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PIEDMONT FLOOD HAZARD ASSESSMENT FOR FLOOD PLAIN MANAGEMENT

for Maricopa County, Arizona

USER'S MANUAL

Draft of August 1998 by Hjalmarson

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Forward

A flood hazard commonly is thought to involve the sudden and potentially catastrophic inundation of land by a fluvial system. Many potential risks and dangers, however, are the result of progressive change such as the filling of stream channels and headcutting that gradually leads to avulsion and stream piracy. A truer perception of potential risk and danger to life and property is to think of a hazard as both progressive and sudden. According to Schumm (1994), faulty perceptions of fluvial systems have lead to faulty predictions and unnecessary damage and litigation.

Evidence of floods and flood processes are recorded in the piedmont landforms of Maricopa County. Landforms are surface features that have distinguishing characteristics. Many of these characteristics are the result of past storms and floods. Piedmonts are the broad sloping landforms located between the mountains and the valley floor. Subcategories of landforms within the piedmont include alluvial fans, relict fans, pediments and alluvial plains. Distinctive characteristics of pediments and relict fans are the products of erosion. Distinctive characteristics of alluvial plains and many alluvial fans are the products of sediment accumulation. Several spatial characteristics of these landforms are indices to flood processes operating in the past and to the state of the landforms (Graf, 1977).

Indicators such as rock varnish, cementation of deposits and channel incision may be used to define the age of the landform surface. For example, the absence of surface disturbance by fluvial processes of erosion and sediment deposition for thousands of years suggests the landform is old and has been stable. A young surface may be actively aggrading by fluvial sediment deposition because it has been frequently flooded. It is this relation between surface age, surface form, and flood processes that allows a "geomorphological understanding of floods"(Baker, 1994).

Reproducible and typically reliable flood hazard delineation on piedmonts can be made at reasonable cost because the general location of floods is predictable using geomorphic evidence. Floods on piedmont slopes have a degree of predictability. Most flood properties can be accurately predicted where the landform geometry, sedimentation and hydraulic roughness are relatively stable. Reasonable estimates of flood properties can also be made for areas subject to bank erosion, flow-path movement or sediment deposition (Pearthree, 1991). The intensity of flood hazard, that is related to the flow velocity, flow depth, channel bank erosion and flow-path movement, can be estimated using several indicators or observable properties. This flood- hazard indicator relation makes it possible for engineers and hydrologists, possibly with the assistance of geomorphologists, to realistically define flood hazards as described in this manual.

Acknowledgments

H. W. Hjalmarson, PE, consulting hydrologist under the direction of Joe Tram, Dave Johnson and Ted Lehman of the Flood Control District, originally prepared this user's manual. The manual was first released in draft format on December 8, 1997 for review and comment by engineers, hydrologists, geologists and other interested parties. District staff will make necessary revisions to the manual using comments received and will reissue the manual at a later date.

Many hydrologists, engineers, geologists, soil scientists and flood-plain managers at the local, county, state and federal levels, in the consulting community and at universities have made direct and indirect contributions to the development of methods used in this manual. The original draft was reviewed by Stanley A. Schumm, Ph.D., P.G., Philip A. Pearthree, Ph.D., John E. Fuller, P.E. and Bill Jenkins, P.E. Additional comments by Mike Grimm of the Federal Emergency Management Agency have also been incorporated in the manual.

The often under utilized soils information for flood hazard assessment presented in U.S. Soil Conservation Service Reports *Soil survey of Aguila-Carefree area, parts of Maricopa and Pinal counties, Arizona* (1986) and *Soil survey of Maricopa County, Arizona, central part* (1977) contributed greatly to the methods in this manual. Soil surveys are an important part of the method to consistently and reproducibly delineate those areas subject to active flooding.

Table of Contents

1 INTRODUCTION ---- 1

1.1 Objectives ---- 1
1.2 Piedmonts ---- 2
1.3 Flow and flood terminology ---- 4
1.4 Limitations ---- 5
1.5 Perspectives ---- 6
1.6 Approach ---- 8
1.7 Overview ---- 9
1.8 Standards ---- 11

2 PIEDMONT LANDFORMS OF MARICOPA COUNTY ---- 12

2.1 Landforms ---- 13
2.1.1 Relict fans ---- 13
2.1.1.1 Transverse relief ---- 15
2.1.1.2 Relict fans and pediments ---- 15
2.1.2 Pediments ---- 17
2.1.2.1 Granite pediments ---- 17
2.1.2.2 Drainage pattern ---- 19
2.1.2.3 Drainage texture ---- 19
2.1.3 Alluvial Fans ---- 20
2.1.3.1 Composition ---- 20
2.1.3.2 Shape ---- 21
2.1.3.3 Topographic break ---- 21
2.1.3.4 Drainage texture ---- 21
2.1.3.5 Topographic maps ---- 21
2.1.4 Alluvial plains ---- 22
2.2 Identification ---- 22
2.2.1 Indicators ---- 24
2.2.2 Office indicators ---- 24
2.2.2.1 Drainage pattern ---- 26
2.2.2.2 Drainage texture ---- 27
2.2.2.3 Vegetation ---- 28
2.2.3 Field indicators ---- 28
2.2.3.1 Channel shape and capacity ---- 28
2.2.3.2 Sediment ---- 30
2.2.3.3 Age indicators ---- 32
Desert pavement ---- 32
Desert varnish ---- 32
2.3 Summary ---- 32

3 IDENTIFICATION OF STABLE AND UNSTABLE AREAS ON PIEDMONTS OF MARICOPA COUNTY ---------- 35

3.1 Indicators of flood limits and landform stability on piedmonts ----------36
3.1.1 Stable areas ----------37
3.1.2 Unstable areas----------38
3.1.3 Basis of indicator method----------38
3.1.4 Words of caution ----------41
3.2 Relict fans----------42
3.3 Pediments ----------42
3.4 Alluvial Fans ----------44
3.4.1 Precautions ----------47
3.4.2 What parts of fan are active/inactive (< 10,000 years)? ----------48
3.4.2.1 Depth of incision----------49
3.4.2.2 Flow path movement ----------49
3.4.2.3 Drainage basin----------50
3.4.3 Additional information----------51
3.5 Alluvial plains----------52
3.6 Variables that affect fluvial hazards ----------52
3.7 Summary ----------54

4 DEFINITION OF 100-YEAR FLOOD HAZARDS---------- 56

4.1 Methods for defining 100-year hazards ----------57
4.1.1 Relict fans and pediments ----------58
4.1.2 Inactive alluvial fans----------58
4.1.2.1 Rating curve method for allocating split flow ----------62
4.1.2.2 Cross sections----------64
4.1.2.3 Channel conveyance-slope method ----------65
4.1.2.4 Soil characteristics----------67
4.1.2.5 Discussion ----------69
4.1.3 Active alluvial fans----------69
4.1.3.1 Flood hazard management in Maricopa County ----------70
4.1.3.2 Fans with random flow paths ----------71
4.1.3.3 Supercritical flow velocities and translatory wave ----------72
4.1.3.4 Published examples of geomorphic hazard assessments ------72
4.1.3.5 Published examples of modeled hazard assessments ----------73
4.1.4 Alluvial plains ----------73
3.2 Summary ----------73

5 APPLYING THE ASSESSMENT TO EXAMPLE SITES---------- 78

5.1 The South Mountain Park alluvial fan----------78
5.1.1 Type of landform----------80

5.1.1.1 Composition----82
5.1.1.2 Morphology ----82
5.1.1.3 Location----82
5.1.2 Active and inactive areas of the alluvial fan ----83
5.1.2.1 Fan Building at the South Mountain Park site----83
5.1.2.2 Selected observations along the potentially active area ----84
5.1.2.3 Summary of active and inactive areas ----85
5.1.3 Estimated 100-year flood hazards----85
5.1.3.1 Characteristics of recent deposited sediment ----85
5.1.3.2 Shear strength along the channels ----89
5.1.3.3 Infrequent fan building events----90
5.1.3.4 Summary of 100-year flood conditions----91
General map of 100-year flood conditions ----92
Estimate of active and inactive areas for 100-year flood Conditions ----93
Rough check of the estimated 100-year flood conditions ----95
5.2 The White Tank Park relict fan ----97
5.2.1 Embayment area----97
5.2.2 Area below the mountain front ----99
5.2.3 Type of landform---- 100
5.2.3.1 Composition---- 100
5.2.3.2 Morphology ---- 100
5.2.3.3 Location---- 101
5.2.4 Active and inactive areas of the alluvial fan ---- 101
5.2.4.1 Inactive area---- 101
5.2.4.2 Active areas along throughflow channel ---- 103
5.2.5 Drainage Basin---- 103
5.2.6 Characteristics of recently deposited sediment---- 103
5.2.7 The 100-year flood---- 103
5.2.8 Summary---- 104
5.3 The Skyline Wash alluvial fan---- 110
5.3.1 Introduction---- 110
5.3.1.1 Road log ---- 110
5.3.1.2 Background and materials for field inspection---- 110
5.3.2 Type of landform---- 112
5.3.2.1 Composition---- 112
5.3.2.2 Morphology ---- 113
5.3.2.3 Location---- 113
5.3.3 Active and inactive areas of the alluvial fan ---- 115
5.3.3.1 Source of sediment ---- 115
5.3.3.2 Flow path movement---- 117
5.3.3.3 Vegetation ---- 118
5.3.3.4 Channels ---- 118
5.3.3.5 Gravel pit ---- 120

5.3.3.6 Surface age indicators and soil development ---------- 121
5.3.3.7 Distribution of sediment along the fan ---------- 121
5.3.3.8 Summary of active and inactive areas ---------- 124
5.3.4 Estimated 100-year flood hazards ---------- 124
5.3.4.1 Peak discharge and channel conveyance considerations ---- 125
Peak discharge for 100-year flood ---------- 125
Channel conveyance below hydrographic apex ---------- 125
Flow paths and flow spreading ---------- 127
5.3.4.2 Infrequent fan building events ---------- 127
5.3.4.3 Summary of 100-year flood conditions ---------- 127
West side of fan ---------- 129
Shadow area ---------- 129
East side of fan ---------- 130
5.3.4.4 Rough check of the estimated 100-year flood conditions ---- 131
5.3.5 Brief comments on hazard assessment for adjacent landforms ------- 132
5.3.5.1 Prospect Wash ---------- 132
5.3.5.2 Coyote Wash ---------- 133
5.3.5.3 Rattler Wash ---------- 133
5.3.5.4 Skyline Wash above hydrographic apex ---------- 133

6 ACRONYMS ---------- 135

7 GLOSSARY ---------- 136

8 MISCELLANEOUS METHODS ---------- 142

8.1 U. S. Geological Survey Professional Paper 352C ---------- 142
8.2 U. S. Soil Conservation Service TR-25 ---------- 144
8.3 USGS Water -Resources Investigations Report 91-4171 ---------- 146
8.4 USGS Water -Resources Investigations Report 93-4169 ---------- 147
8.5 Sediment grain size along an idealized fan ---------- 148

9 REFERENCES ---------- 152

Tables

1.1 Outline of geomorphic-engineering approach to piedmont flood hazard assessment ---- 10
2.1 Component landforms, common soil types and significant characteristics of piedmonts of Maricopa County ---- 14
2.2 Steps for identification of piedmont landforms for assessment of flood hazards ---- 23
2.3 Selected indicators of landforms and flood hazards in Maricopa County ---- 25
3.1 Indicators of stable flow paths on piedmont landforms ---- 39
3.2 Selected characteristics of stable and unstable flood hazard areas of piedmont landforms ---- 43
3.3 Steps for defining and characterizing alluvial fans ---- 45
3.4 Variables affecting fluvial hazards on piedmonts over long periods ---- 53
4.1 Defining and characterizing 100-year floods on piedmont landforms of Maricopa County ---- 59
4.2 HEC-RAS output for subcritical flow split using rating method ---- 64
5.1 Distribution of particle size at the upper, middle and lower sites along the west side of the fan ---- 122

Figures

1.1 Isometric sketch of piedmont ---- 3
2.1 Typical flood hazards and landforms on piedmonts in Maricopa County ---- 13
2.2 Sketches of transverse cross sections of piedmont landforms ---- 16
2.3 Drainage texture and drainage texture relations for relict fans, pediments and inactive alluvial fans (from Hjalmarson and Kemna, 1991) ---- 27
2.4 Cross sections of throughflow and tributary channels showing deposited sediment ---- 29
2.5 Cumulative graphs of material size versus frequency indicative of landforms in Maricopa County ---- 31
2.6 Example map of soil, topography and landforms that represents the completion of stage 1 of the method ---- 34
3.1 Sketch of typical calcium carbonate development and photograph of typical conglomerate as seen in road cuts and along cut banks of stream channels ---- 38
3.2 Example map of landforms and stable (inactive) and unstable areas ---- 55
4.1 Example of flooding on inactive alluvial fan ---- 60
4.2 Example of flooding on an area with incised distributary channels near Carefree ---- 61
4.3 Example of split flow at a channel fork ---- 63
4.4 Distribution of flow at split using the rating method ---- 65
4.5 Sketch of stable distributary flow paths showing distribution of 100-year flood peak discharge and estimated flood boundaries ---- 68
4.6 Example of major flooding on an alluvial plain ---- 74
4.7 Example of floodflow on an alluvial plain in north Phoenix ---- 75
4.8 Example of 100-year flood hazards ---- 76
5.1 Aerial photograph of South Mountain Park site showing topographic contours, soil types, piedmont landforms and other characteristics ---- 78
5.2 Mapped soils ---- 80
5.3 Profile of stream channel through active part of alluvial fan ---- 83
5.4 Orthophoto map of South Mountain Park site showing landforms with active and inactive areas ---- 88
5.5 Cumulative sediment size-frequency graphs for South Mountain Park alluvial fan ---- 89
5.6 Cross section about 200 feet upstream of the hydrographic apex showing the approximate level of the 100-year flood ---- 88
5.7 Orthophoto map of South Mountain Park site showing landforms, active and inactive areas and estimated 100-year flood areas ---- 93
5.8 Cross-section at upper end of area DF at elevation contour 1190 showing the level of 100-year flood and distribution of channel conveyance ---- 94
5.9 Aerial photograph of White Tank Park site showing topographic contours, soil types, piedmont landforms and other characteristics ---- 98
5.10 Soil types ---- 101
5.11 Aerial photograph of White Tank Park site showing landforms with active and inactive areas and location of photographs ---- 102

5.12 Photograph of right bank below roadway showing relict boulder Conglomerate ---------- 105
5.13 Photograph of right bank where the active channel bends to the left above the park restroom building shown in the background ---------- 105
5.14 Photograph looking upstream at nickpoint of entrenched channel ---------- 106
5.15 View looking south at right bank a few hundred feet downstream of the nickpoint where the channel is about 8 to 9 ft. deep---------- 107
5.16 View looking downstream and east at the overflow area on right side of the Channel where there is recent aggradation ---------- 107
5.17 View looking downstream at main channel of aggrading area located Several feet east of the park boundary---------- 108
5.18 Aerial photograph of White Tank Park site showing landforms, active and inactive areas and estimated 100-year flood hazard areas---------- 109
5.19 Aerial photograph of Skyline Wash site showing topographic contours, soil types, piedmont landforms and other characteristics---------- 111
5.20 Photograph looking upstream along channel on right (west) side of Skyline Wash alluvial fan ---------- 113
5.21 Elevation profile of stream channel at Skyline Wash landform ---------- 114
5.22 Profile of channel slope along center of the Skyline Wash alluvial fan ---------- 114
5.23 Orthophoto and topographic map of Skyline Wash site showing corrected soil types and landforms with active and inactive areas ---------- 116
5.24 Cross sections located below the hydrographic apex of the Skyline Wash alluvial fan ---------- 119
5.25 Cross sections located at the 1362, 1350 and 1340 ft. topographic contours Shown in Figure 5.24 below the hydrographic apex---------- 120
5.26 Views of desert pavement with some desert varnish on stable parts of fan------ 121
5.27 Cryptogamic crust in small first order channel on soil type 98 about 100 ft. north of McDowell Road on west side of fan---------- 122
5.28 Cumulative graph of material size versus frequency along central axis of the fan where there is little evidence of recent throughflow---------- 123
5.29Distribution of channel conveyance at cross sections below the hydrographic apex---------- 126
5.30 Orthophoto map of Skyline Wash site showing landforms, active and inactive areas and estimated 100-year flood areas ---------- 128
5.31 View looking south along subdivision road where local runoff has eroded channels into soil type AGB along the sides of the road---------- 130
5.32 View looking south from below Watson Road at channel of Prospect Wash --- 133
MM.1 Relation between width-depth ratio (F) and weighted mean percent silt-clay (M) at sites with straight reaches of distributary channels---------- 143
MM.2 Unconfined compressive strength and tractive power as related to channel stability---------- 144
MM.3 Ideal active alluvial fan---------- 149
MM.4 Distribution of representative grain size (D_{50}) along an idealize alluvial fan---- 150

MM.5 Direction of shift in relation between grain size and distance below hydrographic apex to maintain equilibrium rate of aggrading for decreasing fan angle (α), decreasing Manning roughness coefficient (n), increasing discharge (Q) and decreasing infiltration for ideal active alluvial fan ---------- 155

1

INTRODUCTION

The objective of the manual along with a brief description of the geomorphic and flood hazards of piedmonts is first discussed in this chapter. A brief discussion of the traditional engineering approach and how this approach might be improved is briefly discussed in the limitations section of this chapter. The significance of differences between common perspectives of engineers and geomorphologists is briefly presented for background and insight to the relation between geomorphology and flood hazards. An overview and organization of the manual follow the general approach of the manual.

The intended audience of this manual is a desert region flood specialist or a flood hazard assessment team with complimentary expertise in engineering, hydrology and geomorphology that is familiar with FEMA methods and the geomorphic framework of desert regions like Maricopa County. **Much of the background information in the manual is basic for geomorphologists and is presented to facilitate a consistent, fundamental and reproducible delineation of the flood hazard of stable and unstable areas.** The differential diagnosis technique, which uses several indicators of landform type and stability, relies mostly on published soil surveys. The use of published soil survey maps reduces field time effort and costs and should result in reproducible results. Landform identification and flood hazard assessment is also facilitated using published surficial geology maps. Engineers and hydrologists who have difficulty understanding some of the concepts and applying the methodology should acquire the assistance of someone with expertise in geomorphology and soils.

1.1 Objectives

The objectives of this manual are to show (1) how flood hazards on *piedmonts* (see glossary) in Maricopa County are related to landforms, (2) how to go about performing an examination of specific sites for the identification of *unstable (active)* and *stable (inactive)* flood hazard zones and (3) how to accurately and reproducibly delineate those areas subject to active flooding. In Maricopa County, areas of active flooding are considered floodway districts in order to maintain conveyance corridors for the transport of floodwaters and sediment down the piedmonts past development. The recognition of whether a specific site is actively undergoing general aggradation or degradation and/or is in a general state of equilibrium or disequilibrium is important for design of structures and flood hazard mitigation. Once recognized it is also essential to prevent encroachment that results in the effects of disequalibrium such as unwanted channel scour and sedimentation. This manual explains how contractors in Maricopa County should go about assessing flood hazards on piedmonts, which include alluvial fans, to

meet the *Guidelines and Specifications for Study Contractors* (FEMA, 1995) and County requirements.

Areas where any flow path uncertainty can be ignored for the assessment of flood hazard are called stable areas in this manual. Stable areas include many hillsides and most areas of relict fans, pediments and inactive alluvial fans. Flow paths and flood boundaries for these stable areas are considered predictable using traditional engineering methods and standard-step hydraulic methods like HEC-RAS (COE, 1995). Detailed approaches to flood insurance studies that result in determination of 100-year flood elevations (FEMA, 1995) typically are for stable areas.

Unstable areas are where the flow path uncertainty *"is so great that this uncertainty cannot be set aside in realistic assessments of flood risk or in the reliable mitigation of the hazard"* (National Research Council, 1996). Traditional engineering methods generally are inappropriate for areas with changing flow paths and where sediment from upslope source areas is being deposited on the piedmont. Unstable areas include active alluvial fans, a few distributary flow areas (See section 1.3 for definition) and some alluvial plain areas where there is active sedimentation or erosion. Areas of flow path uncertainty and boundaries for these areas are typically predictable using geomorphic methods. Unstable areas have characteristics of younger surfaces such as undeveloped soil profiles and wide-shallow channels that can be defined using geomorphic analysis. Generally speaking, the decision of whether to use engineering or geomorphic methods also depends on the level of accuracy required and the scale of the assessment.

This manual translates useful *morphologic* and other technical information into engineering terms for appropriate use in conjunction with Drainage Design Manuals for Maricopa County, Volumes I and II. Use of this *Piedmont Flood Hazard Assessment for Flood Plain Management User's Manual for Maricopa County, Arizona* will result in improved identification of actual flood hazards. Flood hazard identification typically starts with determining the scope of flood insurance studies outlined in Chapter 2 of the Guidelines and Specifications for Study Contractors (FEMA, 1995).

1.2 Piedmonts

Most of Maricopa County is in the Basin and Range Physiographic Province where fault-block mountains are separated by intervening plains. The mountain ranges are consolidated rock and stream deposits generally cover valley floors. Axial streams that are located in the valley head in adjacent mountains and traverse the piedmont drain the basins. Piedmonts are broad, gently sloping and low relief plains located between mountain ranges and axial drainage.

A piedmont lies or is formed at the base of a mountain or mountain range (Figure 1.1). A piedmont is a complex part of an erosion-depositional system where sediment eroded

from mountains is transported by a stream (*wash*) across the piedmont to a valley where it is deposited. Piedmonts occupy a large portion of Maricopa County. Piedmont slopes range from less than 1 percent near the valley floors to more than 10 percent near the mountains. Typical piedmonts consist of pediments and/or *relict fans* on the upper slopes adjacent to the mountains and *alluvial plains* on the lower slopes adjacent to the valley floors or base level streams. *Active alluvial fans* (fans that are presently aggrading and eroding) can occur anywhere on the piedmont as shown in Figure 1.1. Many piedmonts in Maricopa County were formed by the lateral coalescence of separate alluvial fans into a landform called a *bajada*.

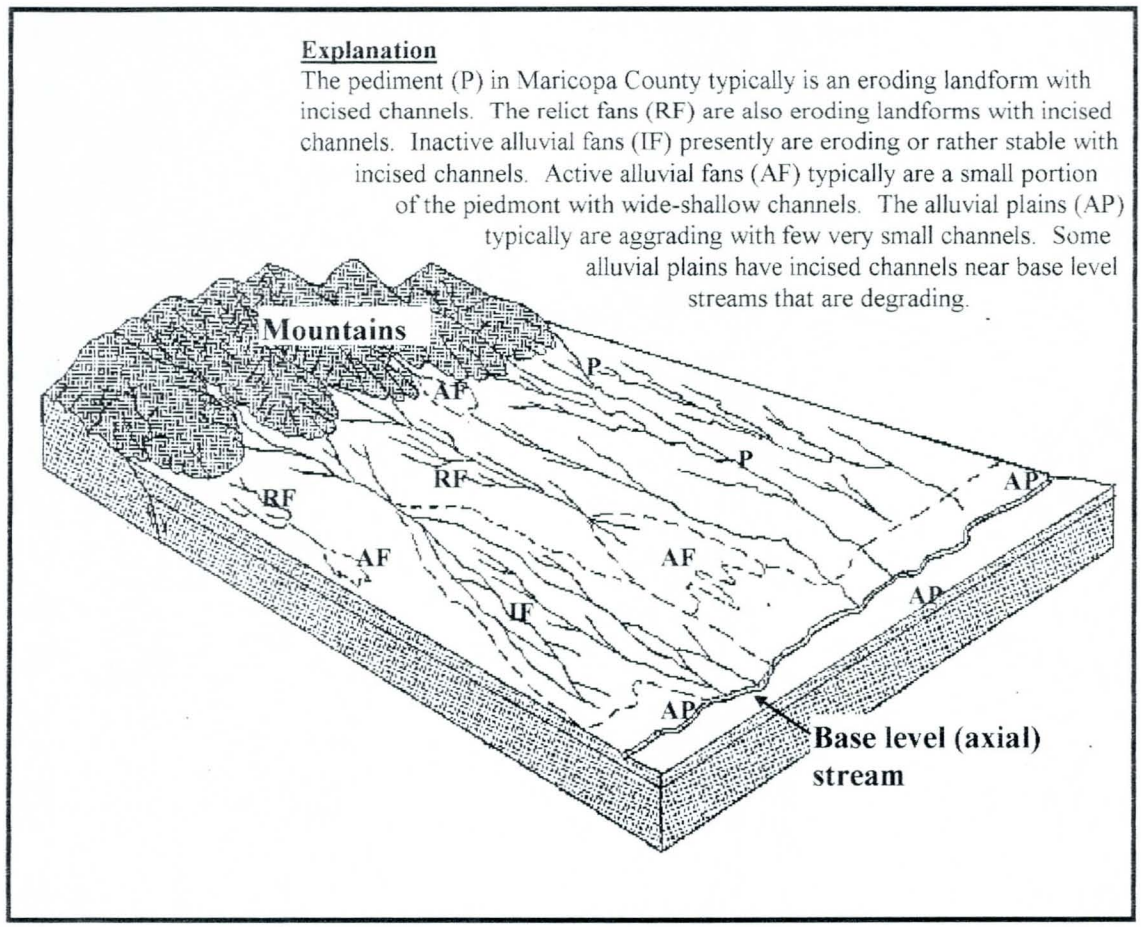


Figure 1.1. Isometric sketch of piedmont

Piedmonts in Maricopa County have areas of both tributary stream channels (See the relict alluvial fans (RF) and pediments (P) of Figure 1.1) and distributary stream channels (See the inactive alluvial fan (IF) of Figure 1.1). Floodwater from the tributary mountain streams enters the piedmont in channels and as overland flow along the mountain front and in embayments like the *embayment* shown in Figure 1.1 where the upper active alluvial fan (AF) is located. Floodwater may also originate from rainfall directly on the piedmont. Much of the floodflow crosses the piedmont slopes in defined channels of

relict or inactive alluvial fans and pediments. Floodflow that enters active alluvial fans and alluvial plains becomes unconfined and can spread laterally at shallow depths. However, other flow characteristics of active alluvial fans and alluvial plains are quite different. Active alluvial fans typically have steeper slopes than alluvial plains. In addition, active alluvial fans are formed by material from the upper piedmont and mountains while alluvial plains are also formed by deposits along base level streams. Because the surface of typical active fans in Maricopa County commonly is composed of sand with gravel and scattered cobbles with only a few scattered boulders and some low vegetation, the surface is hydraulically rather smooth (Manning n <0.040) and floodflow velocities are near or above the critical state in channels where slopes exceed about 2 percent. **Active alluvial fans function primarily as a terminus for sediment and water whereas the channels of pediments, relict fans and inactive alluvial fans function as transport corridors for sediment and water.** A most significant difference between active alluvial fans, pediments and relict or inactive alluvial fans is the paths of flow on active alluvial fans can change gradually or suddenly (avulse) during flooding.

Relict fans are erosion remnants of old alluvial fans. These remnants are called *fan terraces* in NRCS soil survey reports (Camp. 1986), *erosion fan remnants* in a desert landform report for soil surveys by Peterson (1981), older alluvial surfaces in a flood hazard report of piedmonts by Field and Pearthree (1992) and a heterogeneous assortment of generally weakly consolidated slope-wash deposits by Cooley (1977). For this manual, relict fans are simply sediment deposits with well-developed calcium carbonate in the soil profile and/or cemented conglomerate. Relict fans can be classed as inactive alluvial fans where a sufficient amount of the remnant remains to be classed as an alluvial fan landform as described in Chapter 2 of this manual.

1.3 Flow and flood terminology

The variety of terminology related to the flow of water over landforms to rivers and flow that leaves defined river channels is confusing. For example, Hogg (1982) gives a good discussion of the numerous meanings of terms. Much of this confusion has been cleared in Arizona State Standard 4-95 for *Identification of and Development within Sheet Flow Areas*. With a few exceptions, this State Standard is used as a basis for definitions and identifying characteristics of flow types in this manual (See the glossary at the end of the manual). The following clarifies and discusses some minor differences in the use of terms between State Standard 4-95 and this manual:

Alluvial fan flooding is flooding that occurs only on alluvial fans (National Research Council, 1996). Alluvial fan flooding can include distributary flow, sheet flow and sheet flooding.

Distributary flow occurs in channels that have a distributary drainage network. Such a network is composed of multiple bifurcation and typically rejoining of channels. Distributary patterns occur on braided rivers, river deltas and alluvial fans (Morisawa, 1985) and on highly weathered pediments. The term "distributary flow area" was used

by Hjalmarson and Kemna (1992) to describe this drainage pattern on active and inactive alluvial fans and on weathered pediment landforms in Arizona as discussed later in this manual.

Sheet flow is **overland flow** or down slope movement of water taking the form of a thin, continuous film over relatively smooth soil or rock surfaces and not concentrated into channels larger than rills (National Research Council, 1996). This flow typically is short lived with a limited travel distance. Most surface runoff starts as overland flow and commonly enters rills before it is concentrated in channels. Natural overland flow is characterized by several lateral down slope concentrations of flow rather than uniform sheet flow (Emmett, 1970).

Sheet flooding. For this manual, the more restrictive definition and characteristics given in Arizona State Standard 4-95 (1995), which says, "Sheet flooding is a type of surface runoff which occurs on broad, unconfined floodplains with low relief." are used for alluvial plains of piedmonts. According to Hogg (1982) a **sheet flood** is simply a sheet of unconfined floodwater moving down a slope. This definition implies a sheet flood is less frequent than a sheet flow. The Committee on alluvial fan flooding of the National Research Council (1996) was more specific when they defined sheet flood as "a broad expanse of moving, storm-borne water that spreads as a thin, continuous, relatively uniform film over a large area in an arid region and that is not concentrated into well defined channels; its distance of flow is short and its duration is measured in minutes or hours. Sheet floods usually occur before runoff is sufficient to promote channel flow, or after a period of sudden and heavy rainfall."(See glossary of terms in this manual). An excellent description of sheet flooding on an alluvial fan in Colorado is given by Blair and McPherson (1994) suggests characteristics comparable to one of the earliest and most interesting documented sheet floods in southern Arizona (McGee, 1897). These definitions generally compliment the definition and description of sheet flooding given in Arizona State Standard 4-95 (1995).

1.4 Limitations

The frequency, magnitude and location of flood and sediment events are of considerable interest for the welfare and safety of those occupying piedmonts. Precise definition of the occurrence and nature of these hazardous floods is complicated by several factors including unstable channel boundaries, uncertain flood flow-frequency relations and the threshold nature of basin sediment yield and transport. While generally accepted standard-step methods such as HEC-2 (COE, 1990b) and HEC-RAS (COE, 1995); unit-graph or hydrographic storm rainfall-runoff models such as TR-55 (NRCS, 1986) and HEC-1 (COE, 1990a); and sediment yield models such as RUSLE (Soil and Water Conservation Society, 1995) represent the engineer's current set of tools for characterizing flood conditions, these tools may be limited for specific sites. To overcome some of these limitations, geomorphologic tools are used to supplement engineering tools to produce a more reliable definition of the flood hazard.

To compensate for potential errors or limitations of predictions the engineer typically takes the conservative approach that uses a factor of safety. Modern engineering and geology use several generalizations to depict, for example, runoff, peak discharge, channel behavior, sediment transport and sediment yield. These general relations may not be precise for specific sites. For example, the estimate of the 100-year flood peak discharge is not very precise for streams in Maricopa County (Thomas, Hjalmarson and Waltemeyer, 1997). Much of this difficulty is because of the variability of basin factors at specific sites and also because of the nonstationarity of climate and variability of storms. This conservative approach is recommended providing the conclusions reached are substantiated by field evidence.

The realistic and rather simple engineering and geomorphologic tools presented in this manual for the assessment of unstable and stable flood hazards have limitations that will be discussed in the manual. This user's manual should be used with judgment based on knowledge of and experience with engineering methods and geomorphologic processes of arid and semi-arid landforms.

1.5 Perspectives

Identification of unstable channels and flow paths can be viewed from both structural and non-structural perspectives. The structural advocate might recommend that there is no need to identify unstable flow paths in favor of "total" structural control of an incised channel or an unstable alluvial fan. On the other hand, because the unstable channel and changing flow paths are part of a *fluvial* system in a state of quasi-equilibrium that can be quantified, the non-structural advocate might recommend avoidance or "setback" and no effort to stabilize the channel or flow paths. The limited-time approach may use costly structures while the unlimited time approach may be in direct conflict with land use and development pressures. This manual attempts to identify the nature of piedmont flood hazards to enable an enlightened or compromise approach to land development and use between these diverse positions.

Some engineers, geomorphologists and flood plain managers share a biased perception of floods on piedmonts such as *alluvial fan flooding* because the term conjures up images of debris flows, loss of life and destruction of property. Attention has been on the published accounts of spectacular sediment and flow dynamics over a few minutes and hours at the expense of less dramatic (longer time span) processes and landform conditions. Unbiased estimates of future flood hazards should consider several factors of process dynamics (Schumm, 1991) such as the rate of basin (source) debris accumulation, debris-flow potential and the redistribution of deposited sediment by local rainfall.

Baker (1994) recently described extreme stereotype positions on flood hazard definition held by engineers and geomorphologists. Baker points out that because flood damages continue to rise the effectiveness of conventional flood science that uses idealized mathematical models and theoretical generalization of flood frequency is doubtful. He points out that the models should be calibrated using geologic and hydrologic data. A

geomorphologic approach to understanding floods uses indices of real processes that are recorded in sediments and landforms. Baker concludes that geomorphic flood hazard analysis provides insight to understanding the problem.

The use of geomorphic evidence of past floods to predict the future flood hazard is analogous to the use of streamflow gage data to estimate the 0.01 probability flood. A probability distribution typically is fitted to past annual peak discharge data at a streamflow gage and this flood frequency relation is used to estimate the magnitude of the 100-year flood that is then used to define the flood boundaries. In a like manner, the geomorphic evidence of past floods such as sediment deposition, surface texture, channel bank erosion and particle rounding and sorting is used to predict the nature and location of future floods. **Thus, both the engineering and geomorphologic approaches use past information to make predictions.**

The difference in the engineering and geomorphologic approaches in the use of the 100-year peak discharge is significant. For example, the typical engineer must have a value of the peak discharge for the 0.01 probability flood to run the standard step model and produce flood boundaries is accordance with traditional riverine methods. On the other hand, the geomorphologist does not need a value of the 0.01 probability flood to define flood limits of geologically recent floods. The geomorphologist examines recent deposits to define the water level boundary, profile and/or discharge. It is important to note that the geomorphic approach does not rely on stable flow path geometry. Thus, the geomorphic approach becomes more useful as the amount of landform instability increases. For arid piedmont areas like Maricopa County where many streams have years with no flow and some landforms are unstable the use of probability distributions may be invalid (Hjalmarson and Thomas, 1992) and the use of fixed geometry methods to define flood limits may also be invalid.

Perhaps the greatest difference in the perspectives and concerns of engineers and geomorphologists is the span of time of interest. Engineers typically are concerned with the present, near past and near future while geologists and geomorphologists are additionally interested in the far past and far future (Schumm, 1991). Except for problems such as hazardous waste, engineers commonly are concerned with conditions for the next 50 to perhaps few hundred years while the geologist commonly is interested in the past millions of years. This problem is being overcome as more engineering prediction is being accomplished using earth science information.

The above diverse viewpoints can be used together to produce a better definition of the true flood hazard. The geomorphic approach can be used to compliment the conventional engineering approach that uses idealized but consistent models such as HEC-1, HEC-2/HEC-RAS and flood frequency methods outlined in Bulletin 17B (U. S. Water Resources Council, 1981). **Thus, the engineering and geomorphic approaches are complementary and more effective when used together.** An example of the application of both approaches in the City of Fort Collins, CO is given by Grimm (1996).

1.6 Approach

Procedures developed for interpreting the earth (Schumm, 1991), for characterizing incised channels (Schumm and others, 1988) and for identifying alluvial fans and alluvial-fan areas subject to flood hazard (NRC, 1996) form the basis for identifying flood hazards on piedmonts. Procedures in the Alluvial Fan Flooding report (NRC, 1996) are the direct result of FEMA, as the enforcer of the NFIP, asking the NRC for help on the alluvial fan flooding controversy. The NRC alluvial fan method is adopted and modified for piedmonts of Maricopa County to assist engineers and hydrologists in defining and characterizing areas subject to flooding. The three stages of this method progressively focus on the definition of flood hazard zones as follows (See also Table 1.1 for these stages and the requirements for study contractors):

1. Recognizing and characterizing the kind and extent of piedmont landforms and showing these landforms on a map.

2. Defining the nature of the piedmont landform environment and identifying unstable and stable components of the piedmont and showing these areas subject to various flood hazards on a map.

3. Identifying and applying methods for defining and characterizing areas affected by the 100-year flood and showing these areas on a map.

Stage 1 uses indicators such as soil type to determine the type and extent of the landform -- pediment, relict fan, alluvial fan or alluvial plain--on the piedmont. Stage 2 also uses indicators and relations (see sections 8.1 to 8.3) to delineate the type and extent of flood hazard. The use of indicators in stage 1 is a form of differential diagnosis or the art of distinguishing between one landform and another, and selecting the landform that comes closest to the findings (Schumm, 1991). The indicators in stage 2 are used in a like manner to distinguish between one type of flood hazard and another (stable or unstable areas). Because a single indicator seldom produces a reliable diagnosis, several indicators are used to critically evaluate the landform and the flood hazard. The completion of stages 1 and 2 should satisfy the reconnaissance requirements of section A5-2A of FEMA Manual 37 *Guidelines and Specifications for Study Contractors* (FEMA, 1995) as follows:

> *When it is determined that an area in a community is subject to alluvial fan flooding, a thorough reconnaissance of the area should be made in order to determine the source of flooding, the apex, the boundaries of the area, the limits of entrenched channels and the locations of barriers to flow (natural or manmade) that render some areas more flood prone than others, and locations of single- and multiple-channel regions. The reconnaissance should make use of available topographic, geologic, and soil maps; aerial photographs; historic records; and site inspections.*

Stage 3 is the selection of appropriate method(s), such as an engineering method like HEC-RAS or the geomorphologic method defined in this manual, to define the extent of the 100-year flood.

The above three-stage assessment generally is concerned with relatively short spans of time of decades to a few hundred years (the historic period). It is not concerned with how the mountains were formed or whether relict alluvial fans were formed 1 or 10 million years ago because these issues concern periods of time beyond the scope of present and projected flood hazards. It is important, however, to distinguish among the three basic materials--bedrock, relict valley fill deposits and recent fluvial deposits--because whether an area is unstable or stable depends largely on the underlying rock and sediments.

This manual is concerned primarily with the regulatory or base flood with a recurrence interval of 100-years. To approach this end, time scales up to about 10,000 to 15,000 years that represent the Holocene geologic epoch may be used. For the short term, old maps and aerial photographs may be available to provide a good historical record that can be used to predict for decades. For the long term, soil development, desert pavement and desert varnish may be used. For intermediate spans of time, empirical relations can be used to predict the direction of change and, to a lesser degree, the magnitude of change. These are generally statistical or threshold relations between, for example, channel morphology and some independent variable such as discharge. The resulting relations can be used in an attempt to predict stream response to altered conditions for decades and perhaps centuries. **Because it may not be practical to precisely use a 0.01 probability for flood regulation, evidence of inundation, sedimentation and channel movement may span longer periods, and therefore the probabilities will be smaller, to be conservative on the side of caution as discussed previously.**

1.7 Overview

This manual is a step-by-step procedure for characterizing piedmont landforms and associated flood hazards, especially areas subject to flooding on active and inactive alluvial fans. Chapter 1 is this introduction. Chapter 2 (STAGE 1) is a description of how to identify and produce a map of the four major landforms - pediments, relict fans, alluvial fans and alluvial plains - on piedmonts. Chapter 3 (STAGE 2) is a procedure for identifying where the flood hazards are on pediments, relict fans, alluvial fans and alluvial plains and how to produce a map of these hazard areas. Chapter 4 (STAGE 3) is a discussion of realistic methods for definition of 100-year flood hazards and Chapter 5 is the application of the procedure to three sites in Maricopa County. Chapter 5 also includes detailed descriptions of selected techniques for identifying stable and unstable areas and defining the 100-year flood hazard. The three basic stages of this progressive procedure are described in chapters 2 to 4, respectively, of this manual (See Table 1.1).

Table 1.1 Outline of geomorphic-engineering approach to piedmont flood hazard assessment.

Stage*	Chapter	Task, procedure and required products.
1	2	**Recognize and characterize piedmont landforms.** Identify landform using procedures given in Tables 2.1 and 2.2 using indicators in Table 2.3 and Chapter 2. A map showing the topography, soils, surficial geology and significant features such as desert pavement and vegetation of the pediment, relict fan, alluvial fan and/or alluvial plain is produced.
2	3	**Define the nature of the landform environment.** Identify stable and unstable areas using indicators given in Chapter 3 and Table 3.1 and selected characteristics of stable and unstable flood hazard areas given in Table 3.2. For alluvial fan landforms identified in Stage 1 define stable and unstable areas using steps given in Table 3.3. For active alluvial fans identify the source of sediment in the drainage basin. A map showing areas subject to stable and unstable flood hazards with supporting field observations of significant factors such as the location and amount of sediment deposition, erosion, vegetation and flow path movement is produced.
3	4	**Define the 100-year flood hazards.** Characterize the 100-year flood hazards of piedmont landforms as outlined in Table 4.1 and described in Chapter 4. For stable areas characterize the 100-year flood using guidelines in FEMA Manual 37 (FEMA, 1995) and appropriately supplemented with geomorphic methods**. For unstable areas such as active alluvial fans estimate the 100-year flood hazards using geomorphic methods possibly supplemented by traditional hydraulic methods. A map showing both stable and unstable areas subject to the 100-year flood is produced.
--	5	**Report findings and assumptions for the three stages as shown for the two sample sites in Chapter 5.** An engineering report is produced that includes but is not restricted to the following items: (1) a discussion of how the map of the landforms, the map of the stable and unstable areas and a map of the 100-year flood were produced, (2) a discussion of how soil classification maps were used, (3) surveyed channel cross sections and stream profiles, (4) hydraulic computations including conveyance-slope estimates and (5) substantiation of conclusions reached with significant field evidence, assumptions and limitations.

*** Modified from stages used by the National Research Council (1996).**

**** Appendix A5 of FEMA Manual 37 typically should not be used.**

There are four sections at the end of the manual-- acronyms, glossary, miscellaneous methods and references. The miscellaneous methods are published (or are based on published) geomorphologic and engineering methods for assessing channel and landform stability and the intensity of fluvial hazard that can be used in Chapters 3 to 5 of this manual. The glossary is taken primarily from Alluvial Fan Flooding by the National Research Council (1996).

1.8 Standards

Flood studies must be accomplished in accordance with standards of FEMA, ADWR and the FCDMC. For example, documentation standards given in State Standard ***Instructions for organizing and submitting technical documentation of flood studies*** (SSA1-97) should be followed.

2
PIEDMONT LANDFORMS OF MARICOPA COUNTY

This chapter is a description of piedmonts and the four major sub-landforms that comprise piedmonts in Maricopa County. Piedmonts of Maricopa County are the sloping landforms that typically lie between isolated block mountains and aggraded desert plains of the Basin and Range Province (Fenneman, 1931). The four major sub-landforms are relict fans, pediments, alluvial fans and alluvial plains. These landforms can be reliably identified using several combined criteria. Each landform has some significance to floodplain managers and engineers and each has distinctive characteristics. The description of the four landforms is followed by a discussion of several identifiers that are readily used to recognize the type of landforms. An example map at the end of this chapter shows the kind and extent of some piedmont landforms and represents the completion of stage 1 of this manual.

Flood hazards on piedmonts of Maricopa County are related to the four landforms as shown in Figure 2-1. Nearly all of the streams draining the mountains and piedmonts flow only in direct response to rainfall. Floodwater is typically confined to defined channels of pediments and relict fans (Table 2.1).

Channels of streams typically draining mountainous areas of a few square miles cross pediments and relict fans. Tributary channels on the pediments and relict fans typically drain to these larger *throughflow channels*. On lower pediment slopes there may be a transition to alluvial fans or bajadas, and the channels may split and form a network of distributary channels. Many of these distributary channels are incised in developed soils and have stable paths of flow. Below some mountain fronts, pediments and relict fans the flow in channels loses confinement (at a topographic break) and active alluvial fans are formed.

Active alluvial fans are aggrading landforms where sediment is deposited by spreading floodwater and flow paths may change. On bajadas and alluvial plains with little transverse relief and little channel incision, floodflow may be shallow and unconfined. These rather smooth landforms include former (in the geologic context) flood plains of base-level streams, such as lower Cave Creek and the Salt River, and alluvial apron-like deposits that lack the undulating form of several coalesced alluvial fans (bajadas). Clearly, the association between the surface features of the four major landforms of piedmonts and the extent of flooding is useful to engineers and floodplain managers.

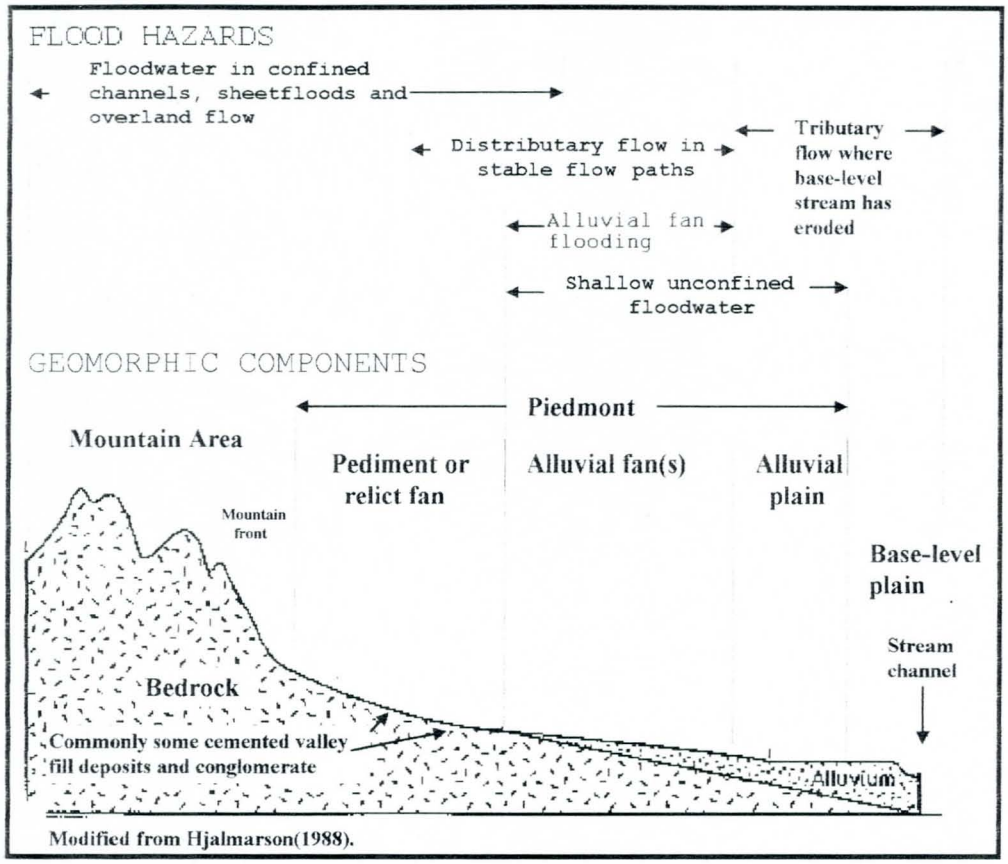


Figure 2-1. Typical flood hazards and landforms on piedmonts in Maricopa County.

2.1 Landforms

Several important distinguishing characteristics of relict fans, pediments, alluvial fans and alluvial plains are described in this section. In general, distinctive characteristics of pediments and relict fans are the products of erosion and distinctive characteristics of alluvial plains and many alluvial fans are the products of sediment accumulation. A summary of general characteristics of the four major landforms is listed in Table 2.1 and characteristics of relict fans, pediments, alluvial fans and alluvial plains are described in the remainder of this section.

2.1.1 Relict fans

A relict fan is an erosion remnant of an old alluvial fan that was formed in a past geologic epoch and hardened by cementation. Many relict fans in Maricopa County are a heterogeneous assortment of generally weakly consolidated slope-wash deposits (Cooley, 1977). These deposits generally form a thin but widespread mantle on generally firmly

Table 2.1. Component landforms, common soil types and significant characteristics of piedmonts of Maricopa County

Landform	Component Landform (common soil types)[1]	Significant characteristics[2]
Relict Fan	Erosion Fan remnant (Mohall-Contine, Gunsight-Chuckawalla- Rillito, Pinamt, Tremant-Ebon- Momoli-Carefree, Eba-Pinaleno, Laveen, Mohave-Continental)	Typically incised channels in cemented conglomerate of cobbles and boulders. Drainage typically is tributary but small pockets of distributary channels may occur. Some relict fans have a ridge-valley morphology. Incised throughflow streams typically are more than 10 ft. deep and less than 20 ft. deep with steep banks. Desert pavement and rock varnish are common on flat interfluves. General slope typically is 1-6 percent.
	Inset Alluvial Fan (Carrizo, Gilman, Antho, Estrella, Glenbar)	Generally small and confined between relict fan remnants. Fluvial deposit that can act like a floodplain with high potential for scour and fill. Much of the alluvial fan material may be from gulling of the relict fan and such material may be bouldery.
Pediment	Bedrock remnant (Gran-Rock outcrop, Gran-Wickenburg complex, Cherioni-Rock outcrop association)	Incised channels generally formed in bedrock and old soils. Drainage typically is tributary but distributary channels may be present especially on lower slopes. There are many first order tributary channels. Parent rock typically is granite with large granite boulders on the upper slopes near the mountains. The crests of transverse slopes are small and shoulders are steep. General slope typically 2-5 percent.
	Inset Alluvial Fan (Anthony-Arizo complex, possibly Eba-Pinaleno and Carrizo)	Generally small alluvial fan confined between pediment. Fan typically widens like a partially opened fan and lower part typically narrows as distributary channels rejoin. Fluvial deposit that typically is actively aggrading and eroding with possible balance of sediment over past few hundred years.
Alluvial Fan	Active Alluvial Fan (Carrizo, Gilman, Antho, Brios, Estrella, Glenbar, Coolidge, Valencia, Torrifluvents, Maripo)	Fluvial deposits with little, if any, calcium carbonate development. Fan shaped in plan view with hydrographic apex at topographic break. Typically no desert varnish. Stream channels are wide with little incision or channels are very small. Active portions of alluvial fans in Maricopa County typically are a small part of an alluvial fan that is mostly inactive. General slope 1-10 percent.
	Inactive Alluvial Fan (Laveen, Anthony, Antho, Momoli, Mohave, Pinamt, and other soils of relict fans)	Fluvial deposits with much carbonate in K soil horizon. Fan shaped typically with distributary network of incised-throughflow channels. Transverse slopes of interfluves are flat. Interfluves typically drained by small channels that are tributary to throughflow streams. Interfluve slopes are stable and throughflow streams typically are incised less than 3 ft.. General slope typically 1.5 - 4 percent.
Alluvial Plain	Piedmont Toe (Gilman, Estrella[3], Glenbar, Momoli, Denure, Antho, Contine, Mohall, Avondale)	Aggrading or rather stable fluvial deposit with little transverse relief and small throughflow channels. Channels typically are less than 1 ft. deep. Few tributary channels head on the surface. Little, if any, rock varnish but possibly some desert pavement. Can be channel incision of a few feet where there has been general headcutting of base- level stream. General slope is 0-3 percent.

[1] Soil complexes on NRCS maps include one or more of the soil types associated with the indicated landform.

[2] These characteristics may be observed on topographic maps, aerial photographs and by field inspection.

[3] Some of this soil is associated with alluvial fans by Camp (1986) and with alluvial plains in this manual. This soil is associated with alluvial plains for this manual because Estrella loam (Soil type 50) typically is at the toe of piedmonts, the slope is small and the landform does not meet the criteria for alluvial fans (NRC, 1996). This is an example of a few minor inconsistencies between this manual and NRCS soil surveys that have no effect on the reliability of the method.

cemented boulder conglomerate at least a few feet thick. See Christenson and Purcell (1985), Machette (1985), Compton (1977), Field and Pearthree (1992) and Camp (1986) for descriptions of pedogenic soil development and calcic horizons. Many relict fan areas are the remaining parts of larger landforms that have eroded away or have been partially buried. The head of some relict fans is at a mountain front (commonly the Ebon or Cipriano soil series (Camp, 1986)) and is easily identified because the general slope change is abrupt at the mountains. The typical lower slopes or toe of the relict fans is where the conglomerate is covered by recent fluvial material.

2.1.1.1 Transverse relief

Some relict fans have distinct rounded transverse hillside shoulders with concave foot slopes as shown in the first sketch of Figure 2.2. Relict fans with these ridges have a distinct texture and appearance that can be easily seen on color-infrared and other aerial photographs. The transverse relief, between 3 feet and 15 feet, usually can be seen on 7.5- minute series USGS topographic maps. Peterson (1981) describes these landforms as follows:

> *"The typically broadly rounded shoulders meet from either side to form a narrow crest and merge smoothly with the concave back slopes. In ideal examples, the slightly concave foot slopes of adjacent ballenas merge to form a smoothly rounded drainageway."*

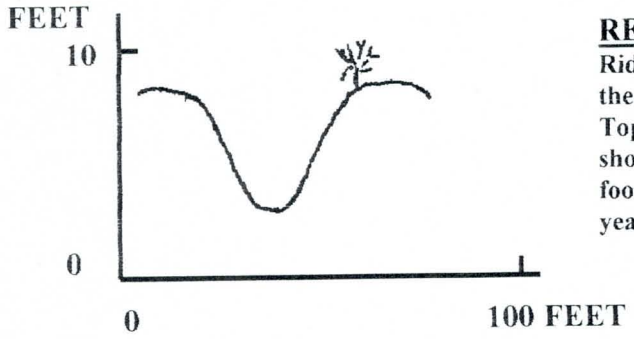
Other more recently dissected hillsides have an abrupt break at the shoulder with steep back slopes along incised throughflow streams as shown at the left bank of the large channel in the second sketch of Figure 2.2. The larger channels that head in the mountains commonly are separated by wide interfluves that are cut by small tributary channels, which form, on the relict fan. These tributary channels are V-shaped with narrow beds composed of little fluvial material. The larger throughflow channels that head in the mountains commonly have flat beds with exposed conglomerate nickpoints and boulders and cobbles.

Relict fans undergoing dissection have characteristics similar to typical incised channels described by Schumm and others (1988, page 128). Examples of incised channels are shown in Figures 5.9 to 5.14 of the White Tank Park site in Chapter 5 of this manual.

2.1.1.2 Relict fans and pediments

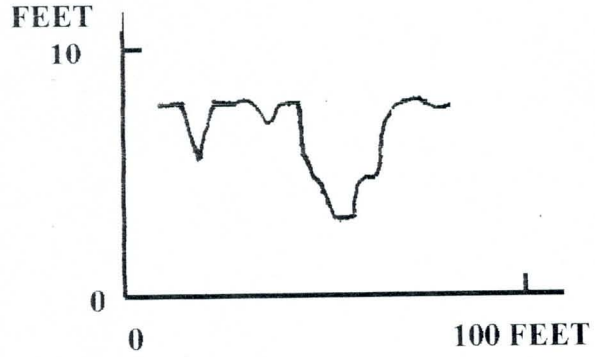
Typical relict fans and pediments in Maricopa County are modern erosion features. Pediments are underlain by bedrock whereas relict fans are erosion remnants of old-hardened (inactive) alluvial fans.

Many relict fans and pediments have similar flood characteristics. For example, relict fans and pediments typically have tributary drainage patterns and the 100-year flood is



RELICT FAN (RF)

Ridges and valleys of some relict fans where the ridges have a general parallel appearance. Tops of ridges can be wider and flatter that shown here. Ridge shoulders are convex and foot slopes are concave. The level of the 100-year flood typically is well below the ridges.

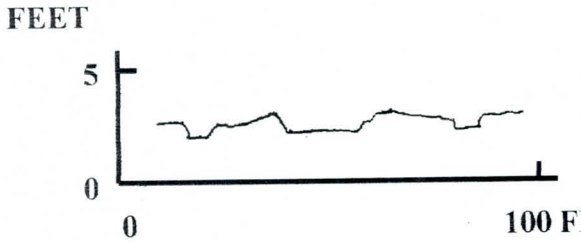


RELICT FAN OR PEDIMENT (RF & P)

Incised channels where larger channels typically head in mountains and have flat beds with fluvial bed material. Bed material in larger channels can be boulders and cobbles where incised in relict fan of boulder conglomerate or where mountains and pediment are metamorphic or volcanic rock.

INACTIVE ALLUVIAL FAN (IF)

Incised channels where large flat bed channels typically head in the mountains and transport sediment from the upslope areas. The drainage network of the larger channels is distributary and of the smaller channels is tributary. Larger channels typically are lined with paloverde and/or mesquite trees.



ACTIVE ALLUVIAL FAN (AF)

Wide channels with low banks. Bed and banks of active channnel can be higher than bed and banks of nearby channels. Channel beds typically are flat.

Figure 2.2 Sketches of transverse cross sections of piedmont landforms.

confined to defined channels and adjacent land. A significant difference is the *drainage texture* of relict fans typically decreases upslope and the drainage texture of pediments typically increases upslope (Hjalmarson and Kemna, 1991). The drainage texture (spacing of the low order drainage channels depicted by the crenulation count on contours of USGS 7.5 minute topographic maps) of relict fans, pediments and inactive alluvial fans is discussed later in this chapter.

2.1.2 Pediments

Pediments are developed on bedrock and are formed by weathering and erosion. Pediments of Maricopa County may resemble inactive alluvial fans and relict fans largely because the surface of pediments can be covered with sand and gravel a few inches to a few feet thick. The form of the surface reflects the slope and shape of the bedrock surface (Twidale, 1982, p. 190). Upper slopes commonly are bouldery and more gentle lower slopes are gravel, sand and silt.

Most pediments in Maricopa County are granite or granite-like igneous rocks where the head of the pediment is at a mountain front. The pediment head is easily identified because the slope change at the toe of mountain fronts is abrupt. There are fewer large boulders on the pediment than on the mountain and, except for inselbergs, the size and number of the boulders decreases downslope. For this user's manual, the toe of the pediment is defined or where the bedrock is sufficiently covered by fluvial material and/or weathered granite that is not visible along eroded channel banks and there are no large boulders on the land surface. Most of the surface material at the pediment toe is coarse sand from the weathered granite. For this user's manual, a pediment is where there are bedrock exposures, even if the exposures are scarce along incised channels.

2.1.2.1 Granite pediments

Most pediments are thought to form by back-weathering erosion of the mountains and pediments with accompanying alluviation on lower slopes where there are alluvial fans, bajadas and alluvial plains by lateral planation or by deep weathering and stripping. Granite areas, and possible other igneous rock areas, are formed by in situ weathering and down-weathering and the transition from the pediment to the alluvial fan-like area is a function of the depth of underlying weathered granite. These fan-like areas commonly have inset fluvial deposits that form the core of the fan-like area at and closely below the apex. When exposed to percolating water or the fluctuating water surface of aquifers, granite can weather to great depths. Recorded depths of weathering are from 50 m to more than 200 m in humid regions and 40 to 50 m in semiarid regions (Twidale, 1982, p. 71). Moss (1977) found weathering of granite at the Union Hills sand pits in Maricopa County to depths of 37 ft. and to depths of 90 ft. at a drill hole.

According to Twidale (1982, p. 190) the slope of granite pediments of the world varies between 1/2° to 7° (0.87 to 12.4 percent) but they typically are inclined at 1/2° to 2-1/2°

(0.87 to 4.4 percent). The grade of pediment slopes in Maricopa County is in the mid to upper range of these typical values. In addition, slope changes along the profile of granite pediments and piedmonts of Maricopa County are typical where most profiles are slightly concave upward and other profiles are uniform or rectilinear.

Granite piedmonts may be at the root of the disagreement about the distinction of pediments and alluvial fans among geomorphologists. For example, the discussion and reply between V. C. Miller (1971) and D. O. Doehring (1971) over the definition of pediments and alluvial fans and the discrimination of them (Doehring, 1970) may be the result of in situ weathering. In situ weathering of granite produces fan-like areas of distributary channels; and, as Doehring suggests, a distributary drainage network forms where weathering depths are more than about 50 ft. (Doehring, 1970. p. 3109). Miller appeared to discount the discrimination problem simply because a pediment is an erosion surface and an alluvial fan is a depositional surface. Mammerickx (1964) observed that the stream pattern of not-so-deep dissection (less than 3 feet) was distributary (braided is the term used by Mammerickx) while the stream pattern for deeper dissection was not distributary.

Davis (1938, p. 1361) recognized the weathering similarities of igneous rocks but he also was clear that granite rocks weather differently than other igneous rocks in arid climates. Davis, in his contrasting of *sheetfloods* and streamfloods on weathered granite, points out that both are engaged in erosion, transport and deposition but sheetfloods are more engaged in erosion and transportation. Davis shows an example of the concentrating of sheetflooding at a highway culvert and the resulting streamflooding at the culvert with a distributary channel network below. This manmade conversion of sheetflood into streamflood and then back to sheetflood is similar to some natural drainage networks on granite piedmonts in Maricopa County.

Some pediments have been tilted and in places tilted by normal faults (Cooley, 1977). Some deposits on pediments are cemented conglomerates. According to Twidale (1982), pediments of Arizona are planate rock surfaces or "rock pediments". Twidale reports that "McGee (1897) recorded his amazement on encountering these forms in Arizona late last century. They were different from anything previously recorded:"

> *At first sight the Sonoran district appears to be one of half-buried mountains, with broad alluvial plains rising far up their flanks, and so strong is this impression on one fresh from humid lands that he finds it difficult to trust his senses when he perceives that much of the valley-plain area is not alluvium but planed rock similar or identical with that constituting the mountains...*
>
> *During the first expedition ...it was noted with surprise that the horseshoes beat on planed granite or schist or other hard rocks in traversing plains 3 or 5 miles from mountains rising sharply from the same plains without intervening foothills (McGee, 1897, pp. 90-91).*

Some distributary channel networks on granite piedmonts reside on weathered granite and not on alluvium. Inset fluvial deposits have formed at topographic breaks and these deposits are separated by weathered granite interfluves that have developed soil. The fluvial deposits are along some active drainageways below the apex and upslope of a network of distributary channels incised to depths less than 3 ft. Scour and fill of the fluvial deposits during floods may influence the formation of the distributary channels in the weathered granite downslope. Studies of these stream networks in Maricopa County show little or no movement of flow paths for the past 50 years (National Research Council, 1996 and Rhoads, 1986).

In conclusion, users of this manual should be aware of the above controversy surrounding granite pediments in Maricopa County. Landforms commonly thought to be alluvial fans by FEMA appear to be weathered residual granite or a mix of weathered residual granite and fluvial deposits. The stream pattern of these controversial areas is distributary and flow paths are stable (See the Carefree example site in National Research Council, 1996). Channels are incised less than 3 ft. and are lined with paloverde and mesquite trees. The flood hazard assessment (Stage 3 in Chapter 4) and use of hydraulic models as described in this user's manual is not significantly affected by this controversy.

2.1.2.2 Drainage pattern

Near the mountains on upper slopes of pediments, the drainage pattern is tributary. Floodwater typically is confined to well defined channels in these areas (Table 2.1).
On the lower slopes, the drainage pattern is a mixture of tributary, distributary and anastomosing. The defined channels on the lower slopes are less incised. The 100-year flood typically is confined to defined channels and adjacent small terraces of pediments. On lower slopes where the channel depths are small, the 100-year floodwater can spread over adjacent land. For further discussion of the drainage pattern on pediments of Maricopa County, see Moss (1977), Rhoads (1986) and Hjalmarson (1978).

2.1.2.3 Drainage texture

Drainage texture, as depicted by upslope crenulation count on contour lines of USGS 7.5-minute topographic maps, commonly increases upslope on pediments. According to Doehring (1970), the drainage texture of pediments is finer (more low-order drainage channels) in the upslope direction. Pediments commonly have many streams of various sizes from rills to streams with large incised channels, and many of these streams head on the pediment.

The transition at the upper slopes of pediments generally is easy to identify because the transition from the mountain to the alluvial plain is direct with a marked change in the slope of the land surface at the mountain fronts. The transition of the lower pediment slopes to alluvial plains and fans is more difficult to identify because the slope of the land surface is nearly constant or is changing only gradually. Drainage texture, however,

typically changes at the transition as suggested by the regression relations in Figure 2.2-b discussed later in this chapter (Doehring, 1970 and Hjalmarson and Kemna, 1991).

2.1.3 Alluvial Fans

An alluvial fan is *"a sedimentary deposit at a topographic break, such as the base of a mountain front, escarpment, or valley side, that is composed of fluvial and/or debris flow sediments and which has the shape of a fan either fully or partly extended."*(NRC, 1996). Alluvial fans of Maricopa County typically were formed in Quaternary time when there was general subsidence in the Basin and Range province and filling of intermountain valleys with alluvium. These *alluvium* deposits have been subjected to structural warping, tilting, uplifting and subsidence that continue today. The current episode of the geologic history of Arizona is one of general erosion (Cooley, 1977). Some streams erode rock from mountain areas and deposit the detritus below a topographic break to form a rather evenly sloping cone called an alluvial fan.

The reader may question the relevance of the above brief geologic history to the flood hazard assessment. The geologic history admittedly is beyond the scope of this manual but it can be important. For example, the geologic history can be very important if landform and flood characteristics of alluvial fans and other landforms are transferred to sites in Maricopa County and visa versa. Characteristics of alluvial fans and other landforms described in technical literature may be different for sites in Maricopa County that have different geologic pasts.

Many alluvial fans in Maricopa County have evolved or matured to a general state of inactivity where much of the fan is segmented by incised channels (see third sketch of Figure 2.2). These channels commonly have a distributary drainage network and these flow paths may be considered stable for regulatory purposes. Other alluvial fans or parts of segmented alluvial fans are actively aggrading and/or are subject to movement of flow paths (See forth sketch of Figure 2.2). A procedure for distinguishing older and young alluvial fans is described in Chapter 3 of this manual. The following is a procedure for recognizing and characterizing alluvial fans based on the National Research Council (1996) report *Alluvial Fan Flooding.*

2.1.3.1 Composition

An alluvial fan is a sedimentary deposit of loose, unconsolidated or weakly consolidated sediments. For much of Maricopa County Camp (1986) and Hartman (1977) have mapped these sedimentary deposits in NRCS Soil Survey reports. These typical soil types are listed in Table 2.1. The investigator can also use published geologic maps such as the Arizona Highway Geologic Map (Cooley, 1967), maps of Arizona showing selected alluvial, structural, and geomorphic features (Cooley, 1977), maps by the U.S. and Arizona Geological Surveys (Arizona Geological Survey, 1997) and maps in several technical journal reports by specialists such as Wells (1977). Modern sedimentary

deposits are shown in yellow on recent geologic maps and typically labeled "Qal". Field reconnaissance should be done to verify that the landform is a sedimentary deposit.

2.1.3.2 Shape

Alluvial fans are landforms that have the shape of a fan either partly or fully extended. Modern and old flow paths radiate outward to the perimeter of the fan toe. Old flow paths can be eroded away or erased by wind, rain and sheet flow. Young alluvial fans typically are convex upward in the transverse direction. The transverse convexity can be eroded away on older alluvial fans or lost by coalescence with adjacent alluvial fans.

2.1.3.3 Topographic break

Alluvial fans are located at a topographic break. This locus of markedly more channel migration and sedimentation is called the *topographic apex*. The topographic apex is where the stream widens and corresponding flow depths decrease resulting in less sediment transporting power. The topographic apex is the uppermost apex of the alluvial fan and may not be the present location where sediment deposition starts. The hydrographic apex is the highest location of an active alluvial fan and the topographic apex is the highest point on the alluvial fan. Both apexes are or were, respectively, at topographic breaks where flow paths are or were unstable.

2.1.3.4 Drainage texture

Doehring (1970) observed that the drainage texture on alluvial fans with incised channels generally was constant along the axis of fans. Studies by Hjalmarson and Kemna (1991) also showed drainage texture of inactive alluvial fans was uniform in the upslope direction on 7.5-minute topographic maps.

2.1.3.5 Topographic maps

Alluvial fans usually can be identified on standard 7.5-minute series of USGS topographic maps, which provide useful information to delineate alluvial fan boundaries. Identifying characteristics are:

- Bifurcating intermittent stream symbols on maps depict distributary channels.
- Small wash or intermittent stream symbols that end abruptly in an area with smooth contours also may depict distributary flow on the fan surface.
- Broad areas of piedmont that are marked with the sand symbol (stippled pattern) may depict aggrading areas and possibly bifurcating channels.
- Relative drainage texture domains depicted by contour-crenulation counts (small rounded upslope projection of a contour line) provide excellent clues to the type of landform and potential alluvial fans (Hjalmarson and Kemna, 1991

and the Henderson Canyon example (National Research Council, 1996)). The drainage texture of active areas of distributary flow normally is uniform in the upslope direction.

- Smooth contours that are parallel and either straight or slightly convex pointing downstream in plan view indicate mild transverse relief that may result from bifurcating channels. Contours with relatively large and narrow crenulations may reveal remnants of old inactive fans.

It is important to note that concentric semicircular contours that bow downslope do not necessarily depict an active alluvial fan. Many older alluvial fans that have developed tributary channels and presently are eroding have concentric semicircular contours that bow downslope. Eroding fluvial processes are active on these old surfaces and alluvial fan processes (aggradation) no longer are active except where an active fan has formed within an old fan. It is common for older alluvial fans to host active alluvial fans. Thus, a portion of a semicircular contour that bows downslope that is smooth and bounded by relatively large and narrow crenulations may indicate bifurcating flow and the alluviation of an active alluvial fan.

2.1.4 Alluvial plains

Many alluvial fans, in particular the lower portions of alluvial fans, coalesce into a generally smooth and nearly level surface called an alluvial plain (Figures 1-1 and 2-1). An alluvial plain is either a relict floodplain of a base level stream or a very low gradient (< 0.5 percent) fan delta built onto the basin floor (Peterson, 1981). Alluvial plains may abut defined channels at the basin floor or they may transition into floodplains (the basin floor) of base level streams. The upper and lower boundaries of alluvial plains can be indistinct with intricately mixed sediment from upslope areas of the piedmont and base level stream. Fortunately, precise boundaries typically are not necessary for flood hazard definition because the flood hazard of alluvial plains, adjacent alluvial fan toes and adjacent floodplains of base level streams is typically from shallow floodwater except where there is channel incision from lowering of the base level stream. The user of this manual is encouraged to use NRCS soil maps (see Table 2.1 for soil types) and detailed geologic maps to define alluvial plains based on sediment composition.

2.2 Identification

The type of landform is identified using indicators such as drainage texture, rock varnish, cementation of deposits and channel shape. Some of the indicators used for landform identification such as rock varnish and desert pavement are also indicators of age or surface stability discussed in Chapter 3 of this manual. For example, many relict fans and some pediments are covered with desert pavement that suggests the landform is old and the surface is stable because fluvial processes of erosion and sediment deposition have not disturbed the surface for thousands of years. The steps and indicators of this method of flood hazard assessment are based on several publications and sources

including those used by Christenson and Purcell (1985), Hjalmarson and Kemna (1991), Philip A. Pearthree, written communication (1992), CH_2M Hill (1992), Hjalmarson and Tram (1996) and the National Research Council (1996).

The general steps for piedmont landform identification are shown in Table 2.2. The user should first obtain topographic, geologic and soil maps, aerial photographs and any technical reports such as journal articles on the geomorphology, geology, soil, vegetation, and flooding in order to determine the general morphology and location of the

Table 2.2. Steps for identification of piedmont landforms for assessment of flood hazards.

Recognizing landforms	Data information source
1. Define general setting (Geology, tectonics, soils, relief)	Geologic, topographic and soil maps. General reference.
2. Define physical setting and type of landform	
Geomorphology of source area (relief, slopes, feeder channel geometry, vegetation distribution, size of source area, drainage pattern)	Topographic maps, aerial photographs.
Geomorphology of piedmont (size, relief, slopes, channel geometry, vegetation type and distribution, surface color and soil)	Topographic maps, soil maps, aerial photographs.
Location of landform (Is at a topographic break? Is it at a mountain front? Is it an isolated remnant or *inselberg*? Is it inset on a larger landform?)	Topographic maps and aerial photographs.
3. Verify and refine landform characteristics	
Composition and age (Bedrock or a sedimentary deposit, soil development, desert varnish, desert pavement, surface color and caliche)	Field work using geologic maps and soil surveys
Morphology (Plan view shape, drainage pattern and spacing, channel incision and geometry, ridges and valleys)	Field work using topographic maps and aerial photographs.
Location of landform (Is it at a topographic break? Is it at a mountain front? Is it an isolated remnant or *inselberg*? Is it inset on a larger landform?)	Fieldwork using topographic maps and aerial photographs.

landform(s) along the piedmont and in the area. The second step is to use topographic maps, soil maps and aerial photographs to define the morphology of the drainage basin and the piedmont landform in order to recognize the landform. The third step, like the second step, is a continuation or refinement of the identification of the landform(s) using a field inspection of the channels and land surfaces in order to determine the composition, morphology and location of the landform. The field inspection can also be efficiently used to collect hydraulic data for hydraulic and sediment yield models. Several indicators of the major landforms in Maricopa County are listed in Table 2.3 and are described in the remainder of this chapter.

2.2.1 Indicators

Several indicators are especially helpful in determination of the type of landform on the piedmont. Some of the indicators have been discussed in previous sections for specific landforms in this manual. These "office" and "field" indicators are used to recognize pediments, relic fans, alluvial fans and alluvial plains. Office indicators are obtained from topographic maps, soil survey maps, geologic maps and aerial photographs in order to determine the type, location and morphology of the landform. Field indicators, used in step 3 above, are obtained from field observations of the stream channels and geomorphic surface, vegetation types, soil characteristics, desert varnish and desert pavement. A field examination involves walking (or driving) over the surface of the landform and along stream channels and examining cut banks, road cuts and other exposures; vegetation type and location; surface characteristics such as desert pavement, rills, desert varnish; soil development; and surface geology. Maps of these features are produced along with detailed field notes. A good starting point for landform identification is the location of the particular site of interest on the typical desert profile showing mountains and the piedmont (Figure 2.1).

2.2.2 Office indicators

Landforms can be identified on standard 7.5-minute series of USGS topographic maps especially when used in conjunction with good quality aerial photographs. The appearance of coutour lines is related to landform type as follows:

- Fan shaped, concentric and semicircular contours that bow downslope may depict an alluvial fan if there is little channel incision as indicated by small or few contour crenulations.
- Smooth contours that are straight and parallel (or slightly convex pointing downstream in plan view) indicate mild relief with active sediment deposition in geologic time. Such contours indicate active alluvial fans or alluvial plains.

Table 2.3. Selected indicators of landforms and flood hazards in Maricopa County.

INDICATOR	LANDFORM AGE[1]	LANDFORM STATE[2]	FLOOD FREQ-UENCY[3]	SIGNIFICANCE FOR IDENTIFYING LANDFORM AND STABILITY (TYPICAL)
Morphology				
ridge & valley	O	S	--	On relict fans and pediments.
Throughflow Channels[4]				
incised > 10 ft.	O	S	> Q_{100}	On relict fan surfaces where side-slope shoulders are convex and foot slopes are smooth and concave.
incised < 3 ft.	I	S	> Q_5	On inactive fans where transverse foot slopes are steep and shoulders are smooth and convex and summits between channels are smooth and fairly flat.
incised < 2 ft.	Y	U	Q_2	On unstable surfaces where banks are steep and channel width-depth ratio > 10 at bank full stage.
incised <1 ft.	Y	?	any	On alluvial plains with smooth surfaces and very little cross-drainage relief
Drainage pattern				
tributary				
parallel channels	O	S	> Q_{50}	On relict fans and pediments where ridges between first and second order streams are parallel.
dendritic channels	I	S	> Q_{10}	On relict fans and pediments and inactive areas of alluvial fans.
distributary	I,Y	?	--	On active and inactive alluvial fans and, in places, on granite or granite-like pediments
faint with wide areas between flow paths	Y	U	any	On alluvial plains where the slope is not great enough to override the influence of minor topographic irregularities.
Vegetation				
Creosote bush	O	S	> Q_{50}	On old calcium carbonate rich soil.
Saguaro	O	S	> Q_{50}	On stable surfaces.
Desert trees	I,O	MS, S	> Q_5	Along channel banks.
	Y	U	any	Scattered over area.
Soil development				
Reddish color	I	MS	?	On pediments, relict fans, inactive alluvial fans and alluvial plains and may indicate the surface is stable.
B horizon	O	S		May indicate the surface is stable.
Calcic horizon	O	S		Indicates surface has been stable for hundreds of years.
Desert varnish				
None	?	?	?	May indicate the surface is unstable. Does not form on granite or limestone and where ground cover vegetation is dense.
Some	O, I	MS, S	>Q_{10}	Varnished rocks may be reworked from older upslope surfaces such as bedrock. Also, surface may be removed by erosion.
Much	O	S	> Q_{100}	Varnished boulders and larger cobbles with few varnished smaller stones.
Desert pavement	O	S	> Q_{50}	Dense "pavement" with smooth surface.

1 Y=young (<500 years), I = intermediate (>500 and <10,000 years), O = old (>10,000 years) and ? = inconsistent indicator of age.
2 S = stable (flow paths not expected to change over regulatory period), MS = moderately stable(flow paths may change in places during regulatory period of 100 years), U = unstable (flow paths expected to change in places during large floods) and ? = not a consistent indicator of state.
3 Approximate recurrence interval at bank full level as shown in Figure 2.3. May include small adjacent overflow areas.
4 Values are for drainage basins less than 5 mi^2.

- Concentric semicircular contours that bow downslope may also depict a relict fan if the contour *crenulations* are large (indicating at least 3 ft. depth of dissection) and the drainage pattern that has developed on the landform is *dendritic* or tributary (typically observed on aerial photographs). Eroding fluvial processes are active on most of these relict surfaces and alluvial fan processes (aggradation and erosion) no longer are active except where an active fan has formed within an old fan. An older alluvial fan may host an active alluvial fan (Table 2.1).
- A portion of a semicircular contour that bows downslope that is smooth and bounded by relatively large and narrow crenulations may indicate bifurcating flow and alluviation of an active alluvial fan.

Aerial photographs used in conjunction with topographic maps are useful for defining the drainage pattern and areas of active scour, fill and sediment deposition as follows:

- A light surface color seen on aerial photographs usually indicates a young surface that has been recently eroded or subject to sediment deposition. Active alluvial fans, alluvial plain areas and sand channels typically have a light surface color.
- A dark surface color results from weathering of the surface stones. A dark surface typically indicates an old surface of desert varnish, desert pavement or oxidized soil common to relict fans and mountain slopes.
- Many active alluvial fans have a light surface with a radiating drainage pattern. Many relict fans have a dendritic drainage pattern with a dark surface of desert varnish.

Stereo pairs of aerial photographs used in conjunction with topographic maps and field measurements of channel geometry are useful for defining the amount and extent of channel incision. Old-stable landforms such as relict fans and pediments clearly have greater amounts of channel incision than young-aggrading landforms such as active alluvial fans (See Table 2.1).

Soil survey reports and maps of the NRCS are an excellent source of information on the type of landform. Soil survey reports typically identify the landform associated with mapped soil units (Camp, 1986 and Hartman, 1977). Common soil types corresponding to piedmont landforms of Maricopa County and surrounding areas are noted in Table 2.1. A major advantage of published NRCS soil surveys is the mapping is consistently accomplished in accordance with standards. A disadvantage for new users of the published NRCS soil surveys is that the reports are written for a wide range of uses and are not specifically for landform identification and flood hazard assessment. Users of soil surveys are encouraged to get assistance from NRCS soil scientists (602-280-8837).

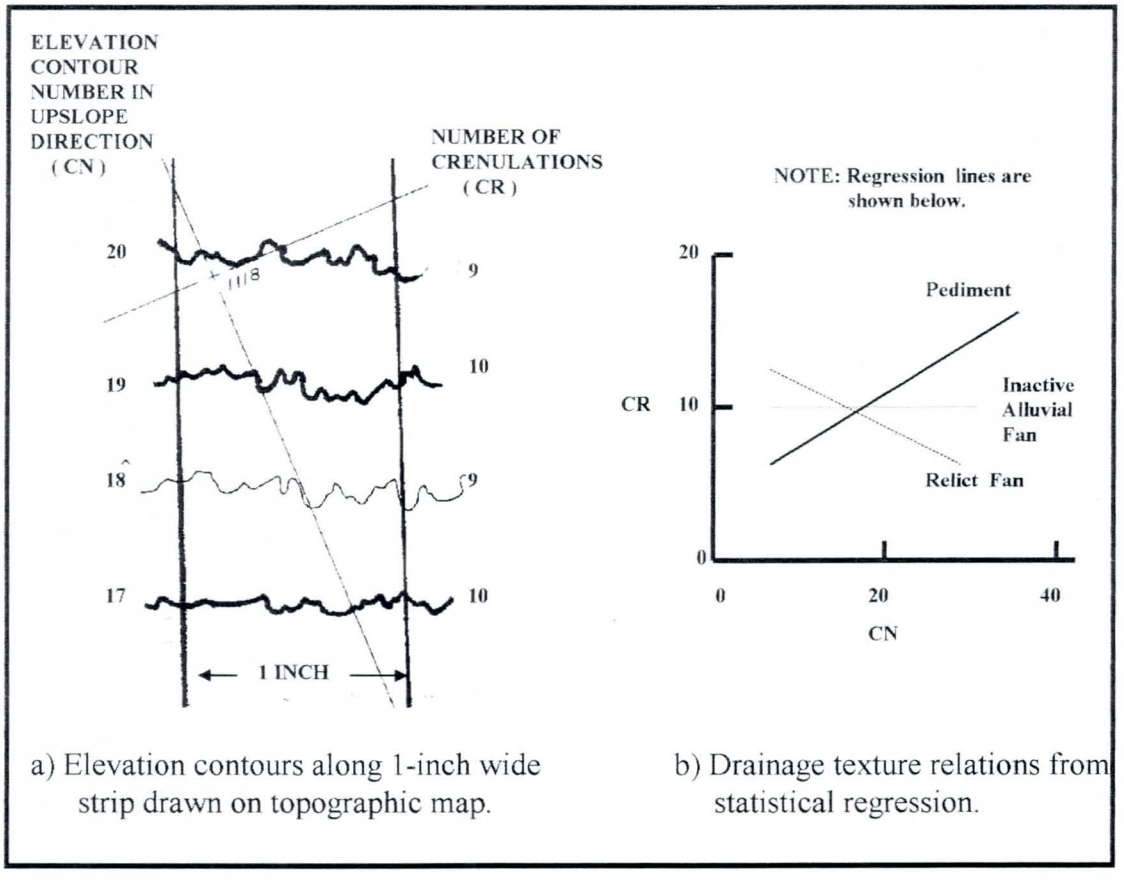
2.2.2.1 Drainage pattern

A tributary drainage pattern is characteristic of relict fans and pediments. Floodwater typically is confined to well defined channels (Table 2.1). The 50-year flood typically is confined to defined channels and adjacent small terraces. Along many throughflow

channels, the 100-year flood is also confined to defined channels and adjacent small terraces. For further discussion of the drainage pattern on relict fans and pediments, see sections 2.1.1.2 and 2.1.2.2 of this manual, Rhoads (1986) and Peterson (1981).

2.2.2.2 Drainage texture

Relative drainage texture domains depicted by contour-crenulation counts (small rounded upslope projection of a contour line) provide excellent clues to the type of landform and potential alluvial fans (Hjalmarson and Kemna, 1991). Drainage texture is measured as the number of low-order drainage channels (crenulations) along uniform widths of contour lines on topographic maps (See example in Figure 2.3a). The spacing of low order drainage channels is depicted by the crenulation count on contours of USGS 7.5-minute topographic maps. The drainage texture can be used to distinguish relict fans, pediments and inactive alluvial fans as shown in Figure 2.3b. Many relict fans have a characteristic decreasing drainage texture in the upslope direction that differs from the drainage texture of pediments and inactive alluvial fans (See for example sections 2.1.1.2, 2.1.2.3, 2.1.3.4 and 2.1.3.5 of this manual and Doehring (1970 and 1971) and Hjalmarson and Kemna (1991)).



a) Elevation contours along 1-inch wide strip drawn on topographic map.

b) Drainage texture relations from statistical regression.

Figure 2.3 Drainage texture and drainage texture relations for relict fans, pediments and inactive alluvial fans (from Hjalmarson and Kemna, 1991).

The difference in the drainage texture of relict fans and pediments has an effect on the overland flow elements of HEC-1 and slope lengths of TR-55 and RUSLE. Another difference is some relict fans, unlike most pediments, have broad rather smooth areas with little tributary channel incision between throughflow streams.

2.2.2.3 Vegetation

Vegetation type and distribution, as seen on good quality aerial photographs, can also be a reliable indicator of landform. For example, saguaro cacti, jumping cholla and creosote bush are seldom on very active alluvial fans and are typically on old surfaces of relict fans and pediments. Isolated saguaro cacti and creosote bush do however, occur on parts of unstable landforms and thus are not a definitive indicator. Creosote bush, for example, is on several alluvial plains. Abundant mature saguaro cacti may be found on relict fans, pediments and inactive alluvial fans adjacent to the unstable land of aggrading alluvial fans on which there are very few saguaros.

Many distributary channels of inactive alluvial fans and pediments are lined with abundant paloverde trees and bushes. The native riparian vegetation affords resistance to bank erosion and channel migration but is present because the land is stable. Desert trees and bushes tend to be scattered about on active alluvial fans suggesting the absence of stable flow paths.

2.2.3 Field indicators

Indicators for landform and flood hazard identification are summarized in Table 2.3.

2.2.3.1 Channel shape and capacity

Nearly all of the streams draining the mountains and piedmonts flow only in direct response to rainfall. Some typically significant flood related characteristics of piedmont streams in Maricopa County are:

> *Throughflow streams* typically pass from their steeply graded mountain canyons to incised channels of pediments and relict fans and deposit sediment on alluvial fans and alluvial plains where they lose topographic confinement. These throughflow streams connect the mountains and deposition parts of the system, and are a major influence on the morphology upslope of the valley floor (Figure 1.1).
>
> Some streams build an alluvial fan, a sloping radiating deposit, which focuses at the point called the *hydrographic apex* where active fluvial sediment deposition starts.

Some streams build alluvial plains, a gently sloping rather smooth deposit, which is formed as floodwater spreads over base-level plains as *sheet flow*.

Some throughflow streams serve as sediment and water transportation corridors between the mountains and base-level streams. These transport channels commonly form where there has been recent base-level lowering.

Some streams head (begin) on relict fans, pediments and inactive portions of alluvial fans. These streams are tributary to throughflow and base-level streams.

A field examination of the form and size of throughflow and tributary channels can reveal important indicators of the type of piedmont landform and the flood hazard. Most throughflow streams are flat bottomed with a bed of deposited sediment (Figure 2.4) that is remobilized during floods. Most tributary streams that head on the piedmont are somewhat V-shaped with a narrow channel bottom and little, if any, deposited sediment. Some throughflow streams are channels that have cut to form gullies. According to investigators such as Graf (1982) and Hedman and Ostercamp (1982), the active channels are in the bottom and the form and size of these gullies is not related to discharge except in a very general sense. The user should be aware that the gullied depth (Figure 2.4) for piedmont streams of Maricopa County probably is related to factors such as changes of vegetation cover and not necessarily flood discharge. However, general relations between channel capacity and flood frequency are useful for identification of relict fans, pediments, alluvial fans and alluvial plains.

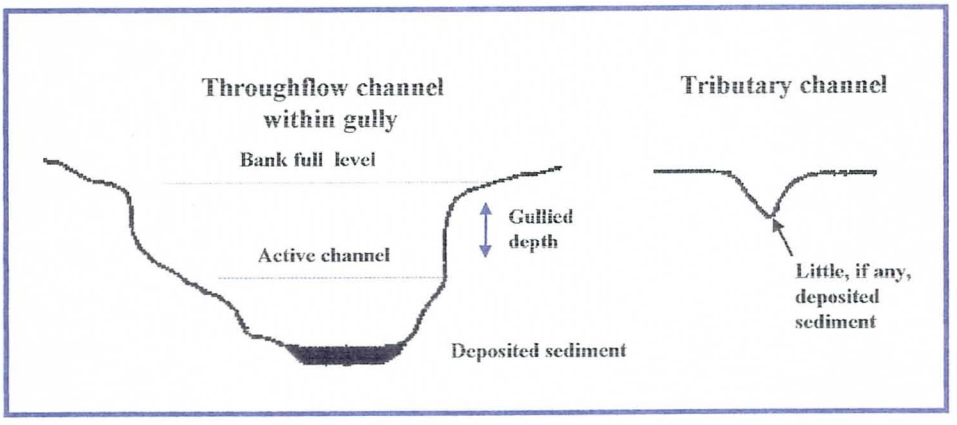


Figure 2.4. Cross sections of throughflow and tributary channels showing deposited sediment.

General relations of bank full capacity and recurrence interval are shown in Table 2.3 for piedmont landforms. For example, the 100-year flood nearly always is less than bank full capacity for relict fans with convex side-slopes shoulders and concave foot slopes. The bank full capacity of throughflow streams crossing most pediments is more than the 50-year flood and the 100-year flow is confined between defined ridges. The bank full

capacity along distributary channels of inactive alluvial fans typically in more than the 5-year flood and seldom is more that the 25-year flood. Throughflow channel capacity of active alluvial fans and inset alluvial fans typically are about the 2-year flood and seldom are more than about the 10-year flood.

The capacity of tributary streams that form on piedmont landforms is variable and may be related to the drainage pattern on relict fans and pediments (Table 2.1). Where first and second order streams of relict fans and pediments have a parallel appearance, the bank full capacity typically is greater than the 50-year flood (Table 2.3). For more radiating dendritic patterns the bank full channel capacity is much less and typically is more than the 10-year flood. On pediments the 100-year floodwater that over tops banks usually is confined to adjacent overflow areas. On smooth-flat relict fans, the 100-year floodwater can spread over wide areas as sheet flow and the sheet flow may become concentrated downslope.

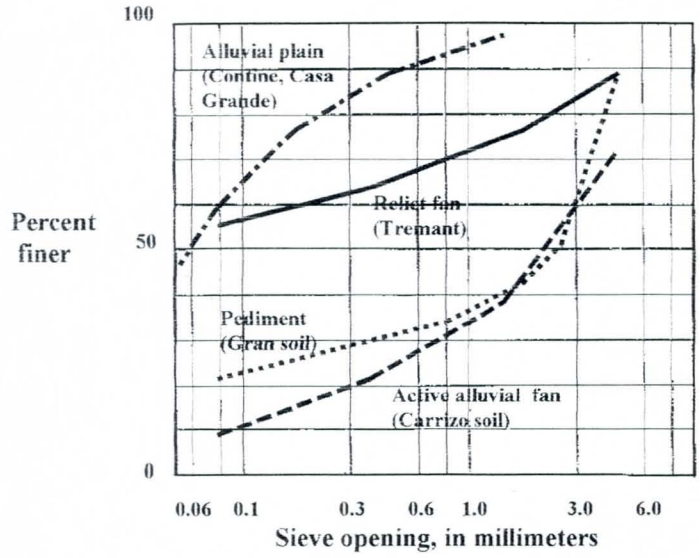
2.2.3.2 Sediment

The sediment in alluvial plains generally has a much finer distribution of grain size than the surface material of alluvial fans, relict fan and pediments (Figure 2.5.a). Although the particle size of material on a landform is not necessarily used as an indicator to predict the type of landform, landforms do exhibit some common sediment characteristics that are used for this manual.

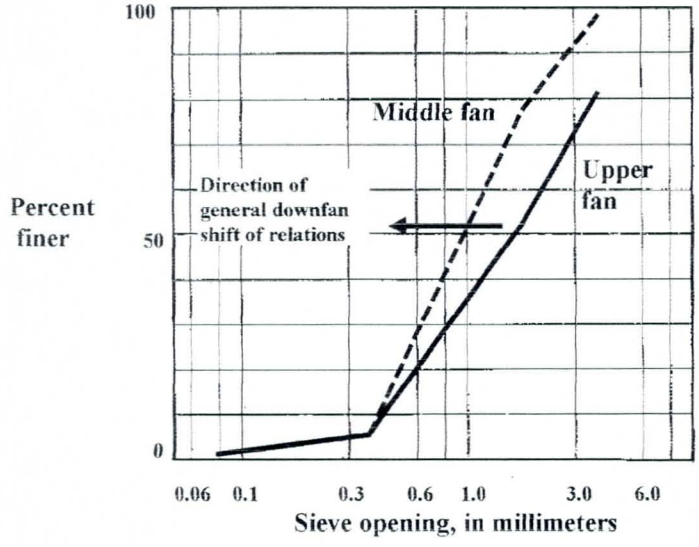
A few useful relations of soil particle size follow:

- Several relict fans have a grain size distribution like that shown for the Tremant soil in Figure 2.5.a).
- Material of relict fans ranges from clay to boulders and characteristics vary possibly because relict fans are formed by both debris flow and water flow deposits and these deposits have different characteristics (Bull, 1964).
- The grain size shape and distribution of weathered pediment material is related to the parent material and is dependent on the underlying rock type.
- Sediment in active alluvial fan deposits ranges in size from clay to boulder and tends to be somewhat sorted partly because recent deposits in Maricopa County are typically from water floods.
- There typically is a general increase in sorting down active fans and a shift in the grain (*clast*) size, such as the median grain size (D_{50}) as shown in Figure 2.5.b.

It is important to note that active alluvial fans can be composed of a wide range of material size. Most active fans in Maricopa County have coarse sand with some gravel and scattered cobbles near the hydrographic apex. The lower or outer parts of the fan may be composed of fine sand, silt and clay with small tongues of coarser material such as Carrizo soil. These distal fan areas (toes) coalesce and transition into alluvial plains with a similar material size and heterogeneity as the active fan toes. A simple quantitative example of how sediment might be distributed along an active alluvial fan is



a. Indicative graphs for major landforms with corresponding NRCS soil type.



b. Active alluvial fan at southern end of White Tank Mountains. Samples were collected about 3 to 6 inches below the surface that appeared light colored on aerial photographs.

Figure 2.5. Cumulative graphs of material size versus frequency indicative of landforms in Maricopa County.

in *Sediment grain size along an idealized active alluvial fan* in the Miscellaneous Methods chapter of this manual.

2.2.3.3 Age indicators

Indicators of land-surface age (Table 2.3) are useful indicators of the type of landform because, for example, relict fans, pediments and inactive alluvial fans are old landforms typically with old surfaces and active alluvial fans and many parts of alluvial plains are young landforms. Another important use of age indicators is for the definition of flow path stability discussed in Chapter 3 of this manual.

Desert pavement

A concentration of pebbles and cobbles on the land surface is known as desert pavement (Compton, 1977). Desert pavement is best seen in the field and is indicative of old surfaces (relict fans and pediments) formed by the removal of fine grained material by wind, soil creep and sheet flow. Desert pavement usually forms on inactive surfaces where there are pebbles and cobbles in the deposits. Pavement can also form on young coarse-grained alluvial fans (Christenson and Purcell, 1985). Thus, pavement development is not always a reliable indicator of surface age and type of landform. The mantled layer (commonly a single layer) of closely spaced pebbles typically is found on relict fans, portions of alluvial fans that are not active and occasionally on alluvial plains. Areas such as active alluvial fans and stream channels that are prone to flooding typically do not have desert pavement. Desert pavement can resemble stream channel armoring except the stones are not *imbricated.*

Desert varnish

Desert varnish is one of the best indicators of surface stability and the age of piedmont landforms in Maricopa County because it is easily observed and reliable. Dark brown and blackish layers of clays and manganese and iron oxides form on the surface of stable rocks over thousands of years. Although the dark appearance of rock varnish is not precisely related to age, the simple presence of rock varnish on piedmonts in Maricopa County is indicative of old surfaces such as those of relict fans. For example, a very dark varnished desert pavement may be present on very old-flat interfluves of relict fans. Soluble surfaces of carbonates and friable rocks such as granite that weather rapidly do not support varnish. For additional information on rock varnish, see Liu and Dorn (1996), Dorn and Oberlander (1982) and Dorn and others (1989).

2.3 Summary

Relict fans, pediments, alluvial fans and alluvial plains are the four major landforms of piedmonts in Maricopa County. Each landform can be recognized using identifiers such as desert pavement, surface color, vegetation type and location, desert varnish, transverse relief, drainage texture, drainage pattern, composition, sediment particle size and amount

of soil development. The identification of landform type is reliable when several identifiers point to a particular type of landform.

Soil survey reports by the Natural Resources Conservation Service provide valuable information on the type of landform and fluvial processes. These often under utilized reports show soils information on 7.5-minute orthophoto maps. Most soil types correspond to morphology and landform types. Use of NRCS reports *Soil survey of Aguila-Carefree area, parts of Maricopa and Pinal counties, Arizona* (1986) and *Soil survey of Maricopa County, Arizona, central part* (1977) will contribute greatly to the identification of landform type and the overall assessment of flood hazards on piedmonts.

Published geologic maps of the Arizona Geological Survey (1997) are also a valuable source of information with implications for piedmont flood hazard assessment.

An example map of a mountain and the downslope piedmont landforms is shown in Figure 2.6. For this particular example the landforms were identified in the soil survey report (Camp, 1986) and verified using procedures in this chapter of the manual. For typical studies the aerial photographs, any surficial geology and all the indicators will accompany the map of the landforms. The mapped landforms shown in Figure 2.6 are the result of stage 1 of this method and provide the geomorphic basis for the flood hazard identification (Table 1.1).

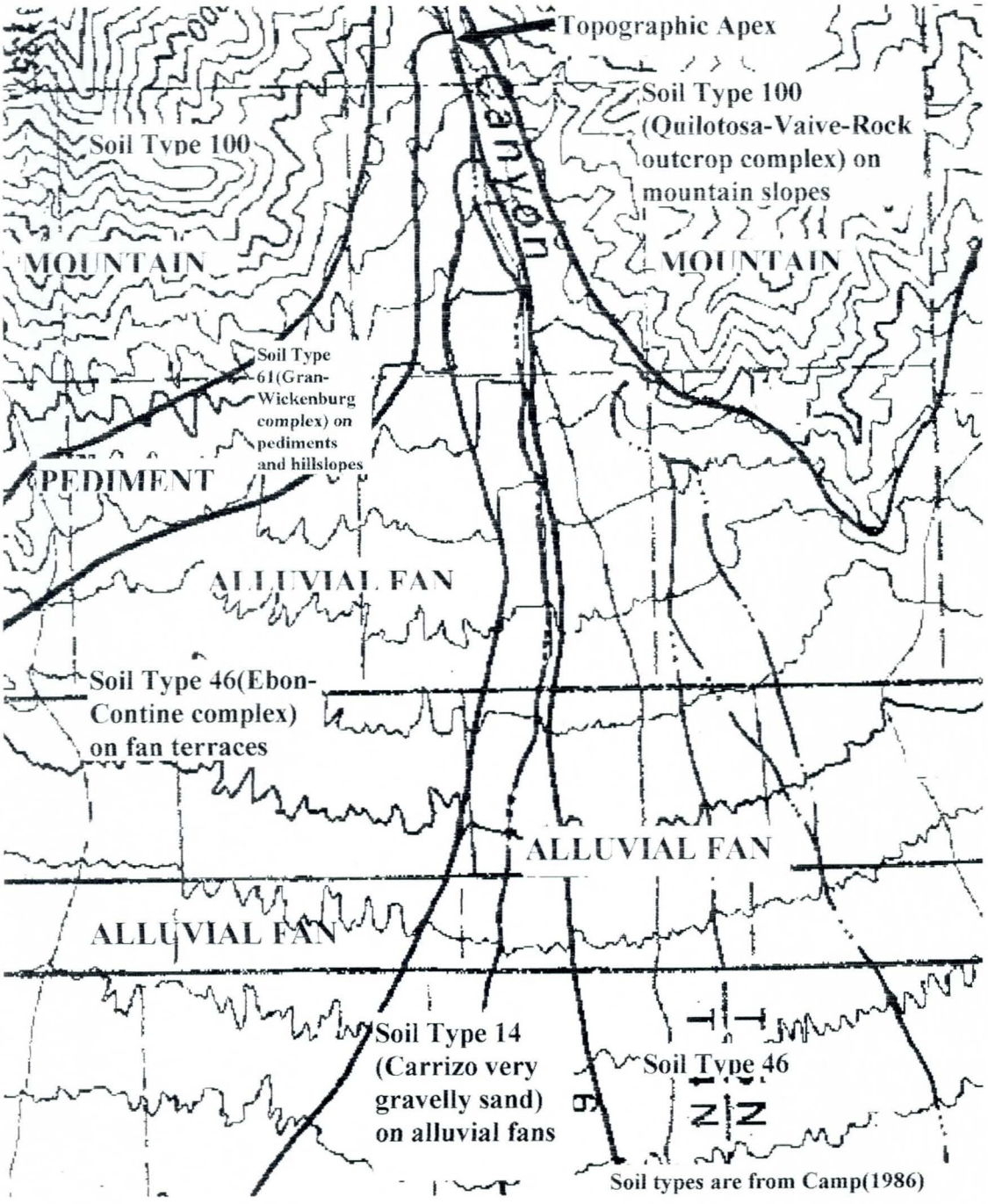


Figure 2.6. Example map of soil, topography and landforms that represents the completion of stage 1 of the method.

3
IDENTIFICATION OF STABLE AND UNSTABLE AREAS ON PIEDMONTS OF MARICOPA COUNTY

A procedure for identifying the nature and location of flood hazards on the four major piedmont landforms is outlined in this chapter. These flood hazards are broadly classed as areas with either stable or unstable flow paths. Unstable areas, which include active alluvial fans, are subject to changes in geometry. These changes are such that the errors of a conventional flood hazard assessment are so large as to render the assessment unreliable. Stable areas include most hillsides and defined channels of relict fans, pediments and inactive alluvial fans. Flow paths of stable areas are predictable using geomorphic methods based on channel shape, surface geology, soil development and landform morphology. Flood boundaries for these stable areas are predictable using classic engineering methods based on hydraulic factors of roughness, grade and channel cross section geometry.

Stable areas also include sheet flow and many split flow areas. These split flow areas may have an uncertain distribution of flow where the hydraulic geometry, grade and roughness are relatively stable but small obstructions or small amounts of scour or fill associated with the generally shallow flow depths can alter the distribution of floodflow. The uncertainty of the flow distribution for these stable areas may or may not be set aside depending on site conditions.

Areas with *uncertain flow paths* where the flow path uncertainty *"is so great that this uncertainty cannot be set aside in realistic assessments of flood risk or in the reliable mitigation of the hazard"* (NRC, 1996) are called unstable areas. Unstable areas include active alluvial fans, a few distributary flow areas and some alluvial plain areas where there is active sedimentation or erosion (See Table 2.3). Areas of flow path uncertainty and boundaries for these areas are predictable using geomorphic methods.

As used in this manual, the terms stable and unstable are relative states of hazard on the landform. Obviously, all piedmonts of Maricopa County are undergoing change as a result of erosion, deposition, differential loading and tectonic movement. Where the change is slow and progressive and the effect such as channel movement is also slow, the landform is considered relatively stable. Where the change is sudden and the effect such as a channel *avulsion* is likely to occur during the 100-year flood regulatory period, the landform is considered unstable. A landform can also be considered unstable if slow-progressive change results in a sudden event such as the rapid evacuation of accumulated debris from a mountainous drainage basin to the piedmont. For excellent discussions of

natural processes and man's activities associated with perceptions of the relative state of landforms see Schumm (1994) and Graf (1977).

This chapter (stage 2 of the method), like Chapter 2, uses readily observable indicators. These indicators are used to delineate areas of potential flooding on each of the landforms. Many of the stability indicators are simple measures of age and weathering like the desert pavement and desert varnish discussed in Chapter 2. More sophisticated dating techniques such as the radiocarbon and optical dating used by White and others (1996) are beyond the scope of this manual. The digging of observation/test trenches for studying surfical geology and soils is also beyond the scope of this manual. An excellent example of the use of *stratigraphy*, geomorphology and age dating to produce a detailed map of surfical geology was produced by Hereford (1996). The mapped deposits by Hereford are directly related to flood hazards but such detail is unnecessary for most sites in Maricopa County. A possible exception may be where the 100-year flood hazard is changing because of nonstationary climatic factors as discussed in Chapter 4 of this manual. The indicators used in this manual produce reliable assessments of landform type and flood hazards for most cases.

The definition of active or unstable areas was discussed by the NRC Committee on Alluvial Fan Flooding (NRC, 1996) as follows:

> *Because it is not possible to predict with zero uncertainty where the next flood will occur on an alluvial fan, we resort to the traditional method of the geologist and rely on the dictum "the past, as preserved in the geologic record, is key to understanding the present and to predicting the future." Using this reasoning, the geologist concludes that the area of deposition on an alluvial fan shifts with time, but the next episode of flooding is more likely to occur where the most recent deposits have been laid down than where deposits of greatest antiquity occur.*
>
> *Once the planner has incorporated this basic philosophy into efforts to identify those parts of the fan that are active, the next step is to decide what period will be used to define active. As a conservative standard, in some areas it is easy to separate the parts of a fan that formed more than 10,000 years ago from those parts that formed during the past 10,000 years, the Holocene epoch. In many places in the southwestern United States, it is less easy to see a clear Pleistocene/Holocene change, but one can subdivide Holocene deposits on a much finer time scale.*

3.1 Indicators of flood limits and landform stability on piedmonts

Several indicators of stable and unstable areas that typically are related to age and weathering are given in this section (See also section 2.2.3.3). Other more computationally complex published geomorphologic and engineering methods that can be used to supplement the assessment for channel and landform stability and the intensity

of fluvial hazard are given in Section 8, the Miscellaneous Methods section of this manual. Also, procedures for defining the boundaries of active and inactive areas of alluvial fans are given in Hjalmarson and Kemna (1991) (See section 8.3 of this manual) and National Research Council (1996).

3.1.1 Stable areas

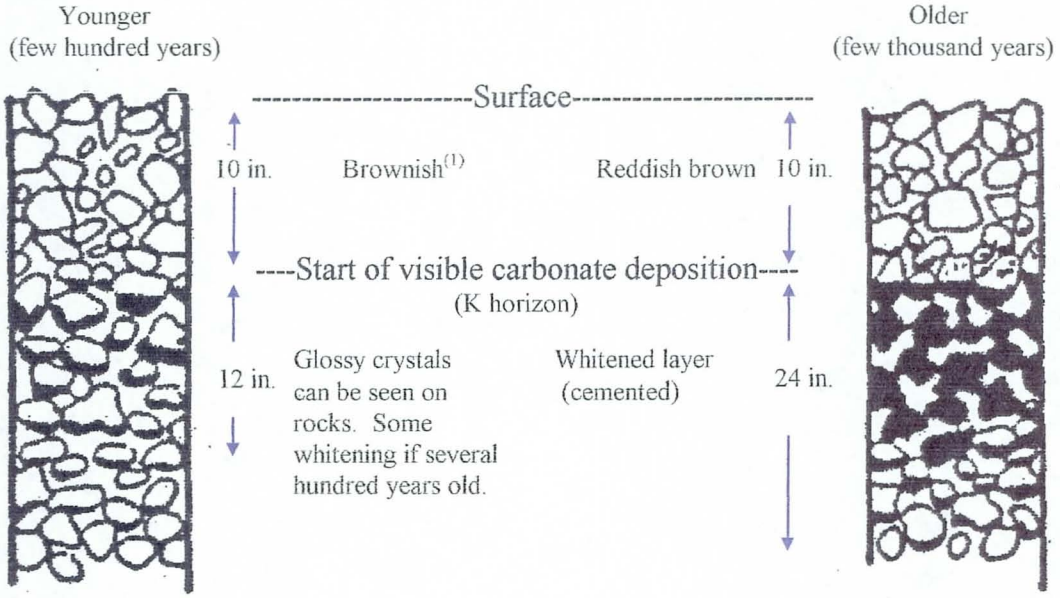
Stable is the relative state of the geometry and roughness of a channel, network of channels or landform where any foreseeable changes of geometry and roughness will not impact flood risk. The paths of floodflow on many piedmont landforms are stable for the reasons given in Table 3.1. The most fundamental indicator of flow path movement, especially when also applied to similar surrounding areas, is the movement of throughflow channels over a period of at least 40 years. Flow paths may be stable if no throughflow channel movement is observed from comparison of good quality aerial photographs and if there are no documented accounts of channel movement (See items 1 and 2 of Table 3.1). For addition discussion of flow path movement see section 5.1.3.3 of this manual. It is very important, however, that other indicators also point to stable surface conditions before flow paths are considered stable.

Visible soil carbonate zones like that shown in part A of Figure 3.1 is another excellent indicator of an older-stable surface. A well developed soil with dark reddish-brown sandy clay *loam* or clay texture a few inches below the surface is also a good indicator the surface of the landform is stable. Characteristic old-stable surfaces have well-developed tributary drainage networks incised in Pleistocene sediments or bedrock separating throughflow channels. The throughflow channels are not perched above the adjacent land and channel incision of more than 3 ft. below adjacent inactive fan surface is typical of stable tributary and distributary flow paths (See for example the bank in part B of Figure 3.1 that can be seen at the White Tank Park site discussed later in this manual). See Christenson and Purcell (1985), Machette (1985), Compton (1977) and Camp (1986) for descriptions of pedogenic soil development and calcic horizons.

Characteristically stable landforms in Maricopa County are sparsely covered with scattered large trees except along the banks of throughflow channels where large paloverde, ironwood, and/or mesquite are abundant. Large trees along the channel banks tend to stabilize the flow paths but bank stability is needed for the trees to grow. Such trees would be washed away and not reach maturity if the flow paths were changing very much. In addition, banks with tree roots below the channel bed tend to be more stable than banks with tree roots perched above the channel bed. Elevated tree roots that may indicate recent bed erosion and bank instability are not common along natural channels of piedmonts in Maricopa County.

The relations between channel width and discharge and mean depth and discharge for channel cross sections are typical of cross sections formed in cohesive bank material (See item 11 of Table 3.1). These hydraulic geometry relations indicate the throughflow channels and flow paths are stable.

A. Typical Calcium carbonate accumulation in gravely material indicated by black shading
(Thicknesses are typical and can vary)



(1) Recent surface deposits such as those along active stream channels and on active alluvial fans will be light colored--commonly light gray or tan--because the weathered coating has been removed by erosion and residence time has been too short for new oxidation to be visible.

B. Photograph of conglomerate along incised channel of relict fan
(Photo is near site in Figure 5.9 of White Tank Park site discussed in section 5.2)

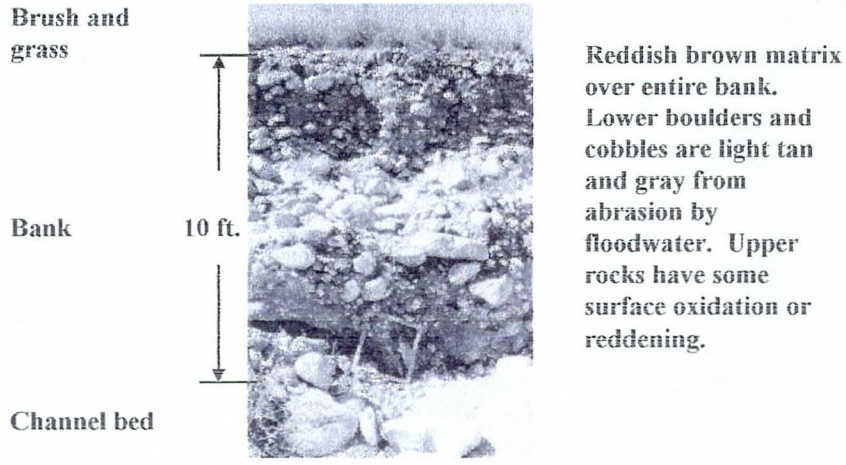


Figure 3.1 Sketch of typical calcium carbonate development and photograph of typical conglomerate as seen in road cuts and along cut banks of stream channels.

Table 3.1. Indicators of stable flow paths on piedmont landforms.

BASED ON AVAILABLE AERIAL PHOTOGRAPHS AND PUBLISHED INFORMATION

1. There has not been channel movement, the formation of new channels, and/or mudflow or debris flow deposits on the landform or portions of the landform as depicted by comparison of old and recent aerial photographs and topographic maps.
2. There are no documented eyewitness accounts or geologic evidence of recent channel movement, formation of new channels, and/or mudflow or debris flow deposits on the landform or portions of the landform.
3. Using soils depicted on 7.5-minute orthophoto quads of the Natural Resource Conservation Service soil surveys, (a) the soils of the landform are old fan remnants, fan terraces, cemented gravel or are highly developed, (b) the soil texture along the active drainageways does not decrease downslope and (c) the soil texture of the predominant soils increases or is uniform downslope.
4. Using geologic maps, the drainageways are incised into Pleistocene or older material.
5. Using aerial photographs, there are abundant large trees such as paloverde along the defined drainageways and the *interfluves* may be covered with scattered trees.
6. There is adequate channel capacity to convey the 100-year flood between stable interfluves based on estimated channel size using 7.5 minute or more detailed topographic maps. Flow paths may also be stable where channel capacity is less but additional indicators that point to stability are needed.

BASED ON COMPUTATIONS USING PUBLISHED MAPS AND TECHNICAL MANUALS

7. The size of the alluvial fan is large relative to the size of the drainage basin.

BASED ON SURVEYED CROSS SECTIONS AND SAMPLES OF CHANNEL BED AND BANK MATERIAL

8. Measurements of the proportion of silt and clay in the channel banks show that large amounts of sediment suspended by floodwater have been deposited along the wetted perimeter of the channel banks.
9. Measurements of vane shear corresponding to computed tractive power at many cross sections consistently plot in the non-erosive region of the relation of tractive power and unconfined compressive strength published in Natural Resources Conservation Service TR-25 indicating the channel banks are non-erosive or stable.
10. Measurements of the particle size of the bed material at many sites along the drainageways show a uniform distribution of particle size along the defined channels indicating the mobile bed material passing the apex is conveyed through the network of defined distributary channels.
11. Data from measurements of channel geometry and bed and bank material samples at several cross sections consistently plot in the stable region of the relation between channel width-depth ratio and percent silt-clay along the wetted perimeter published in U. S. Geological Survey Professional Paper 352C (Schumm, 1961).

The use of the large channel capacity in item 6 of Table 3.1 is conservatively cautious. Lesser discharges may also be contained between stable ridges of stable areas. For example, the 25-year flood may overflow developed soil with a surface armored with desert pavement. The duration of overtopping may be only a few minutes, flow velocities may be less than 5 ft/s and overtopping may occur only a few times over a century. Such infrequent overflow would not be a realistic cause of instability. Thus, sites with lesser channel capacities may be stable but additional assessment is needed for the determination.

3.1.2 Unstable areas

Unstable is the relative state of the geometry and roughness of a channel, network of channels or landform where any changes of geometry and roughness cannot be set aside in realistic assessments of flood risk. Flow paths on piedmonts of Maricopa County that are considered unstable typically do not have the characteristics of stable areas given in Table 3.1. An area obviously has unstable flow paths if there is documented movement, abandonment or formation of throughflow channels since aerial photographs, land surveys and topographic maps have been available.

Evidence that a surface is geologically very young and therefore unstable is also useful. Reliable indicators that the surface is young are: (1) the lack of developed soil as indicated by little oxidation or reddening in the upper few inches, (2) the absence of surface weathering on non-granite landforms as indicated by the lack of desert pavement and rock varnish, and (3) the presence of throughflow channels and banks that are perched above the adjacent land when viewed across the channel profile. Several indicators are needed that point to flow path instability because, for example, a single indicator such as the lack of desert varnish may also indicate an eroding surface where the stones have washed away by sheet floods. Young (unweathered) surfaces that are aggrading, as suggested by transverse mounding (perching) when viewed across the landform, have unstable paths of flow.

Less reliable but useful indicators of unstable flow paths are: (1) the throughflow channels have large width-to-depth ratios, typically more than 50, that are characteristic of channels formed in noncohesive material, (2) the estimated 100-year flood overtops the banks of throughflow channels and inundates much of the landform including many of the ridges and interfluves separating the channels, and (3) the scattering of large trees such as paloverde over the landform with the absence of distinctly abundant trees along the banks of throughflow channels. The trees are scattered over much of an area suggest some local flow path movement or the absence of defined flow paths during the life of the trees or frequent enough overflow and sheet flooding to supply the water needs of the trees. Thus, scattered trees do not always mean that flow paths are unstable.

3.1.3 Basis of indicator method

The nature and extent of flooding is estimated using several indicators. All flow path stability properties of a particular landform cannot be accurately predicted but reliable

assessment of stability is made where several stability indexes point to a particular stability condition. The cumulative but differing effects of these indexes are commonly expressed as observable properties. Because of the observable relationships of, for example, pediment and alluvial fan properties we say that pediments and fans with discrete sets of properties have a degree of predictability on the stability factors. Most of the information essential to defining active and inactive areas of flooding is obtained by field examination of the piedmont. Other important information is obtained from topographic maps, soil surveys, aerial photographs, maps of surficial geology and reports of flooding. This is the scientific basis of the determination of active and inactive areas and assessment of which active areas are stable or unstable.

3.1.4 Words of caution

The postdiction and prediction of the nature and location of floodflow can be tenuous. Similar effects or equifinality can be caused by different processes (Schumm, 1991). Large events such as massive sediment laden floods can be obscured by subsequent erosion and burial. Debris flow deposits can be remobilized by water floods and redeposited downslope. The evolution of a landform surface, especially the surface of an alluvial fan, can cause a difficult problem for the interpretation of field evidence concerning flooding and for the prediction of future flood risk (NRC, 1996).

It is important that all indicators point to the same condition of flow path stability if the determination is reliable. It is also important that the assessor(s) is experienced in engineering, hydrology and geomorphology and is familiar with FEMA methods and the geomorphic framework of desert regions like Maricopa County. Reliable assessments are made where all stability indexes described in this manual point to a particular stability condition.

If a mixed set of indicators is experienced certain indicators would prevail. Although the author has not experienced a mixed set of indicators, the possibility is anticipated. For example, items 1-4 of Table 3.1 are more significant than items 5 and 6. Soil characteristics and surficial geology are considered very important indicators. Also, any observations of flow path movement obviously are very reliable indicators that the landform is unstable. Conversely, the lack of recent flow path movement is not necessarily an indicator of stability where there has been little recent flooding. Other possible exceptions include items 7 and 11 that are based on general relations and thus subject to chance variation. A mixed set of indicators should be carefully examined for obvious errors and the likely cause, such as the absence of recent floods, of the mix. Where indicators for a particular site are mixed and it is not obvious if the landform is stable or unstable, a more experienced investigator, preferably a geomorphologist, should be consulted to help resolve the issue. More sophisticated methods than those described in this manual may be needed to assess stability.

A particular mixed set of indicators might occur because of the variable nature of summer thunderstorms that produce most of the large floods on piedmonts in Maricopa

County. For example, all indicators except the observed flow path movement (item 1, Table 3.1) for a particular site might suggest a landform is unstable. The absence of flow path movement may simply be the result of random chance that the site did not experience large floods for the period of photographic record. Measurements of flow path movement using a larger sample of surrounding landforms with similar characteristics, such as the same type of soil, might be a more reliable indicator. For this particular example, a general relation that showed flow path movement may be a more reliable indicator than the observed lack of movement at the particular site. This technique is reliable if the site in question does not exhibit singularity (Schumm, p. 75, 1991) and the sample has similar characteristics.

3.2 Relict fans

Flooding on relict fans is from overland flow and flow in defined channels (Table 3.2). The geometry and roughness of the channels, network of channels or land surface typically can be considered stable for assessments of flood risk. These landforms are called fan terraces by the NRCS and are "broad coalescent plains that have been incised by streams"(Camp, 1986).

Along incised throughflow streams the steep banks have some instability; although the banks of many incised channels are well cemented and boulder material with moderate stability. The floors of the throughflow channels typically are fairly flat and composed of only coarse sediment because of the high flow competency. The well-developed soils, abundance of rock varnish and common desert pavement are indicative of old and stable surfaces. Because the dark rock varnish develops over thousands of years with stable conditions, it can be inferred that the floodwater from upslope mountains has been conveyed past these varnished surfaces in throughflow streams for thousands of years.

The 100-year flood typically is confined to defined channels and land adjacent to channels of throughflow streams and floodwater seldom looses energy and deposits much sediment. On some relict fans, 100-year floodwater also is confined within tributary streams that head on the fan (See for example figure 4.1 in the next chapter of this manual). On other relict fans that are dissected by incised throughflow streams the 100-year floodwater from rainfall directly on the fan may be unconfined and spread over wide-flat interfluves as sheets before becoming tributary flow.

Slopes typically are stable with a low *probability* of downslope movement of material and a low potential for erosion. Steeper slopes may not be stable.

3.3 Pediments

Flooding on pediments is from overland flow and flow in defined channels (Table 3.2). The geometry and roughness of the channels, network of channels or land surface typically can be considered unchanging or stable for assessments of flood risk.

Table 3-2. Selected characteristics of stable and unstable flood hazard areas of piedmont landforms.

Landform	Component Landform (State)	Significant stability and flood characteristics
Relict Fan	Erosional Fan remnant (Stable)	Remnants of broad coalescent plains or bajadas that have been incised by streams for thousands of years. The presence of large areas of varnished desert pavement suggests the surface of this landform is very stable in many places and floodflow has been conveyed past these stable areas for thousands of years. The 100-year flood is confined to throughflow channels and small overbank areas adjacent to the defined channels.
	Inset Alluvial Fan (Unstable)	These typically bouldery fluvial deposits can have a great aggradation and erosion potential and are unstable. The 100-year flood can spread over much of these areas.
Pediment	Bedrock remnant (Stable)	Nearly all of these landforms are eroding and stable. Relatively small areas along larger channels are subject to scour and fill. The 100-year flood typically is confined to defined channels of throughflow streams and streams that head on the pediment.
	Inset Alluvial Fan (Unstable)	These fluvial deposits resemble flood plains except the inset fan may be subject to more erosion and deposition than typical flood plains. Inset deposits of sediment can be the "apex" of distributary channels.
Alluvial Fan	Active Alluvial Fan (Unstable)	Fluvial deposit with little or no calcium carbonate development, no insitu rock varnish development, and seldom any desert pavement. The surface typically is a light tan or grey color that is indicative of recent abrasion of the weathered surface during sediment transport. Some areas not recently eroded or that have received sediment may be darkened by weathering. Typical channels are poorly defined with large width-to-depth ratios and may have a braided pattern in addition to a general radiating pattern below the hydrographic apex. Typical clasts are angular, sorted and unweathered. Both the maximum and average clast size of the sediment deposits decreases rapidly downfan. Deposits are mounded across the fan unless there has been erosion and/or co-mingling with adjacent alluvial fans.
	Inactive Alluvial Fan (Stable)	Fluvial deposit with much carbonate in K soil horizon , reddish upper soil horizon, desert pavement, rock varnish, incised throughflow channels, trees along the throughflow channels and developed tributary drainage systems that head on the fan surface. Very old inactive alluvial fans are relict fans.
Alluvial Plain	Piedmont Toe (Generally stable but some areas may be unstable.)	Rather stable or possibly aggrading fluvial deposit with little transverse relief except where channels are incised as the result of lowering of base-level stream. Floodwater of the 100-year flood may spread over large areas like that shown in Figures 4.6 and 4.7. Areas with low slopes, lack of flow confinement, little aggradation and developed caliche soil that resists erosion are stable. Areas may be unstable where there is much aggradation. Where channels are incised the gully walls may be unstable and headcutting may progress upslope.

Channel banks typically are stable and hillslopes are relatively stable. The banks of throughflow streams may be locally steep and unstable when undercut. Only relatively small areas along larger channels are subject to active scour and fill. Nearly all of area is slowly eroding and stable. The 100-year flood typically is confined to defined channels of throughflow streams and streams that head on the pediment but some sheetflow is typical on lower slopes (See for example figure 4.2 in the next chapter of this manual).

3.4 Alluvial fans

Many alluvial fans in Maricopa County have active areas of flooding and sediment deposition inset in much older fans that are inactive and stable. Fans in Maricopa County are somewhat similar to fans in Death Valley that are formed mostly by water flood processes described by Hunt (1975) and Hunt and Mabey (1966). Fans in Death Valley, however, have a greater tectonic influence. Young alluvial fans are actively growing over their entire surface while older fans have both active and inactive parts. Many young-active parts of fans are lighter colored than older parts because of weathering; some active parts of fans may appear dark because of greater vegetation density. Active parts of alluvial fans are subject to sediment deposition and erosion. **Inactive parts of alluvial fans may be subject to flooding but flow paths are not changing and there is no significant active sediment deposition.** Indicators of stable and unstable fans are given in Table 3-2 and the steps for defining the type of alluvial fan and active and inactive areas are given in Table 3.3.

A discussion of the complex flooding and landform formation processes on alluvial fans is beyond the scope of this user's manual and is given in *Alluvial fan flooding* (NRC, 1996). Other published reports related to information in this chapter include *The occurrence and role of arid zone alluvial fans* (Harvey, 1989), A *study of surficial processes and geomorphic history of a basin in the Sonoran Desert, southwestern Arizona* (Wells, 1976), *Landforms of the basin and range province-defined for soil survey* (Peterson, 1981), *Map of Arizona showing selected alluvial, structural, and geomorphic features* (Cooley, 1977), *Fluvial sediment concepts* (Guy, 1970) and *Geomorphic controls of alluvial fan deposition in the Sonoran desert, southwestern Arizona* (Wells, 1977). **Insight into the behavior of many incised channels on piedmonts is given in *Incised channels-morphology, dynamics and control* (Schumm, Harvey and Watson, 1988).** The changing fan conditions over time are given by the National Research Council (1996) as follows:

> *Even if the fan is still a zone of active accumulation, the locus of that deposition may vary between fans or on the same fan during its lifetime. Distributaries develop most frequently where aggradation is intense and thus may shift the centers of active sedimentation across or along the fan. Deposition also may shift down the fan if the uplift rate in the mountain source exceeds the deposition rate at the fan head. This can cause trenching of the source canyon and the upper fan or intense episodes of debris flow and stream transport associated with increased runoff. In the latter cases, the channel may be*

Table 3.3. Steps for defining and characterizing alluvial fans.

CHARACTERISTIC	DATA SOURCE	FUNCTION (Define on topographic map)
Type of fan?		
Alluvial, debris flow, or composite?	Field work	Examine morphology, facies assemblages and other evidence of sedimentary processes
Ideal, composite, or segmented?	Topographic maps & field work	Make profiles along fan.
Incised/not incised?	same as above	Throughflow and local channels.
Drainage patterns	Topographic maps & aerial photos	Tributary, Distributary and/or Anastomizing?
What parts of fan are active(< 10,000 years) and/or inactive? If practicable, use time scales less than 10,000 years.		
Depth of incision	Topographic maps & fieldwork	(Depth of incision <2ft, about 3ft, 3 ft-10 ft, >10 ft)
Flow path movement	Aerial photographs	Rate of movement and proportion of channels.
Fan surface morphology	Topographic maps & field work	(Bar & channel, smooth, deeply dissected)
Desert pavement and desert varnish	Aerial photos & field work	(None, weak, moderate, strong development)
Soil characteristics	Soil maps and field work (trenching)	(B-horizon development and $CaCO_3$)
Is the drainage basin typical of those found above active alluvial fans?		
Sediment supply	Soils maps, aerial photos and field work	(Abundant, moderate or little medium to coarse grained sediment on steep basin slopes or along channel incised in relict fan)
Basin shape	Topographic map	(Rounded or elongated)
Drainage pattern	Topographic map and aerial photos	(Uniform or non-uniform length of first and second order channel segments)

entrenched below the upstream part of the fan surface and all deposition and attendant channel shifting or change occurs on the lower portions of the fan. Appreciation of such changes is important for understanding flood hazards on fans because (1) some of the changes occur sufficiently quickly to affect channels on time scales relevant to engineering analyses, so that it is important to know whether a particular fan is undergoing a change at the present time, and (2) geologically recent, but no-longer active, processes may leave a morphologic signal on the fan or in the source basin that must be interpreted in order to refine estimates of recent changes in flood hazard.

Fans grow in a variety of ways and the thickness generally increases at the slope transition formed at the fan toe, as it is progressively buried (Hooke and Dorn, 1992). Deposits near the apex commonly are remobilized and redeposited farther down the fan on and below the fan toe. French (1995) gives a method of estimating the depth of sediment deposition at these slope transitions on fans. The most permanent deposition typically begins at the toe and propagates both up the fan and below the toe where the slope typically diminishes.

The evolution of the fan surface causes a difficult problem for the interpretation of field evidence concerning alluvial fan flooding and for the prediction of future flood risk. For example, if a part of a fan surface has not been disturbed by flooding or erosion for 15,000 years, its surface will have become weathered and covered by a soil-profile and vegetation. The surface of such a fan will be very different from the surface of a nearby channeled and actively evolving area. An important geomorphologic and hydrologic question for flood risk analysis is whether the older surface has evolved out of the flood zone or whether it simply has not been flooded for 15,000 years because random channel migration across the fan took the locus of flooding and sedimentation far from the site for that length of time.

If, for example, the active sedimentation zone is now migrating into the older surface through lateral bank erosion, or lies at an elevation only a few meters below that surface (i.e., within the range of flood stage), or if upstream of the site there is an opportunity for avulsions that could lead channels or sheetfloods across the older surface, then the older surface lies within the zone subject to alluvial fan flooding. If, by contrast, channels have become entrenched during the past 15,000 years for one of the reasons given above, the elevation difference between the recently active sedimentation zone and the older surface may be greater than any flood or debris flow stage conceivable in the current regime of climate, hydrology, or land use in the source area. In this case, "overbank" flooding is not possible. Maximum conceivable flood heights, albeit approximate because of the assumptions that must be made about potential changes of bed elevation, are predictable through methods described by Burkham (1988) for floods and Whipple and Dunne(1992) for debris flows. If field inspection reveals that the margin between the older and the recently active surfaces is armored with bouldery or cohesive sediment, and if the ages of trees along this margin as well as the aerial photographic record (now approximately

50 years old) indicate little or no migration of that boundary, then one's confidence is increased that lateral bank erosion does not threaten the site.

A fundamental step in the evaluation of alluvial fan flooding at a particular site is an examination of evidence of recent flooding or fan activity. Sources of basic readily available information are aerial photographs, topographic maps and soil surveys. The flood evaluation (includes assessment of debris flows) should include a field examination of hydraulic and geologic conditions of the fan and drainage basin (Table 3.3).

Active fans in Maricopa County typically are a relatively small (larger than a few tens of acres) fluvial deposit with the following:

- Little or no calcium carbonate development.
- No insitu rock varnish development, and seldom any desert pavement.
- The surface typically is a light tan or gray color that is indicative of recent abrasion during sediment transport.
- Some areas not recently eroded or that have received sediment may be darkened by weathering.
- Typical channels are poorly defined with large width-to-depth ratios and may have a braided pattern in addition to a general radiating pattern below the hydrographic apex.
- Typical clasts are angular to subangular, sorted and unweathered (See for example Hereford and others (1996)). The poorly rounded clasts reflect the short distance of transport. An exception to the common angular clasts is where the alluvial fan material is second or third generation sediments derived from relict fans.
- Both the maximum and average clast size of the sediment deposits decreases down the fan (See for example Blissenback (1954) and Hjalmarson and Tram (1995)).
- Deposits are mounded across the fan unless there has been erosion and/or co-mingling with adjacent active alluvial fans.

3.4.1 Precautions

The evaluation of alluvial fan flooding should include gathering information on alluvial fan flooding for the site and for the area from various sources; conducting a reconnaissance type field inspection and, if indicated, collecting engineering and geologic data; preparing a technical report based on the investigation; and making an appraisal of the likelihood, extent and severity of mass flows and water flows. Such an evaluation should be made by a qualified engineer, geologist and/or hydrologist with professional experience and technical knowledge of slope stability, flood hydraulics, flood hydrology, sedimentary facies and alluvial fan processes. For many alluvial fans the various flood indicators provide limited or partial information and therefore, assumptions and limitations should be described as information is combined for the overall evaluation. **It should be recognized that all sites on an active alluvial fan are subject to risk and many sites on inactive alluvial fans are subject to insignificant risk.** Because the flood assessment of alluvial fans is more uncertain than the more

traditional flood assessment of floodplains, assumptions and judgments are more common and should be made clear and be part of the written evaluation. These documented assumptions and judgments may be periodically reexamined as our understanding of alluvial fan processes improves.

It is important to note that the field indicators and assessment for each example alluvial fan are not necessarily complete. Only general physical characteristics of each alluvial fan and the more pertinent field indicators are described. Additional indicators that may yield useful information include (1) several engineering methods of channel stability assessment and sediment yield (Chapter 4 of this Manual) and (2) geologic methods of defining sedimentary facies of Holocene and late Pleistocene deposits in order to estimate the magnitude, extent and likelihood of recent mass or water flows (Chapters 4 and 5 of this Manual). All indicators should point toward a particular type of fan and degree of flood hazard or level of fan activity. Discrepancies among the indicators should be resolved as part of the assessment. An outline for defining and characterizing the alluvial fan environment is given in Table 3.3.

3.4.2 What parts of fan are active/inactive (< 10,000 years)?

Careful inspection of channels, sediment exposed by cut banks and road cuts and surface material for recent movement of sediment typically may identify if and where there is flow path movement. Ideally, any movement over the past few hundred years is most useful for making inferences about movement over the next 100-years. Such a refined distinction is complex and may be unrealistic for practical usage at some sites. A more practical technique that can be accomplished by many technical specialists is the field inspection for evidence of recent channel movement, channel avulsion, formation of new channels, marked changes in channel geometry and sediment deposition (National Research Council, 1996). Experience has shown that fan areas active over the past few hundred years have also been active over much of the Holocene Epoch. Thus, to simplify the assessment and to be conservative on the side of caution, "recent" evidence of flow path movement may span a few thousand years without introducing significant error for most sites. This issue was discussed by the NRC Committee on Alluvial Fan Flooding (NRC, 1996) as follows:

> *The term active refers to that portion of a fan where flooding, deposition, and erosion are possible. If flooding and deposition have occurred on a part of a fan in the past 100 years, clearly that part of the fan is active. If flooding and deposition have occurred in the past 1,000 years, that part of the fan can be considered to be active. However, it becomes more difficult to determine whether or not a part of the fan that has not experienced sedimentation for (say) more than 1,000 years really is active, that is, that there is some likelihood of flooding and sedimentation under the present climate. A systematic approach to the problem of estimating whether a place may be inundated after a long period of inactivity is suggested in Chapter 2, the section " Change Over Time," which deals with processes by which flooding and deposition can migrate across an*

alluvial fan to invade places that have long been outside the zone of active deposition, even in the current climate. Since there is no clear analytical technique for making such projections, estimates of the probable spatial extent of inundation involve systematically applied judgment, and the combination of hydraulic computations and qualitative interpretations of geologic evidence concerning the recent history and probable future evolution of channel forms, as well as flooding and sedimentation processes.

Field (1994) and CH_2M Hill (1992) found significant channel movement with dramatic channel modifications in the upper part of the White Tank Fan located on the western slopes of the White Tank Mountains near the southern end. Field (1994) shows how the active part of the fan is identified using aerial photographs, a straigraphic cross section and a field inspection.

3.4.2.1 Depth of incision

According to Field (1994) historical aerial photographs, surficial features, and limited subsurface trenching on five fluvially dominated alluvial fans in Arizona demonstrate that channel abandonment occurs along bends and/or where bank heights are low. Several large floods on the fans during the photographic record produced no significant channel changes and may have actually inhibited future diversions along certain reaches by eroding channel beds and increasing bank heights. One of the five fans studied by Field was the White Tank Fan described above where the channels in the upper active fan are generally incised < 2 ft. with a width-depth ratio >10 and the channel of the lower inactive fan are incised about 3 ft. with a width-depth ration <10. These channel and other fan characteristics are in good agreement with the flood hazard indicators in Table 2.3 of this manual. The channel and fan characteristics of Field's other sites are also in agreement with the indicators of this manual.

3.4.2.2. Flow path movement

New paths of flow where channels are incised are formed by the long known general process of stream piracy (Shelton, 1966, p. 138 and fig. 134). There is simple stream piracy (capture) on some alluvial fans such as site 30 of Hjalmarson (1994) and the Tiger Wash site studied by Field (1994) in western Maricopa County. Field (1994) discusses how channels of fans in Maricopa County bifurcate "...through a process of stream capture in which overbank flow from the main channel accelerates and directs headward erosion of a smaller channel heading on the fan." The pulsing nature of sediment transport and deposition by short-lived floods along piedmont streams discussed in section 2.A of this manual "...is critical in the migration process, because the greatest amount of overbank flow is generated where bank heights are lowest."(Field, 1994).

The upslope overtopping of low channel banks and corresponding inflow and erosion of the head of a nearby channel certainly is a convincing explanation for gradual/sudden channel avulsion/bifurcation because the head of all channels ends before a divide is

reached (the progressively decreasing drainage area above the channel head in not able to provide runoff to sustain headward channel cutting). Stream piracy, the taking of the drainage basin of one stream (prominent stream) by another stream (pirate stream), can occur for several reasons including one or more of the following: (1) the pirate stream has a steeper gradient near the point of capture, (2) the course of the pirate stream is in more easily eroded rock, (3) the erosion potential, associated to the sediment load, of the pirate stream is larger, and (4) the channel of the prominent stream is aggrading. Items (1) and (4) are characteristics of site 30 in a USGS study (Hjalmarson, 1994).

It is important to be aware that sediment debris is deposited on alluvial fans in a complex manner. Deposits from large floods can be remobilized, transported downfan and redeposited (See the Rudd Creek, Utah site in National Research Council, 1996). The flow velocities may be high and possibly unstable (Hjalmarson and Phillips, 1997). Hooke and Rohrer (1979) found that higher discharge floods tend to flow down the axis of the fan while lesser floods can be turned to the sides of the fan. Hooke and Rohrer also found that for gentler slopes the floods are more easily diverted to the flanks. A literature review of documented floods on alluvial fans shows a variety of fluvial processes and areas of inundation during single large floods.

Although the processes of channel diversion are different on debris-flow fans, a literature review of documented avulsions demonstrates that flow on debris-flow fans is also commonly diverted into preexisting channels. These findings suggest that the location of future channels on alluvial fans may be more predictable than previously thought, although information on the frequency of diversions is still limited.

3.4.2.3 Drainage basin

The drainage basin of very active alluvial fans typically is bowl shaped where first and second order streams drain quickly to the hydrographic apex (See for example Blair and McPherson (1994) and McPherson and Blair (1993)). Active fans are also associated with high relief drainage basins (See for example Hjalmarson and Kemna (1991), Anstey (1965) and Blair and McPherson (1994). Loose debris accumulates within the basin upstream of the hydrographic apex until large floods transport the debris to the alluvial fan. A supply of material above the hydrographic apex is needed for active fan building.

Two sources of fan building material are typical of active alluvial fans in Maricopa County. The first is material derived from channel incision, or headcutting, into relict fans. This source is below the mountain front and commonly between the topographic and hydrographic apices. The second source of material is from sediment production in the mountainous drainage basin. Loose debris typically accumulates along the beds and banks of stream channels until the debris is transported by large floods to the alluvial fan. For most active alluvial fans in Maricopa County a supply of loose material along the basin channels is visible on good quality aerial photographs.

The absence of an abundant supply of unconsolidated medium to coarse granular sediment above the hydrographic apex suggests the alluvial fan is not active. For example, the supply of fan building material may have decreased with time as active channels incised into a relict fan. An alluvial fan may not be very active if (1) there is not a supply of material along the steep slopes of the drainage basin and (2) the profile of channels incised in relict fans to depths of more than 10 ft. is smooth. A smooth channel profile suggests there is no significant headcutting and associated limited supply of eroded material for fan building.

corrected by Wm

3.4.3 Additional information

There is a considerable amount of useful published information on the stratigraphy of alluvial fan deposits. While much of this literature is for specialists in fluvial deposits and sedimentary geology, some is useful for the stability assessment of this manual.

According to many geologists, technical specialists including Nilsen (1987), Blair, and McPherson (1994) alluvial fan deposits are recognized mostly by their physical characteristics. Several physical indicators are used because each indicator is not necessarily unique. Exposures of unconsolidated sediments in active fan channels can be examined in the field and samples of sediment can be collected and analyzed. Major physical indicators of active alluvial fan deposits found in the stratigraphic record according the Nilsen and Blair and McPherson are as follows:

- The deposits are located relatively close to their source area with a limited radial length.
- Deposition is dominantly by unidirectional, high-energy fluid flow, on steep slopes.
- The deposits are typically very poorly sorted and may have a great range in grain size.
- Clasts are poorly rounded, reflecting the short distance of transport. An exception to the common angular clasts is where the alluvial fan material is second or third generation sediments derived from relict fans.
- The deposits are compositionally immature and have a great range in composition, depending upon the types of rocks present in the source area.
- The deposits are characterized by major changes in lateral and vertical facies, particularly in the downfan direction.
- The deposits are characterized by rapid downfan decrease in both average and maximum clast sizes.
- The deposits generally contain very small amounts of organic matter because of the oxidizing conditions of sedimentation.
- Facies are predominantly planar-bedded associated with upper-regime water flow.
- The depositional bodies have a lenticular or wedge-shaped geometry and typically form clastic wedges.
- The deposits may be characterized by a radial sediment dispersal system.

For other useful information on the identification and dating of alluvial fan deposits from the stratigraphic record, see Bull (1987), Blissenbach (1954), Massari (1996), Blair and

McPherson (1992), Blair, Clark and Wells (1990) and Hereford (1996). The map of surficial geology that includes deposits of specific floods, along the Colorado River in the Grand Canyon by Hereford shows the detail possible using geologic methods.

Cryptobiotic soil surfaces (cryptogamic soil) are an indication of surface stability in arid and semi-arid deserts. These darkened surfaces are composed of cyanobacteria, lichens and mosses (Belnap, 1995) and may require hundreds of years to establish a soil cover. According to Belnap, recovery after surface disturbances is hampered by large amounts of moving sediment. Distrubed crusts in Maricopa County may recover in a few years and new crusts may form in 10 to 20 years. The presence of large areas of cryptogamic crust is a reliable index of surface stability for a few tens of years and possibly for a few hundred years.

3.5 Alluvial plains

These landforms are generally stable because of low slopes (usually less than 1 % but possibly 3%) and low rates of aggradation. Small-shallow continuous and discontinuous stream channels spaced at 100-500 ft. intervals that head on upslope piedmont and mountain areas dissect many alluvial plains. Because of the little transverse relief, except where channels are incised by headword erosion as the result of lowering of a base-level stream or where there are inselbergs, floodwater of the 100-year flood is rather unconfined and may spread over large areas (Table 3.2) and deposit sand, silt and clay. Very few rock fragments (size > 2mm) reach alluvial plains from upslope piedmont areas and mountains. Most of the area is subject to sheet flooding from rainfall directly on the alluvial plain or from upslope runoff that spreads over large areas at shallow depths. Major floods spread over the large-smooth areas between channels at depths of 1 ft. or more (Rhoads, 1986).

The flow path uncertainty can be ignored for the assessment of flood hazards of many alluvial plains. Most of the large floods are sheet floods or simply a sheet of unconfined floodwater moving down slope. Floodflow is not concentrated into well-defined channels. The distance of flow is relatively short and its duration is measured in minutes or hours. The area flooded can be rather large as shown in Figures 4.6 and 4.7 of this manual. Except for aggrading areas and areas of base level lowering and headcutting along throughflow channels, flow paths are rather certain for alluvial plain. Thus, most alluvial plains are considered stable for flood hazard assessment.

3.6 Variables that affect fluvial hazards

Users of this manual should be aware that landform changes because of nonstationary runoff, sediment loads and base level could affect the assessment of stable and unstable areas using the indicator method. The indicator method is based largely on historical information that may not reflect future conditions if, for example, the climate is fluctuating or watershed conditions change. Changes of discharge, sediment load and base level of a piedmont landform can affect flood hazards as given in Table 3.4. For

example, the likelihood of channel avulsion on an alluvial fan increases with increasing time simply because more sediment laden floods from the watershed are experienced. Also, if discharge on a landform increases then dissection of the landform is expected because of excessive erosion. This issue was addressed by the Committee on Alluvial Fan Flooding (NRC, 1966) as follows:

> *Judging where flooding and deposition might occur is particularly important in cases where land use patterns are substantially altered by human activity (e.g., the Wasatch Range, Utah) or where recent decades have been marked by more intense storm patterns. As an example of the latter, storms in southern Arizona have changed in this century from moderate-sized summer events with sources in the south to much larger fall and winter events coming from the west-southwest (Pacific Ocean). Some of this change in storm conditions is attributed to the increasing frequency of El Nino climatic events over the past few decades. In such cases, it probably is prudent to define active as more than just those parts of the fan that have been the sites of flooding and deposition in the past 100 or 1,000 years.*

Table 3.4. Variables affecting fluvial hazards on piedmonts over long periods.

Fluvial hazards	Variables							
	Time	Discharge		Sediment load		Base level	
		increase	decrease	increase	decrease	up	down
Erosion							
dissection		x			x		x
Deposition							
aggradation			x	x		x	
Pattern change							
development							
of pattern		x			x		x
avulsion	x	x		x		x	

In regard to flooding on piedmonts of Maricopa County, the issue is whether the El Nino fluctuation affects the flood frequency of small mountainous basins. Because of the large variance of annual flood peaks this is a difficult issue to resolve. Clearly, any climate fluctuations make the assessment of stable and unstable areas less precise. Also, both engineering and geomorphic assessments of fluvial hazards and risk are affected by trends in factors such as the peak discharge of floods. The delineation of stable and

unstable areas should be conservative to allow for any trends. If nonstationary site conditions are suspected, the following published studies of trends of climate, geomorphology, sediment yield and vegetation may be consulted.

1.--The behavior of fluvial systems and in particular, the understanding of the cause of incised channels, is described by Schumm, Harvey and Watson(1988). Channel incision may be the result of changes imposed on the system such as climate fluctuations or changes within the system such as the accumulation of sediment to threshold levels where gullying occurs. Channel incision is a natural occurrence in semi-arid regions like Maricopa County that may be independent of climate fluctuations. For additional interesting discussion of "Geomorphic implication of climate change", see Schumm (1969).

2.-- Abrahams, Parsons and Wainwright (1995) found interrill runoff and erosion increased as a result of replacement of grassland with shrubland at Walnut Gulch in southeastern Arizona during the past 100 years. There is some evidence of rill, interrill and channel erosion on piedmonts of Maricopa County that is similar to rill erosion at Walnut Gulch.

3.-- Nonstationarity or trends of annual peak discharge at USGS gages on streams draining areas less than 200 mi^2 were not detected for Arizona as part of an analysis of flood frequency of the western U. S.(Thomas, Hjalmarson and Waltemeyer, 1997). The highly variable nature of flood peak discharge in Maricopa County may mask the identification of recent changes, if any, of discharge.

4.-- A study of the variation of warm-season rainfall in the northern Arizona region shows a recent decrease of wet years and an increase of dry years has reduced runoff, sediment loads and erosion(Hereford and Webb, 1992).

5.--Studies in southern Arizona have shown a slight decline in the frequency of heavy rains (Cooke, Warren and Goudie, 1993).

3.7 Summary

There is a strong correlation between the age of the landform and the terms stable and unstable (See Figure 2.3). For example, relict fans are old and typically are stable. Stability is the relative state of hazard on the landform. Several indicators of stability are included in the discussion of type of landforms in Chapter 2 of this manual.

An example map of stable and unstable flood hazards is shown in Figure 3.1. Figure 3.1 is the result of stage 2(Table 1.1) and is the progression from Figure 2.7.

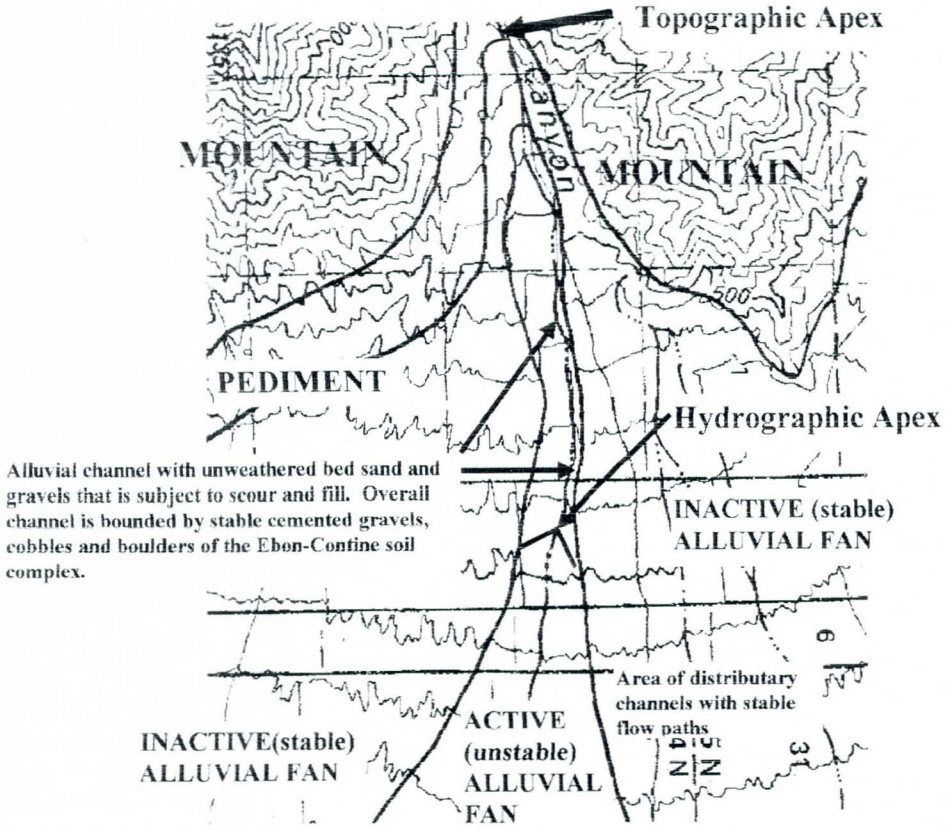


Figure 3.2 Example map of landforms and stable (inactive) and unstable areas.

4
DEFINITION OF 100-YEAR FLOOD HAZARDS

This chapter is a discussion of flood hazards in Maricopa County and realistic methods for defining these hazards for flood plain management. Clearly, before the 100-year flood hazard is assessed, it is important to properly identify the type of landform(s) as described in Chapter 2 of this manual and to define the nature and location of flood hazards (stable and unstable areas) of the particular landform as described in Chapter 3 of this manual. Traditional engineering methods are preferred for the definition of 100-year flood hazards at stable areas as defined in Chapter 3. Geomorphic methods are preferred for the definition of the flood hazard at unstable areas.

There are distinct differences in areas subject to flooding on relict fans, pediments, active alluvial fans, inactive alluvial fans and alluvial plains. Where flow paths are stable and flow is reasonably confined, standard hydraulic engineering methods such as backwater computations are used to define the elevation (or depth), velocity and extent of the 100-year flood. These backwater computations use a specific peak discharge estimated for the 100-year flood. This 100-year peak discharge and the accounting of energy losses from surface friction and hydraulic expansion form the foundation of the engineering methods. An accounting of flow energy is performed along the flow path. Where there are changing channel conditions and other unstable conditions, the accounting of flow energy is uncertain and geomorphic methods are used mostly to supplement the traditional engineering methods. For active alluvial fans and alluvial plains where the flow is unconfined and/or there is substantial sediment accumulation, normal backwater profile computations for flood definition may be inappropriate. Geomorphic methods are used to assess flood hazards on active alluvial fans.

Geomorphic methods generally are superior to traditional engineering methods for hazard definition on active alluvial fans because the magnitude of the 100-year peak discharge is not very important. The problem is that the geometry of the active-fan surface changes during flooding because of scour, fill and flow path movement below the hydrographic apex. Floodwater and sediment spread over wide areas at shallow depths and at high velocities. The state of flow may be supercritical or subcritical or changing in time and space during flooding. There is evidence that floodflow tends to follow the preflood channels but there is also geologic evidence that flow paths change over long periods. Thus, because during many floods the flow paths change, flow depths are shallow, flow is somewhat unconfined and expanding and sediment is deposited, remobilized and transported further downslope, the precise amount of the flood peak discharge at the hydrographic apex or the precise preflood geometry within the bounds of the fan are not very important. It is more important to delineate the active alluvial fan area using geomorphic techniques because the hazard within these bounds is severe.

Traditional engineering methods are particularly applicable to the defined channels of relict fans and pediments. Hydraulic methods given in Volume II of the Drainage Design Manual for Maricopa County (1996) and Guidelines and Specifications for Study Contractors (FEMA, 1995) are appropriate for most reaches although some attention to sediment, scour and bank erosion is needed.

Traditional hydraulic methods may also be used for stable (inactive) alluvial fans and weathered granite pediments where there are many channel forks and joins. A few inactive alluvial fans and weathered pediments, however, have distributary and unchanging flow paths with changing channel geometry (mostly bed scour) and roughness. The proportion of flow that splits at the channel forks may change some from one flood to the next or during a flood (the distribution of discharge may be dependent on the frequency of the particular flood peak discharge). For most of these forks there is some bed scour during high flow. A possible solution to this flow splitting is a probability based method discussed by the Committee on Alluvial Fan Flooding (NRC, 1996). A preferred solution for flow splitting on these landforms is the use of traditional hydraulic methods like those described in the Arizona State Standards of Practice Report for Lateral Migration and Channel Degredation (June 7, 1995) to estimate the amount of bed scour at channel forks. Obviously, a site that exhibits the characteristics given in Table 3.1 is a candidate for channel conveyance-slope methods to estimate the level and extent of the 100-year flood. In general, physically based methods that consider site processes and hydraulics, in particular channel geometry, grade and roughness and channel bed and bank material are preferred.

The precise definition of flood characteristics on alluvial plains is difficult mostly because of the spreading of floodwater over large areas at shallow depths. Unlike the flow on most alluvial fans, flow entering alluvial plains typically is lower regime. In the rapid expansion of tranquil flow, a major hydraulic issue is the uncertain loss of head to surface roughness and eddies. Flood depths can be estimated using methods given in the Arizona State Standard for Identification of and Development within Sheet Flow Areas (SSA 4-95).

Traditional engineering methods are least applicable for definition of flood levels (or depths), velocities and boundaries on active alluvial fans of Maricopa County because the paths of flow may change as a result of sediment deposition and erosion as previously discussed. Also, the rapid expansion of both tranquil and rapid flow is a major issue where there are no known practical hydraulic solutions to the precise definition of flood depths, velocities and boundaries. The most severe hazard on many active alluvial fans is from avulsions and sediment deposition and to a lesser degree from inundation. For additional discussion of engineering and geomorphologic methods see Pearthree (1991).

4.1 Methods for defining 100-year hazards

For active alluvial fans the most severe hazard is from sediment deposition, high velocities, flow path movement and erosion (NRC, 1996). Floodplain maps should

attempt to show both the flood hazard involving inundation and the hazards associated with sediment deposition, bank erosion and avulsions. Because the definition of 100-year flood characteristics must be legally and politically defensible, the engineering and geomorphologic methods should also be documented and defensible.

The general approach is to use standard hydraulic methods where applicable and to supplement the computed flood profiles, velocities and boundaries with a geomorphic assessment (See Table 4.1). **For unstable areas, the flood hazard assessment is accomplished using geomorphic methods and possibly supplemented with appropriate hydraulic methods.**

4.1.1 Relict fans and pediments

On relict fans and many pediments (including the portions upslope of the weathered granite discussed in Section 2.2.1 of this manual) the floodwater typically is confined to narrow channels (See for example Figure 4.1). There is also shallow overland flow on the slopes of pediments and relict fans (see *Overland Flow* in State of Arizona Standard 4-95) and sheet flooding on flat interfluves of some relict fans (see *Natural and Urban Sheet Flow* in State of Arizona Standard 4-95).

Normal backwater profile computations using the standard step method for flood definition are appropriate for these areas. In addition to the traditional hydraulic conditions, the fieldwork should focus on identification of any distributary channels, inset alluvial fans and stream piracy. In general, stream piracy should be considered only where floodwater of large floods could presently enter the pirate channel because piracy may not progress at an engineering time scale.

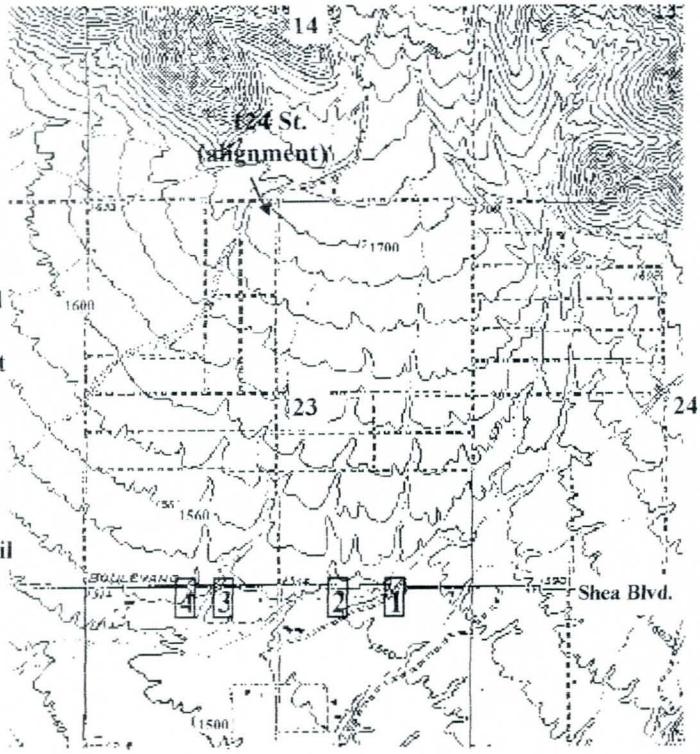
The 100-year flood hazard on weathered granite pediments with distributary flow paths that are described in section 2.2.1 of this manual is assessed using methods for inactive alluvial fans as described below.

4.1.2 Inactive alluvial fans

On inactive alluvial fans and those weathered granite pediment areas described in section 2.2.1 of this manual, floodwater typically is along incised channels and adjacent stable land (See for example Figure 4.2). There typically are smooth-flat and/or stable ridges that separate the incised channels and these ridges are above the level of major floods from rainfall in the mountains and upper piedmont.

Table 4.1 Defining and characterizing 100-year floods on piedmont landforms of Maricopa County.

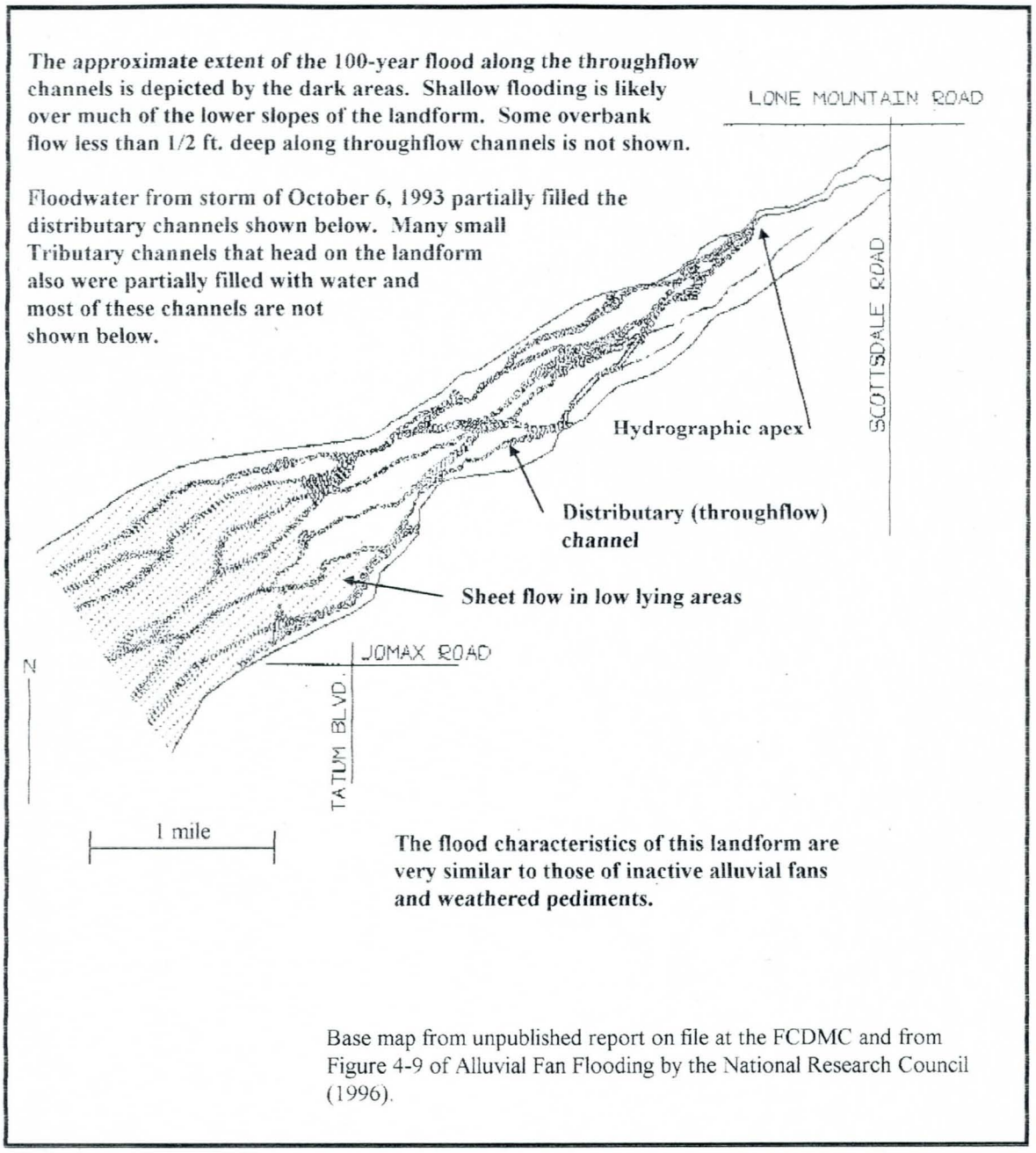
CHARACTERISTIC	DATA SOURCE
1. Drainage basin (water and sediment source area)	
Area	Topographic maps, aerial photos and field inspection
Flood frequency relations	Drainage Design Manual, Vol. I, Hydrology
Channel capacity at basin mouth (topographic apex)	Field work and surveying
Debris flow potential/frequency	Field inspection
Sediment supply and grain size characteristics	Field work/soil survey reports/ aerial photos
2. Define the type of landform as given in Chapter 2 of this manual.	
3. Define stable and unstable areas of flood hazard as given in Chapter 3.	
Where has historic flooding occurred? (Examine photos, vegetation, soils, pavement and varnish)	Historic aerial photos/ soil maps/ vegetation/ geologic mapping/ flood reports
Examine geometry and composition of channels (width, depth, gradient, deposits in banks)	Field work/ surveying/Misc. methods of this manual
4. Define areas of confined and unconfined flow on the particular landform	
Characterize flow during historic events	Aerial mapping/ field mapping
Characterize prehistoric flows--map deposits	Aerial photos/ field mapping
Determine the type of processes suggested by deposits (Give reasons why deposits suggest water flood or debris-flow processes.)	Fieldwork
5. For any stable channels define 100-year flood profiles	Traditional hydraulic methods
6. Estimate debris flow potential and areas of hazard	Geomorphic mapping/soil maps/ aerial photos/field work
7. Estimate areas of erosion hazard	same as item 6 above
8. Estimate areas of sedimentation hazard	same as item 6 above



Floodwater for storm of June 22, 1972 was confined to defined channels. Indirect measurements of peak discharge made by USGS. According to the NRCS(Camp, 1986) the Ebon soil is on fan terraces. Channels are incised between 3 and 15 ft.

Station	Stream and place of determination	Drainage area, (sq. mi.)	Discharge (cfs)	Unit runoff (csm)
1	Shea Wash, SE 1/4 sec. 23, T. 3 N., R. 5 E., at Shea Blvd.	1. 79	945	528
2	Shea Wash trib No. 3, SE 1/4 sec. 23, T. 3 N., R. 5 E. , at Shea Blvd.	.09	86	956
3	Shea Wash trib. No. 2, SW 1/4 sec. 23, T. 3 N., R. 5 E., at Shea. Blvd	.14	103	736
4	Shea Wash trib. No. 1, SW 1/4 sec. 23, T. 3 N. , R. 5 E. . at Shea. Blvd.	.12	80	667

Figure 4.1 Example of flooding on relict fan.



Base map from unpublished report on file at the FCDMC and from Figure 4-9 of Alluvial Fan Flooding by the National Research Council (1996).

Figure 4.2. Example of flooding on an area with incised distributary channels near Carefree.

Normal backwater profile computations using a model such as HEC-RAS (COE, 1995) that computes profiles through stream junctions (channel forks and joins) are appropriate for many throughflow channels. These precise profile computations may require a great number of cross sections because 100-year floodwater in the many distributary flow paths traverses long piedmont slopes at shallow depths. Where precise computations of water

surface profiles using energy or momentum based methods are unwarranted, the use of channel conveyance and slope estimates for definition of flood boundaries may be satisfactory and cost effective. Thus, flood boundary definition using ratings based on channel conveyance may be appropriate for some networks of distributary channels.

Both the rating curve and normal profile methods have a built in safety factor because the peak discharge is apportioned through the network of channel reaches by assuming that the flood peaks coincide at all forks and joins. The natural attenuation of flood peaks that results from channel storage and the unequal timing of peaks in the separated channels below splits and above joins is ignored in this method. This accounting of peak flow is based on the simple assumption that the joining of separated flood peaks is at the peak discharge. This method reduces the impact of underestimating the magnitude of flow in separated distributary channels. The impact reduction can be significant below joins because of the flashy nature of piedmont floods and the associated attenuation of peaks as floodwater spreads into a network of channels. The risk to homes along these stable networks of distributary channels may be significantly reduced by use of this conservative accounting method.

Development of inactive alluvial fans should recognize that throughflow channels convey both floodflow and sediment. Development that is set back from these channels and does not interfere with the water and sediment transport can have long term environmental benefits.

Delineation of major tributary streams that head on the inactive fans or weathered pediments is important to maintain an open flow path to the throughflow streams. Tributary streams typically drain areas much less than 1 mi^2 and flow depths are typically less than 1 or 2 ft. Streams draining such small areas may not be identified as subject to FEMA flood hazard delineation but may fall under state and county regulations. For example, the State of Arizona Standard for watercourse bank stabilization (SSA 7-98) includes all watercourses with drainage areas more than 1/4 mi^2 or a 100-year discharge estimate of more than 500 ft^3/s (See Arizona Revised Statute 48-3605(a)).

In addition to the definition of traditional hydraulic conditions, the fieldwork should focus on identification of any areas of sediment deposition and impending stream piracy. Floodflow on some inactive fans becomes unconfined on lower slopes like that for the Carefree alluvial fan (NRC, 1996). For unconfined sheet flow see *Natural and Urban Sheet Flow* in State of Arizona Standard 4-95.

4.1.2.1 Rating curve method for allocating split flow

For distributary channel networks where the channel in which water-surface profiles are being computed splits into 2 or more separate channels, each channel must be considered a separate reach. This is demonstrated using the fork in Figure 4.3 where the total discharge is split into unknown components in the right and left channels. It is desired to determine the stream profile and the distribution of flow in the right and left channels.

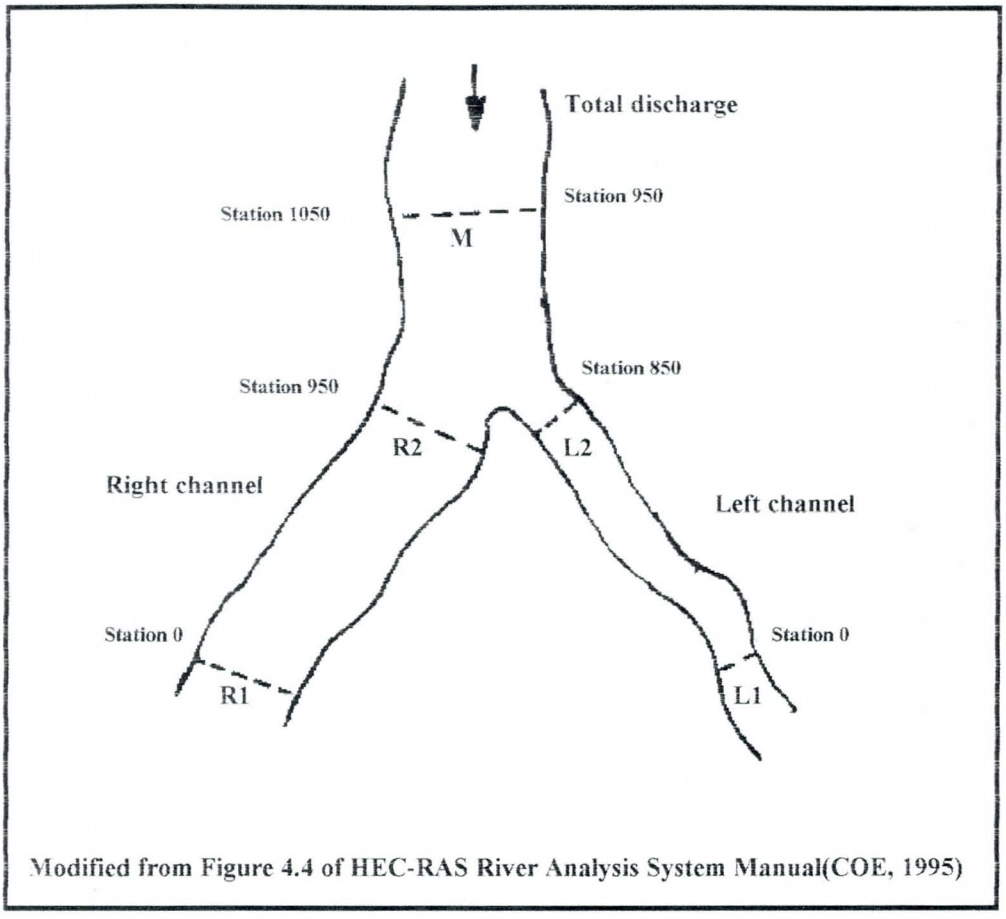


Figure 4.3. Example of split flow at a channel fork.

The problem is that the division of the flow into the right and left channels is not known and the HEC-RAS (COE, 1995) model assumes the user has determined the correct flow in each channel. To use HEC-RAS to compute water-surface profiles the division for subcritical flow is accomplished as follows.

The right and left channels are calibrated by establishing a stage-discharge relation for section M (Figure 4.3). For example, beginning at section R1 and working up the right channel, the water surface profiles for various discharges are computed up to M. A minimum of three discharges is needed that span the correct discharge for the right channel. For this example four discharges were used for each channel as shown in Table 4.2. The rating, computed water-surface elevation at M versus discharge (See computations in Table 4.2), is plotted as in Figure 4.4, with a solid line. A similar rating is established at section M for the left channel, and plotted with a dashed line in Figure 4.4. The crossing of the two curves determines the proper subdivision of the total discharge into the right and left distributary channels. For further information on the use of this technique see Computation of Water-Surface Profiles in Open Channels (Davidian, 1984).

4.1.2.2 Cross-sections

Cross sections used for normal backwater profile computations should be representative of the channel reach between them and should span the width of landform that includes the channels which might convey the 100-year flood. If there is any doubt about which channels may convey floodwater, the cross sections should span the channels across the entire width of the landform between the boundaries defined in Chapter 3. Cross sections are placed at intervals along the network of channels that will subdivide the distributary channels into a series of subreaches of relatively uniform geometry and roughness. Cross sections may be located at contour lines of a detailed topographic map because the shallow flow is approximately perpendicular to contours and the section shape may be estimated from the map information. Cross sections should be located above and below all forks and joins of the network of channels such that the fork or join is in the middle of the subreach (see Figure 4.3). In general, cross sections should be established in accordance with procedures in water-surface profiles user's manuals such

Table 4.2. HEC-RAS output for subcritical flow split using rating method.

RAS Plan: Rating.split 6/4/96

Reach	River Sta.	Q Total (cfs)	Min Ch Elev. (ft)	W.S. Elev (ft)	Crit W.S. (ft)	E.G. Elev (ft)	E.G. Slope (ft/ft)	Vel Chnl (ft/s)	Flow Area (sq ft)	Top Width (ft)	Froude No.
Right	1050	200	92.00	93.78		94.36	0.0157	6.12	32.68	18.71	0.82
Right	1050	200	92.00	93.70		94.34	0.0182	6.42	31.14	18.68	0.88
Right	1050	200	92.00	93.63		94.33	0.0205	6.68	29.96	18.65	0.93
Right	1050	200	92.00	93.73*		94.35	0.0173	6.32	31.65	18.69	0.86
Right	950	160	90.00	91.90		92.62	0.0198	6.80	23.53	12.76	0.88
Right	950	145	90.00	91.79		92.46	0.0198	6.57	22.07	12.71	0.88
Right	950	130	90.00	91.67		92.29	0.0197	6.32	20.58	12.67	0.87
Right	950	150**	90.00	91.82		92.51	0.0198	6.65	22.56	12.73	0.88
Right	0	160	71.00	72.90	72.74	73.62	0.0200	6.82	23.46	12.76	0.89
Right	0	145	71.00	72.78	72.63	73.45	0.0200	6.60	21.98	12.71	0.88
Right	0	130	71.00	72.66	72.52	73.29	0.0200	6.35	20.46	12.66	0.88
Right	0	150	71.00	72.82	72.67	73.51	0.0200	6.67	22.48	12.73	0.88
Left	950	200	92.00	93.62		94.33	0.0211	6.73	29.71	18.65	0.94
Left	950	200	92.00	93.77		94.36	0.0158	6.14	32.57	18.71	0.82
Left	950	200	92.00	93.96		94.44	0.0115	5.54	36.10	18.79	0.70
Left	950	200	92.00	93.72*		94.34	0.0174	6.33	31.60	18.69	0.86
Left	850	40	90.00	91.75		92.18	0.0199	5.26	7.60	4.70	0.73
Left	850	55	90.00	92.16		92.67	0.0200	5.73	9.60	4.87	0.72
Left	850	70	90.00	92.55		93.13	0.0199	6.08	11.51	5.02	0.71
Left	850	50**	90.00	92.03		92.52	0.0200	5.59	8.94	4.81	0.72
Left	0	40	73.00	74.75	74.42	75.18	0.0200	5.27	7.59	4.70	0.73
Left	0	55	73.00	75.16	74.75	75.67	0.0200	5.74	9.59	4.87	0.72
Left	0	70	73.00	75.55	75.04	76.12	0.0200	6.09	11.49	5.02	0.71
Left	0	50	73.00	75.03	74.64	75.51	0.0200	5.60	8.94	4.81	0.72

as HEC-2 (U.S. Army Corps of Engineers, 1990) and WSPRO (Shearman, 1990) and the Guidelines and Specifications for Study Contractors (FEMA, 1995).

The subdivision of cross sections should be accomplished based on channel geometry. Each of the channels that potentially may convey floodflow should be subdivided to facilitate the analysis of the amount and distribution of floodflow in the network of channels. The computer program should be capable of tabulating hydraulic characteristics for the subsections at many elevations for each cross section (see for example WSPRO (Shearman, 1990)). Across some channel networks the roughness of defined channels is markedly less than the roughness of adjacent land and the subdivision should define the roughness differences. Well-defined channels with low roughness may have critical-flow conditions and the adjacent rougher land with shallower floodflow may have subcritical-flow conditions. Thus, the computer program should be capable of managing values of Q at both critical and normal depths for the subareas at several water-

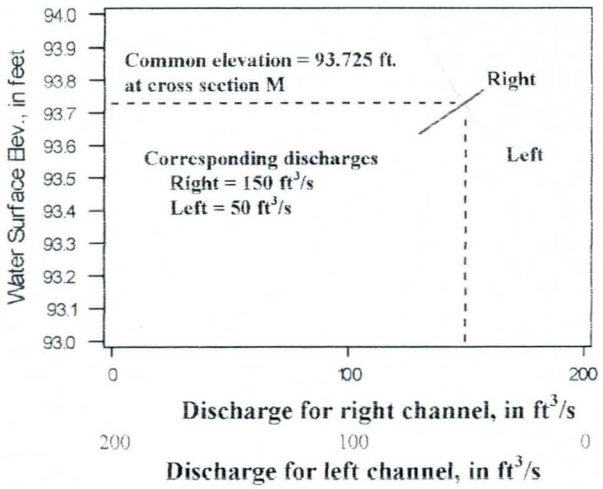


Figure 4.4 Distribution of flow at split using the rating method.

surface elevations. Where defined throughflow channels are relatively small and meander there may be additional roughness from the meanders as floodwater rises above the defined banks of the small channels and "short circuits" or passes over the meanders. Such "short circuits" are likely on granite pediments in Maricopa County. Thomsen and Hjalmarson (1991) discuss subdivision of cross sections and the estimation of roughness coefficients for streams in Arizona.

4.1.2.3 Channel conveyance-slope method

Some networks of distributary channels convey floodflow in many small channels that have many forks and joins (see for example the distributary channels is Figure 4.2). In order to define the extent of flooding, each of the channel segments must be defined as a separate reach with a unique peak discharge. Many computations of flow apportionment

at the forks and joins and many standard step-backwater or forewater computations for the many individual reaches are needed. The problem is these computations are time consuming, expensive because of the data requirements and possibly unnecessary especially where flow depths and velocities are not very hazardous. The channel conveyance-slope method greatly simplifies the data and computation requirements and should be considered for these areas.

Flow apportionment based on channel conveyance and slope may be used for these less hazardous networks (networks composed mostly of small channels) of stable distributary channels. The peak discharge is apportioned through the network of channel links (reaches) by assuming the flood peaks coincide at all divides and joins. A single cross section for each of the distributary channels below each fork (See for example sections R2 and L2 in Figure 4.3) is used. By assuming lower regime flow velocities and a uniform water level at the head of the distributary channels, flow is easily apportioned using channel conveyance and slope. The estimates are further simplified where the slope difference along the channels is small and can be ignored. The resulting estimated peak discharge and corresponding channel conveyance (or even channel area where channel roughness is uniform) are used to estimate flood boundaries for each reach. This technique can produce reliable and low-cost delineation of the location and extent of flooding on distributary networks of channels especially if the throughflow channels are kept free of obstructions.

This approximate technique may be used for distributary channel networks on inactive alluvial fans and those granite pediment areas described in section 2.2.1 of this manual, where the hazard is not very great. The major steps for apportioning 100-year flood peak discharge and estimating the flood boundaries using the conveyance-slope method follow:

1.-- Define the 100-year peak discharge above the hydrographic apex (see Figure 4.2 for an illustration of an hydrographic apex above a complex network of distributary channels. The hydrographic apex and boundaries of the landform were defined in Chapter 3. The 100-year peak discharge is estimated using the drainage basin area and flood-frequency relation using sources given in Table 4.1.

2.-- Define the throughflow and major tributary watercourses throughout the landform on a detailed topographic map. The flow paths and should lie within the bounds of the landform defined using methods in Chapter 2.

3.-- Estimate limits of flooding along each distributary channel. High ridge lines separating the channels can be defined on detailed topographic maps. The width of flooding should be within the flood limits defined in Chapter 3 of this manual.

4.-- Identify each distributary channel reach that has a channel fork or join at the upstream end and a channel fork, join or outlet at the downstream end.

5.-- Select a cross section near the middle of each reach that represents the hydraulic conditions of the reach. The cross section must represent channel conveyance below any fork at the upper end as discussed in the previous paragraph and in USGS report Computation of Water-Surface Profiles in Open Channels (Davidian, 1984). Although not the rule, several subreaches may be needed for some reaches if hydraulic conditions change significantly along the reach.

6.-- Define areas and subareas of cross sections.

7.-- Select Manning's *n* for the areas and subareas.

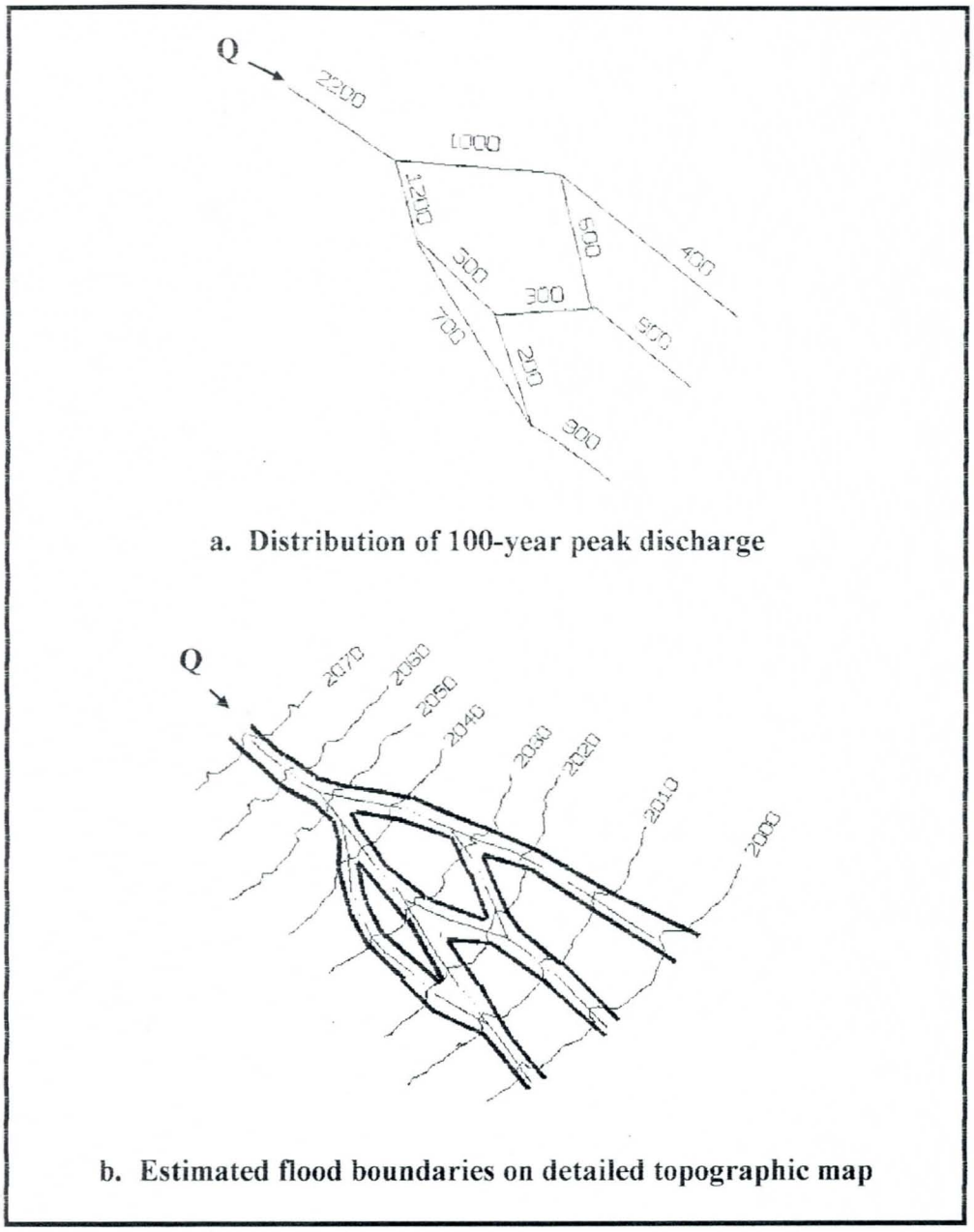
8.-- Compute and tabulate conveyance and discharge for the area and/or subareas of the cross sections and define the stage-discharge relation above and below all channel forks. The distribution of wide-shallow flow approaching a channel fork can be used in conjunction with the channel capacities below the fork to apportion peak discharge at the fork. Engineering judgment is needed for the apportionment of flow at forks because the splitting of peak discharge is related to both the distribution of the wide-shallow flow approaching a fork as well as the channel capacities below the fork.

9.-- Apportion or route the peak discharge at the channel forks using the rating curves for each reach of distributary channel and the assumption the water surface is horizontal across head of each channel fork and the slope of the channels is the same as discussed above. The distribution of peak flow for this simple technique is based on the assumption that the joining of separated flood peaks is at the peak discharge. The peak discharge is apportioned through the network of channel reaches by assuming that the flood peaks coincide at all forks and joins (Figure 4.5.a). Any reduction of peak discharge from channel storage and transmission losses to infiltration into the channel beds is assumed to offset tributary inflow for this simple example. Allowance should be made for inflow from any large tributaries.

10.-- Estimate the flood boundaries on the detailed topographic map using conventional engineering techniques (Figure 4.5.b).

4.1.2.4 Soil characteristics

The apportionment of flow at all forks has some uncertainty as previously discussed. Because of this uncertainty, the verification of the computed flood limits by briefly examining the soils and channel morphology along each of the individual reaches is recommended for all sites in Maricopa County. If the present soil characteristics are related to past and future flooding, this use of soils can be a low-cost physically based means of supplementing the hydraulic computations. Physically based methods like soil age may be more reliable in dealing with uncertainty than methods based on assumptions of the nature of uncertainty (See for example Figure 3-10 of NRC, 1996).



a. Distribution of 100-year peak discharge

b. Estimated flood boundaries on detailed topographic map

Figure 4.5. Sketch of stable distributary flow paths showing distribution of 100-year flood peak discharge and estimated flood boundaries.

Soil development characteristics should be used to supplement the delineation of flood boundaries using the hydraulic methods (See Table 4.1). These soil characteristics may be more detailed than those used in the stability assessment outlined in Chapter 3 of this manual. For example, the stability assessment in Chapter 3 relies mostly on surface characteristics like color, desert pavement and rock varnish and methods that are more detailed might include an analysis of soil development by a soil scientist. There is a

correlation between the age of soil and the areas flooded along the channels (NRC, 1996, p. 111 and Cain and Beatty, 1968). Sediment deposited within the general bounds of the 100-year flood should be recent (young and unweathered).

4.1.2.5 Discussion

The precise and approximate techniques for allocating peak discharge and defining flood boundaries may be modified to account for infiltration, attenuation and tributary inflow effects. Large networks of distributary channels with small drainage basins may have a relatively large component of tributary peak discharge from within the channel network that should be included in the hydrology. For example, a significant portion of the total storm runoff on October 6, 1993 at the Carefree, Arizona site (Figure 4.2) was from within the bounds of the network of distributary and tributary channels (NRC, 1996) and below where flow was last confined. For some networks of distributary channels, it may suffice to assume the runoff directly from the inactive alluvial fans and granite pediment areas offsets the loss of incoming peak discharge at the hydrographic apex to infiltration. For example, in the simple example given in section 4.1.2.3 (step 9) the tributary inflow was assumed to offset losses to infiltration along the throughflow channels.

The numerous distributary channels function to convey water and sediment through and from the inactive alluvial fans and weathered pediments. Those areas along throughflow channels subject to inundation by floods up to the 100-year flood might be set aside as floodway districts in order to maintain conveyance corridors for the transport of the floodwater and sediment down the piedmonts past development. Development that is set back from these throughflow paths may help maintain the natural sediment and runoff balance and prevent unwanted channel scour and sedimentation within and downstream from these areas.

4.1.3 Active alluvial fans

Active alluvial fans generally serve as a terminus for water and sediment while streams convey water and sediment. The major hazard on active fans in Maricopa County is one of both sudden and long-term sedimentation and erosion where a site may become buried or become part of a new active channel. The temporary inundation by floodwater traditionally associated with *riverine* hazards may be a lesser hazard on active alluvial fans. On active alluvial fans there is *alluvial fan flooding* as described in the Glossary of this user's manual and in *Alluvial Fan Flooding* by the NRC(1996).

The 100-year peak discharge at the hydrographic apex is only a partial index of the hazard. Traditional step backwater methods of defining profiles and flood boundaries for the 100-year flood has little meaning because the floodwater typically becomes unconfined and spreads in various flow paths at uneven levels. The paths of flow may change during flooding as a result of sedimentation and erosion. Deposited sediment is remobilized and redeposited downfan by subsequent floods. On some fans large floods may transport and deposit large amounts of debris that eventually is translocated by

smaller less sediment laden floods. The resulting morphology may appear deceptively simple and invite overly simplified probabilistic depiction of the hazard as that developed by Dawdy (1979).

The natural path of floodwater over alluvial fans in Maricopa County is not random during a time span of a few hundred years (CH_2M Hill, 1992 and Pearthree, 1991). For active fans like those in the County, the preflood topography influences the location of major flooding (NRC, 1996). Nonetheless, alluvial fans or portions of alluvial fans in Maricopa County that are active are subject to infrequent flashy sediment laden torrents. All of the active area is considered potentially dangerous and risky for development. **Only major flood control works will mitigate flood hazards on active alluvial fans** (NRC, 1996).

4.1.3.1 Flood hazard management in Maricopa County

The active alluvial fan defined using the geomorphic methods in Chapter 3 of this manual is an area of great potential risk and danger to development and life. In the absence of major engineering measures to mitigate the fluvial hazard, this entire area is reserved in order to receive sediment and floodwater without altering and thereby increasing the distribution of hazard across the fan to inactive areas and to areas downslope.

> **The high hazard area should be regulated similar to the floodway district in the typical riverine floodplain.**

An important requirement in the final definition of flood hazard involves a review of the distinction between active and inactive areas on the fan. The topography of the fan, in particular the relation between the stream channel and the fan surface, is re-examined using the best available maps. Using the best estimate of the 100-year peak discharge, the capacity of the channel at and below the hydrographic apex is next examined. If the channel(s) is so incised that the 100-year flood cannot break out of its channel(s), the fan must be further evaluated before it is considered active. A fan surface that is above the level of the 100-year flood may not be very active.

In the identification of stable and unstable areas, Chapter 3 of this manual, an alluvial fan is considered active if there is recent evidence of flow path movement and other disturbance by flooding during the Holocene geologic epoch. In the absence of a finer time scale, the past 10,000 to 15,000 years is a convenient and practical period to use as discussed in Chapter 3 of this manual. Use of this period is expected to result in a satisfactory and conservative assessment of the flood hazard for most alluvial fans.

Fans with a nonstationary flood hazard typically evidenced by recent movement of the hydrographic apex may need further assessment of activity. Many stream channels in Arizona are incised as a result of geologically recent climate change (Cooke and Reeves, 1976; Hereford and Webb, 1992; Waters, 1985; and NRC, 1996). Fans with recent

channel incision that make portions of the fan less active may require a precise dating and field assessment of the fan surface by a qualified soil scientist or geologist in order to define the flood hazard. The 100-year flood test described above should be applied to these less active areas. A more detailed examination of the fan stratigraphy as discussed in section 3.4.3 of this manual may be needed. These less active fans or less active portions of fans are a special case and require supportive documentation of site conditions and interpretations by qualified soil scientists, geologists and engineers.

The evaluation should also include a detailed field examination of the drainage basin and supply of fan building material. Very active fans have an abundant supply of unconsolidated medium to coarse granular material along the steep slopes and channels of the drainage basin. Active fans may also have a material supply along incised channels of relict fans. A fan may become less active as the rate of channel incision in the relict fan has lessened over time. Such decreased fan activity may be difficult to demonstrate but the lack of an abundant supply of fan building material suggests a low activity. The channel beds above the hydrographic apex of active alluvial fans typically are composed of unconsolidated sand, gravel, cobbles and scattered boulders.

Alluvial fan surfaces that: (1) are classed as active using indicators of Chapter 3, (2) are generally above the level of the 100-year flood, and (3) do not have an abundant supply of sediment above the hydrographic apex are not considered very active. The user should be aware that an "abundant sediment supply" is related to the size of the alluvial fan that is located below the sediment supply. For example, a sediment supply may be considered abundant for a small alluvial fan and less than abundant for a large alluvial fan. In this regard, Hjalmarson and Kemna (1991) found that fans with relatively large drainage basins were more active than fans with relatively small drainage basins. These areas of low activity may be defined using methods given in this manual and possibly supplemented using methods by Hjalmarson and Kemna (1991).

Mitigation of hazards on active alluvial fans is beyond the scope of this manual but in general, hazards on fans with a low level of activity might be mitigated using less than major engineering measures. Any engineering measures should not increase the fluvial hazard at other locations on or below the active fan.

4.1.3.2 Fans with random flow paths

For the very few alluvial fans in Maricopa County that may not exhibit obvious preferred flow paths, the assumption of absolute uncertainty where the floods might occur on the fan surface may be made. This special case where there are no channels on the fan meets the FEMA *Guidelines and Specifications for Study Contractors* (1995) but should be used only as a last resort.

4.1.3.3 Supercritical flow velocities and *translatory wave* considerations

Flow velocities at the hydrographic apex may be supercritical and flow may expand as unconfined flow over the fan surface (McPherson and Blair, 1993). Flow velocities may remain supercritical and possibly unstable along the upper fan as evidenced by an observed sheet flood with migrating waves in the active deposition lobe of a fan (Blair and McPherson, 1994). Oblique expansion waves (Chow, 1959) may form where the channel banks widen and the waves may continue down the fan. Where the channel width-depth ratio is large and Froude numbers are greater than 1.6, the flow may be unstable causing large-wide translatory waves (Hjalmarson and Phillips, 1997). High flow velocities, sheet flood and translatory waves are common documented characteristics of alluvial fan flooding (NRC, 1996).

There is no known practical step forward method to precisely define the water-surface profile or a method to define the single-event fan profile for the hazardous conditions described above. With active sediment transport deposition where slopes are both steep and mild, many assumptions of channel and sediment conditions are needed. An example of such assumptions for channel slope and width is given by French (1995) in his estimate of the channel profile where the slope changed from steep to mild. Quantitative estimates like the hypothesized approach used by French should consider accounts of actual floods like those of Blair and McPherson (1994).

4.1.3.4 Published examples of geomorphic hazard assessments

Examples of a few geomorphic assessments of flood hazard that reflect to some degree the probability of the design or regulatory flood have been published. The major advantage of geomorphic assessments is they are physically and process based. A major disadvantage of geomorphic methods may be that traditional expressions of flood event probability are limited. A major advantage of traditional hydraulic engineering methods in the United States is that the flood event probability is estimated and then converted to computed elevations and mapped boundaries. A major disadvantage of this traditional method is that assumptions of channel stability, friction and eddy losses and flow-path location may be severely limited.

Useful examples of fluvial hazard assessments with maps of hazard zones for are found in CH_2M Hill (1992), Kellerhals, R and Church, M.(1990), Thurber Engineering Ltd. (1983), Whitehouse, I. E. and McSaveny, M. J. (1990) and Field and Pearthree (1992).

Examples of illustrated accounts of flow path stability and/or severity of flood hazard are provided in Hjalmarson, H. W. (1994) (See section 8.4 of this manual), Hjalmarson, H. W. (1978), Hjalmarson, H. W., and Tram, J. (1995), Hjalmarson, H. W., and Kemna, S.P. (1991) (See section 8.3 of this manual), Pearthree, P.A. (1991), and Rhoads, B. L. (1986).

Examples of geologic maps of flood deposits with corresponding age designations that are especially useful for conditions in Maricopa County are found in Blair, C. B. and McPherson, J. G.(1992), Blair, C. B. and McPherson, J. G.(1994), Hunt, C. B.(1975), Hunt, C. B. and Mabey, D. R. (1966) and Wells, S. G. (1977).

4.1.3.5 Published examples of modeled hazard assessments

Examples of modeling debris or water flows on alluvial fans are given in Anderson-Nichols and Co.(1981) and O'Brien, J. S. and Fullerton, W. T.(1990).

An example of a laboratory model and short term and long-term flood risk is discussed in Zarn, B. and Davies, R.H. (1994).

4.1.4 Alluvial plains

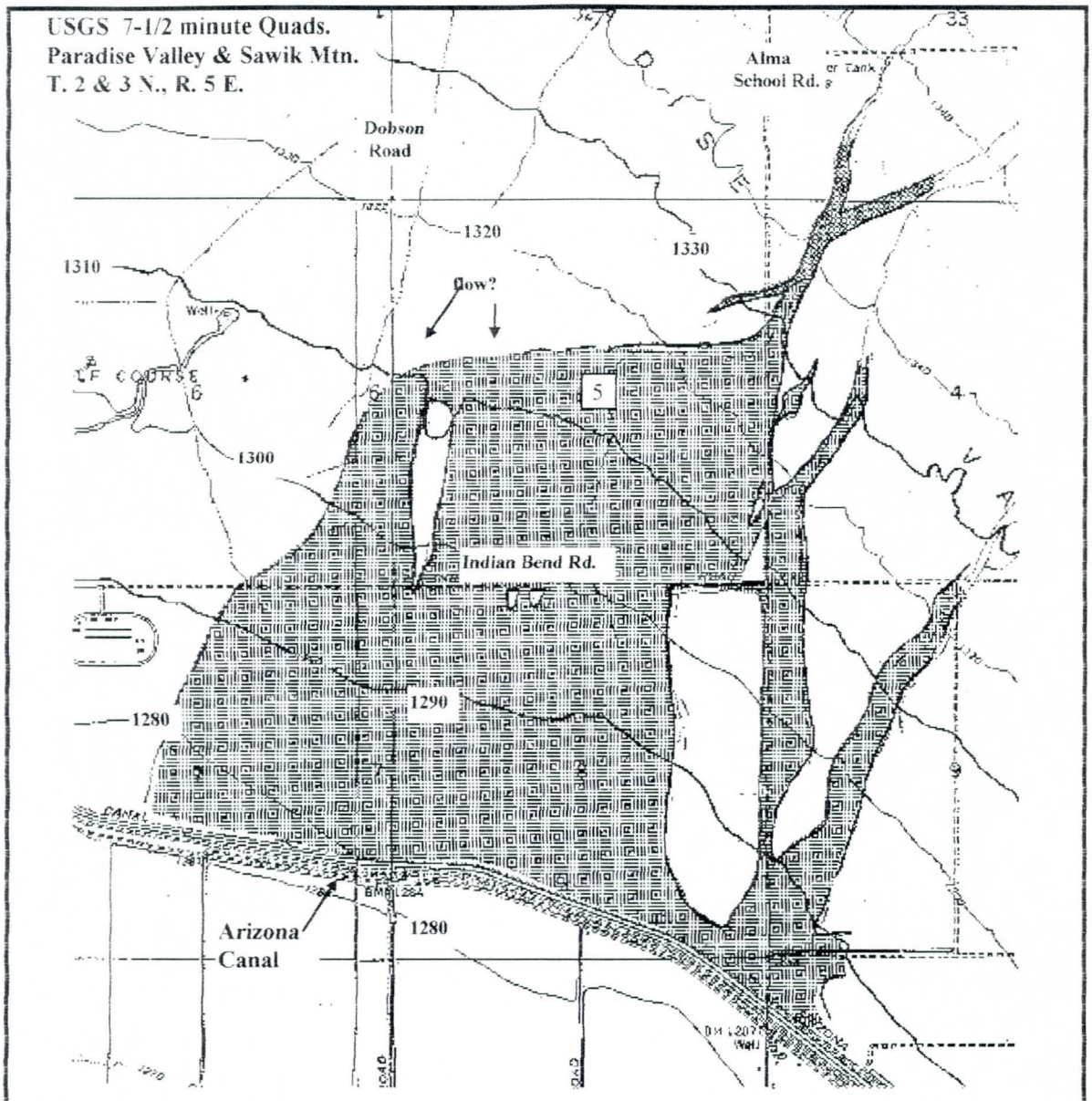
Alluvial plain flooding typically is shallow and unconfined (see *Anastomosing Flow* and *Agricultural Sheet Flow* in State of Arizona Standard 4-95). Flow paths of the shallow flow follow the general grade of the land slope but are easily affected by obstructions such as roads(See for example Figures 4.6 and 4.7). The rapid spreading of floodflow shown in figure 4.7 was accompanied by a significant decrease of flood depth. Separated flow, uneven flow levels, varying surface roughness and complex eddies complicate any precise definition of flood characteristics. There is no known convenient and practical method of computing water surface profiles for the flow conditions depicted in Figures 4.6 and 4.7. Because the land is generally smooth with slopes usually less than 1 percent, estimated flood depths are used for flood plain management.

For most alluvial plains the flooding hazards should be defined using the FEMA *Shallow Flooding* methods given in the Guidelines and Specifications for Study Contractors (1995).

Deposited sediment (typically sand, silt and clay) can be a problem on alluvial plains. Sediment may be deposited in tongue shaped sheets as sheet floods spread out below channels. Local low bars of sand with some gravel may be deposited below locations where flow spreads and the slope lessens.

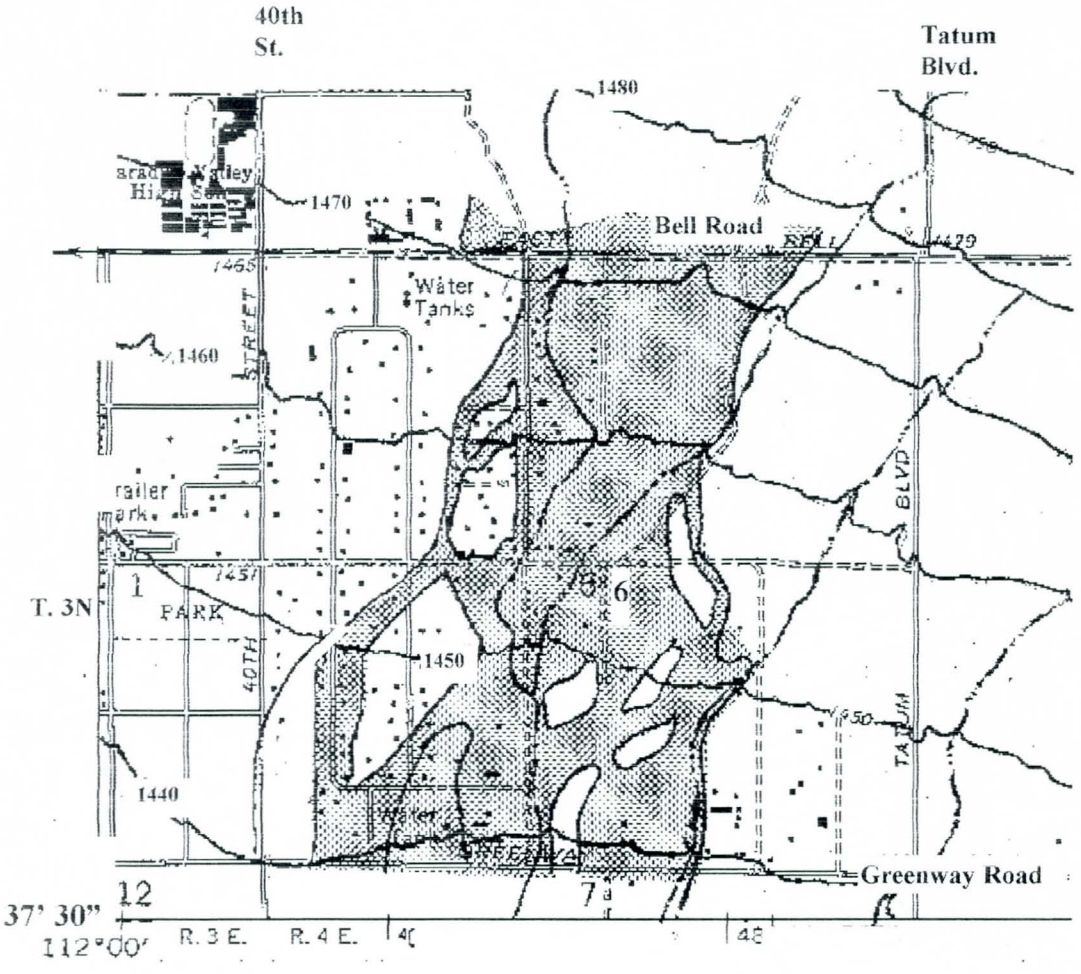
4.2 Summary

Standard hydraulic engineering methods such as backwater and forewater computations are used to define the profile, velocity and extent of the 100-year flood for flow confined to stable channels and within relict fans and pediments. Floodway areas that include the limits of recent channel movement between stable banks should be delineated and reserved for the conveyance of floodwater and sediment. See for example the channel upstream from point A of Figure 4.8.



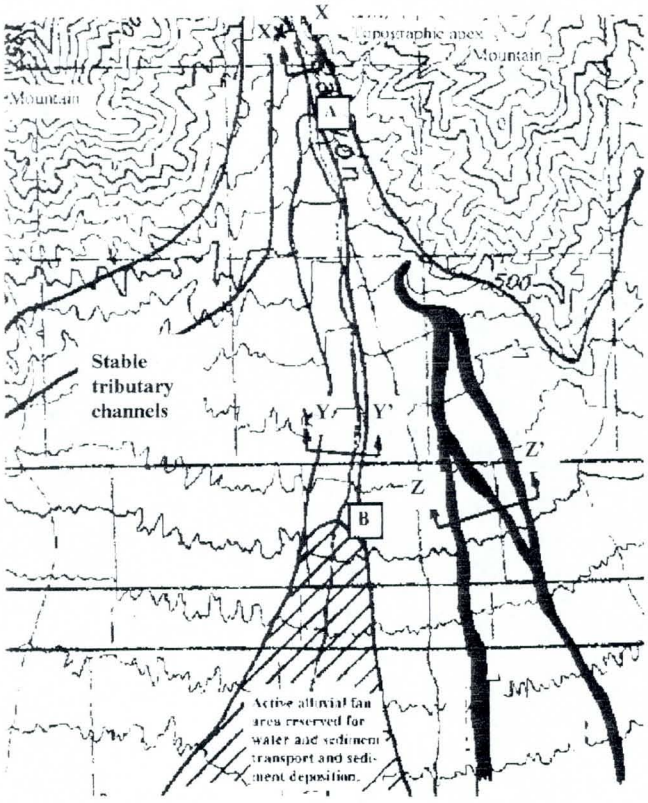
Flood of June 22, 1972. Most floodwater was from Shea Wash that crosses Shea Blvd. in the SE 1/4 sec. 23, T. 3N., R. 5E. Shea Wash (Site 22 of Hjalmarson and Kemna, 1991) is an active alluvial fan with the hydrographic apex 4 miles upstream of Indian Bend Road and 3/4 mile downstream of Shea Blvd. at sec. 26, T. 3N., R. 5E. The drainage area for the alluvial fan is 2.33 mi^2. The peak discharge at the fan apex was 1,300 ft^3/s with a unit peak discharge of 560 $ft^3/s/mi^2$. Four indirect measurements of peak discharge at tributaries on a relict fan in the drainage basin were made by the USGS at Shea Blvd.. The area downstream of the apex to the Arizona Canal is about 5.46 mi^2. The total area above the Arizona Canal in the scene is about 7.79 mi^2. Based on USGS aerial photographs of the flood, most of the runoff was from the drainage basin above the fan apex. The corresponding recurrence interval for this flood was about 25 years.
The average slope of the plain is 0.0053 with little transverse relief. The average spacing between the small channels upslope of Indian Bend Road is about 500 ft.. Below Indian Bend Road there are fewer than 5 small crenulations per mile of width across the alluvial plain. The dirt roads have some effect on the flow paths but the *swale*-like areas indicated by the contours have little discernible effect on flow paths. The entire mapped area of flooding was inundated at the time the photographs were take on June 22, 1972.

Figure 4.6 Example of major flooding on an alluvial plain.



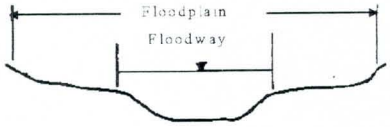
Flood of June 22, 1972. General land slope is 0.0066 with about 1000 ft. spacing between the small 1 ft. deep channels. The water is moving along the general maximum slope gradient but not always normal to the contours. Roadways and road berms and other small obstructions have an affect on the flow paths. Many small islands are not shown. Flow depths appear to be about 1/2 ft. or less except in the small channels. A below ground swimming pool in the flooded area of the scene was not inundated. According to the NRCS(Camp, 1986) the Gilman soil is on flood plains and alluvial fans and is subject to shallow flooding. The hazard of water erosion is slight and the hazard to dwellings and small commercial buildings is severe. The surface is considered stable.

Figure 4.7 Example of floodflow on an alluvial plain in north Phoenix.



Cross section X-X'

Representative cross section for stable cut in fan terrace and pediment above point A.



Banks and some of bed outcrops are gravel, cobbles and boulder s cemented by caliche. Traditional hydraulic methods used.

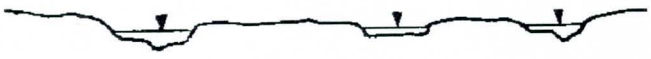
Cross section Y-Y'

Representative cross section of unstable sand bed channel confined between stable banks

Ebon-Contine soil(fan terrace) on banks. Bed is unweathered sand and gravel typical of active(modern) washes. Geomorphologic methods used and unstable area between stable banks is reserved for the conveyance of water and sediment.

Cross section Z=Z'

Cross section of stable distributary channels on fan terrace. Defined channels are reserved for the conveyance of water and sediment.



This figure is the progression of Figures 2.6 and 3.2.

Figure 4.8 Example of 100-year flood hazards.

Where there are changing channel conditions, geomorphic methods are used in conjunction with traditional engineering methods. Floodway type areas that are reserved for the conveyance of floodwater and sediment which include the limits of recent channel movement between stable banks should be delineated. See for example the channel between points A and B of Figure 4.8.

For active alluvial fans and alluvial plains the flow is unconfined and normal backwater profile computations for flood definition are inappropriate. Geomorphic methods, possibly supplemented by traditional hydraulic methods, are used to define the flood hazard areas of active alluvial fans.

Land considered stable under natural conditions might be subject to considerable erosion if flow is concentrated by development. Stable or inactive alluvial fan areas, especially areas with little transverse relief, may become active if roads and other development direct floodflow from active onto inactive fan areas.

Only major engineering measures can be used to mitigate the fluvial hazard on fully active fans. On more stable fans, minor engineering measures may be used to mitigate the hazard providing the hazard at other locations remains at acceptable levels. In the absence of engineering measures, the surface of active alluvial fans is reserved in order to receive and/or convey sediment and floodwater without altering and thereby increasing the distribution of hazard across the active fan and to areas downslope. See for example the active alluvial fan shown in Figure 4.8.

For networks of distributary channels that convey floodflow in many small channels that have many forks and joins the channel conveyance-slope method described in section 4.1.2.3 is a practical means for apportioning 100-year flood peak discharge and estimating the flood boundaries. Figure 4.2). See for example the distributary channels shown in Figure 4.8.

5
APPLYING THE ASSESSMENT TO EXAMPLE SITES

Three readily accessible sites located within parks in Maricopa County are used to demonstrate the assessment method. The first site is in Phoenix South Mountain Park and the second site is in the White Tank Park and the third site is at the southern end of the White Tank Mountains. Methods described in Chapters 2-4 form the basis of the flood hazard assessment for each of the sites. The assessments show that appropriate supplemental information not specifically given in Chapters 2-4 can be used. The user is reminded that geologic maps, soil surveys, topographic maps, aerial photographs and field observations are the fundamental sources of information used for the assessment. Some flexibility of writing style and technical content is demonstrated but the three-stage approach (1. Recognize and characterize piedmont landforms, 2. Define the nature of the landform environment, and 3. Define the 100-year flood hazards) outlined in Table 1.1 is closely followed.

5.1 The South Mountain Park alluvial fan.

The field inspection of this site is made to: (1) verify the type of landform, described as an alluvial fan by the NRCS, using methods in Chapter 2 and steps in Table 2.2; (2) identify active and inactive areas using methods in Chapter 3; and (3) estimate flood hazards, as described in Chapter 4, based mostly on geomorphologic methods using only a rough estimate of the 100-year peak discharge at the hydrographic apex and at any major tributaries. The user should have USGS 7.5-minute topographic maps of the Laveen and Lone Butte Quads, or the equivalent, and should have consulted the NRCS Soil Survey of Maricopa County, Arizona by Hartman (1977). Copies (small scale) of the soil survey maps for this site are included in this manual. The user should consider reading this section of the manual and obtain any needed referenced material before making a field inspection of the site.

The South Mountain Park site is located in an embayment at the west side of the Phoenix Mountains (Figures 5.1 and 5.2). The landform is accessed on the San Juan Road that starts at the park entrance guard house (mile 0) and crosses a saddle and enters the drainage basin at mile 2.1. At mile 2.5 the incised main channel can be viewed from a pullout-parking area on the left (south) where the channel is deeply cut into pediment material mapped by Hartman (1977) as the Cherioni-Rock (CO) outcrop complex. At mile 2.6 the road crosses a small tributary from the right or north. The topographic apex is approximately at mile 3.5. A major tributary from the north is crossed at mile 3.8 where cemented cobbly-bouldery conglomerate is visible on the right bank to the right or upstream of the road. At milepost 4.0 the road is on the fan terrace mapped by the NRCS as Carrizo-Ebon complex on alluvial fans (Hartman, 1977, shown as CeD in Figures 5.1 and 5.2). The lower mountain slopes located about 1/4 mile to the right are

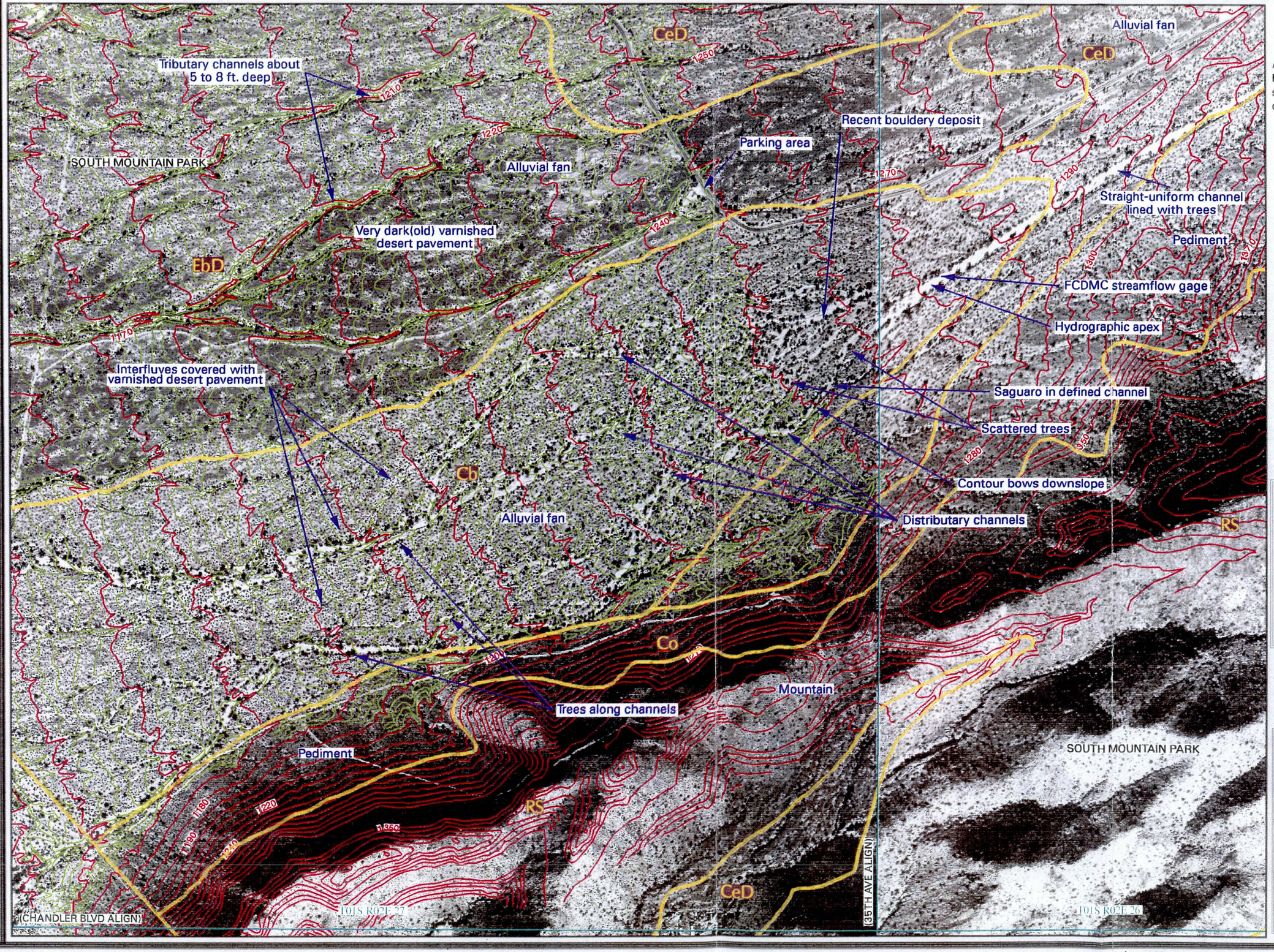
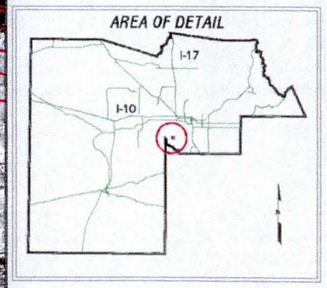


FIGURE 5.1

Aerial photograph of South Mountain Park site showing topographic contours, soil types, piedmont landforms and other characteristics.



Metadata Notes:
(1) Aerial Photography, HIS, Dec 1996
(2) Soil data, digitized in-house, 1:20,000,
(3) Topography, Laveen ADMS, 1:4800, June 1990

SYMBOLS

- Soil Boundaries
- Index Contours (10 ft)
- Intermediate Contours (2 ft)

1" = 500'

0 250 500

gravely-bouldery material with some bedrock outcrops and are covered in places with cholla that is typical of the Ebon soil in Maricopa County. At mile 4.45 are the hydrographic apex and the FCDMC streamflow gage about 400 ft. to the left (south) of the road. The surface of the old alluvial fan material to the right (north) is covered with varnished desert pavement. To the south of the road the material generally is younger and the varnish on the desert pavement becomes much lighter as one nears the gage and channel. A parking area located to the southwest of the roadway at mile 4.7 is a good location to park for a field inspection of the alluvial fan and the FCDMC gages.

5.1.1 Type of landform

In regions like central Arizona where there is relatively little geological recent tectonic activity and mountain uplift, the loci of deposition of most active alluvial fans shifts downslope from the mountain fronts. According to Bull (1977, p. 252) the fanhead trench can be "...removed as a possible area of deposition and the degree of soil-profile development will provide clues as to the length of time since the fanhead area last received deposits." These general conditions apply to the South Mountain Park site

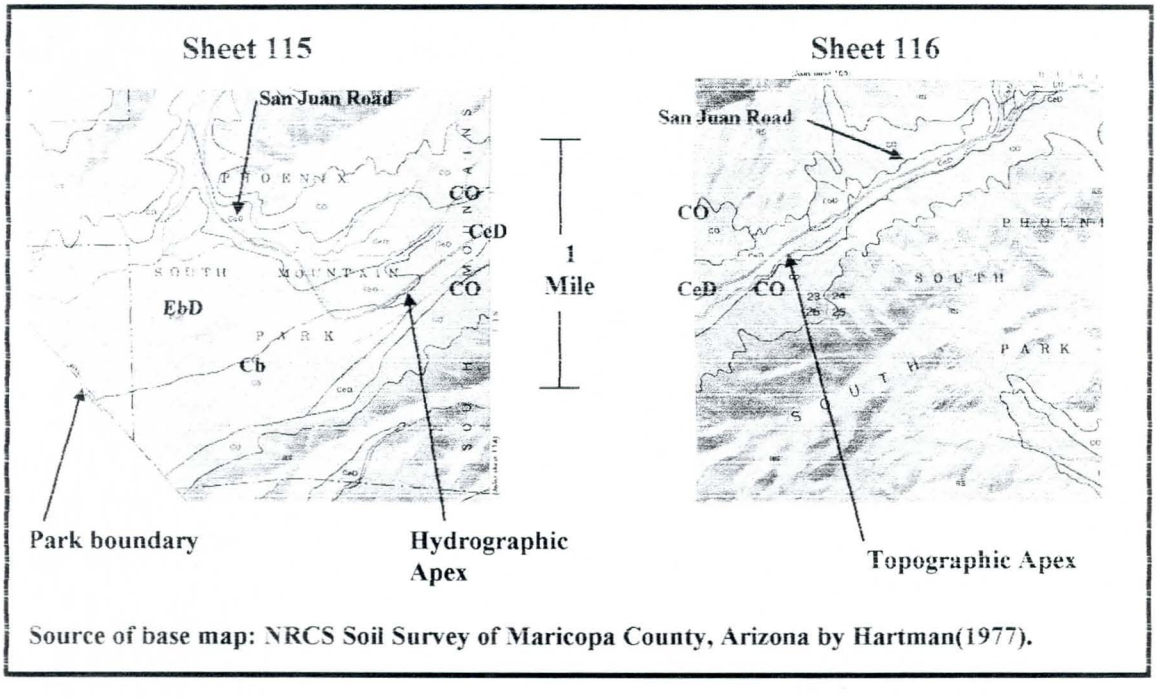


Figure 5.2 Mapped Soils

where there is a trench draining the surrounding mountain slopes. The trench divides into a few distributary channels a few hundred feet below the FCDMC streamflow gage (Figure 5.1). The area of distributary channels appears surrounded by land covered with dark gravel that is visible in Figure 5.1 and in the field. This widespread varnished desert pavement suggests the landform and surface exposure age are very old because the

landform has been incised and no longer receives sediment as discussed by White and others (1996) (See also section 2.2.3.3 of this manual). The distributary channels are surrounded by an abandoned deposition surface (a relict fan) where the erosion rate (if any) has been small.

Erosion and runoff in inter rill areas of the relict fan may have increased as grass may have been replaced by shrubs during the past 100 years as described by Abrahams, Parsons and Wainwright (1995). Fine sediment is found under the shrubs that form islands where the shrubs regenerate, especially in the middle and lower fan area. The shrub islands are surrounded by desert pavement near the distributary channels and desert varnish a few tens of feet shoreward of the channel banks where it appears difficult for new shrubs to establish. These islands of fines are aeolian in origin and are surrounded by desert pavement. These islands at the South Mountain Park site are somewhat similar to the conditions at Walnut Gulch (Abrahams, Parsons and Wainwright, 1995).

The vegetation along the distributary channel banks, located to the south and west of San Juan Road, is paloverde, ironwood and mesquite. Below the hydrographic apex, the trees are scattered over an area of distributary channels (See section 2.2.2.3 of this manual for the significance of scattered vegetation). Creosote bushes are scattered over the entire fan including the channels and ridges where there is typically carbonate in the soil. There are also saguaro cacti on the varnished ridge land between the channels. A few living and a few fallen saguaros (see general location on Figure 5.1) are also in the less active channels: saguaros seldom are found in active channels where there is scour and fill. The saguaro cacti and creosote bushes in some of the channels and on the adjacent land are uncommon in Maricopa County and suggest the landform is rather stable. About 1,500 ft. below the hydrographic apex most of the trees are along the channels suggesting stable flow paths.

The drainage area above the hydrographic apex is about 2.0 mi^2 with a relief ratio of about 0.12. The 100-year peak discharge is about 2,600 ft^3/s using methods by Thomas, Hjalmarson and Waltemeyer (1997) for flood regions 12 and 13. The basin is steep bedrock on three sides, somewhat bowl shaped and with many first order streams directly entering the main channel. These basin conditions are ideal for generating flash floods.

The Phoenix South Mountain Park landform (soils EbD and Cb, Figures 5.1 and 5.2) was identified as an alluvial fan based on the composition, morphology and location of the landform using methods of Chapter 2 in this manual and descried below. For this particular site, the landform could be reliably identified using the NRCS soil survey (Hartman, 1977) and the USGS 7.5 minute topographic maps. A field inspection of the channels, road cuts and surface was made to verify the identification. Indicators observed on aerial photographs and in the field consistently verified the landform is an alluvial fan.

5.1.1.1 Composition

The landform is constructed from deposits of coarse, angular gravel sediments that can be observed in road cuts and along cut banks of washes. The angular material is typical for alluvial fans and clearly suggests a source area a short distance upslope. Along the southern part of the fan there is an accumulation of recent loose unconsolidated to weakly consolidated coarse sediments especially within two thousand feet of the hydrographic apex shown in Figure 5.1 (See section 2.1.3.1 for general discussion). The material is mapped as Carrizo gravely sandy loam soil on alluvial fans by the NRCS (Hartman, 1977) (Cb on Figure 5.2).

The northern part of the landform is an old deposit of angular gravel, cobbles and small boulders that is cemented. The coarse material observed along cut banks is imbricated suggesting fluvial process rather than debris flow process. Evidence of debris flows has not been found on the landform. The surface is rather smooth and flat and is covered with desert pavement and generally dark rock varnish. This material is mapped as Ebon gravely loam on old alluvial fans (EbD in Hartman, 1977 and on Figure 5.2). The upper part is mapped as the Carrizo-Ebon complex on alluvial fans.

5.1.1.2 Morphology

The landform has a partly extended fan shape bounded by the toes of the adjoining mountains (See sections 2.1.3.2, 2.1.3.4 and 2.1.3.5 for general discussion). The highly crenulated contours shown on the available 7.5-minute series USGS topographic maps (Laveen and Lone Butte Quads) have a slight convex shape in the downslope direction (See also Figure 5.1).

The contours on the south part of the landform (soil type Cb), where there are many distributary channels below a single-straight channel, bend more sharply downslope for a distance of about two thousand feet below the end of the single channel. The upper fan is convex upward in the transverse direction and this transverse mounding is apparent when viewed across in the field. The contours of the lower part of the landform are rather straight with several small crenulations that depict the small-incised channels. The aerial photograph (Figure 5.1) clearly shows a fan shaped braided channel network in the upper fan and a few tree lined distributary channels separated by several small undissected areas along the south side in the mid and lower fan.

5.1.1.3 Location

The landform is located at an old *topographic apex* (Figure 5.2) where floodflow, that was confined between mountain slopes, became laterally unconfined (see section 2.1.3.3 for general discussion). The hydrographic apex is located about 1 mile below the topographic apex, where the approximately 90 ft. wide and 5 ft. deep channel looses lateral confinement. The profile of the channel shows a slight decrease of grade below

the hydrographic apex because of the deposited sediment (Figure 5.3). The piedmont landforms are shown on Figure 5.1.

5.1.2 Stable and unstable areas of the alluvial fan

Most of the alluvial fan clearly is stable (inactive) with old developed soil covered with varnished desert pavement (See chapter 3 for general discussion). These soils are the Ebon gravely loam (soil type Ebd) and the Carrizo-Ebon complex (soil type CeD). The throughflow tributary channels are cut about 5 to 8 ft. into the cemented conglomerate of these inactive areas. Several small tributaries head on the inactive fan. There is a potentially active alluvial fan in the upper part of soil type Cb (Carrizo) where there is recent sediment deposition and filling of small channels (See Table 2.1 for common soil types).

Channel boundaries depicted on aerial photographs of 1936 and 1990 were examined by CH_2M HILL (1992). A comparison of these stream channels revealed no significant change in the channel location for the 55-year period. This lack of flow path movement suggests that (1) movement, if any, is small and not discernible on the aerial photographs, (2) there was no movement because there were no large floods during the 55-year period, or (3) movement does not occur because the fan is not aggrading and not active.

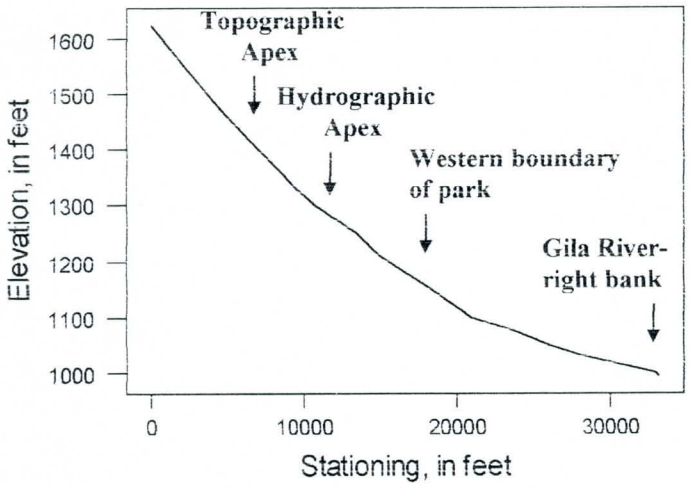


Figure 5.3. Profile of stream channel through active part of alluvial fan.

5.1.2.1 Fan Building at the South Mountain Park site

The primary sedimentation processes that build alluvial fans may be short-lived rare rock slides, debris flows and sheet floods that actively transport rock to the fan site (Blair and McPherson, p. 454, 1994). Sediment typically flows though a channel from an upland

drainage basin to the fan site. Fan building events may result when basin sediment accumulation reaches a critical mass that can be moved during major floodwater or major accumulation of water within soil masses. Where fluvial processes are dominant, as in nearly all of Maricopa County, basin sediment accumulation is facilitated where periods of little or no basin runoff are long.

For example, at the South Mountain Park site, the slow accumulation of sediment in the incised basin channels is suggested because many years with little or no runoff are common and the mean annual flood is very small. At the USGS streamflow gage no. 09512200, located in the adjacent drainage to the east, the 2-year flood (19 ft^3/s) is a small portion of the 100-year flood (4,740 ft^3/s) suggesting that there are long periods where runoff is insufficient to transport sediment from the basin. Because the drainage basin above the South Mountain Park site shares a drainage divide with the drainage basin for USGS gage 09512200, the flood characteristics are probably similar. Thus, infrequent large floods are likely to transport sediment that has accumulated in the basin channels over long periods, and deposit this sediment on the alluvial fan of the South Mountain Park site.

5.1.2.2 Selected observations along the potentially active area

Evidence of channel scour and fill are clearly visible in cut bank exposures of the distributary channels (soil type Cb) from the hydrographic apex to near the Park boundary to the west (Figure 5.4). There is more bed and bank scour along the distributary channels of the right (north) side of the active alluvial fan. There is also some scour and fill along the left channels but not to the extent as on the right side where a few old trees have recently exposed roots. Just below the hydrographic apex a short distance below the FCDMC streamflow gage the first channel bifurcation (fork) is from overflow into a channel on the right. This channel has recently (probably less than few hundred years before present based on the steep cuts in places along the banks) scoured and is headcutting into the main channel on the left. Most of the bedload from the drainage basin has been in the main channel and the flow that spills over the low right bank has carried less sediment. The overflowing floodwater on the right has picked up a new bed load by scouring a deeper channel for several hundred feet down the fan. This scour appears to be the final phase of stream capture that will progress during future floods. The distribution of floodflow at this first fork is expected to continue changing with a progressive, or possibly sudden, increase in flow to the right.

There are several closely spaced distributary channels in the upper two thousand feet of this part of the fan (soil type Cb). The generally unweathered angular and cobbly-bouldery bed material is considerable evidence of recent floodflow over much of the area that is about one thousand feet wide in the middle and lower slopes (Figure 5.4). Some of the interfluves have lightly varnished stones and there are several saguaro cacti and large paloverde and ironwood trees. The trees are scattered over much of this upper fan suggesting (1) some local flow path movement or the absence of defined flow paths during the life of the trees or (2) frequent enough overflow and sheet flooding to supply

the water needs of the trees. This evidence suggests the flow paths may change on the order of a few tens of feet as a result sediment deposition and erosion. The large clast size of the bed material and the recent deposits also suggest large floods cause much of the sediment transport, deposition and movement because small floods do not have the stream power to transport such material. The absence of fines in these coarse deposits indicates subsequent smaller flows and direct rainfall and sheetflow have remobilized and transported the smaller material down the distributary channels.

5.1.2.3 Summary of active and inactive areas

Most of the alluvial fan is inactive based on (1) the old developed soil that is covered with varnished desert pavement, (2) the throughflow tributary channels are cut about 5 to 8 ft. into cemented conglomerate, (3) several small tributaries head on the inactive fan and (4) the comparison of stream channels shown on aerial photographs revealed no significant change in the channel location for a 55 year period.

There is an active alluvial fan inset in the southern part of the inactive fan located in the upper area defined as soil type Cb. This fan is considered active based on (1) the recent deposited coarse sediment in the upper part of this area, (2) the cross-profile mounding of this sediment (3) the several wide-shallow distributary channels in the upper part of this area and (4) the recent deposition that has filled some of the small channels and redistributed conveyance across the fan.

In the lower part of the area defined as soil type Cb there are distributary channels separated by stable interfluves that are covered with varnished stones. The desert pavement in this area is lighter and less developed than on the surrounding inactive fan areas (soil types EbD and CeD). The larger channels are incised 2 to 3 ft. This area with distributary channels is younger than the inactive areas of soil types EbD and CeD but there is no evidence of recent flow path movement. On this basis the area is considered inactive but subject to varying distribution of discharge in the several channels because of the nonstationary hydraulic conditions at the first fork and flow path movement, although probably small, at the active alluvial fan upstream. This relatively inactive alluvial fan area is mapped separately from the other inactive alluvial fan area because of these conditions (Figure 5.4).

5.1.3 Estimated 100-year flood hazards

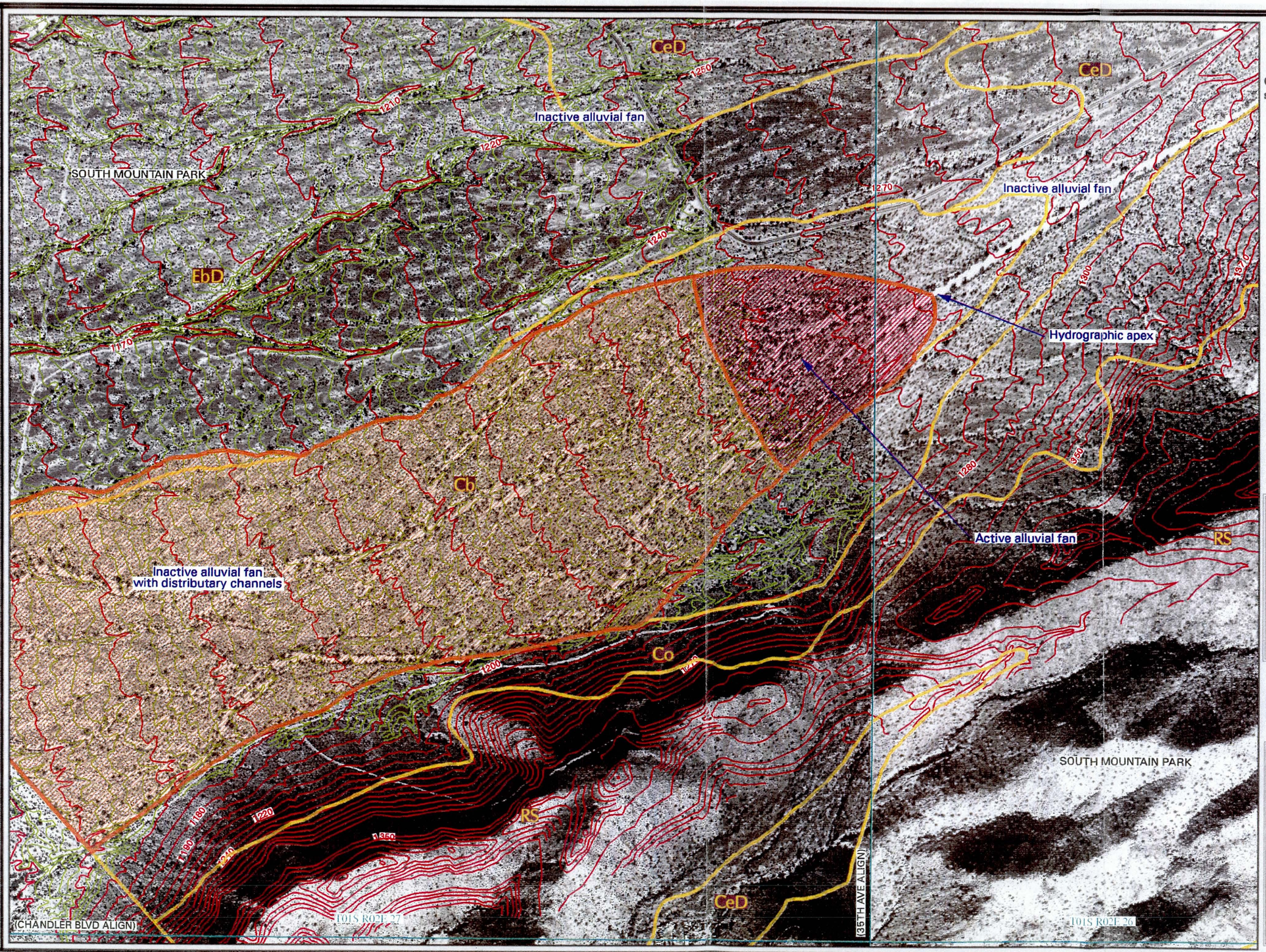
Methods given in Chapter 4 are used and discussed in this section. Some of the methods used to characterize the flood hazard are not specifically described in Chapter 4 and demonstrate the flexibility of the method.

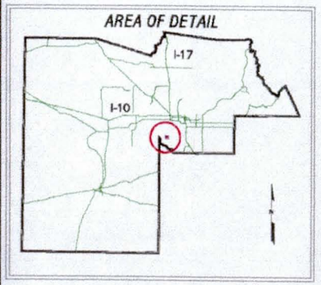
5.1.3.1 Characteristics of recent deposited sediment

At first glance the material along the active distributary channels may appear like a recent debris flow but there are no classic remnants characteristic of debris flows (For

FIGURE 5.4

Orthophoto map of South Mountain Park site showing landforms with active and inactive areas.





Metadata Notes:
(1) Aerial Photography, HIS, Dec 1996
(2) Soil data, digitized in-house, 1:20,000,
(3) Topography, Laveen ADMS, 1:4800, June 1990

SYMBOLS

- Soil Boundaries
- Index Contours (10 ft)
- Intermediate Contours (2 ft)

1" = 500'

0 250 500

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examples of debris flows see Whipple and Dunne (1992), National Research Council (1996) and Costa (1988)). Some classic characteristics that are missing include (1) marginal levees of coarse material, (2) muddy deposits, (3) cemented non-friable deposits and (4) obvious inverse grading. Deposited sediment along the distributary channels is coarse and angular. In a few places, recent material is deposited on cryptogamic crusts (See last paragraph in section 3.4.3 for general discussion) and in other places, there is local scour and some cutting of old banks. In general, however, the location of the active flow paths, as defined by the recent deposited sediment, appear to not change much except during very large flood flows where the stream power can move the large stones. Within several hundred feet below the hydrographic apex there is a propensity for unconfined flows as floodwater, typically at or near supercritical velocities (based on hydraulic modeling), spreads laterally and looses energy.

Along the major channels of the drainage basin above the hydrographic apex, there is an ample supply of coarse sediment from slope failure. These major channels are incised several feet into cemented conglomerate that has sloughed into the channel. The cementing obviously limits the supply. Some of the recently moved stones that are deposited on the active fan have a calcium carbonate coating that suggests remobilization from this nearby source. Some of the angular material of the active alluvial fan appears to be second or third generation sediment derived from the relict fan.

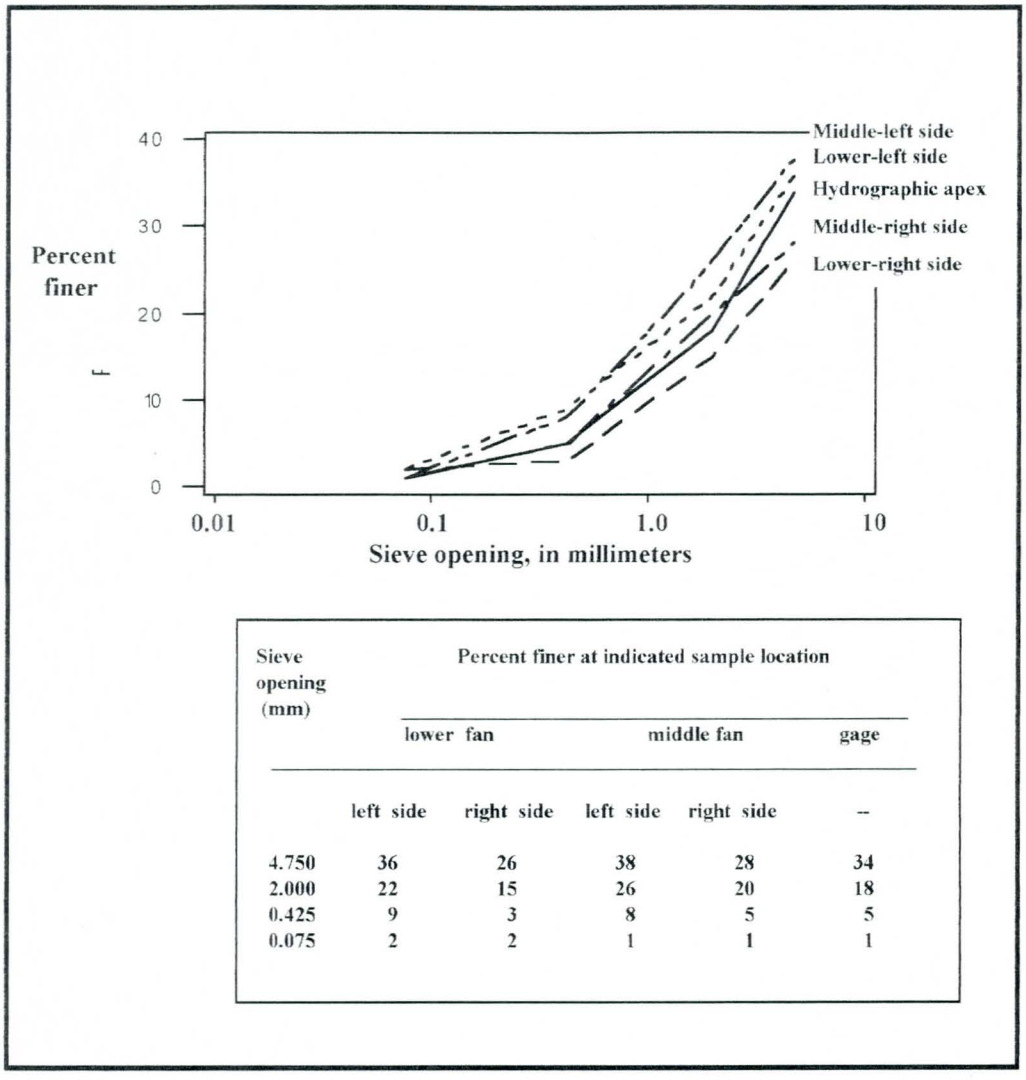
The mean particle size is medium gravel (about one cm) along the active distributary channels based on samples collected on June 24, 1997. Samples were collected at several locations across the channels with a shovel at approximately 2-6 inch depths. Samples at each location were composited. There was no obvious increase of gravel particle rounding from the hydrographic apex to the lower crest stage gages. About 40 percent of the material was coarse gravel (greater than about 2 cm), cobbles with a few small boulders. About 20 percent of the particles were sand and about one or 2 percent were silt and clay (Figure 5.5). Because the sediment apparently was deposited several years ago, undoubtedly by a large flood(s), many of the smaller particles have been remobilized by subsequent floods and translocated downstream beyond the park boundary. Most of the fines have been washed from the coarse bed and bank material leaving the present deposit of angular-coarse gravel and cobbles.

Where there are fluvial processes the sediment texture typically decreases downslope on aggrading alluvial fans because the flow competency decreases as floodwater spreads (Blissenbach, 1954) (See also section 8.5 *Sediment grain size along an idealized fan* of this manual). This relation is useful because aggrading alluvial fans have unstable flow paths. At the South Mountain Park fan there is no discernible change in particle size along the throughflow channels of the active fan (Figure 5.4).

The competency of water flows to transport the non-cohesive and uncemented coarse bed material is briefly evaluated using the following equation, in metric units, from Blair and McPherson (1994):

$\gamma DS = 0.056d^{1.213}$

where γ = specific weight of the fluid, = 1,000 kg/m^3,
D = average flow depth, in meters,
S = grade(slope), in m/m, and
d = diameter of entrained gravel clast, in mm.



Sieve opening (mm)	Percent finer at indicated sample location				
	lower fan		middle fan		gage
	left side	right side	left side	right side	--
4.750	36	26	38	28	34
2.000	22	15	26	20	18
0.425	9	3	8	5	5
0.075	2	2	1	1	1

Figure 5.5. Cumulative sediment size-frequency graphs for South Mountain Park alluvial fan.

At the South Mountain site, the channel grade at the apex is 0.017(about 1 degree) and at the 100-year flood, the flow depth is about 1 m (Figure 5.6). From the above equation, the diameter of the entrained gravel clast is 11 cm. Clearly, because most of the sediment is smaller than 11 cm, most of the rock can be moved by large floods past the apex to the active alluvial fan. The above equation is one of several competency

equations available in technical literature and is not necessarily recommended for all sites in Maricopa County.

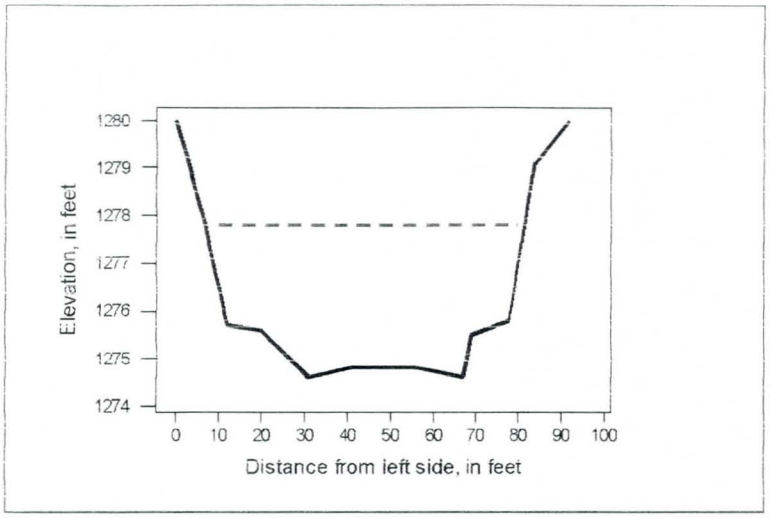


Figure 5.6. Cross section about 200 feet upstream of the hydrologic apex showing the approximate level of the 100-year flood.

5.1.3.2 Shear strength along the channels

Bank stability of channels in cohesive soils can be roughly evaluated using shear strength in the tractive power approach of TR-25 (USDA, 1977). At the South Mountain Park site the banks are incised in cemented conglomerate and only short reaches have developed cohesive bank material. Thus, only a rough measure of bank stability is made from shear strength estimates at this site. Twenty-three estimates of material shear strength were made along the channels from the hydrographic apex to the lower crest stage gages. The surface shear strength of the silty areas along the right bank at the hydrographic apex is about 800 lb/ft^2 based on a few measurements on June 25, 1997 with a Torvane shear device (CL-600A) by Soil Test. The measured shear of the cryptogamic crust on the flat-smooth surface a few feet shoreward on the right overbank was between 1,000 and 1,200 lb/ft^2. At the lower section of crest-stage gages, the average measured shear on the cryptogamic crusts at several locations was about 1,000 lb/ft^2 with a range of 700 to 1,240 lb/ft^2. The measured shear strength below the crusts was about 50 to 60% of the crust shear strength. The measured shear along the bank surface in the few places where the surface appeared stable and there was donoring (Hjalmarson and Tram, 1995) was 460 to 600 lb/ft^2 . The bank shear at 1/2-inch depth below the surface was about 50% of the surface shear.

The measured shear stress of the silty places along the banks, range of 460 to 800 lb/ft^2, is almost 1/2 the shear stress of other sites in Maricopa County with stable banks but about 2 or 3 times the shear stress of sites in Maricopa County with active alluvial fans (unpublished data by Winn Hjalmarson and Joe Tram on file at the FCDMC). The shear

strength of the cryptogamic crusts, range of 700 to 1,240 lb/ft^2, is in agreement with other piedmont sites in Maricopa County. The approximate 50% increase of shear strength resulting from the crusts also is in agreement with other sites in Maricopa County. The large amount of cryptogamic crusts along the distributary channels suggests the fan has been stable for several years. The cohesive strength, however, developed from donoring was not great and was limited to only a few locations.

5.1.3.3 Infrequent fan building events

Estimates of flow path movement are inherently difficult in the arid southwestern United States where at specific sites there are many years of no flow with few flood events of large magnitude that transport sediment to the fan. There is evidence on some alluvial fans of flow paths moving considerable distances over short periods of time (a few hours) but such movement is infrequent. Thus, the comparison of flow paths (where space is regarded as a continuous variable as depicted on aerial photographs) at different observable times (where time is regarded as a discrete variable) has a relatively short time scale while the process being modeled has long time scale during at least the Holocene Epoch. If flow path movement were relatively frequent and uniform in space then estimates of flow path movement, if any, could be estimated using discrete intervals with some reliability. Thus, because flow path movement, if any, on a particular space such as the South Mountain Park site is infrequent the detection and characterization of movement in terms of transverse and lateral rates is tenuous.

The problem can be demonstrated using elementary probability. For example, <u>if</u> the movement of a single flow path in the network of distributary channels resulted from floods equal to or greater than the 50-year flood then the probability of movement in 40 years (the discrete interval between aerial photographs of the flow paths) is:

$$P_m = 1 - (1 - 1/50)^{40} = 1 - 0.45 = 0.55$$

but if flow path movement was less frequent and the result of perhaps the 200-year flood, then the probability of any movement in 40 years is:

$$P_m = 1 - (1 - 1/200)^{40} = 1 - 0.82 = 0.18$$

Thus, the same average rate of movement (for example feet per year across the alluvial fan) may result for both cases but the detection of movement is likely in the first case and unlikely in the second case. The average rate is used here to demonstrate that detection of flow path movement is much more difficult using discrete time intervals if the causation is infrequent. Obviously, an average rate of movement has little meaning for the assessment of flood hazards where movement is sudden and infrequent.

Clearly, alluvial fan processes in Maricopa County may produce variable flow paths in space and time. This variability can be observed continuously or more commonly at discrete intervals of time. **There are several processes, each of which produces**

change at different time and space scales. For example, a debris-laden flow may be a low-frequency high-magnitude event that produces large spatial variance for small areas over very small intervals of time. On the other hand, erosion of interfluval areas by sheetflow from direct rainfall is a high frequency (low magnitude) event that produces small space variance over very long time intervals and over large areas. Many such processes are at work on the South Mountain Park alluvial fan. In addition, the imprint of past processes of different geologic epochs that produced the relict fan has an influence on processes today.

As we focus on the active and inactive areas and flood characteristics of the South Mountain Park alluvial fan we are challenged by the several processes and in particular the apparent infrequent occurrence of recent debris laden floods on the southern 1/3 of the fan (the area defined by soil type Cb and the active and inactive alluvial fans). Because the fan building floods are infrequent and not precisely known, we might be inclined to ignore the different ages of the surface material. For example, for the characterization of alluvial fan flooding for flood insurance studies we might impose rigid constraints (Dawdy, 1979) over the entire fan because of our limited understanding of the processes rather than use process-based indicators that reflect some understanding of the processes. Although our understanding of flow path movement at the South Mountain Park fan is limited, it is clear that a large part of the fan is inactive and that part of the fan which has experienced recent sediment deposition, can in the interest of being conservative, be considered active. It is a difficult task indeed to estimate hazards associated with a large boulder laden debris torrent with an unknown but infrequent recurrence interval of perhaps a few hundred years.

5.1.3.4 Summary of 100-year flood conditions

Several characteristics suggest that the south side of the alluvial fan is active. The clasts on this part of the fan are unweathered and angular and thus suggest recent transport. The radial sediment dispersal system below the hydrographic apex and the mounding across the upper fan are also characteristic of an active alluvial fan. There is an ample supply of coarse sediment along the large channels in the drainage basin. There is no doubt the active fan area shown in Figure 5.4 is subject to sediment deposition, change in channel conveyance and some flow path movement. The frequency of fan building flood events is uncertain, however, and may be on the order of a few hundred years. Secondary processes including direct rainfall and sheetflow and water floods from the drainage basin have remobilized and transported the smaller grains down the fan.

Characteristics of the recent deposits that suggest the south part of the fan is not very active are (1) the channel deposits are sorted and contain a small range in grain size, (2) the downfan deposits are rather uniform in both average and maximum clast size and (3) there are weathered (developed soil) areas between the distributary channels in the upper fan. About 1,500 ft. below the hydrographic apex there is no evidence that suggests the tree lined flow paths have moved for many (perhaps a few thousand) years.

5.1.3.4.1 General map of 100-year flood conditions

A map of unstable flood-hazard areas (UPF) where flow paths are considered unstable is shown in Figure 5.7. Area UFP starts at the hydrographic apex and includes the several distributary channels where there has been recent sediment deposited. The sediment forms a general mounding across the fan that can be easily seen in the field and where the trees are scattered across the fan surface below the hydrographic apex. At the downstream part of area UFP, an eroding surface is indicated because there is no mounding across the fan.

Area UFP is considered subject to alluvial fan flooding as described by the National Research Council (1996) and the level of activity is low, especially for the downstream part, as described Chapter 4. Area DF is considered a stable area of distributary channels where the amount of 100-year floodflow in each of the channels is dependent on the upstream flow paths that are unstable and where channel capacity may be changing.

The boundary common to areas DF and UFD is about 2,000 ft. below the active area where there is active sediment deposition and erosion (Figure 5.4). The boundary is placed conservatively far down the fan to (1) assure that the flow paths entering area DF can be considered stable, (2) to assure that floodflow is spread over much of the common boundary and (3) to allow for the natural apportionment of 100-year floodwater in the several channels. Because of the interlacing network of numerous small distributary channels between the common boundary of areas DF and UFD and the hydrographic apex there is ample opportunity for floodwater to spread across the downstream end of area UFD.

Because there are only a few islands separating the many distributary channels, the water surface elevation is assumed uniform at the downslope end of area UFD. For a uniform water surface elevation for the100-year flood (See Figure 5.8a) the floodwater entering area DF is apportioned in the distributary channels using channel conveyance. At elevation contour 1190, located a few feet below the boundary common to areas DF and UFD, the distribution of conveyance across the 1092-ft. wide fan is shown in Figures 5.8b and 5.8c.

5.1.3.4.2 Estimate of active and inactive areas for 100-year flood conditions

The cross section and approximate distribution of the above conveyance is shown in Figure 5.8. About 65 percent of the area at the cross section is inundated by the 100-year flood. The cross-section geometry was defined using topographic map contour data (See Figure 5.1) and the conveyance for the subareas was defined using WSPRO (Shearman, 1990). The total capacity of the channel network at the cross section is about 3 to 4 times the magnitude of the 100-year flood before floodwater spreads over the adjacent inactive fan areas.

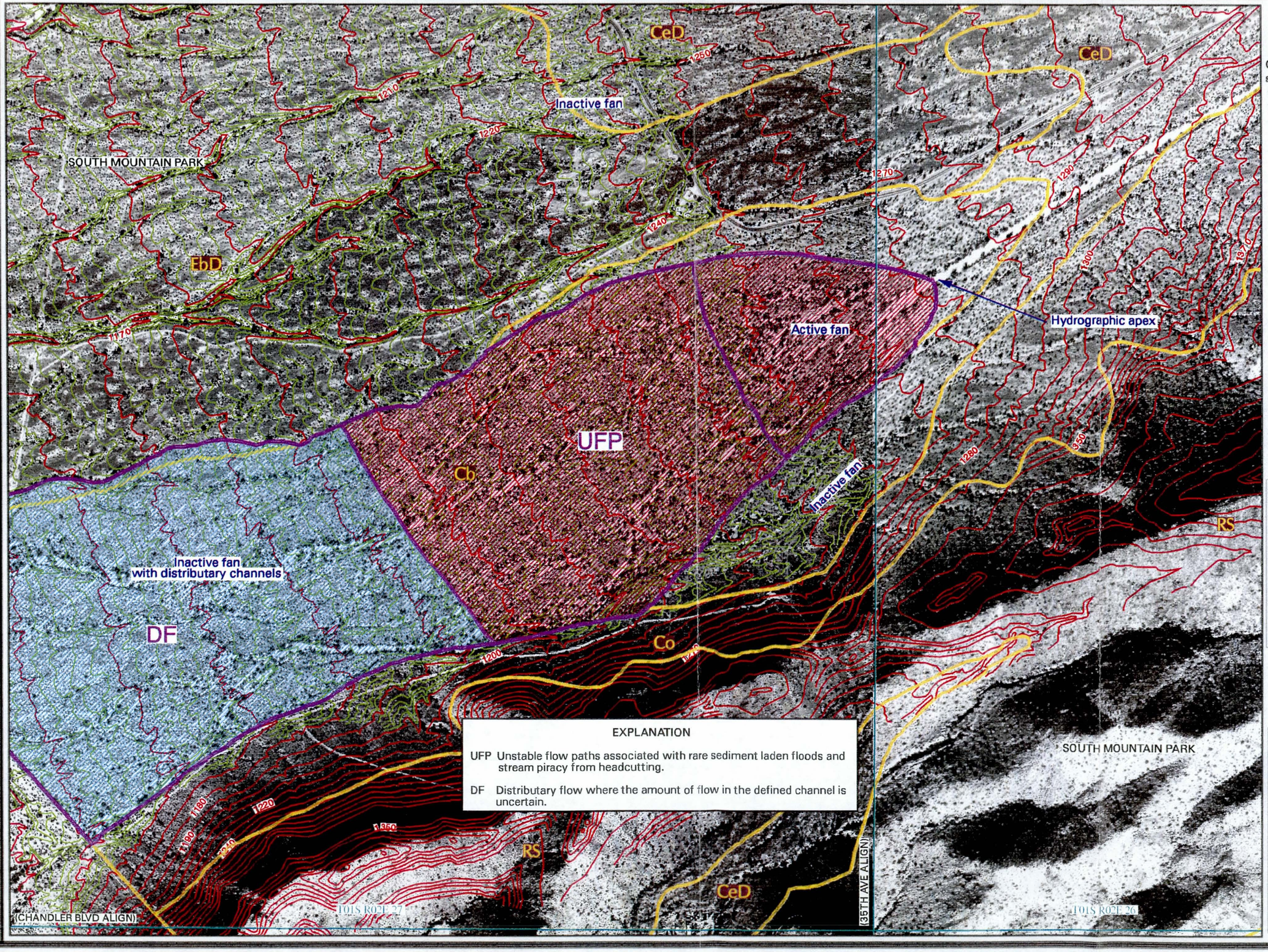
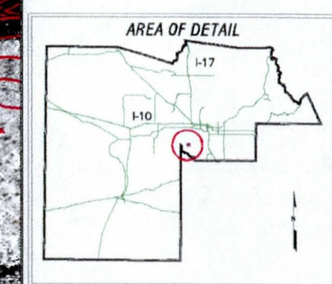


FIGURE 5.7

Orthophoto map of South Mountain Park site showing landforms, active and inactive areas and estimated 100-year flood hazard areas.



Metadata Notes:
(1) Aerial Photography, HIS, Dec 1996
(2) Soil data, digitized in-house, 1:20,000,
(3) Topography, Laveen ADMS, 1:4800, June 1990

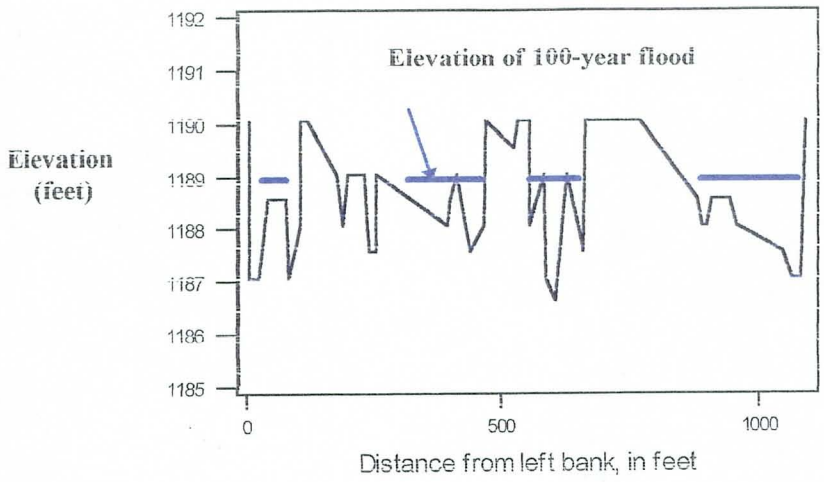
SYMBOLS

- Soil Boundaries
- Index Contours (10 ft)
- Intermediate Contours (2 ft)

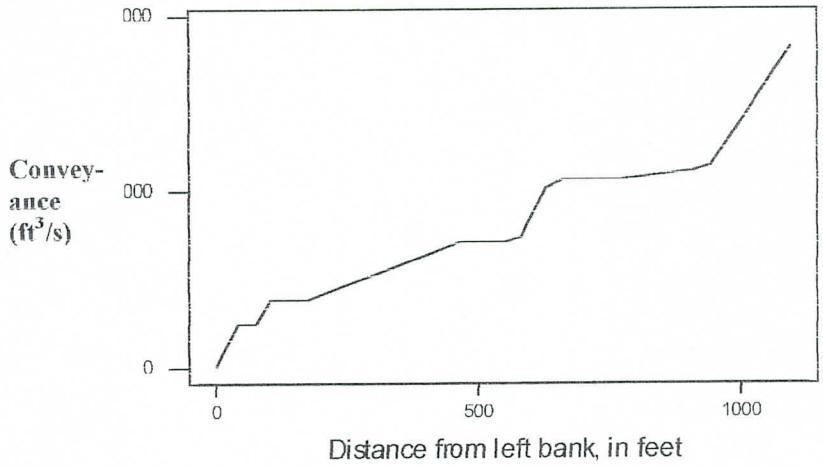
1" = 500'

0 250 500

a. Elevation of 100-year flood



b. Approximate distribution of conveyance across fan



c. Computed conveyance

Distance from left bank (ft)	Conveyance(ft^3/s)
0	0
0-40	2354
40-75	231
75-162	1306
102-530	3215
530-580	213
580-625	2861
625-660	523
660-910	528
910-945	231
945-1092	6721

Figure 5.8. Cross-section at upper end of area DF at elevation contour 1190 showing the level of 100-year flood and distribution of channel conveyance.

Areas DF and UFP (Figure 5.7) are within soil type Cb that is Carrizo gravely sandy loam found in stream channels, low terraces near stream channels and on alluvial fans (Hartman, 1977). Flooding in the area defined by soil types EbD and CeD is sheetflow and flow in defined channels. Flooding on most of the other land in the scene is from overland flow and flow in defined channels draining mountainous areas. Standard hydraulic engineering methods are recommended for all areas except DF and UFP. Geomorphologic methods are satisfactory for area UFP.

Methods described in section 4.1.2 for inactive alluvial fans are appropriate for area DF. These methods were not applied to this example and the results would be similar to the area with distributary channels shown in Figures 4.5 and 4.8. The discharge in the several small channels could be estimated from the distribution of channel conveyance shown previously at elevation contour 1190. Because the flow entering area DF from area UTP is wide and shallow and therefore has a somewhat uncertain distribution of discharge in the several channels, the approximate channel conveyance-slope technique described in section 4.1.2.3 is considered appropriate. The use of soil characteristics described in section 4.1.2.4 to substantiate and refine the estimated flood boundaries for the conveyance-slope estimates is very important for this site.

5.1.3.4.3 Rough check of the estimated 100-year flood conditions

A rough check of the assessment can be made using methods described in section 8.3 of this manual by Hjalmarson and Kemna (1991). This check of the assessment uses a relation between flood-hazard degree and physiographic characteristics of the alluvial fan and the drainage basin. The USGS report *Flood Hazards of Distributary-Flow Areas in Southwestern Arizona* must be consulted for an explanation of the method and the following results:

Equation 9 on page 54 of Hjalmarson and Kemna is appropriate for estimating the degree of flood hazard at the South Mountain Park site. The area of the distributary flow area (DFA) extends beyond the Park boundary onto the Gila River Indian Reservation and corresponds to soil type Cb (Figures 5.1 and 5.2)

$$B = 6.21 - 0.62DD + 25.6MRDA - 1.19H + 2.70K$$

where

B = flood-hazard degree,
DD = ratio of the area of the alluvial fan (DFA) divided by the area of the drainage basin,
MRDA= mean relief ratio of the drainage basin,
H = average contour sinuousity of four to six contours evenly spaced within the DFA, and
K= average contour-band widths of four to six contours evenly spaced within the drainage basin.

The values of the independent variables are DD = 0.33, MRDA = 0.12, H = 2.06 and K = 0.32. The estimate flood-hazard degree is B = 7.5.

According to Hjalmarson and Kemna, a degree of 8 corresponds to a network of distributary channels where most ridges can be overtopped by the 100-year flood but the location of the channels is stable. Hjalmarson and Kemna classed this flow condition as unstable because the distribution of flow across the DFA may be uncertain. This condition corresponds to area UPF (Figure 5.5). A flood-hazard degree of 7 corresponds to stable flow paths where less than 1/2 of the stable ridges is above the 100-year flood (Table 1 of Hjalmarson, 1994). This area closely corresponds to area DF (Figure 5.5). Thus, the single rather simple numerical rating of 7.5 supports the flood hazard assessment using methods given in this manual.

5.2 The White Tank Park relict fan.

The White Tank Park site is located on the east piedmont of the White Tank Mountains mostly between the alignments of Peoria and Olive Avenues. The upper part of the site is in a small embayment where there are remnants of relict debris flows. The site is accessed at the park entrance (mile 0) on west Olive Ave near the center of the inactive (relict) fan (Figure 5.9). The primary area of interest is located west of the park boundary.

The field inspection of this site is made to: (1) verify the type of landform, described as an alluvial fan by the NRCS, using methods in Chapter 2 and steps in Table 2.2; (2) identify active and inactive areas using methods in Chapter 3; and (3) estimate flood hazards, as described in Chapter 4, based mostly on geomorphologic methods using only a rough estimate of the 100-year peak discharge at the hydrographic apex and at any major tributaries. The user should have USGS 7.5 minute topographic maps of the Waddell and White Tank Mtns. SE Quads., or the equivalent, and should have consulted the NRCS Soil Surveys of Maricopa County, Arizona by Hartman (1977) and Camp (1986). Copies (at a small scale) of the soil survey maps for this site are included in this manual. The user should consider reading this section of the manual and obtain any needed referenced material before making a field inspection of the site.

5.2.1 Embayment area

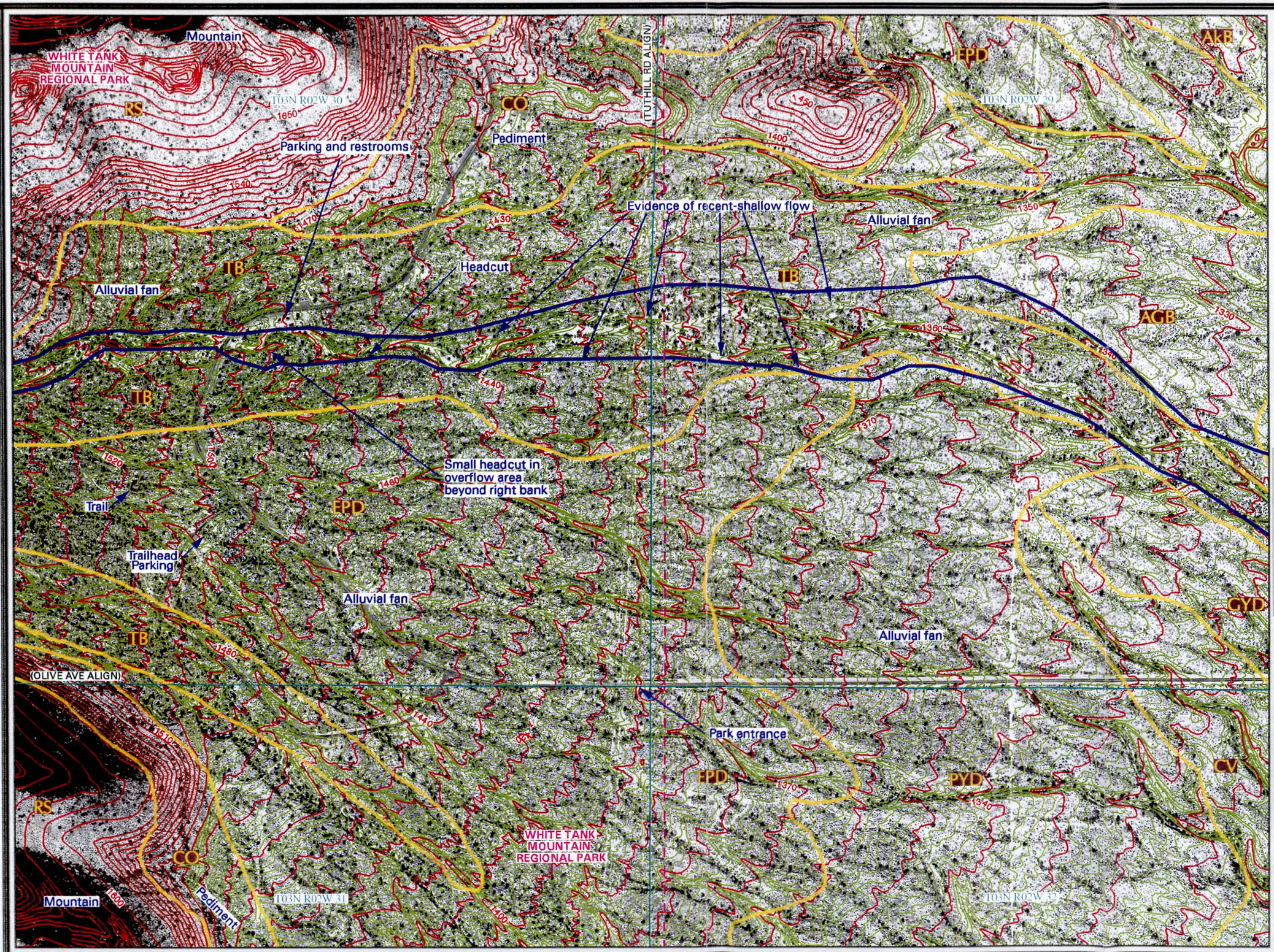
The embayment area can be accessed by proceeding 0.55 mile beyond the park entrance and turning left on the paved road. The parking on the right (mile 0.62) is the head of a trail that leads to the topographic apex of the relict fan. The trail is along the right bank side of the incised channel about 1/2 mile from the trailhead. The topographic apex is about 1 mile from the trailhead at an elevation of about 1,800-ft.

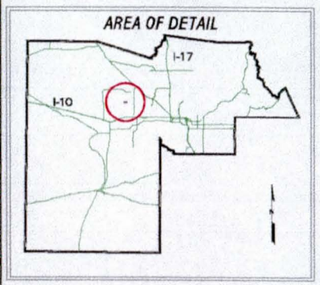
The drainage area at the topographic apex is about 3.0 mi^2 with a corresponding 100-year flood peak discharge of about 3,400 ft^3/s (Thomas, Hjalmarson and Waltemeyer, 1997) (Other appropriate methods of estimating peak discharge such as the FCDMC's Hydrology Manual could also be used). Based on channel conveyance-slope estimates, this discharge is confined to the large incised channel along the left side of the embayment at the toe of the bedrock mountain. At the topographic apex, the estimated level of the 100-year discharge is within a couple of feet of the top of the right bank. Evidence of historic floodwater overtopping the right bank was not observed. The channel capacity is greater than the 100-year discharge in the embayment area.

Large angular boulders with some visible imbrication in places are exposed along the banks of the channel. The exposed rock is cemented a few feet below the land surface. There are remnants of an old terrace about 8 to 10 ft. above the streambed in a few places. These banks and terraces can be readily observed a short distance to the north of the trail about 1/2 to 3/4 mile from the trailhead.

FIGURE 5.9

Aerial photograph of White Tank Park site showing topographic contours, soil types, piedmont landforms and other characteristics.





Metadata Notes:
(1) Aerial Photography, HIS, Dec. 1996
(2) Soil data, ALRIS, 1:24000, 1975
(3) Topography, White Tanks/Agua Fria ADMS, 1:4800, Dec 1987 - Feb 1990
(4) Park Boundary, Maricopa County Association of Governments, unknown scale, 1993

SYMBOLS

- Soil Boundaries
- Index Contours (10 ft)
- Intermediate Contours (2 ft)
- Regional Park Boundary

1" = 600'

0 300 600

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The surface of the landform that lies just below the mountains is covered with varnished boulders and cobbles indicating the landform is old and stable. There are several old debris lobes a few feet high and several tens to a couple of hundred feet long (The lobes are located to the west of the area shown in Figure 5.9). These lobes have snouts of large boulders and are similar to the debris lobes on the relict part of the Henderson Canyon alluvial fan near Borrego Springs, California (National Research Council, 1996). The debris mounds have inverse grading and many of the fines have washed from the debris matrix.

Of fundamental importance is this surface is old and stable. Some the details about the debris lobes are not needed for the assessment but are presented because such lobes are not common in central Arizona. Because the mounds are old (apparently early or pre-Holocene) the characteristics are not precisely like fresher deposits described by Costa (1988) or the clast poor, matrix rich lobes described by Blair and McPherson (1994). The lobes also may be similar to the sieves described by Hooke (1967). Clearly, the active channel has incised into old fluvial (water and debris flow) deposits.

5.2.2 Area below the mountain front

The mid- and lower-relict fan can be viewed along Olive Ave. starting at the Beardsley Canal about 2 miles east of the park entrance (to the east of the area shown in Figure 5.9). Many small tributary channels head on the fan surface. The interfluves are covered with desert pavement and there is a well-developed carbonate zone about 1 ft. below the surface. The throughflow channel can be examined by continuing straight at mile 0.55 mile beyond the park entrance, crossing the wash at mile 0.75 and parking on the right at the restrooms and picnic tables (mile 0.82) (See Figure 5.9).

About 4.10 mi^2 is drained by the incised channels at the road crossing near the restrooms. The corresponding 2-, 10-, and 100-year flood peak discharges are about 100, 820 and 4,400 ft^3/s (Thomas, Hjalmarson and Waltemeyer, 1997). The user is reminded that the precise amount of peak discharge is not needed for this assessment unless it is determined that profiles are needed for the 100-year flood in stable channels. For example, a 100-year discharge of about 5,600 ft^3/s was independently estimated and used to define the limits of the 100-year flood discussed later in this manual. The user should keep in mind that the peak discharge is not needed to determine the type of landform and stable and unstable areas.

Channel incision is progressing upslope as evidenced by a large headcut. The bouldery sediment produced by the incision has produced downstream deposition at the inset alluvial fan. This "out-of-phase" effect of channel incision is further described by Schumm, Harvey and Watson (1988).

5.2.3 Type of landform

The landform was identified as an alluvial fan with an incised channel composed of a headcut and a relatively small downstream channel area of active aggradation and erosion. Sediment in this aggrading channel area has spread laterally over adjacent land. Procedures outlined in Chapter 2 of this manual were used.

5.2.3.1 Composition

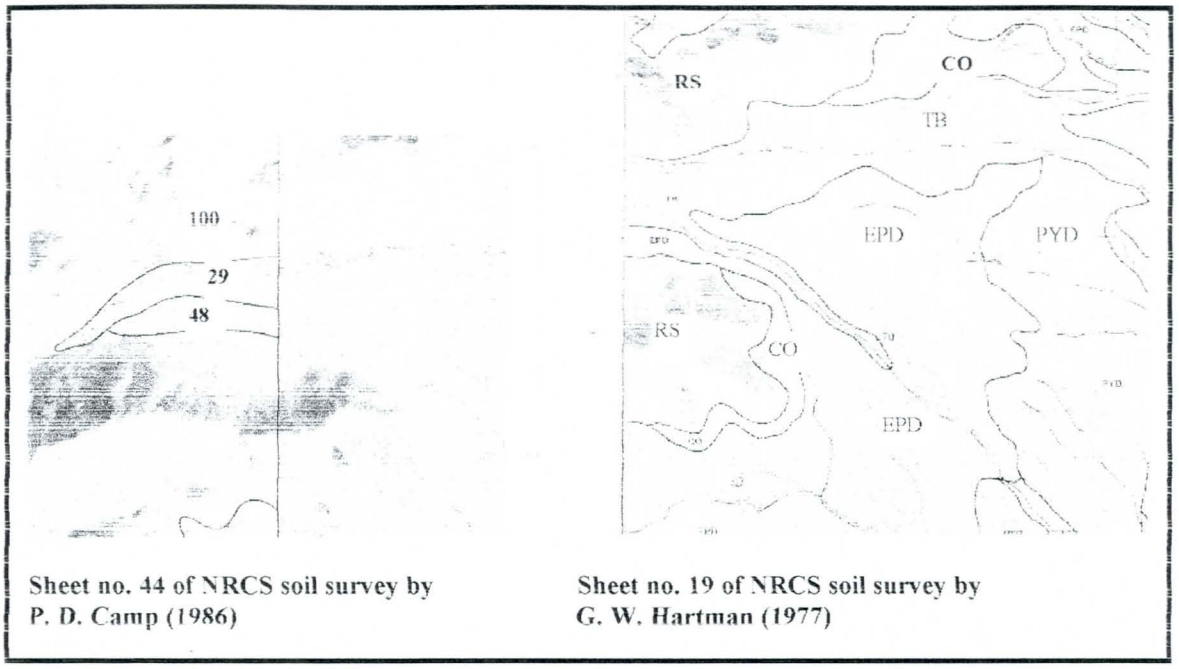
The area along the incised channel was classed by Hartman (1977) as torrifluvents (map unit TB) consisting of young unconsolidated gravely, cobbly and stony alluvium on young alluvial fans (Figure 5.9). Camp (1986) classed the adjoining area to the west as a fan terrace (map unit 29) that is calcareous a few inches below the surface (Figure 5.9). Cemented gravely, cobbly and stony alluvium can be observed along most of the channel. Young unconsolidated gravely, cobbly and stony alluvium was observed along the channel near and to the east of the eastern park boundary (Figure 5.9). This narrow area of unconsolidated material resembles an inset alluvial fan (See Table 2.1) but it is classed here as an alluvial channel that is both aggrading and eroding.

Much of the upper area is mapped by both Hartman (1977) and Camp (1986) as the Ebon-Pinamt complex (soil type EPD and 48, respectively) (Figures 5.9 and 5.10) of old alluvial fans that form on the piedmont along the base of the White Tank Mountains. The middle area is mapped by Hartman as the Pinamt-Tremant complex (PYD) of gently to steep sloping land of old alluvial fans. The lower area is also mapped as an old alluvial fan (CV, AGB, GYD) that is nearly level to gently or moderately sloping.

Thus, except for the young unconsolidated gravely, cobbly and stony alluvium along the incised channels, the entire area is identified by the NRCS as an old alluvial fan. The vegetation is creosotebush, paloverde, bursage with some cholla cactus. There is cementation at depth below the upper reddish-yellowish subsoil. The surface is covered with desert pavement that is varnished. The upper area is bounded by the Cherioni-Rock outcrop complex (CO) (a pediment at the base of the mountain front) and rock outcrop (RS) of the White Tank Mountains.

5.2.3.2 Morphology

The landform has a partly extended fan shape with the upper part bounded by the toes of adjoining mountain slopes. Below the mountain front the fan widens and coalesces with adjacent relict or inactive alluvial fans. The highly crenulated contours shown on the available 7.5-minute series USGS topographic maps (Waddell and White Tank Mtns. SE Quads) have a distinct convex shape in the downslope direction to about 1 mile east of the mountain front (see Figure 5.9 and the above listed USGS topographic maps).



Sheet no. 44 of NRCS soil survey by P. D. Camp (1986)

Sheet no. 19 of NRCS soil survey by G. W. Hartman (1977)

Figure 5.10. Soil types.

5.2.3.3 Location

The site is located next to the mountain front like typical relict and inactive alluvial fans (See Figures 1.1 and 2-1). The topographic apex is at a topographic break at the top of the embayment near the toe of the bedrock mountain. The present channel is incised at this location. There is no hydrographic apex within the park boundaries.

5.2.4 Active and inactive areas of the alluvial fan

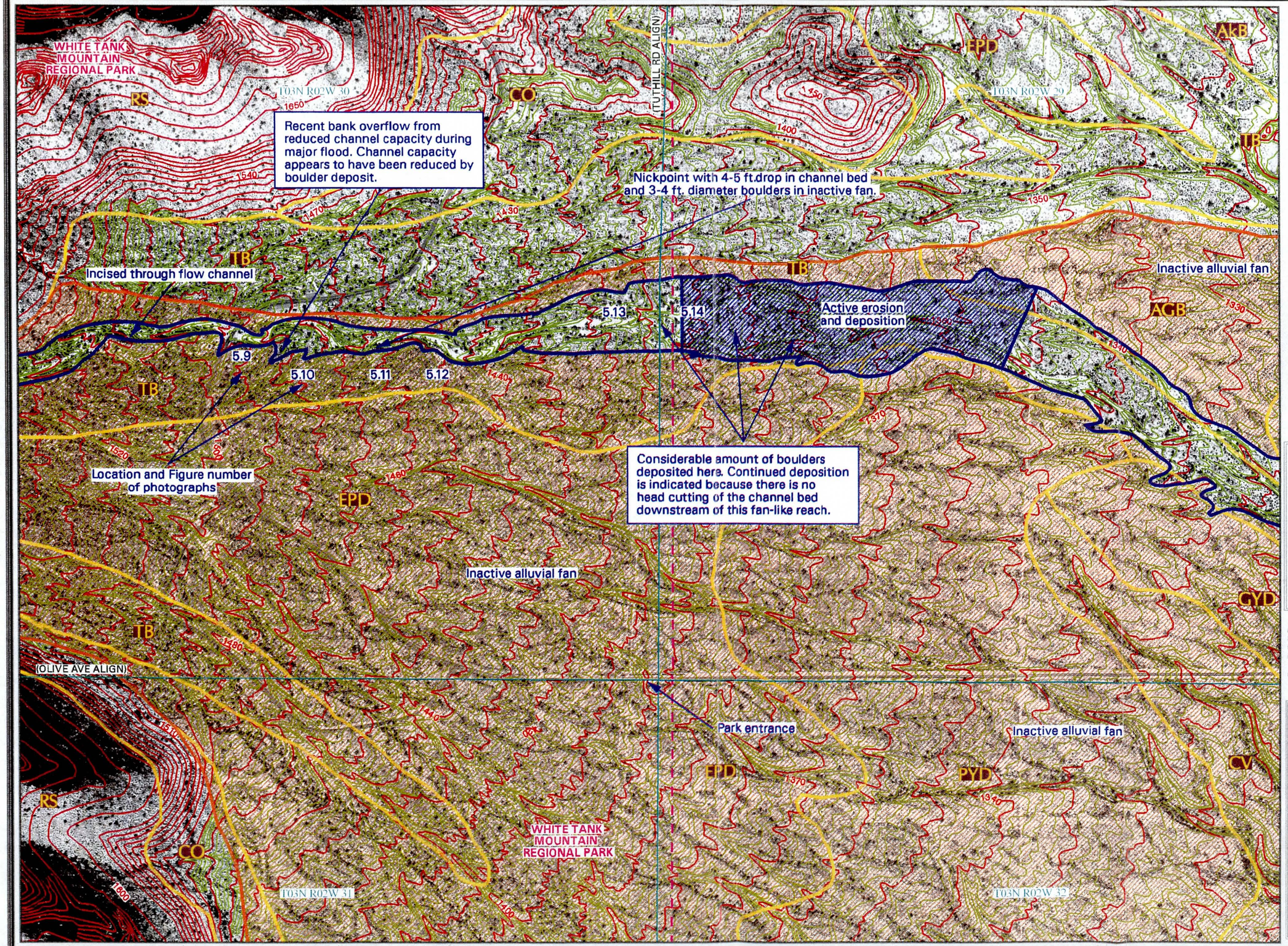
Active and inactive areas are identified using methods in Chapter 3.

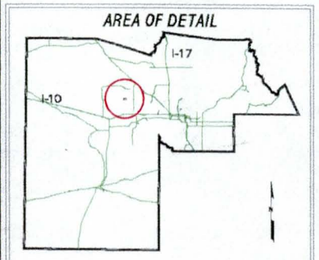
5.2.4.1 Inactive area

Most of the alluvial fan is inactive with old developed soil covered with varnished desert pavement (Figure 5.11). These soils are mostly the Ebon-Pinamt complex. The throughflow tributary channel is cut nearly 10 ft. in places into the cemented conglomerate. Several small tributaries head on the inactive fan. The landform clearly meets the criteria of a stable area as defined in Chapter 3 of this manual.

FIGURE 5.11

Aerial photograph of White Tank Park site showing landforms with active and inactive areas and location of photographs.





Metadata Notes:
(1) Aerial Photography, HIS, Dec. 1996
(2) Soil data, ALRIS, 1:24000, 1975
(3) Topography, White Tanks/Agua Fria ADMS, 1:4800, Dec 1987 - Feb 1990
(4) Park Boundary, Maricopa County Association of Governments, unknown scale, 1993

SYMBOLS

- Soil Boundaries
- Index Contours (10 ft)
- Intermediate Contours (2 ft)
- Regional Park Boundary

1" = 600'

0 300 600

/add/adm_gs/projects/wynn/figure511.ami 09/08/98.14:06:50.Tue

5.2.4.2 Active areas along throughflow channel

The long narrow aggrading area starting near the eastern park boundary and extending downstream about 600 ft. resembles an inset alluvial fan using procedures in Chapter 2. Although this area is aggrading in places and starts at a topographic break, it does not have the shape of a fan. Rather, it is an area where upslope headcut sediment is deposited and subsequently moved further downstream during floods of various magnitudes. The aggrading/eroding part of this area meets the criteria of an unstable area, like that of an inset alluvial fan, given in Chapter 3 of this manual. Fluvial hazards along the throughflow channel are shown in Figure 5.12 to 5.17 (See Figure 5.11 for location of photos). The user should examine the landform in the field and not rely on the photographs alone. For example, a field examination of the nickpoint and likely eventual stream piracy mentioned in Figure 5.13 should show the importance of using this method.

5.2.5 Drainage Basin

The drainage basin above the road crossing is 4.10 mi^2 with a long-narrow tributary area on the north. The basin is about 4 miles long with a width of about 1-mile. The general shape is elongated and not bowl shaped like mountainous basins above many active alluvial fans. The drainage of the first and second order streams is not quick and does not coincide at the topographic apex. Because there is not an abundant supply of unconsolidated sand, gravel and cobble material in the basin and the basin is not bowl shaped, active fan building is not expected at the mountain front based on the basin characteristics.

5.2.6 Characteristics of recent deposited sediment

Much of the stony sediment along the aggrading/eroding part of the throughflow channel is transported from the relict alluvial fan by infrequent large floods.

5.2.7 The 100-year flood

The computed boundaries of the 100-year flood are shown in Figure 5.18. These boundaries are from a traditional step backwater computation using a peak discharge of about 3,200 at the restrooms and 3,500 ft^3/s at the park boundary. The area of active erosion and deposition (Figure 5.11) closely agrees with the computed 100-year flood boundaries. Three small geomorphic hazard areas that lie outside the traditional 100-year flood boundaries are shown in figure 5.18. There has been recent flow in these areas possibly as the result of reduced channel conveyance from temporary filling of the channel with coarse sediment.

The safe setback distance for development is also shown in Figure 5.18. The setback allowances were for a Level 1 analysis given in the "Watercourse System Sediment Balance" State of Arizona Standards SSA 5-96. It is interesting that for this site the three

small "geomorphic" hazard areas that lie outside the bounds of the 100-year flood limits are within the setback limits. This supports the use of the setback limits defined by the Arizona Department of Water Resources.

Floodwater on the inactive alluvial fan is in defined tributary channels.

5.2.8 Summary

Most of the landform is old with small tributary streams that form on the inactive fan. The inactive fan is eroding slowly and is stable. Along the throughflow stream there is active headcutting and sediment deposition. The computed 100-year flood boundaries represent the minimum fluvial hazard. There should be setback from the incising reaches to allow for bank failure and channel widening.

Aggrading areas and areas adjacent to these areas along the throughflow channel from the park boundary to at least 600-ft, downstream are especially hazardous. The channel geometry of this area can change during flooding and development can be buried by sediment debris. Some of the aggradation near the park boundary is very recent and suggests that sediment deposition may spread to adjacent land as upstream headcutting continues to supply sediment. The safe setback distance for development along this aggrading area is at least that defined in State of Arizona Standards SSA 5-96 and shown in Figure 5.18.

Boulder position shows imbrication and boulder angularity suggests a nearby source of material--probably the White Tank Mountains. Of significance for present flood plain management is that the relict channel bank is steep and has been cut by recent flow and only large amounts of stream power can move the large-angular rock. The frame of the square grid shown here and in the following photographs is 1.5 ft. outside dimension.

Figure 5.12. Photograph of right bank below roadway (See Figure 5.10 for location) showing relict boulder conglomerate.

Figure 5.13. Photograph of right bank where the active channel bends to the left above the park restroom building shown in the background. Bank erosion and overtopping from pileup has occurred along the right bank and can be expected during large floods. Overtopping was near the square frame (1.5 ft. outside dimension) shown on the right bank. Several feet beyond the bank and out of view is a nickpoint that forms the head of another channel on the inactive alluvial fan. This nickpoint, which is a location on the profile where there is an abrupt change of elevation (Schumm and others, 1988), is slowly eroding headward and may eventually intersect the bank shown in the scene. The rate of nickpoint movement is related to the amount and frequency of overflow from the active channel in the scene. Factors such as the boulder deposit in the center of the scene must be considered in an estimate of when stream piracy may occur. For example, the boulder deposit has reduced channel conveyance at this location and may be moved downstream by large floods and thereby reduce the amount of bank overtopping.

Figure 5.14. Photograph looking upstream at nickpoint of entrenched channel. There is a 4 to 5 ft. drop of bed elevation at the nickpoint and the 3 to 4 ft. boulders are from the cemented conglomerate of the inactive alluvial fan. The conglomerate is resistant to erosion to depths of at least several feet and thus a slow rate of arroyo growth may be expected for a 100-year regulatory period. The rate of head cutting may increase when the large boulders in the scene are washed downstream perhaps to be deposited in the aggrading area shown in photographs 5.15 and 5.16.

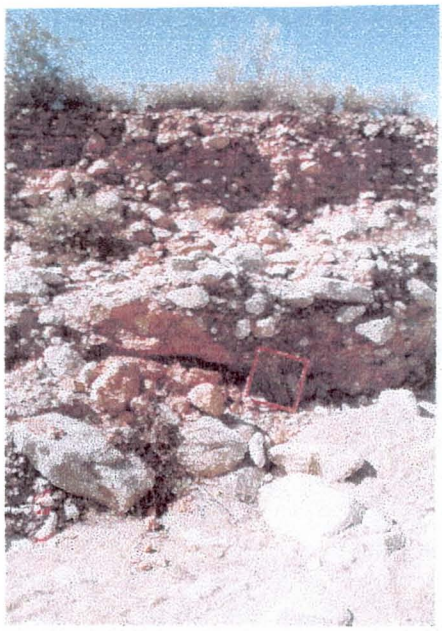
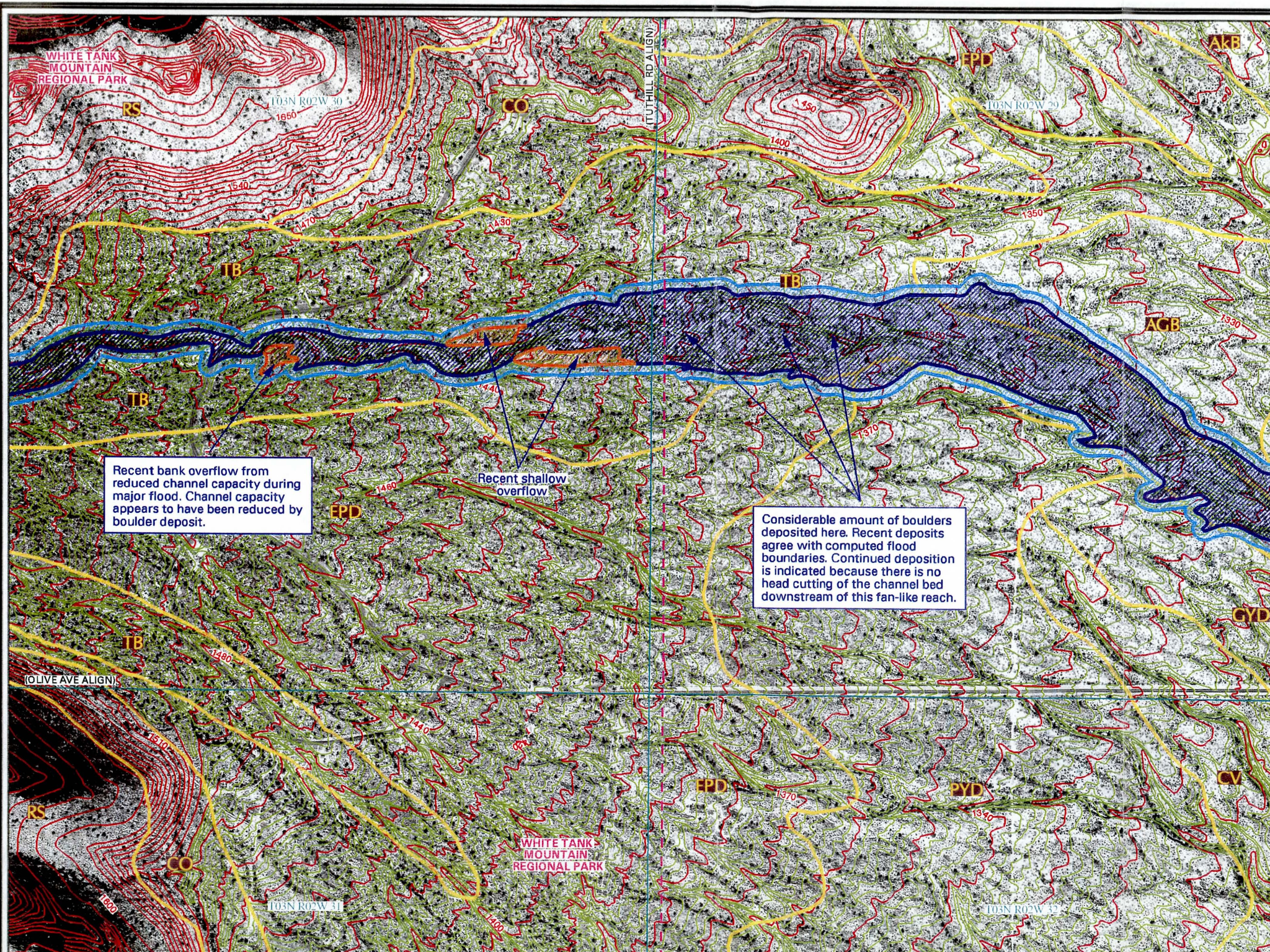
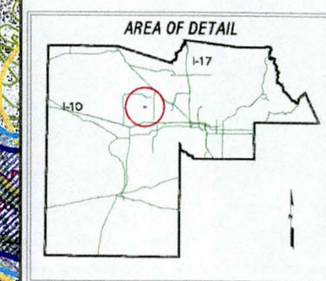


Figure 5.15. View looking south at right bank a few hundred feet downstream of the nickpoint where the channel is about 8 to 9 ft. deep. The upper 4-ft. of bank is composed of angular boulders that are smaller than the boulders of the lower material. The lower material may be more erosion resistant than the upper bank but the difference, if any, is not considered for flood assessment for the 100-year regulatory period.

Figure 5.16. View looking downstream and east at the overflow area on right side of the channel where there is recent aggradation. The overflow channel profile and the inactive alluvial fan profile are the same in this scene and floodflow can spread laterally a few hundred feet. The lobe-like boulder deposit is a few hundred feet below the breakout from the arroyo.

Figure 5.17. View looking downstream at main channel of aggrading area located several feet east of the Park boundary. This formerly entrenched channel has filled with the material shown in the scene. The profile of the channel and the inactive fan are nearly the same and floodwater can spread a few hundred feet to the north and south. The small branching channels of the left and right of the scene rejoin several hundred feet beyond the scene. Other braided appearing reaches are located downstream along the throughflow channel. Floodwater in these smaller downstream reaches spreads in a few channels and then becomes confined only to spread again further downstream.





Metadata Notes:
(1) Aerial Photography, HIS, Dec. 1996
(2) Soil data, ALRIS, 1:24000, 1975
(3) Topography, White Tanks/Agua Fria ADMS, 1:4800, Dec 1987 - Feb 1990
(4) Park Boundary, Maricopa County Association of Govemments, unknown scale, 1993
(5) Floodplains, White Tanks/Agua Fria ADMS, 1:4800, Dec 1989 - Feb 1990

SYMBOLS

- Soil Boundaries
- Index Contours (10 ft)
- Intermediate Contours (2 ft)
- 100 YR FEMA Floodplain Limits
- Setback Area Boundary
- Regional Park Boundary

1" = 600'

0 300 600

FIGURE 5.18

Aerial photograph of White Tank Park site showing landforms, active and inactive areas and estimated 100-year flood hazard areas.

5.3 The Skyline Wash alluvial fan

5.3.1 Introduction

The Skyline Wash alluvial fan is located in a wide embayment on the southern piedmont of the White Tank Mountains. The site is to the north of Interstate Highway 10. Runoff from the drainage basin is retained above I-10 at FDCMC Buckeye Flood Retaining Structure No. 3 that is readily visible when looking north from I-10. The drainage basin heads in the rugged White Tank Mountains. The alluvial fan is bounded by Prospect Wash on the west and Rattler Wash on the east. There is an old gravel pit on the alluvial fan that complicates this assessment. The toe of the Skyline Wash alluvial fan is cut by I-10 and the Buckeye No. 3 flood retention structure.

A four-wheel drive vehicle is recommended for access in the active parts of the fan and in the active channels at this site especially in the channels to the north of McDowell Road.

5.3.1.1 Road log

The Skyline Wash site is accessed from I-10 by turning south at Jackrabbit Trail (Exit 121). At mile 1.8 turn west (right) at Yuma Road. Proceed west for about 4.5 mile (mile 6.3) and turn north at Watson Road. Proceed north 2 miles (mile 8.3) to McDowell Road and make note of the following: (a) pass under I-10 at about mile 7.0 (See Figure 5.19), (b) the storm water retention dam on the right (mile 7.2) that blocks floodwater from the Skyline Wash fan and other drainage basins, (c) at mile 7.3 the lower fan can be accessed on road to the right and (d) at mile 8.0 the road crosses Prospect Wash where the gully is cut into rather young alluvium (NRCS soil type TB) and the depth of incision is restricted in places by bedrock (old cemented conglomerate like material) that forms the bed. Turn east (right) at McDowell Road. A relict fan (NRCS soil type 98) with desert pavement and desert varnish is on the left. Proceed 0.1 mile onto the western edge of the active alluvial fan (See Figure 5.19). The upper part of the fan area (to the left) is mapped as drainageways and flood plains by the NRCS (Camp, 1986). The lower fan area (to the right) is mapped as alluvial fan that is 1 to 3 miles from the mountains (Hartman, 1977).

The hydrographic apex is about 0.6 mile upstream to the left or north of McDowell Rd. The apex can be accessed by driving up the first active channel using 4-wheel drive. The hydrographic apex is located in a reach about 150 ft long where flow is in one 200-ft. wide channel confined by bedrock banks. The channel above the apex can also be accessed by vehicle. Large amounts of sediment are in the channels and floodplains above the hydrographic apex.

5.3.1.2 Background and materials for field inspection

The field inspection of this site is made to: (1) verify the type of landform, described as an alluvial fan and as drainageways and flood plains by the NRCS, using methods in Chapter 2 and steps in Table 2.2; (2) identify active and inactive areas using methods in

Figure 5.19 belongs here

5.19 Aerial photograph of Skyline Wash site showing topographic contours, soil types, piedmont landforms and other characteristics

Basically combine the topo, soils and the stuff on Figure 2 "Mapping limits & study reaches".

Orient on page as Figure 2 "Mapping limits & study reaches"
Show topography and township, range and sections.
Show soil types as mapped on the NRCS published maps.
Show the drainage boundaries as in Fig2 but also show the boundary above the hydrographic apex.
Show text highlighted in red on the working figure.

Chapter 3; and (3) estimate flood hazards, as described in Chapter 4, based mostly on geomorphologic methods using only a rough estimate (a level 2 estimate as defined in State of Arizona Standard 2-96) of the 100-year peak discharge at the hydrographic apex and at any major tributaries. The user should have USGS 7.5 minute topographic maps of the Valencia and White Tank Mtns. SE Quads, or the equivalent, and should have consulted the NRCS Soil Surveys of Maricopa County, Arizona by Hartman (1977) and Camp (1986).

During a field examination of this site, an error in the placement of boundary lines for soil type was found. The mapped soil types (Hartman, 1977) and the location of the floodwater retardation structure apparently were incorrectly displaced 1,000 feet to the west along the east side of the site south of McDowell Rd. The published soils maps that include this error are shown in Figure 5.19. The corrected soils maps are shown in Figure 5.23. The NRCS state soil scientist confirmed that this correction appears to be correct. As discussed in section 2.2.2 the state soil scientist is available to assist users with published soil surveys.

Geologic mapping and the assessment of flood hazards have been accomplished for parts of the White Tank Mountain piedmont by Field and Pearthree (1992). This geomorphic analysis and mapping, that includes the Skyline Wash alluvial fan, is used to refine the assessment of the 100-year flood hazard. In addition, the degree of flood hazard was estimated at four alluvial fans located nearby on the western piedmont of the White Tank Mountains (Hjalmarson and Kemna (1991) and Hjalmarson (1994). These fans demonstrate the variety of active and inactive areas of alluvial fans in the area. The user should consult the report by Field and Pearthree (1992), read this section of the manual (Section 5.3) and obtain any other needed referenced material before making a field inspection of the site.

Excellent aerial photographs with topographic contours at 2 ft. intervals were available at a scale of 1 inch=200 feet (DEI Professional Services, November 10, 1997). Aerial photos of March 10, 1953 and March 31,1976 were used for the assessment of flow path movement.

5.3.1 Type of landform

Landform clearly is an alluvial fan with a topographic apex in an embayment based on the following composition, location and morphology.

5.3.1.1 Composition

Antho-Carrizo complex (Hartman, 1977) and Antho-Carrizo-Maripo complex for adjacent upslope unit (Camp, 1986) (Figure 5.19). Soil is on floodplains and drainageways according to Camp and on alluvial fans according to Hartman. The mapping by Camp is to the north of McDowell Rd. where the drainageways are more defined and, in places, on apparent old conglomerate (Figure 5.20). The cemented material that forms the channel bed in Figure 5.20 is very old and the unconsolidated

material including the sub-angular boulders along the banks is young. The mapping by Hartman is to the south of McDowell Rd where there are few defined throughflow channels and most channels are wide with low banks. The soil types agree with the common types for alluvial fans in Table 2.1.

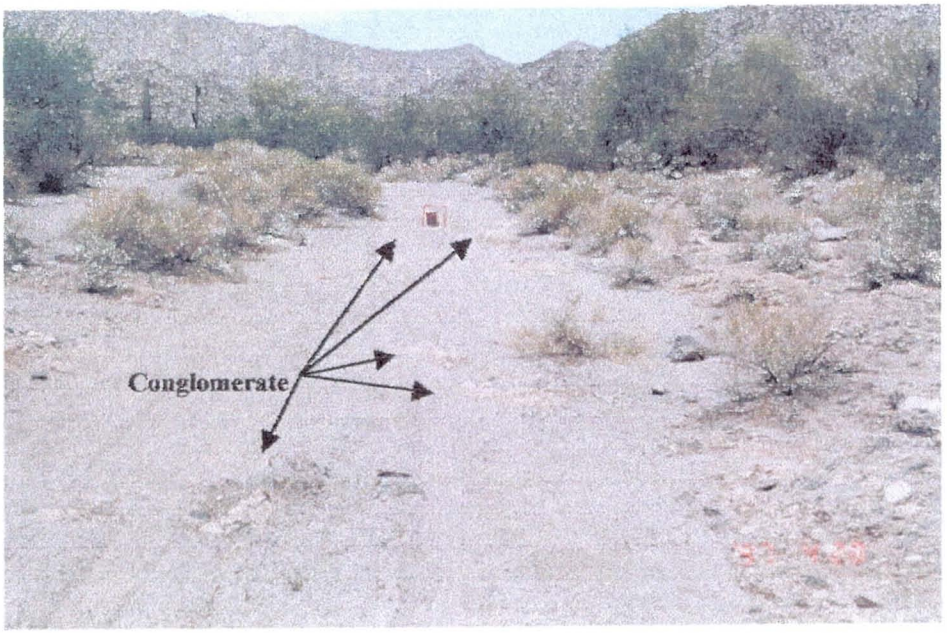


Figure 5.20. Photograph looking upstream along channel on right (west) side of Skyline Wash alluvial fan.

5.3.1.2 Morphology

The landform has a shape of a partly extended fan that is readily seen on the USGS Valencia, AZ Quad. 7.5 minute series topographic map. The transverse cross sections along the lower fan are similar to the typical cross section for active alluvial fans shown in Figure 2.2. The channels in the upper fan are distributary (See Table 2.3).

5.3.1.3 Location

The topographic apex is approximately at an elevation of 1,510 ft near the upslope end of young unconsolidated sediment (NRCS soil type 3 (Camp, 1986)) at the edge of the fan terrace. There is more that one topographic apex depending on which tributary channel is selected. There is a slight slope decrease at this location (Figures 5.21 and 5.22) and there is some widening of the channel.

The hydrographic apex is located in the NW1/4 of section 34, T. 2 N., R. 3.W at a topographic break where there is an abrupt widening of the banks (Figure 5.19). The precise location of the hydrographic apex cannot be seen on the Valencia Quad.

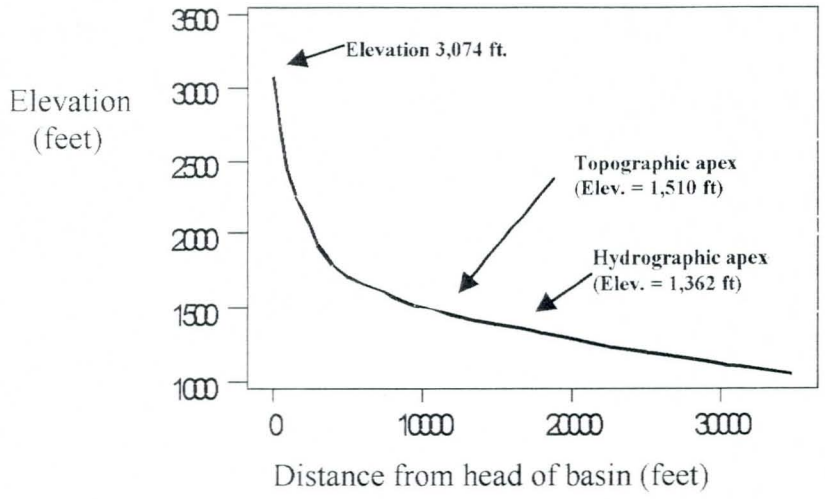


Figure 5.21. Elevation profile of stream channel at Skyline Wash landform. Below the hydrographic apex the channel is along the east side of the alluvial fan.

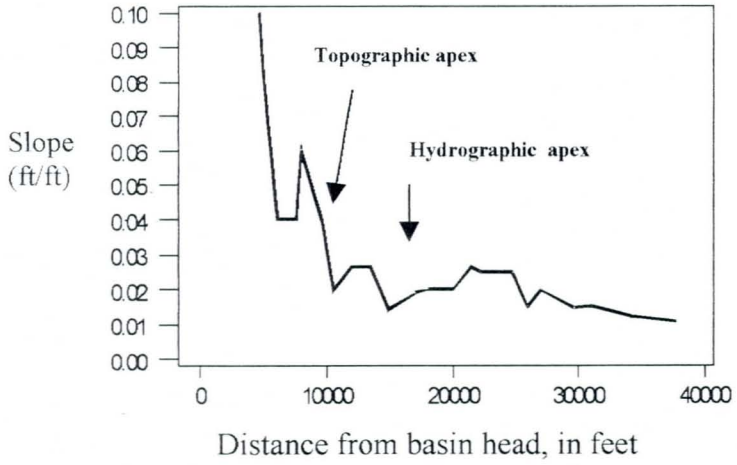


Figure 5.22 Profile of channel slope along center of the Skyline Wash alluvial fan.

The alluvial fan is on the upper piedmont at a location similar to the uppermost alluvial fan shown in Figure 1.1.

5.3.2 Active and inactive areas of the alluvial fan

Initial clues that indicate the alluvial fan has both active and inactive areas are gleaned from the soil survey reports and the 7.5-minute series topographic map.

> **Note: The USGS topographic maps are not included with this manual and the user can substitute the topography depicted in Figure 5.19.**

The distribution and size of the contour crenulations changes both across and down the fan. For example, at and upslope of the 1,300 ft. contour there are several distinct crenulations that suggest defined and possibly stable channels. Another example is downslope of the 1,300-ft. contour there are few crenulations in the middle of the fan suggesting active sediment deposition (See section 2.2.2) or possibly eolian effects.

> **Note: It is important to realize that the channels depicted by the crenulations may be tributary, distributary and/or throughflow channels. Aerial photographs and a field examination are used with the topographic maps to define the channels. In this regard, contour crenulations that appear to represent channels may represent other features such as a group of debris flow mounds.**

The drainage basin is bowl shaped where much of the drainage quickly reaches the hydrographic apex. Many active alluvial fans have bowl shaped drainage basins (See section 3.4.2.3).

The corrected NRCS soil survey is shown in Figure 5.23. Both of the NRCS soil surveys (Hartman, 1977 and Camp, 1986) report that much of the alluvial fan is composed of Antho, Carrizo and Maripo soil types that are associated with young sediments. About 20 percent of the area above McDowell Rd. that is mapped as unit 3 is Carrizo soil along drainageways. About 30 percent of the area (soil type AGB) south of McDowell Rd. is Carrizo soil that is in channels that form a braided pattern across large bodies of Antho soils. Camp (1986) describes the Carrizo soils as severely limited for urban use because they are subject to flooding. In the lower fan area, there are fingers of relict fans (soil types 98, GYD and HCL) that separate the areas of younger sediments. These old sediments include small areas of Carrizo and other younger soils along drainageways. The more stable parts of the surface of soil types GYD and HCL are gravelly loam (desert pavement).

5.3.3.1 Source of sediment

A large amount of loose sediment is visible along the larger drainage channels upslope of the hydrographic apex using aerial photographs (Figure 5.23). Much of this very gravely sand debris is along the western drainage channels. This unconsolidated material can be transported to the fan mostly because floodflow velocities are great along the steep channels.

Figure 5.23 belongs here.

Figure 5.23 Orthophoto and topographic map of Skyline Wash site showing corrected soil types and landforms with active and inactive areas.

This is about same as Fig. 5.19 except as follows:

Show the corrected location of the soil types as shown on the 1"=800 ft worksheet by Hjalmarson.

Do not show soil types below the retention dam. Show the AGB, GYD, 98 and so forth.

Show the drainage divide around the gravel pit.

show active and inactive areas

The supply of accumulated debris is the Carrizo soil that is a large portion of soil type 3 and a small portion of soil type 98 described by Camp (1986). Channel slopes above the hydrographic apex exceed 2 percent (Figures 5.21 and 5.22) and many channel beds have rather wide reaches with scattered trees. These characteristics were verified by a field inspection of the channel material. A general description of the Carrizo soil is given in Camp (1986).

5.3.3.2 Flow path movement

Flow path movement was evaluated using an Army Map Service aerial photograph of March 10, 1953 (Number 220 at about 1" = 1150 ft.) on file at the FCDMC. A second aerial photograph of March 31,1976 on file at Landiscor Aerial Information in Phoenix, AZ was also used. The recent photography of Nov. 10, 1997 is of excellent quality while the 1953 photograph is slightly faded. The detail on the 1953 photograph is satisfactory. Detail in the 1976 photograph was very clear.

The gravel pit is shown on the 1953 photograph with a haul road heading southeast to a military landing strip. Unconsolidated material has been removed from the pit to depths of more than 10 ft. in several places before bedrock was encountered. The sand and gravel operation continued after 1953 because the gravel pit appears slightly larger in the 1976 photograph. Since 1976 the gravel pit has enlarged to the north and has completely intercepted a large throughflow channel near the central axis of the fan. Other much smaller throughflow channels were also intercepted by the gravel pit.

Other than the large impact of the gravel pit, no major changes of the flow paths were observed. Some channel erosion in the upper fan was apparent during the 44-year period. Some channel filling with more development of narrow networks of braided channels also was visible along the sides of the fan. New sediment deposition was along the west channel south of McDowell Rd. and along the eastern two channels that split a few hundred feet north of McDowell Rd. Channel scour with widening was visible below the hydrographic apex along the eastern two channels that presently bypass the gravel pit. Some scour along the west channel below the apex also was apparent.

The throughflow channel on the west side appears to have scoured and widened below the hydrographic apex above McDowell Rd. About 0.2 mile downstream of McDowell Rd. there appears to have been some sediment deposition since 1953. More recent small braided channels are visible below McDowell Rd. in the 1997 photograph.

Below the hydrographic apex, the two throughflow channels on the east appear to have widened a small amount and possibly downcut. Downcutting is restricted by exposed bedrock (apparently cemented relict material) that is readily observed in the field. A new channel is cutting from the northern throughflow channel across to Coyote Wash (Figure 5.23). There is considerable evidence of active bank erosion along the steep banks. About 0.5 mile below the apex, the channel on the east appears unchanged. About 0.2 mile above McDowell Rd, this channel forks where recent sediment deposition is apparent. There is recent filling and development of small braided channels along both of the forks

to the detention dam downstream. There appears to be more sediment deposited along the eastern fork.

The gravel pit clearly has intersected the large fourth channel near the center of the fan below the hydrographic apex. Other much smaller throughflow channels also were intersected by the pit. The gravel pit intersects flow across the center of the alluvial fan and diverts it to the large throughflow channel on the east side of the fan. A couple of other small throughflow channels pass between the large throughflow channel on the west of the fan and the west edge of the gravel pit. These small throughflow channels appear in the three aerial photographs to convey only small amounts of overflowing floodwater. Based on the field inspection, only relatively small amounts of flow can enter the fan near the west side of the pit and east of the large throughflow channel. The present geometry and roughness conditions below the apex suggest that only very shallow flow of major floods can enter this area.

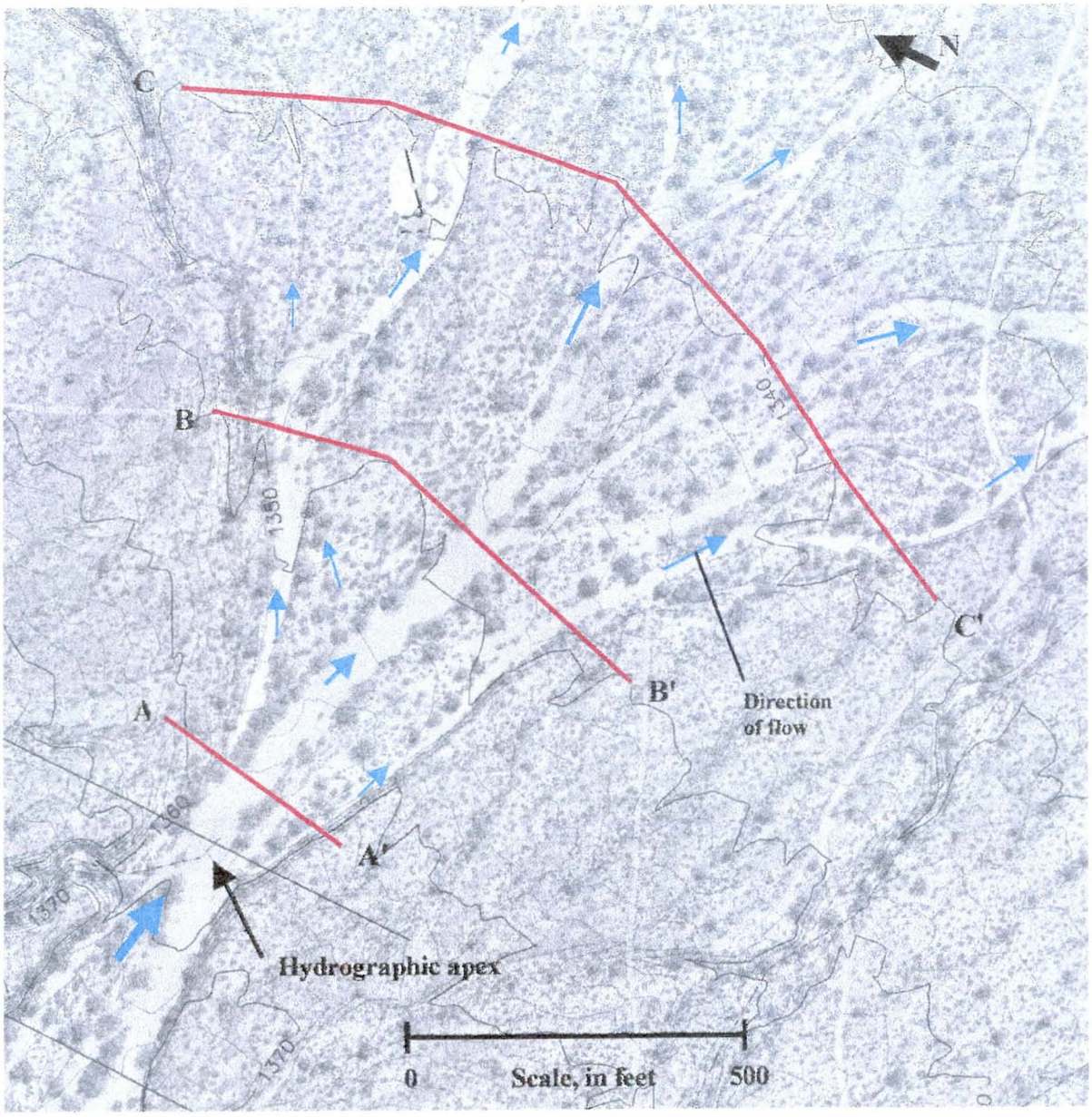
5.3.3.3 Vegetation

A mix of areas with channels lined with trees or areas with scattered trees are visible on the aerial photographs. For example, the scattered paloverde trees over much of the center and west of the upper fan below the hydrographic apex suggests the fan is unstable (Tables 2.3 and 3.1). Within this area, however, are at least two faint channels lined with trees that suggest some stability. About 1,500 ft below the hydrographic apex the channel on the west is lined with trees to about 3,500 ft below the hydrographic apex just below McDowell Rd. suggesting this reach is stable. On the east side of the fan below the hydrographic apex, the trees are mostly along the channel also suggesting that this channel has not moved for several years.

5.3.3.4 Channels

Four rather large throughflow channels are below the hydrographic apex. The most distinct throughflow channels are along the edges of the upper fan (See Figures 5.23 and 5.24). Below McDowell Rd., the channel on the west progressively becomes less distinct (Figure 5.23) where there are several channel forks and the channel depths decrease. Along the eastside of the fan the two channels join and form a single channel that has several small tributaries including Coyote Wash. A few hundred feet upstream of McDowell Rd. the east channel splits into two distinct flow paths. A fourth rather large channel in the upper fan enters the gravel pit area and becomes indistinct on the aerial photographs (Figure 5.23).

In the upper alluvial fan many channels are wide with low banks like those shown for cross sections BB' and CC' (Figures 5.24 and 5.25). Many channel cross sections shown in fan sections BB' and CC' are similar (after allowance is made for scale differences of the abcisa and ordinate) to the cross section in Figure 2.2 for typical active alluvial fans. The large and fairly deep channel on the west of the fan shown in cross section CC' is more typical of an inactive alluvial fan (See third cross section in Figure 2.2). South of



(Base map of 11/10/97 at 1" = 200 feet and 2' contour interval from DEI Professional Services)

Figure 5.24. Cross sections located below the hydrographic apex of the Skyline Wash alluvial fan

McDowell the throughflow channels for soil type AGB are or become less than 2 ft. deep suggesting the fan is unstable (See Table 2.3).

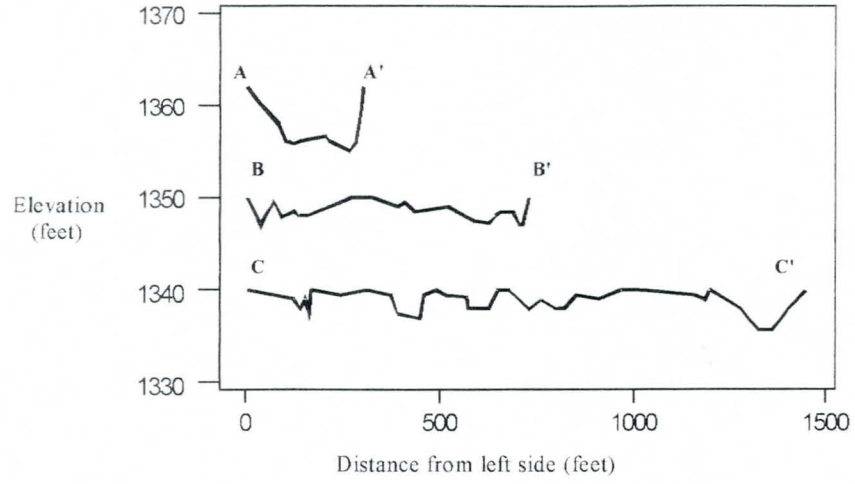


Figure 5.25 Cross sections located at the 1362, 1350 and 1340 ft. topographic contours shown in Figure 5.24 below the hydrographic apex.

5.3.3.5 Gravel pit

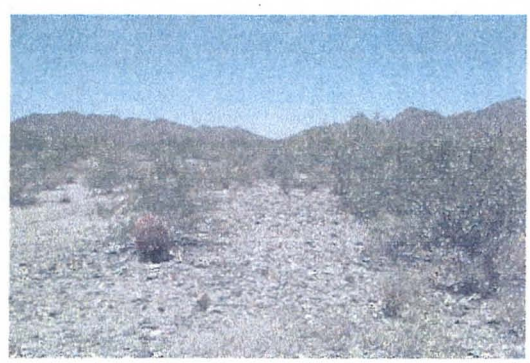
As previously mentioned, the rather large throughflow channel is headcut where it enters the gravel pit. The headcutting is progressing upstream at roughly 10 ft/year and the channel near the pit has scoured about 5 or 6 ft. This headcutting will progress upstream toward the hydrographic apex and the rate of progression may increase as more throughflow is intercepted. A small alluvial fan has developed in the pit below the headcut channel. Large amounts of sediment will be deposited in the pit as more throughflow enters the pit. Flow exits the gravel pit area a few hundred feet upslope of a small inselberg (Figure 5.23).

The gravel pit has intersected floodwater that under natural conditions would have entered the shaded area below the pit (Figure 5.23). This area below the pit is removed from natural throughflow except where the dirt subdivision roads have intersected flow that under natural conditions probably would remain to the west of the shaded area. Both the north-south and east-west roads have an impact on the distribution of floodflow south of McDowell Rd. These roads intersect the generally southeast natural flow in the numerous small channels. Some flow and sediment is diverted into the shaded area mostly by the east-west roads near the center of section 3. This diversion can be seen on the aerial photographs with the detailed topography and in the field.

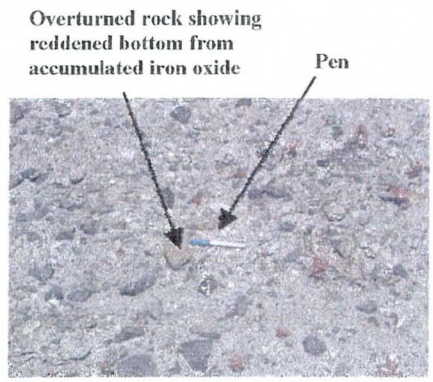
5.3.3.6 Surface age indicators and soil development

The profiles of soil exposed along cut banks in soil types 3 and AGB show little development suggesting the surface is young and unstable (Table 2.3 and section 3.1.2). Profiles along cut banks in soil types 98, HLC and GYD show some calcium carbonate.

There is little desert pavement on much of the fan. Some desert pavement with a generally light desert varnish is on many of the interfluves in soil types 98, HLC and GYD. Typical desert pavement and desert varnish on the stable areas of the Skyline Wash alluvial fan is shown in Figure 5.26.



a. View looking upslope at desert pavement with some desert varnish on interfluves of soil type GYD.



b. View looking down at desert pavement at west side of fan about 100 ft. north of McDowell Rd on soil type 98.

Figure 5.26. Views of desert pavement with some desert varnish on stable parts of fan.

There are many small areas of cryptogamic crusts on the more stable areas of the fan (Figure 5.27). These crusts are an indication of surface stability (See section 3.4.3).

5.3.3.7 Distribution of sediment along the fan

Sediment samples were taken at three sites along the western throughflow on April 28, 1997. The samples were across the channel near the hydrographic apex (apex sample), across the channel a few feet upstream of McDowell Road (upper sample) and 3,000-ft downstream across a large distributary channel (middle sample). Several samples were taken at each site at about 3-6 inch depth and composited. The particles were angular and subangular and a change in rounding down the fan was not obvious. The percent of sediment greater than the sieves at the three sites is shown in Table 5.1 and in Figure 2.5b.

The darkened surface is composed of cyanobacteria, lichens and mosses (Belnap, 1995) and may require hundreds of years to establish. The presence of large areas of cryptogamic crust is a reliable index of surface stability for a few tens of years and possibly for a few hundred years. There are many small crusted areas on the alluvial fan. There appears to be more crust on the relict fans (soil types 98, HLC and GYD). Some of this crust to the left and above the pen is covered with a thin veneer of recent sediment.

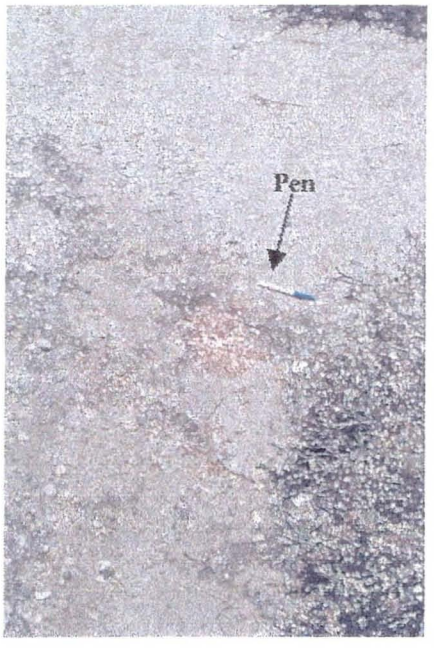


Figure 5.27. Cryptogamic crust in small first order channel on soil type 98 about 100 ft. north of McDowell Road on west side of fan.

Table 5.1 Distribution of particle size at the upper, middle and lower sites along the west side of the fan.

Sieve No.	Sieve size	Percent greater than indicated size		
	mm	Middle site	Upper site	Apex site
4	4.7	2.623	17.361	17.677
10	2.0	21.311	39.583	43.561
40	.42	95.082	88.889	91.540
200	.074	99.672	99.306	99.747

The upper and apex samples are very similar and suggest there is no deposition in the reach. There is much less large material in the middle sample, suggesting there is deposition of coarser material (mostly larger than coarse sand (>.42mm)). Apparently, there is enough stream power to move the silt and clay past the lower site. Thus, the west part of the fan (Soil type AGB) appears to be aggrading below McDowell Road. Above McDowell Road, the sediment is moving on through in the confined channel (See Figure 5.20).

Sediment samples also were collected along the central axis of the fan on July 10, 1998. These samples were in the less active appearing area between the east and west throughflow channels from just north of McDowell Rd. to near the fan toe upstream of the flood retaining structure. Samples were composited for three sites located across the fan at McDowell Road, about 1/2 mile downslope of McDowell Rd. and at the third site about 1 mile below McDowell Rd. These samples were collected at 2-14 inch depths in soil type AGB. No calcium carbonate or much reddening from oxidation was observed at these depths. A small down-fan decrease in the proportion of sand particles is apparent (Figure 5.28) thus suggesting alluvial fan processes like those discussed in section 8.5 of this manual. It is uncertain how much the distribution of sediment in this less active area has been affected by secondary processes of remobilization and redeposition along fan. The greater proportion of gravel near the fan toe above the retention dam (Figure 5.28) may be the result of secondary processes where the finer material has been translocated downfan.

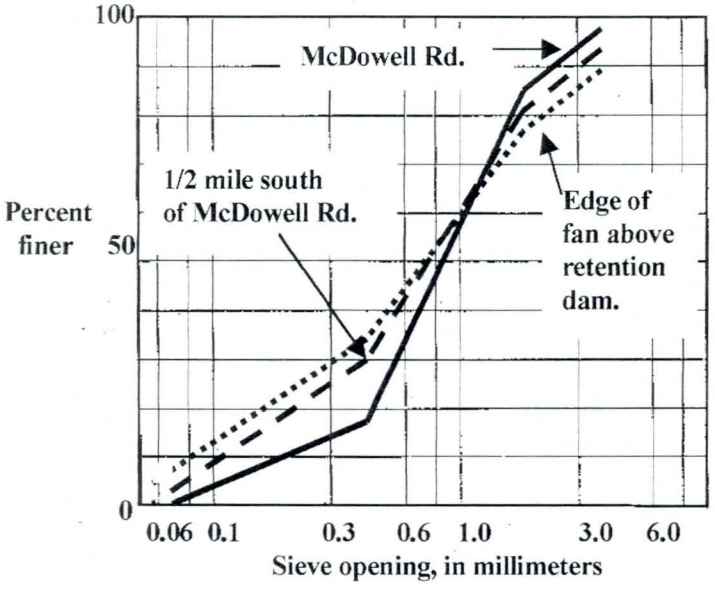


Figure 5.28. Cumulative graph of material size versus frequency along central axis of fan where there is little evidence of recent throughflow.

5.3.3.8 Summary of active and inactive areas

The channels on the east and the west sides of the fan have recently eroded to bedrock in places and the banks, especially along the east channels, have eroded and widened. Before the gravel pit was constructed, the center of the fan also was active to a much lesser degree than both sides of the fan. Thus, under natural conditions the sides of the fan were more active than the center of the fan. Because the gravel pit has intersected floodflow that would have entered the fan center, the area below the pit is considered inactive (Figure 5.23). To be conservative on the side of caution the user is that if the gravel pit were not present, much of the alluvial fan would be considered active based on (1) the young soil (types 3 and AGB), (2) the several small throughflow channels that are visible across the upper fan on the 1953 and 1976 aerial photographs and (3) the generally scattered appearance of the trees below the apex.

The large gravel pit, however, intercepts throughflow that would have entered the middle of the fan defined by soil types 3 and AGB. Thus, throughflow that normally would have entered the center of the fan is presently diverted across the fan to the large channel on the east side of the fan. The "shadow" area below the pit affected by this intersection and diversion is shown by the cross-hatched area in Figure 5.23.

The dirt subdivision roads at and to the south of McDowell Rd. have interfered with the natural flow paths. Because of the small relief across the fan in this area, some shallow floodflow in the western throughflow area has been diverted to the east along the roadways for a few hundred feet. The numerous small ridges and channel depressions were smoothed when the roadways were bladed. These smoothed roads efficiently convey shallow flow to the east. Some minor erosion has occurred along the roads. Thus, small amounts of floodwater presently enter the western edge of the "shadow" area below the gravel pit.

Inactive areas generally correspond to soil types 98 and TB. In the lower east part of the fan above the retention dam, the inactive areas only roughly correspond to the soil types. The inactive areas shown in Figure 5.23 are based mostly on the older appearing surface features including the desert pavement (Figure 5.26a), the predominance of vegetation along the channels and the developed tributary drainage network on the fan surface.

The inactive area in the southeast part of the fan that generally corresponds to soil type HLC has little relief a few hundred feet south of McDowell Rd. Flow paths appear stable in this area but the area appears subject to sheetflow.

5.3.4 Estimated 100-year flood hazards

The stable and unstable areas are the basis for the 100-year floods hazards. The stable and unstable areas are reviewed and modified as necessary by incorporating an estimate of 100-year conditions. The peak discharge for the 100-year flood is estimated using methods by Thomas, Hjalmarson and Waltemeyer (1994). Channel conveyance is next evaluated for the upper fan to demonstrate the varying distribution of discharge across the

fan during a major flood. The impact of the gravel pit and the subdivision roads are then considered to produce a map of the 100-year flood hazards.

5.3.4.1 Peak discharge and channel conveyance considerations

The magnitude of the 100-year flood is used to evaluate and demonstrate the potential flow spreading and flow path movement below the hydrographic apex. Stable geometry and roughness are assumed for these idealized computations. Channel conveyance is estimated at three cross sections in the upper fan and the average channel slope for each section is determined. The channel capacity for the 100-year flood and flow path stability is then examined using conveyance-slope estimates. This particular channel conveyance based demonstration of flow spreading is not required for defining and characterizing areas affected by the 100-year flood as defined in Chapter 4 of this manual.

Peak discharge for 100-year flood

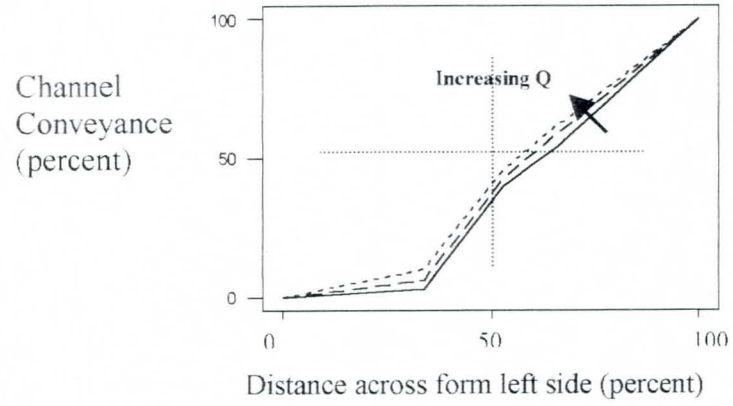
The magnitude and frequency of floods from the 3.93 mi^2 drainage basin above the hydrographic apex was estimated using methods by Thomas, Hjalmarson and Waltemeyer (1994) for flood region 12. The peak discharge of the 100-year flood is 5,030 ft^3/s for the rugged basin with a mean basin elevation of about 1,850-ft. This level 2 method of estimating of the peak discharge of the 100-year flood (See State of AZ standard 2-96) is sufficiently precise for this demonstration.

Based on this regional method of estimating the magnitude and frequency of floods, the estimated peak discharge is not very precise. This imprecision is inherent in any estimate of the peak discharge of the 100-year flood. The average standard error of prediction for flood region 12 is 39 percent (Thomas, Hjalmarson and Waltemeyer, 1994). For the Skyline Wash alluvial fan, this standard error corresponds to a range of peak discharge from 1,960 to 6,990 ft^3/s. This imprecision, that is often overlooked in traditional analyses, should be considered when using the geomorphic methods for this or any other site in Maricopa County.

Channel conveyance below hydrographic apex

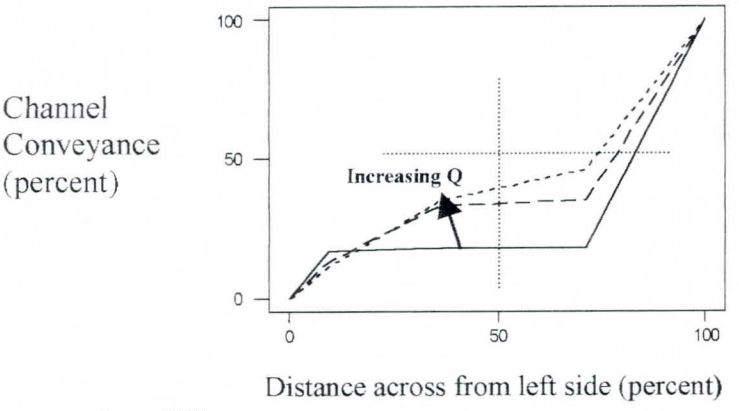
Cross sections used are shown in Figure 5.24. Cross section AA' is at elevation contour 1,362, section BB' is at contour 1,350 ft and section CC' is at contour 1,340 ft. Cross sections are along the contours because the flow typically is perpendicular to the ground slope. On the average, the ground slope is approximately the same as the hydraulic grade and both are perpendicular to the elevation contour. Cross sections AA', BB' and CC' are shown in Figure 5.24. The total channel conveyance corresponding to the contour elevations is 160,000, 45,500 and 68,300 ft^3/s for sections AA', BB' and CC' respectively. The distribution of conveyance across the fan is shown in Figure 5.29. High flow conditions depicted by the dotted line correspond to the 100-year flood.

Cross section AA'



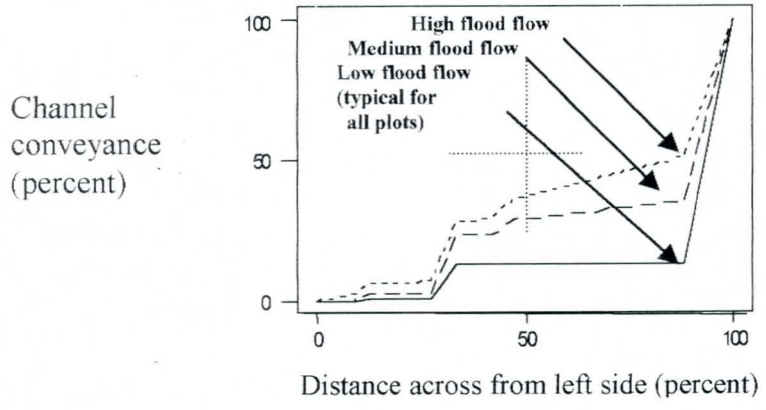
The distribution of channel conveyance (K) for the low, medium and high flows remains rather constant as discharge increases. Except for the brushy & rocky left bank, the distribution of K is rather uniform across the channel.

Cross section BB'



Water surface is assumed to be horizontal at the 1350-ft elev. contour. For low flows most of the K is on the right side with a small portion on the left side and none in the middle. The distribution of K becomes uniform as discharge increases.

Cross section CC'



Water surface is assumed to be horizontal at the 1340-ft elev. contour. For low flows most of the K is on the right side with a small portion in the left-center and none in the middle. The distribution of K does not change significantly as discharge increases.

Figure 5.29. Distribution of channel conveyance at cross sections below the hydrographic apex.

Flow paths and flow spreading

At cross section AA' the conveyance is rather evenly distributed across the channel for all floods. Thus, as the amount of flood discharge changes the distribution of discharge remains rather uniform and unchanging if the roughness, geometry and slope remain constant. The 100-year peak discharge of 5,030 ft^3/s is easily contained between the bedrock banks.

At cross section BB' most of the conveyance for small floods is in the right channel. As flood discharge increases the conveyance becomes more evenly distributed across the section. For bankfull conditions across the fan, the channel capacity is roughly 6,400 ft^3/s or 27 percent more than the 100-year discharge of 5,030 ft^3/s. This channel capacity is within the standard error of prediction for the 100-year flood (a peak discharge of 1,960 to 6,990 ft^3/s) that was discussed previously. Clearly, land within the entire cross section could be inundated by the 100-year flood. In addition, because the distribution of conveyance changes with discharge, it appears likely that floodwater can spread across the fan at section BB' in varying amounts.

At cross section CC' part of the floodflow becomes separated in the right channel and remains separated for high flows. The bankfull capacity is about 9,600 ft^3/s or about 90 percent more than the 100-year peak discharge. Overtopping of defined banks by the 100-year flood appears likely in the center and left side of the fan. Apparently a large portion of 100-year floodwater becomes separated and confined along the channel at the right of the fan.

For the assumed stable channel conditions, the hydraulic conditions represented by cross section BB' control the distribution of floodwater across the upper fan and thereby control the distribution of floodwater for the entire fan. The distribution of flow changes with increasing and decreasing discharge and the entire upper fan can be inundated. Thus, flow paths are somewhat unstable even for the highly idealized condition of stable geometry. Some flow path stability is evident at the right end of cross section CC' and when flow reaches this channel the flow is confined and separate from the flow to the left (east). for some distance downstream.

5.3.4.2 Infrequent fan building events

Evidence of recent large floods with large amounts of scour and fill was not found. The coarse sand and gravel sediment with a few cobbles and scattered boulders that is in the larger channels above the hydrographic apex is a large source of sediment for fan building.

5.3.4.3 Summary of 100-year flood conditions

The gravel pit effectively intercepts throughflow across the center of the fan (Figure 5.30). The amount of intercepted floodflow will increase with time because of the headcutting along the large throughflow channel. The potential volume in the pit for

Figure 5. 30 belongs here Orthophoto map of Skyline Wash site showing landforms, active and inactive areas and estimated 100-year flood areas

sediment deposition is more than 500 times the predicted annual sediment yield of the drainage basin using a method by Flaxman (1972). Flood peaks will be attenuated in the pit mostly because of detention storage in several low-lying areas. This means that the pit will effectively intercept water and sediment for many years. Floodwater and sediment entering the pit are redirected to the east side of the fan.

West side of fan

The throughflow area along the west side of the fan is subject to scour, fill, and channel avulsion. Much of this area will be inundated by a 100-year flood. This west area is very active.

Shadow area

Before development the approximately western two-thirds of the shadow area was active and the approximately the eastern one-third of the shadow area was inactive. The gravel pit has intersected floodwater that under natural conditions could have entered most of the shadow area below the pit (Figures 5.23 and 5.30). The dirt subdivision roads, however, have intersected some floodflow that under natural conditions would have remained to the west of the shadow area. As previously stated, these north-south and east-west roads have an impact on the distribution of floodflow in the shadow area at and south of McDowell Rd.

Soils in much of the shadow area are easily eroded where flow is concentrated. Some of the most severe recent erosion along subdivision roads in the shadow area is shown in Figure 5.31 (See Figure 5.30 for location of photograph). This erosion is from local runoff. Erosion along the east-west subdivision roads is much less severe than that shown in Figure 5.31. However, the potential erosion where floodflow is concentrated along roads in the shadow area (soil type AGB) is great.

During major flooding, throughflow floodwater and some sediment will be directed down the roads toward the east. Floodwater along the roads will be shallow but prolonged flooding may erode channels along the roads. Slopes along the rather smooth subdivision roadways exceed 1 percent and shallow flow velocities are near critical. The erosion potential is rather high and scour like that shown in Figure 5.31 could occur. Thus, appropriate engineering measures (for example a small levee) must be taken to prevent floodwater from entering this area if this area is to be classed as outside the limits of the 100-year flood.

Any engineering measures should allow for sediment deposition along the west side of the fan. Many acre-feet of sediment debris are expected during the 100-year flood. In addition, because this is an active alluvial fan, engineering measures should not impact the active areas outside the defined shadow area. As previously discussed, the gravel pit (considered a significant engineering measure) has altered the flow distribution across the fan. There is evidence this impact may not be large mostly because little throughflow has

entered the middle part of the fan for possibly 1,000 years (See Field and Pearthree, 1992).

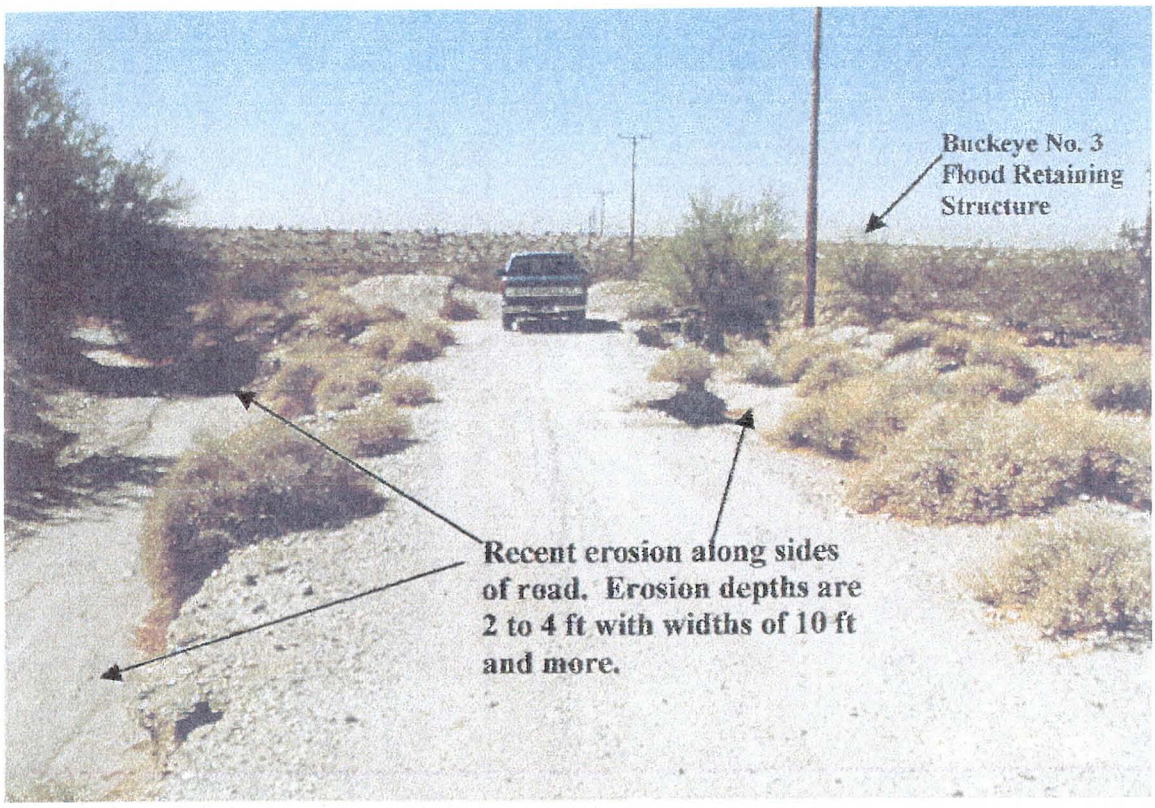


Figure 5.31. View looking south along subdivision road where local runoff has eroded channels into soil type AGB along the sides of the road

However, because of the nonstationary effect of the gravel pit such as the progressive headcutting at the inflow channel to the pit, engineering measures should provide an ample factor of safety to allow for unknown trends (See section 3.6 of manual). Over time, less floodwater is expected along the west side of the fan and more floodwater is expected along the east side of the fan as more floodwater is intercepted by the gravel pit as discussed in section 5.3.3.5.

East side of fan

The channel bed and banks north and east of the gravel pit also are eroding. The eroded bed and bank material along with the sediment yielded from the drainage basin also has been deposited along the east side of the fan below the gravel pit. Because of the filling of the channels generally below McDowell Rd. the low-lying inactive fan area (See Figure 5.23) on the southeast part of the fan is included in the 100-year flood limits. There is evidence this area has been inundated by large floods but there is no evidence of sediment deposition and associated flow path movement. Because floodwater is

progressively diverted to this area by the gravel pit (See section 5.3.3.5), some additional water and sediment are expected on the lower east side of the fan.

There is active headcutting along the defined channels that cross the fan to the north of the gravel pit. A new channel that cuts across to Coyote Wash is forming near the northern boundary of the 100-year flood limits. There is evidence of active bank erosion along the steep banks. This entire area is subject to high velocity floodwater and channel movement and formation.

Traditional 100-year flood boundaries in the 100-year flood zones shown in Figure 5.30 will not be reliable. Any flood elevations and flood limits computed from step backwater methods such as HEC-RAS are considered only rough approximations because of the uncertain flow paths and channel instability as previously discussed. Clearly, the distribution of flow below the hydrographic apex is uncertain and the channel geometry in the upper fan is unstable and changing.

The shadow area is not very active (Cross-hatched area in Figure 5.30). Much of the shadow area was not very active before the gravel pit was constructed. After the gravel pit was constructed and before the subdivision roads, the shadow area was inactive because there were no throughflow channels in the area. Because the subdivision roads divert throughflow from the active area to the west into the shadow area, the shadow area is considered inactive but subject to shallow flow and erosion where flow is concentrated. The erosion is minor at the present (August 1998) but a large flood may erode channels into the area and divert throughflow into the area from the west. This problem can be easily corrected with a small-engineered levee or other minor-engineered measure. The shadow area would then be subject to hazards common to steep-erodible tributary streams (Figure 5.31).

5.3.4.4 Rough check of the estimated 100-year flood conditions

A rough check of the assessment can be made using methods by Hjalmarson and Kemna (1991) described in section 8.3 of this manual. This check of the assessment uses a relation between flood-hazard degree and physiographic characteristics of the alluvial fan and the drainage basin. The USGS report *Flood Hazards of Distributary-Flow Areas in Southwestern Arizona* must be consulted for an explanation of the method and the following results:

> Equation 9 on page 54 of Hjalmarson and Kemna is appropriate for estimating the degree of flood hazard at the Skyline Wash alluvial fan site. The area of the distributary flow area (DFA) extends slightly beyond the retention dam in places but generally corresponds to the area between the hydrographic apex and the dam.
>
> $B = 6.21 - 0.62DD + 25.6MRDA - 1.19H + 2.70K$
>
> where
>
> B = flood-hazard degree,

DD = ratio of the area of the alluvial fan (DFA) divided by the area of the drainage basin,
MRDA= mean relief ratio of the drainage basin,
H = average contour sinuosity of four to six contours evenly spaced within the DFA, and
K= average contour-band widths of four to six contours evenly spaced within the drainage basin.

The values of the independent variables are DD = 2.0/3.93=0.51, MRDA = 0.124, H = 1.64 and K = 0.60. The estimate flood-hazard degree is B = 8.7.
According to Hjalmarson (1994) (See section 8.4 of this manual), a degree of 8 corresponds to a network of distributary channels where most ridges can be overtopped by the 100-year flood but the location of the channels is stable. Hjalmarson classed this flow condition as unstable because the distribution of flow across the DFA may be uncertain. This area closely corresponds to the relatively small stable area and the east part of the "shadow" area (Figure 5.23). A flood-hazard degree of nine corresponds to unstable channels or flow paths where most of the ridges may be overtopped and the location of the channels can change. (Table 1 of Hjalmarson, 1994). This area closely corresponds to the more active parts of the unstable area (Figure 5.23). The single rather simple numerical rating of 8.7 using methods by Hjalmarson and Kemna (1991) for sites in central and southern Arizona roughly supports the flood hazard assessment using methods given in this manual.

5.3.5 Brief comments on hazard assessment for adjacent landforms

5.3.5.1 Prospect Wash

Prospect Wash heads in the mountains to the west of the Skyline Wash basin. The deep-narrow channel crosses soil type 98 (Camp, 1986) at the toe of a mountain. The channel then crosses soil type TB (Hartman, 1977) to the west of the Skyline Wash fan. The relict fan material above the McDowell Rd. alignment is stable. The much younger torrifluvients (type TB) are not very consolidated and are stratified. The channel of Prospect Wash is deeply cut (gullied) into both landforms and downcutting in the torrifluvients is restricted in places by bedrock (Figures 5.30 and 5.32). The channel generally is incised more than 10 ft to about 1/2 mile above the retention dam where incision decreases to less than 4 ft. The channel meets the stable criteria given in this manual mostly because of the depth of incision (See for example Table 2.3 and Figure 2.3) and 100-year floodwater typically is confined in the channel. Traditional hydraulic methods (rigid-boundary flood analysis) will produce approximate flood elevations and boundaries. Setbacks are appropriate for management of 100-year flood hazards. A setback from the steep-erodible banks is important along this wash because there is active bank erosion in places.

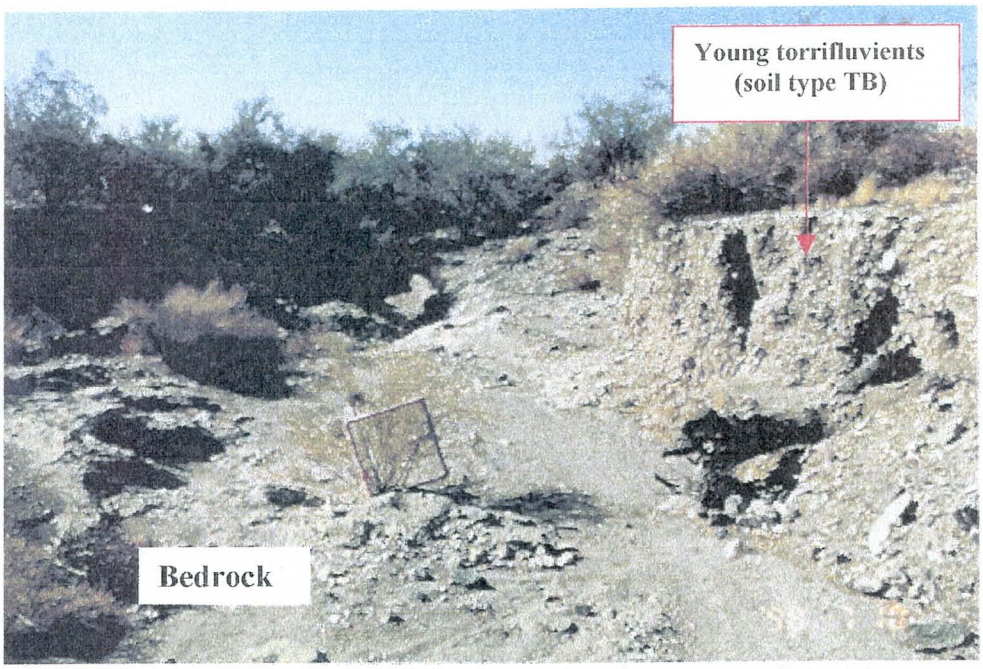


Figure 5.32. View looking south from below Watson Road at channel of Prospect Wash.

5.3.5.2 Coyote Wash

Coyote Wash heads in the mountains and crosses a relict fan (type 98) before joining the eastern channel of the Skyline Wash alluvial fan. The channel is rather stable and traditional hydraulic methods apply above the throughflow channel that forms the east boundary of the Skyline Wash alluvial fan.

5.3.5.3 Rattler Wash

Rattler Wash heads in the mountains to the east of the Skyline Wash drainage basin (Figure 5.19). The upper channels are in the bedrock mountains. Below the mountains the channel is deeply cut into relict fan (soil type 98) with cemented banks. Incision is more than 10 feet. Near McDowell Rd., incision and confinement are lost and the wash forms the east end of the active Skyline Wash alluvial fan. A few hundred feet above McDowell Rd. the channel is stable and traditional hydraulic methods are appropriate. Near McDowell Rd., the 100-year flood spreads over a wide area (soil types 3 and AGB).

5.3.5.4 Skyline Wash above hydrographic apex

At and to about 1/2 mile above the hydrographic apex the within the channel is unconsolidated and coarse (soil type 3) and is easily moved by the high flood velocities. There typically are several small channels along the watercourse and floodwater spreads

over wide areas at rather shallow and variable depths. Channel roughness varies across the channel mostly because of the scattered vegetation that in places is aligned parallel with the paths of flow (See Figure 6A of Phillips and others (1998) for the effects of aligned vegetation). This area is bounded by relict fan material (type 98) that is consolidated and somewhat stable. Because flow is generally confined, traditional hydraulic methods can be used to produce a rough estimate of the 100-year flood limits. The channel bed geometry is not stable and subdivision of cross-sections to define alpha (the velocity head coefficient) is complex. In general, channels can move between the consolidated banks of soil type 98.

About 1/2 mile above the hydrographic apex the channels are cut into relict fan (type 98) and are much narrower and stable. These channels typically are more than 10 ft. deep with rather stable banks. Flow typically is confined and traditional hydraulic methods can be used to define the limits of the 100-year flood. Setbacks should be used because the banks are steep and subject to some movement.

In the upper reaches above the relict fan, the channels are confined between steep bedrock canyons. The channels typically are incised and stable.

6
ACRONYMS

FEMA	Federal Emergency Management Agency
FCDMC	Flood Control District of Maricopa County
HEC	Hydrologic Engineering Center
NFIP	National Flood Insurance Program
NRC	National Research Council
NRCS	Natural Resources Conservation Service
COE	U.S. Army Corps of Engineers
USDA	U.S. Department of Agriculture
USGS	U.S. Geological Survey

7
GLOSSARY

(Source, unless otherwise indicated: Alluvial fan flooding, National Research Council, 1996)

Active Those locations where flooding, erosion, and/or deposition have occurred on the landform such as an alluvial fan in relatively recent time(the historic period), and probably will continue to occur on that part of the landform.

Alluvial Pertaining to or composed of alluvium, or deposited by a stream or running water.

Alluvium A general term for clay, silt, sand, gravel, or similar unconsolidated detritus material deposited during comparatively recent geologic time by a stream or other body of running water as a sorted or semisorted sediment in the bed of the stream or its floodplain or delta, or as a cone or fan at the base of a mountain slope; esp. such a deposit of fine-grained texture (silt or silty clay) deposited during time of flood.

Alluvial fan A sedimentary deposit at a topographic break, such as the base of a mountain front, escarpment, or valley side, that is composed of fluvial and/or debris flow sediments and which has the shape of a fan either fully or partly extended.

Alluvial fan flooding A type of flood hazard that occurs only on alluvial fans. It is characterized by flow path uncertainty so great that this uncertainty cannot be set aside in realistic assessments of flood risk or in the reliable mitigation of the hazard. An alluvial fan flooding hazard is indicated by three related criteria: (a) flow path uncertainty below the hydrographic apex, (b) abrupt deposition and ensuing erosion of sediment as a stream or debris flow loses its competence to carry material eroded from a steeper, upstream source area, and (c) an environment where the combination of sediment availability, slope, and topography creates an ultrahazardous condition for which elevation on fill will not reliably mitigate the risk.

Alluvial plain A level or gently sloping tract or a slightly undulating land surface produced by extensive deposition of alluvium, usually adjacent to a river that periodically overflows its banks; it may be situated on a flood plain, a delta, or an alluvial fan.

Alluvial plain flooding A type of flood hazard that occurs only on alluvial plains. It is characterized by sheet flow (Arizona State Standard 4-95), sediment deposition and channel erosion where the base-level stream has lowered.

Anastomosing The branching and rejoining of channels to form a netlike pattern.

Avulsion A sudden cutting off or separation of land by a flood or by an abrupt change in the course of a stream, as by a stream breaking through a meander or by a sudden changes in current, whereby the stream deserts its old path for a new one.

B horizon A mineral horizon of a soil, below the A horizon, sometimes called the zone of accumulation and characterized by one or more of the following conditions: an alluvial accumulation of humus or silicate clay, iron, or aluminum; a residual accumulation of sesquioxides or silicate clays; darker, stronger, or redder coloring due to the presence of sesquioxides- a blockly or prismatic structure.

Bajada A broad, continuous alluvial slope or gently inclined detrital surface, extending along and from the base of a mountain range out into and around an inland basin, formed by the lateral coalescence of a series of separate but confluent alluvial fans, and having an undulating character due to the convexities of the component fans- it occurs most commonly in semiarid and desert regions, as in the southwestern United States. A bajada is a surface of deposition, as contrasted with a pediment (a surface of erosion that resembles a bajada in surface form), and its top often merges with a pediment.

Calcic horizon A secondary calcium carbonate accumulation in the lower B-horizon that occurs as coatings on clasts and as lenses in fine-grained sediment matrices; it is at least 15 cm thick and contains 15 percent or more calcium carbonate.

Clast An individual constituent, grain, or fragment of a sediment or rock, produced by the mechanical weathering (disintegration) of a larger rock mass.

Contour crenulation An uphill kink or barb in a contour line but not a gentle bend of the line(Doehring, 1970). The uphill kink typically represents gullies or first order streams.

Crenulation Small-scale folding that is superimposed on larger-scale folding. Crenulations may occur along the cleavage planes of a deformed rock.

Debris flow A mass movement involving rapid flowage of debris of various kinds under various conditions; specifically, a high-density mudflow containing abundant coarse-grained materials and resulting almost invariably from an unusually heavy rain.

Dendritic A tree-like pattern, typical of most drainage networks.

Desert pavement Surfaces of tightly packed gravel that armor, as well as rest on, a thin layer of silt, presumably formed by weathering of the gravel. They have not experienced fluvial sedimentation for a long time, as shown by the thick varnish coating the pebbles, the pronounced weathering beneath the silt layer, and the striking smoothness of the surface, caused by obliteration of the original relief by downwasting into depressions.

Desert varnish A dark coating (from 2 to 500 microns thick) that forms on rocks at and near the Earth's surface as a result of mineral precipitation and eolian influx. The chemical composition of rock varnish typically is dominated by clay minerals and iron and/or manganese oxides and hydroxides, forming red and black varnishes, respectively. With time the thickness or the coating increases if abrasion and burial of the rock surface do not occur. As a result, clastic sediments on alluvial fan surfaces that have been abandoned for long periods of time have much darker and thicker coatings of varnish than do younger deposits.

Distributary flow Diffuse flow where there is a distinct channel fork at a outflowing branch of a stream. Areas with distributary flow typically are composed of channel forks, joins and outlets. Active alluvial fans and granite pediments typically are characterized by distributary flow (Hjalmarson).

Embayment A recess or indentation in the mountain front forming an open bay-like formation typically composed of sediment derived from the surrounding mountain slopes. This definition is for this manual and is in the context of the mountains and valleys of Maricopa County.

Eolian Pertaining to the wind; esp. said of rocks, soils, and deposits (such as loess, dune sand, sand some volcanic tuffs) whose constituents were transported (blown) and laid down by atmospheric currents, or of landforms produced or eroded by the wind, or of sedimentary Structures (such as ripple marks) made by the wind, or of geologic processes (such as erosion and deposition) accomplished by the wind.

Fluvial Of or pertaining to or living in a stream or river; produced by river action, as in a fluvial plain.

Hydrographic apex The highest point on an alluvial fan and some granite pediments in Maricopa County where flow is last confined.

Imbricated Overlapping or shingling of pebbles in the watercourse(H. W. Hjalmarson).

Inactive Those locations where flooding, erosion, and/or deposition have not occurred on a landform such as an alluvial fan in relatively recent time, and probably will not occur on that part of the landform.

Inselburg A prominant isolated residual knob or hill partly buried by the debris derived from and overlapping its slopes(Hjalmarson and Kemna, 1993).

Interfluve The area between rivers; esp. the relatively undissected upland or ridge between two adjacent valleys containing streams flowing in the same general direction.

Lithology The description of rocks, esp. sedimentary clastics and esp. in hand specimen and in outcrop, on the basis of such characteristics as color, structures, mineralogic composition, and grain size.

Loam A rich, permeable soil composed of a friable mixture of relatively equal and moderate proportions of clay, silt, and sand particles, and usually containing organic matter (humus) with a minor amount of gravelly material. It has somewhat gritty feel yet is fairly smooth and slightly plastic. Loam may be of residual, fluvial, or eolian origin, and includes many loesses and many of the alluvial deposits of flood plains, alluvial fans, and deltas.

Loamy Said of a soil (such as a clay loam and a loamy sand) whose texture and properties are intermediate between a coarse-textured or sandy soil and a fine-textured or clayey soil.

Morphology The external structure form, and arrangement of rocks in relation to the development of landforms; the shape of the Earth's surface; geomorphology.

Pediment A broad, flat or gently sloping, rock-floored erosion surface or plain of low relief, typically developed by subaerial agents (including running water) in an and or semiarid region at the base of an abrupt and receding mountain front or plateau escarpment, and underlain by bedrock (occasionally by older alluvial deposits) that may be bare but more often partly mantled with a thin and discontinuous veneer of alluvium derived from the upland masses and in transit across the surface. The longitudinal profile of a pediment is normally slightly concave upward, and its outward form may resemble a *bajada* (which continues the forward inclination of a pediment).

Piedmont (adj .) Lying or formed at the base of a mountain or mountain range; e.g. a *Piedmont* terrace or a *piedmont* pediment. (n.) An area, plain, slope, glacier, or other feature at the base of a mountain; e.g. a foothill or a bajada.

Probability The quantification of risk.

Relict A landform that has survived decay or disintegration (such as an *erosion remnant)* or that has been left behind after the disappearance of the greater part of its substance (such as a *remnant island).*

Relief ratio The average slope of a drainage basin; the ratio of maximum relief to basin length.

Riverine Pertaining to or formed by a river. Situated or living along the banks of a river;e.g. a "riverine ore deposit."

Rock varnish *See desert varnish.*

Scour (a) The powerful and concentrating clearing and digging action of flowing air or water, esp. the downward erosion by stream water in sweeping away mud and silt on the outside curve of a bend, or during time of flood. (b) A place in a stream bed swept (scoured) by running water, generally leaving a gravel bottom.

Sheetflood A broad expanse of moving, storm-borne water that spreads as a thin, continuous, relatively uniform film over a large area in an arid region and that is not concentrated into well defined channels; its distance of flow is short and its duration is measured in minutes or hours. Sheetfloods usually occur before runoff is sufficient to promote channel flow, or after a period of sudden and heavy rainfall.

Sheet flow An overland flow or downslope movement of water taking the form of a thin, continuous film over relatively smooth soil or rock surfaces and not concentrated into channels larger than rills. Also, the more restrictive definition and characteristics given in Arizona State Standard 4-95 (1995) can be used for alluvial plains of piedmonts.

Stable The relative state of the geometry and roughness of a channel, network of channels or landform where any changes of geometry and roughness can be set aside in realistic assessments of flood risk.

Stratigraphy (a) The branch of geology that deals with the definition and description of major and minor natural divisions of rocks (mainly sedimentary, but not excluding igneous and metamorphic) available for study in outcrop or from subsurface, and with the interpretation of their significance in geologic history: It involves interpretation of features of rock strata in terms of their origin, occurrence, environment, thickness, lithology, composition, fossil content, age, history, paleogeographic conditions, relation to organic evolution, and relation to other geologic concepts. (b) The arrangement of strata, esp. as to geographic position and chronological order of sequence.

Swale (a) A slight depression, sometimes swampy, in the midst of generally level land. (b) A shallow depression in an undulating ground moraine due to uneven glacial deposition. (c) A long, narrow, generally shallow, trough-like depression between two beach ridges, and aligned roughly parallel to the coastline.

Throughflow streams Are streams that head in the mountians and cross piedmonts to base level streams or to depositional landforms on lower piedmont slopes(H. W. Hjalmarson).

Topographic apex The head or highest point on an active alluvial fan.

Translatory wave A gravity wave that propagates in an open channel and results in appreciable displacement of the water in a direction parallel to the flow.

Uncertain distribution of flow Means that the distribution of flow at channel splits (forks) is not precisely known because the channel geometry may change with time and

because of hydraulic model limitations such as common assumptions of steady flow or a horizontal water level above the split (H. W. Hjalmarson).

Uncertain flow path Means that the perceived, historical channel or network of channels cannot be relied on to convey the base flood without the creation of new flow paths or the abandonment of existing flow paths.

Unstable The relative state of the geometry and roughness of a channel, network of channels or landform where any changes of geometry and roughness cannot be set aside in realistic assessments of flood risk.

Wash (a) A term applied in the western U.S. (esp. in the and semiarid regions of the south west) to the broad, shallow, gravelly or stony, normally dry bed of an intermittent or ephemeral stream, often situated at the bottom of a canyon; it is occasionally filled by a torrent of water. (b) Loose or eroded surface material (such as gravel, sand, silt) collected, transported, and deposited by running water, as on the lower slopes of a mountain range, esp. coarse alluvium.

8
MISCELLANEOUS METHODS

8.1 U. S. Geological Survey Professional Paper 352C

A technique for distinguishing between stable and unstable ephemeral stream-channel cross sections and the corresponding instability of flow paths associated with aggrading channels are given by Schumm (1960 and 1961). The technique requires measurements of channel width, depth and gradient and samples of channel bed and bank material with the computed weighted mean percent silt-clay at cross sections along the stream channel. The percent silt-clay is taken as that part of the sample smaller than the 200-mesh sieve of 0.074 mm. Cross sections should be located in uniform reaches that represent the channel gradient, width and depth along the stream. The method provides a suggestion that either aggradation of degradation is or has occurred (S. A. Schumm, written communication, Jan. 4, 1998).

Channel depth can be difficult to measure precisely because there may be recent scour or fill of the channel bed. Where there is recent scour along the banks the depth is the height above the channel profile to the top of the scour or deposited floodmarks, whichever is higher. Where there is recent fill along the channel the depth is the height above the channel profile (thalweg) to the first permanent surface or bank. Thus, the depth generally represents the distance from the thalweg to the height of the active channel within which the bed material is mobile. The stage of the channel-forming discharge (dominant discharge) is assumed to be at the top of the lowest bank. Channel width is the distance between the top of the banks. The width-depth ratio (F) is for the bank-full stage.

The percent silt-clay along the channel perimeter is determined as follows(Schumm, 1960, p. 18):

$$M = \frac{Sc(W) + Sb(2D)}{W + 2D} \qquad \text{(MM.1)}$$

where M = weighted mean percent silt-clay,
Sc = percentage silt-clay in channel bed (Schumm, 1960),
Sb = percentage silt-clay in banks,
W= channel width , and
D = channel depth.

The width-depth ratio (F) is related to the weighted mean percent silt-clay (M) as follows:

$$F = 255M^{-1.08} \qquad \text{(MM.2)}$$

The orderly plotting of the points well on the left or "degradation" side of the relation (Equation MM.2) indicates that channel degradation could be occurring (Figure MM.1). Points that plot well above the relation are characteristic of aggrading channels. For further information see page 63 of Schumm (1961).

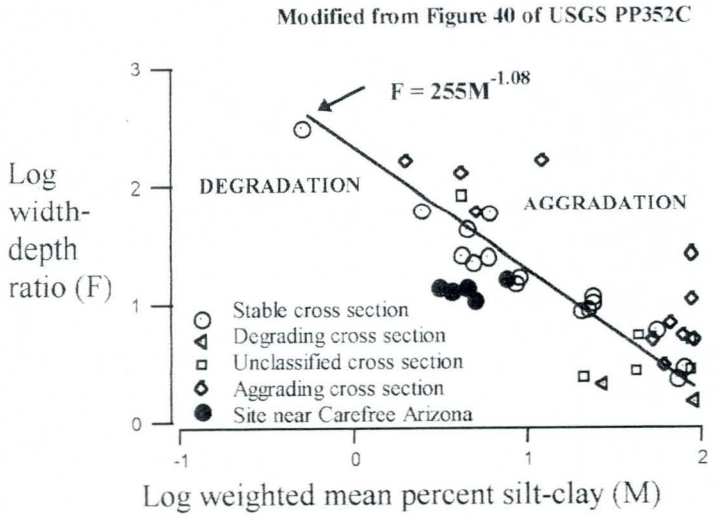


Figure MM.1. Relation between width-depth ratio (F) and weighted mean percent silt-clay (M) at sites with straight reaches of distributary channels.

The weighted mean percent silt-clay (M) is based on a mix of geologic processes. The bed material is actively being transported through the channels while the bank material is not mobile and was deposited a long time ago. Thus, the relation defined by equation MM.1 is empirical and might not be supported by process theory.

The silt and clay (Sb of equation MM.1) in ephemeral channel banks on piedmonts of Maricopa County is mostly from plastering. Relatively stable alluvial channel banks become plastered with suspended sediments left by infiltrating floodwater. The bank material grades from more silts and clays at and near the bank surface to coarser texture at depth perpendicular to the bank surface. For additional information on the effect of fine cohesive sediment at shallow depths along the wetted perimeter of the banks see Osterkamp and Harrold (1982). Clearly, the particle size distribution of fluvial deposits along the banks of alluvial channels may be used to assess flow path and channel stability.

Unstable channels of aggrading areas exhibit little plastering of suspended material along the wetted perimeter of channels. The texture of bank material of unstable channels grades little, if any, with depth perpendicular to the bank surface. The texture of the

shallow bank material is the same as the texture of the deep bank material. An application of this method is given in Hjalmarson and Tram(1995).

8.2 U. S. Soil Conservation Service TR-25

The U. S. Natural Resources Conservation Service developed a procedure to evaluate the stability of channels in cohesive soils in the western United States(USDA, 1977). This procedure, known as the tractive power approach, is specifically for channels in cohesive or partially cohesive lithified soils. In the tractive power approach the aggregate stability of soils related to erosion by floodwater is assessed by use of the unconfined compression test. The compressive strength of a soil sample is determined along with a computation of the tractive power of the floodflow and plotted on figure MM.2 (USDA, 1977, figure 6-15). Soils with a large compression strength relative to the tractive power of the streamflow can be expected to resist the erosive effects of the streamflow.

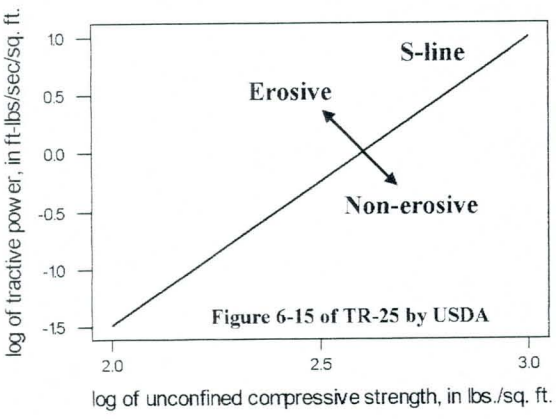


Figure MM.2 Unconfined compressive strength and tractive power as related to channel stability.

For this manual, vane shear measurements are suggested for *in place* shear strength of the bed and bank soils of the distributary channels. *In place* field tests are useful where it is difficult to obtain and transport undisturbed samples of the soils (USDA, 1977, p. 3-29). According to the USDA (1977, p.3-30) and Vanoni (1975, p. 109 and 112) the in situ shear strength can be determined using vane shear meters. A potential advantage of vane shear strength is that it is determined in the plane of the erosion forces as opposed to compression measurements that are made perpendicular to the shear forces exerted by floodflow. The shear strength is related to the unconfined compressive strength of the soil.

The tractive power approach is the result of limitations of tractive stress methods based on simple index properties determined for disturbed soils. Natural undisturbed soils have additional erosion resistance related to geological processes such as cementation in the B-horizon of developed soils and the presence of tree roots, grasses and cryptogamic crusts. According the U. S. Soil Conservation Service, the tractive power approach overcomes some of the limitations of the tractive stress methods.

The tractive force on a stream channel is the force of the water on the wetted perimeter. The unit tractive force is the average tractive force per unit of wetted area. In a uniform flow the tractive force is equal to the component of gravity acting on the body of water in the direction parallel to the stream channel. Briefly, the total tractive force is as follows:

Tractive force = wALS = lb/ft^3(ft^2)(ft)(ft/ft) = lb

where w = unit weight of water, in lb/ft^3,
A = wetted area, in ft^2,
L = length of channel reach, in ft, and
S = channel slope.

Unit tractive force = T_O = wALS/PL = wRS = lb/ft^3(ft)(ft/ft) = lb/ft^2

where R = hydraulic radius, in feet = A/P.

The unit tractive force is also the tractive stress. The product of the mean velocity and the tractive stress is the tractive power. It is important to note that the tractive power is for a unit area (1ft^2) of the wetted perimeter as shown by the following units.

TP = T_OV = lb/ft^2(ft/sec) = ft-lb/sec/ft^2

where V = mean velocity, in ft/sec.

The tractive power for cross sections was determined using methods in TR-25 (U. S. Department of Agriculture, 1977, p.6-33). A kinematic viscosity of 1.42 x 10^{-5} (water temperature of 50°F) may be used.

As stated previously, the compressive strength of the in situ bed and bank material may be estimated using measured shear strength by a vane meter. Several measurements of shear should be made on both banks and on the bed at the channel reach of interest. The average shear strength for bare soil at each site is suggested. According to two U.S. Soil Conservation Engineers (oral communication with Gary Conoway, Portland, Oregon and John Harrington, Phoenix, Arizona) the use of unconfined shear strength in place of unconfined compression strength for the relation given in Figure MM.2 (USDA, 1977, figure 6-15) adds a factor of safety of about 2 (based on the Mohr's circle diagram for vertical and lateral pressures) which is useful for design purposes. Because shear

strength, which is half the value of the compression strength, was used for the analysis a conclusion that the banks are stable is considered very conservative. An application of this method is given in Hjalmarson and Tram (1995).

There is a marked difference in the shear stress of typical channel beds and banks of piedmont streams in Maricopa County. The shear strength of the channel bed can be about 1/5 the shear strength of the banks. Many beds of the distributary channels are erosive but scour is restricted at depth by underlying cemented sediments.

The shear stress of grassed banks or banks covered with cryptogamic crusts may be 50 percent more than the shear stress of uncovered banks. The increased shear strength associated with the grass and crusts may be partially offset by the decrease of shear strength associated with soil wetting. Because floods are short lived, any grasses, trees and cryptogamic crusts along the banks afford some protection against erosion.

8.3 USGS Water -Resources Investigations Report 91-4171

The intensity of flood hazard on active and inactive alluvial fans and weathered pediments with distributary channel networks is related to flow path stability using regression techniques. A wide variety of flood intensity is depicted in *Flood hazards of distributary-flow areas in southwestern Arizona* by Hjalmarson and S. P. Kemna (1991)

Abstract: Distinguishing features of flood hazards of distributary-flow areas in southwestern Arizona were studied using hydrologic and physiographic characteristics. These characteristics were defined for 39 sites that included both areas with a single diffluence (separation of a single channel) and two channels separated by a high ridge as well as more complex areas where active alluvial fans spread floodflow in an erratic manner. Areas drained above the primary diffluences (apices of alluvial fans) ranged from 0.48 to 95.9 square miles and the distributary-flow areas ranged from 0.32 to 38.8 square miles.

Primary diffluences (hydrographic apices as defined in this manual) can be identified by using 7.5-minute topographic maps, aerial photographs and reconnaissance, soils and geologic maps, and field reconnaissance. A procedure for consistently identifying the primary diffluence(hydrographic apex as used in this manual) is based on established physiographic and hydrologic principles. Major factors used to identify and categorize distributary flow areas below the primary diffluences include (1) differences in vegetation density across distributary-flow areas; (2) differences in soil color across distributary-flow areas; (3) drainage texture of some distributary-flow areas, pediments, and inactive alluvial fans; and (4) the random nature of channel links.

The flood-hazard degree for five types of distributary flow is based on the potentially erratic paths of floodflow. A higher hazard degree (or intensity) was assigned to areas where the potential for lateral relocation of flow paths was large. The flood-hazard degree is related to physiographic characteristics such as the size and number of drainage

channels of the distributary-flow area, the slope of the drainage basin, and the average contour-band width of the drainage area.

8.4 USGS Water -Resources Investigations Report 93-4169

An illustrative account of various landforms with distributary-flow channels on piedmonts of Maricopa County. Several photographs of sites are given in *Potential Flood Hazards and Hydraulic Characteristics of Distributary-Flow Areas in Maricopa County, Arizona* by Hjalmarson (1994).

Abstract: Flood hazards of distributary-flow areas in Maricopa County, Arizona, are related to the stability of flow paths, which can be defined using topographic maps, aerial photographs of distributary-flow areas, soil characteristics, and channel cross sections. Five distributary-flow areas that represent the range of flood-hazard degree associated with flow-path stability are discussed in this report. At sites where flow paths are unstable, channels are commonly perched above adjacent low-lying land, which is inundated by floodwaters that overtop the banks. Sites with stable paths of flow have abundant mature paloverde trees and other vegetation along distributary channels that are incised into the landform. Floodflow is apportioned through a network of distributary channels at one site using channel conveyance-slope methods.

The 2-year flood can transport the noncohesive bed material in the main channel at the primary diffluence of the sites selected for the study. The channel competence represented by the maximum grain size that could be moved at the peak discharge of the 2-year flood is typically at least twice that needed to move 90 percent of the bed material.

The average value of width, depth, and velocity exponents of the hydraulic-geometry relations at the primary diffluences of the sites are similar to theoretical exponents for streams with cohesive bank material and the average exponents of stream channels in other areas in the United States. Values of the exponent of channel width, however, show a high degree of unexplained scatter, thus the use of average hydraulic-geometry relations is considered inappropriate for characterizing flood hazards for specific distributary-flow areas in Maricopa County.

No evidence has been found that supports the use of stochastic modeling of flows or flood hazards of many distributary-flow areas. The surface of many distributary-flow areas is stable with many distributary channels eroded in the calcreted surface material. Many distributary-flow areas do not appear to be actively aggrading today, and the paths of flow are not changing.

8.5 Sediment grain size along an idealized fan

Alluvial fan characteristics are related to the water and sediment that enters the active fan at the hydrographic apex. Fan characteristics are also related to the remobilization of fan sediment from rainfall and wind directly on the fan surface. Active fans tend to adjust or reach a state of **equilibrium rate of aggrading** over long periods. Over long periods the shear stress over the fan surface may reach this equilibrium state where there is no net change of aggradation rate. Thus, shear stress on the surface is a function of water and sediment entering and leaving the active fan. Because of the wide range of water and sediment discharge, typically from thunderstorms, the values of shear stress(represented by the value of D_{50}) and discharge(q) are the result of time integration over the wide range of storm values. These conditions, which form the basis of this idealized method, are similar to commonly used conditions for channel morphology studies (Osterkamp, Lane and Foster, 1983) and are similar to considerations for channel stability given by the COE (1990) as follows:

In considering channel stability, continuity of transport over a year or more is generally more important than in one event lasting a few days or hours. To compute transport over a period of time, a transport rate vs. discharge table is normally combined with a flow-duration table. It is important, however, not to overlook the low-frequency events. In some rivers a low-frequency flood event may transport as much sediment as several years of ordinary flows.

The distribution of sediment grain size along an active alluvial fan may be roughly estimated using an allowable mean velocity relation (COE, 1990) for the ideal fan shown in Figure MM.3. The bounds of the fan are represented by a simple segment of a circle. The slope along the radius is uniform and the elevation along each arc is constant. Also, the surface roughness is uniform over the entire fan area and roughness does not change with flow depth. Water flood processes are assumed.

The water flood conditions for the fan are first estimated (Equations MM.3-MM.6). An expression for initial sediment movement is then incorporated in the analysis (Equation MM.7). The median grain size at initial sediment movement, that is a function of shear stress criteria and grain roughness (COE, 1990), represents the material along the fan.

The area of the fan (A_f) shown in Figure MM.3 is:

$$A_f = L^2\alpha/2 \qquad \text{(MM.3)}$$

where L = radius of fan in feet and
α = angle of fan in radians. Also,
ℓ = distance below apex.

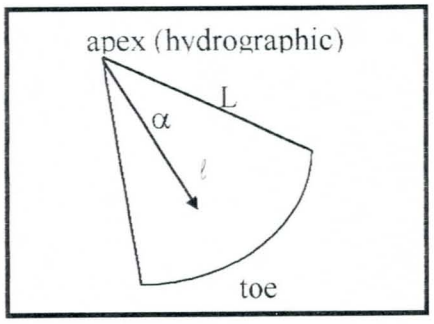


Figure MM.3. Ideal active alluvial fan.

The length of arc (wetted perimeter) across the fan at distance ℓ from the apex is:

$$WP = \ell\ \alpha\ /4 \qquad \text{(MM.4)}$$

where WP =$L\alpha/4$ at the fan toe.

Manning's equation is assumed to define the hydraulic conditions with uniform flow depth(h) and velocity(V) across the fan arc. For this ideal fan, both V and h are a function of the distance from the apex. Using Manning's equation,

$$V = q/A = (1.486/n)\ R^{2/3}\ S^{1/2}$$

where n = Manning roughness coefficient,
q = representative discharge over a long period of time,
A = area of cross section along arc,
R = hydraulic radius = h for wide-shallow flow, and
S = slope.

For a uniform n and S and substituting h for R,

$$V = [(1.486/n)\ S^{1/2}]\ h^{2/3} \qquad \text{(MM.5)}$$

Combining equations MM.4 and MM.5 with q = AV = WP h V and rearranging

$$\ell = [4/\alpha\ ]\ [q\ /\ [(1.486/n)\ S^{1/2}]\ ]\ \ h^{-5/3}$$

and rearranging

$$h = [\alpha/4((1.486/n)\ S^{1/2}\ )/q)]^{-3/5}\ \ell^{-3/5} \qquad \text{(MM.6)}$$

An relatively simple expression for allowable mean velocity (V) for initial sediment movement in terms of depth (h) and grain size is used. The following is equation 2.3.7 of Stability of Flood Control Channels(COE, 1990):

$$V_a = 10.66\, h^{1/6}\, D_{50}^{1/3} \qquad \text{(MM.7)}$$

where V_a = allowable mean velocity in feet per second and
D_{50} = grain size in feet

The median grain size (D_{50}) is assumed to be representative of the of the sediment mixture. Combining equations MM.6 and MM.7

$$D_{50} = 0.0027\, n^{-3}\, S^{3/2}\, [\, [\alpha/4((1.486/n)\, S^{1/2})/q)]^{-3/5}\, \ell^{-3/5}]^{3/2} \qquad \text{(MM.8)}$$

If there is no loss of floodflow to infiltration then n, S, α, and q are constant. The discharge (q) is equal to the discharge at the apex (Q). The relation between D_{50} and ℓ is shown by the dashed line in Figure MM.4.

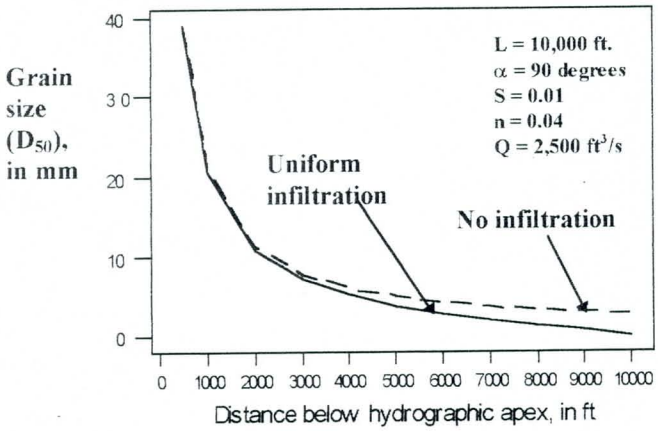


Figure MM.4. Distribution of representative grain size (D_{50}) along an idealized active alluvial fan.

If floodflow is lost to infiltration along the fan surface and the loss is a function of fan area along the length of the ideal fan, then q = Q - constant $(\alpha/2)\, \ell^{2}$ and q = Q at ℓ = 0 and q = 0 at ℓ = L. This assumption of no flow past the fan toe represents an opposing extreme condition to that used in the previous example (dashed line of Figure MM.4). Thus, the constant = $2(Q/\alpha)\, L^{-2}$ and

$$q = Q(1 - (\ell / L)^2) \qquad \text{(MM.9)}$$

Substitution of equation MM.9 in equation MM.8 produces a relation like the solid line shown in Figure MM.4.

The lessening of grain size along active alluvial fans and many alluvial plains has been recognized for many years. Thus, the idealized relations show nothing new in this regard. However, some insight may be gleaned into the effects of development on active fans. For example, if the infiltration along an active fan is reduced with all other factors kept constant, the grain size along the fan must increase in order to maintain the equilibrium rate of aggrading along the fan. This increase, that is greatest at the fan toe, means that coarser fan material is needed to offset the additional stream power in order to maintain a state of equilibrium. The effects of changing other factors such as fan roughness and active fan width (angle α) on the grain size of the fan may also be examined using this technique (See Figure MM.5). The user is reminded that the grain size characteristics are for the long-term equilibrium rate of aggradation based on the family of floodflows represented by the discharge (q).

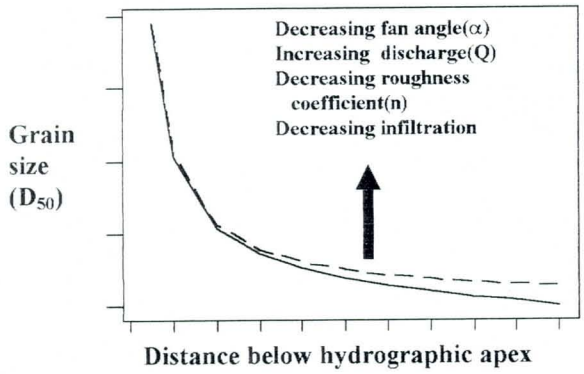


Figure MM.5. Direction of shift in relation between grain size and distance below hydrographic apex to maintain equilibrium rate of aggrading for decreasing fan angle(α), decreasing Manning roughness coefficient(n), increasing discharge(Q) and decreasing infiltration for ideal active alluvial fan.

9
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