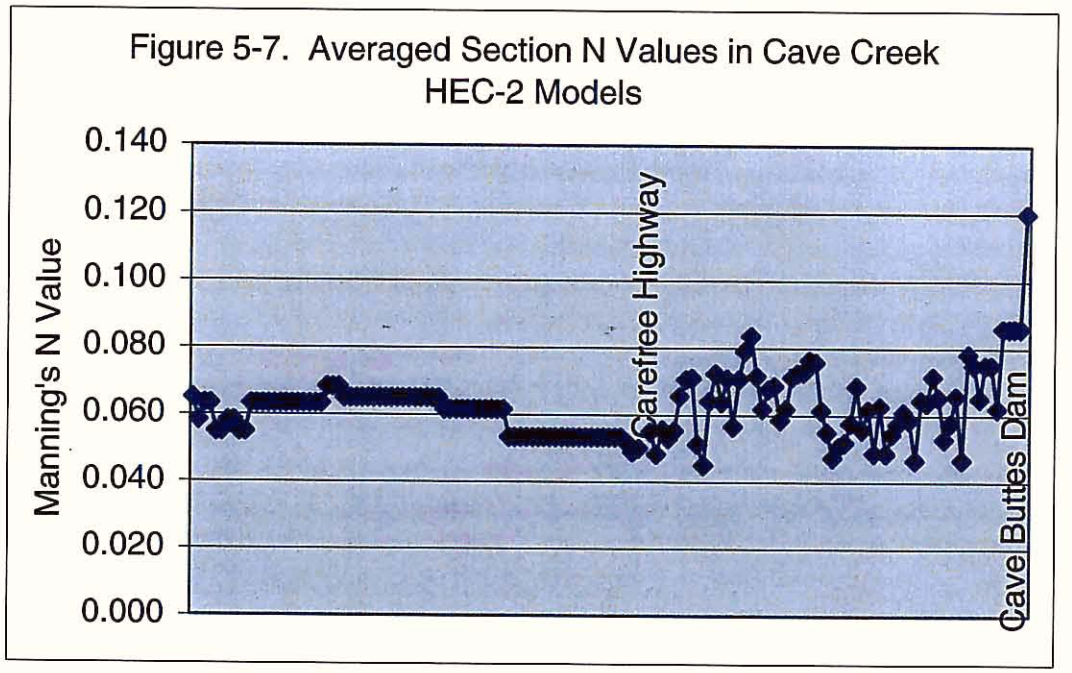
The two Cave Creek HEC-2 models were combined and converted to HEC-RAS format by Stantec (1999) for the Cave Creek Watercourse Master Plan project. Likewise, the Apache Wash HEC-2 model was also converted to HEC-RAS format (Stantec, 1999) The converted HEC-RAS models were delivered to ASL Consulting Engineers (ASL) and distributed to the project team.

The original HEC-2 models were developed for delineation of the 100-year floodplain and floodway. Therefore, the modifications described in the previous section were required to use the converted HEC-RAS model for the sedimentation and geomorphic analyses, and to evaluate the hydraulics of floods other than the 100-year event. This section summarizes the 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.

Irregularities in the Original HEC-2 Models. The following are noted as modeling irregularities in the original HEC-2 models and/or the HEC-RAS model provided to JEF:

1. Manning's N Values. The Willdan HEC-2 model used NH records, rather than composite values of N for the channel, left overbank, and right overbank (NC record). In some cases, up to thirteen N values were used on an NH record for a single cross section. N values used in the Willdan HEC-2 model also varied widely between adjacent cross sections. Although it may be possible to predict N values with the precision implied in the Willdan HEC-2 model within an individual cross section for a specific flow rate, the results would be misleading for the lateral stability assessment, which considers a wide range of flow rates and the potential for channel change. Furthermore, NH records are not recognized by the HEC-6 model. The

abrupt change in N value definition between the GVSCE and Willdan HEC-2 models and the longitudinal inconsistency are illustrated in Figure 5-7. An example of the N value definition for a cross section from the Willdan model is shown in Figure 5-8.



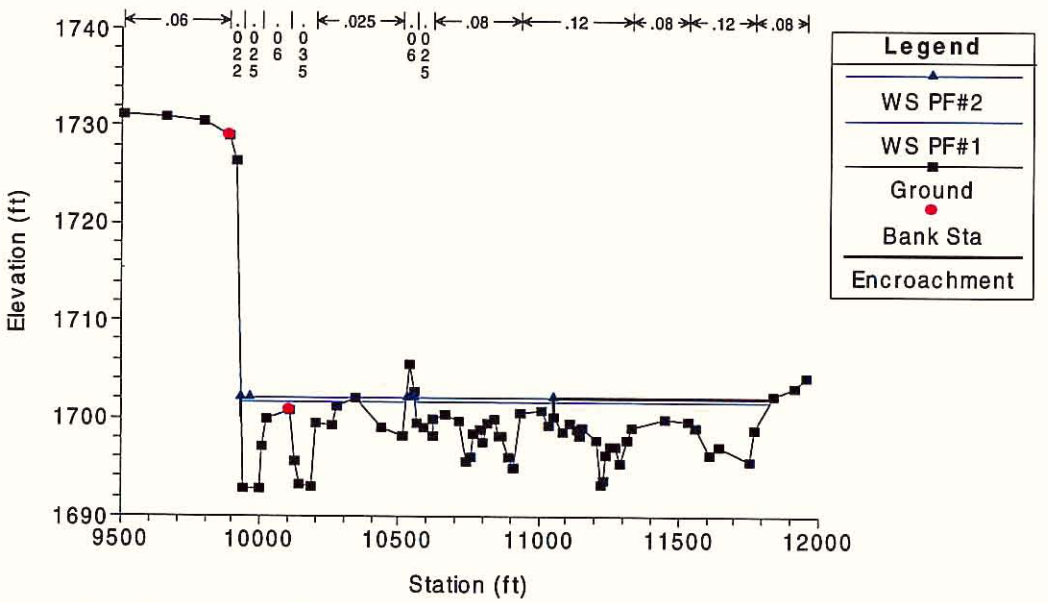


Figure 5-8. Example of Excessive N Value Division of Cross Section. Note how bank stationing is inadequate for use in geomorphic analysis.

2. Channel Bank Stationing. The HEC-2 models for the different reaches in the study area defined the right and left channel bank stations differently. For the lateral

stability assessment, the bank station was defined as the top of bank for the portion of the cross section actively transporting sediment.

3. Number of Cross Section Points. The HEC-2 model cross section data implied highly complicated and intricate overbank cross section geometry. These sections may depict the point elevations predicted by the digital terrain model (DTM) at an individual section, but probably do not accurately reflect the overall geometry of the reach between sections. An example of an excessive number of cross section points is shown in Figure 5-9.

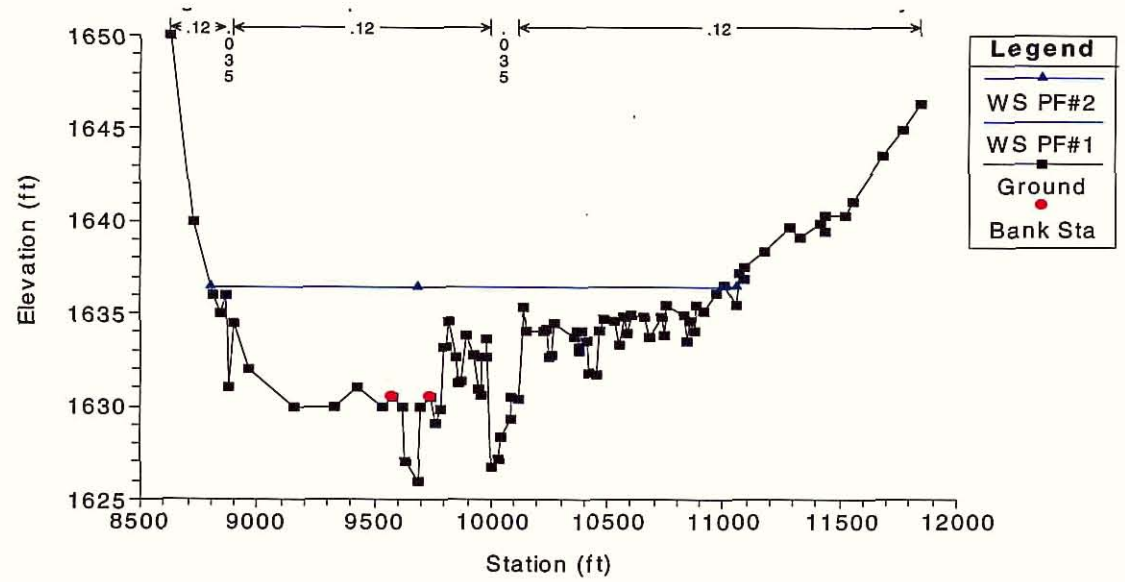


Figure 5-9. Example of Excessive Number of Cross Section GR Points.

Other cross sections in the original HEC-2 models included a large number of elevation points well outside the floodplain limits. An excessive number of elevation points reduces the computational efficiency of the model. An example of a cross section with too many elevation points outside the floodplain is shown in Figure 5-10.

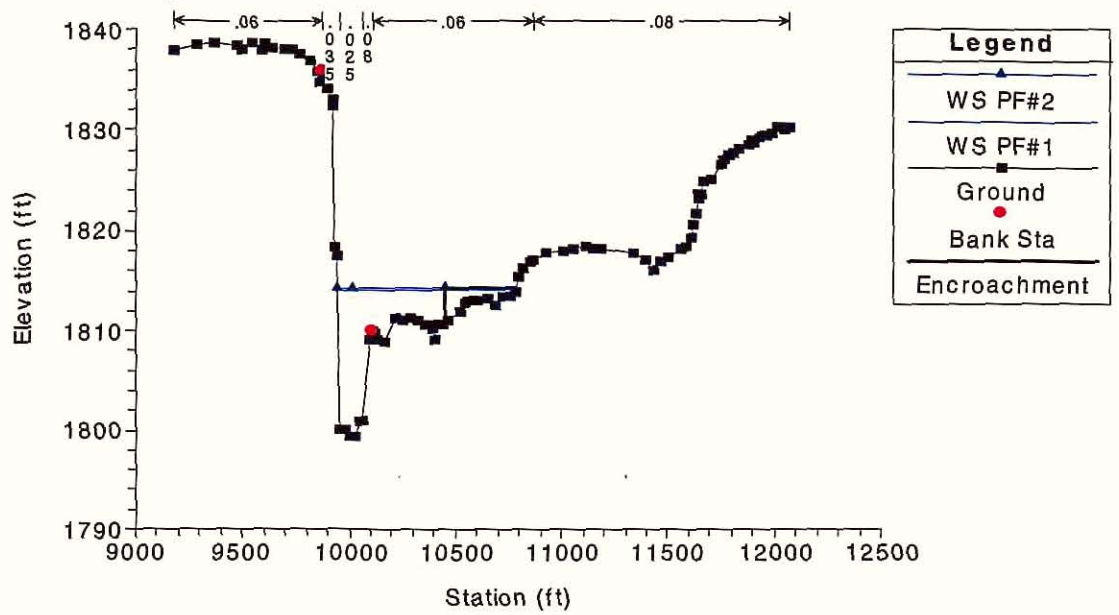


Figure 5-10. Example of Excess Cross Section Points Outside of Floodplain.

4. Cross Section Alignment. A number of the cross sections in the original HEC-2 models are not properly aligned to be perpendicular to flow. In general, these alignments probably do not significantly impact the predicted 100-year water surface elevation, especially where located in the reach affected by maximum ponding backwater from Cave Buttes Dam. Poorly aligned cross sections can be readily identified by examining the HEC-RAS output for large variations in flow distribution between adjacent cross sections. Examples of poorly aligned cross sections in Cave Creek HEC-2 model included the following:
   - Station 24.646. The right overbank portion of the cross section is aligned too far upstream, and is not perpendicular to the primary flow direction. Therefore, the elevations of the right overbank channels are well above the main channel elevations. Little or no flow is modeled in the right overbank, and flow in the main channel is overestimated. Approximately 10-20% of the cross sections in the HEC-2 model downstream of Carefree Highway are not aligned perpendicular to the primary flow direction for some part of the cross section.
   - Station 25.010. The cross section intersects the main channel at a sharp bend, but was not dog-legged to reflect the bend. Therefore, the channel width indicated by the ground reference (GR) data is about double the actual channel width, resulting in an overestimate of the channel discharge. This error occurs frequently in the overbank channels of the HEC-2 model for Cave Creek downstream of Carefree Highway.

   While there may be only a minor impact on the 100-year event from poorly aligned cross sections, there is an impact on the accuracy of the hydraulic data derived from the HEC-RAS modeling of the low to moderate sized floods considered in the geomorphic analysis, particularly for the overbanks. Where possible, portions of these cross sections were realigned using the Flood Insurance Study (FIS) topographic mapping.

5. Thalweg Location. The *thalweg* in the HEC-2 model for Cave Creek downstream of Carefree Highway is located outside of the main channel, as indicated from interpretation of field evidence and aerial photographs. The location of the thalweg station does not affect the accuracy of the HEC-RAS modeling.

6. Wheeler Sand & Gravel Pit. The excavations associated with the Wheeler mining operation are not depicted by the 1996 topographic mapping and HEC-2 cross section data. Therefore, it is noted that the modeling applies to pre-mining channel conditions.

7. Ineffective Flow Areas. Several ineffective flow areas such as tributary confluences, flow expansion and contractions, and small "holes" in the overbanks were not coded out of the HEC-2 model for Cave Creek downstream of Carefree Highway. For example, the left overbank area of the cross section shown in Figure 5-10 above is located in an ineffective flow area caused by an abrupt expansion where Cave Creek enters the Cave Buttes Dam impoundment, but was modeled as an effective flow area in the Willdan HEC-2 model.[1]

8. Cave Buttes Dam Backwater Effect. The HEC-2 models used a starting water surface elevation based on the maximum ponding level upstream of Cave Buttes Dam. The assumption of maximum ponding is not conservative with respect to velocity (and hence lateral instability) for floods which occur at lower ponding depths. For the geomorphic analysis, the normal depth method was used as the starting water surface elevation.

9. HEC-RAS Run Message. A "BCKWTR 57" message of unknown origin and meaning is printed in the line output between sections 27.169 and 27.226 when the HEC-RAS is run (DOS window). The same message occurs in the line output between cross sections 31.630 and 31.750 in the HEC-RAS model. The cause of this message was not determined.

Modifications to HEC-RAS Model. The original HEC-2 models were developed for the specific purpose of delineating the 100-year floodplain and floodway. The HEC-RAS model 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 output, the following changes were made to the HEC-RAS model:

1. Discharge. HEC-1 peak flow rates and hydrographs for the 2-, 10- and 100-year events for existing and future conditions were provided by ASL and entered into the HEC-RAS data file. In addition, a range of *discharges* in 500 to 1,000 cfs increments

[1] Note that in the Willdan HEC-2 model, the area described for the cross section in Figure 5-10 is within the backwater reach of Cave Buttes Dam. Therefore, incorrectly coding the ineffective flow area would have no significant impact on the predicted 100-year water surface elevation. For the Cave Creek lateral stability assessment, which uses a different starting water surface elevation, the ineffective flow area at this section must be coded to correctly model the flow.

was entered in the HEC-RAS files to generate reach-averaged rating curves of hydraulic data.

2. Reach Length. For Cave Creek, cross sections at a confined canyon reach upstream of the Stagecoach Pass alignment (Section 31.91) were removed to reflect the upstream study limit at Carefree Highway. The reach between Carefree Highway and Section 31.91 will be modeled as a sediment *supply reach* for the actual study reach and to assess impacts of alternatives on the upstream channel reaches. The reach lengths for the Apache Wash system models were not modified.

3. Starting Water Surface Elevation. The modified HEC-RAS model uses normal depth as the starting water surface elevation rather than the maximum impoundment elevation upstream of Cave Buttes Dam to assess the potential for erosive velocities during periods of low storage upstream of the dam.

4. N Values. Manning's N values were selected using the following guidelines and procedures:
   - Generalized Cross Section. Each cross section was divided into three sections – left overbank, main channel, and right overbank.
   - Channel N Values. An N value of 0.036 was used for single channel reaches with minimal channel vegetation, few bars and islands, and relatively simple geometry. An N value of 0.044 was used where the main channel was divided, had more significant channel vegetation, large bars or small islands, and had more complex geometry or other obstructions. Minor variations in channel values were used as warranted by field evidence and engineering judgment.
   - Overbank N Values. An N value of 0.07 was used for shallow overbank flow areas with relatively uniform topography that are dominated by sediment deposition. Along Cave Creek, these areas generally had moderately dense vegetation with seasonal grass cover. An N value of 0.06 was used for overbanks with multiple channels with moderate flow depths that are dominated by net erosion. Along Cave Creek, these areas generally had less well vegetated *interfluves*, but had more dense vegetation along the banks of the multiple channel areas. The multiple channels areas have higher conveyance capacity than the shallow overbank flow areas.
   - FCDMC Manual. The District Manual Estimated Manning's Roughness Coefficients for Stream Channels and Flood Plains in Maricopa County, Arizona (Thomsen and Hjalmarson, 1991) provides guidelines for estimating Manning's N value. An example site from the District's Manual at Cave Creek downstream of Carefree Highway reports 10-year N values of 0.040 for the main channel, and 0.060 for the right overbank. The 100-year N values reported for the same site are 0.080, 0.032, and 0.050 for the left overbank, main channel, and right overbank respectively.
   - USGS Data. A recent USGS Professional Paper Verification of Roughness Coefficients for Selected Natural and Constructed Stream Channels in Arizona (Phillips and Ingersoll, 1998) reports Manning's N values for streams in central Arizona. The Cave Creek sites discussed in the USGS report are not directly

applicable to the study reach. For an analogous reach of Skunk Creek, the USGS computed channel roughness coefficients of 0.031 to 0.052, depending on vegetative growth and channel maintenance practices.

- Expected Velocity. Given that the HEC-RAS modeling was conducted to help predict lateral migration, Manning's N values were selected to be conservative with respect to velocity.
- Flow Regime. Based on the existing channel slope, field observations and engineering judgment, it was assumed that flow would be subcritical or near critical (*Froude number* < 0.9), and Manning's N values were selected appropriately.

5. Bank Stationing. Right and left channel bank stations were defined using the following guidelines:
   - Consistency with Field Data. The main channel was defined based on field observations such as the presence of a *cut bank*, bank vegetation, steep bank slope, and a contrast in sediment characteristics from the channel bed.
   - Channel Forming Discharge. It was assumed that the main channel could contain the 2-year peak discharge, and that the bankfull discharge had a recurrence interval of 10 to 25 years on Cave Creek, and 2 to 25 years on the Apache Wash system.
   - Multiple Channel Reaches/Braided Flow. Where multiple channels or strongly braided flow occurred, the main channel was defined as the largest channel contiguous with the better defined main channels upstream and downstream.
   - HEC-RAS Output. Bank stations were selected such that the HEC-RAS model output would accurately depict values of depth, width, area, and velocity for the channel and each overbank.
   - Top of Bank. Channel stations were defined at the top of the primary channel bank.

6. Main Channel Containment. Where the potential for divided flow or multiple channels existed, the HEC-RAS "levee" option was used to assure that the 2-year discharge was contained in the main channel. For larger floods, flows were allowed to extend into multiple, divided flow paths if these flow paths were hydraulically connected to the main channel at some point upstream. This hydraulic connection was verified from aerial photographs, field data, and HEC-RAS modeling. In general, levees were defined on the bank slopes just above the 2-year water surface elevation.

7. Extraneous GR Points. GR points located well above the 100-year water surface elevation, closely spaced GR points that were not required to describe the overall cross section geometry, and GR points that were not representative of the overall reach geometry were removed from the model.

8. Effective Flow Boundaries. Effective flow boundaries were added to cross sections in reaches with sharp flow expansions or contractions, at tributary confluences, and near the Carefree Highway bridge.

9. Reach-Averaged Data. The modifications of the HEC-RAS model were completed with the perspective that the model output would be averaged by reach, rather than used at individual cross sections. Therefore, it can be assumed that minor irregularities in hydraulic properties at individual cross sections "wash out" in the reach averaged values.

HEC-RAS Modeling. 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

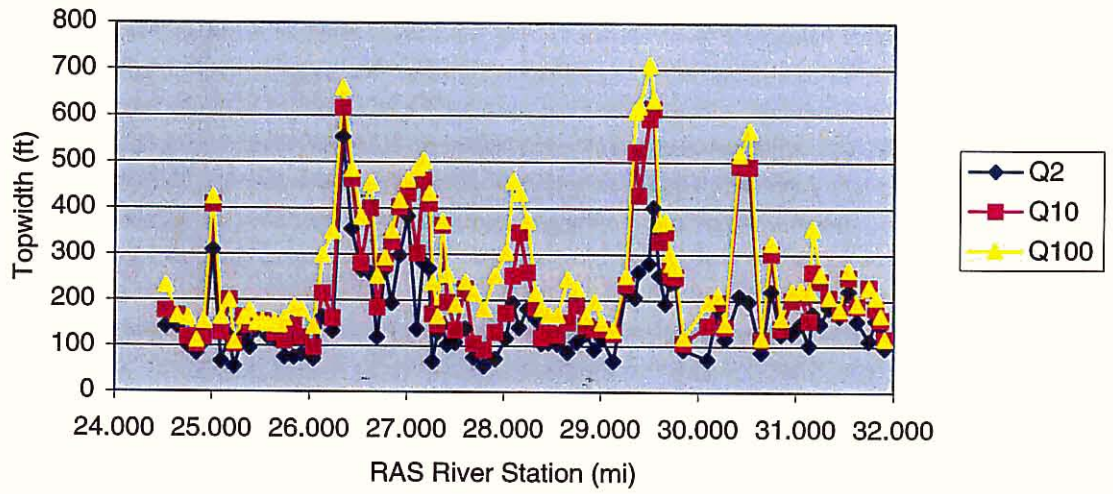
The basic data developed for use in the engineering and geomorphic analyses were described in the previous section of this Chapter. Channel capacity, or bankfull discharge capacity, was discussed in Chapter 4 of this report.

The HEC-RAS modeling results indicate that there is no clear hydraulic basis for identifying subreaches within the study area. While there are geomorphic, geographic, visual, jurisdictional and hydrologic changes along each of the four streams in the study area, there are no consistent, regular, and significant changes in flow depth, velocity, topwidth, energy slope, channel slope, conveyance capacity, or unit discharge that can be used to define continuous subreaches, or that can be tied to specific break points. This conclusion is illustrated by the plots of hydraulic data for Cave Creek, Apache Wash, Paradise Wash, and Desert Hills Wash presented below.

Cave Creek. Values of channel topwidth, depth (hydraulic and maximum), channel velocity, energy slope, and channel capacity plotted versus the HEC-RAS river stationing are shown in Figures 5-11 to 5-16.

Topwidth. Computed channel topwidth is highly variable between adjacent cross sections. Topwidth is greatest in the reaches disturbed by historical mining, such as the Tanner mining area which was located from about Station 26.0 to 27.4. The 2-, 10- and 100-year topwidths are relatively similar in magnitude at any single cross section, indicating that the channel bottom is filled by the 2-year event.

Figure 5-11. Cave Creek - Channel Topwidth



Flow depth. The maximum flow depth varies greatly between adjacent cross sections, but shows no consistent trend with distance along the study reach. The hydraulic depth increases slightly in the upstream direction for the 100-year event. The greatest depths occur in Reaches 1, 2, and 3, which are located near reaches of historical sand and gravel mining. These reaches may have been deepened by mining or by upstream migration of *headcuts* from the mines.

Figure 5-12. Cave Creek - Maximum Depth

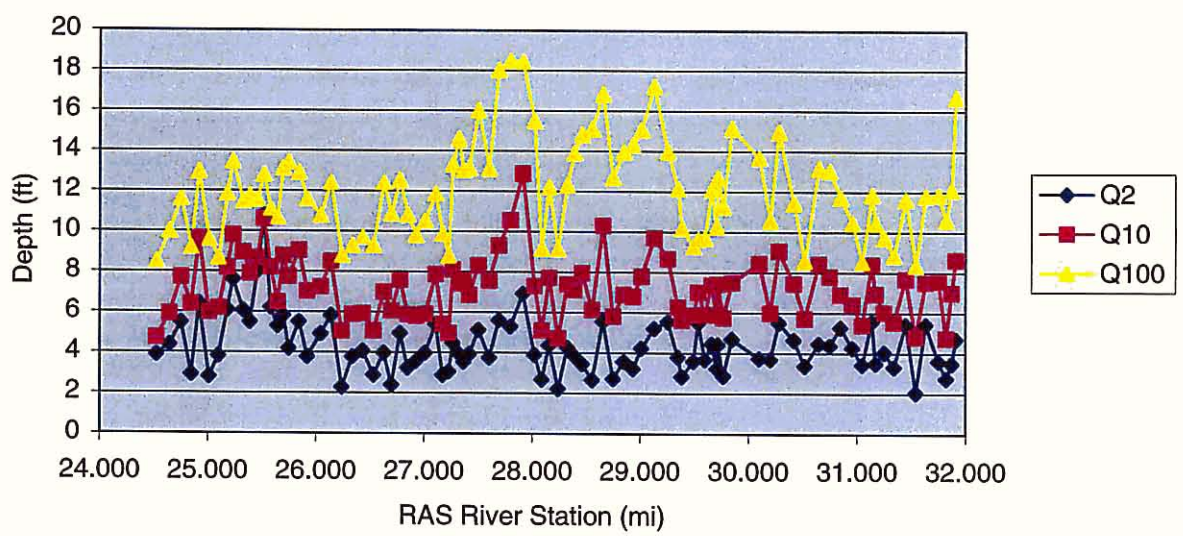
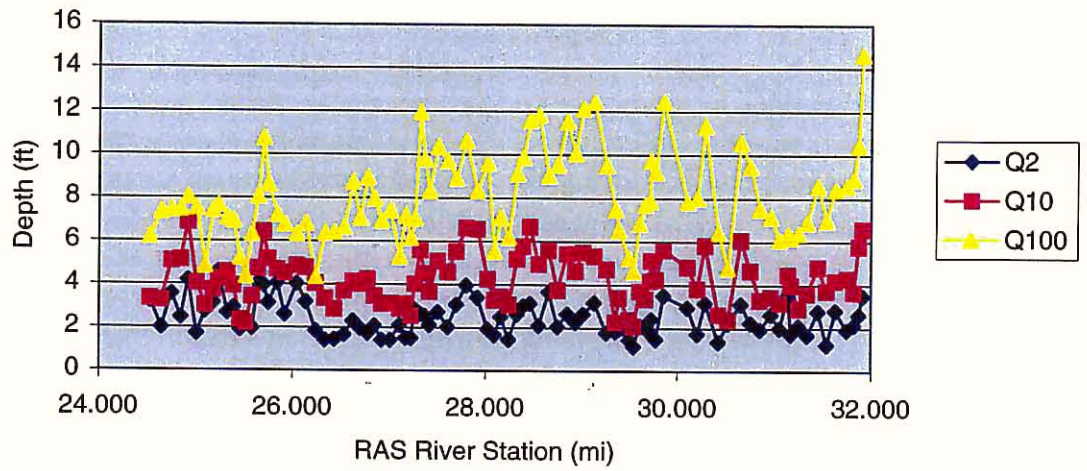
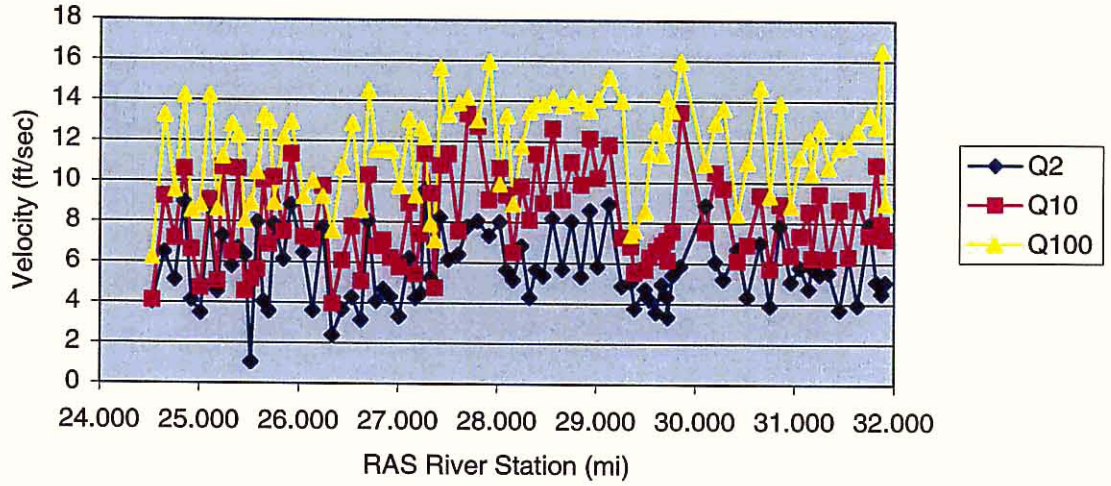


Figure 5-13. Cave Creek - Hydraulic Channel Depth



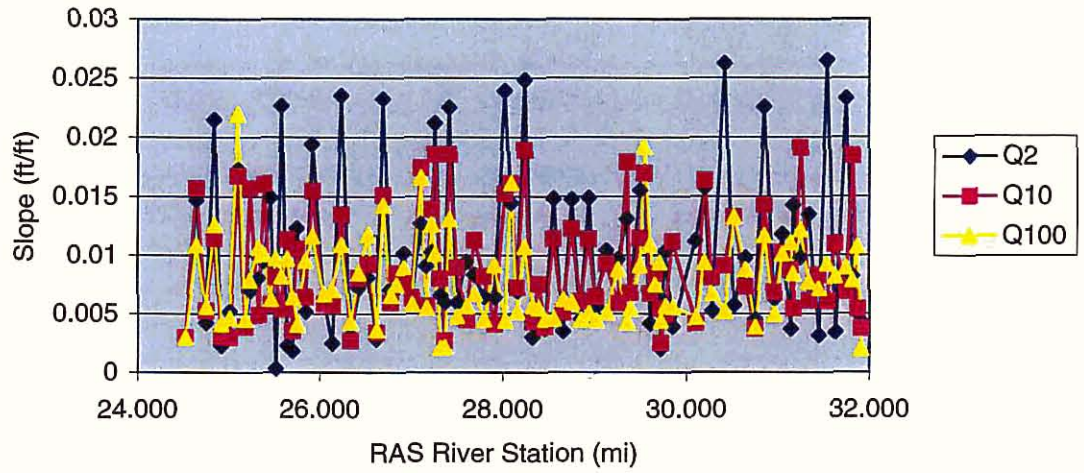
Channel velocity. Channel velocity varies greatly between adjacent cross sections, but shows no significant trends along the stream profile. The highest velocities are in the reaches with the greatest depths.

Figure 5-14. Cave Creek - Channel Velocity



Energy slope. The computed energy slope is highly variable between adjacent cross sections, with no distinct trend within the study reach.

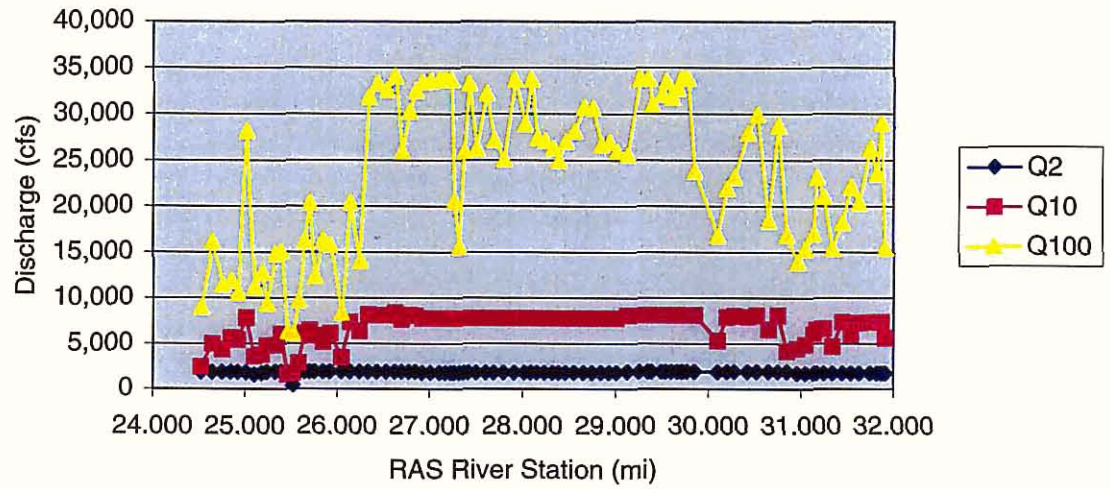
Figure 5-15. Cave Creek - Energy Slope



Channel slope. Channel slope was shown in Figure 4-47, in the discussion of longitudinal profile. Slope within the study reach is relatively uniform throughout the modeling reach.

Channel capacity. Channel capacity was estimated as the proportion of the peak discharge conveyed in the main channel. Channel capacity was less variable between adjacent cross sections than the other hydraulic variables considered. The straight slope of the plots of the 2- and 10-year channel capacity versus stream length shown in Figure 5-16, indicate that these discharges are contained within the main channel. The 100-year peak discharge overflows the channel and inundates portions of the floodplain, although it is fully contained at numerous cross sections as well. Channel capacity is lowest in Reach 5, which has less than 10-year capacity at most sections. Channel capacity increases dramatically in the historically mined reaches (1, 2, and 3).

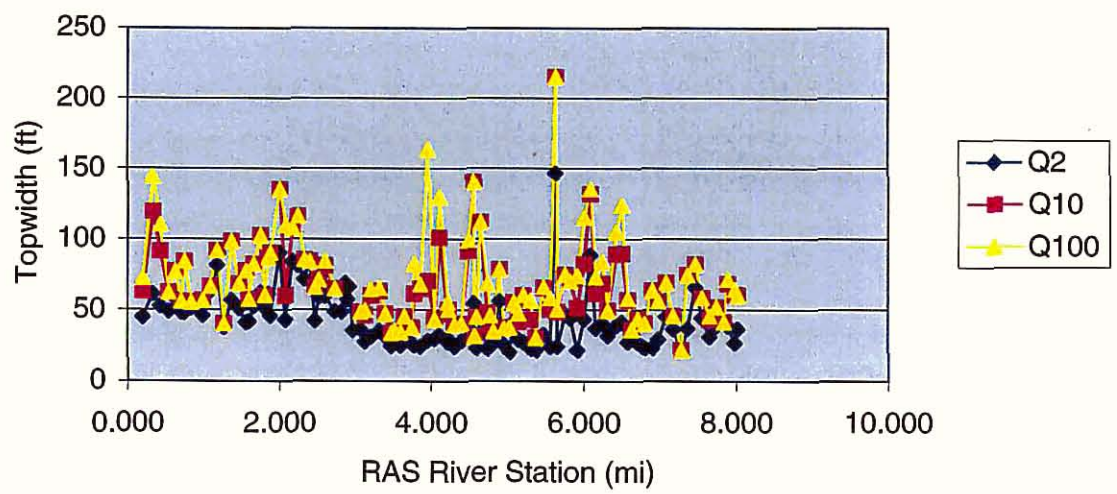
Figure 5-16. Cave Creek - Channel Discharge



Apache Wash. Values of channel topwidth, depth (hydraulic and maximum), channel velocity, energy slope, and channel capacity plotted versus the HEC-RAS river stationing are shown in Figures 5-17 to 5-22.

Topwidth. Computed channel topwidth is highly variable between adjacent cross sections, and generally increases in the downstream direction. The topwidth decreases upstream of the Paradise Wash and Desert Hills Wash confluences due to the decrease in discharge. The 10- and 100-year topwidths are relatively similar in magnitude at most cross sections, indicating that the channel bottom is filled by the 10 year event.

Figure 5-17. Apache Wash - Channel Top Width



Flow depth. The maximum channel and hydraulic flow depths vary significantly between adjacent cross sections, and generally decrease in the upstream direction for the 10- and

100-year events. The 2-year depths remain relatively constant within the study reach. The greatest depths occur in Reaches 1 and 2, and decrease upstream, primarily due to the decrease in discharge above the Paradise Wash and Apache Wash confluences.

Figure 5-18. Apache Wash - Channel Depth

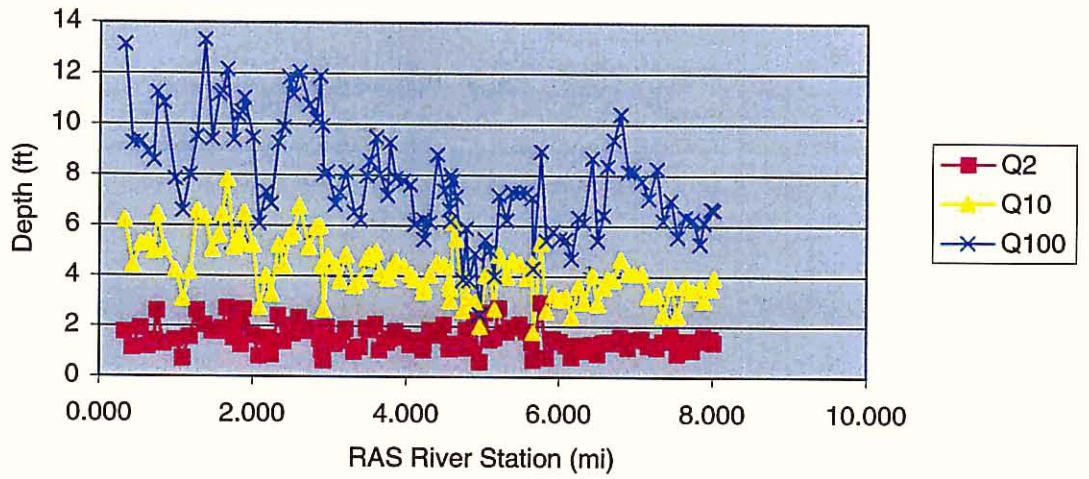
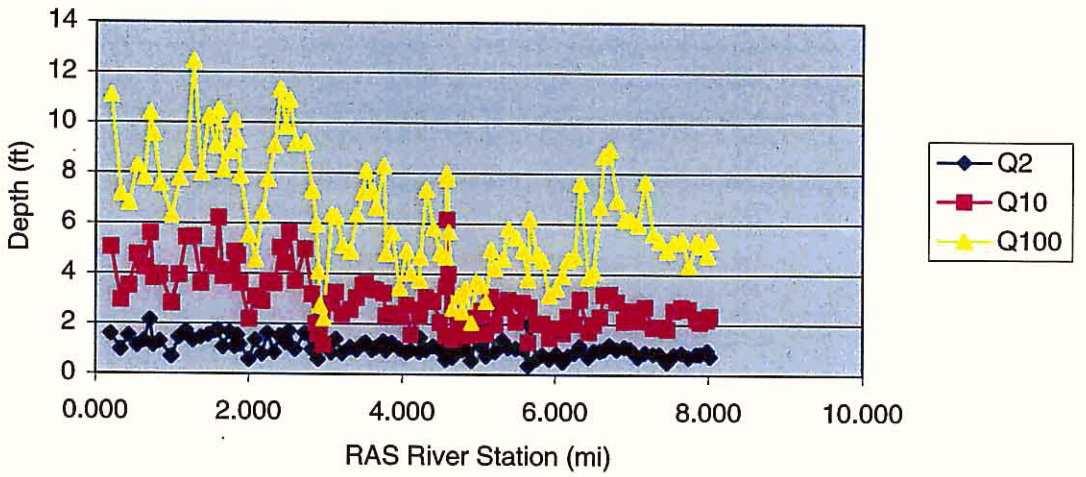
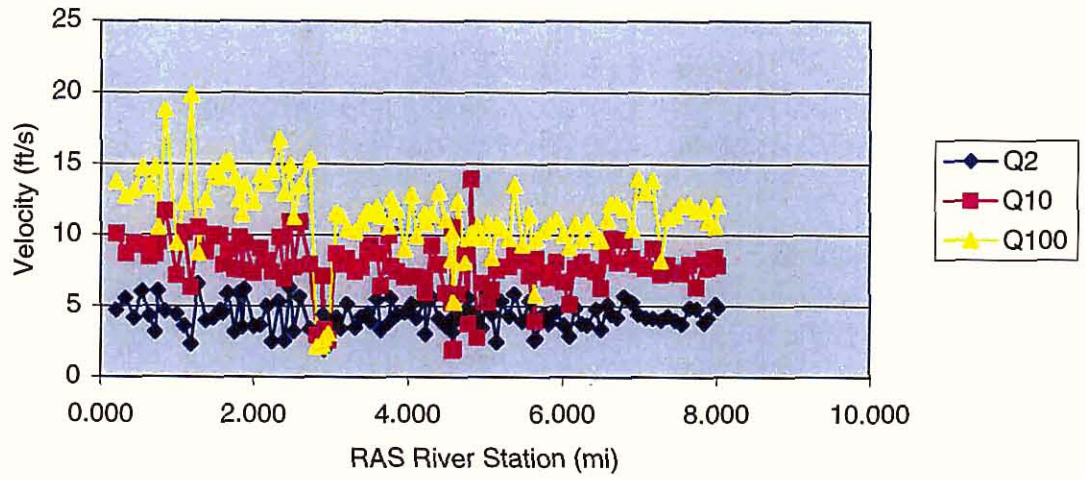


Figure 5-19. Apache Wash - Hydraulic Depth



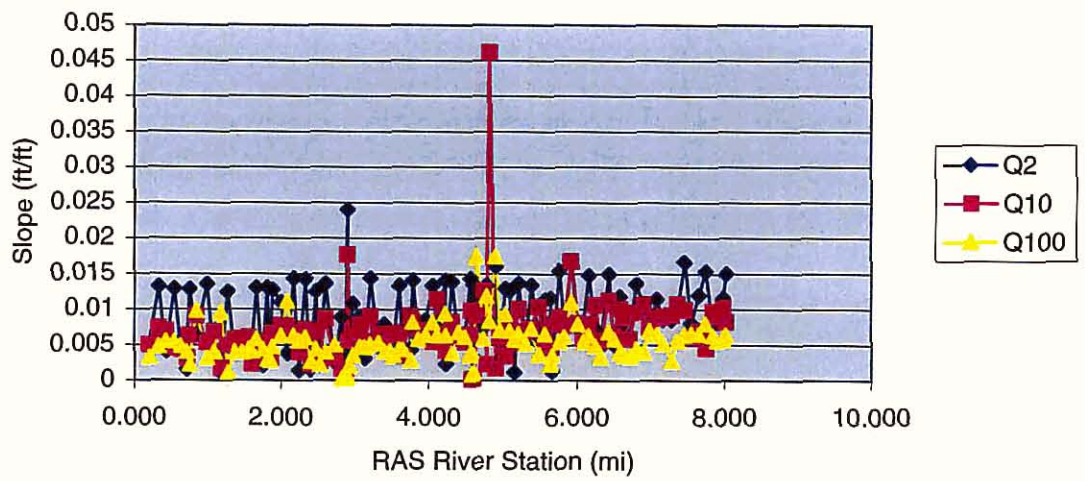
Channel velocity. Channel velocity varies greatly between adjacent cross sections, and decreases slightly in the upstream direction for the 10- and 100-year events. The highest velocities are in the reaches with the greatest depths and highest channel capacities.

Figure 5-20. Apache Wash - Channel Velocity



Energy slope. The computed energy slope is highly variable between adjacent cross sections, with a slight decrease in the downstream direction within the study reach.

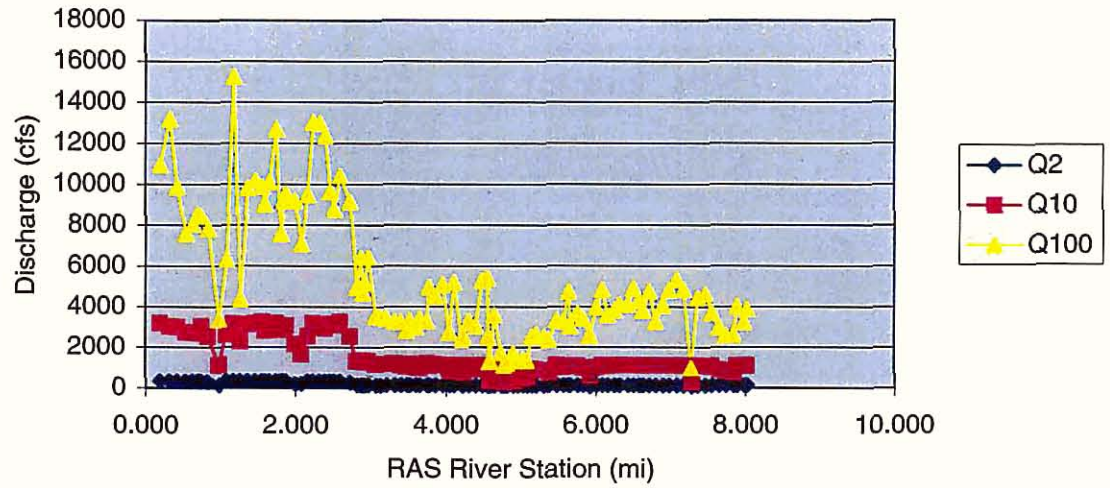
Figure 5-21. Apache Wash - Energy Slope



Channel slope. Channel slope was shown in Figure 4-48, in the discussion of longitudinal profile. Slope within the study reach decreases in the downstream direction, and is flattest near the Cave Buttes Impoundment area.

Channel capacity. Channel capacity was estimated as the proportion of the peak discharge conveyed in the main channel. Channel capacity was less variable between adjacent cross sections than the other hydraulic variables considered. The straight slope of the plots of the 2- and 10-year channel capacity versus stream length shown in Figure 5-22 indicate that these discharges are contained within the main channel. The 100-year peak discharge overflows the channel and inundates portions of the floodplain.

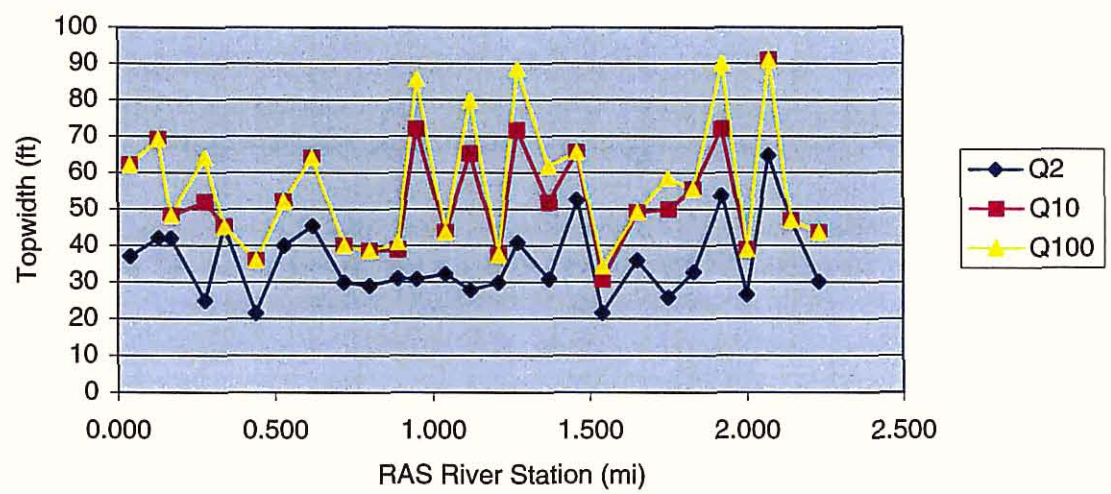
Figure 5-22. Apache Wash - Channel Discharge



Paradise Wash. Values of channel topwidth, depth (hydraulic and maximum), channel velocity, energy slope, and channel capacity plotted versus the HEC-RAS river stationing are shown in Figures 5-23 to 5-28.

Topwidth. Computed channel topwidth is variable between adjacent cross sections, although not as drastically as on Cave Creek or Apache Wash. There is a slight decrease in the channel topwidth in the downstream direction on Paradise Wash, perhaps indicating historical incision near the Apache Wash confluence. The 10- and 100-year topwidths are relatively similar in magnitude at most cross sections, indicating that the channel bottom is filled by the 10-year event.

Figure 5-23. Paradise Wash - Channel Topwidth



Flow depth. The maximum channel and hydraulic depths vary between adjacent cross sections, and show no consistent trend with distance along the study reach.

Figure 5-24. Paradise Wash - Maximum Depth

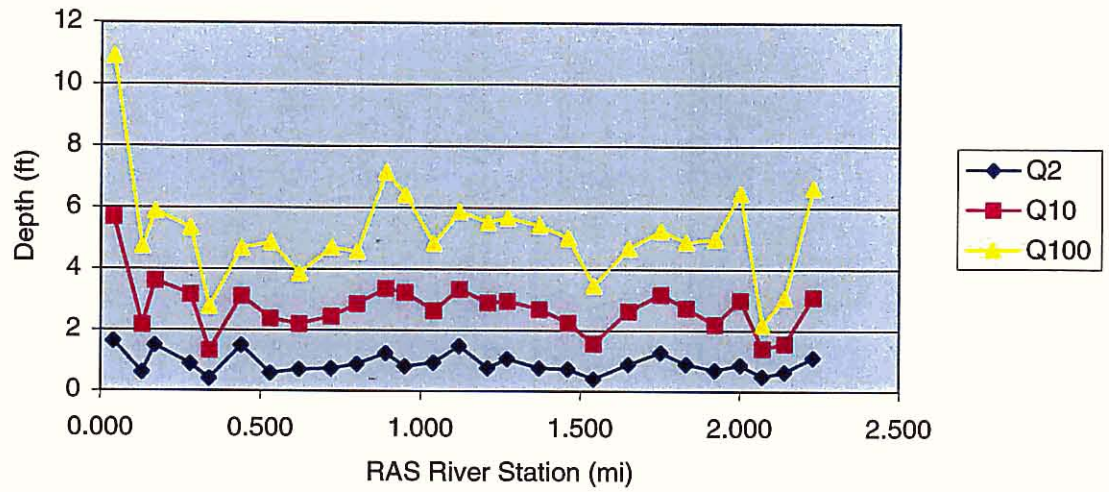
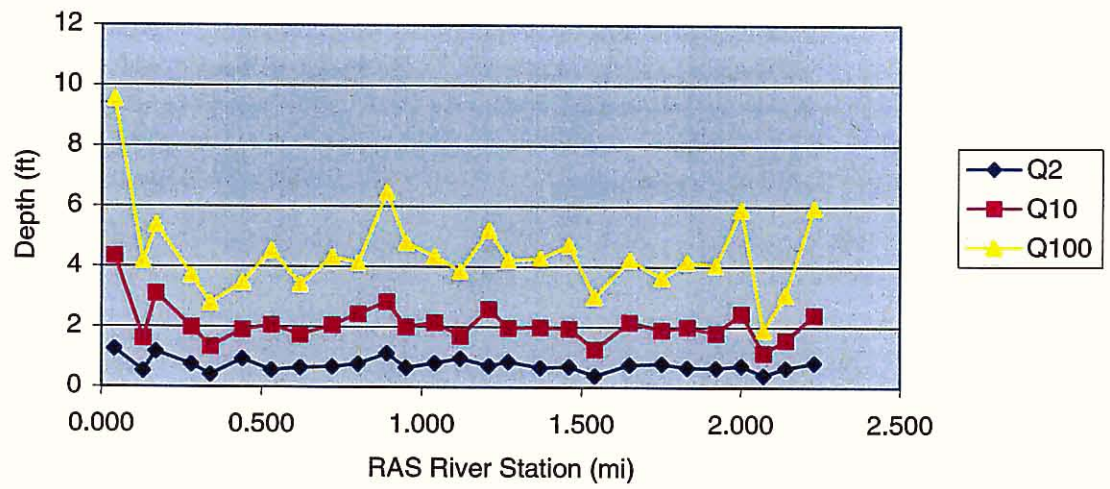
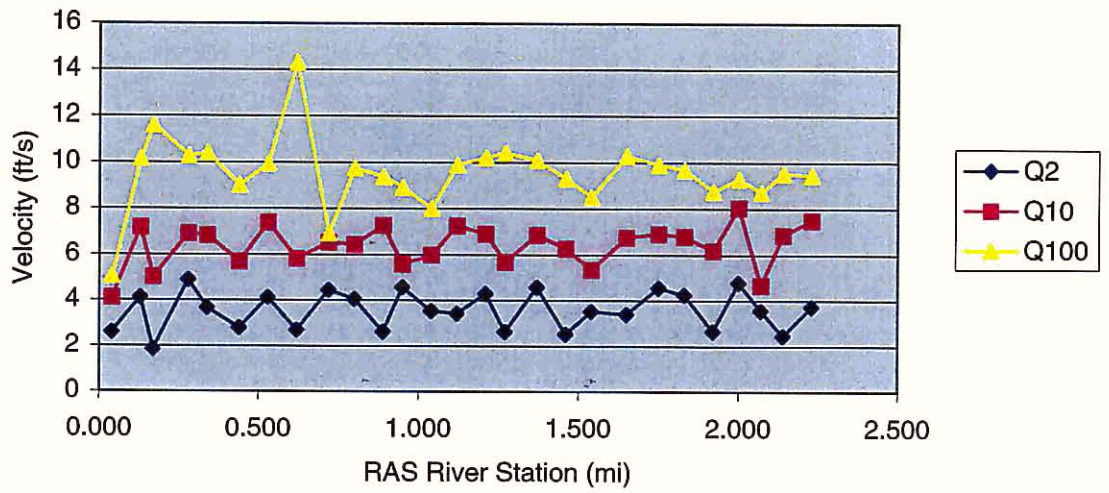


Figure 5-25. Paradise Wash - Hydraulic Depth



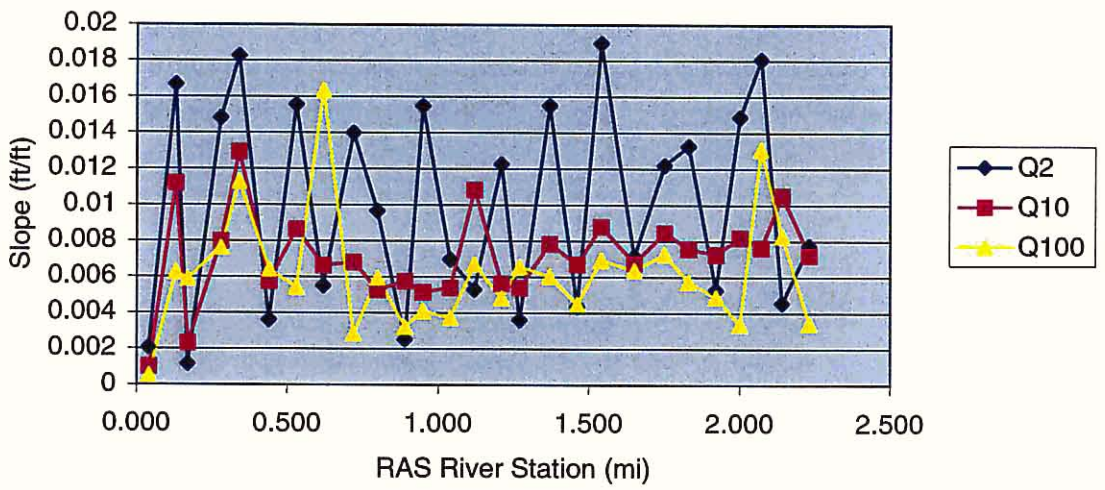
Channel velocity. Channel velocity varies minimally between adjacent cross sections, and shows no overall trend with stream length. The greatest variation between adjacent cross sections occurs for the 100-year event.

Figure 5-26. Paradise Wash - Channel Velocity



Energy slope. The computed energy slope is highly variable between adjacent cross sections, with no distinct trend within the study reach. Note that the energy slope does not consistently decrease from the 2- to the 100-year event.

Figure 5-27. Paradise Wash - Energy Slope

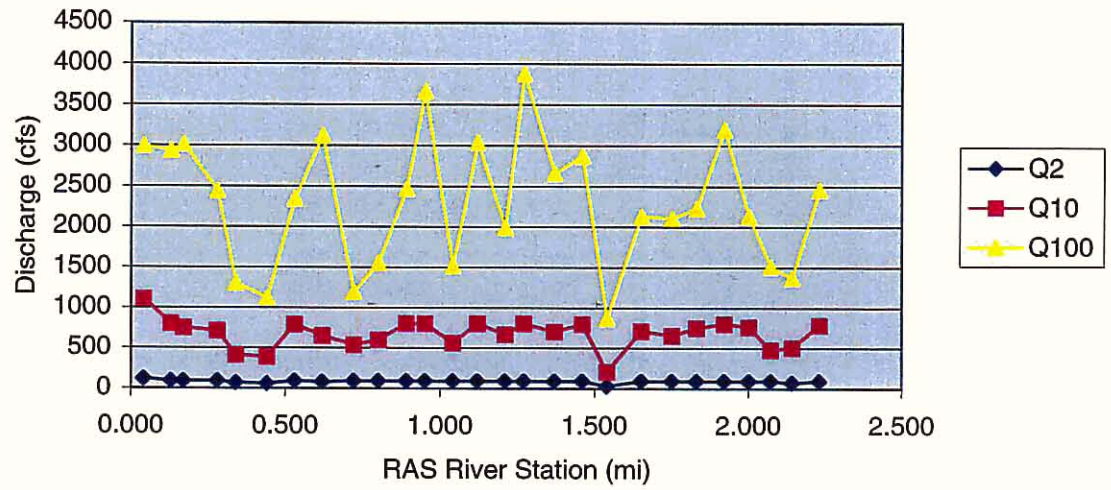


Channel slope. Channel slope was shown in Figure 4-49, in the discussion of longitudinal profile. Slope is relatively uniform within the study reach, with a slight increase above the Apache Wash confluence.

Channel capacity. Channel capacity was estimated as the proportion of the peak discharge conveyed in the main channel. Channel capacity was less variable between adjacent cross sections than the other hydraulic variables considered, except for the 100-year profile. The straight slope of the plots of the 2-year channel capacity versus stream length shown in Figure 5-28 indicate that the 2-year flood is largely contained within the main channel. The 10-and 100-year peak discharges overflow the channel and inundate

portions of the floodplain, although they are fully contained at some cross sections as well.

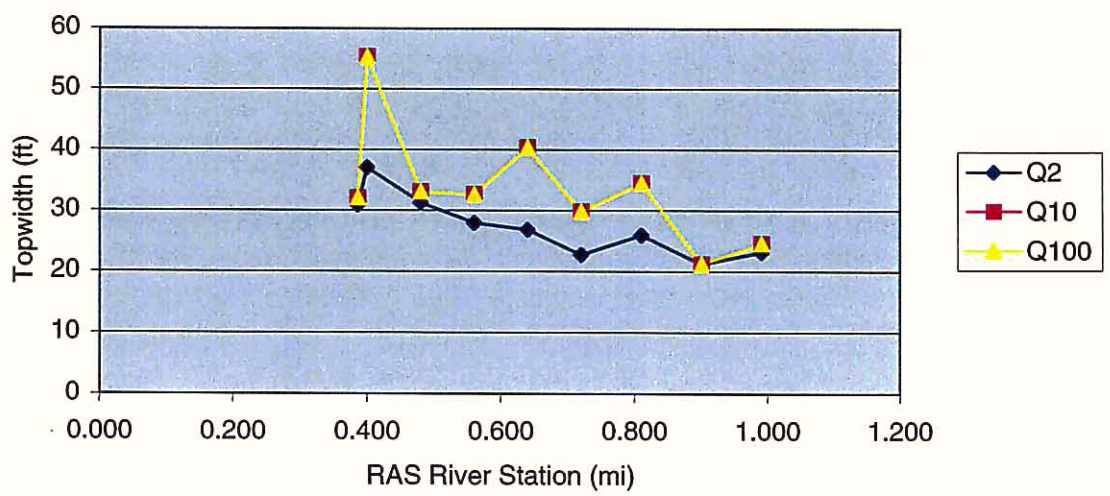
Figure 5-28. Paradise Wash - Channel Discharge



Desert Hills Wash. Values of channel topwidth, depth (hydraulic and maximum), channel velocity, energy slope, and channel capacity plotted versus the HEC-RAS river stationing are shown in Figures 5-29 to 5-34.

Topwidth. Computed channel topwidth increases in the downstream direction on Desert Hills Wash, with moderate variability between adjacent cross sections during the 10- and 100-year events. The 10- and 100-year topwidths are relatively similar in magnitude at most cross sections, indicating that the channel bottom is filled by the 10 year event.

Figure 5-29. Desert Hills Wash - Channel Topwidth



Flow depth. The maximum channel and hydraulic depths increase slightly in the upstream direction, with gradual variation between adjacent cross sections.

Figure 5-30. Desert Hills Wash - Maximum Depth

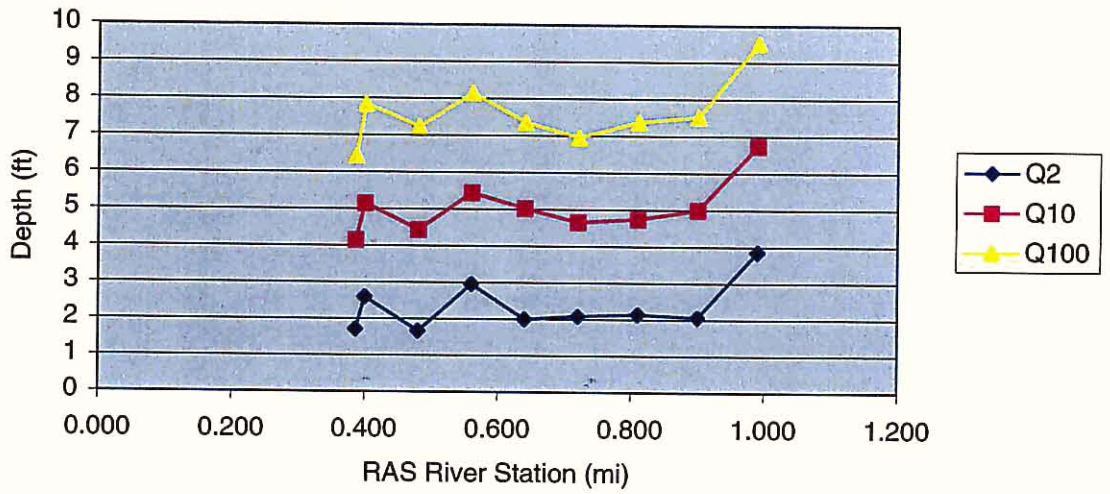
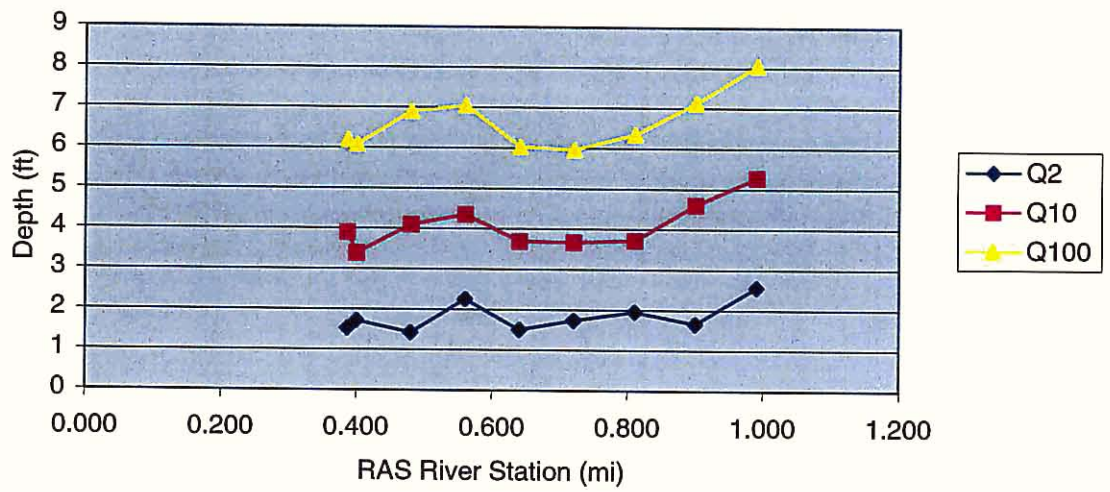
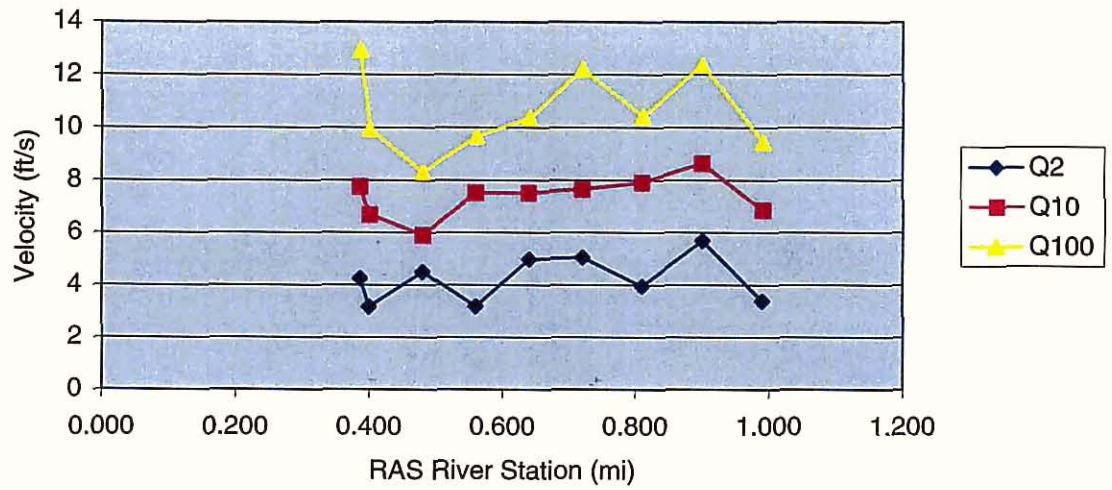


Figure 5-31. Desert Hills Wash - Hydraulic Depth



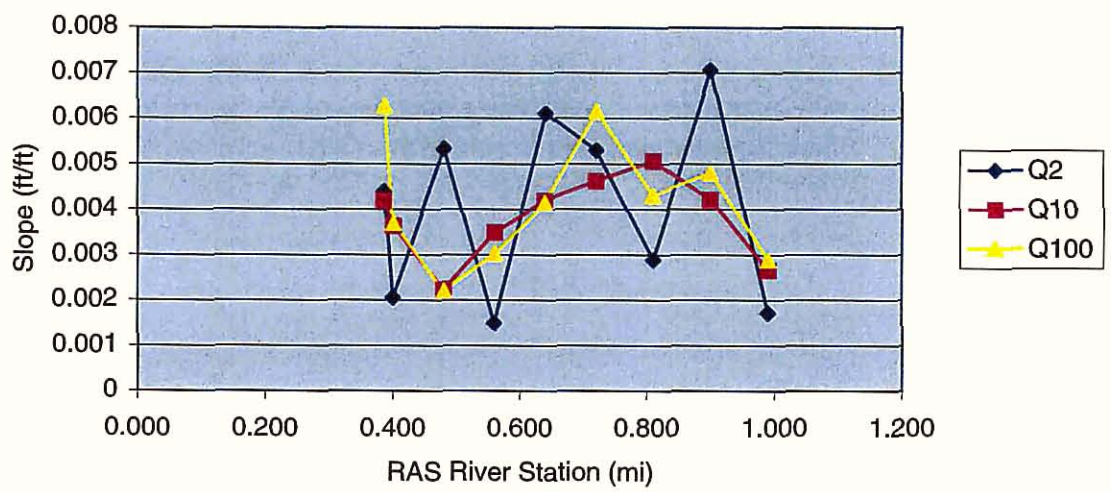
Channel velocity. Channel velocity is relatively consistent between adjacent cross sections and over the length of the Desert Hills Wash reach.

Figure 5-32. Desert Hills Wash - Channel Velocity



Energy slope. The computed energy slope is highly variable between adjacent cross sections, with no distinct trend within the study reach or between recurrence intervals.

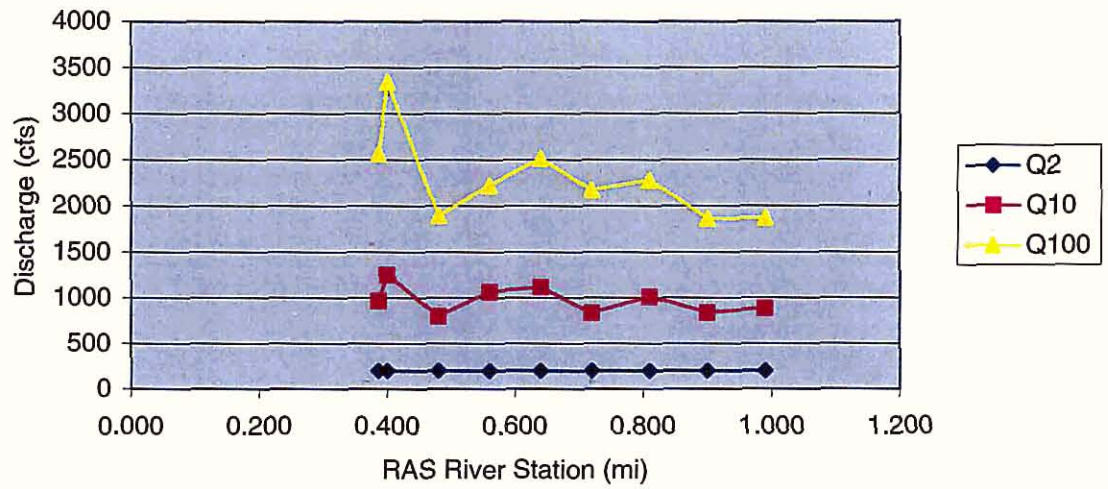
Figure 5-33. Desert Hill Wash - Energy Slope



Channel slope. Channel slope was shown in Figure 4-50, in the discussion of longitudinal profile. Slope within the study reach is uniform throughout the modeling reach.

Channel capacity. Channel capacity was estimated as the proportion of the peak discharge conveyed in the main channel. The straight slope of the plot of the 2-year channel capacity versus stream length shown in Figure 5-34 indicates that the 2-year peak discharge is contained within the main channel. The 10- and 100-year peak discharges overflow the channel and inundate portions of the floodplain, although the 10-year flood is fully contained at several cross sections. Channel capacity increases slightly in the downstream direction.

Figure 5-34. Desert Hills Wash -Channel Discharge



Conclusions. Although the general changes in hydraulic characteristics summarized above could be defined from the HEC-RAS output, the changes lacked obvious break points or did not change significantly within the study reach. In addition, the changes in the different hydraulic parameters were not concurrent at any cross section. For these reasons, no subreaches could be defined on the basis of the HEC-RAS data. Therefore, the streams were subdivided based on hydrologic, geomorphic, and geographic distinctions.

Sediment Data

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 Geophysiscal 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 can be difficult. 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. The longitudinal variation in grain size is not necessarily linear in *pool* and *riffle* streams. In

100-year events. The 2-year depths remain relatively constant within the study reach. The greatest depths occur in Reaches 1 and 2, and decrease upstream, primarily due to the decrease in discharge above the Paradise Wash and Apache Wash confluences.

Figure 5-18. Apache Wash - Channel Depth

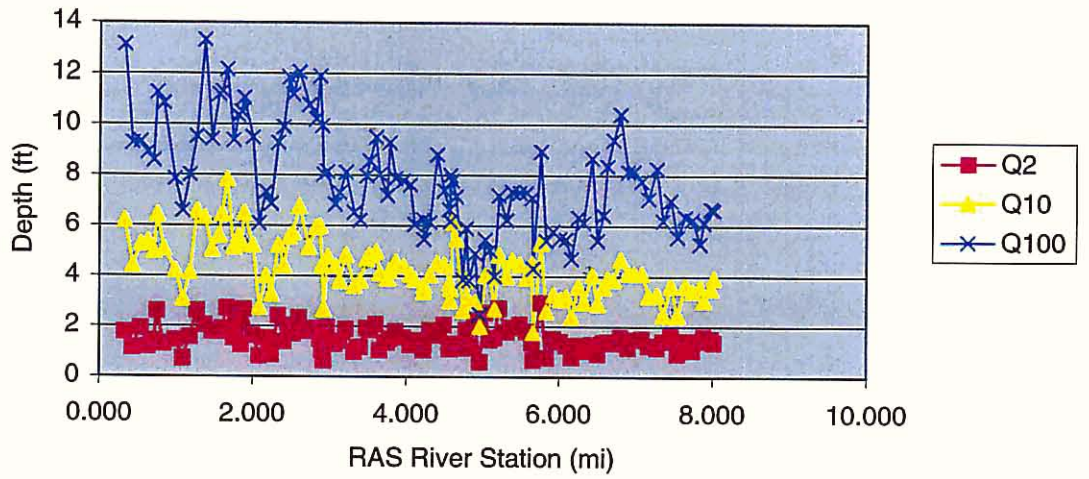
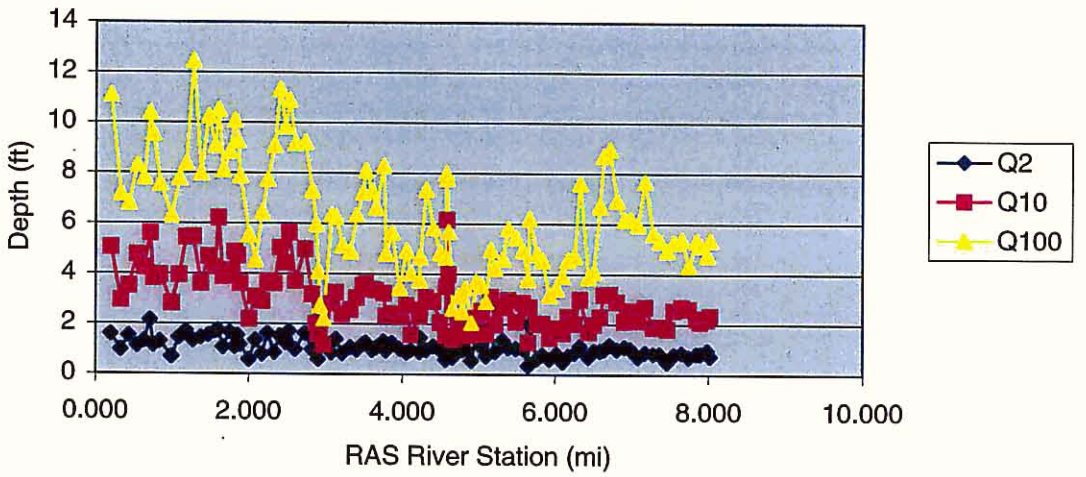


Figure 5-19. Apache Wash - Hydraulic Depth



Channel velocity. Channel velocity varies greatly between adjacent cross sections, and decreases slightly in the upstream direction for the 10- and 100-year events. The highest velocities are in the reaches with the greatest depths and highest channel capacities.

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. Sections 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 procedure for surface counting (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 5-35) 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.

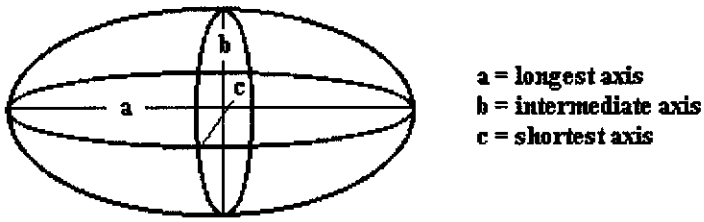


Figure 5-35. Three dimensions of a sediment grain.

For sediment grains too small to be reliably measured using the survey tape or other ruler, the sand grain sizing folder (affectionately called the "sand-o-meter") 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 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 the four streams in the study reach. Sieve samples were collected at each of the channel soil pit locations. Boulder counts were completed at 1,000 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. Upper Cave Creek/Apache Wash Watercourse Master Plan Sediment Sampling Results

Reach	Mean (mm)	D90 (mm)	D84 (mm)	D50 (mm)	D16 (mm)	D10 (mm)	Max (mm)	Min (mm)
Cave Creek								
SR	93.0	145.0	105.0	19.0	1.8	0.8	250.0	0.07
1	125.0	160.0	115.0	19.0	1.6	0.8	400.0	0.10
2	87.0	105.0	69.0	11.5	1.4	0.7	290.0	0.07
3	60.0	69.0	45.0	5.0	0.9	0.6	190.0	0.07
4	78.0	90.0	51.0	4.5	0.9	0.5	275.0	0.07
5	79.0	85.0	55.0	8.0	1.6	1.1	260.0	0.07
Apache Wash								
SR	20.0	29.0	22.5	7.0	1.6	1.2	41.0	0.10
1	38.0	50.0	40.0	6.7	0.6	0.3	90.0	0.05
2	85.0	106.0	75.0	13.0	0.8	0.4	160.0	0.05
3	63.0	58.0	40.0	9.5	1.7	0.9	152.0	0.04
4	31.0	35.0	27.0	7.0	1.6	0.9	80.0	0.04
5	17.0	17.0	12.5	3.5	0.9	0.6	37.0	0.07
Paradise Wash								
SR	41.0	52.0	38.0	9.4	1.7	1.0	100.0	0.10
1	34.0	39.5	31.0	13.5	3.4	2.4	60.0	0.20
Desert Hills Wash								
SR	42.0	48.0	40.0	12.2	1.3	0.8	81.0	0.07
1	43.0	50.0	34.0	8.0	1.6	1.2	110.0	0.07

Sediment sampling data and plots of bed sediment distributions are provided in Appendix D.

Engineering Methodologies

Engineering methodologies for evaluating channel stability and estimating future bank erosion applied to the Cave Creek/Apache 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 policy 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. This State Standard methodology was applied to Cave Creek and its tributaries.

Limitations. The 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. Cave Creek has a drainage area of 124 square miles at Carefree Highway. Apache Wash, Desert Hills Wash, and Paradise Wash have drainage areas 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 have occurred on portions of Cave Creek, Apache Wash, and Paradise 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. In-stream mining occurred at several locations along Cave Creek in the past, with one current large mining operation. Bridges or culverts that alter natural flow patterns have been constructed on Apache and Paradise Washes. Desert Hills Wash was rerouted as a result of the failure of the Bosco Tank spillway.
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. 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.
6. 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.

Because of the limitations listed above, the results of the Level 1 erosion setback methodology may not be accurate for the study reaches of the Cave Creek/Apache Wash Watercourse Master Plan.

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. All the bank materials along Cave Creek, Apache Wash, Paradise Wash, and Desert Hills Wash are stratified with widely varying sedimentological characteristics.
2. Cohesive and vegetated bank materials. Instructions for assessing the stability of cohesive materials or well-vegetated channel banks are lacking. In general, the bank materials within the study area include cohesive, well vegetated soil units.

The basic Level 2 procedures, allowable velocity, tractive force, and tractive power analyses were applied to Cave Creek and its tributaries as part of the detailed geomorphic and engineering analysis of lateral stability described elsewhere in this report.

The Level 3 methodology, which is recommended for streams where application of the Level 1 or 2 approaches is not warranted, is not well defined, but is analogous to the methodologies used in this study.

Results. The results of applying the Level 1 methodology to Cave Creek and its tributaries are shown in Table 5-3. The Level 1 erosion hazard setbacks are shown on erosion hazard maps available from ASL Consulting Engineers.

Table 5-3. Upper Cave Creek/Apache Wash 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
Cave Creek							
	C400R	31400	177	443	33500	183	458
	C400	33800	184	460	36000	190	474
	C410	33800	184	460	35800	189	473
	C518	36700	192	479	39700	199	498
	C528	38100	195	488	41400	203	509
Apache Wash							
	23T	5706	76	189	7408	86	215
	22T	7213	85	212	7403	86	215
	20T	7534	87	217	7727	88	220
	20MT	13541	116	291	13890	118	295
	ET	17136	131	327	17944	134	335
	DT	18413	136	339	19252	139	347
Desert Hills Wash							
	F5T	10259	101	253	10761	104	259
	20MT	13541	116	291	13890	118	295
Paradise Wash							
	12T	4049	64	159	4152	64	161
	11T	5232	72	181	5401	73	184
	10T	5763	76	190	5992	77	194

Note: Concentration point locations (e.g. C400, 12T, etc) are described and illustrated in the Hydrology Report prepared for this study by ASL (1999).

The results for the setback equation for straight channels is most applicable to Cave Creek. 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 the streams in the study area:

- There was poor correspondence to erosion hazard delineations made using the detailed procedures described in the remainder of 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 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 these limitations, the State Standard Level 1 methodology is not recommended for the streams in the study area, and was not considered in the definition of the erosion hazard zones described in Chapter 6 of this report.

HEC-6 Modeling

HEC-6 models of the study area were prepared by Stantec as part of the scope of services for the Upper Cave Creek/Apache Wash Watercourse Master Plan. The HEC-6 modeling effort is described in a separate report (Stantec, 1999), but is summarized below.

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 -

  $\text{Sediment}_{(in)} - \text{Sediment}_{(out)} = \text{Change in Sediment Volume}$

  Change in Bed Elevation = Change in Sediment Volume ÷ 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. A number of 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[2] (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. Upper Cave Creek/Apache Wash Watercourse Master Plan HEC-6 Modeling Assumptions and Limitations

Assumption/Limitation	Assumption Valid for Study Reach?
One Dimensional	No. But probably gradually varied
Uniform Scour or Deposition	No. Braided system with bars
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 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.

[2] Stream segment as defined for HEC-6 is a reach with uniform discharge, no tributaries, or special conditions.

Methodology. The sediment deficit predicted by the Stantec HEC-6 model 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 was obtained by inserting a $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.

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 was modified to the following:

$$X_{wtd} = 0.01\ X_{100} + 0.09\ (X_{100} + X_{10})/2 + 0.1\ (X_{10} + 0)/2$$

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 Upper Cave Creek/Apache Wash Watercourse Master Plan, can then be estimated using the following equation:

$$X_{tot} = 60 * X_{wtd}$$

Two methods for estimating the erosion distance were used. Method 1 consisted of averaging the predicted erosion distance for individual cross sections within each reach.

[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.

Cross sections with a estimated sediment surplus were considered to have a zero bank erosion distance, and the reach-average value was used. Method 2 consisted of using reach-averaged erosion distances after removing the positive values. There were no cases in which the reach average had a net sediment surplus and a zero erosion distance using Method 1 and Method 2.

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 erosion will occur during large floods. Smaller floods will have minimal erosion, with much larger amounts of erosion occurring during the largest floods. Interestingly, the predicted bank erosion distances are similar for Cave Creek, Apache Wash, and Paradise Wash despite differences in discharge, flow duration, and field conditions. However, field and historical evidence suggest that Apache Wash and its tributaries have experienced less lateral migration than Cave Creek. Apache Wash and Paradise Wash have much denser bank vegetation and are less *incised* than Cave Creek, and have not had in-stream sand and gravel mining like Cave Creek, which probably accounts for the difference between historical responses and the predicted responses. The predicted bank erosion distances are lowest for Desert Hills Wash.

Table 5-5. Upper Cave Creek/Apache Wash Watercourse Master Plan
HEC-6 Sediment Deficit Translation to Bank Erosion Distance Estimates (ft)

Reach	Bank Height		Channel Reach Length (ft)	HEC6 Deficit		Deficit Applied to Bank (ft)				Erosion Distance (ft)					
						Left Bank		Right Bank		Average Annual		Project Planning Period			
												Method 1		Method 2	
	Left (ft)	Right (ft)		Q100 TOTAL yd^3	Q10 TOTAL yd^3	Q100 Total	Q10 Total	Q100 Total	Q10 Total	Left	Right	Left	Right	Left	Right
Cave Creek															
SR	13.8	14.9	661	-1629	-917	-4.8	-2.7	-4.5	-2.5	-1.6	-1.5	-97	-90	-321	-299
1	29.3	12.5	460	-4	460	0.0	0.0	0.0	0.0	0.0	0.0	0	0	-129	-327
2	23.7	11.9	464	-1285	-535	-3.2	-1.3	-6.3	-2.6	-0.8	-1.6	-49	-98	-207	-420
3	18.0	13.8	351	1081	272	0.0	0.0	0.0	0.0	0.0	0.0	0	0	-345	-401
4	11.0	9.7	414	1549	775	0.0	0.0	0.0	0.0	0.0	0.0	0	0	-280	-311
5	7.8	8.9	471	445	-6	0.0	0.0	0.0	0.0	0.0	0.0	-1	-1	-369	-322
Apache Wash															
SR	6.4	5.7	371	-309	-45	-3.5	-0.5	-3.9	-0.6	-0.5	-0.5	-27	-30	-176	-201
1	8.3	7.8	387	-465	-32	-3.9	-0.3	-4.2	-0.3	-0.3	-0.4	-21	-22	-124	-141
2	6.8	6.7	370	8	53	0.0	0.0	0.0	0.0	0.0	0.0	0	0	-111	-107
3	5.5	6.3	336	240	115	0.0	0.0	0.0	0.0	0.0	0.0	0	0	-156	-143
4	11.6	11.6	369	55	-87	0.0	-0.6	0.0	-0.6	-0.3	-0.3	-16	-16	-139	-154
5	10.0	8.2	461	71	-91	0.0	-0.5	0.0	-0.7	-0.3	-0.3	-16	-19	-155	-154
Paradise Wash															
SR	5.1	3.4	450	-352	-57	-4.1	-0.7	-6.2	-1.0	-0.6	-0.8	-33	-51	-123	-232
1	5.4	4.7	401	-44	-26	-0.5	-0.3	-0.6	-0.4	-0.2	-0.2	-12	-13	-93	-103
Desert Hills Wash															
SR	4.6	5.0	455	-223	-76	-2.9	-1.0	-2.6	-0.9	-0.6	-0.6	-39	-36	-39	-36
1	4.0	4.0	369	-44	29	-0.8	0.0	-0.8	0.0	0.0	0.0	-3	-3	-30	-30

Note: Results based on latest revision of Stantec HEC-6 model for Cave Creek and its tributaries.

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. Upper Cave Creek/Apache Wash 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.

$$V_b = 0.64\ D^{(4/9)} \qquad \text{for } D < 6.0 \text{ mm}$$
$$V_b = 0.5\ D^{1/2} \qquad \text{for } D > 6.0 \text{ mm}$$

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 relation for cohesive soils.

$$V_b = 3.15\ d^{(1/3)}\ D^{(2/3)} \quad \text{(non-cohesive soils)}$$
$$V_b = 7.5\ d^{(1/6)}\ \tau_c^{1/2} \quad \text{(for cohesive soils)}$$

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-*scour*ing flood control channels, as shown in Table 5-7.

Table 5-7. Upper Cave Creek/Apache Wash 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. Upper Cave Creek/Apache Wash 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	5	2.5	Very Soft	5	2.0
(sand)	10	4.0		10	2.5
10	5	4.5	Average	5	3.5
(gravel)	10	5.5		10	4.0
100	5	9.5	Very Stiff	5	5.5
(cobbles)	10	10.5		10	6.0

Results. Using the 2-, 10-, and 100-year velocities, and bed sediment characteristics, the four methodologies described above were applied to each of the stream reaches on the four streams in the study area. Mean channel velocity for each stream reach is shown in Table 5-9.

Table 5-9. Upper Cave Creek/Apache Wash Watercourse Master Plan Reach-Averaged Channel Velocity (ft/s)			
Reach	**2-Year**	**10-Year**	**100-Year**
Cave Creek			
1	5.7	8.5	12.2
2	6.6	10.0	13.0
3	5.4	8.0	11.3
4	5.4	7.6	10.9
5	5.8	7.5	10.5
Apache Wash			
1	4.5	7.2	11.3
2	4.3	8.3	11.3
3	3.1	4.4	4.6
4	4.5	8.7	13.6
5	4.6	9.2	13.7
Paradise Wash			
SR	3.7	6.7	9.5
1	3.5	6.3	9.6
Desert Hills Wash			
SR	4.6	7.7	11.0
1	3.8	7.0	10.2

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 to 5-13. Where the allowable velocities are exceeded by the predicted HEC-RAS reach-averaged velocity, erosion (E) is expected.

Cave Creek. Most of the methodologies used indicate that the banks of Cave 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 the USACOE values of erodibility for igneous bedrock (Table 5-10).

Table 5-10. Upper Cave Creek/Apache Wash Watercourse Master Plan Allowable Velocity Results – Cave Creek							
Reach	**Fortier & Scobey**	**BUREC**	**Neill: Non-Cohesive**		**Neill: Cohesive**		**USACOE**
			Velocity	**Erosive?**	**Velocity**	**Erosive?**	
2-Year							
1	S/E	E	2.9 ft/s	E	9.3 ft/s	S	S/E
2	E	E	2.2 ft/s	E	10.1 ft/s	S	S/E
3	S/E	E	1.2 ft/s	E	9.4 ft/s	S	S/E
4	S/E	E	1.2 ft/s	E	9.5 ft/s	S	S/E
5	S/E	E	1.8 ft/s	E	10.3 ft/s	S	S/E
10-Year							
1	E	E	3.5 ft/s	E	13.8 ft/s	S	S/E
2	E	E	2.7 ft/s	E	15.4 ft/s	S	E
3	E	E	1.4 ft/s	E	13.7 ft/s	S	S/E
4	S/E	E	1.4 ft/s	E	13.3 ft/s	S	S/E
5	S/E	E	2.0 ft/s	E	13.2 ft/s	S	S/E
100-Year							
1	E	E	4.6 ft/s	E	20.0 ft/s	S	E
2	E	E	3.3 ft/s	E	20.0 ft/s	S	E
3	E	E	1.8 ft/s	E	19.6 ft/s	S	E
4	E	E	1.6 ft/s	E	19.1 ft/s	S	E
5	E	E	2.4 ft/s	E	18.5 ft/s	S	E

Notes:
E = allowable velocity exceeded; erosion expected
S = allowable velocity not exceeded; erosion not expected
S/E = no clear trend, some sections exceed allowable velocity – some sections do not

Apache Wash. Most of the methodologies used indicate that the banks of Apache 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 Apache Wash is more subject to erosion at higher flow rates, and that Reaches 4 and 5 may be more subject to erosion than Reaches 1 and 2.

Table 5-11. Upper Cave Creek/Apache Wash Watercourse Master Plan Allowable Velocity (ft/s) Results – Apache Wash							
Reach	**Fortier & Scobey**	**BUREC**	**Neill: Non-Cohesive**		**Neill: Cohesive**		**USACOE**
			Velocity	**Erosive?**	**Velocity**	**Erosive?**	
2-Year							
1	S/E	E	1.1 ft/s	E	5.3 ft/s	S	S
2	S/E	E	1.8 ft/s	E	5.2 ft/s	S	S
3	S	E	1.4 ft/s	E	5.0 ft/s	S	S
4	S/E	E	1.2 ft/s	E	5.4 ft/s	S	S/E
5	S/E	E	0.8 ft/s	E	5.5 ft/s	S	S/E
10-Year							
1	E	E	1.5 ft/s	E	8.7 ft/s	S	S/E
2	E	E	2.5 ft/s	E	10.0 ft/s	S	E
3	S/E	E	1.8 ft/s	E	6.7 ft/s	S	S/E
4	E	E	1.8 ft/s	E	10.5 ft/s	S	E
5	E	E	1.2 ft/s	E	11.0 ft/s	S	E
100-Year							
1	E	E	1.3 ft/s	E	13.6 ft/s	S	E
2	E	E	3.2 ft/s	E	13.6 ft/s	S	E
3	S	E	2.4 ft/s	S/E	6.6 ft/s	S	E
4	E	E	2.3 ft/s	E	16.3 ft/s	S	E
5	E	E	1.5 ft/s	E	16.4 ft/s	S	E

Notes:
E = allowable velocity exceeded; erosion expected
S = allowable velocity not exceeded; erosion not expected
S/E = no clear trend, some sections exceed allowable velocity – some sections do not

Paradise Wash. Most of the methodologies used indicate that the banks of Paradise Wash are erodible throughout the entire study reach for events above the 10-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 5-12 indicate that Paradise Wash is more subject to erosion at higher flow rates, and is generally considered subject to lateral erosion due to excessive velocities except where cohesive soils are present.

Table 5-12. Upper Cave Creek/Apache Wash Watercourse Master Plan Allowable Velocity (ft/s) Results – Paradise Wash							
Reach	**Fortier & Scobey**	**BUREC**	**Neill: Non-Cohesive**		**Neill: Cohesive**		**USACOE**
			Velocity	**Erosive?**	**Velocity**	**Erosive?**	
2-Year							
Supply	S	E	1.2 ft/s	E	4.2 ft/s	S	S
Reach 1	S	E	1.6 ft/s	E	4.2 ft/s	S	S
10-Year							
Supply	E	E	1.7 ft/s	E	8.1 ft/s	S	E
Reach 1	E	E	2.3 ft/s	E	9.5 ft/s	S	S/E
100-Year							
Supply	E	E	2.2 ft/s	E	11.3 ft/s	S	E
Reach 1	E	E	2.9 ft/s	E	11.5 ft/s	S	E

Notes:
E = allowable velocity exceeded; erosion expected
S = allowable velocity not exceeded; erosion not expected
S/E = no clear trend, some sections exceed allowable velocity – some sections do not

Desert Hills Wash. Most of the methodologies used indicate that the banks of Desert Hills 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 5-13 indicate that Desert Hills Wash is more subject to erosion at higher flow rates.

Table 5-13. Upper Cave Creek/Apache Wash Watercourse Master Plan Allowable Velocity (ft/s) Results – Desert Hills Wash							
Reach	**Fortier & Scobey**	**BUREC**	**Neill: Non-Cohesive**		**Neill: Cohesive**		**USACOE**
			Velocity	**Erosive?**	**Velocity**	**Erosive?**	
2-Year							
Supply	S/E	E	2.1 ft/s	E	5.6 ft/s	S	S
Reach 1	S	E	1.5 ft/s	E	4.5 ft/s	S	S
10-Year							
Supply	E	E	2.7 ft/s	E	9.4 ft/s	S	E
Reach 1	E	E	2.0 ft/s	E	8.4 ft/s	S	S/E
100-Year							
Supply	E	E	3.1 ft/s	E	13.3 ft/s	S	E
Reach 1	E	E	2.4 ft/s	E	12.3 ft/s	S	E

Notes:
E = allowable velocity exceeded; erosion expected
S = allowable velocity not exceeded; erosion not expected
S/E = no clear trend, some sections exceed allowable velocity – some sections do not

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 banks 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[4] 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 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 3)
- 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 discharge are nearly equivalent. However, on ungauged ephemeral streams where flow events are rare, the average annual *discharge* (Figure 2-4 and 2-5) is difficult to determine. Bankfull discharge estimates were described in Chapter 4, and ranged from the 4- to the 100-year event for the stream reaches in the study area. To account for the discrepancies in what flow rate is appropriate for equilibrium slope analyses, 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- and 100-year events better approximate bankful*l* conditions on the streams in the study area. 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

[4] Equilibrium slope is also referred to as stable slope or limiting slope.

A large number of equilibrium slope equations were used to illustrate the range of possible results, as well as the inherent inability of this approach to precisely define the future slope of a channel. There are far too many variables that impact or control stream slope for any single one- or two-parameter equation to predict with a high degree of certainty. Therefore, the range of results was interpreted as an indication of the expected future trend of slope adjustment, while recognizing the potential for a range of reasonable outcomes.

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.[5]

$$S_s = 18.28\, n^2\, F^{0.133}\, F_r^{2.133}\, Q_{dd}^{-0.133}$$

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)

[5] *Transport limited means that the sediment inflow equals or exceeds the reach transport capacity.*

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)
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, unless their *watersheds* become fully developed 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
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 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)

$K_{mpm} = 0.19$
Q/Q_{bf} = Ratio of total flow to flow over the channel
Q_{bf} = Dominant discharge (cfs)
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 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 5-14 to 5-16 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. In general, the equilibrium slope equations indicate that long-term degradation will occur as the channels adjust to more stable, flatter slopes. 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. Long-term degradation (or aggradation) can be predicted by comparing the equilibrium slope and existing channel

slopes for a given reach. The equilibrium slope data indicate that the greatest amount of long-term *scour* will occur during the largest floods, which supports the conclusions of the bankfull discharge analysis (Chapter 4), as well as the *armor*ing and scour calculations presented in this Chapter.

Cave Creek. As shown in Table 5-14, the predicted equilibrium slope for Cave Creek is lower than the existing channel slope throughout the study reach, with one exception. The average predicted slope based on the 2-year peak discharge in Reach 5 is equal to the existing channel slope. Therefore, the least amount of long-term degradation is expected in Reach 5. The greatest amount of long-term degradation should occur in Reaches 3 and 4, where the difference between the average equilibrium slope and the existing channel slope is greatest.

Apache Wash. As shown in Table 5-15, the predicted equilibrium slope for Apache Wash is generally lower than the existing channel slope throughout the study reach, with two exceptions. The average predicted slopes based on the 2-year peak discharge in Reach 2 and Reach 3 are greater than the existing channel slopes. Therefore, aggradation may occur over the long-term during smaller floods in Reaches 2 and 3. The greatest amount of long-term degradation should occur in Reach 1, where the difference between the average equilibrium slope and the existing channel slope is greatest.

Paradise Wash. As shown in Table 5-16, the predicted equilibrium slope for Paradise Wash is lower than the existing channel slope within the study reach, with one exception. The average predicted slope based on the 2-year peak discharge in Reach 1 is greater than the existing channel slope. Therefore, aggradation may occur during small floods in the future. The greatest amount of long-term degradation should occur in the *Supply reach* (which extends several hundred feet into the study area), where the difference between the average equilibrium slope and the existing channel slope is greatest.

Desert Hills Wash. As shown in Table 5-16, the predicted equilibrium slope for Desert Hills Wash is greater than the existing channel slope. Therefore, long-term aggradation is expected, with the greatest amount of aggradation expected during the most frequent events.

Table 5-14. Upper Cave Creek/Apache Wash Watercourse Master Plan
Equilibrium Slope Analysis Results – Cave Creek (ft/ft)

Method	Reach 1			Reach 2			Reach 3			Reach 4			Reach 5		
	Q2	Q10	Q100	Q2	Q10	Q100	Q2	Q10	Q100	Q2	Q10	Q100	Q2	Q10	Q100
Schoklitsch	.0027	.0013	.0005	.0021	.0009	.0005	.0029	.0014	.0006	.0028	.0014	.0007	.0021	.0013	.0007
Meyer-Peter, Muller	.0047	.0027	.0013	.0035	.0018	.0011	.0049	.0027	.0014	.0050	.0054	.0041	.0035	.0050	.0040
Shields	.0028	.0015	.0007	.0014	.0007	.0004	.0007	.0004	.0002	.0005	.0003	.0001	.0008	.0006	.0003
Lane	.0024	.0013	.0006	.0012	.0006	.0003	.0007	.0004	.0002	.0005	.0003	.0002	.0007	.0005	.0003
Average	.0032	.0017	.0008	.0021	.0010	.0023	.0023	.0012	.0006	.0022	.0018	.0013	.0018	.0018	.0014
Bray	.0144	.0144	.0144	.0109	.0109	.0109	.0067	.0067	.0067	.0062	.0062	.0062	.0090	.0090	.0090
Henderson	.0066	.0034	.0018	.0041	.0021	.0012	.0025	.0013	.0007	.0036	.0022	.0013	.0032	.0021	.0013
BUREC	.0046	.0016	.0006	.0028	.0009	.0003	.0017	.0006	.0002	.0013	.0006	.0002	.0016	.0008	.0004
AMAFCA	.0089	.0087	.0068	.0097	.0085	.0063	.0092	.0091	.0073	.0087	.0076	.0078	.0081	.0078	.0077
Average	.0086	.0070	.0059	.0069	.0056	.0047	.0050	.0044	.0037	.0050	.0041	.0039	.0055	.0049	.0046
Measured Slope	.0092			.0091			.0083			.0080			.0055		
Predicted Trend	Degradation			Degradation			Degradation			Degradation			Degradation		

Table 5-15. Upper Cave Creek/Apache Wash Watercourse Master Plan
Equilibrium Slope Analysis Results – Apache Wash (ft/ft)

Method	Reach 1			Reach 2			Reach 3			Reach 4			Reach 5		
	Q2	Q10	Q100	Q2	Q10	Q100	Q2	Q10	Q100	Q2	Q10	Q100	Q2	Q10	Q100
Schoklitsch	.0024	.0009	.0004	.0025	.0007	.0003	.0033	.0018	.0012	.0023	.0006	.0002	.0020	.0005	.0002
Meyer-Peter, Muller	.0029	.0015	.0011	.0029	.0011	.0010	.0047	.0026	.0017	.0031	.0010	.0007	.0027	.0009	.0008
Shields	.0019	.0008	.0004	.0037	.0013	.0006	.0028	.0014	.0007	.0018	.0006	.0003	.0007	.0002	.0001
Lane	.0017	.0007	.0004	.0032	.0011	.0005	.0025	.0012	.0006	.0016	.0005	.0002	.0007	.0002	.0001
Average	.0022	.0010	.0006	.0030	.0010	.0006	.0033	.0018	.0010	.0022	.0006	.0003	.0015	.0005	.0003
Bray	.0081	.0081	.0081	.0118	.0118	.0118	.0099	.0099	.0099	.0083	.0083	.0083	.0055	.0055	.0055
Henderson	.0059	.0023	.0013	.0139	.0052	.0031	.0063	.0023	.0012	.0026	.0010	.0005	.0011	.0004	.0003
BUREC	.0048	.0010	.0004	.0057	.0011	.0005	.0231	.0045	.0015	.0031	.0006	.0002	.0015	.0003	.0001
AMAFCA	.0080	.0063	.0061	.0074	.0062	.0044	.0085	.0053	.0018	.0080	.0053	.0048	.0065	.0051	.0045
Average	.0067	.0044	.0040	.0097	.0061	.0050	.0119	.0055	.0036	.0055	.0038	.0035	.0037	.0028	.0026
Measured Slope	.0086			.0075			.0059			.0062			.0058		
Predicted Trend	Degradation			Degradation			Degradation			Degradation			Degradation		

Table 5-16. Upper Cave Creek/Apache Wash Watercourse Master Plan
Equilibrium Slope Analysis Results – Paradise Wash & Desert Hills Wash (ft/ft)

Method	Paradise Wash						Desert Hills Wash					
	Supply reach			Reach 1			*Supply reach*			Reach 1		
	Q2	Q10	Q100	Q2	Q10	Q100	Q2	Q10	Q100	Q2	Q10	Q100
Schoklitsch	.0041	.0012	.0005	.0039	.0011	.0005	.0015	.0006	.0003	.0019	.0006	.0003
Meyer-Peter, Muller	.0048	.0021	.0017	.0056	.0022	.0015	.0016	.0016	.0022	.0018	.0015	.0019
Shields	.0043	.0015	.0007	.0058	.0020	.0009	.0021	.0009	.0006	.0014	.0006	.0004
Lane	.0038	.0013	.0007	.0051	.0017	.0008	.0017	.0008	.0005	.0012	.0005	.0003
Average	.0043	.0015	.0009	.0051	.0018	.0009	.0017	.0010	.0009	.0016	.0008	.0007
Bray	.0098	.0098	.0098	.0121	.0121	.0121	.0114	.0114	.0114	.0089	.0089	.0089
Henderson	.0074	.0029	.0017	.0056	.0022	.0012	.0046	.0023	.0016	.0048	.0023	.0015
BUREC	.0069	.0015	.0007	.0091	.0019	.0008	.0027	.0009	.0005	.0024	.0007	.0004
AMAFCA	.0099	.0076	.0064	.0095	.0065	.0058	.0042	.0036	.0040	.0031	.0032	.0036
Average	.0085	.0055	.0046	.0091	.0057	.0050	.0057	.0045	.0043	.0048	.0038	.0036
Measured Slope	.0101			.0086			.0034			.0018		
Predicted Trend	Degradation			Degradation			Aggradation			Aggradation		

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 degradation is expected for the streams in the study area, except for Desert Hills Wash. The actual magnitude of the expected degradation will be based in part on the potential for *armor*ing, sediment supply, and the magnitude and frequency of the flows experienced in the future.

Armoring

When the channel sediment transport capacity exceeds the upstream sediment supply, the balance of the sediment load may be eroded from the channel itself, causing the channel to degrade. Finer sediments can be transported at more frequent lower discharges and velocities than the coarser bed sediments, which may require large floods to be moved. Therefore, finer sediment tends to be preferentially removed from the channel bed, resulting in progressively coarser channel bed material over time, as long as the upstream sediment supply is limited. This process 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)
$K_{mpm} = 0.19$
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 Lushey (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 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 5-17 to 5-20. 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 5-17 to 5-20 was rated by comparing data collected in the field with the predicted depth of scour required to form an armor layer. 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.

Cave Creek. As shown in Table 5-17, the bed of Cave Creek will experience general scour during most significant floods. The bed material is large enough to form an armor layer during the 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. Reaches 2 and 3 are least likely to form armor layers, based on the depth of scour required. Field evidence suggests that some of 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 5-17. Upper Cave Creek/Apache Wash Watercourse Master Plan Armoring Analysis Results – Cave Creek

Reach	Methodology – Critical Armor Diameter (mm)				Average Critical Diam.	Field D50 (mm)	Armor Layer Likely?	Depth to Armor
	MPM	CBV	Yang	Shield				
2-Year Flood								
1	46	67	72	67	67	19.0	Yes	1.5 ft
2	51	84	90	78	76	11.5	Yes	3.1 ft
3	37	61	65	74	59	5.0	Yes	3.7 ft
4	40	64	69	76	62	4.5	Yes	3.1 ft
5	42	71	76	81	68	8.0	Yes	3.3 ft
10-Year Flood								
1	83	147	157	119	127	19.0	Yes	3.3 ft
2	95	197	210	144	162	11.5	No	9.5 ft
3	64	129	138	126	114	5.0	No	9.5 ft
4	61	117	125	116	104	4.5	No	5.1 ft
5	60	116	124	117	104	8.0	No	5.8 ft
100-Year Flood								
1	132	293	314	195	234	19.0	No	7.8 ft
2	129	325	348	193	249	11.5	No	>20 ft
3	99	251	268	198	204	5.0	No	>20 ft
4	101	230	246	193	192	4.5	No	>20 ft
5	97	222	237	188	186	8.0	No	>20 ft

MPM = Meyer-Peter, Muller CBV = Competent Bottom Velocity
Yang = Yang's Incipient Motion Shield = Shield's Method

Apache Wash. As shown in Table 5-18, an armor layer forms at a relatively shallow depth on the bed of Apache Wash during the 2-year flood, except in Reach 5. Reaches 2 and 3 appear to be effectively armored for the 2-year flood without significant scour, and may form an effective armor layer during a 10-year flood. For the 100-year event, and for the 10-year event in Reaches 1, 2, and 5, 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 are coarser than the reach-averaged sediment distribution and will be armored, at least for the 2- and 10-year floods.

Table 5-18. Upper Cave Creek/Apache Wash Watercourse Master Plan Armoring Analysis Results – Apache Wash

Reach	Methodology – Critical Armor Diameter (mm)				Average Critical Diam.	Field D50 (mm)	Armor Layer Likely?	Depth to Armor
	MPM	CBV	Yang	Shield				
2-Year Flood								
1	23	39	41	29	33	6.7	Yes	1.1 ft
2	26	36	38	27	32	13.0	Yes	0.5 ft
3	14	20	21	27	20	9.5	Yes	0.3 ft
4	22	41	44	29	34	7.0	Yes	2.7 ft
5	17	41	44	28	33	3.5	No	15.8 ft
10-Year Flood								
1	44	100	107	55	76	6.7	No	>20 ft
2	66	132	141	69	102	13.0	Yes	4.0 ft
3	23	46	49	38	39	9.5	Yes	2.0 ft
4	51	146	156	69	106	7.0	No	>20 ft
5	46	162	173	75	114	3.5	No	>20 ft
100-Year Flood								
1	85	243	259	106	173	6.7	No	>20 ft
2	95	241	258	98	173	13.0	No	>20 ft
3	27	84	89	37	59	9.5	Maybe	5.1 ft
4	95	353	377	130	240	7.0	No	>20 ft
5	81	366	391	133	243	3.5	No	>20 ft

MPM = Meyer-Peter, Muller CBV = Competent Bottom Velocity
Yang = Yang's Incipient Motion Shield = Shield's Method

Paradise Wash. As shown in Table 5-19, minimal scour is required to armor the bed of Paradise Wash during the 2-year and smaller floods. However, for the 10- and 100-year events the depth of scour 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 are coarser than the reach-averaged sediment distribution and will be armored, at least for the 2- and 10-year floods.

Table 5-19. Upper Cave Creek/Apache Wash Watercourse Master Plan Armoring Analysis Results – Paradise Wash

Reach	Methodology – Critical Armor Diameter (mm)				Average Critical Diam.	Field D50 (mm)	Armor Layer Forms?	Depth to Armor
	MPM	CBV	Yang	Shield				
2-Year Flood								
SR	18	27	28	22	24	9.4	Yes	0.5 ft
1	16	25	26	21	22	13.5	Yes	0.4 ft
10-Year Flood								
SR	41	87	93	51	68	9.4	No	>20 ft
1	33	75	81	44	58	13.5	No	>20 ft
100-Year Flood								
SR	64	169	180	79	123	9.4	No	>20 ft
1	62	179	191	82	129	13.5	No	>20 ft

MPM = Meyer-Peter, Muller CBV = Competent Bottom Velocity
Yang = Yang's Incipient Motion Shield = Shield's Method

Desert Hills Wash. As shown in Table 5-20, minimal scour is required to armor the bed of Desert Hills Wash during the 2-year and smaller events. For the 10- and 100-year events the depth of scour required to form an armor layer is too great to be effective at limiting scour.

Table 5-20. Upper Cave Creek/Apache Wash Watercourse Master Plan Armoring Analysis Results – Desert Hills Wash

Reach	Methodology – Critical Armor Diameter (mm)				Average Critical Diam.	Field D50 (mm)	Armor Layer Forms?	Depth to Armor
	MPM	CBV	Yang	Shield				
2-Year Flood								
SR	21	41	44	27	33	12.2	Yes	1.0 ft.
1	14	28	29	18	22	8.0	Yes	0.5 ft.
10-Year Flood								
SR	45	112	120	57	84	8.0	No	>20 ft
1	36	92	99	44	68	9.4	No	>20 ft
100-Year Flood								
SR	78	229	244	98	162	12.2	No	>20 ft
1	66	201	215	82	141	8.0	No	>20 ft

MPM = Meyer-Peter, Muller CBV = Competent Bottom Velocity
Yang = Yang's Incipient Motion Shield = Shield's Method

Conclusions. The following conclusions can be drawn from the armoring analysis results summarized in Tables 5-17 to 5-20 for the study area:

- 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 must 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.

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 the streams in the study area 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:

$$Z_a = 0.0137\ V^2_m$$

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. Given the similarity of Skunk Creek to the streams in the study area, it was assumed that antidunes could form in the study reach, except in *riffles* or 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 evidence of a low flow thalweg was observed on the streams in the study area. Therefore, the low-flow thalweg component of scour was assumed to be zero for 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 $\alpha < 17.8^\circ$
= computed value when $0.5 < r_c/T < 10.0$, or $17.8^\circ < \alpha < 60^\circ$
= computed value when $\alpha = 60^\circ$ when $r_c/T < 0.5$, or $\alpha > 60^\circ$

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. No such structures exist within the study limits at the present time.[6] Therefore, a local scour component was not included in the scour estimates.

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 *armor*ed, the depth of long-term scour for the streams in the study area would exceed ten feet in most cases. Alternatively, if the depth of entrenchment since Hohokam occupation of the area were used, the long-term scour would be five to seven feet on Cave Creek. A practical rule of thumb for determining a reasonable long-term estimate

[6] Carefree Highway is the upstream limit of the study. Scour associated with the Carefree Highway was evaluated by Stantec (1999).

for undisturbed *watersheds* is to use the height of the floodplain terrace above the channel bottom or the bank height (Table 5-5).

Results. Scour estimates for each of the four streams in the study area obtained from the City of Tucson scour equations are summarized in Tables 5-21 to 5-24. In general, the largest component of scour other than long-term scour is the bend scour. General scour is typically less than one foot. 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.

Cave Creek. Scour estimates for Cave Creek are shown in Table 5-21. The non-linearity in the scour trend between the three *discharges* evaluated most likely reflects differences in channel geometry and *bankfull* capacity relative to the channel hydraulics. Without the bend scour, the total scour along Cave Creek is less than five feet, which conforms well with the depth of the observed clay-rich layer in the soil pits.

Table 5-21. Upper Cave Creek/Apache Wash Watercourse Master Plan Scour Estimates – Cave Creek (ft.)

Reach	Total Zt	General Zgs	Antidune Za	Bend Angle	Bend Zbs	Local Zls	Thalweg Zlft
Q2							
1	0.7	-0.7	1.1	12.4	0.0	0.0	0.0
2	0.8	-0.4	1.3	13.8	0.0	0.0	0.0
3	0.7	-0.8	1.0	14.9	0.0	0.0	0.0
4	5.8	-1.2	1.2	24.5	3.9	0.0	0.0
5	5.9	-1.0	1.5	32.2	3.8	0.0	0.0
Q10							
1	9.9	-0.7	2.0	24.6	6.6	0.0	0.0
2	11.6	-0.2	2.5	24.6	7.6	0.0	0.0
3	8.9	-0.9	1.9	24.6	5.9	0.0	0.0
4	9.4	-1.2	2.1	24.6	6.2	0.0	0.0
5	9.2	-1.2	2.2	24.6	6.0	0.0	0.0
Q100							
1	3.5	-0.3	4.4	12.4	0.0	0.0	0.0
2	3.9	0.3	4.5	13.8	0.0	0.0	0.0
3	2.7	-0.9	4.1	14.9	0.0	0.0	0.0
4	15.6	-1.1	3.4	24.5	10.2	0.0	0.0
5	14.7	-1.1	3.6	32.2	9.5	0.0	0.0

Apache Wash. Scour estimates for Apache Wash are shown in Table 5-22. The total scour depths are significantly less than for Cave Creek due to the lower discharge, flow depths, and channel velocities. Predicted scour depths conform well to estimates of scour based on the depth of the clay-rich sublayer observed in the soil pits. Overall, the depth of scour is not significant on Apache Wash. The greatest amount of scour is predicted for Reaches 3 and 5.

Table 5-22. Upper Cave Creek/Apache Wash Watercourse Master Plan Scour Estimates - Apache Wash (ft.)							
Reach	Total Zt	General Zgs	Antidune Za	Bend Angle	Bend Zbs	Local Zls	Thalweg Zlft
Q2							
1	0.3	-0.1	0.5	0.0	0.0	0.0	0.0
2	0.3	-0.1	0.5	0.0	0.0	0.0	0.0
3	0.3	-0.4	0.5	0.0	0.0	0.0	0.0
4	0.4	-0.1	0.6	0.0	0.0	0.0	0.0
5	0.5	-0.1	0.7	0.0	0.0	0.0	0.0
Q10							
1	1.0	0.2	1.1	0.0	0.0	0.0	0.0
2	1.1	0.2	1.2	0.0	0.0	0.0	0.0
3	1.4	0.3	1.5	0.0	0.0	0.0	0.0
4	0.8	-1.0	1.1	0.0	0.0	0.0	0.0
5	1.9	0.5	2.0	0.0	0.0	0.0	0.0
Q100							
1	2.2	0.7	2.0	0.0	0.0	0.0	0.0
2	2.9	1.0	2.5	0.0	0.0	0.0	0.0
3	3.6	1.1	3.2	0.0	0.0	0.0	0.0
4	1.4	-1.9	1.5	0.0	0.0	0.0	0.0
5	5.2	1.9	4.2	0.0	0.0	0.0	0.0

Paradise Wash. Scour estimates for Paradise Wash are shown in Table 5-23. The conclusion that only minimal scour occurs on Paradise Wash is supported by field observations and by the depth of the clay-rich sublayer in the channel soil pits.

Table 5-23. Upper Cave Creek/Apache Wash Watercourse Master Plan Scour Estimates - Paradise Wash (ft.)							
Reach	Total Zt	General Zgs	Antidune Za	Bend Angle	Bend Zbs	Local Zls	Thalweg Zlft
Q2							
SR	0.0	0.0	0.0	0.0	0.0	0.0	0.0
1	0.2	-0.1	0.4	0.0	0.0	0.0	0.0
Q10							
SR	0.0	0.0	0.0	0.0	0.0	0.0	0.0
1	0.8	0.0	1.1	0.0	0.0	0.0	0.0
Q100							
SR	0.0	0.0	0.0	0.0	0.0	0.0	0.0
1	2.2	0.5	2.2	0.0	0.0	0.0	0.0

Desert Hills Wash. Scour estimates for Desert Hills Wash are shown in Table 5-24. On Desert Hills Wash, scour increases with recurrence interval.

Table 5-24. Upper Cave Creek/Apache Wash Watercourse Master Plan Scour Estimates - Desert Hills Wash (ft.)							
Reach	Total Zt	General Zgs	Antidune Za	Bend Angle	Bend Zbs	Local Zls	Thalweg Zlft
Q2							
SR	0.6	-0.2	0.9	0.0	0.0	0.0	0.0
1	0.6	-0.2	0.9	0.0	0.0	0.0	0.0
Q10							
SR	1.6	0.2	2.1	0.0	0.0	0.0	0.0
1	1.5	0.2	2.0	0.0	0.0	0.0	0.0
Q100							
SR	3.3	0.8	3.4	0.0	0.0	0.0	0.0
1	3.2	0.9	3.3	0.0	0.0	0.0	0.0

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 Chapter 4, and were used to estimate whether the bed elevation had moved up or down during the period of record from 1962 to 1999. Historical aerial photographs were used to estimate bank heights, from which bed elevation changes could be extrapolated, as described in Chapter 3. 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 5-25.

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 5-14 to 5-16). The slope difference multiplied by a stream reach length is the amount of adjustment in bed elevation at the upstream end of the reach. Due to the lack of natural grade control which would provide a pivot point for slope adjustments, reach lengths of 1,000 and 5,000 feet were used for the predictions shown in Table 5-25 to illustrate the direction and scale of expected change. As shown in Table 5-25, reach lengths of 5,000 feet result in somewhat improbable predicted long-term scour depths, given that less than 40 feet of net long-term scour over the past 500,000 years is recorded by the surficial geology. Nonetheless, the data in Table 5-25 clearly predict significant long-term scour throughout most of the study area, except on Desert Hills Wash.

Table 5-25. Upper Cave Creek/Apache Wash Watercourse Master Plan
Summary of Long-Term Degradation/Aggradation Data Sources

Reach	Field Assessment	Longitudinal Profile	Archaeological Data (ft/yr)	Aerial Photo Interpretation (ft)	Geologic Mapping (ft/yr)	Equilibrium Slope Adjustment – Reach Length (ft)					
						Q2		Q10		Q100	
						1000 ft	5000 ft	1000 ft	5000 ft	1000 ft	5000 ft
Cave Creek											
1	Degradation	Degradation	-0.01 ft/yr	-0.3 to -9.2	-0.01 to -0.0001	-0.6	-3.0	-2.2	-11.0	-3.3	-16.5
2	Degradation	Degradation	-10 to -15 ft.	-0.4 to -6.9		-2.2	-11.0	-3.2	-16.0	-4.4	-22.0
3	Degradation	Degradation		-7.2 to -7.9		-3.3	-16.5	-3.9	-19.5	-4.6	-23.0
4	Degradation	Degradation		-1.3 to -1.7		-3.0	-15.0	-3.8	-19.0	-4.1	-20.5
5	Stable	Degradation	No information	-6.9 to +4.3		0.0	0.0	-0.6	-3.0	-0.9	-4.5
Apache Wash											
1	Stable	Degradation	No information	-0.7 to -4.0	-0.01 to -0.0001	-1.9	-9.5	-4.2	-21.0	-4.6	-23.0
2	Stable	Degradation	No information	-0.7 to -4.0		2.2	11.0	-1.4	-7.0	-2.5	-12.5
3	Degradation	Degradation	No information	-2.0 to +2.1		6.1	30.5	-0.4	-2.0	-2.3	-11.5
4	Stable	Stable	No information	-2.0 to +2.1		-0.7	-3.5	-2.4	-12.0	-2.7	-13.5
5	Stable	Aggradation	No information	+0.9 to +1.0		-2.1	-10.5	-3.0	-15.0	-3.2	-16.0
Paradise Wash											
SR	Stable	Degradation	No information	+0.8 to +3.0	-0.01 to -0.0001	-1.6	-8.0	-4.6	-23.0	-5.4	-27.0
1	Stable	Aggradation	No information	+0.8 to +3.0		0.5	2.5	-2.9	-14.5	-3.6	-18.0
Desert Hills Wash											
SR	Stable	Degradation	No information	-4.8 to +2.1	-0.01 to -0.0001	2.3	11.5	1.2	6.0	1.0	5.0
1	Stable	Degradation	No information	-4.8 to +2.1		3.0	15.0	2.0	10.0	1.8	9.0
Source of Data	Chapter 4 Appendix B	Chapter 3 Fig. 3-15 to 19	Chapter 3	Chapter 3 Table 3-13 to 23	Chapter 4 Fig. 4-38	Values computed by the following equation: (equilibrium slope - existing channel) x reach length (ft.)					

Summary. General and long-term scour estimates for the streams in the study area indicate that significant scour is expected for Cave Creek. Significant, but lower amounts of scour are expected for Apache Wash, Paradise Wash. The predicted amount of scour for Desert Hills Wash is the lowest of the four streams considered. Potential bed scour typically undermines the channel banks and causes increase lateral erosion. Therefore, the greatest amount of scour-induced bank erosion in the study area is predicted for Cave Creek. Estimated bank erosion distances should be revised upward where bed scour is significant.

Comparison of Armoring, Scour, and Equilibrium Slope Predictions

Channel degradation can be prevented by *armor*ing 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 5-26 to 5-29. 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 *pool* and *riffle* sequence and the Reach lengths used for this study.

The "Armor v. Scour" and "Armor v. Slope" columns in Tables 5-26 to 5-29 indicates whether scour will be limited by armoring. That is, if the predicted depth of general scour (column 3 in Tables 5-25 to 5-29) 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.

Cave Creek. As shown in Table 5-26, armoring will not prevent long-term degradation (last column). Short term scour will be prevented by armoring in Reaches 4 and 5 during a 2-year event, and in Reaches 1, 2, 4, and 5 during the 10-year event. Scour during the 100-year event will not be checked by armoring. Therefore, bank stability will be most impacted by scour of the bed during the largest floods.

Table 5-26. Upper Cave Creek/Apache Wash Watercourse Master Plan Comparison of Armoring, Scour, and Equilibrium Slope Estimates – Cave Creek								
Reach	Depth to Armor (ft)	Scour Depth (ft)	Stable Slope		Slope Adjustments		Armor v. Scour	Armor v. Slope
			Regime	Actual	1000 ft.	5000 ft.		
Q2								
1	1.5	0.7	0.0086	0.0092	-0.6	-3.0	no	no
2	3.1	0.8	0.0069	0.0091	-2.2	-11.0	no	no
3	3.7	0.7	0.0050	0.0083	-3.3	-16.5	no	no
4	3.1	5.8	0.0050	0.0080	-3.0	-15.0	yes	no
5	3.3	5.9	0.0055	0.0055	0.0	0.0	yes	no
Q10								
1	3.3	9.9	0.0070	0.0092	-2.2	-11.0	yes	no
2	9.5	11.6	0.0056	0.0091	-3.2	-16.0	yes	no
3	9.5	8.9	0.0044	0.0083	-3.9	-19.5	no	no
4	5.1	9.4	0.0041	0.0080	-3.8	-19.0	yes	no
5	5.8	9.2	0.0049	0.0055	-0.6	-3.0	yes	no
Q100								
1	7.8	3.5	0.0059	0.0092	-3.3	-16.5	no	no
2	>20.0	3.9	0.0047	0.0091	-4.4	-22.0	no	no
3	>20.0	2.7	0.0037	0.0083	-4.6	-23.0	no	no
4	>20.0	15.6	0.0039	0.0080	-4.1	-20.5	no	no
5	>20.0	14.7	0.0046	0.0055	-0.9	-4.5	no	no
Notes: No = scour not limited by armoring Yes = scour limited by formation of armor layer								

Apache Wash. As shown in Table 5-27, armoring will not prevent long-term degradation (last column), except in Reach 1 during the 2-year event. Short term scour will be prevented by armoring only in Reach 3 during a 2-year event. Scour during the 10- and 100-year events will not be checked by armoring. Therefore, the banks of Apache Wash will be susceptible to erosion caused by bed scour during most significant floods.

Table 5-27. Upper Cave Creek/Apache Wash Watercourse Master Plan Comparison of Armoring, Scour, and Equilibrium Slope Estimates – Apache Wash								
Reach	Depth to Armor (ft)	Scour Depth (ft)	Stable Slope		Slope Adjustments		Armor v. Scour	Armor v. Slope
			Regime	Actual	1000 ft.	5000 ft.		
Q2								
1	1.1	0.3	0.0067	0.0086	-1.9	-9.5	no	yes
2	0.5	0.3	0.0097	0.0075	2.2	11.0	no	no
3	0.3	0.3	0.0119	0.0059	6.1	30.5	yes	no
4	2.7	0.4	0.0055	0.0062	-0.7	-3.5	no	no
5	15.8	0.5	0.0037	0.0058	-2.1	-10.5	no	no
Q10								
1	>20.0	1.0	0.0044	0.0086	-4.2	-21.0	no	no
2	4.0	1.1	0.0061	0.0075	-1.4	-7.0	no	no
3	2.0	1.4	0.0055	0.0059	-0.4	-2.0	no	no
4	>20.0	0.8	0.0038	0.0062	-2.4	-12.0	no	no
5	>20.0	1.9	0.0028	0.0058	-3.0	-15.0	no	no
Q100								
1	>20.0	2.2	0.0040	0.0086	-4.6	-23.0	no	no
2	>20.0	2.9	0.0050	0.0075	-2.5	-12.5	no	no
3	5.1	3.6	0.0036	0.0059	-2.3	-11.5	no	no
4	>20.0	1.4	0.0035	0.0062	-2.7	-13.5	no	no
5	>20.0	5.2	0.0026	0.0058	-3.2	-16.0	no	no
Notes: No = scour not limited by armoring Yes = scour limited by formation of armor layer								

Paradise Wash. As shown in Table 5-28, armoring will not prevent long-term degradation (last column), except during the 2-year event in the supply reach which extends several hundred feet into the study area. Short term scour will not be prevented by armoring on Paradise Wash. Scour during the 10- and 100-year events will not be checked by armoring. Therefore, the banks of Paradise Wash will be susceptible to erosion caused by bed scour during most significant floods.

Table 5-28. Upper Cave Creek/Apache Wash Watercourse Master Plan Comparison of Armoring, Scour, and Equilibrium Slope Estimates – Paradise Wash								
Reach	Depth to Armor (ft)	Scour Depth (ft)	Stable Slope		Slope Adjustments		Armor v. Scour	Armor v. Slope
			Regime	Actual	1000 ft.	5000 ft.		
Q2								
SR	0.5	0.0	0.0085	0.0101	-1.6	-8.0	no	yes
1	0.4	0.2	0.0091	0.0086	0.5	2.5	no	no
Q10								
SR	>20.0	0.0	0.0055	0.0101	-4.6	-23.0	no	no
1	>20.0	0.8	0.0057	0.0086	-2.9	-14.5	no	no
Q100								
SR	>20.0	0.0	0.0046	0.0101	-5.4	-27.0	no	no
1	>20.0	2.2	0.0050	0.0086	-3.6	-18.0	no	no
Notes: No = scour not limited by armoring Yes = scour limited by formation of armor layer								

Desert Hills Wash. As shown in Table 5-29, armoring will not prevent long-term degradation (last column). Short term scour will be prevented by armoring in Reach 1 during a 2-year event. Scour during the 10- and 100-year events will not be checked by armoring. Therefore, the banks of Desert Hills Wash will be susceptible to erosion caused by bed scour during most significant floods.

Table 5-29. Upper Cave Creek/Apache Wash Watercourse Master Plan Comparison of Armoring, Scour, and Equilibrium Slope Estimates – Desert Hills Wash

Reach	Depth to Armor (ft)	Scour Depth (ft)	Stable Slope		Slope Adjustments		Armor v. Scour	Armor v. Slope
			Regime	Actual	1000 ft.	5000 ft.		
Q2								
SR	1.0	0.6	0.0057	0.0034	2.3	11.5	no	no
1	0.5	0.6	0.0048	0.0018	3.0	15.0	yes	no
Q10								
SR	>20.0	1.6	0.0045	0.0034	1.2	6.0	no	no
1	>20.0	1.5	0.0038	0.0018	2.0	10.0	no	no
Q100								
SR	>20.0	3.3	0.0043	0.0034	1.0	5.0	no	no
1	>20.0	3.2	0.0036	0.0018	1.8	9.0	no	no

Notes:
No = scour not limited by armoring Yes = scour limited by formation of armor layer

Conclusion. The engineering analyses described in the preceding sections indicate that the streams in the study area are subject to net degradation, and will continue to entrench and *scour* in the future.

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
d = sediment size
Q = water discharge
S = slope

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 for (undocumented) over-grazing according to some regional studies (c.f., Earl, 1983). 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. 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 Cave Creek, and because the scale of degradation on the Apache Wash system is much different than on Cave Creek.

The effects of in-stream sand and gravel mining on Cave Creek can also be evaluated using Lane's relation. At the upstream end of an on-line or breached sand and gravel pit, the channel slope is drastically increased (S+). In response, the stream will increase the sediment transport rate (Q_s+). Within the pit the slope is flattened (S-), resulting in decreased sediment transport (Q_s-). Downstream of the pit, the sediment supply is reduced (Q_s-), requiring a decrease in slope (S-, scour).

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 prudent line methodology consists of the following elements:

1. Collect basic stream data. The recommended basic information consists of geology, hydrology, and land use data. Detailed field inspections and comparison of historical channel positions, land use, and longitudinal profile data are also recommended. Baseline HEC-1 and HEC-2 modeling, *sediment yield* and sediment transport analyses should also be prepared.
2. Perform stability analysis. The steps in the stability analysis include the following:
   Level 1
   Step 1: Define Channel Characteristics
   Step 2: Evaluate Watershed Conditions
   - Water yield
   - Sediment yield
   - Land use practices
   - Historical changes
   - Vegetation

   Step 3: Qualitative Assessment of Overall Stream Stability
   - Observed data interpretation (AMAFCA Table 4.2)
   - Schumm stability diagram (AMAFCA Figure 4.2)
   - Arroyo evolution diagram (AMAFCA Figure 3.1)

   Step 4: Evaluate Lateral Stability
   - Field inspection
   - Cross section plots
   - Aerial photograph interpretation

Step 5: Evaluation Vertical Stability
- Profile comparisons
- Lane relation
- Sediment continuity principle
- Equilibrium concepts

Step 6: Evaluate Channel Response to Change
- Lane relation

Level 2

Step 1: Evaluate Flood History & Potential Floods
- Flood response in past
- Wet/dry cycle

Step 2: Evaluate Hydraulic Conditions
- HEC-RAS output

Step 3: Analyze Bed and Bank Material Characteristics
- Sediment distribution

Step 4: Evaluate Watershed Sediment yield
- Existing/historical
- Future changes

Step 5: Analyze Armoring Potential

Step 6: Evaluate Degradation/Aggradation Potential
- Sediment continuity routing
- Equilibrium slope analysis

Step 7: Lateral Erosion Potential
- Historical data – channel movement
- Field inspection
- Plan form relationships
- Lateral migration rate

Step 8: Evaluate Local Scour
- Scour at structures
- Long-term scour
- Contraction scour

3. Level 3: Mathematical and Physical Model Studies

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. No geotechnical data for the channel banks in the Upper Cave Creek/Apache Wash Watercourse Master Plan study area were available. 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 5-36 to 5-39). Therefore, this key element of the prudent line approach described in the AMAFCA manual could not be applied.

Figure 5-36. Cave Creek Bank Stability

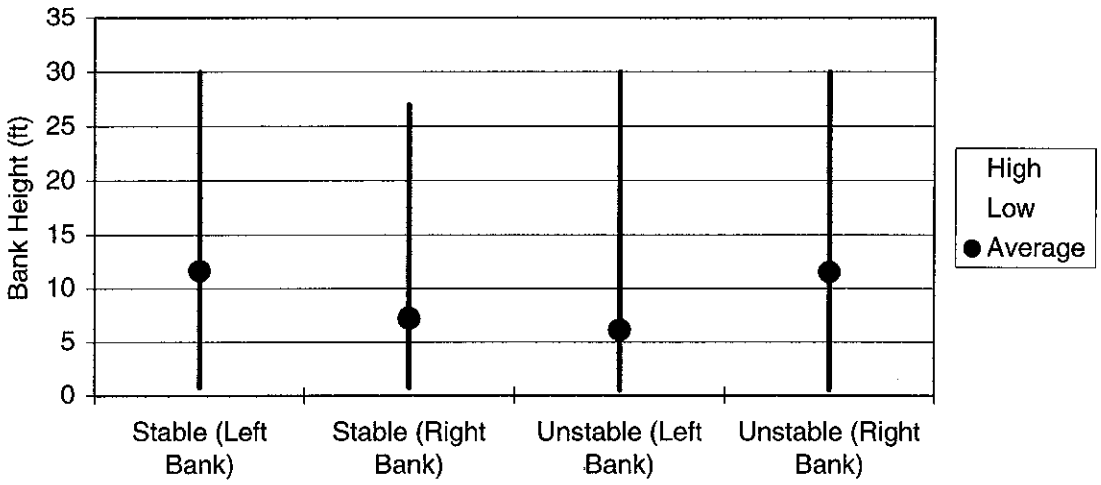


Figure 5-37. Apache Wash Bank Stability

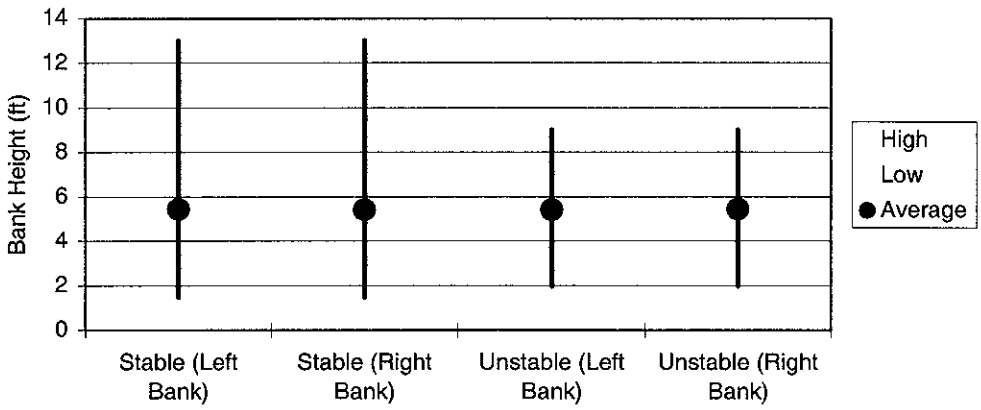


Figure 5-38. Paradise Wash Bank Stability

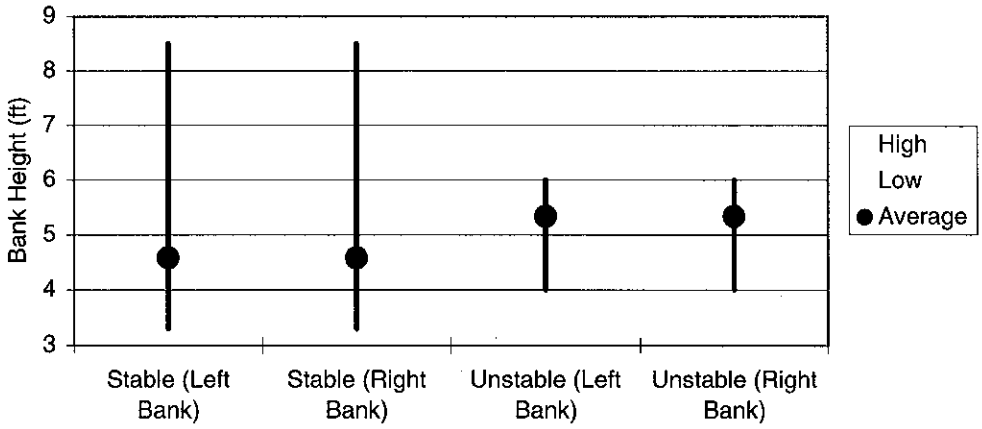
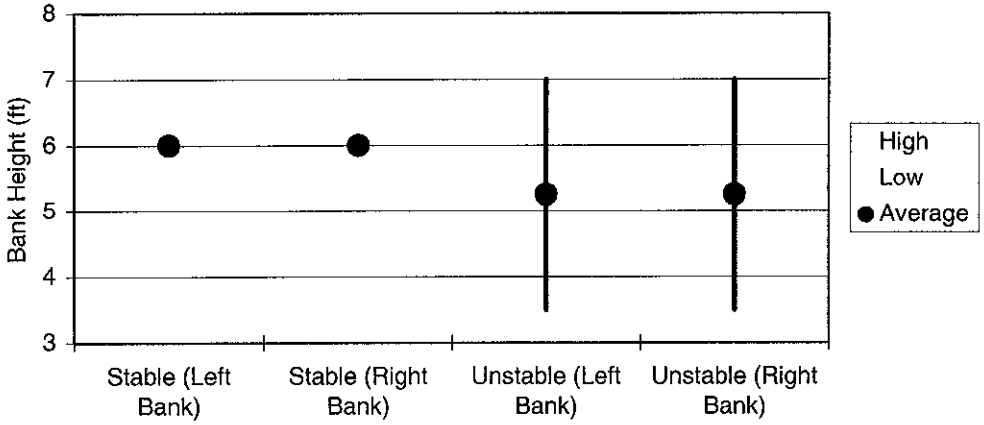


Figure 5-39. Desert Hills Wash Bank Stability



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), 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. HEC-RAS data were developed from modified HEC-2 files prepared for Flood Insurance Studies. Evaluation of plots of reach hydraulic data supported, but did not dictate, the reach divisions used in the study and presented in Chapter 2. The HEC-RAS model was converted to a HEC-6 model to evaluate sediment continuity relationships. The HEC-6 results indicate that erosion will occur during large floods, with lesser or minimal erosion during smaller floods. Sediment deficits computed from HEC-6 were translated into bank erosion distances, and converted to average annual bank erosion amounts. The predicted bank erosion distances are similar for Cave Creek, Apache Wash, and Paradise Wash despite differences in *discharge*, flow duration, and field conditions. Field and historical evidence suggests that Apache Wash and its tributaries have experienced less lateral migration than Cave Creek due to their denser bank vegetation, smaller historical incision, and lack of in-stream sand and gravel mining. The predicted bank erosion distances are lowest for Desert Hills Wash.

Allowable velocity criteria provide general information on the likelihood of bank and channel erosion. The allowable velocity data indicate that all of the banks will erode even in small floods if the banks are not cohesive, but will resist erosion if they are cohesive. Uncertainty in allowable velocity predictions is caused by the effects of soil

cohesion (increases stability), bank vegetation (increases stability), stratified bank sediments (decreases stability), and other local variations ($CaCO_3$ content, piping, bed *scour*, etc.).

Long-term degradation due to channel adjustment to the equilibrium slope is expected for the streams in the study area, except for Desert Hills Wash. The actual magnitude of the expected degradation will be based in part on the potential for *armoring*, sediment supply, and magnitude and frequency of the flows experienced in the future. The channel bed scour depth is probably limited by armoring during frequent flows and small floods. During a large flood, the bed material is too fine to develop a resistant *scour* layer. All of the channel bed material is mobile at some flow rate, 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. 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 significant scour is expected for Cave Creek. Significant, but lower amounts of scour are expected for Apache Wash and Paradise Wash. The predicted amount of scour for Desert Hills Wash is the lowest of the four streams considered. The greatest amount of scour-induced bank erosion in the study area is predicted for Cave Creek. Estimated bank erosion distances should be revised upward where bed scour is significant. The engineering analyses described in the preceding sections indicate that the streams in the study area are subject to net degradation, and will continue to entrench and scour in the future.

Chapter 6
Definition of Erosion Hazard Zones

Introduction

Erosion hazard boundaries for Cave Creek, Apache Wash, Paradise Wash, and Desert Hills 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 conditions 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 ortho-rectified 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 a set of the ortho-rectified aerial photographs of the study reach.

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 60 year period of record was used as a minimum predicted erosion distance. Figure 3-1 shows the *thalweg* position for the 59 years (1940 to 1999) of historical aerial coverage.[1] The maximum measured channel movement distance was plotted on the ortho-rectified aerial photographs. 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. In the lower reach of Cave Creek, which is subject to channel *avulsions*, the maximum channel movement distance during the period of record was about 1,800 feet, equal to the width of the recent geologic floodplain. In the upper reach of Cave Creek, historical channel movement has been less severe, with a maximum channel movement of about 800 feet in the more braided reaches disturbed by human impacts.

Map Element for Historical Channel Movement:

- Former Channel Positions

[1] Length of record equals 104 years if the 1894 GLO survey channel positions are considered.

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. The reaches of greatest historical degradation were coincident with the reaches of historical in-stream mining, but the amount of degradation decreases rapidly in the upstream and downstream direction from the mining sites. This rapid decrease, or limited aerial extent of impact, was interpreted to indicate that an adequate upstream sediment supply exists on Cave Creek. Channel segments that experience recent, historical and pre-historic long-term degradation were identified, estimates for the magnitude of long-term scour were made, and the results were plotted on the ortho-rectified aerial photographs.

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 ortho-rectified photographs of the study area.

Map Element for Archaeological Data:
- No map elements were plotted in compliance with Arizona Antiquities Act that discourages publishing the location of known archaeological sites.

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 (0-1,000 years old) from older, more stable surfaces (1,000 – 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 ortho-rectified photographs of 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 ortho-rectified 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 3 years for the Desert Hills Wash to about 100 years in the degraded reach adjacent to the abandoned sand and gravel mine (Tanner). A variety of equations based on empirical data were applied, and the average widths were plotted on the ortho-rectified aerial photographs to indicate channels sections of expected widening (lateral erosion) or narrowing. 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-year width in the braided multiple channel reach, and the 10-year width for the single channel reaches.

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 ortho-rectified 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 ortho-rectified aerial photographs 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 ortho-rectified aerial photographs 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 ortho-rectified aerial photographs 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 Cave Creek was verified using field data from the study reach, as presented in Chapter 4. The 3:1 intercept line was plotted on the ortho-rectified aerial photographs 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. The computed total[3] 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 ortho-rectified aerial photographs 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. On Cave Creek between the Carefree Highway Bridge and the Tributary #2 confluence, the dominant form of channel erosion is gradual or episodic bank retreat (accretive erosion) by undercutting, tensional failures, and shear stress during periods of flow. Accretive erosion is also the dominant form of lateral movement on Desert Hills Wash Downstream of the Tributary #2 confluence on Cave Creek. In the latter reach, the channel has experienced very rapid shifts in channel position (avulsive channel change) that leaves islands of low terraces between active channel braids. In the reaches subject to *avulsions*, the active floodplain occupies the entire recent geologic floodplain, which is subject to future erosion. Avulsions also occur on portions of Apache

[2] The angle of repose is the maximum angle of slope at which alluvium will remain in place without sliding.

[3] Total sediment deficit, not the cumulative sediment deficit reported in the HEC-6 output.

Wash and Paradise Wash. Accretive erosion also occurs within the avulsive reaches in the study area.

Map Elements for Lateral Erosion Mechanism:

- *Avulsion potential is reflected in the width erosion hazard boundaries*

Impacts of Mining-Induced Entrenchment

In-stream sand and gravel mining has lowered the bed elevations up to 14 feet within mined reaches along Cave Creek. In the two subreaches located between Effluent Wash and the upstream limit of the abandoned Tanner mine, this entrenchment has changed the channel pattern from a braided stream subject to channel *avulsion*s to a *incised* single channel stream subject to erosion by lateral migration. Over the short term, the risk of channel avulsions is low in this reach. If mining were to cease and the channel were to recover its natural channel geometry, the risk of avulsion would probably return to natural levels. For the purposes of long-term land use planning, given the objectives of the watercourse master plan, it was assumed that the natural (pre-mining) avulsion potential would be used as the basis for the erosion hazard boundaries. It is also noted that upstream development on Tributary #2 may decrease *sediment yield* to the reach over the long term, and slow or prevent the recovery of the natural channel processes even if future in-stream mining were stopped.

Measurements

All measurements of expected or predicted erosion were taken from the top of bank. Top of bank was identified on the aerial photo-topographic maps 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 ortho-rectified aerial photographs of 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 adjacent to the main channels of Cave Creek, Apache Wash, Paradise Wash, and Desert Hills Wash. 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 ortho-rectified aerial photographs of the study area as summarized above. The following three erosion hazard zones were defined:

- Severe Erosion Hazard Zone
- High Erosion Hazard Zone
- Moderate 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 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 high erosion hazard zones are not coincident with the 100-year floodway, nor is the moderate 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.

Table 6-1. Upper Cave Creek/Apache Wash Watercourse Master Plan
Some Variables Affecting River Behavior and River Characteristics That Can Change With Time

Variable	Variable Subgroup	River Characteristics
Hydrology	Dominant Discharge Mean Annual Discharge Flow Duration Statistics Variation with Season Diversions and Storage Flow Source	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 *Armor*ing Bedrock Outcrop & Control Human Modifications Bank Protection Grade Control Roadway Crossings Utility Crossings
Flow	Width Depth Hydraulic Radius Friction Factor Velocity Topwidth Turbulence Temperature Transmission Losses	
Flood Characteristics	Magnitude (peak) Duration (flashy?) Ratio of Peak to Base Flow Ratio of Rare to Frequent Floods Channel Capacity Losses Reservoirs/Flood Storage	
Streambed and Bank Sediment	Mean Diameter Size Distribution *Armor*ing Potential Cohesion *Stratigraphy*	
Climate	Precipitation Type (snow?) Precipitation Intensity Precipitation Duration Seasonal Distribution Temperature/Evaporation	
Time Scale	Engineering (short-term) Geologic (long-term)	
Channel Vegetation	Vegetation Type Root Depth Root Density Branch/Foliage Density Trunk Pliability Growth Rate Germination Cycle Grazing Practices	
Watershed Characteristics	Vegetation Cover Slope Drainage Area Elevation Geology Valley Slope *Sediment yield* Human Impacts – Urbanization Grazing Practices	

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 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 Cave Creek and its tributaries.

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 Upper Cave Creek/Apache Wash Watercourse Master Plan study area developed using the criteria outlined above are shown in Exhibit 3. 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 Cave Creek and its main tributaries in the study area drain. 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 Cave Creek and its tributaries have experienced net degradation over the past 700,000 years as the area transformed from an *alluvial fan* to an entrenched river system. Entrenchment during recent geologic time has created a series of older, stable terraces that confines existing and future channel movement within a relatively well-defined corridor. Stream classification data indicate that the streams in the study area are subject to frequent bank erosion and rapid lateral channel movement, except where they are stabilized by bank vegetation, carbonate-cemented soil units, or bedrock. Hydrologic data for the study area indicates that there has been extreme variability in annual and seasonal flow volume, peaks, and duration, but the largest peaks and volumes have occurred during the winter.

In Chapter 3, historical information was summarized to illustrate the types of channel changes that have occurred in the study area in the past. Archaeological data collected along Cave Creek imply that channel erosion has affected the Cave Creek stream corridor for more than 1,000 years. During the period of Hohokam occupation, Cave Creek changed from an *intermittent* channel with frequent shallow overbank flooding to an *incised* braided stream that rarely inundated its floodplain. The archaeological data indicate that erosion is not simply the result of modern human impacts on the channel and watershed. Natural cycles of stream degradation and lateral migration must be accounted for in the watercourse management plan.

GLO survey data, channel position data digitized from aerial photographs, and comparison of modern and historical topographic data were used to document channel change over the past 100 years. GLO data document apparent channel *avulsions* on Cave Creek and Apache Wash in which the channel moved up to 1,278 feet across the floodplain. The magnitude of accretive erosion on Cave Creek and Apache Wash was significantly less, with lateral moves ranging from 4 to 82 feet between 1894 and 1981. Comparison of historical maps and aerial photographs indicate that Cave Creek has been subject to both accretive and avulsive lateral movement. Gradual accretive erosion averaged less than one foot per year in the study area, but avulsions caused shifts of more than 1,000 feet. Paradise Wash and Desert Hills Wash were more stable than Cave Creek or Apache Wash during the period of record. Comparison of digitized channel positions before and after the 1993 flood, indicated avulsions can occur during a flood with a 25-

year recurrence interval. Accretive erosion during the 1993 was minimal in most of the study area, although field evidence suggests that local bank failures occurred throughout the entire study area.

Comparison of channel elevations obtained from topographic mapping and aerial photographs indicates that Cave Creek exhibited a trend toward net degradation from 1960 to 1999. Total degradation of up to 10 feet occurred between 1962 and 1996 in portions of the study area, primarily in areas of in-stream sand and gravel mining. Degradation occurred at a much faster rate during the 18 year span from 1962 to 1979 than during the 17 year span from 1980 to 1996. Mixed trends of degradation and aggradation occurred along Apache Wash, with an estimated maximum annual degradation rate of about 0.3 feet/year. Topographic data show that Paradise Wash generally experienced slight aggradation or no significant change between 1962 and 1990, with a maximum aggradation rate of 0.1 feet/year. Desert Hills Wash has experienced degradation at an average rate of about 0.2 feet/year within the study limits. The average channel width of Cave Creek in the study area increased from 1894 to 1996, with a slight decrease in average width from 1984 to 1996. The average channel widths in Apache Wash, Paradise Wash and Desert Hills Wash have been very stable for the past 60 years. Plots of historical channel position indicate that the overall channel pattern and sinuosity has not changed significantly within the period of record.

In Chapter 4, geomorphic analysis techniques based on field observations, interpretation of the surficial geology, and application of empirical and theoretical data were used to evaluate the lateral stability. Field observations made along Cave Creek indicate that study reach is subject to lateral erosion and channel avulsions, has experienced historical degradation, and has been extensively impacted by human activities. Field observations made along Apache Wash, Paradise Wash, and Desert Hills Wash indicate that the study reaches are more laterally stable than Cave Creek and have not experienced significant long-term degradation or human impacts. Field data suggest that the frequency of channel avulsions on Cave Creek (Reaches 3, 4, and 5) is greater than on Apache Wash or Paradise Wash. The stability predictions associated with the modified Brice and Rosgen classification schemes indicated that the streams in the study area are susceptible to rapid lateral migration and bank erosion.

The ages and relative heights of the geomorphic surfaces in the study area indicates that portions of Cave Creek, Apache Wash and Paradise Wash have been subject to channel avulsions and net degradation for at least the past 10,000 years. The long-term rate of accretive channel change has been slow (< 1feet/year laterally, <0.01 feet/year vertically). Modern rates of incision (1960-1999) estimated from topographic mapping and aerial photographic interpretation were somewhat faster, but within the range of long-term geologic rates of incision.

The magnitude and recurrence interval of the *bankfull discharge* varies widely for the streams in the study area, with little continuity in the values between adjacent cross sections. The highest estimates of bankfull discharge occurred in the sections of channel that were mined for sand and gravel. The poor continuity in bankfull discharge

magnitude and frequency between 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. This slow response is expected in streams whose geometry is formed primarily by large, infrequent floods. The difference in bankfull recurrence interval are due to historical incision and disturbance by sand and gravel mining. The high recurrence interval of bankfull discharge for the streams in the study area indicates that stream stability is influenced more by the large floods, rather than the small annual floods. Therefore, the stability analyses should focus on the affects of the largest floods.

Channel pattern equations predict a straight braided channel pattern for Cave Creek, with less strongly expressed braiding expected on Apache Wash and Paradise Wash in the future. Desert Hills Wash is likely to maintain its existing slightly *sinuous* to weakly meandering channel pattern in the future. The channel geometry analysis indicates that the streams in the study are more erosive than similar streams in other areas of the semi-arid west. The slopes are steeper, the channel velocities higher, and the depths greater. Cave Creek will tend to erode its banks during floods that exceed the 10-year event, but will experience only localized bank erosion during the 2-year flood. Likewise, Apache Wash and Paradise Wash will experience only local bank erosion during 2-year floods, but will tend to widen during the largest floods. The existing and predicted width for Apache Wash differ by a factor of two to three for the 100-year event, indicating a strong tendency for lateral erosion during extreme floods. Desert Hills Wash has a tendency to widen and erode its banks during any flood, according to the hydraulic geometry equations. The channel geometry analysis indicates that almost all of the stream reaches in the study area are oversteepened and *incised*, and experience erosive velocities during most flows.

The hydraulic geometry regression equation results indicate that the study reaches are more incised than the average *ephemeral* wash, with the exception of Reach 3 of Apache Wash. The slower increase in width as *discharge* increased implies that the channels have well-consolidated banks, which constrain lateral erosion while concentrating erosive work on the bed of the channel. Desert Hills Wash may be the most efficient stream in the area at transporting sediment through and out of the system, leading to more consistent erosion and degradation along its course than along the other three streams in the study area.

In Chapter 5, engineering methodologies were applied to the stream reaches in the study area to estimate the potential and magnitude of future bank erosion. HEC-6 results indicate that erosion will occur during large floods, with lesser or minimal erosion during smaller floods. Sediment deficits computed from HEC-6 were translated into bank erosion distances, and converted to average annual bank erosion amounts using a probability weighting procedure. The predicted bank erosion distances are similar for Cave Creek, Apache Wash, and Paradise Wash despite differences in discharge, flow duration, and field conditions. Field and historical evidence suggests that Apache Wash and its tributaries have experienced less lateral migration than Cave Creek due to their

denser bank vegetation, smaller historical incision, and lack of in-stream sand and gravel mining. The predicted bank erosion distances are lowest for Desert Hills Wash.

Allowable velocity criteria provide general information on the likelihood of bank and channel erosion. The allowable velocity data indicate that all of the banks will erode even in small floods if the banks are not cohesive, but will resist erosion if they are cohesive. Long-term degradation due to channel adjustment to the equilibrium slope is expected for the streams in the study area, except for Desert Hills Wash. The actual magnitude of the expected degradation will be based in part on the potential for *armor*ing, sediment supply, and magnitude and frequency of the flows experienced in the future. The channel bed scour depth is probably limited by armoring during frequent flows and small floods, but not during high flow rates during large flood events. All of the channel bed material is mobile at some flow rate, and will be transported during moderate to large flood events. Cobble and boulder transport should be considered in the sediment routing analysis. General and long-term scour estimates for the streams in the study area indicate that significant scour is expected for Cave Creek. Significant, but lower amounts of scour are expected for Apache Wash, Paradise Wash. The predicted amount of scour for Desert Hills Wash is the lowest of the four streams considered. The greatest amount of scour-induced bank erosion in the study area is predicted for Cave Creek.

In Chapter 6, erosion hazard zone boundaries for Cave Creek, Apache Wash, Paradise Wash, and Desert Hills Wash were defined and identified based on the results of the geomorphic, historical and engineering analyses of lateral stability. The historical, geomorphic, and engineering analysis indicate that Cave Creek and its tributaries are subject to significant lateral erosion hazards that could endanger development near the stream corridors.

Recommended Management Practices

> *"It appears that a 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 north Phoenix corridor has experienced high growth rates during the past 5 years. At the same time, bank erosion and channel movement have created problems for new development near major stream systems elsewhere in the Phoenix metropolitan area. The analyses summarized in the previous chapters have shown that bank erosion is not a new phenomenon in the Upper Cave Creek/Apache Wash Watercourse Master Plan study area. The recommended management alternatives are intended to promote safe development of river corridors in the future.

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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)

General Recommendations

The following general recommendations are intended for management of all four stream corridors within the study area:

1. Adopt the recommended erosion hazard zones 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:

   - 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 proposed bank stabilization, if any, will not deleteriously affect reaches or development upstream and downstream.
   - Demonstrate the stability of proposed bank stabilization, if any. 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 the bank stabilization, if any, 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. The permit requirements should include the following:

   - Developers must include a note on the plat indicating that the homes or structures are built within an area subject to potential erosion.
   - Demonstrate that proposed bank stabilization, if any, will not deleteriously affect reaches or development upstream and downstream.
   - Demonstrate the stability of proposed bank stabilization, if any. 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 the bank stabilization, if any, 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 for 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 recommendation should be followed:

   - 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.
   - On-line excavations should be avoided.

7. Future Monitoring. Channel stability should be monitored periodically to assess impacts of floods, 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 Apache Wash, Paradise Wash, and Desert Hills Wash at the Carefree Highway.

- Initiate monitoring stations at the field sections established for this study. Cross section 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
Bibliography

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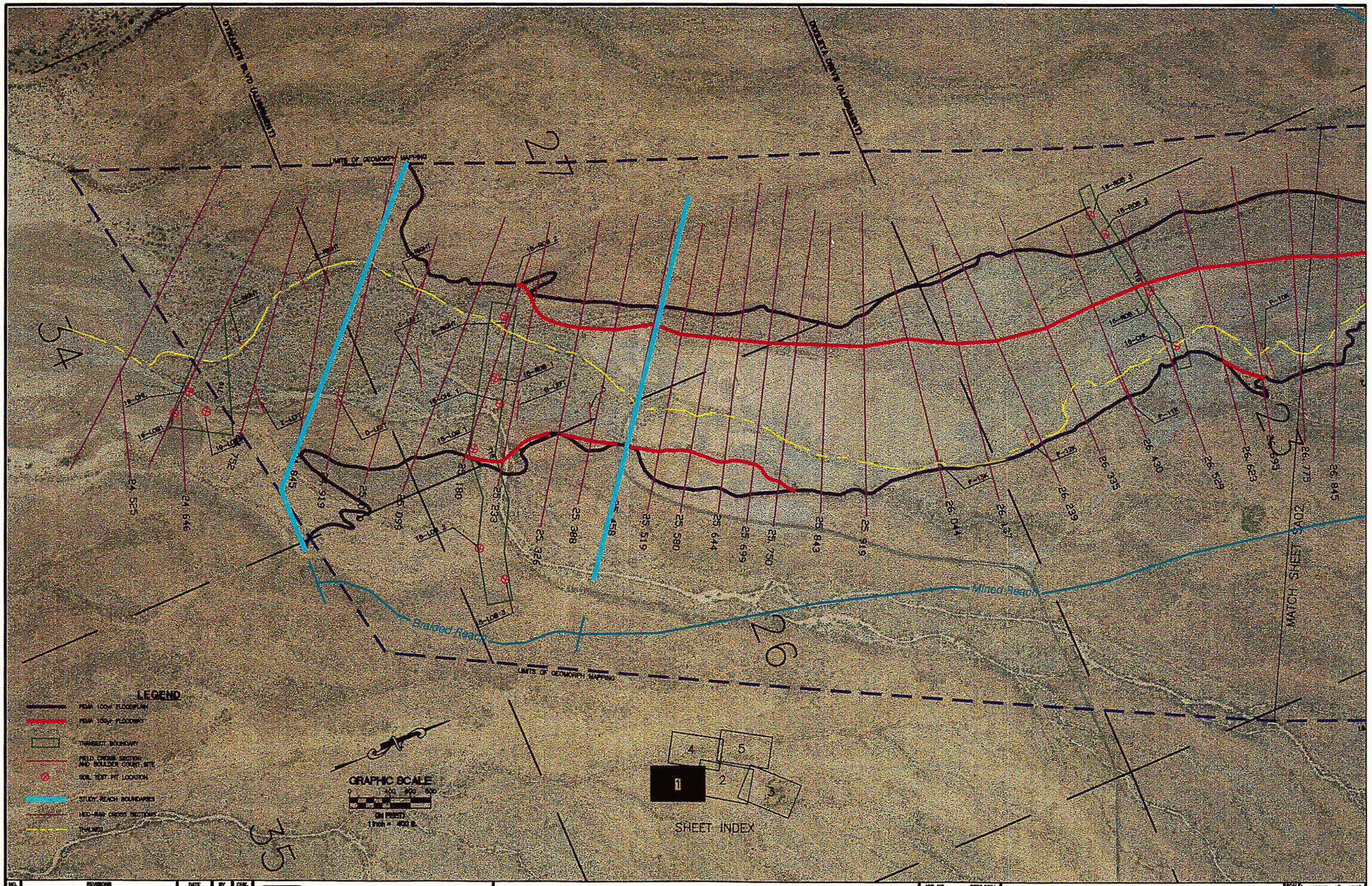
Chapter 9
Glossary

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.
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.
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.

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 – Excessive erosion of a streambed or a bank.
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.



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UPPER CAVE CREEK AND APACHE WASH WATERCOURSE MASTER PLAN
FCD 97-45

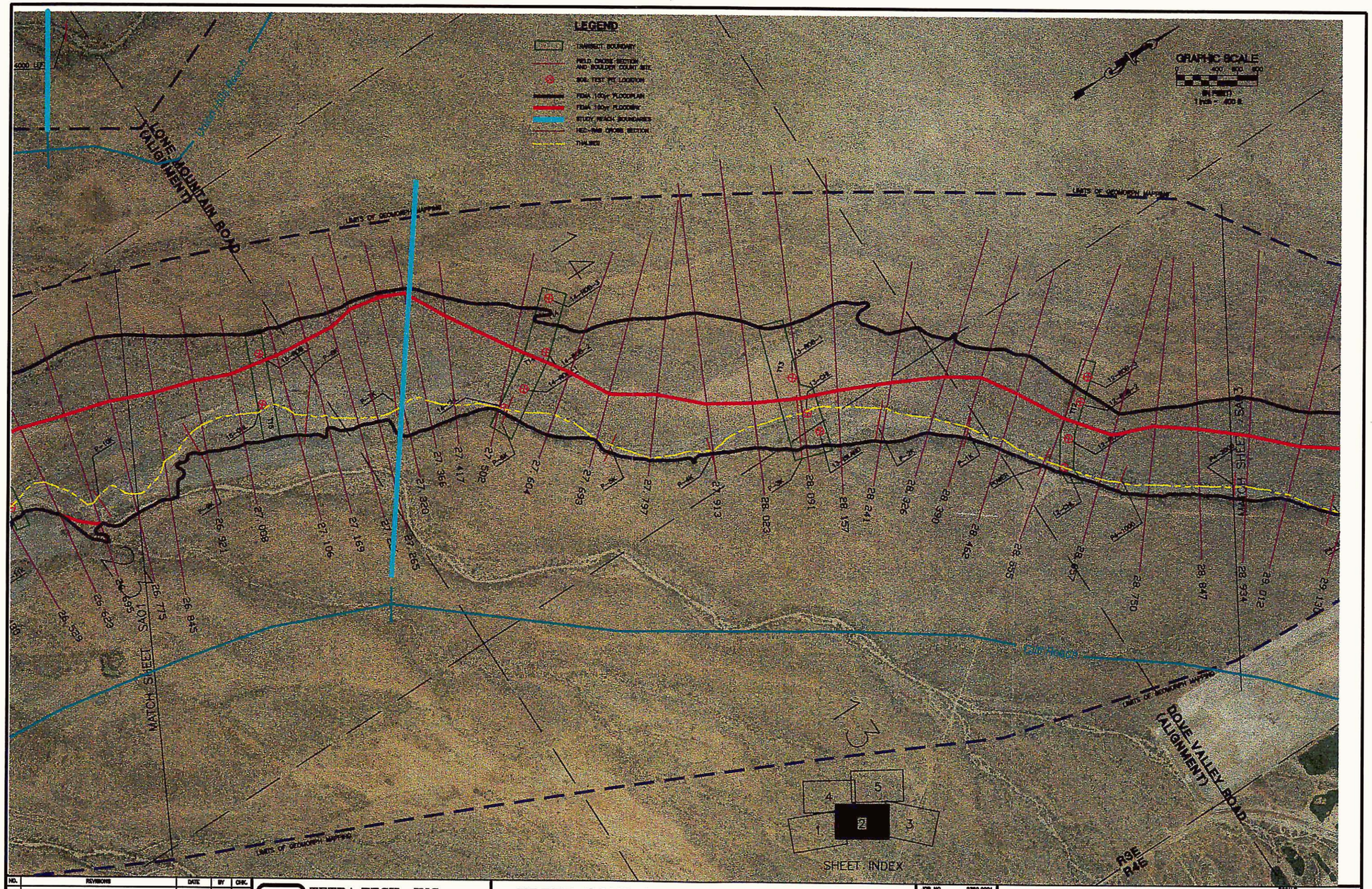
JOB NO.	2350.0001
DESIGNED BY:	JAD
DRAWN BY:	CBO
CHECKED BY:	JAD
APPROVED BY:	TRL
DATE:	12/27/00

EXHIBIT 1
MAP OF STUDY AREA

SCALE: HORIZ: 1" = 400'

DRAWING NO. SA01

SHEET NO. 1 OF 5



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UPPER CAVE CREEK AND APACHE WASH WATERCOURSE MASTER PLAN FCD 97-45

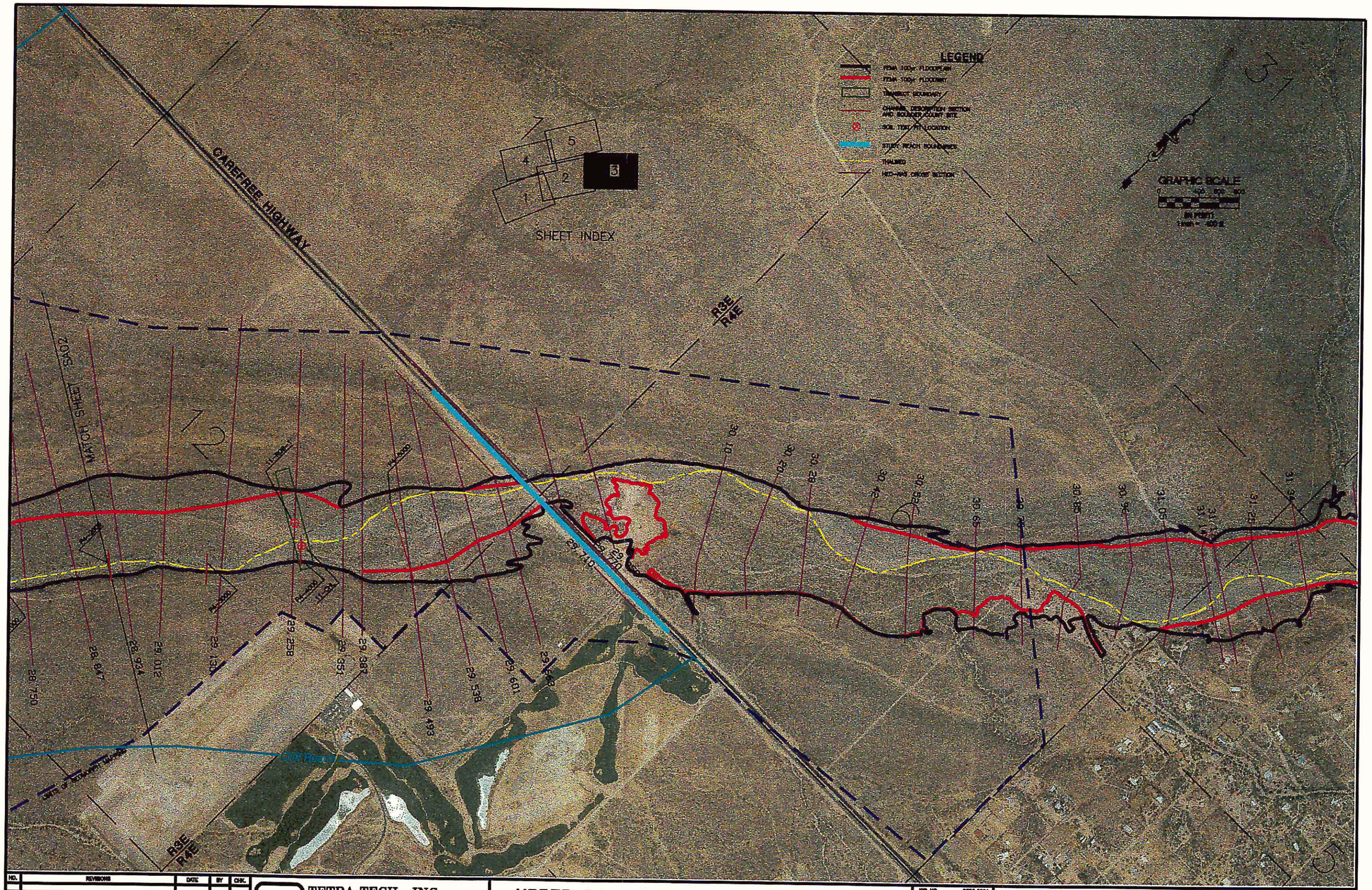
JOB NO.	2360.0001
DESIGNED BY	JAD
DRAWN BY	CBD
CHECKED BY	JAD
APPROVED BY	TRL
DATE	12/27/00

EXHIBIT 1
MAP OF STUDY AREA

SCALE: HORIZ: 1" = 400'

DRAWING NO. SA02

SHEET NO. 2 OF 5



NO.	REVISIONS	DATE	BY	CHK.

2300SA03.DWG

TETRA TECH, INC.
INFRASTRUCTURE SOUTHWEST GROUP
501 North 44th Street, Suite 125, Phoenix, AZ 85008
(602) 629-1100 FAX (602) 629-1166

UPPER CAVE CREEK AND APACHE WASH WATERCOURSE MASTER PLAN
FCD 97-45

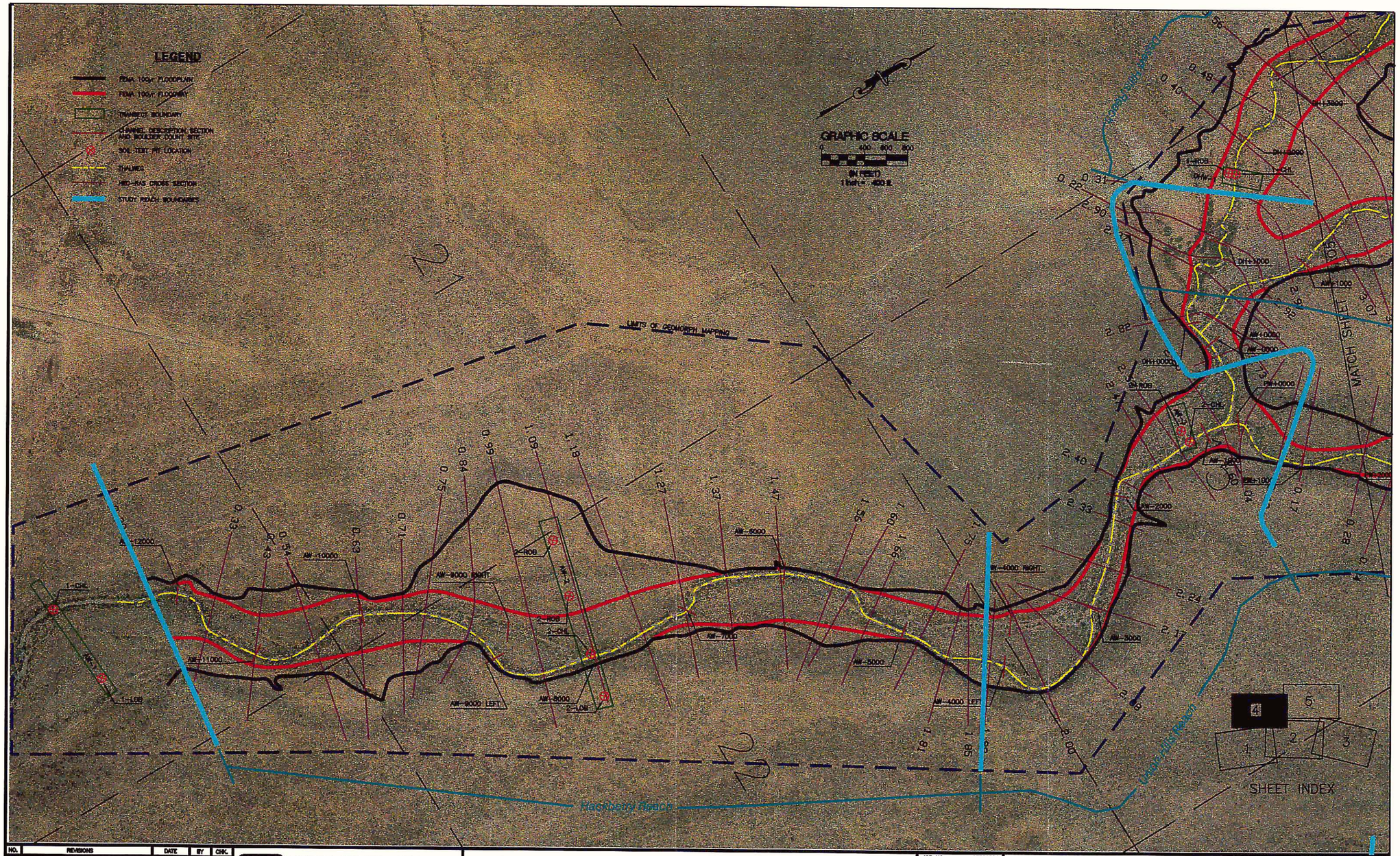
JOB NO.	2300.0001
DESIGNED BY:	JRD
DRAWN BY:	CBC
CHECKED BY:	JRD
APPROVED BY:	TRL
DATE:	12/27/00

EXHIBIT 1
MAP OF STUDY AREA

SCALE: HORIZ: 1"= 400'

DRAWING NO. SA03

SHEET NO. 3 OF 5



NO.	REVISIONS	DATE	BY	CHK.

23502SA04.DWG

TETRA TECH, INC.
INFRASTRUCTURE SOUTHWEST GROUP
501 North 44th Street, Suite 125, Phoenix, AZ 85008
(602) 629-1100 FAX (602) 629-1188

UPPER CAVE CREEK AND APACHE WASH WATERCOURSE MASTER PLAN
FCD 97-45

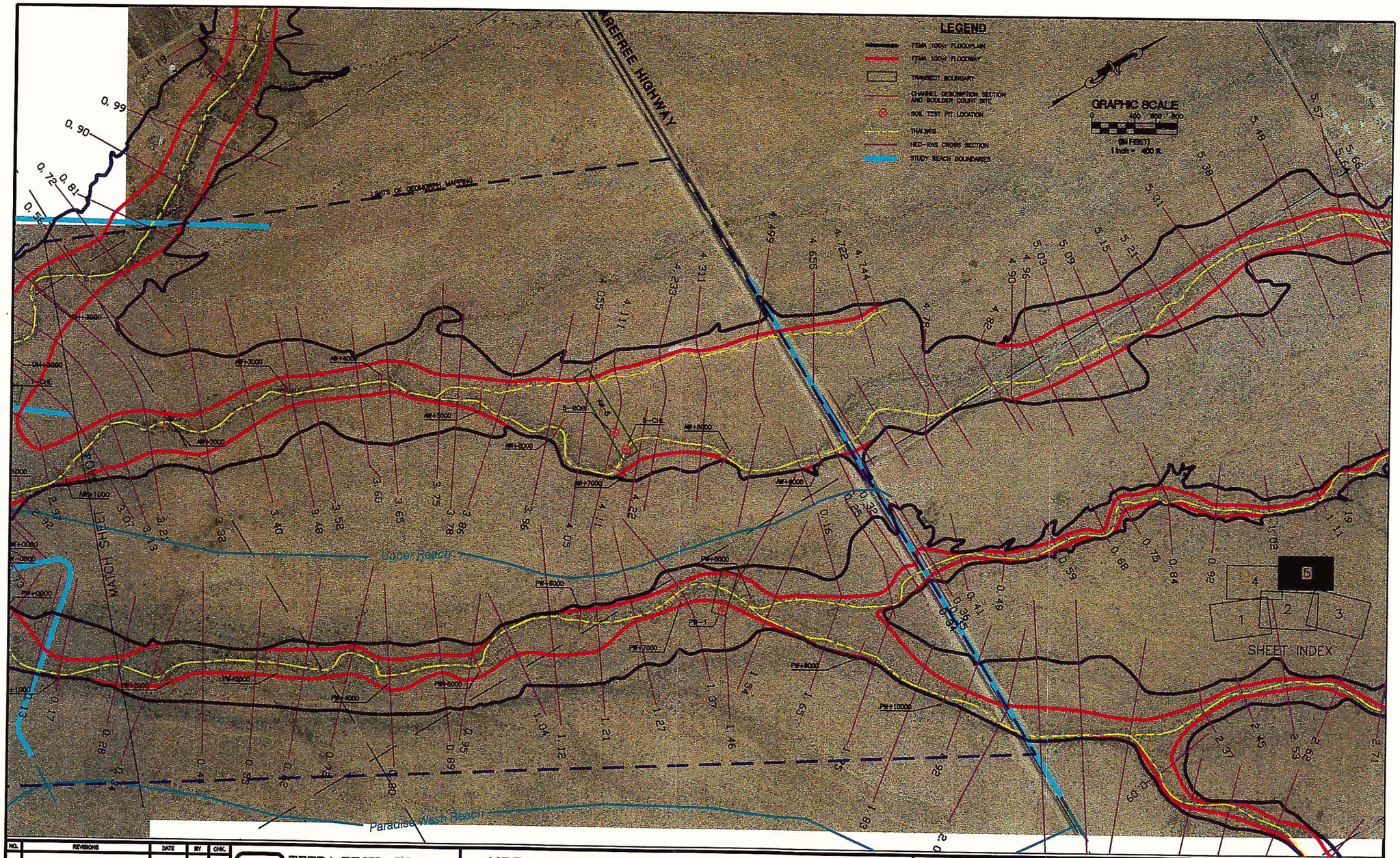
JOB NO.	23500001
DESIGNED BY:	TRL
DRAWN BY:	CBO
CHECKED BY:	JAD
APPROVED BY:	TRL
DATE:	12/27/00

EXHIBIT 1
MAP OF STUDY AREA

SCALE: HORIZ: 1"= 400'

DRAWING NO. SA04

SHEET NO. 4 OF 5



NO.	REVISIONS	DATE	BY	CHK.

2360SA05.DWG

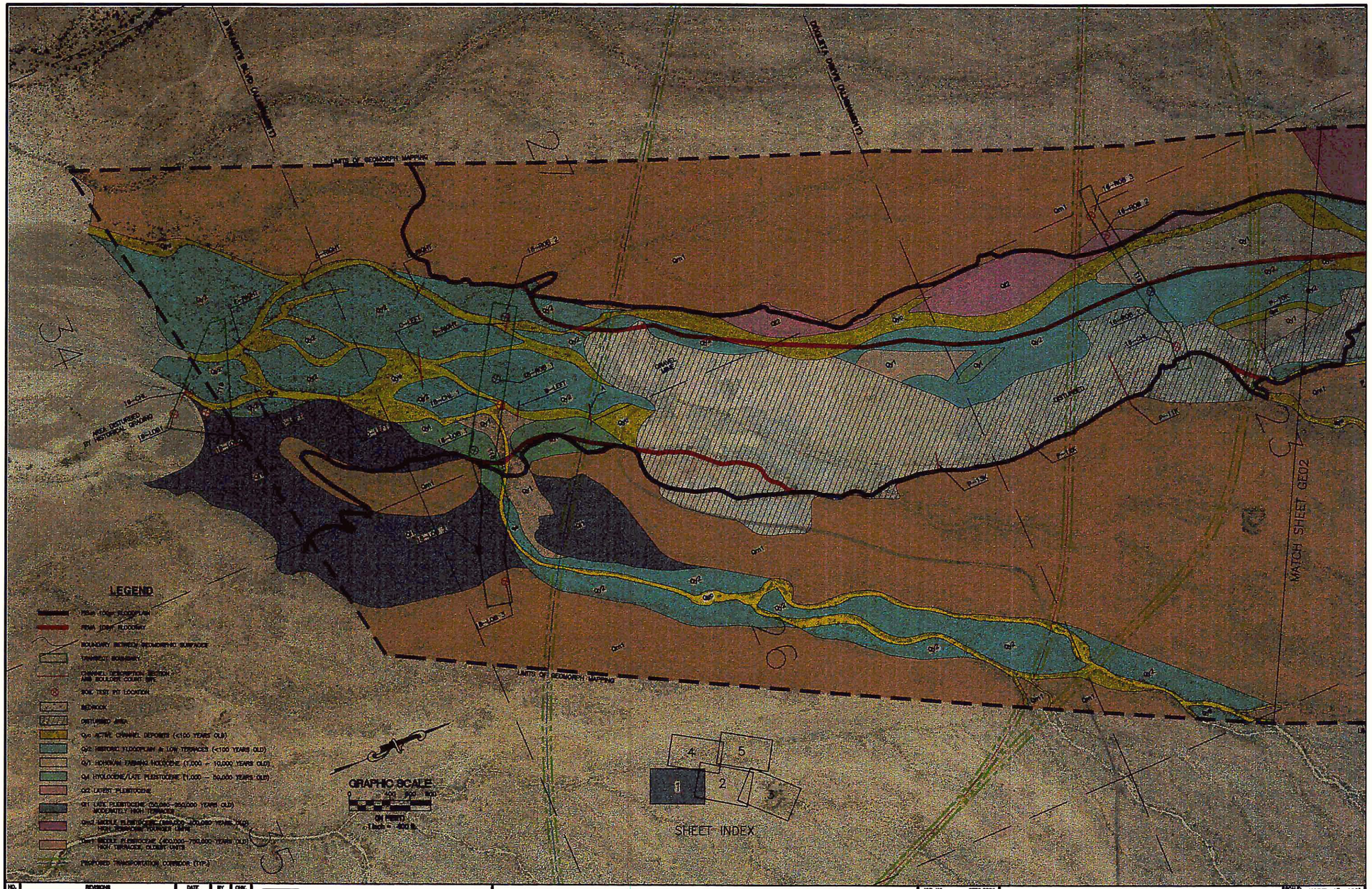
TETRA TECH, INC.
INFRASTRUCTURE SOUTHWEST GROUP
501 North 44th Street, Suite 125, Phoenix, AZ 85008
(602) 629-1100 FAX (602) 629-1188

UPPER CAVE CREEK AND APACHE WASH WATERCOURSE MASTER PLAN
FCD 97-45

JOB NO.	23600001
DESIGNED BY:	JAD
DRAWN BY:	CBC
CHECKED BY:	JAD
APPROVED BY:	TRL
DATE:	12/27/00

EXHIBIT 1
MAP OF STUDY AREA

SCALE: HORIZ: 1"= 400'
DRAWING NO. SA05
SHEET NO. 5 OF: 5



NO.	REVISIONS	DATE	BY	CHK.

2350GE01.DWG

TETRA TECH, INC.
INFRASTRUCTURE SOUTHWEST GROUP
501 North 44th Street, Suite 125, Phoenix, AZ 85008
(602) 629-1100 FAX (602) 629-1188

UPPER CAVE CREEK AND APACHE WASH WATERCOURSE MASTER PLAN
FCD 97-45

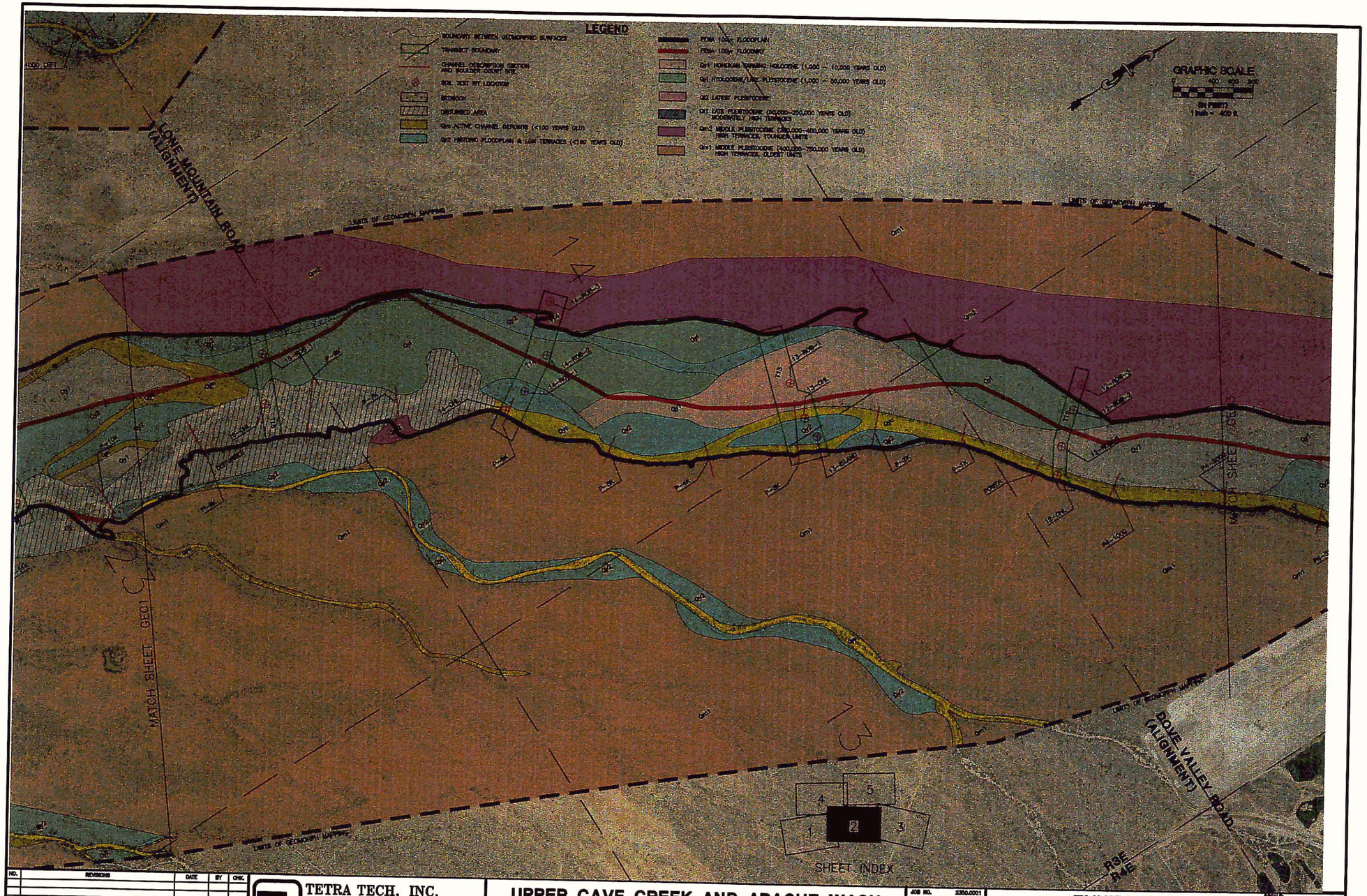
JOB NO.	2350.0001
DESIGNED BY:	JAD
DRAWN BY:	CBC
CHECKED BY:	JAD
APPROVED BY:	TRL
DATE:	12/27/00

EXHIBIT 2
MAP OF
GEOMORPHIC SURFACES

SCALE: HORIZ: 1"= 400'

DRAWING NO. GE01

SHEET NO. 1 OF 5



NO.	REVISIONS	DATE	BY	CHK.

2350GE02.DWG

TETRA TECH, INC.
INFRASTRUCTURE SOUTHWEST GROUP
501 North 44th Street, Suite 125, Phoenix, AZ 85008
(602) 629-1100 FAX (602) 629-1188

UPPER CAVE CREEK AND APACHE WASH WATERCOURSE MASTER PLAN
FCD 97-45

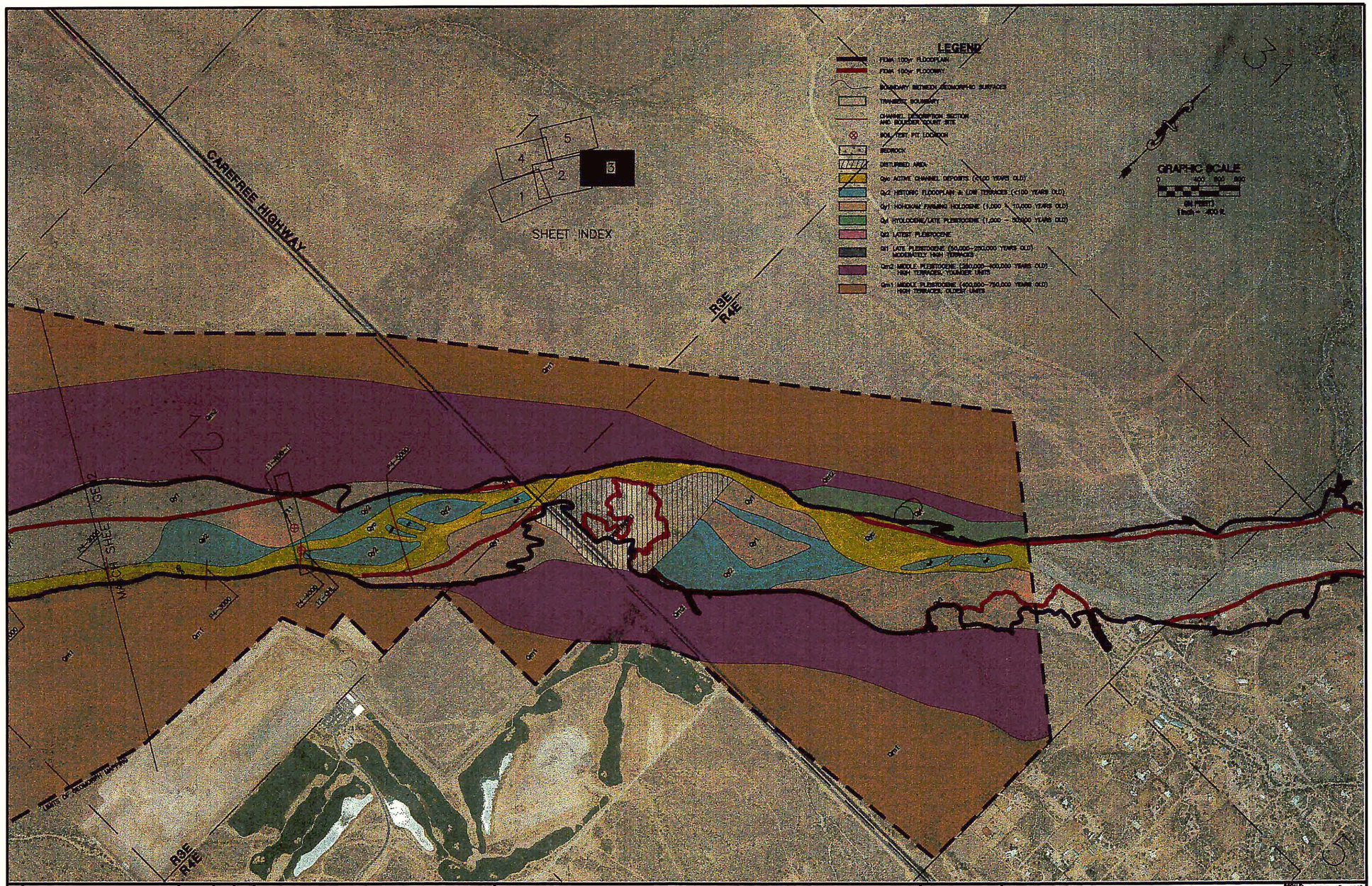
JOB NO.	2350.0001
DESIGNED BY:	JAD
DRAWN BY:	CBC
CHECKED BY:	JAD
APPROVED BY:	TRL
DATE:	12/27/00

EXHIBIT 2
MAP OF GEOMORPHIC SURFACES

SCALE HORIZ: 1"= 400'

DRAWING NO. GE02

SHEET NO. 2 OF 5



NO.	REVISIONS	DATE	BY	CHK.

2300GE03.DWG

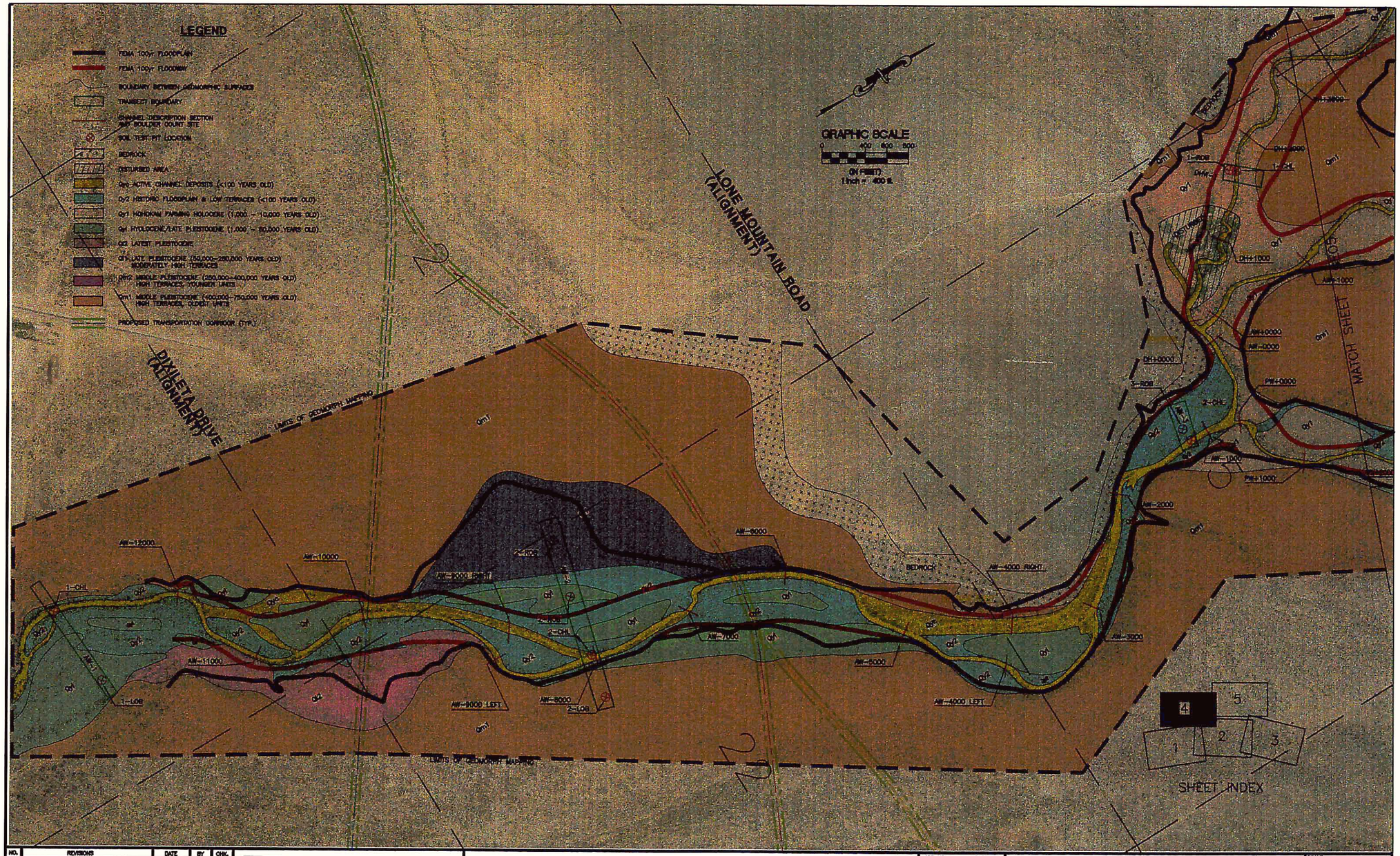
TETRA TECH, INC.
INFRASTRUCTURE SOUTHWEST GROUP
501 North 44th Street, Suite 125, Phoenix, AZ 85008
(602) 629-1100 FAX (602) 629-1188

UPPER CAVE CREEK AND APACHE WASH WATERCOURSE MASTER PLAN
FCD 97-45

JOB NO.	2300.0001
DESIGNED BY:	JKD
DRAWN BY:	CEG
CHECKED BY:	JKD
APPROVED BY:	TRL
DATE:	12/27/00

EXHIBIT 2
MAP OF GEOMORPHIC SURFACES

SCALE: HORIZ: 1" = 400'
DRAWING NO. GE03
SHEET NO. 3 OF 5



NO.	REVISIONS	DATE	BY	CHK.

23500ED4.DWG

TETRA TECH, INC.
INFRASTRUCTURE SOUTHWEST GROUP
501 North 44th Street, Suite 125, Phoenix, AZ 85008
(602) 629-1100 FAX (602) 629-1166

UPPER CAVE CREEK AND APACHE WASH WATERCOURSE MASTER PLAN FCD 97-45

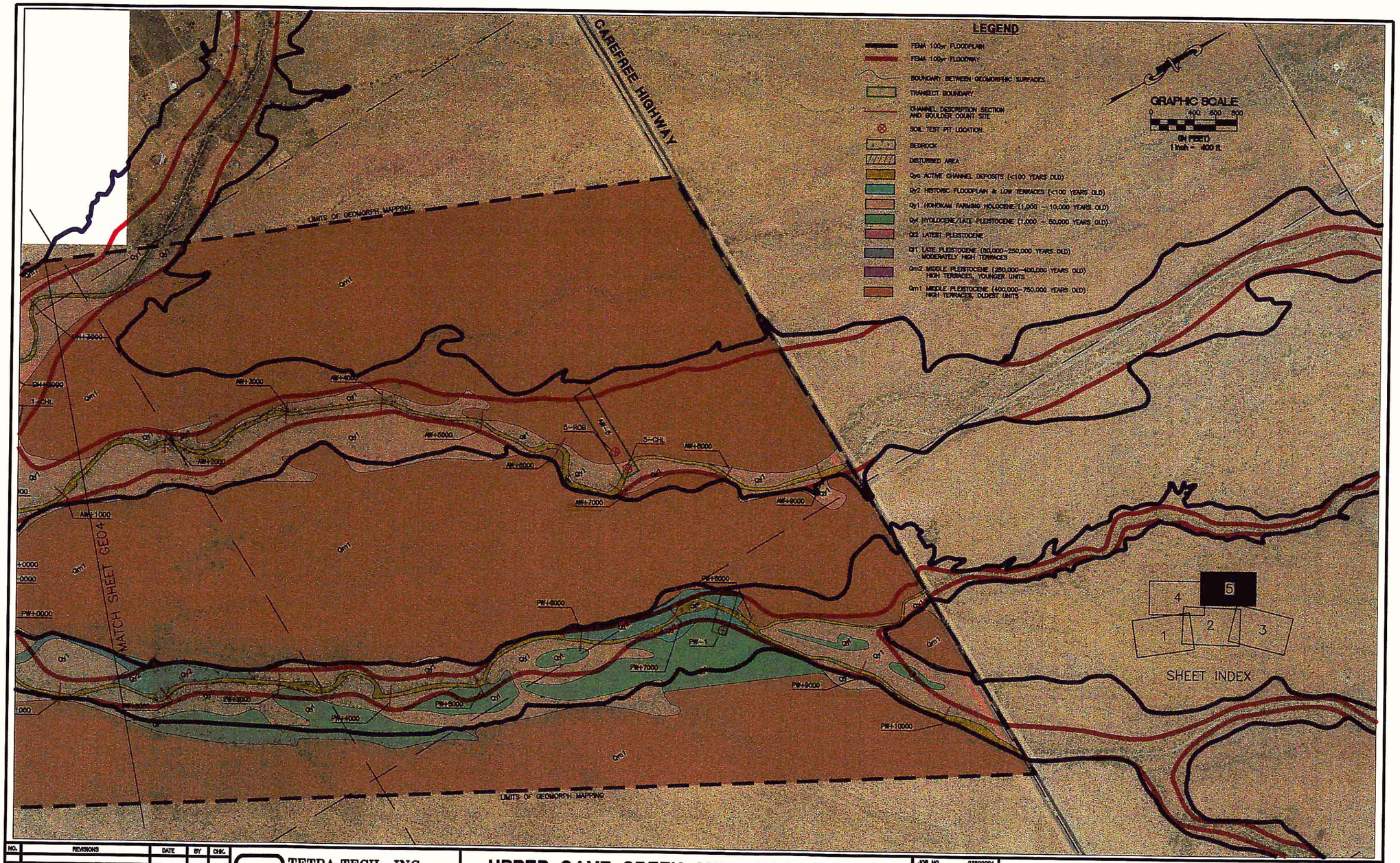
JOB NO.	23500001
DESIGNED BY:	TRL
DRAWN BY:	CBC
CHECKED BY:	JAD
APPROVED BY:	TRL
DATE:	12/27/00

EXHIBIT 2
MAP OF GEOMORPHIC SURFACES

SCALE: HORIZ: 1"= 400'

DRAWING NO. GE04

SHEET NO. 4 OF 5



NO.	REVISIONS	DATE	BY	CHK.

23500GE05.DWG

TETRA TECH, INC.
INFRASTRUCTURE SOUTHWEST GROUP
501 North 44th Street, Suite 125, Phoenix, AZ 85008
(602) 629-1100 FAX (602) 629-1186

UPPER CAVE CREEK AND APACHE WASH WATERCOURSE MASTER PLAN
FCD 97-45

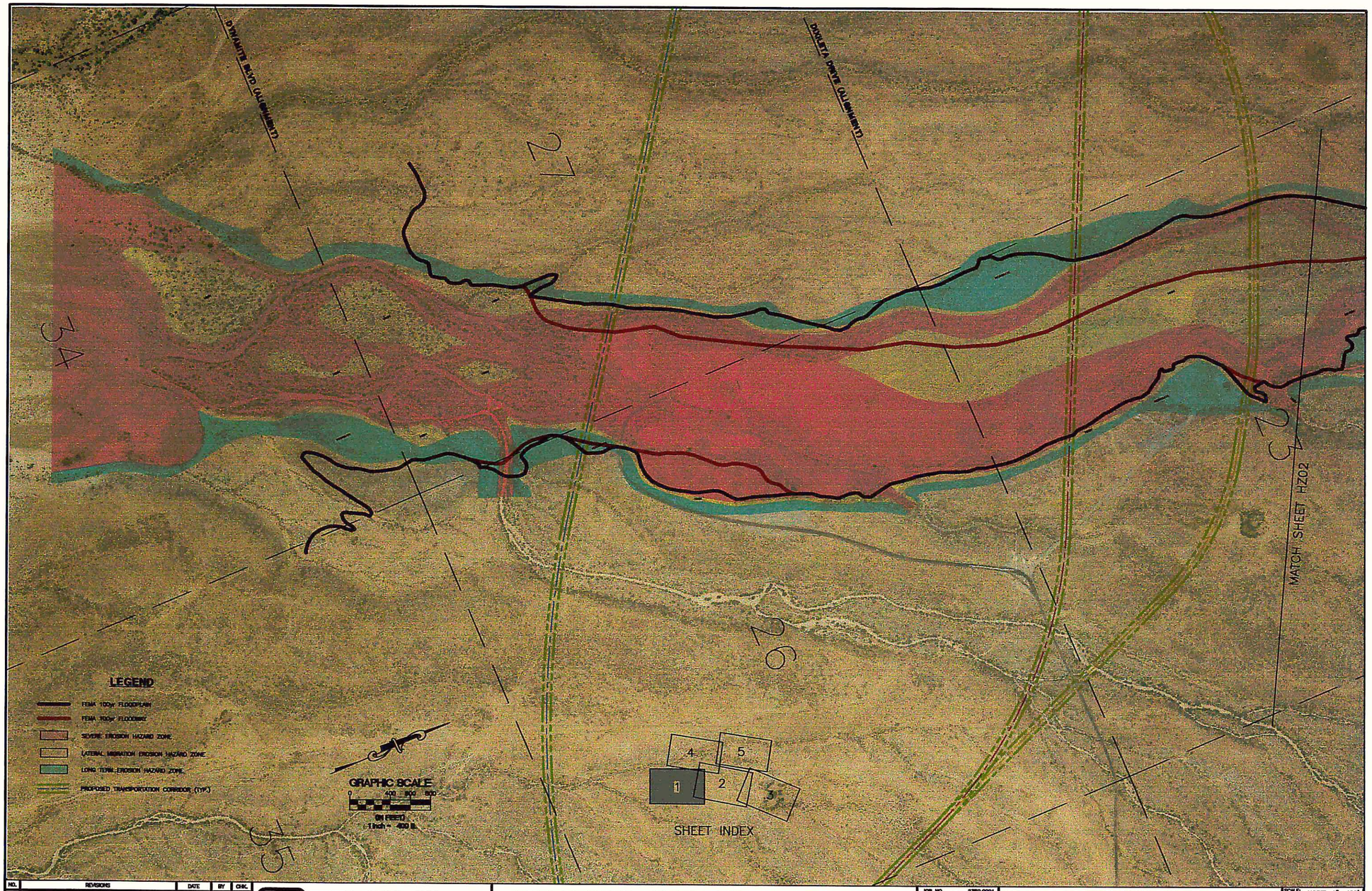
JOB NO.	23500001
DESIGNED BY:	JAD
DRAWN BY:	CBC
CHECKED BY:	JAD
APPROVED BY:	TRL
DATE:	12/27/00

EXHIBIT 2
MAP OF GEOMORPHIC SURFACES

SCALE: HORIZ: 1"= 400'

DRAWING NO. GE05

SHEET NO. 5 OF 5



NO.	REVISIONS	DATE	BY	CHK.

2350GED1.DWG

TETRA TECH, INC.
INFRASTRUCTURE SOUTHWEST GROUP
501 North 44th Street, Suite 125, Phoenix, AZ 85008
(602) 629-1100 FAX (602) 629-1186

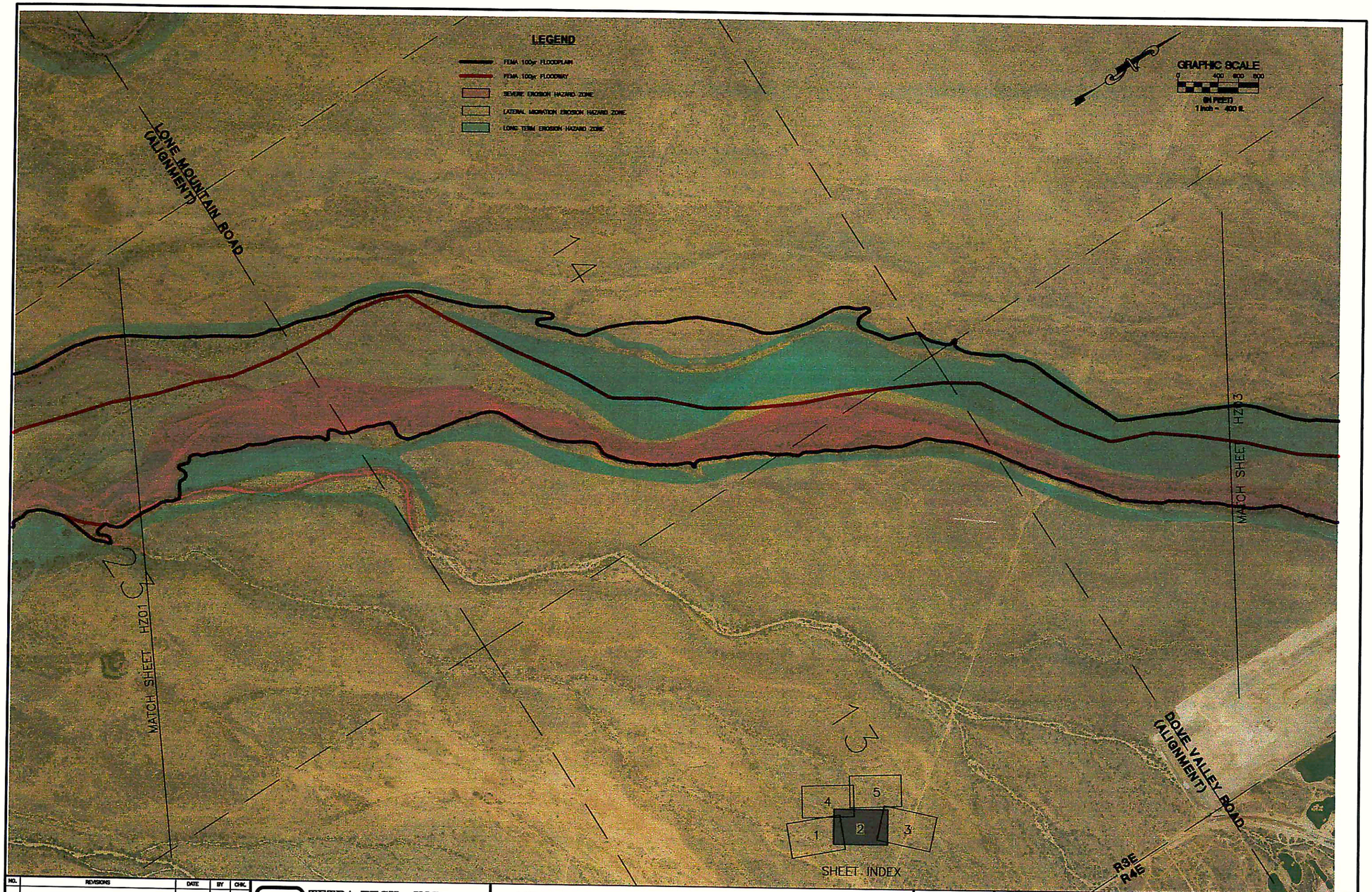
UPPER CAVE CREEK AND APACHE WASH WATERCOURSE MASTER PLAN
FCD 97-45

JOB NO.	2350.0001
DESIGNED BY:	JAD
DRAWN BY:	CBC
CHECKED BY:	JAD
APPROVED BY:	TRL
DATE:	12/27/00

EXHIBIT 3
EROSION HAZARD BOUNDARY MAP

SCALE: HORIZ: 1" = 400'
DRAWING NO. HZ01
SHEET NO. 1 OF: 5

E:\23500001\HECRAS\2350hz01.dwg Wed Apr 04 14:00:48 2001 By CBC



NO.	REVISIONS	DATE	BY	CHK.

2350HZ02.DWG

TETRA TECH, INC.
INFRASTRUCTURE SOUTHWEST GROUP
501 North 44th Street, Suite 125, Phoenix, AZ 85008
(602) 629-1100 FAX (602) 629-1186

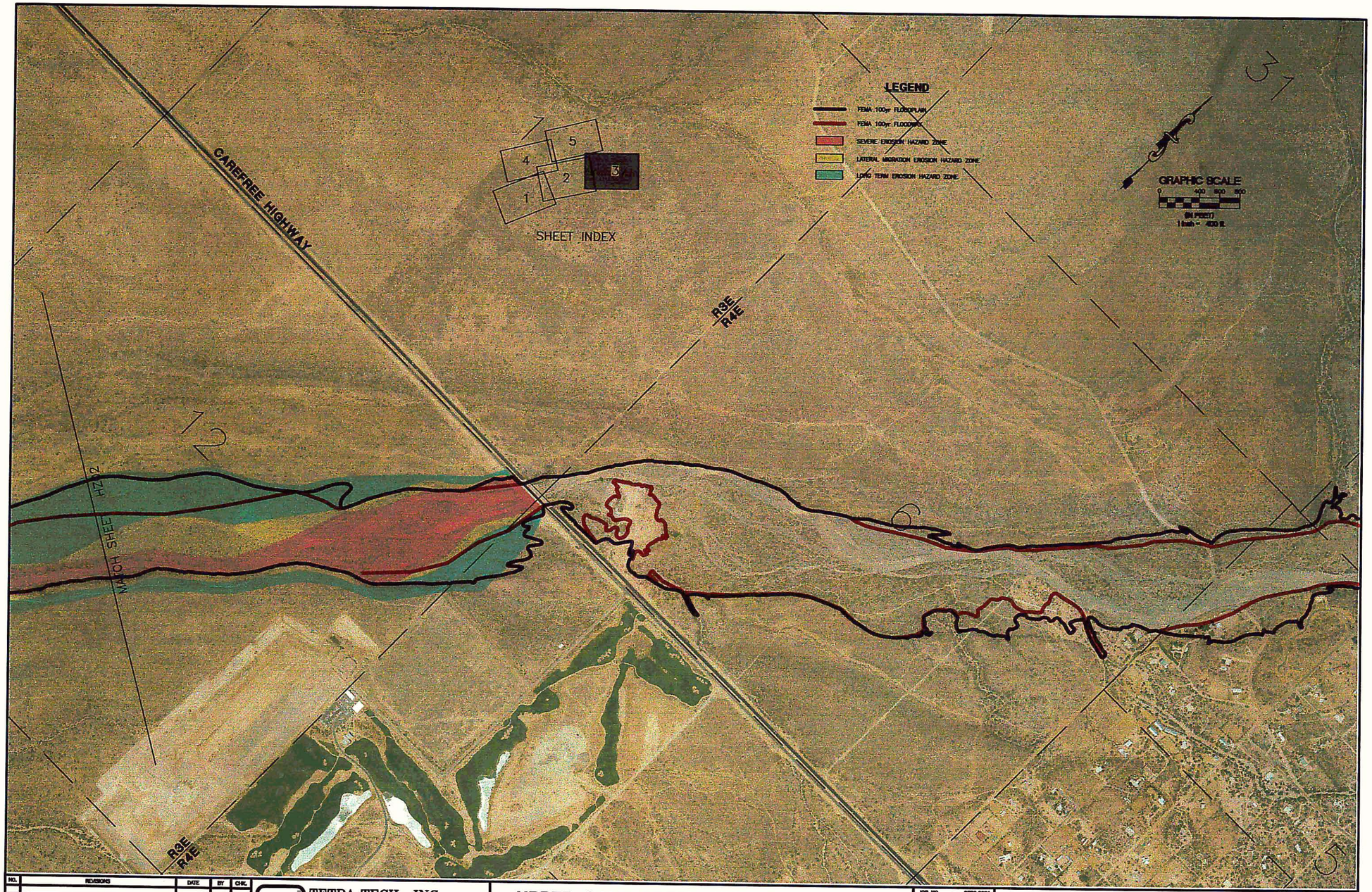
UPPER CAVE CREEK AND APACHE WASH WATERCOURSE MASTER PLAN
FCD 97-45

JOB NO.	2350.0001
DESIGNED BY:	JAO
DRAWN BY:	CBC
CHECKED BY:	JAO
APPROVED BY:	TRL
DATE:	12/27/00

EXHIBIT 3
EROSION HAZARD BOUNDARY MAP

SCALE: HORIZ: 1" = 400'
DRAWING NO. HZ02
SHEET NO. 2 OF 5

E:\23500001\HECRAS\2350hz02.dwg Wed Apr 04 13:40:44 2001 By CBC



NO.	REVISIONS	DATE	BY	CHK.

2350HZ03.DWG

TETRA TECH, INC.
INFRASTRUCTURE SOUTHWEST GROUP
501 North 44th Street, Suite 125, Phoenix, AZ 85008
(602) 629-1100 FAX (602) 629-1186

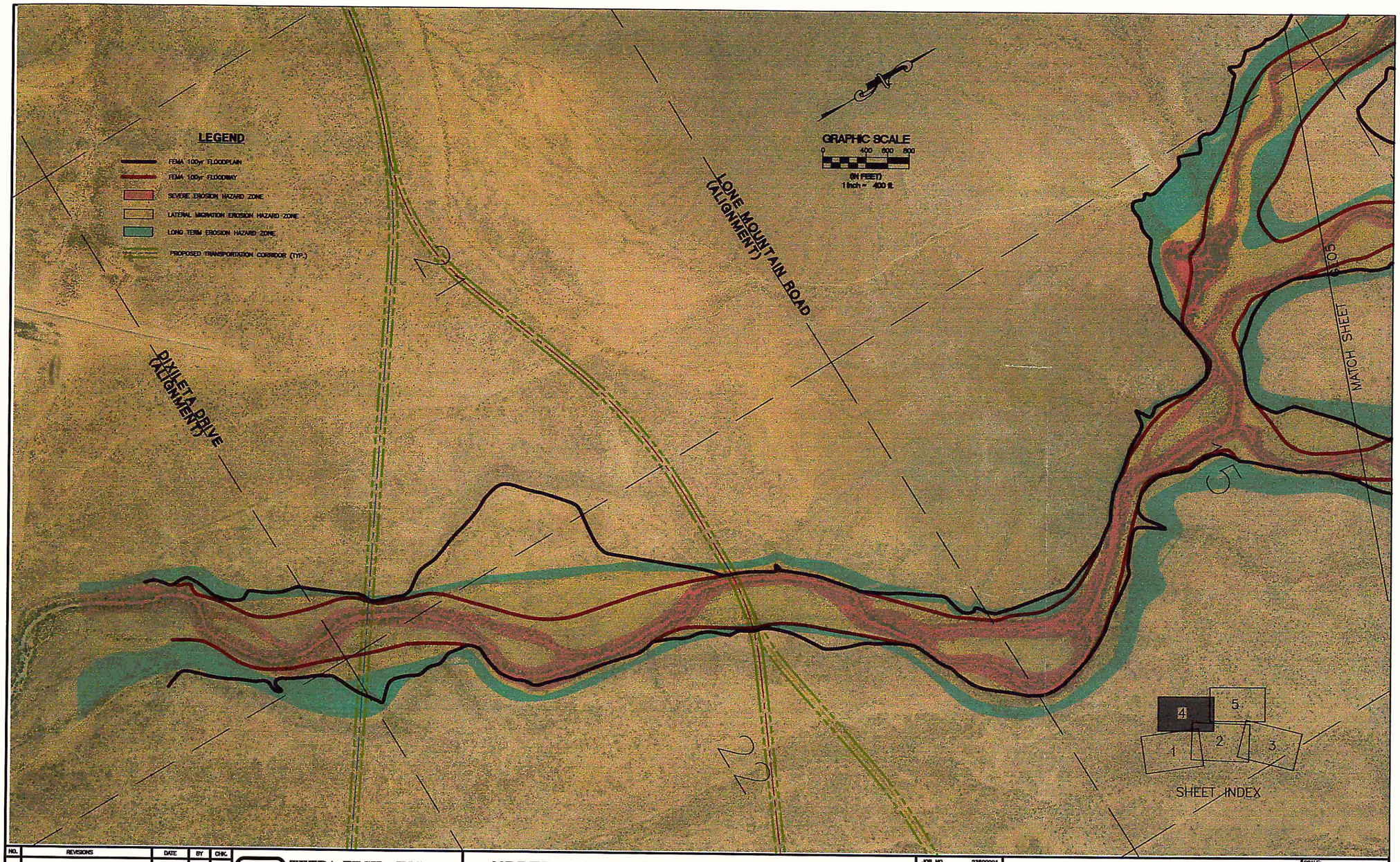
UPPER CAVE CREEK AND APACHE WASH WATERCOURSE MASTER PLAN
FCD 97-45

JOB NO.	2350.0001
DESIGNED BY:	JAD
DRAWN BY:	CBC
CHECKED BY:	JAD
APPROVED BY:	TRL
DATE:	12/27/00

EXHIBIT 3
EROSION HAZARD BOUNDARY MAP

SCALE: HORIZ: 1"= 400'
DRAWING NO. HZ03
SHEET NO. 3 OF 5

E:\23500001\HECRAS\2350HZ03.dwg Wed Apr 04 13:04:01 2001 By CBC



NO.	REVISIONS	DATE	BY	CHK.

2350HZ04.DWG

TETRA TECH, INC.
INFRASTRUCTURE SOUTHWEST GROUP
501 North 44th Street, Suite 125, Phoenix, AZ 85008
(602) 629-1100 FAX (602) 629-1188

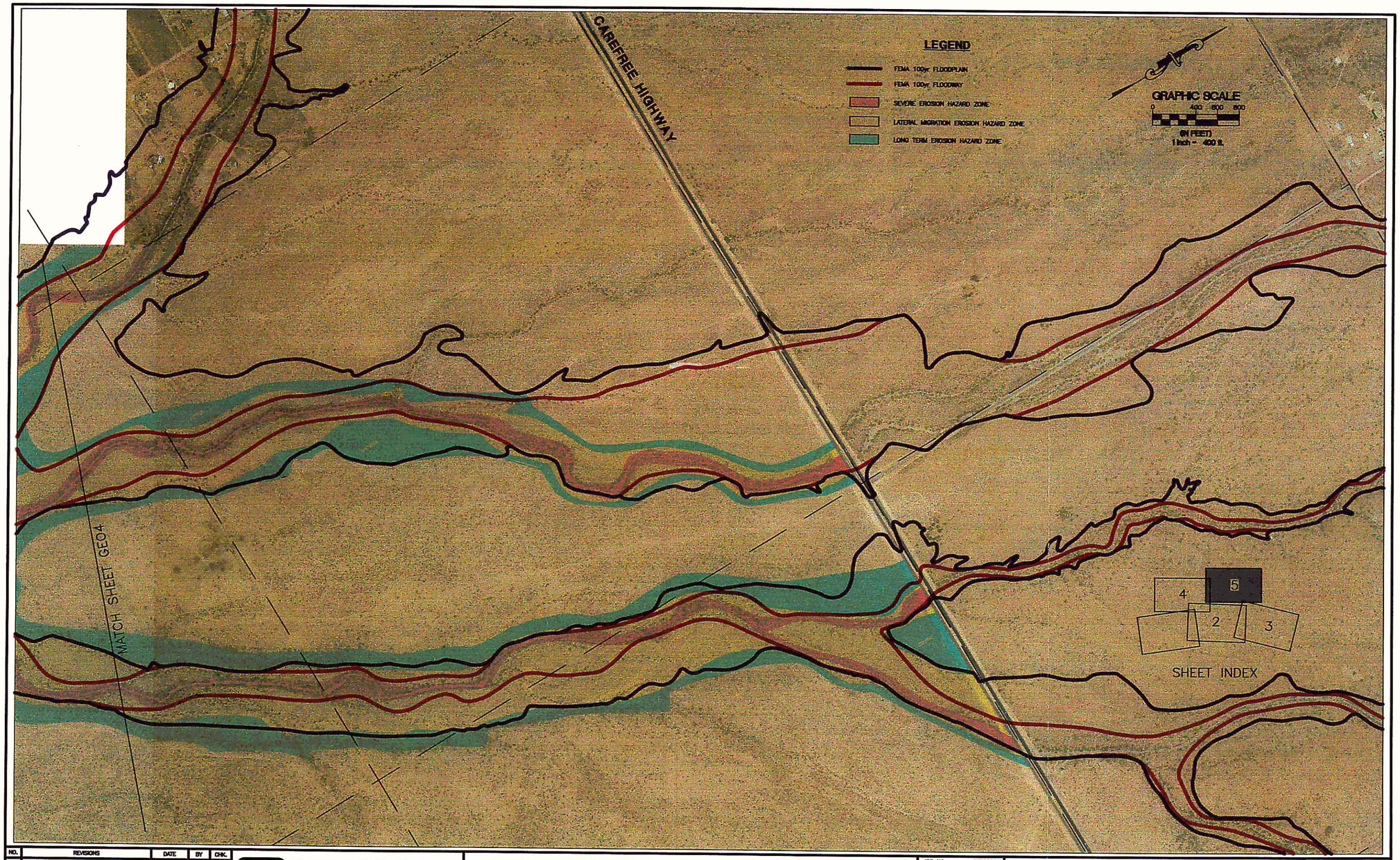
UPPER CAVE CREEK AND APACHE WASH WATERCOURSE MASTER PLAN
FCD 97-45

JOB NO.	23500001
DESIGNED BY:	TRL
DRAWN BY:	CBC
CHECKED BY:	JAD
APPROVED BY:	TRL
DATE:	12/27/00

EXHIBIT 3
EROSION HAZARD BOUNDARY MAP

SCALE: HORIZ: 1"= 400'
DRAWING NO. HZ04
SHEET NO. 4 OF: 5

E:\235000C ECRAS\2350hz04.dwg Wed Apr 04 12:30:34 2001 By CBC



NO.	REVISIONS	DATE	BY	CHK.

2350HZ05.DWG

TETRA TECH, INC.
INFRASTRUCTURE SOUTHWEST GROUP
501 North 44th Street, Suite 125, Phoenix, AZ 85008
(602) 629-1100 FAX (602) 629-1186

UPPER CAVE CREEK AND APACHE WASH WATERCOURSE MASTER PLAN
FCD 97-45

JOB NO.	23500001
DESIGNED BY:	JAD
DRAWN BY:	CBC
CHECKED BY:	JAD
APPROVED BY:	TRL
DATE:	12/27/00

EXHIBIT 3
EROSION HAZARD BOUNDARY MAP

SCALE: HORIZ: 1"= 400'
DRAWING NO. HZ05
SHEET NO. 5 OF: 5

E:\2350000CRAS\2350HZ05.dwg Wed Apr 04 15:56:12 2001 By CBC