Re-analysis of Alluvial Fans No. 5 and No. 6 in Scottsdale and Phoenix, Maricopa County, Arizona based on 2003 FEMA Alluvial Fan Guidelines

Shimin Li, Ph.D., P.E., Senior Civil Engineer
Bing Zhao, Ph.D., P.E., Branch Manager
Engineering Application Development and River Mechanics Branch
Engineering Division
Flood Control District of Maricopa County (FCDMC)
2801 W. Durango Street
Phoenix, Arizona 85009

September 24, 2014

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Shimin Li

Registered Professional Engineer (Civil) CERTIFICATE NO. 35160 SHIMIN LI Date Signed 9/24/14 ARIZONA, U.S.A.

Expires 12/31/15

Registered Professional Engineer (Civil) CERTIFICATE NO. 32345 BING ZHAO Date Signed 9/25/14 ARIZONA U.S.A.

Expires 12/31/2016

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Appendix 1. Typical Alluvial Fan Morphology (Cottonwood Canyon, Death Valley, California) 60

Shimin Li

Registered Professional Engineer (Civil)
CERTIFICATE NO.
35160
SHIMIN LI
Date Signed 9/24/15
ARIZONA, U.S.A.
Expires 12/31/15

Registered Professional Engineer (Civil)
CERTIFICATE NO.
32345
BING
ZHAO
Date Signed 9/25/15
ARIZONA U.S.A.
Expires 12/31/2016

1. Introduction

Six piedmont areas in Scottsdale and Phoenix, Maricopa County, Arizona were delineated as alluvial fan flooding areas by FEMA in 1993 (FEMA, 1995). The areas are located north of the Central Arizona Project Canal between the McDowell Mountains and Cave Creek (Figure 1). The delineation was based on the 1991 FEMA methodology (FEMA 37) for analyzing areas subject to alluvial fan flooding (Guidelines and Specifications for Study Contractors, 1991). The delineated areas are shown as Zone AO on the FIRM (Figure 1).

In 2003, FEMA published a new methodology for alluvial fan delineation (Guidelines and Specifications for Flood Hazard Mapping Partners, Appendix G: Guidance for Alluvial Fan Flooding Analyses and Mapping, FEMA, April, 2003). The 2003 FEMA methodology is the latest guidelines for alluvial fan delineation. It is a three-stage approach: (1) Stage 1 – recognizing and characterizing alluvial fan landforms; (2) Stage 2 – defining active and inactive areas of erosion and deposition; and (3) Stage 3 – defining the 100-year flood within the defined active and inactive areas by deterministic, probabilistic or geomorphic methods. The purpose of this study is to re-analyze two alluvial fans (Fan 5 and Fan 6) based on the 2003 FEMA's three-stage approach. The following sections are arranged based on the 2003 FEMA guidelines (FEMA, April, 2003).

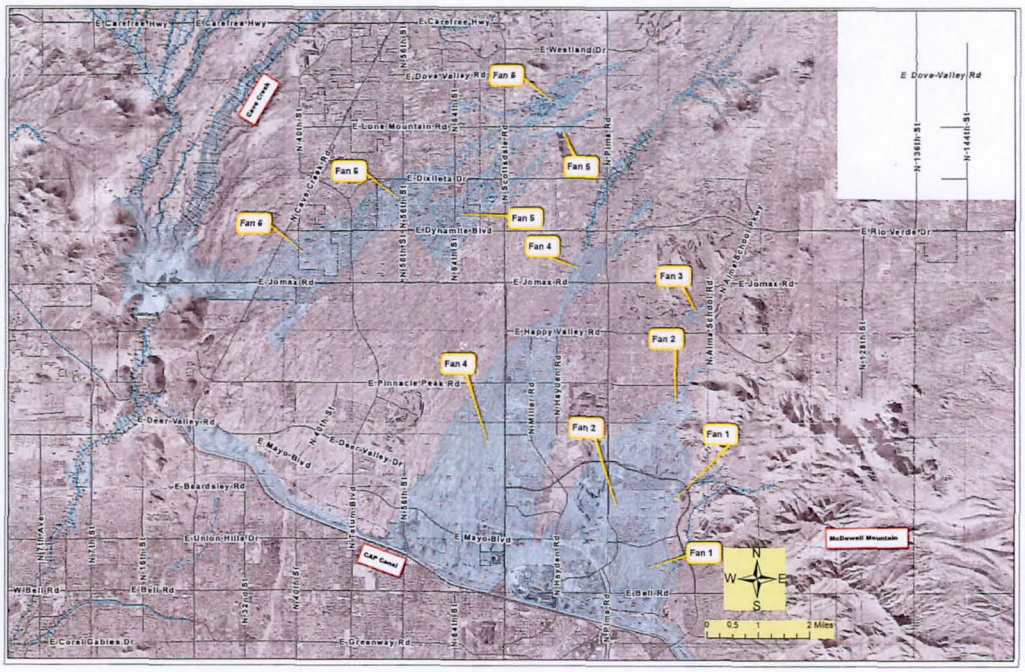


Figure 1. Previously Delineated Alluvial Fans in Scottsdale, Maricopa County, Arizona (FEMA, 1995).

2. Stage 1 -- Recognizing and Characterizing Alluvial Fan Landforms

In Stage 1, an assessment is performed for the previously delineated Fan 5 and Fan 6 to determine if the areas are alluvial fan landforms. This assessment includes the determination of four critical requirements for alluvial fan landform. The four critical requirements are composition, morphology, location, and toe/lateral boundaries. These four critical requirements must be all met based on the 2003 FEMA methodology by using the data from surficial geology, geomorphology, topographic data, aerial photos, and soil maps.

2.1 Composition

Based on the 2003 FEMA methodology, alluvial fans are landforms constructed from deposits of alluvial sediments or debris flow materials. These deposits, "alluviums", are an accumulation of loose, unconsolidated to weakly consolidated sediments. Alluvium refers to sediments transported by either stream flow or debris flows. Geologic maps and field reconnaissance can be used to determine whether the land form is composed of alluvium.

Our determination of the composition of Fan 5 and Fan 6 is based on the Arizona Geological Survey (AZGS) geologic map which is available from AZGS web site (AZGS, 2000a). Figure 2 shows the geologic map units overlaid with FEMA floodplains. Fan 5 and Fan 6 are within the red outline (Zone AO). As can be seen from Figure 2, most of Fan 6 area is in the geologic map unit of Qy (white) and most of Fan 5 area is in the geologic map unit of Qm (yellow). A small area is in Yg unit (brown). These three map units are described as follows (AZGS, 2000b):

Qy: Holocene Surficial Deposits (0-10 ka). Unconsolidated deposits associated with modern fluvial systems. This unit consists primarily of fine-grained, well-sorted sediment on alluvial plains, but also includes gravelly channel, terrace, and alluvial fan deposits on middle and upper piedmonts.

Qm: Late and Middle Pleistocene Surficial Deposits (10 – 750 ka). Unconsolidated to weakly consolidated alluvial fan, terrace, and basin-floor deposits with moderate to strong soil development. Fan and terrace deposits are primarily poorly sorted, moderately bedded gravel and sand, and basin-floor deposits are primarily sand, silt, and clay.

Yg: Middle Proterozoic Granitic Rocks (1400-1450 Ma). Mostly porphyritic biotite granite with large microcline phenocrysts, with local fine-grained border phases and aplite. Associated pegmatite and quartz veins are rare. This unit forms large plutons, including the Oracle Granite, Ruin Granite, granite in the Pinnacle Peak – Carefree area northeast of Phoenix, and several bodies west of Prescott.

Based on above definitions for Qy and Qm, the composition of Fan 5 and Fan 6 areas is mostly loose, unconsolidated or weakly consolidated sediments. Therefore, the Stage 1 composition criterion is met.

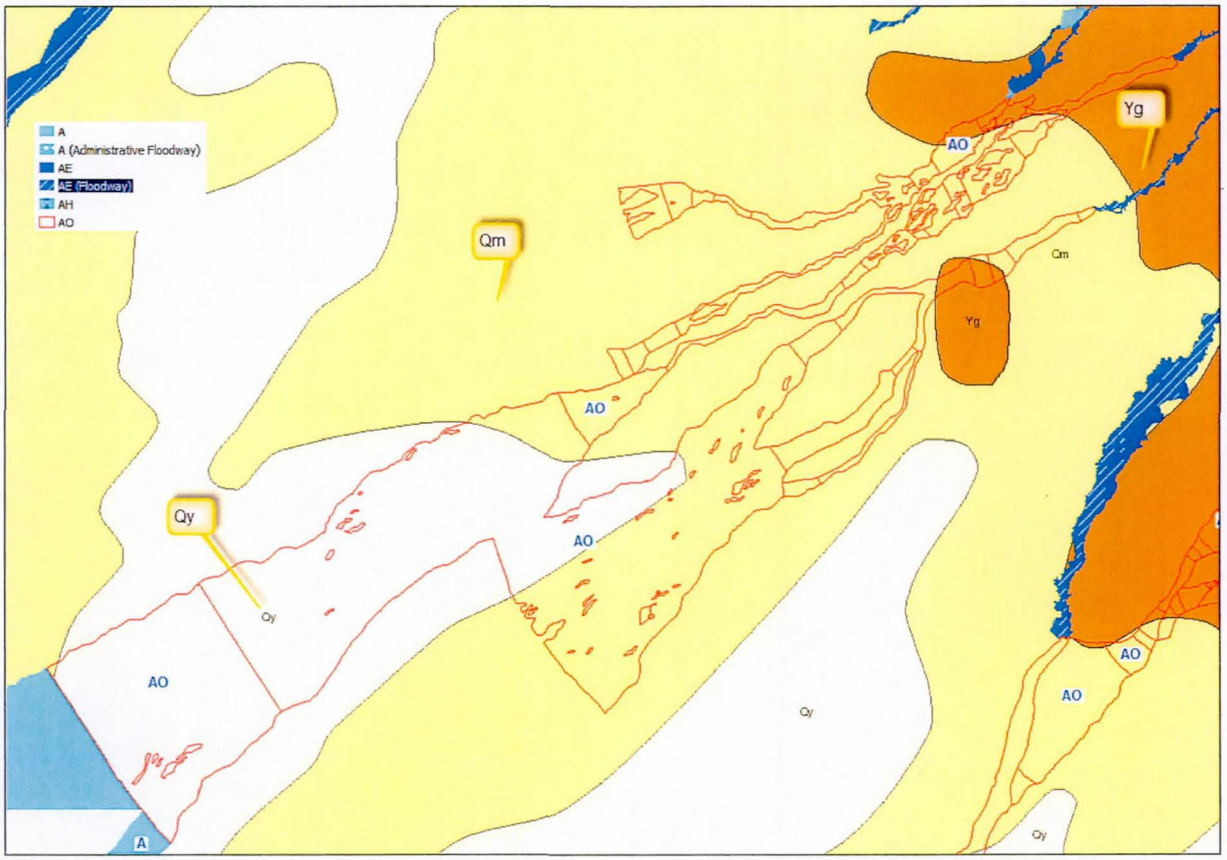


Figure 2. AZGS Geologic Map for Fan 5 and Fan 6 Areas

2.2 Morphology

Based on the 2003 FEMA guidelines, alluvial fans are landforms that have the shape of a fan, either partly or fully extended. Flow paths may radiate outward to the perimeter of the fan; however, drainage may exhibit a range of patterns such as dendritic, anastomosing, and distributary. Topographic maps and aerials photos can be used to assess this criterion.

In this section, the morphology of Fan 5 and Fan 6 is assessed based on topographic data and aerial photos to determine if the plan view has a fan shape. As shown in Figure 3 and Figure 4, Fan 5 and Fan 6 do not appear to have a typical fan shape based on the 10-ft index topographic contours (mapping date: 6/28/2010, NAVD88, 2-ft contour accuracy). The flow paths on Fans 5 and 6 do not appear to radiate outward to the perimeter of the fan because there is no curvature for the topographic contour lines. It may be noted that if a much larger area between Cave Creek and McDowell Mountain is considered, the topographic contour lines appear to have curvatures.

Since the area in Fan 5 and Fan 6 has gone through housing development and the current aerial photos cannot show the land form, the 1953 aerial photos as well as the 2013 aerial photos are used to show the land form. As shown in Figure 5 and Figure 6, the land form does not display a clear fan shape. Figure 7 and Figure 8 show the 2013 aerial photo without/with floodplains. As can be seen, no fan shape can be found.

Therefore, Fan 5 and Fan 6 do not have typical alluvial fan landform morphology. A typical alluvial fan landform with a fan shape can be found at Cottonwood Canyon, Death Valley, California (Appendix 1).

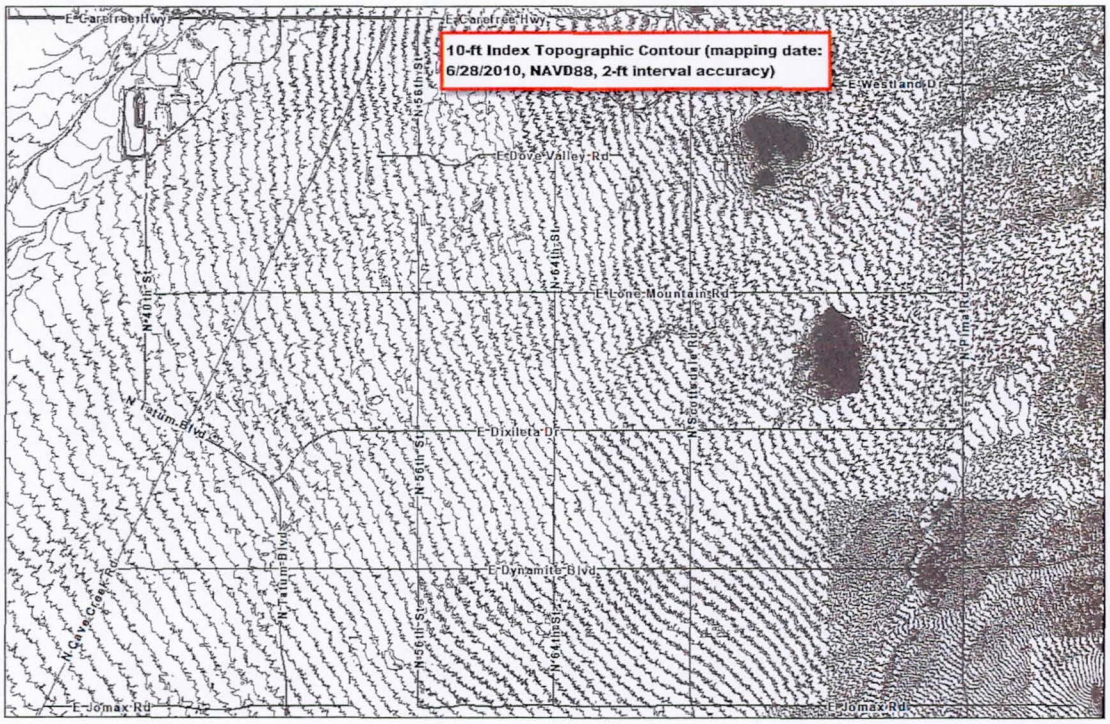


Figure 3. Topographic Data at Fan 5 and Fan 6.

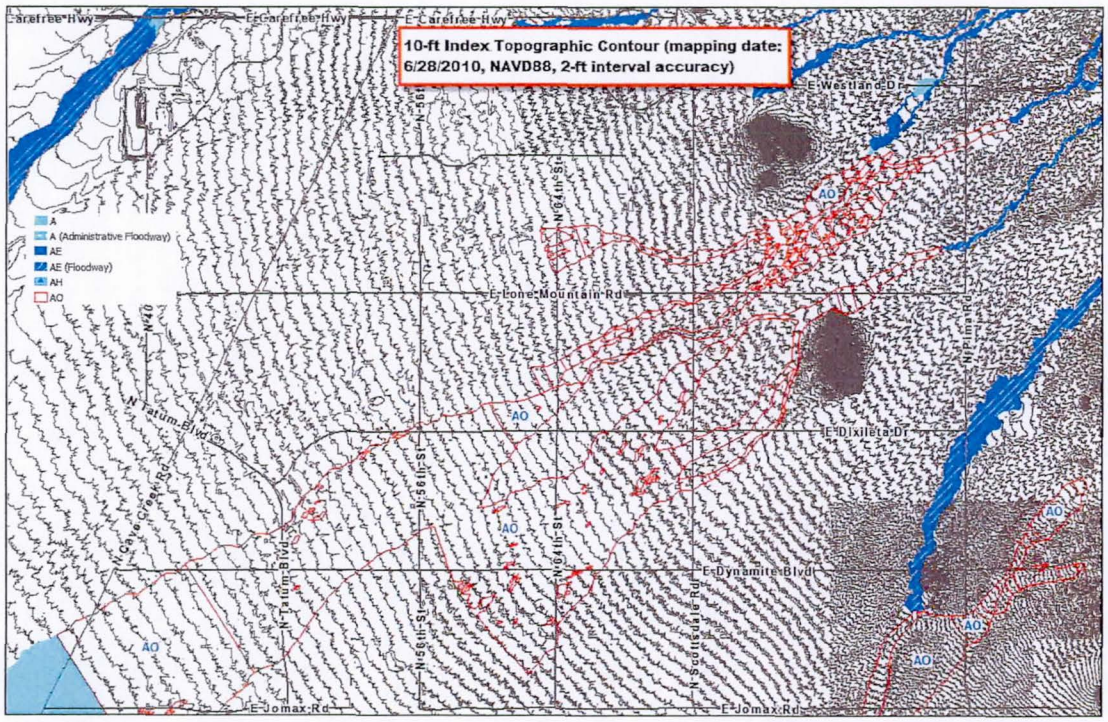


Figure 4. Topographic Data with Floodplains at Fan 5 and Fan 6.

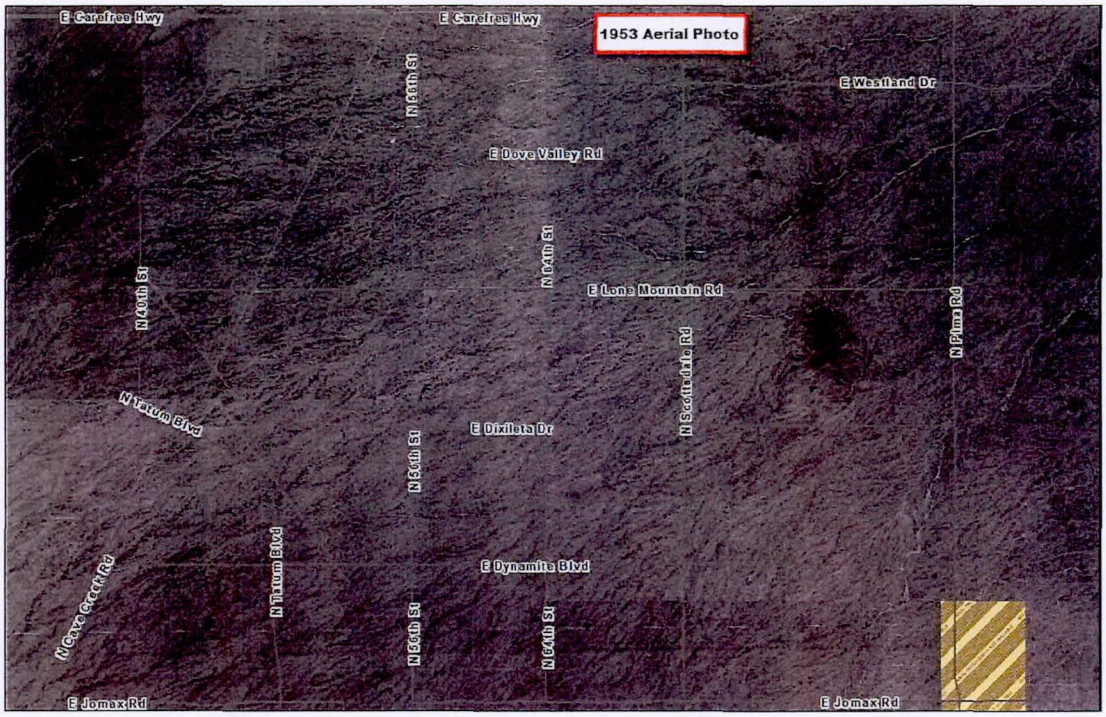


Figure 5. 1953 Aerial Photo.

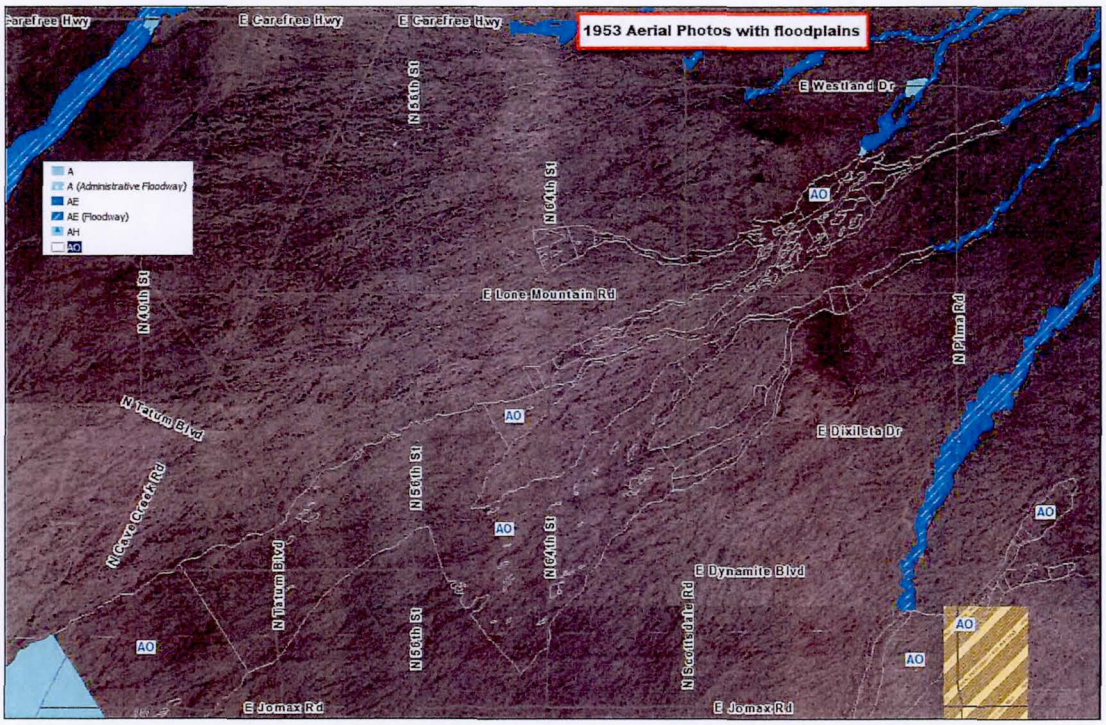


Figure 6. 1953 Aerial Photo with Floodplains.

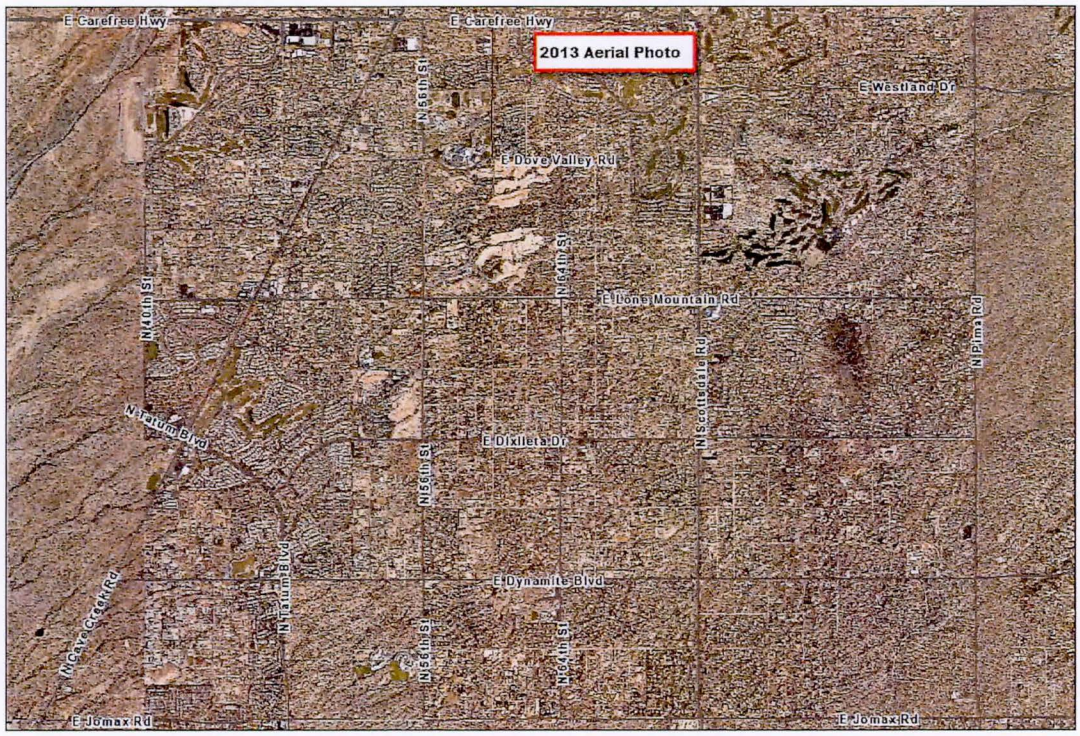


Figure 7. 2013 Aerial Photo

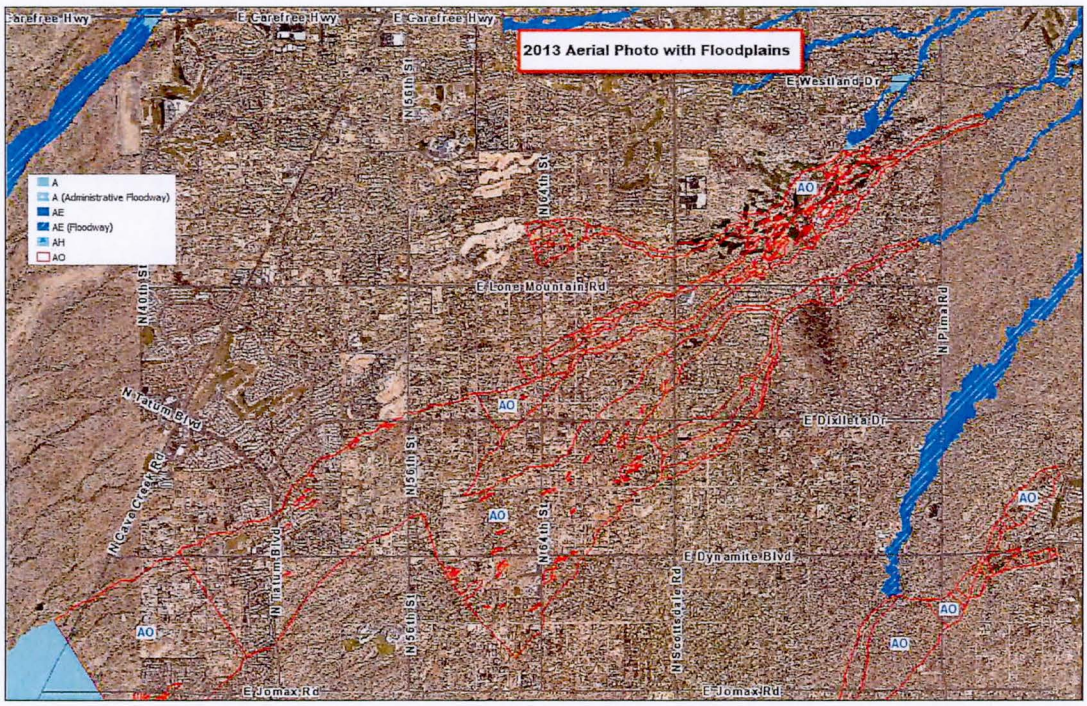


Figure 8. 2013 Aerial Photo with Floodplains

2.3 Location

Based on 2003 FEMA guideline, alluvial fan landforms are located at a topographic break where long-term channel migration and sediment accumulation become markedly less confined than upstream of the break. This locus of increased channel migration and sedimentation is referred to as the alluvial fan apex. The topographic apex is at the extreme upstream extent of the alluvial fan landform. This location is typically at the mountain front. The hydrographic apex is the highest point on the alluvial fan where there exists physical evidence of channel bifurcation and/or significant flow outside the defined channel; its location may be either coincidental with, or at a point downstream of, the topographic apex. The hydrographic apex may depend on the discharge and may vary with the magnitude of the flooding event.

This section will determine if a topographic apex and a hydrographic apex exist for the areas of Fans 5 and 6 based on the above criteria. Figure 9 shows drainage sub-basins that drain to Fan 5 and Fan 6's hydrographic apexes (DEI, 2005). The black polygons on Figure 9 represent drainage sub-basins that drain to Fan 5 and Fan 6. The red polygons represent the upper portion of Fan 5 and Fan 6. The most upstream tips of the red polygons represent the hydrographic apexes. As can be seen from Figure 9, no topographic apex can be assigned for Fan 5 and Fan 6 because Fan 5 and Fan 6 are not near the mountain front.

The identified hydrographic apexes for Fan 5 and Fan 6 are questionable because the FEMA definition clearly indicates that hydrographic apex should be the highest point on the alluvial fan where there exists physical evidence of channel bifurcation. Bifurcations are essentially channel splits. Figure 10 and Figure 11 show that there are more bifurcation

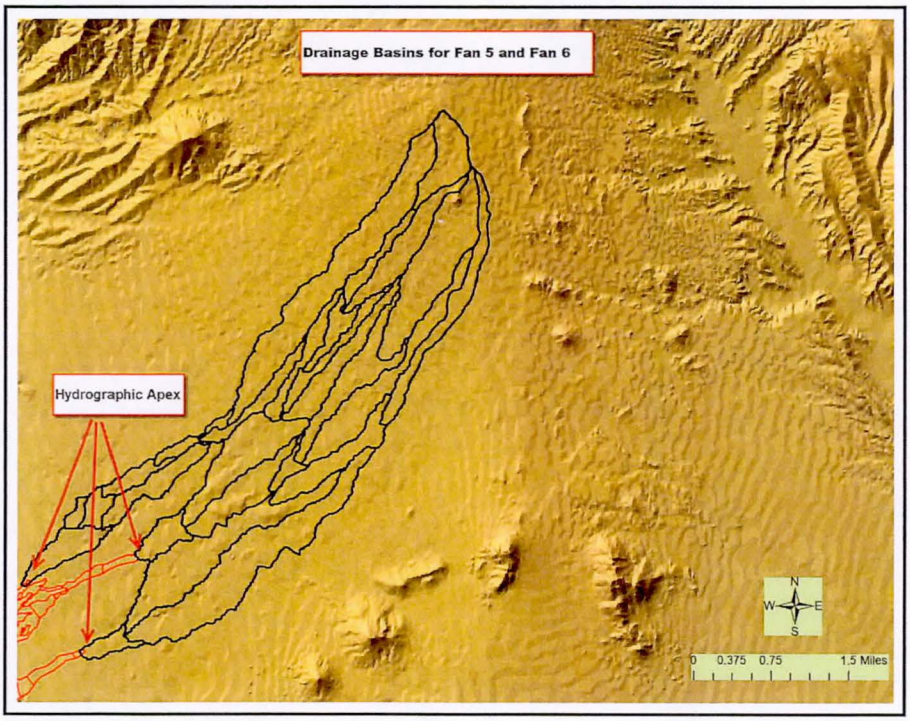


Figure 9. Drainage Basins for Fan 5 and Fan 6 Apexes.

Figure 10. Stream Patterns upstream of Hydrographic Apexes of Fan 5 and Fan 6.

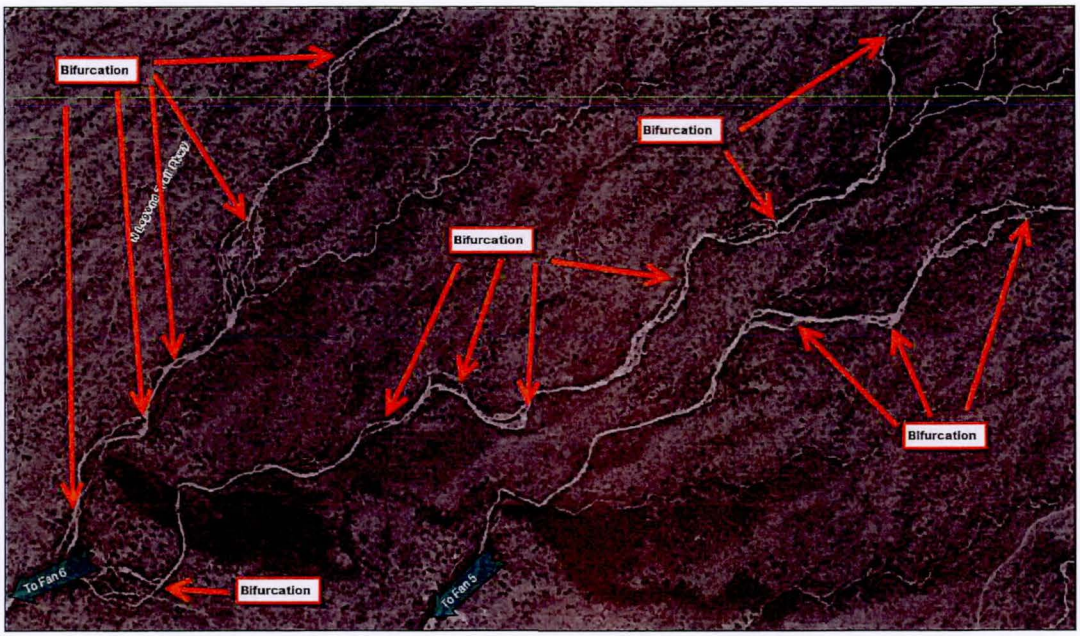


Figure 11. Bifurcations upstream of Hydrographic Apex of Fan 5 and Fan 6.

points upstream of Fan 5 and Fan 6 hydrographic apexes. The highest point should be considered as hydrographic apex. Therefore, Fan 5 and Fan 6 are not located at the typical alluvial fan locations.

2.4 Determination of Alluvial Fan Toe and Lateral Boundaries

2.4.1 Toe Determination

Based on 2003 FEMA guidelines, the toe of an alluvial fan commonly is defined by (1) a stream that intersects the fan and transports deposits away from the fan; (2) a playa lake; (3) an alluvial plain; and (4) smoother, gentler slopes of the piedmont plain. The flow from Fan 5 and Fan 6 will eventually drain to Cave Creek and Cave Buttes Dam. However, Cave Creek should not be considered as a stream that intersects these two areas. The pool area due to the man-made Cave Buttes Dam should not be considered as a playa lake. Based on Rhoads (1986), if the slope is between 0 and 2%, the surface may be classified as an alluvial plain. The longitudinal slopes for Fan 5 and Fan 6 are less than 2%, which suggests Fan 5 and Fan 6 are on a gentle slope and may be on alluvial plain themselves instead of alluvial fans. Using alluvial plain as a toe is impossible for Fan 5 and Fan 6. Therefore, Fan 5 and Fan 6 do not appear to have a clear toe.

2.4.2 Lateral Boundary Determination

Lateral boundaries of alluvial fans are the edges of deposited and reworked alluvial materials. The lateral boundary of a single alluvial fan typically is a trough, channel, or swale formed at the lateral limits of deposition. The lateral boundary also may be a confining mountainside. Lateral boundaries of single alluvial fans can often be identified as a contact of distinct differences between light-colored, freshly abraded, alluvial deposits and darker-colored, weathered deposits with well-developed soils on piedmont plains.

Since Fan 5 and Fan 6 do not have a typical fan shape and there is no clear channel that defines the fan area, the lateral boundary cannot be clearly defined.

2.5 Summary of Stage 1

Fan 5 and Fan 6 meet Stage 1 composition requirement for alluvial fan landform. However, they do not appear to meet other requirements of morphology, locations, toe determination, and lateral boundary determination. Therefore, it cannot be concluded that Fan 5 and Fan 6 have a typical alluvial fan landform based on the 2003 FEMA Stage 1 analysis. However, the 2003 FEMA Stage 2 analysis is still performed to check if there is any active fan area on Fan 5 and Fan 6.

3. Stage 2 – Defining Active and Inactive Areas of Erosion and Deposition

Stage 2 is to "delineate areas of the alluvial fan that are active or inactive in the deposition, erosion, and unstable flow path flooding that builds alluvial fans" (FEMA, 2003, page G-7) and to "narrow the area of concern with regard to active deposition, erosion, and unstable flow paths over a period of time generally exceeding 100 years" (FEMA, 2003, page G-8). The term "active" refers to that portion of an alluvial fan where deposition, erosion, and unstable flow paths are possible (FEMA, 2003, page G-8). Based on FEMA (2003, page G-2), active alluvial fan flooding occurs only on alluvial fans and 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. Inactive alluvial fan flooding is characterized by flow paths with a higher degree of certainty in realistic assessments of flood risk or in the reliable mitigation of the hazard. An active alluvial fan flooding hazard is indicated by the following three related criteria (FEMA, 2003, page G-2):

- Criterion No.1: Flow path uncertainty below the hydrographic apex;
- Criterion No.2: Abrupt deposition and ensuing erosion of sediment as a stream or debris flow loses its ability to carry material eroded from a steeper, upstream source area; and
- Criterion No.3: An environment where the combination of sediment availability, slope, and topography creates an ultrahazardous condition for which elevation on fill will not reliably mitigate the risk.

An alluvial fan landform must meet all above three criteria to be considered as active alluvial fan. If a part of an alluvial fan landform (not the whole fan) meets the above three criteria, then only that part is considered active. It should be pointed out that Criterion No.1 only refers to the large flow path uncertainty that cannot be set aside in realistic assessments of flood risk or in the reliable mitigation of the hazard. Minor flow path uncertainty should not be a concern. Criteria No.2 and No.3 refer to abrupt deposition, erosion, and an ultrahazardous condition for which elevation on fill will not reliably mitigate the risk. These three criteria can be simplified into two major criteria: major channel avulsion and abrupt deposition which will be the basis for the Stage 2 analysis.

A Stage 2 step-by-step procedure is developed by following the 2003 FEMA Stage 2 methodology. It attempts to provide details related to geomorphology, geology, and engineering such that the 2003 FEMA Stage 2 methodology can be more easily implemented in Maricopa County, Arizona. This step-by-step procedure consists of two steps. The first step is geomorphic analysis and subsurface exploration. The second step is engineering analysis. The following discussion provides the background information for this step-by-step Stage 2 procedure.

3.1 Step 1 of Stage 2 Analysis: Geomorphic Analysis and Subsurface Exploration

Step 1 is to apply geomorphic analysis and subsurface exploration to the alluvial fan landform area. Based on FEMA (2003, page G-8), if flooding and deposition have occurred on a part of an alluvial fan in the past 100 years, that portion of the fan can be clearly considered to be active. If flooding and deposition have occurred on a part of an alluvial fan in the past 1000 years, for example, that part of the fan may be subject to future alluvial fan flooding. Since 100 years and 1000 years mentioned in the 2003 FEMA guidelines provide a reasonable time scale for engineering design, both 100 years and 1000 years will be used as age threshold for active and inactive fans in Stage 2 analysis in Maricopa County.

If either geomorphic analysis or subsurface exploration results indicate that the fan or part of fan has a major channel avulsion or abrupt sediment deposition in the past 100 years, then the fan or part of the fan is considered to be active. If there has been no major channel avulsion or abrupt sediment deposition in the past 1000 years, then the fan or part of the fan is considered to be inactive. If either geomorphic analysis or subsurface exploration results indicate that the fan or part of fan has a major channel avulsion or abrupt sediment deposition in the past 1000 years, then the fan or part of the fan is considered to be potentially active and engineering analysis is required, which is Step 2. In general, a 2-feet channel depth is chosen as the threshold that defines a major channel avulsion in Maricopa County. A 2-feet thick sediment deposition depth is chosen as the threshold that defines an abrupt sediment deposition. These two threshold values are only applicable to alluvial fan landform areas in Maricopa County and may be adjusted for special conditions with a prior approval from Flood Control District of Maricopa County.

3.1.1 Geomorphic Analysis

The geomorphic analysis includes surficial geological maps and soil maps, current and historical aerial photos and topographic data, relative dating methods, numerical dating methods, and correlative dating methods (AZGS, 2010a). The purpose for geomorphic analysis is to determine if there has been any major channel avulsion or abrupt sediment deposition on the alluvial fan landform in the past 100 years or 1000 years. Major channel avulsion is defined as a new formation of a channel of at least 2-feet deep on alluvial fan landform areas in Maricopa County. Abrupt sediment deposition is defined as debris flow hazard or 2-feet thick deposit in one flood event on alluvial fan landform areas in Maricopa County. The indicators for debris flow are large isolated boulders, boulderly levees, or sinuous ridges (Jackson, 1987). The procedures outlined in Jackson (1987) can be used to help assess the debris flow condition. Please note that it is possible debris flow path changes during a single flood event (Blair and McPherson, 1998).

Blair and McPherson (1994) suggested that for the debris flow type of fan the surface slope is between 5° (8.7%) to 15° (26%) and for fluvial fan is 2° (3.5%) to 8° (14%). In

Maricopa County, it is recommended that if an alluvial fan is at the mountain front, has a conic shape, and has a fan surface slope of 8.7% (5°) or larger, then the entire alluvial fan area is considered to be active even though the geomorphic analysis may suggest that the incised channel is stable.

Blair and McPherson (1994) suggested that the minimum alluvial fan slope is 1.5° (2.6%). Rhoads (1986) also suggested that if the slope is between 0 and 2%, the surface may be classified as an alluvial plain. 2% may be a reasonable threshold below which an alluvial fan landform is considered to be inactive. In Maricopa County, a threshold slope of 0.5% is selected. If the slope of fan surface area is less than or equal to 0.5% and the fan is at least three miles away from the mountain front, the alluvial fan is considered to be inactive in Maricopa County. The 0.5% threshold value may be increased for special conditions based on historical data and field data (prior approval from Flood Control District of Maricopa County is required).

The preliminary boundary of an active or inactive alluvial fan may be defined by surficial geological map and the NRCS soil map if both maps are available for the study area. In general, surficial geological map indicates if an alluvial fan landform is active or inactive based on geologic time (active: <10,000 years or Holocene). NRCS soil map unit descriptions often indicate if an alluvial fan landform is active or inactive. For example, if soil unit description indicates "alluvial fan," then this soil unit may be active. If a soil unit description indicates "fan terrace," then this soil unit is considered to be inactive. The active fan area from both surficial geological map and NRCS soil map can be used as the preliminary initial active fan area. Since the meaning of "active" in surficial geological map is still in the geologic sense, it may not be applicable to engineering time scale. Further dating techniques should be used to determine if the area is active within 100 years or 1000 years.

Current and historical aerial photos and topographic data can be used to identify major channel avulsion or abrupt sediment deposition. If major channel avulsion or abrupt sediment deposition is identified on a part of the alluvial fan landform, then a dating technique (relative dating, numerical dating, and correlative dating) may be used to identify when the major channel avulsion or abrupt sediment deposition occurred. The numerical dating can be used to date the channel bank material to provide age estimate for the bank formation.

The dating techniques include relative dating, numerical dating, and correlative dating techniques. The relative dating techniques are based on the physical characteristics of a landform, which provide clues as to its age. These physical characteristics include soil profile development, an integrated tributary drainage network, rock varnish, desert pavement, topographic relief, rounding of surface margins, color, and distinctive vegetative suites. Details on relative dating techniques can be found in Hjalmarson et al. (2003) and AZGS

(2010a). The numerical dating techniques provide specific age estimates of fan constituents such as organic material, sand grains, or gravel. One of the numerical dating methods is radiocarbon method which can date from 100 years to 30,000 years. Correlative dating techniques correlate physical attributes of a surface or deposit with similar physical attributes that have been constrained with numerical dating methods such as the correlation of desert varnish microstratigraphy from one region to another. One of the useful methods is varnish micro-lamination (VML). Another useful method is lead-profile dating because the twentieth-century lead from industry pollution has been recorded on rock varnish (Dorn, 1998). More details on dating techniques can be found in AZGS (2010a).

3.1.2 Subsurface Exploration

The subsurface exploration is to use soil samples, test pits, trenches, and natural exposures to obtain sedimentologic and stratigraphic information to evaluate (1) if there has been any major channel avulsion or abrupt deposition in the past; (2) if there is any potential channel stability issue. Soil samples, test pits, trenches or natural exposures shall be used in conjunction with the dating techniques to identify if there is any major channel avulsion or abrupt deposition in the past 100 years and 1000 years. Stream flow, hyperconcentrated flow, debris flow can be distinguished from the subsurface exploration based on the criteria in Giraud (2005).

There are three SCS methods that can be used to evaluate the channel stability for the existing channels (SCS, 1977). They are allowable velocity, tractive stress, and tractive power methods. The allowable velocity method can be used to assess the existing channel bank stability. The tractive stress method provides a method to evaluate the stress at the interface between flowing water and the materials in the channel boundary. Tractive stress is the tractive force per unit area of the boundary. Tractive stress is often called shear stress in hydraulics. The tractive force is the tangential pull of flowing water on the wetted channel boundary. When the computed tractive stress is less than the allowable maximum tractive stress, the channel bank is stable.

In general, the allowable velocity and tractive stress methods are based on correlating a soils erosion resistance with simple index properties determined on disturbed soil samples. In the tractive power method, the aggregate stability of saturated soils is assessed by use of the unconfined compression test. Tractive power is defined as the product of mean velocity and tractive stress. An empirical relationship (S-line) was developed between tractive power and unconfined compressive strength based on field data in the Western states in 1960's by SCS. This S-line becomes a separation line below which the channel is non-erosive and therefore the channel is stable. It may be noted that when a shear strength is measured in the field by a shear strength meter, the unconfined compressive strength may be estimated as twice as the shear strength (page 134, Hjalmarson, 1994).

3.1.3 Merging Geomorphic Analysis and Subsurface Exploration Results

The active areas from both geomorphic analysis and subsurface exploration shall be merged to develop maps for active areas, inactive areas, and potential active areas. If either geomorphic analysis dating results or subsurface exploration dating results indicate that the fan or part of fan had a 2-ft deep avulsion channel or 2-ft thick sediment deposit in the past 100 years, then the fan or part of the fan is active as shown in Figure 12. If both analyses indicate that there has been no 2-ft deep avulsion channel and no 2-ft thick sediment deposit in the past 1000 years, then the fan or part of the fan is inactive. If either geomorphic analysis dating results or subsurface exploration dating results indicate that the fan or part of fan has a 2-ft deep avulsion channel or 2-ft thick sediment deposit in the past 1000 years, then the fan or part of the fan is potentially active and further engineering analysis is required as shown in Figure 12, which is Step 2. Figure 12 is a flowchart for State 2.

It may be pointed out that the engineering analysis may be directly used without performing dating analysis if dating analysis becomes infeasible. The possible reasons for dating infeasibility are that (1) the dating techniques are not available to determine if a particular fan is active or inactive in the past 100 years and 1000 years; (2) the dating results are not accurate enough; (3) the cost for dating analysis is too high; (4) the time that the dating analysis requires is too long; and (5) access to the land or subsurface exploration is too difficult or prohibited.

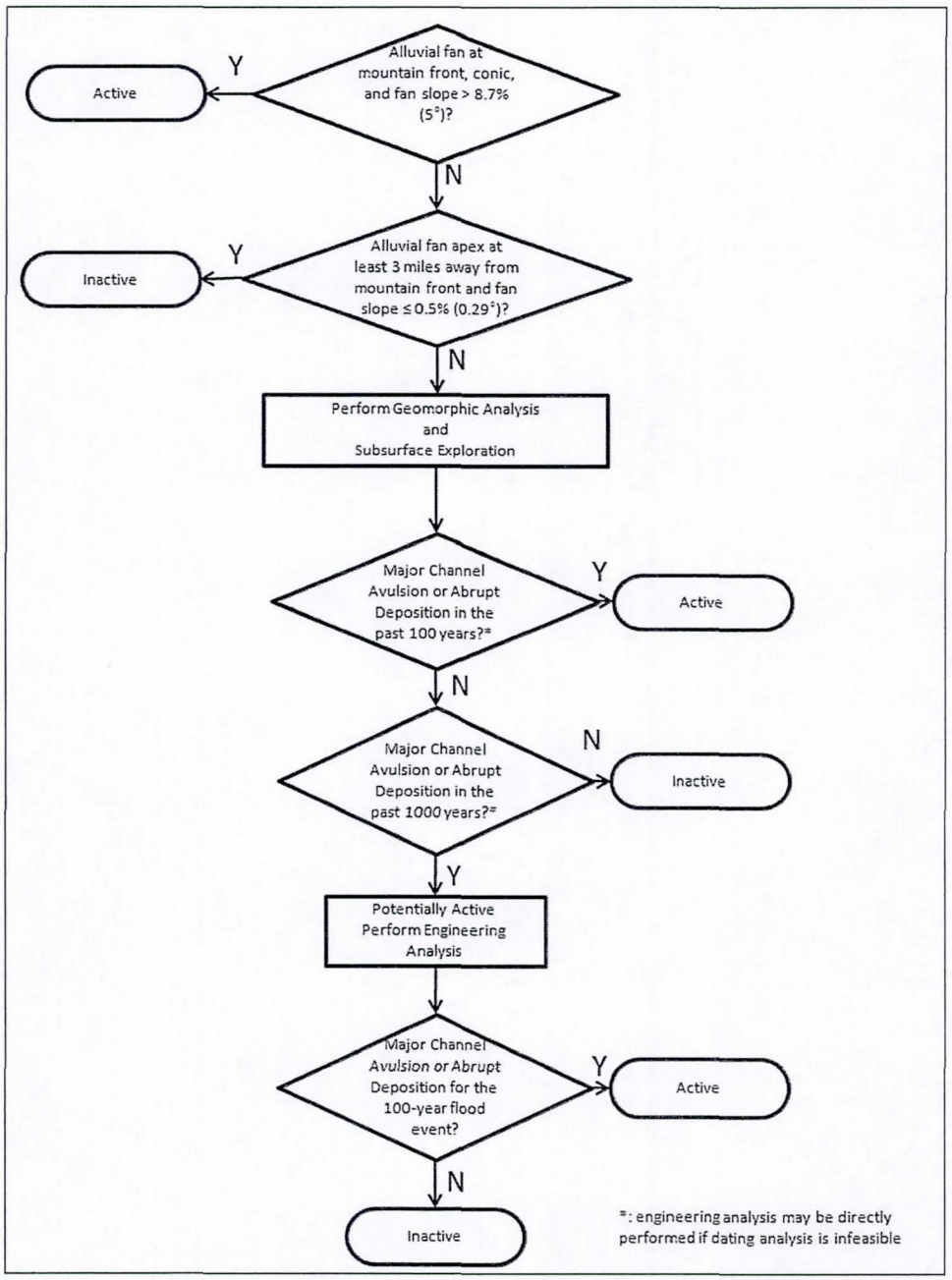


Figure 12. Flowchart for Stage 2 (Determination of Active Alluvial Fan Area).

3.2 Application of Step 1 of Stage 2 to Fan 5 and Fan 6

Although Fan 5 and Fan 6 do not appear to be on a typical alluvial fan landform based on the 2003 FEMA Stage 1 analysis, the 2003 FEMA Stage 2 analysis is still performed to check if there is any active fan area on Fan 5 and Fan 6. In this section, the above Step 1 procedure is applied to Fan 5 and Fan 6 based on the above flowchart (Figure 12).

3.2.1 Geomorphic Analysis on Fan 5 and Fan 6

Figure 9 and Figure 13 show that the apexes of FEMA Fan 5 and Fan 6 are not at a mountain front. Figure 3, Figure 4, and Figure 13 do not show any conic landform in the Fan 5 or Fan 6 area. Figure 13 shows that the land surface of Fan 5 or Fan 6 has a slope ranging from 1.8% to 1.9%. Therefore, since the slopes are less than 8.7% but greater than 0.5%, Fan 5 and Fan 6 are not debris flow fans and cannot be automatically treated as inactive alluvial fan without further geomorphic analysis based on the flowchart on Figure 12.

Figures 14-17 show soil map units from Natural Resources Conservation Services (NRCS). Figure 14 shows that the majority of Fan 5 and Fan 6 is on "fan terraces and stream terraces." A fan terrace is a relict alluvial fan, no longer a site of active deposition, incised by younger and lower alluvial surfaces (Camp, 1986). It is a fan formed during the Pleistocene Epoch (>10,000 years) (Hjalmarson, 1994). Figure 15 shows NRCS soil map units for "flood plains and drainageways." Figure 16 shows NRCS soil maps units for "Pediments and Hill Slopes." Figure 17 shows NRCS soil map units for "Alluvial Fan and Flood Plains." The tiny piece of "Alluvial Fan and Flood Plains" is in fact on Late Pleistocene soil based on AZGS Open-File 92-8 (Pearthree and Wellendorf, 1992), which ranges from 10,000 years to 150,000 years old. Therefore, Fan 5 and Fan 6 are inactive based on the NRCS soil unit descriptions.

A number of geomorphic analyses were performed in the past (National Research Council, 1996). The following sub-sections summarize the findings from those previous geomorphic analyses.

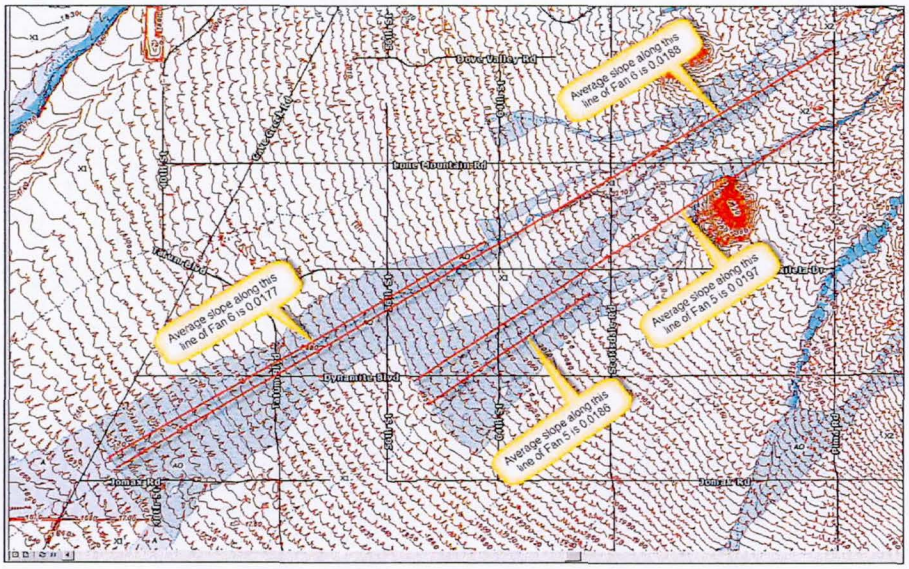


Figure 13. FEMA Fan 5 and Fan 6 Land Surface Slopes

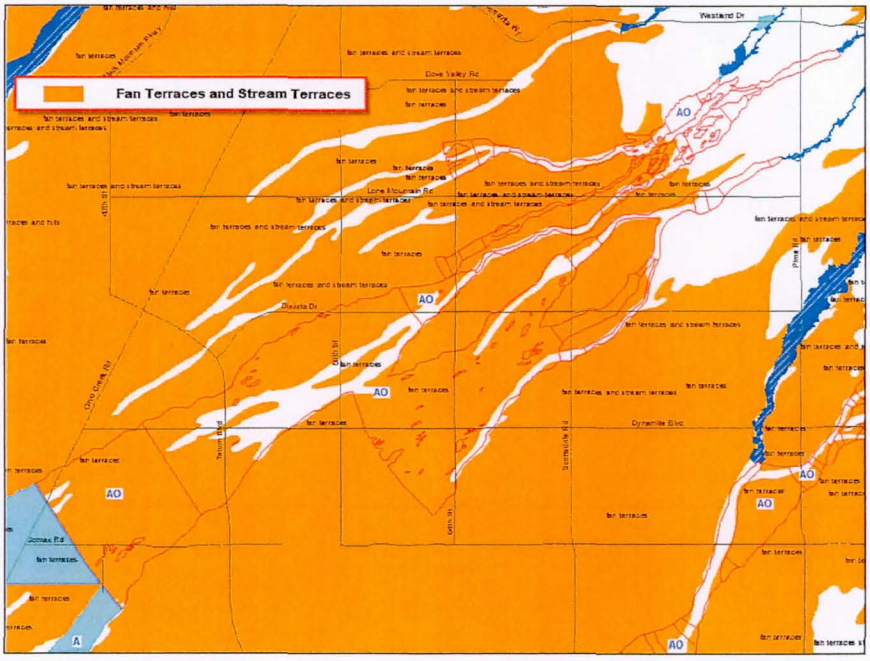


Figure 14. NRCS Soil Map Units for Fan Terraces and Stream Terraces.

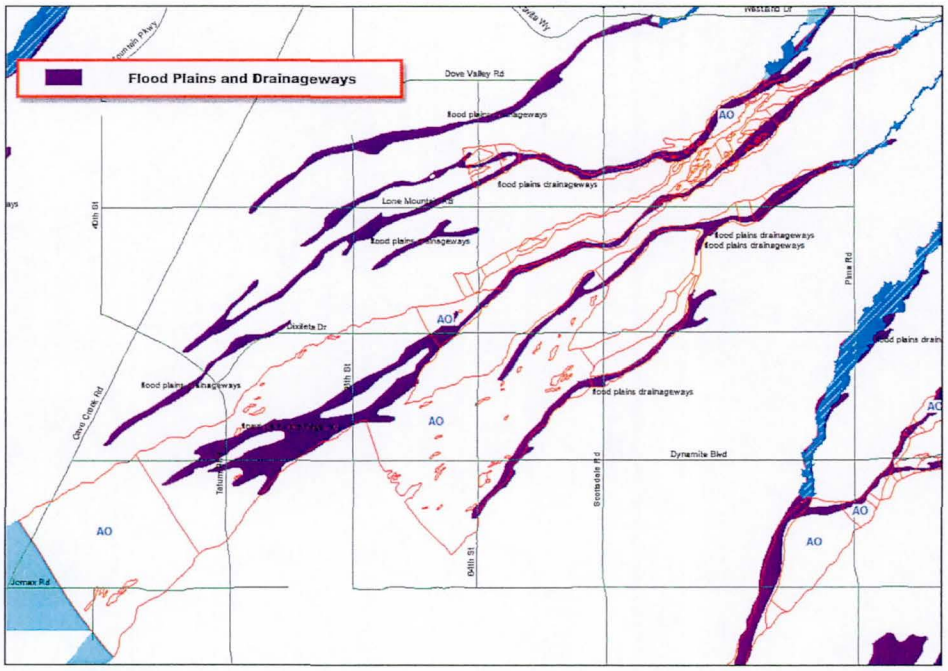


Figure 15. NRCS Soil Map Units for Flood Plains and Drainageways.

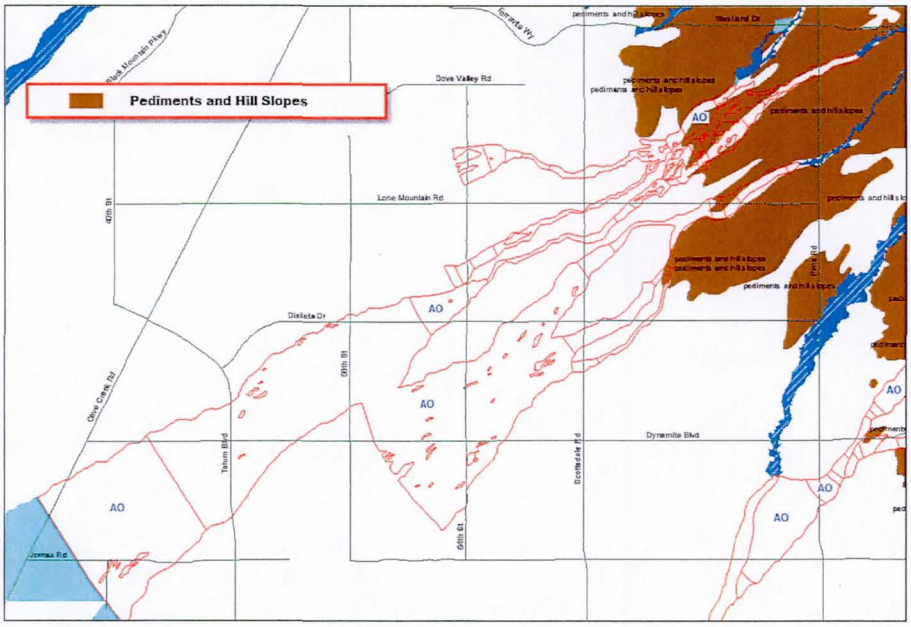


Figure 16. NRCS Soil Map Units for Pediments and Hill Slopes.

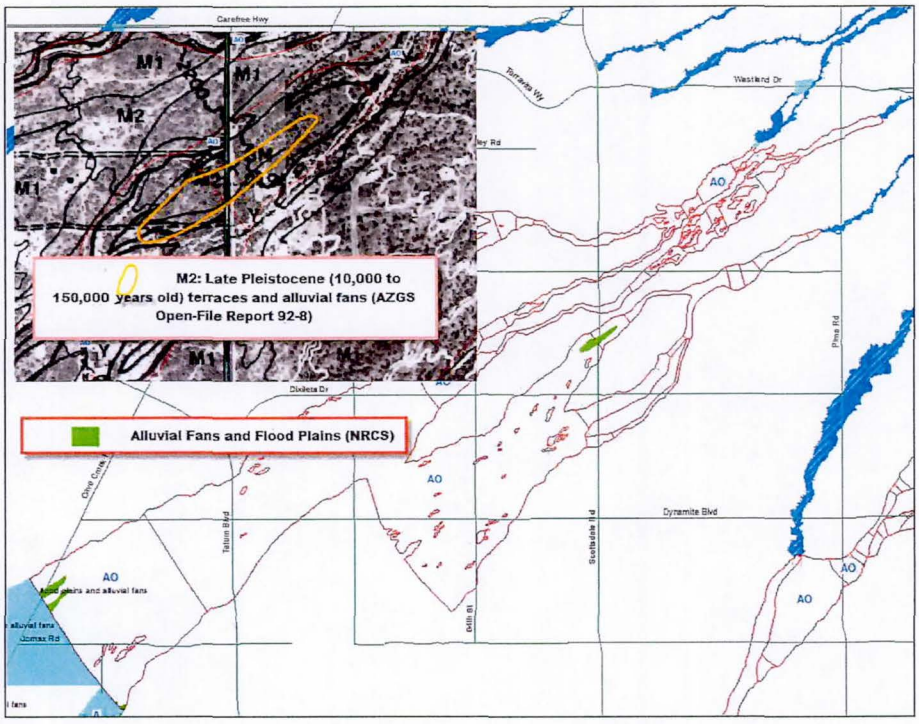


Figure 17. NRCS Soil Map Units and AZGS Geomorphic Map

3.2.1.1 Geomorphic Analysis (National Research Council, 1996)

The National Research Council's 1996 report on alluvial fan flooding is the basis for the 2003 FEMA alluvial fan guidelines. In the report, a geomorphic analysis was documented for Carefree fan in central Arizona about 4 miles south of the town of Carefree and a few miles north of Phoenix (Figure 18). Figure 19 overlays the FEMA floodplains on the geomorphic analysis map. The red outline is the FEMA delineated Fan 5 and Fan 6. As shown in Figure 19, Carefree fan constitutes a very large portion of Fan 6. As discussed by National Research Council (1996), the Carefree fan is not subject to alluvial fan flooding and sedimentation is inactive because flow is confined to network of trenched distributary channels with no evidence of flow path movement and the Natural Resources Conservation Service map designates most areas as fan terraces (page 85, National Research Council, 1996). The following is a summary of National Research Council's findings on Carefree fan.

- There is no evidence of debris flow.
- The flowpaths are confined by stable interfluves and there is little alluviation, there currently is no active flooding on Carefree fan.
- There are no areas on the Carefree fan where flow paths are expected to change.
- Flood flow typically is confined within and adjacent to the trench channels.
- Most of Carefree fan is on fan terrace.

- The tree-lined distributary channels indicate that the flow paths are fixed and in a condition of relative stability. Many of the large Palo Verde and mesquite trees along the channels are visible on the aerial photographs taken on September 7, 1941, March 8, 1953, and March 30, 1991 for Carefree fan. A comparison of these photos indicates that there has been no change in the location of flow paths.
- Rhoads (1986) found no major changes in the form of channel networks in the general region for a 30-year historical period.

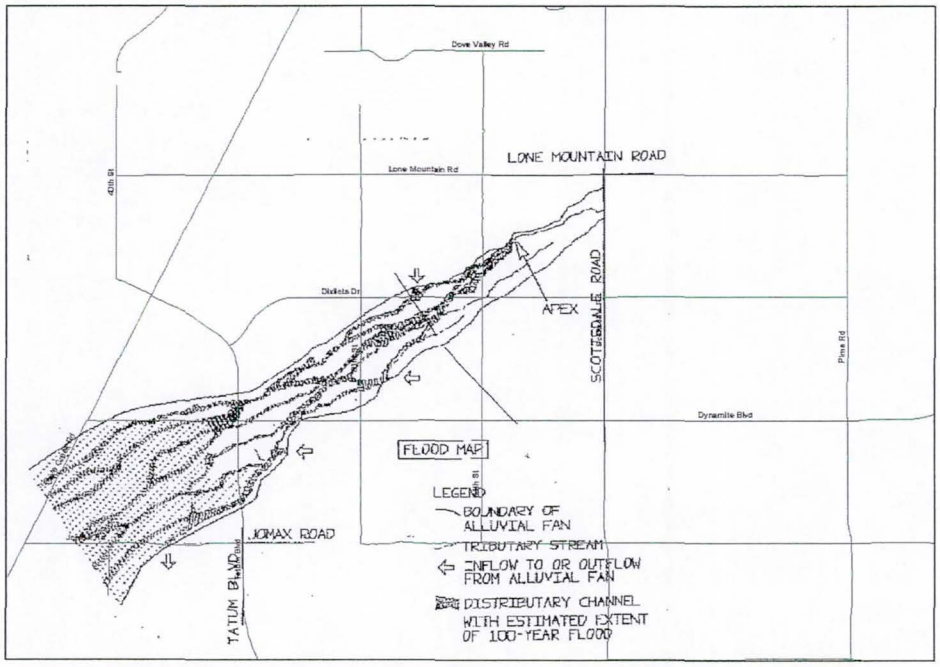


Figure 18. Carefree Fan (National Research Council, 1996)

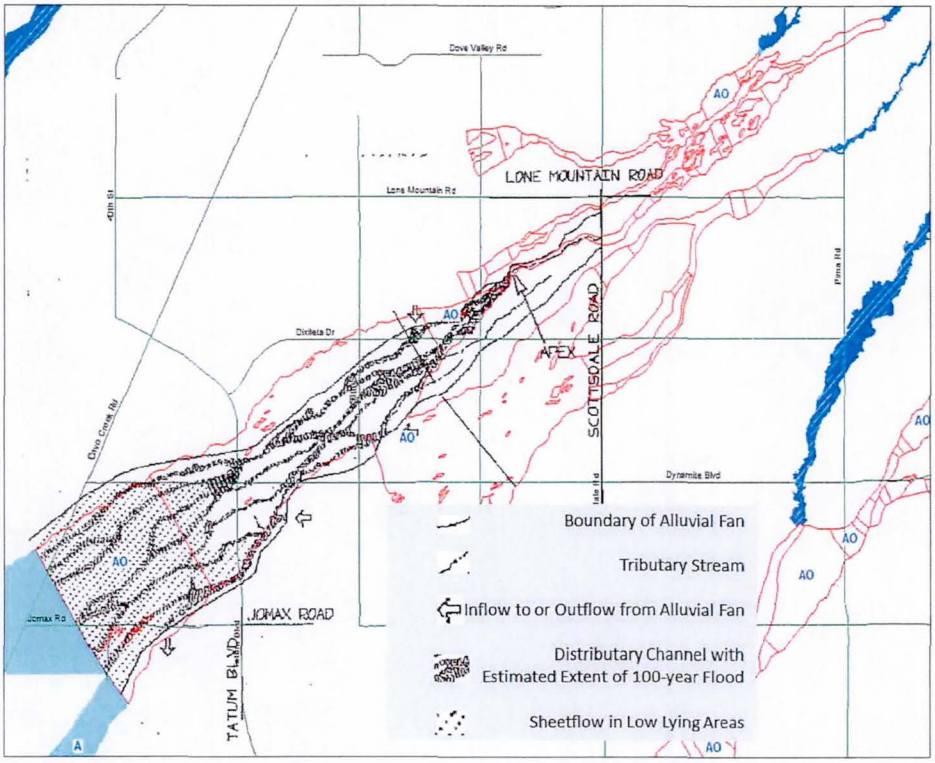


Figure 19. FEMA Floodplains and Carefree Fan

3.2.1.2 Flood Characteristics of FEMA Site 6A

H. W. Hjalmarson (June 3, 1994) analyzed the stability of channels in the major portion of FEMA Fan 6 that receives flood water from FEMA Stream 6A. Figure 20 shows

the Fan 6A, Fan 6B, and Fan 6C. Site 6A used in Hjalmarson (1994) is Fan 6A defined here. As can be seen, Fan 6A constitutes the majority of Fan 6. Hjalmarson considered this area a distributary flow area. From geomorphic analyses, Hjalmarson (June 3, 1994, page 60) concluded that the flow paths of the distributary flow area of site 6A are stable, and he listed the following reasons for his conclusion:

1. There are abundant large Palo Verde and other trees along the banks of the distributary channels and the interfluves are covered with scattered large trees. These large trees along the channel banks tend to stabilize the flow paths. Also, such trees would be washed away and not reach maturity if the flow paths were changing. In addition, few tree roots from lateral bank erosion are visible.
2. No channel movement was observed on the distributary flow area from a comparison of aerial photographs taken in 1940, 1953 and 1991.
3. 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. These hydraulic geometry relations indicate the channels and flow paths are stable.
4. The channels are eroded into the cemented Pleistocene sediments and are not perched above the adjacent land.
5. The soils forming the banks are well developed with dark reddish-brown sandy clay loam and clay loam textures a few inches below the surface and lime masses and may have cemented sediments. Also, the recent deposits along the distributary channels are horizontally stratified indicating the presence of hydraulic processes and not debris flows.
6. There are areas of eroded Pleistocene sediments with triburtary drainage systems between the distributary channels.

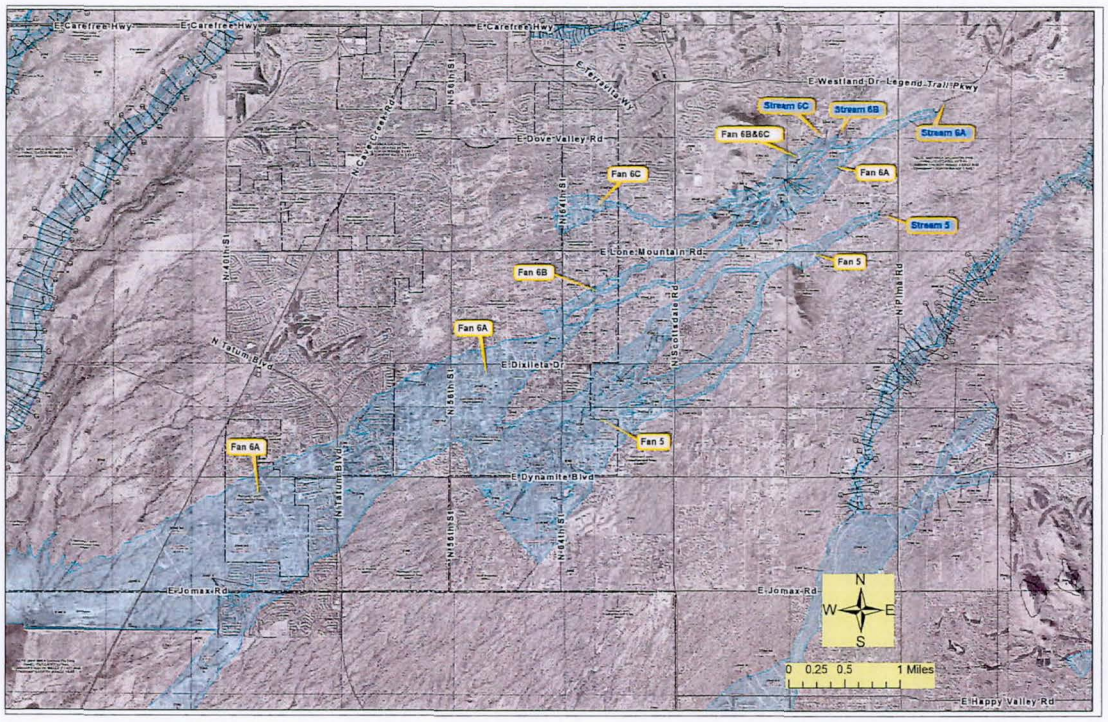


Figure 20. FEMA Floodplains

Hjalmarson (June 3, 1994, page 61) also listed following reasons to support his conclusions. He stated if the flow paths of the distributary flow area of site 6A were unstable, it might have the following characteristics:

1. Large trees such as Palo Verde would be scattered in somewhat of a random fashion over the distributary flow area and not along the channel banks for sites in central and southwestern Arizona.
   Other sites with unstable flow paths in the southwestern U.S may have little vegetation on the distributary flow area.
2. Channel movement on the distributary flow area may be depicted by comparison of aerial photographs taken before and after a major flood and spanning a few tens of years.
3. The hydraulic geometry relations would show the channels are formed in noncohesive material.
4. The channels and banks would be perched above the adjacent land at the same distance below the primary diffluence.
5. The soils of much of the distributary flow area would not be developed except perhaps at great depths. The soils would lack lime masses and cementation at shallow depths and the soils would tend to be lighter or be more yellow and tan at shallow depths and have sandy textures. Also, the soils would lack horizontal stratification, cross-bedding, and/or imbrication usually associated with water flooding (hydraulic processes).
6. Most of the interfluves in the upper distributary flow area would be below the expected level of the 100-year flood.
7. There would be little to no desert varnish on stones in the distributary flow area. The surface of stones such as granite fragments weather easily in the desert environment of the southwestern United States and do not have desert varnish.
8. The size of the distributary flow area would be small relative to the size of the drainage basin above the distributary flow area (Hjalmarson and Kemna, 1991).
9. The computed degree of hazard would be at least 9 using regression equation 9 by Hjalmarson and Kemna (1991, p. 54). Site 6A (site 2 in Hjalmarson and Kemna,1991) has a degree of hazard of 6 according to Hjalmarson and Kemna.
10. The channel links would appear random using the random link model (Hjalmarson and Kemna,1991). The random link model was not used for site 6A because there was an insufficient number of channel links to reliably use the model.

3.2.1.3 Geomorphic Analysis of Flood Hazards on the Northern McDowell Mountains Piedmont, Maricopa County (Pearthree and Wellendorf, 1992)

Pearthree and Wellendorf (1992) conducted geomorphic analysis of flood hazards on the northern McDowell Mountains piedmont, which includes the areas of FEMA Fan 5 and Fan 6. Figure 21 shows a generalized geomorphic map of the northern portion of the McDonald Mountains Piedmont with FEMA floodplain zone (red outlines are for Zone AO). As shown in the map legend, there are three map units, Unit Y, Unit M2, and Unit M1. Unit

Y is for Holocene channels and terraces (less than 10,000 years). Unit M2 is for late Pleistocene terraces and alluvial fans (10,000 to 150,000 years old). Unit M1 is middle Pleistocene alluvial fan remnants (150,000 to 800,000 years old). Since Figure 21 cannot display the details for the map units, the map is sub-divided into five segments to show more details. As shown in Figures 21a-21e, most areas in Fan 5 and Fan 6 are in M2 and M1 map units. The area for Y map unit constitutes a much smaller area on Fan 5 and Fan 6 as compared with M2 map unit and M1 map unit area. The area for Y map unit is for channels.

Pearthree and Wellendorf (1992) found that most of FEMA Fan 5 and Fan 6 land surfaces are older than 10,000 years. Below are their study conclusions (page 7, Pearthree and Wellendorf, 1992):

"The results of our geomorphic investigations clearly indicate the McDowell Mountains piedmont north of Jomax Road (the areas associated with drainages 5 and 6) is not composed of active alluvial fans. Although both drainages 5 and 6 have distributary drainage networks on the piedmont, the areas between channels are composed almost entirely of alluvial surfaces that are of late Pleistocene (10,000 to 150,000 years old) or middle Pleistocene (150,000 to 800,000 years old) age. These inactive fan areas are characterized by substantial soil development, tributary drainage patterns, and the dominance of erosional rather than depositional topography."

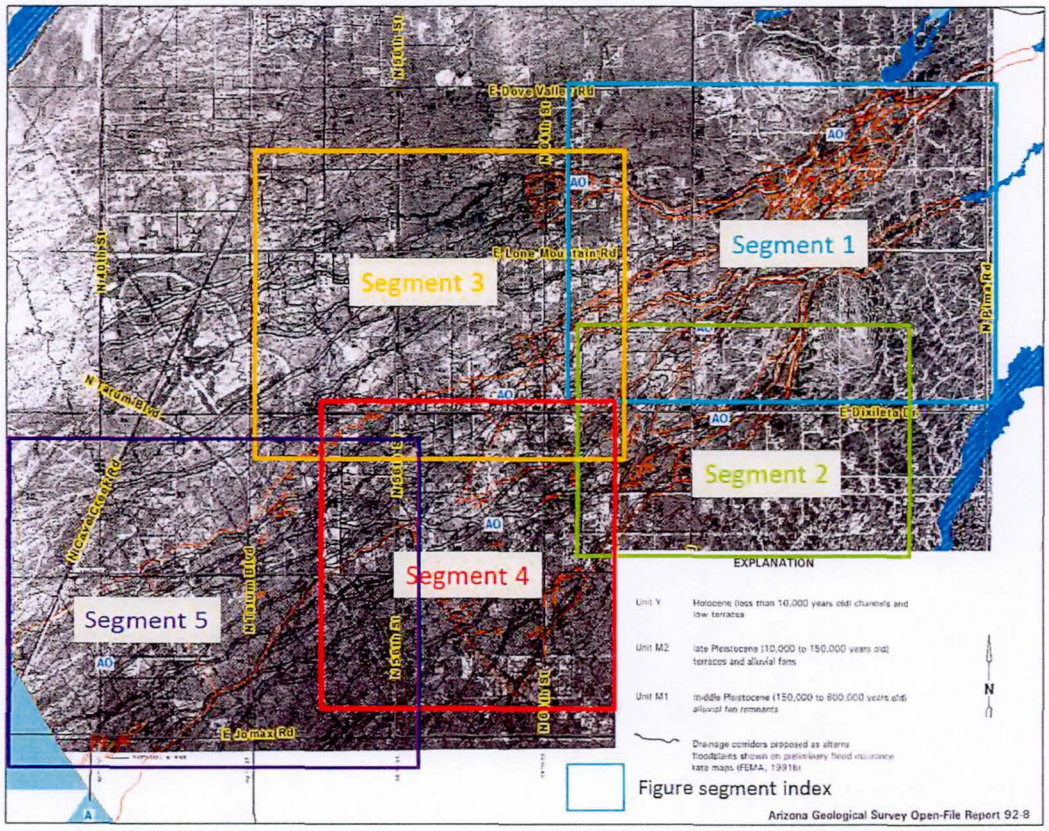


Figure 21. Generalized geomorphic map of the northern portion of the McDonald Mountains Piedmont (Pearthree and Wellendorf (1992)

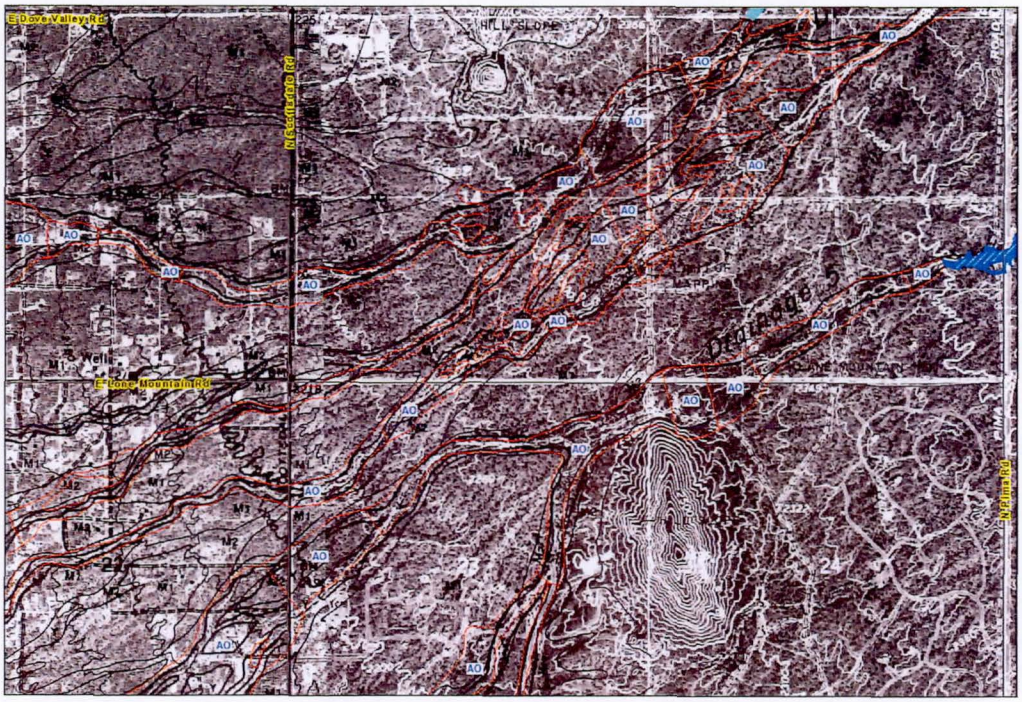


Figure 21a. Segment 1 of Figure 21

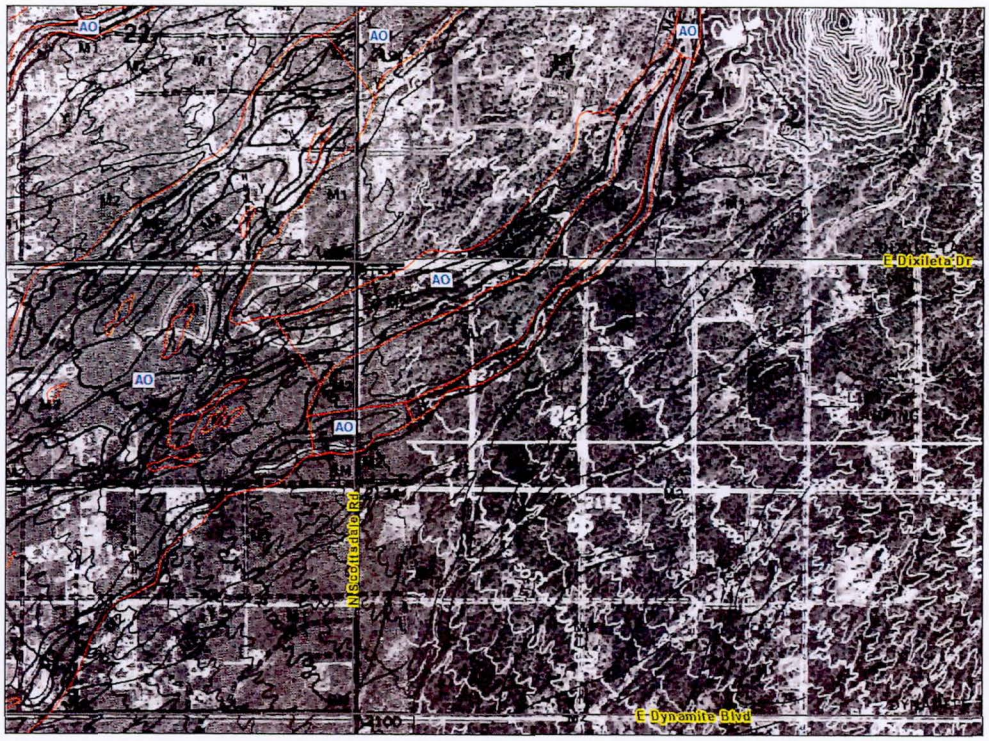


Figure 21b. Segment 2 of Figure 21.

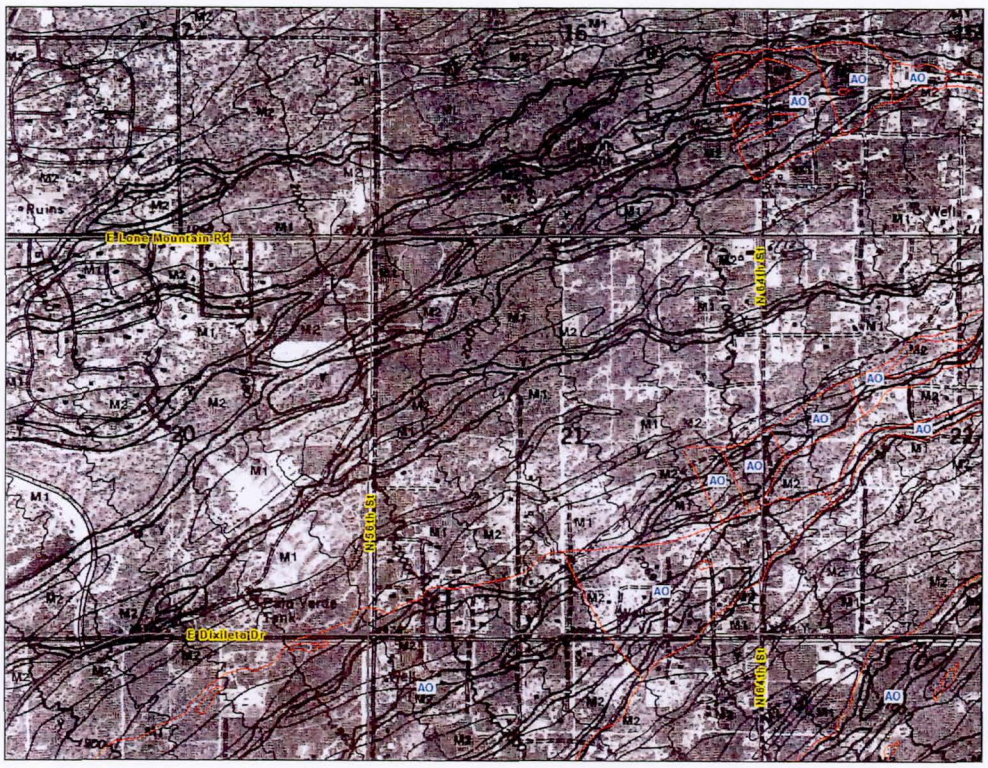


Figure 21c. Segment 3 of Figure 21

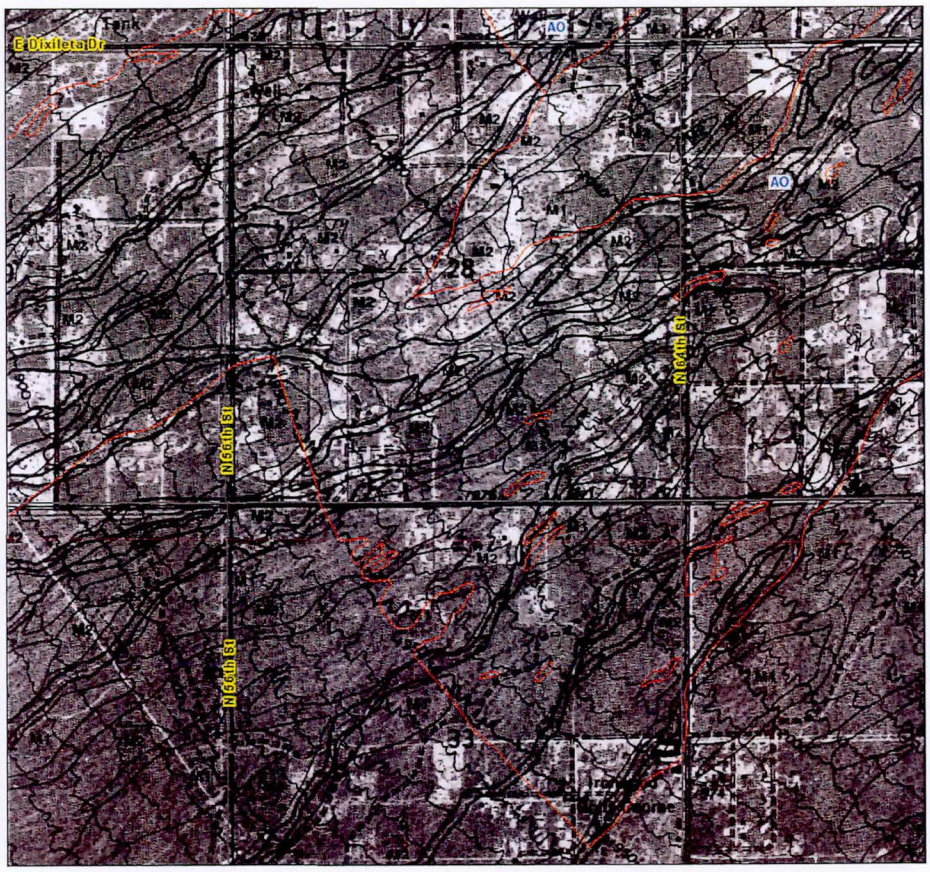


Figure 21d. Segment 4 of Figure 21.

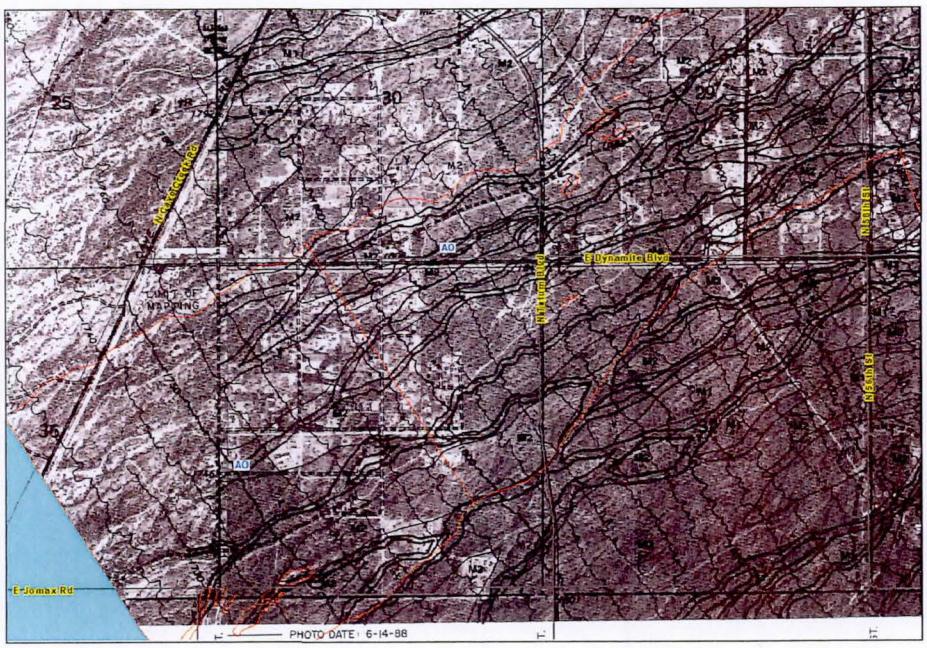


Figure 21e. Segment 5 of Figure 21.

3.2.2 Subsurface Exploration

3.2.2.1 Additional Soil Survey

Figure 22 shows the NRCS soils maps on the 7.5-minute orthophoto quads (Camp, 1986). While the published soils maps on 7.5-minute orthophoto quads were very useful for substantiating the stability and extent of the distributary flow area, a detailed survey of soils on Fan 6A was made by NRCS in July 1993 (Hjalmarson, 1994) to evaluate the usefulness of the less detailed published maps.

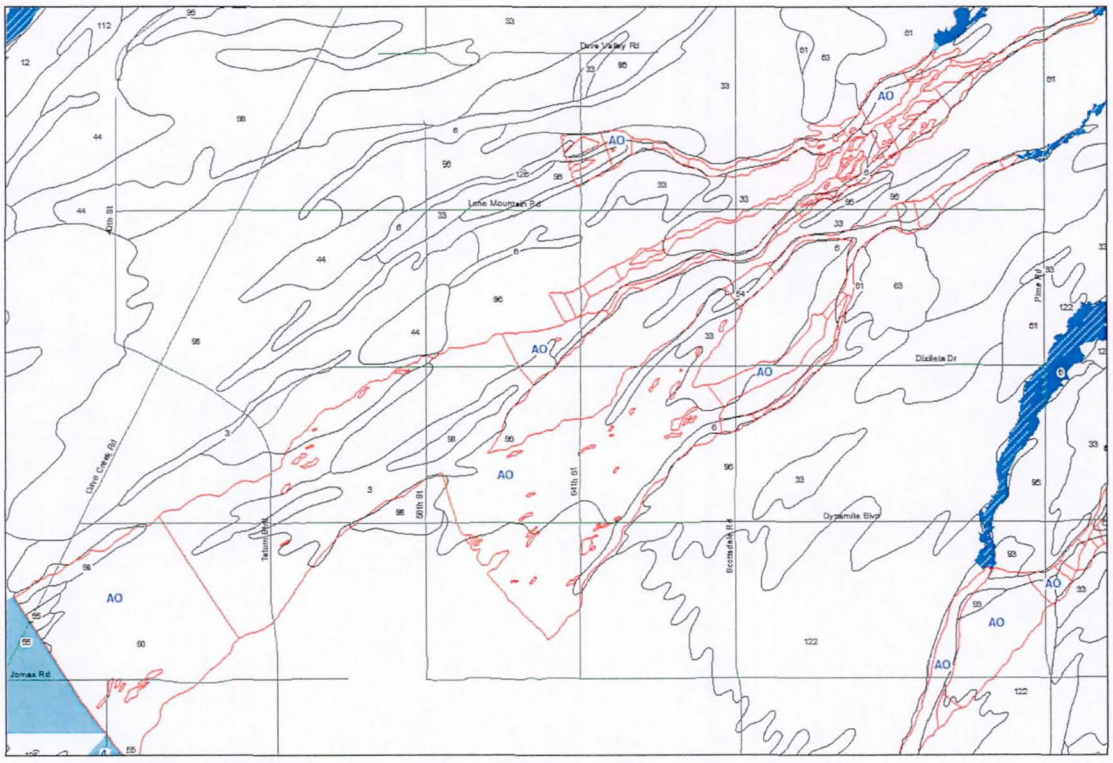
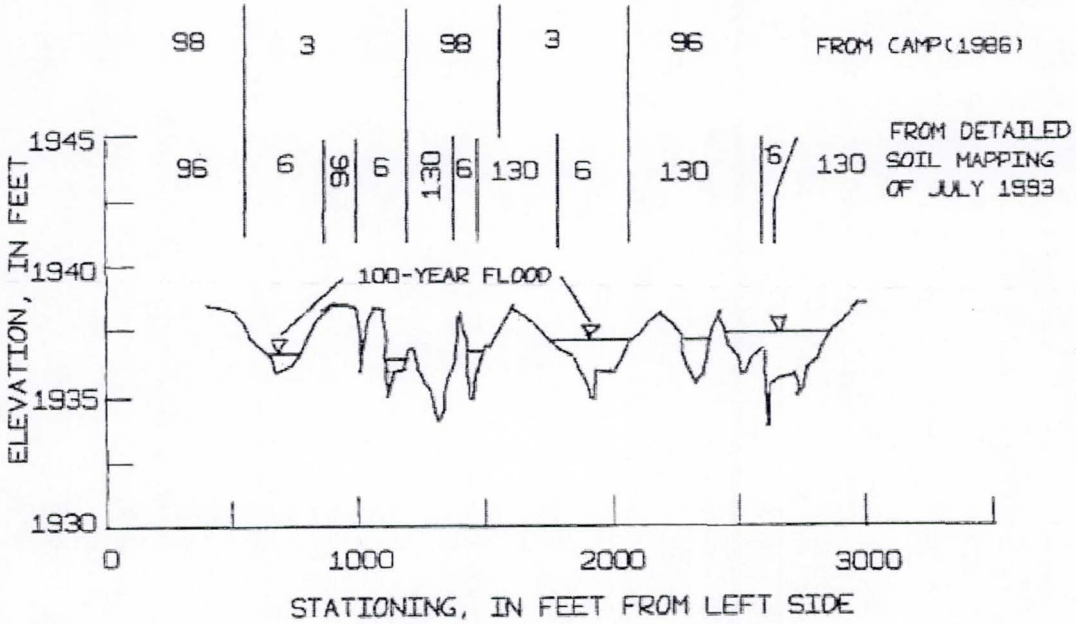


Figure 22. Soil Maps with FEMA Floodplains (Camp, 1986).

Figures 23-25 show three cross-sections with the 1986 soil map units and the 1993 detailed soil map units. Soil map units 3, 6, 54, and 130 are younger soils (Holocene Epoch, <10,000 years). Soil map units 33, 44, 96, and 98 are older soils (older than 10,000 years). As compared in Figure 23-25, the detailed soil survey information further validates the 1986 soil survey.

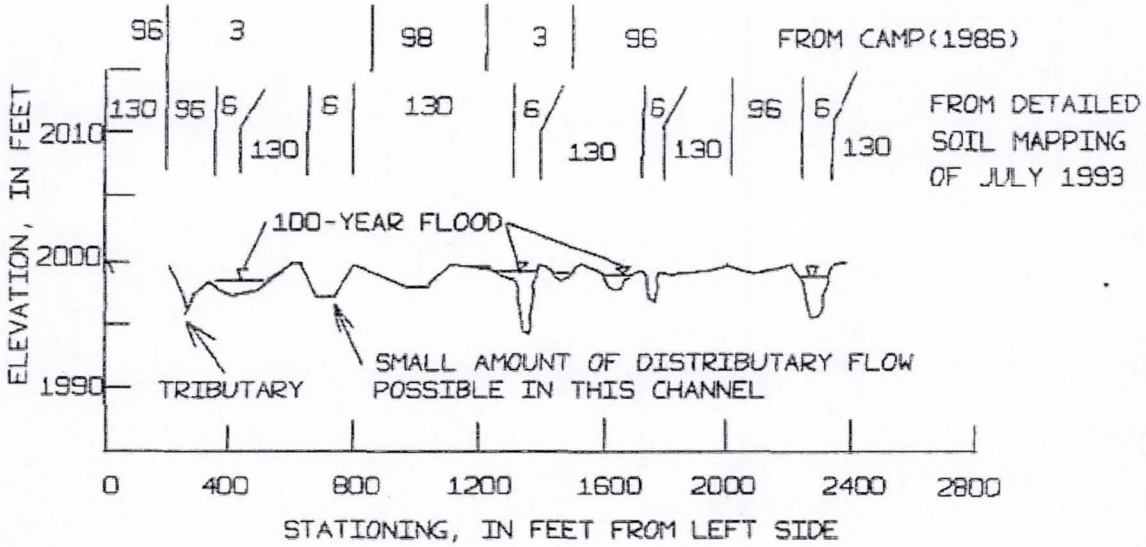


EXPLANATION

SOIL UNIT	NAME OF UNIT	SCS FREQUENCY OF FLOODING	REMARKS
3	ANTHO, CARRIZO	RARE	SAME AS UNIT 6.
6	ANTHONY, ARIZO	RARE, OCCASIONAL	SAME AS UNIT 3.
96	PINALENO	NONE	WELL DEVELOPED GRAVELY CLAY LOAM
98	PINANT-TREMANT	NONE	SIMILAR TO UNIT 96
130	AGUSTIN	NONE	SOME DEVELOPMENT-GRAVELY

CROSS SECTION 1938 SHOWING LEVEL OF 100-YEAR FLOOD AND MAPPED SOIL UNITS.

Figure 23. Comparison of the 1986 and 1993 Soil Map Units on Cross-section 1938 (Hjalmarson, 1994).



EXPLANATION

SOIL UNIT	NAME OF UNIT	SCS FREQUENCY OF FLOODING	REMARKS
3	ANTHO, CARRIZO	RARE	SAME AS UNIT 6.
6	ANTHONY, ARIZO	RARE, OCCASIONAL	SAME AS UNIT 3.
96	PINALENO	NONE	WELL DEVELOPED GRAVELY CLAY LOAM
98	PINANT-TREMANT	NONE	SIMILAR TO UNIT 96
130	AGUSTIN	NONE	SOME DEVELOPMENT-GRAVELY

CROSS SECTION 2000 SHOWING LEVEL OF 100-YEAR FLOOD AND MAPPED SOIL UNITS.

Figure 24. Comparison of the 1986 and 1993 Soil Map Units on Cross-section 2000 (Hjalmarson, 1994).

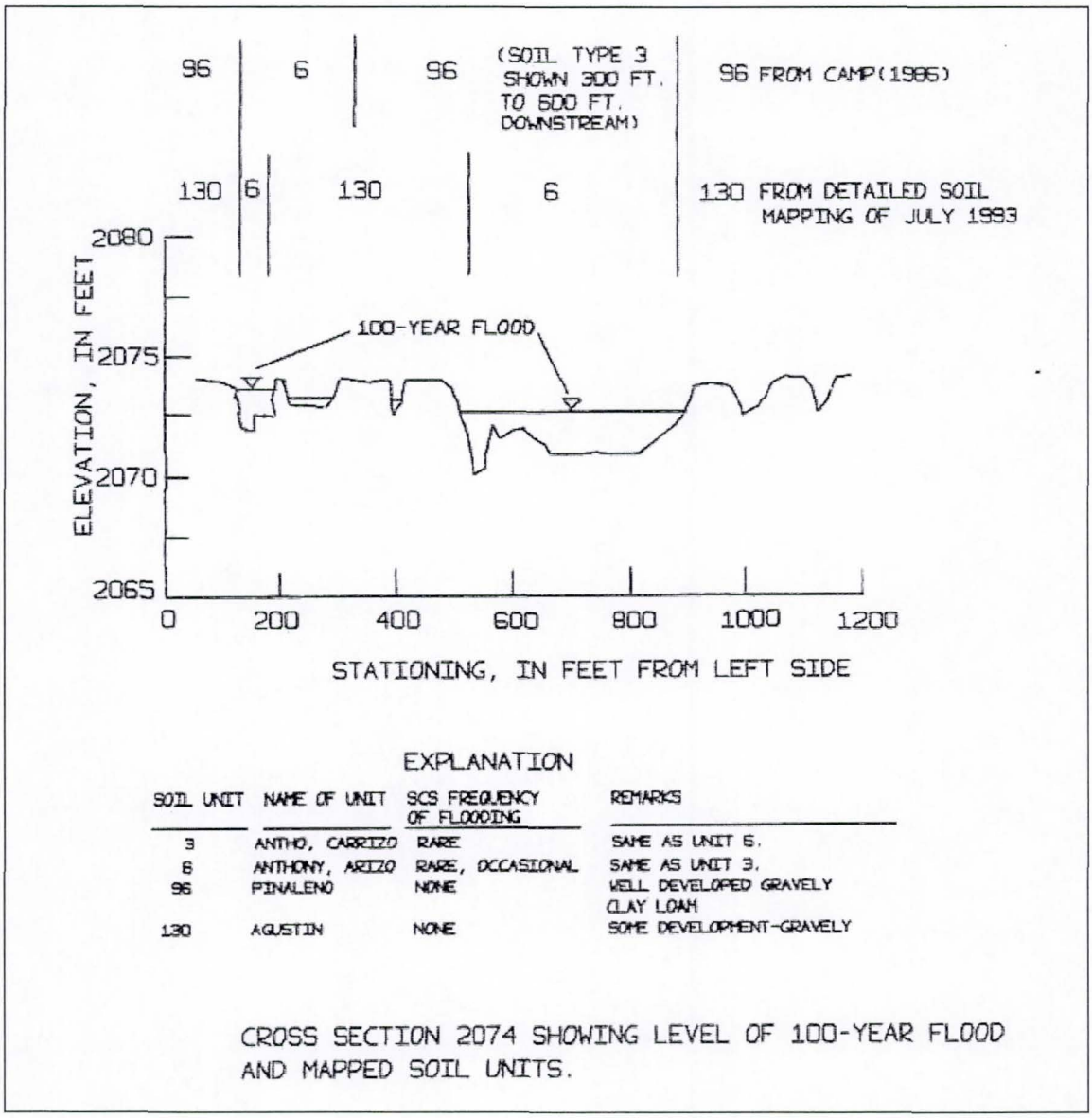


Figure 25. Comparison of the 1986 and 1993 Soil Map Units on Cross-section 2074 (Hjalmarson, 1994).

3.2.2.2 Channel Stability Assessment

Hjalmarson (1994) collected a large number of soil samples in channel bed and channel banks on Fan 6A to assess the channel stability by using a variety of methods. Sixty seven soil samples were collected. Figure 26 shows the soil sampling cross-section locations on Fan 6A. Multiple soil samples on each cross-section were collected at different depths for channel banks and bed. The soil shear strength, sediment size and distribution, vegetation type and size, and channel shape data were collected during February-April, 1994. A number of engineering methods were used to assess the channel stability, which include the SCS tractive power method, USGS method, Federal Highway Administration method, US Army Corps of Engineers method, etc. (Hjalmarson, 1994). The channels and flow paths of Fan 6A were found to be stable for the following reasons:

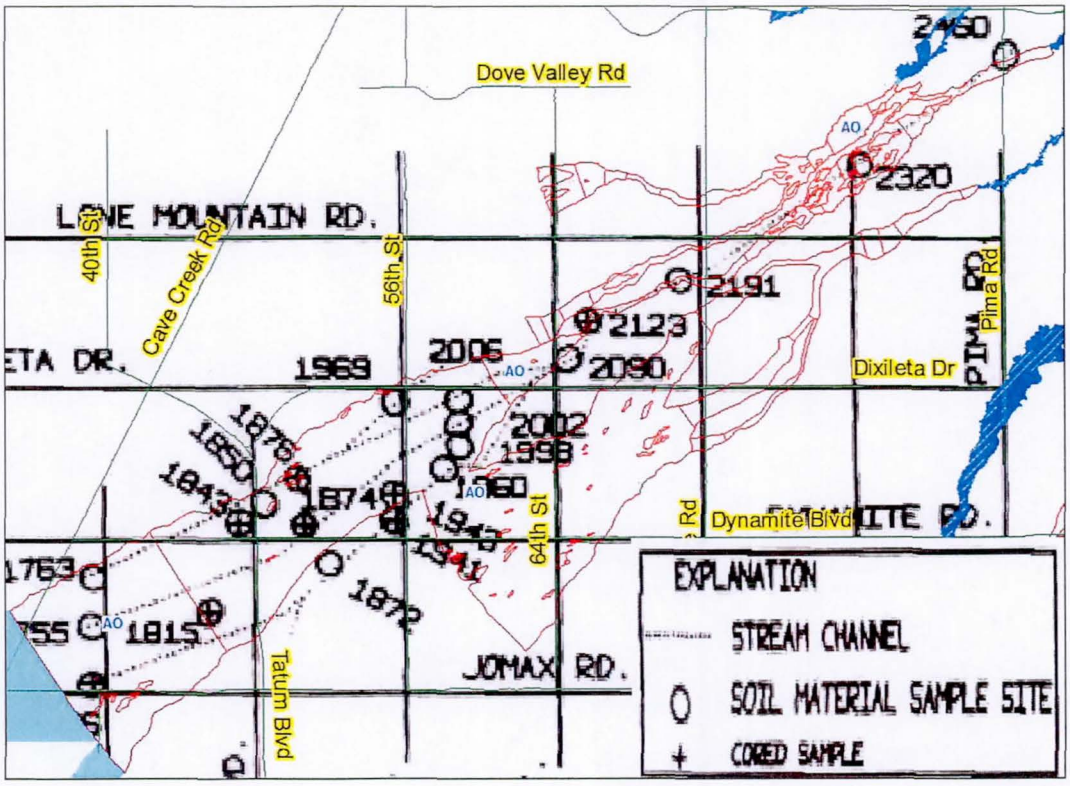


Figure 26. Location of Bed and Bank Material Sample Sites on Fan 6A (Hjalmarson, 1994).

1. 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. The fine material is filtered by the sandy parent bank material as flood water infiltrates stable banks.
2. Measurements of the particle size of the bed material at many sites along the distributary flow area show that the mobile bed material entering the distributary flow area is conveyed through the system of defined distributary channels. This transport of the bed material through the distributary flow area is shown by the uniform distribution of particle size along the channels. The decrease of particle size, which is characteristic of aggrading systems where the finer material is deposited down slope, was not shown by the measurements.
3. Data from measurements of channel geometry and material samples at several cross sections were plotted on the relation between channel width-depth ratio and percent silt-clay along the wetted perimeter published in U.S.Geological Survey Professional Paper 352C. The data for site 6A plotted consistently in the stable region of the relation.
4. Data from measurements of vegetation size and channel geometry show the stream power at nearly all cross sections is insufficient to lay over the trees along the channel banks. The relation of the effect of the 100-year flood on vegetation is from an unpublished paper approved by the U.S. Geological Survey.
5. Measurements of vane shear corresponding to computed tractive power at many cross sections show the channel banks are non-erosive or stable. The data consistently plotted in the non-erosive region of the relation of tractive power and unconfined compressive strength published in TR-25 by the U.S. Soil Conservation Service.
6. The channels are considered stable because depths of floodflow at this site are less than the computed depths of floodflow based on measurements and computations at several cross sections. These computations were made in accordance with the "Maximum discharge design procedure" of HEC15 published by the Federal Highway Administration.
7. Relations of bankfull width, mean depth and channel slope versus channel-forming discharge at several cross sections show the distributary flow area is not aggrading. This assessment was in accordance with procedures published in "Stability of flood control channels" by the U.S. Army Corp of Engineers.
8. Measured vegetation cover along the banks at many transects show the banks are stable using procedures in "Methods for evaluating riparian habitats with applications to management" by the U.S. Department of Agriculture.
9. The critical shear stress associated with banks coated with silt and clay and covered with grass and cryptogamic crusts is at least a few times the critical shear stress of bare soil. This measure of channel stability is from a relation between critical shear stress and

sediment size published in "Sediment engineering" by the American Society of Civil Engineers.

The FEMA Fan 6A area Hjalmarson studied in 1993 is 3.32 square miles and the areas of FEMA Fan 6B and Fan 6C are 0.15 and 0.26 square miles, respectively. FEMA Site 6A makes up 89% percent of FEMA Fan 6. It may be reasonable to believe that Hjalmarson's conclusion concerning the FEMA Fan 6A is also valid for FEMA Fan 6B and Fan 6C. The FEMA Fan 5 is approximately 2 square miles and is located immediately on the south side of FEMA Fan 6. Since geomorphic study by Pearthree concluded that most area of the FEMA Fan 6 and Fan 5 are 10,000 to 800,000 years old alluvial surfaces and Fan 6 and Fan 5 are immediately adjacent to each other, the channels in Fan 5 area should be also stable.

3.2.3 Summary of Step 1 of Stage 2 Application to Fan 5 and Fan 6

Based on geomorphic analysis and subsurface exploration analysis, Fan 5 and Fan 6 are inactive in terms of geologic time scale (>10,000 years). In Maricopa County, an alluvial fan landform that is older than 1000 years is defined as inactive alluvial fan. Since Fan 5 and Fan 6 are older than 1000 years and the channels are stable, they are considered inactive alluvial fan.

3.3 Step 2 of Stage 2 Analysis: Engineering Analysis

Major channel avulsion is defined as a new formation of a channel of at least 2-feet deep. Abrupt deposition is defined as debris flow occurrence or 2-feet thick deposit in one flood event. The purpose of the engineering analysis is to predict any major channel avulsion or abrupt deposition for a 100-year flood event. In this step, major channel avulsion and abrupt deposition will be assessed under a 100-year flood event.

3.3.1 Major Channel Avulsion

3.3.1.1 Channel Overtopping Assessment

The purpose of the channel overtopping assessment is to identify the locations for channel overtopping along the feeder channel and the first-level branch channels for 100-year flood (Figure 27). Small floods usually do not overtop channel banks but constantly carry sediment that usually settles on the channel bed. Major channel avulsion usually occurs at channel overtopping locations during a large flood after previous small floods produce sediment deposits that reduce the channel capacity. Sediment transport modeling can be used to simulate sediment deposition due to small floods to adjust channel geometry. Based on the adjusted channel geometry, an HEC-RAS model or two-dimensional hydraulic model can be used to route a 100-year flood to determine the potential channel overtopping locations, overtopping flow rates, and flow durations.

If sediment transport modeling becomes cost prohibitive, 2-ft and 1-ft deep sediment deposit may be assumed for the feeder channel and the first-level branch channels, respectively, to imitate the accumulated sediment deposit for small flood events. At major bends (30 degrees or larger), a 3-ft deep sediment deposit should be assumed around the bend (500 ft upstream and downstream of the curved area).

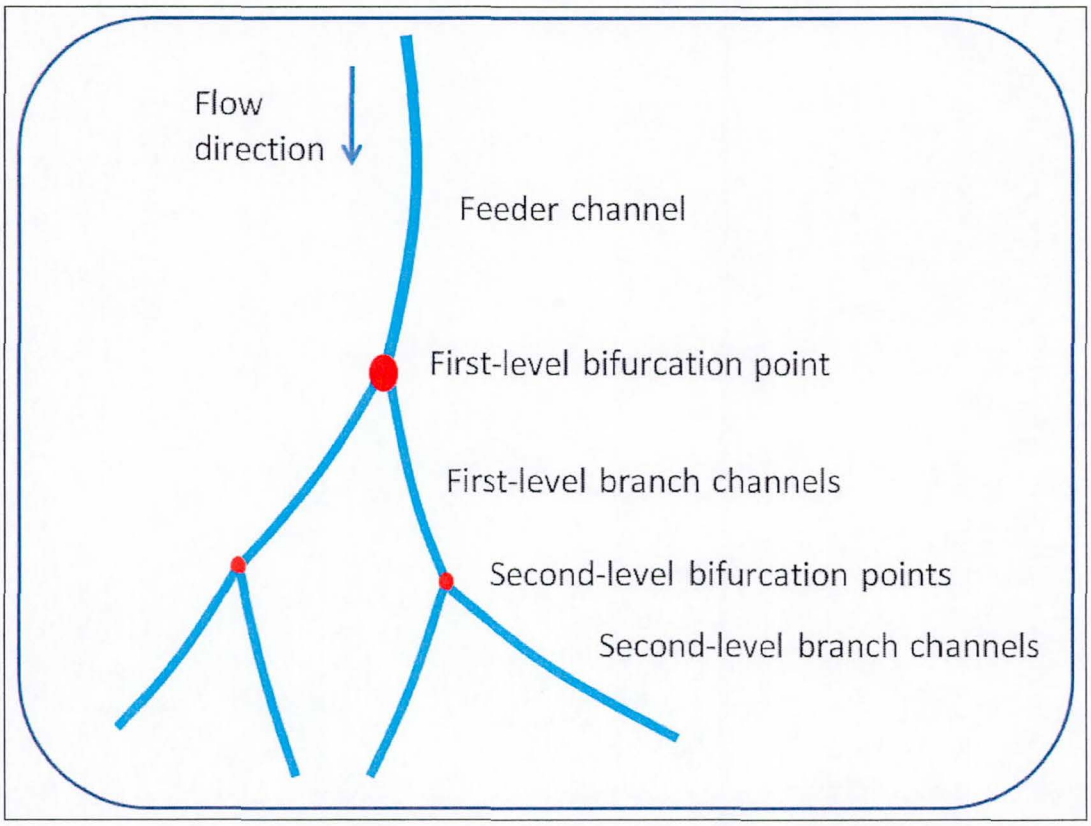


Figure 27. Illustration for Channel Bifurcation on Alluvial Fans

3.3.1.2 Channel Avulsion Assessment

After the channel overtopping locations, flow rates, and durations are identified, the channel avulsion on the fan surface will be assessed. It should be pointed out that it is very difficult to assess if a new 2-feet channel will form given the current available modeling capability. The following avulsion assessment procedure is an approximate method. It may be mentioned that the following avulsion procedure is only related to flow overtopping of an existing channel. Avulsion due to debris flow on a debris flow fan is not covered in this procedure.

Two types of erosion contribute to avulsion. The first type of erosion is downward erosion that occurs as water flows downstream. The erosion occurs if the shear stress is greater than the critical shear stress for sediment incipient motion. This type of erosion may not always occur depending on if the sediment on the overbank can be eroded by the overtopping flow. The downward erosion magnitude also depends on the overtopping flow duration. The second type of erosion is headcut erosion for existing tributary channels which receive the overland flow from the channel overtopping area. The headcut moves upstream as the overland flow enters into the existing tributary channels. The headcut erosion occurs for most avulsion events as long as there is an existing tributary channel. The headcut erosion migration distance also depends on the overtopping flow duration. The erosion areas computed by both downward erosion and headcut erosion are merged into one avulsion area. If the shear stress is not greater than the critical shear stress and there is no existing tributary channels on the fan surface, then the overtopping flow will not create an avulsion hazard.

3.3.1.2.1 Downward Erosion Computation Procedure

a. Estimate representative d_{50} (soil median particle size) for soils on the fan inundation area due to channel overtopping flow.

b. Compute the critical shear stress (τ_c) by $\tau_c = 0.047 d_{50}(\gamma_s - \gamma)$ where d_{50} is the soil median particle size; γ_s is the sediment specific weight typically 165 lb/ft^3; and γ is the water specific weight (62.4 lb/ft^3).

c. Compute the shear stress (τ) at each grid for the inundated areas caused by the channel overtopping flow by using $\tau = \gamma \frac{y + y_{cf}}{2} S$ where γ is the water specific weight (62.4 lb/ft^3); y is the maximum flow depth on the grid from a two-dimensional hydraulic model run; y_{cf} is the channel forming depth from Figure 28, and S is the grid slope which can be a representative fan overland surface slope.

d. If the shear stress is greater than the critical shear stress, the soil will erode and the erosion rate can be computed by $de/dt = K_d*(\tau - \tau_c)$ (Temple and Hanson, 1994) where de/dt is erosion rate in ft/hour; and K_d is the detachment rate coefficient in ft^3/(lb-hour).

K_d can be estimated by using jet test described in ASTM D5852 (NRCS, 1997) or may be computed (Temple and Hanson, 1994) by

$$K_d = \frac{5.66\gamma}{\gamma_S} \exp\left(-0.121 C^{0.406} \left(\frac{\gamma_S}{\gamma} \right)^{3.10} \right) \tag{1}$$

where γ_σ is the sediment specific weight typically 165 lb/ft^3; γ is the water specific weight (62.4 lb/ft^3); and C is the clay in percent.

e. Compute the erosion depth by multiplying the erosion rate (de/dt) by the overtopping duration.

f. Avulsion area is the area where the erosion depth is equal to or larger than 2 ft.

If the clay percent is not available or the erosion rate results estimated above are not reasonable, a simple alternative method may be used. The depth and width of the newly formed channel may be estimated by using empirical channel-forming charts (USACE, 1994). Figure 28 and Figure 29 display the relationships. To use Figures 28 and 29, one can use peak flow rate of the overtopping flow or averaged overtopping flow rate to estimate the newly formed channel depth and width. If the depth is equal to or larger than 2 feet, then the newly formed channel is considered to be a major channel avulsion, therefore, the channel area is considered to be an active alluvial fan area. The layout for the newly formed channel can be developed by using the newly formed channel width. It can start from the main channel overtopping area and extend on the overbank area (along the steepest slope) to reach the existing tributary channel. Although the downstream existing tributary channel width increases at least three times after the overland flow enters into the existing tributary channel (Field, 2001), it is assumed that the newly formed channel width will replace the existing tributary channel width until it merges with a downstream main channel. Therefore, the avulsion channel is defined though it may be conservative because the overtopping flow duration may not be long enough to "carve" the channel.

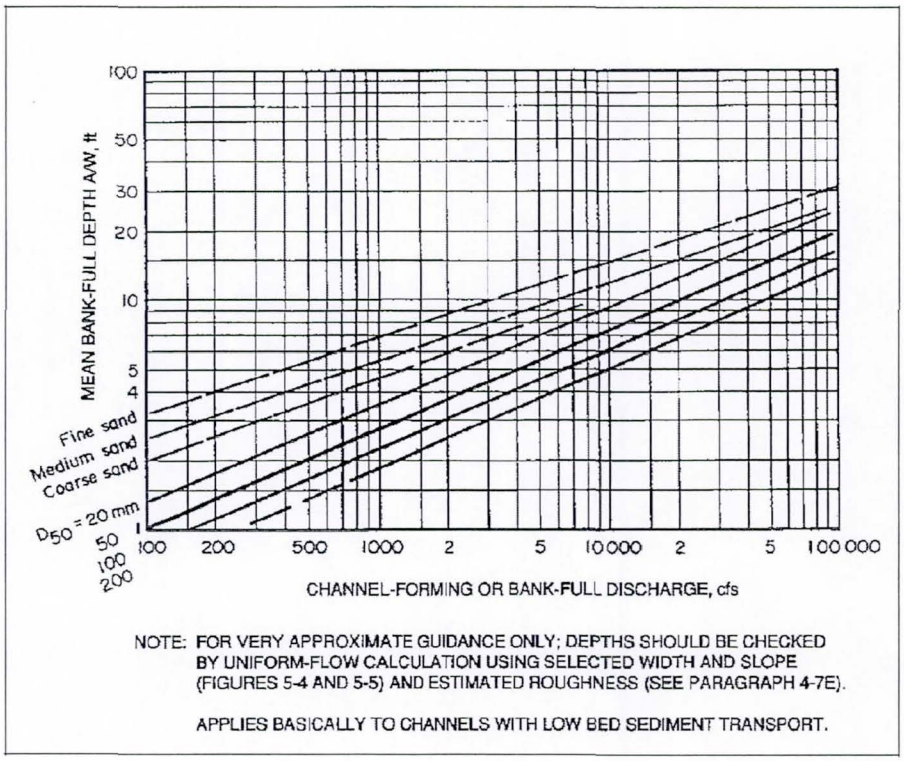


Figure 28. Channel Forming Depth versus Channel Forming Discharge (from USACE, 1994)

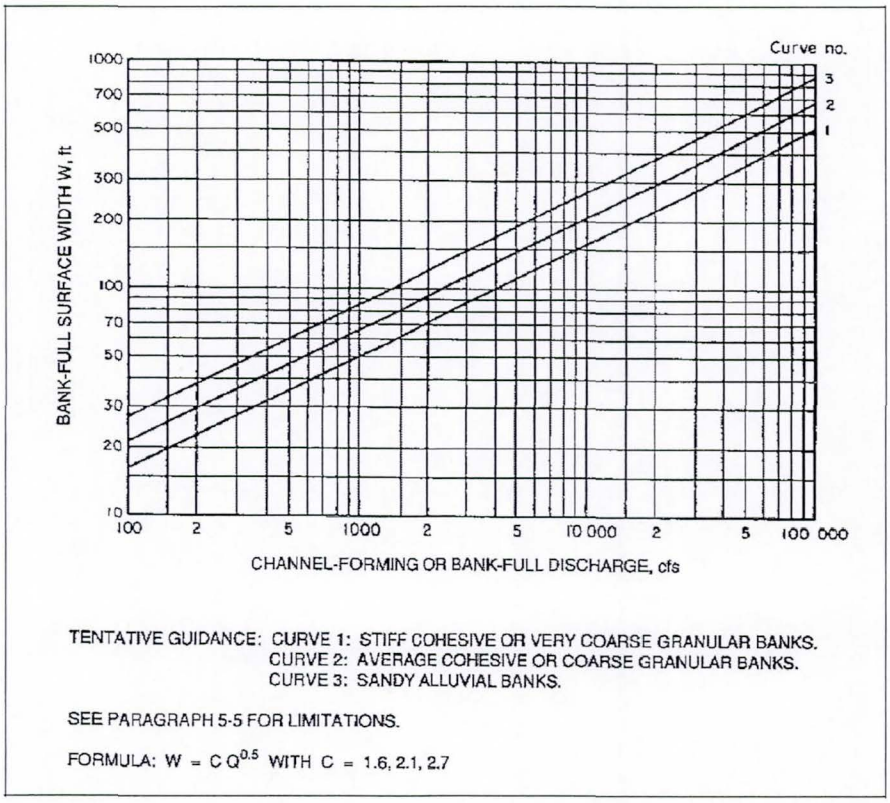


Figure 29. Channel Forming Width versus Channel-Forming Discharge (from USACE, 1994)

3.3.1.2.2 Headcut Erosion

If the overland flow shear stress is less than the critical shear stress, the downward erosion will not occur. This is normally the case for a flat fan slope. However, if there is an existing tributary channel on the overland area and the overtopping flow reaches the channel, the channel upstream end will migrate upward as a headcut erosion process.

3.3.1.2.2.1 Initial Headcut Height

As overland flow enters into the existing tributary channel, it will create a scour hole. The scour hole depth can be estimated by using the Schoklitsch equation (FCDMC, 2012; page 11-120 of FCDMC, 2013a; FCDMC, 2013b). FCDMC standards for Flood Control District of Maricopa County. The scour hole depth equation is

$$Z = \frac{3.15 H^{0.2} q^{0.57}}{D_{90}^{0.32}} - y_m \qquad (2)$$

where

Z = scour depth below streambed (ft),

H = vertical distance between the water level upstream and downstream of the overfall (ft),

q = discharge per unit width (cfs/ft),

D_{90} = particle size for which 90% is finer than (mm), and

y_m = downstream mean water depth (ft), (hydraulic depth).

The unit discharge (q) can be estimated, in a more conservative way, as the overtopping flow peak discharge divided by the channel width for the existing tributary channel. If a 2-dimentional model is available, the peak discharge that enters into the existing tributary channel can be used to compute the unit discharge using the tributary channel width. The Schoklitsch equation can be found in FCDMC (2013a) and is implemented in DDMSW 4.6.4d (FCDMC, 2013b). The headcut initial height will be the sum of the scour depth and the existing channel depth at the upstream end.

3.3.1.2.2.2 Headcut Width

Based on Fields (2001), when overland flow enters into the existing tributary channel, the channel width may increase three times. Herein, the channel width can be estimated by assuming both channel banks will fail at 6:1 slope based on the headcut initial height computed above. 6:1 slope was recommended by Ayres (2004) for alluvial channels. For example, if an existing tributary channel width is 10 feet and depth is 2 feet, the scour hole depth is computed as 1 foot based on Schoklitsch equation, the new channel width is

10+(2+1)*6+(2+1)*6 = 46 feet. Therefore, the headcut face will have a width of 46 feet and a height of 3 feet.

3.3.1.2.2.3 Headcut Migration Rate

If the overtopping flow duration is long enough, the headcut will move upward to reach the overtopping area. However, since the headcut moves at a certain speed, it may not reach the overtopping area. It is important to estimate the headcut migration rate and the distance that the headcut will travel in order to define the active alluvial fan area. Once the headcut migration rate is computed, the distance can be computed based on the overtopping flow duration.

An experiment study was performed by Robinson and Hanson (1994) to study the gully headcut advance rate. The observed headcut advance rates ranged from 0 to 0.4 mm/s. Based on an experimental study of headcut growth by USDA (Bennett, 1999), the headcut migration rate is about between 1.2 and 2 mm/s. The parameters for the experiment study are: flume width = 0.165 m; flume length = 2 m; bed slope = 1%; initial headcut height = 2.5 cm; channel velocity = about 1.5 ft/s; flow rate = 20 to 80 l/min (0.012 to 0.047 cfs); soil components: 77.1% sand, 20% clay, and 2.9% silt.

Hanson and Cook (2004) did an experimental study to analyze the timing and formation process of a dam embankment breach due to flood overtopping. A key erosion feature for the breach is the headcut formation and migration. The experiment parameters are: flume width = 1.8 m; flume length = 29 m; flume height = 2.4 m; initial headcut height = 0.9 m to 1.5 m. The soil properties used in the experiment are as follows (Hanson and Cook, 2004):

Soil Parameters	Soil E	Soil F	Soil 1	Soil 2	Soil 3
Gradation					
% Clay < 0.002 mm	25	13	4	6	26
% Silt	40	30	28	30	48
% Sand	35	57	68	64	26
Liquid Limit	26	16			34
Plastic Limit	9	13			17
Plasticity Index	15	3	NP	NP	17
USCS	CL	SM	SM	SM	CL
Standard Compaction Values					
Maximum Dry Unit Weight (Mg/m^3)	1.90	1.96	1.84	1.86	1.79
Optimum Water Content %	12.0	10.5	9.0	10.5	14.0

The headcut migration rates from this study range from 0.011 mm/s to 2.1 mm/s. The headcut migration prediction equation is as

$$\frac{dX}{dt} = Cq^a h^b \tag{3}$$

where *dX/dt* is the headcut migration rate in m/s, C is the material-dependent coefficient in $s^{-2/3}$, q is the discharge per unit width in m^2/s, h is the initial headcut height in m, and a = b = 1/3. Based on the measured values of *dX/dt*, q and h, the ranges of C values for these five soils are computed. The C values ranges are as follows:

	Minimum C value ($s^{-2/3}$)	Maximum C value ($s^{-2/3}$)
Soil E	2.9×10^{-5}	1.5×10^{-3}
Soil F	3.4×10^{-4}	3.4×10^{-4}
Soil 1	4.4×10^{-5}	2.3×10^{-3}
Soil 2	1.7×10^{-5}	3.3×10^{-3}
Soil 3	4.9×10^{-4}	4.9×10^{-4}

Equation (3) can be used to estimate the headcut migration rate. The following procedure can be used to estimate the headcut migration rate and headcut migration distance and width:

a. Collect soil samples along the potential headcut path and perform sieve analysis to determine D_{90}. An averaged D_{90} value may be used across different soil samples. To be more conservative, the smallest D_{90} may be used.

b. Use Equation (2) to compute the scour depth and initial headcut height.

c. Estimate three percentages from the soil samples: clay, silt, and sand/rock. An averaged value for each percentage can be used across soil samples.

d. Categorize the soil sample based on the soil type (E, F, 1, 2, and 3) based on percentages of clay, silt, and sand. Herein, sand and rock from the soil sample are combined into sand to be more conservative (i.e., sand allows a faster migration than rocks). The criterion to categorize the soil type is the sum of the absolute differences (DIFF) as follows:

$$DIFF = |Clay_0 - Clay_S| + |Silt_0 - Silt_S| + |Sand_0 - Sand_S|$$

where $Clay_0$, $Silt_0$, and $Sand_0$ represent the percentages of the clay, silt, and sand for each of the five soil types (E, F, 1, 2, and 3) from above table; $Clay_S$, $Silt_S$, and $Sand_S$ reprent the percentages of the clay, silt, and sand for the soil sample. For each soil type, the DIFF will be computed. The soil sample belongs to a soil type with the smallest DIFF value.

e. The C values ranges (from above table) for the soil with the smallest computed criterion value (DIFF) should be used to compute the headcut migration rate. Both the minimum and maximum C values should be used to compute the smallest and largest headcut migration rates based on Equation (3). An averaged value of the smallest and largest headcut migration rates can be computed as the final headcut migration rate. To use Equation (3), the unit discharge in Equation (3) may be computed by dividing the overtopping flow peak by the headcut width though the flow rate at the headcut location may be smaller than the overtopping flow peak. However, the use of overtopping flow peak will give a faster headcut migration rate, which is more conservative in terms of estimating avulsion area. If a 2-dimensional model is available, the peak discharge from the 2-dimensional modeling results at the headcut face can be used to compute the unit discharge based on the headcut width.

3.3.1.2.2.4 Erosion Area Caused by Headcut

The headcut travel distance can be computed by multiplying the headcut migration rate by the overtopping flow duration. The erosion area caused by headcut erosion can be delineated by the computed headcut distance and width along the steepest slope from the initial headcut location to the overtopping area.

3.3.1.3 New Flooding Area Caused by Avulsion

Once the avulsion area and depth are estimated, they can be "burned" into the existing topographic data. A 2-dimensional hydraulic numerical model can then be developed to compute the new inundation area. It may be pointed out that since the newly formed channel caused by avulsion will carry flow to a new route, the flow may cause further avulsion downstream. Additional avulsion analysis may be needed.

3.3.1.4 Procedures for Major Channel Avulsion Estimation

a. Identification of channels and channel reaches that have the potential for channel overtopping (existing channel avulsion areas, near apex, channel bends, observed deposition areas, slope break areas ...)

b. Data collection for channel overtopping assessment for 100-year flood under sediment-laden condition with 5 antecedent 10-year flood events (previous HEC-2, HEC-RAS, and HEC-6 models, flow hydrographs for 100-year and 10-year flood events, sieve analysis results from soil samples collected in channels, photos, Manning's n, topographic data, aerial photos, field photos, and other pertinent information).

c. Field visits (photos).

d. Channel overtopping assessment using HEC-RAS sediment transport model (100-year flood, sediment-laden condition, 5 antecedent 10-year flood events) to identify the overtopping locations.

e. Data collection for channel avulsion assessment (d_{50} and clay percent for soil samples on fan overland surface near identified channel overtopping areas, d_{90} for soil samples at the existing tributary channels on overland areas, clay/silt/sand/gravel percentages for soil samples at the existing tributary channels, topographic data for the overland area, fan overland surface slope, overtopping flow hydrograph, aerial photos, field photos, and other pertinent information)

f. Perform downward erosion analysis and/or headcut analysis for each channel overtopping area (if bed shear stress is greater than critical shear stress, perform downward erosion analysis. If not, perform headcut analysis)

g. Estimate and plot the major avulsion area (2-ft erosion avulsion channel due to downward erosion or headcut erosion).

3.3.2 Abrupt Deposition

Abrupt deposition is defined as debris flow or 2-feet thick deposit in one 100-year flood event.

3.3.2.1 Debris Flow

The expected recurrence interval for debris flows in Maricopa County probably exceeds 1,000 years (AZGS, 2010b). This suggests that debris flows are rare events. Most of debris flows will not reach the active areas of alluvial fans, particularly the fans that are located away from the mountain front (AZGS, 2010b). Based on Dorn (2010), there have been at least 56 debris flows in the last century on the north flank of the Ma Ha Tuak Range, Phoenix, Arizona. The storm of January 18-22, 2010 caused three small debris flows on the north side of Ma Ha Tuak Range that traveled 40 m, 80 m, and 130 m. If alluvial fans are located away from the mountain front and have a very mild slope, the debris flow hazard on the alluvial fans should be very minimal. If alluvial fans are immediately located near the mountain front and have a steep slope, debris flow hazard should be considered even though the geomorphic analysis suggests a stable channel condition. Blair and McPherson (1994) suggested that for debris flow type of fan the surface slope is between 5° (8.7%) to 15° (26%). If alluvial fan surface slope is less than 5° or 8.7%, the probability that debris flows will occur should be low. Jackson (1987) also suggested three factors that contribute to debris flows: fan slope $>4^\circ$, watershed area <10 km^2, and basin elevation $>$ 1000 m for Canadian Rocky Mountain areas.

In Maricopa County, if a fan is at the mountain front and has a conic shape with a fan slope greater than 5° (8.7%), then the fan is considered to be active. There is no need to compute the deposit depth. If the fan slope is less than or equal to 5° (8.7%) but larger than 3°

(5%) and the fan apex is within 1 mile of the mountain front, then the debris flow hazard should be assessed. If the fan slope is less than or equal to 3° (5%), the debris flow hazard may not be needed and the standard sediment yield analysis can be used. The factors that affect debris flow are initiation, transport and deposition. AZGS (2010b) gives a detailed discussion on the debris flow process, initiation models and runout models. The initiation models evaluate slope stability to identify potential slope failure. Runout models evaluate the travel distance from the initiation point to the debris flow deposition zone. The recommended models from AZGS (2010b) should be carefully selected to assess the debris flow hazard. The assessment techniques from Giraud (2005) can also be used to assess the debris flow risk.

3.3.2.2 Sediment Deposit Estimation

Engineering analysis should be performed to evaluate if a single flood event may produce 2-ft deep sediment deposit in the depositional area. Sediment yield analysis will be performed for the 100-year flood by using DDMSW 4.6.4d (FCDMC, 2013b) at both the hydrological apex and topographical apex to estimate the sediment flow rate. DDMSW 4.6.4d reports bed load in both volume (ac-ft) and peak flow rate (cfs). DDMSW 4.6.4d reports wash load in volume (ac-ft). Wash load in volume can be used to compute the wash load peak rate by assuming the wash load rate hydrograph follows the same pattern for water flow rate hydrograph. The wash load peak flow rate may be estimated as $Q_{ws_peak} = Q_{water_peak} * Vol_{ws}/Vol_{water}$ where Q_{water_peak} is the water peak flow rate, Vol_{ws} is the wash load volume in ac-ft, and Vol_{water} is the water volume in ac-ft. Once the sediment flow rate hydrograph (wash load and bed load) is known, the sediment deposit can be estimated by using the following methods.

If there are a few well-defined channels downstream of the apex, a one-dimensional sediment transport model such as HEC-6, HEC-6T, Fluvial-12, or HEC-RAS can be used to estimate the sediment deposit areas for each channel for the 100-year flood. The discharge for each channel downstream of the main feeder channel can be estimated by using Manning's equation. However, the angles between the downstream channels and the main feeder channel should be used to estimate the flow rates. It is intuitive to assume the flow rate should be inversely proportion to the angles. The maximum sediment deposit during the entire simulation should be reported as the deposit value. If no channel has sediment deposit more than 2-feet thick, then the area should not be considered active. If one of the channels has 2-feet or more thick sediment deposit, then an area of sediment deposit may be defined as shown the dashed outline in Figure 30. Basically, the downstream end of the sediment deposit area is an arc following the existing contour line and the arc just passes the downstream end of the 2-feet sediment deposit. The upstream end of the sediment deposit area is the apex. The lateral boundaries of the sediment deposit are the lateral erosion lines of the two outer channels. The lateral erosion line can be computed based on a lateral erosion distance measured from the channel banks. The lateral erosion distance can be computed by

multiplying the sum of channel depth and scour depth by 6. 6 is the assumed lateral stability slope (H:V = 6:1) for alluvial channels (Ayres, 2004). The scour depth can be computed based on FCDMC (2013a and 2013b). The active zone due to abrupt deposit is outlined by the dashed line.

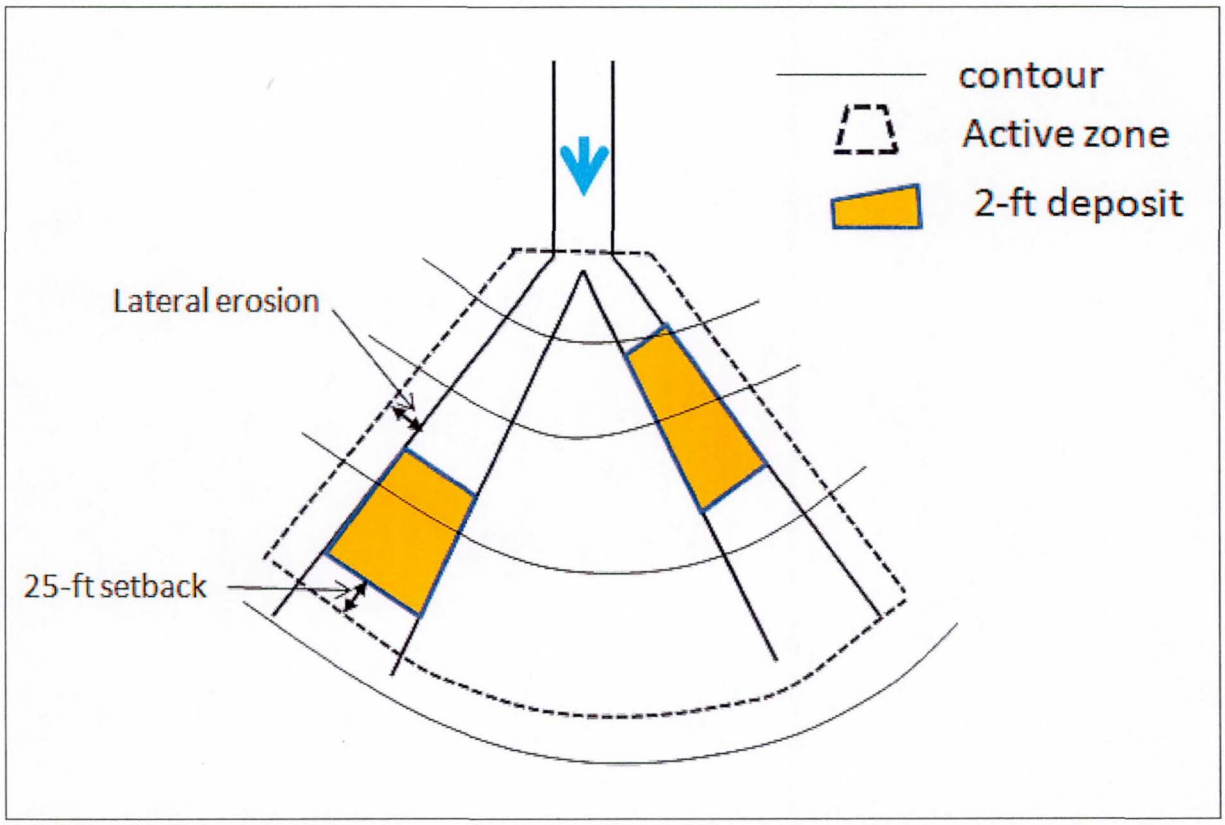


Figure 30. Active Area due to Abrupt Sediment Deposit of at Least 2-ft Deep

Sometimes a simple sediment transport capacity equation Zeller Fullerton equation (FCDMC, 2012) and Manning's equation may be used to estimate the sediment deposit instead of using a one-dimensional sediment transport model. The sediment deposit will occur between two cross-sections if the sediment transport capacity at the upstream cross-section is larger than the sediment transport capacity at the downstream cross-section. The difference in the sediment transport capacity will be uniformly distributed between the cross-sections. The sediment deposit will be estimated for every consecutive pair of cross-sections.

When there are numerous small channels or the downstream channels are not obvious, a two-dimensional sediment transport model can be used to compute the maximum sediment deposit during the simulation. Similar to Figure 30, the active area should include lateral erosion zone on the lateral sides and the most downstream end of the 2-ft sediment

deposit. However, if there are isolated 2-ft sediment deposit areas which are not connected to the main depositional area, they may not be part of the active area.

3.3.2.3 Procedures for Abrupt Sediment Deposition

a. Data Collection (fan surface slope, drainage area, sieve analysis for soil samples at the hydrographic and topographic apexes, peak flow rates and runoff volumes of 100-year flood at the apexes, 100-year flood flow hydrographs at the apexes, soil and land use GIS shape files and other parameters for sediment yield analysis, aerial photos for the drainage area, topographic data, previous hydraulic models, Manning's n, field visit photos,)

b. Field visits (photos)

c. Perform debris flow analysis to identify the debris hazard areas (if fan slope is larger than 3° or 5% but less than or equal to 5° or 8.7%) based on AZGS (2010b). Discussion shall be provided about the selection of an initiation model and a runout model. More data collection is needed to perform this analysis (see AZGS, 2010b).

d. Estimate the flow rates for each split channel if there are split channels.

e. Perform sediment yield analysis and estimate the sediment inflow hydrographs for sediment transport models

f. Perform sediment transport analysis by HEC-RAS sediment transport model, Zeller-Fullerton sediment transport capacity equation, or two-dimensional hydraulic model to identify areas with at least 2-ft maximum deposit during the entire simulation.

g. Perform scour analysis for channels and estimate the lateral erosion distance by multiplying the sum of total scour depth and channel depth by 6.

h. Estimate and plot the abrupt deposition area (at least 2-ft deep deposit). Prepare a GIS polygon shape file.

i. Combine the major avulsion area and abrupt deposition area

3.3.3 Alluvial Fan Active Area

The active area consists of hazardous area caused by major channel avulsion or abrupt deposition. The hazardous area caused by major avulsion is estimated based on downward erosion and upward headcut of at least 2-feet deep due to overtopping of flow in channels. The hazardous area caused by abrupt deposition is estimated based on sediment deposit of at least 2-feet thick. An illustrative example of such an active area can be seen in Figure 31. Figure 31 shows two avulsion channels which join the fan channels downstream. The downstream end of the active area can be following the contour line. When the avulsion channels diverge from the fan channels or the area between the avulsion channel and the fan channels are very large, the area between the avulsion channel and fan channels can be considered inactive as shown in Figure 32.

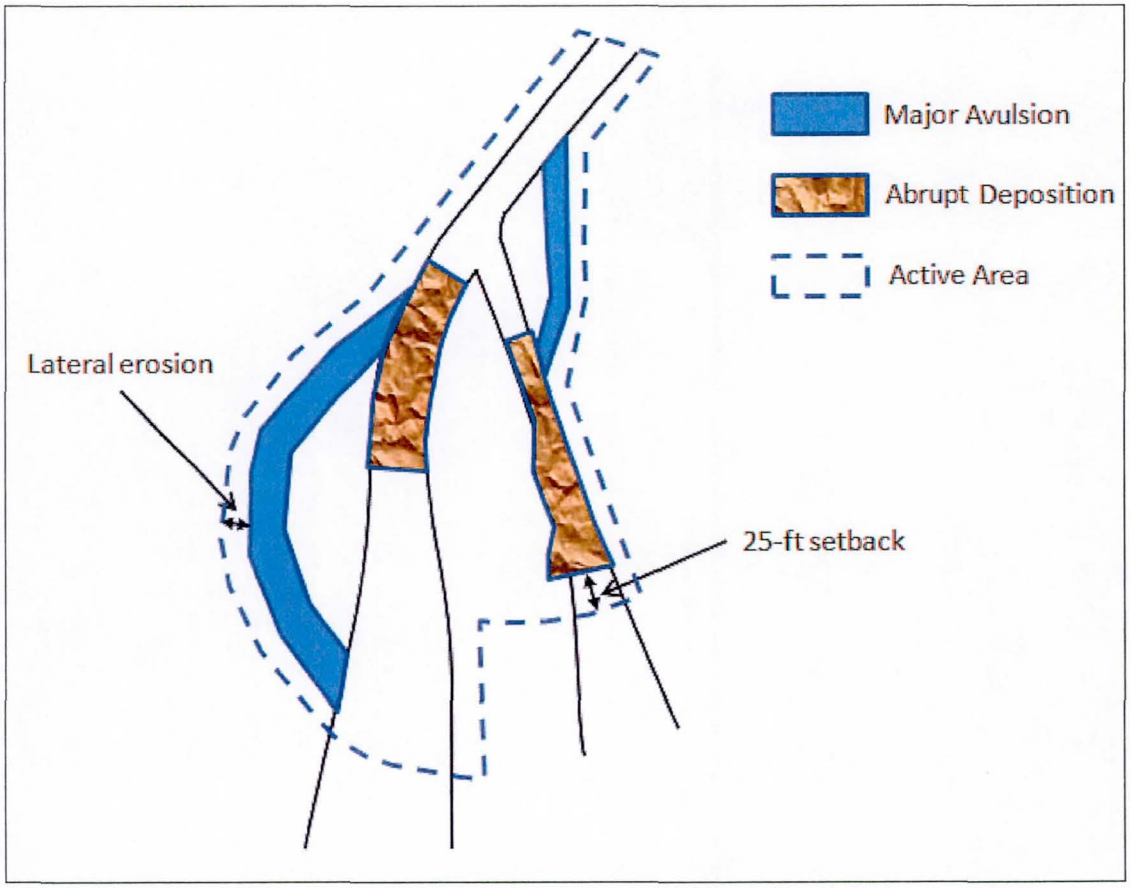


Figure 31. Active Area due to Major Avulsion (≥2-ft erosion) and Abrupt Sediment Deposit (≥2-ft deposit)

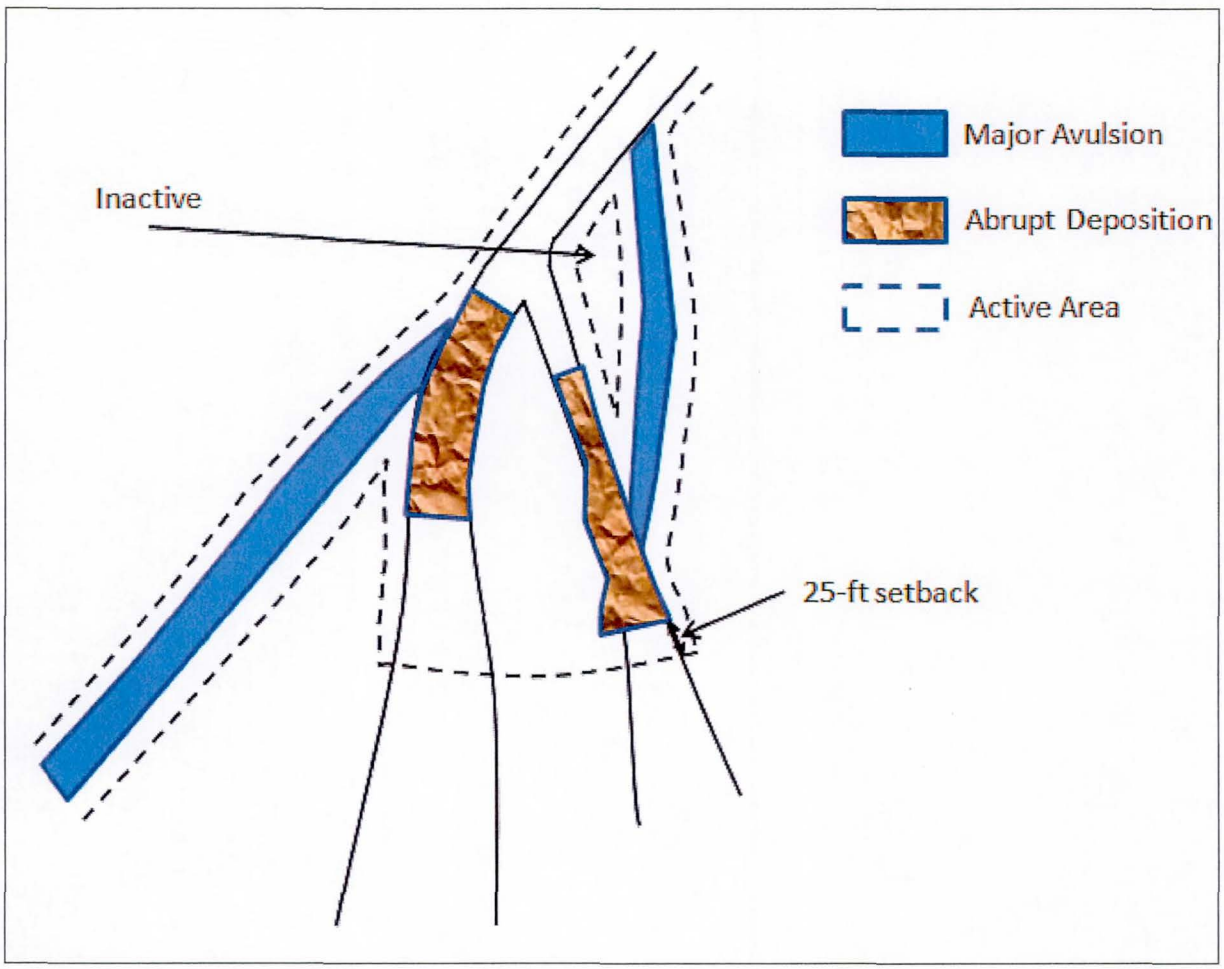


Figure 32. Modified Active Area due to Diverged Major Avulsion (≥2-ft erosion) and Abrupt Sediment Deposit (≥2-ft deposit) and Inactive Area between Avulsion Channel and Fan Channels.

3.4 Application of Step 2 of Stage 2 to Fan 5 and Fan 6

Based on previous Step 1 for geomorphic analysis and subsurface exploration, Fan 5 and Fan 6 are inactive. Therefore, engineering analysis is not necessary for channel avulsion and abrupt sediment deposition analyses.

3.5 Summary of Stage 2

A Stage 2 step-by-step procedure is developed by following the 2003 FEMA Stage 2 methodology with details related to geomorphology, geology, and engineering that are applicable to Maricopa County, Arizona. This step-by-step procedure consists of two steps. Step 1 is geomorphic analysis and subsurface exploration. Step 2 is engineering analysis. Although Fan 5 and Fan 6 do not have a typical alluvial fan landform based on Stage 1 results, this Stage 2 step-by-step procedure is still applied to both fans to determine if they are active or inactive. Based on Stage 2's Step 1 results, Fan 5 and Fan 6 are inactive. Step 2 is not needed since Fan 5 and Fan 6 are determined to be inactive in Step 1. Figure 33 shows how the Stage 2 flowchart is implemented for Fan 5 and Fan 6. The green arrowed line shows how the flow chart is implemented.

4. FEMA Stage 3

Since the FEMA Fan 5 and Fan 6 are inactive, deterministic floodplain delineation methods that can handle distributary flow areas should be applied to the area of FEMA Fan 5 and Fan 6 for the 100-year flood delineation, which will be carried out under a different study.

5. Summary and Conclusions

Six piedmont areas in Scottsdale and Phoenix, Maricopa County, Arizona were delineated as alluvial fan flooding areas by FEMA in 1993 (FEMA, 1995). The delineation was based on the 1991 FEMA methodology (FEMA 37) for analyzing areas subject to alluvial fan flooding (Guidelines and Specifications for Study Contractors, 1991). The purpose of this study is to re-analyze two of the six alluvial fans (Fan 5 and Fan 6) based on the 2003 FEMA's three-stage approach, the latest FEMA guideline for alluvial fan delineation. The results from Stage 1 analysis indicate that Fan 5 and Fan 6 do not have a typical alluvial fan landform. Based on Stage 2 analysis, Fan 5 and Fan 6 are found to be inactive. A deterministic floodplain delineation model that can handle distributary flow areas can be used to re-delineate the study area in Stage 3, which will be carried out under a different study.

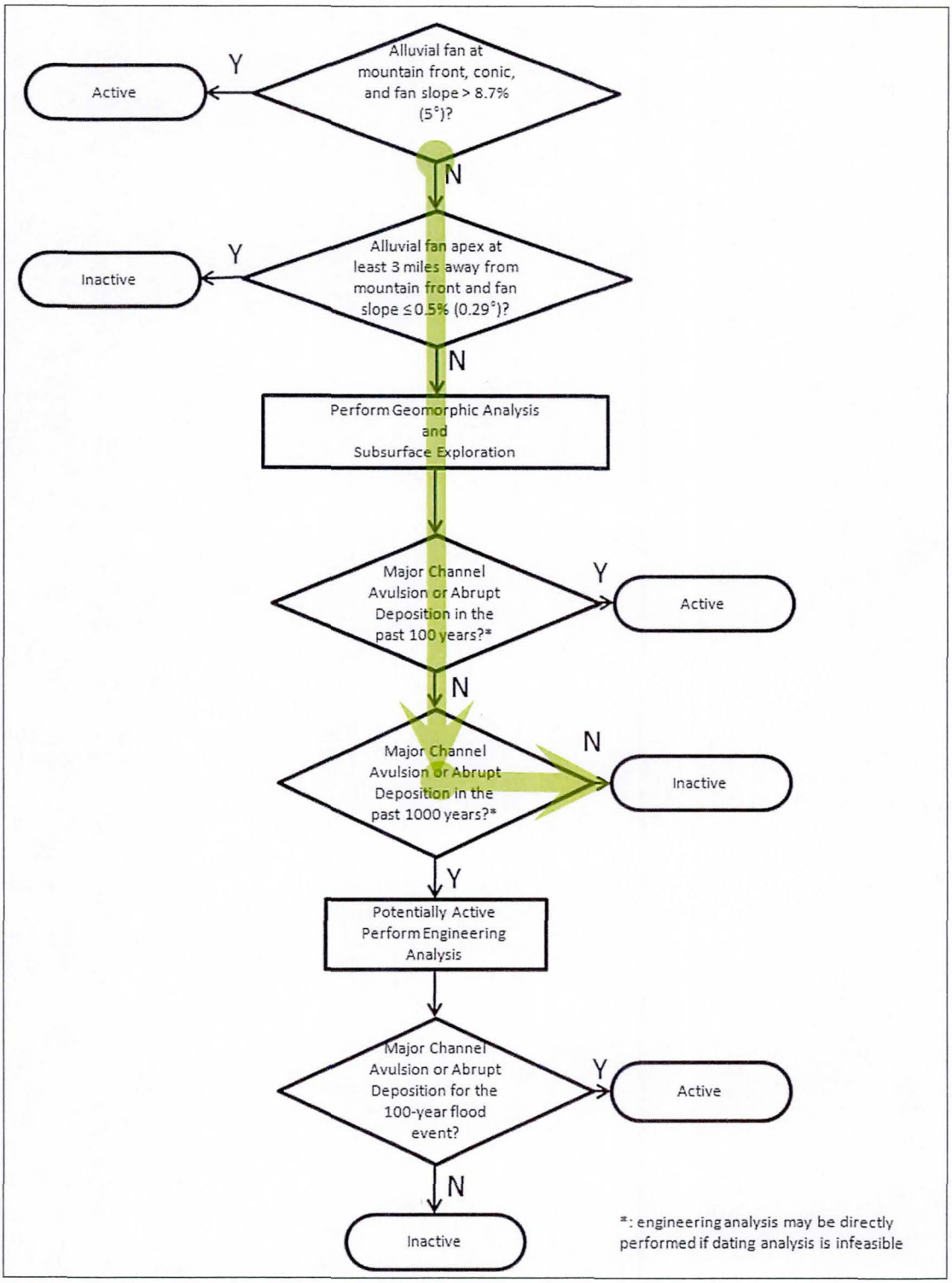


Figure 33 Stage 2 Flowchart Implementation for Fan 5 and Fan 6.

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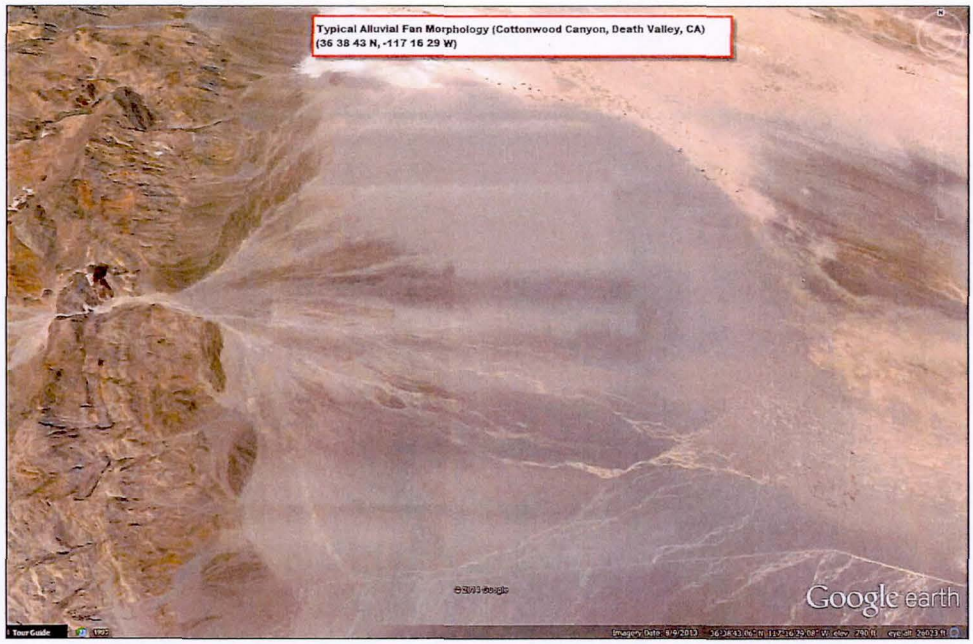
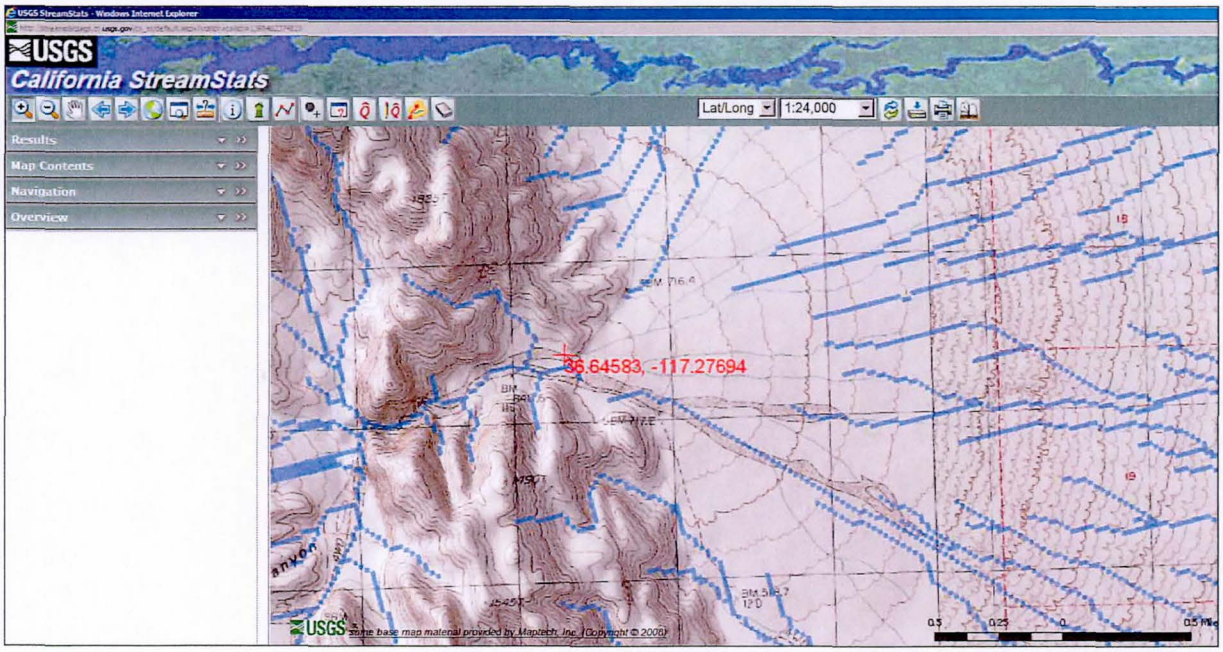
Appendix 1. Typical Alluvial Fan Morphology (Cottonwood Canyon, Death Valley, California)

The following two figures are generated by using Google Earth tool and an Internet interactive map from USGS StreamStats for California (http://water.usgs.gov/osw/streamstats/california.html) for Cottonwood Canyon, Death Valley, California. The exact location (latitude and longitude) can be found from these two figures.