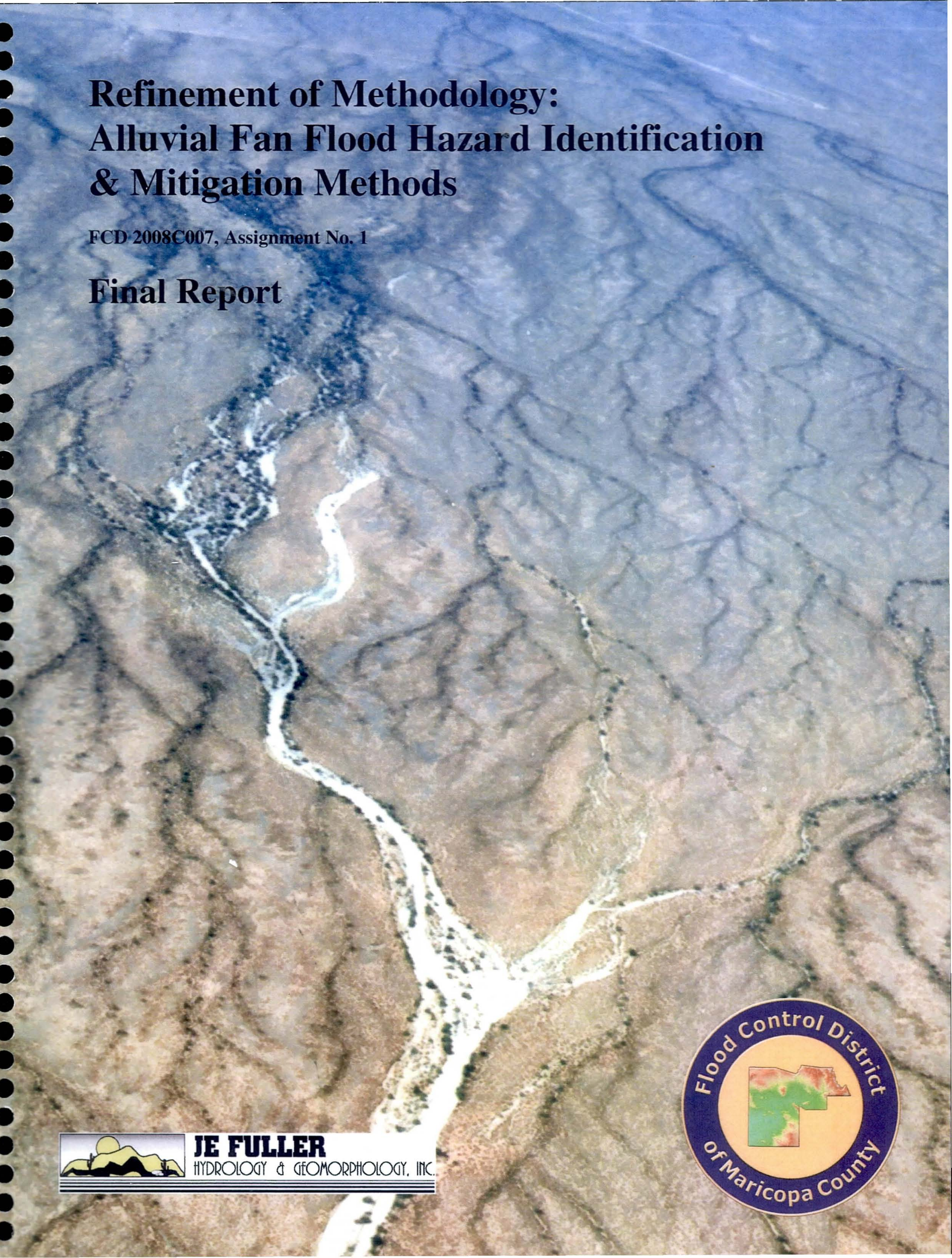
Refinement of Methodology: Alluvial Fan Flood Hazard Identification & Mitigation Methods

FCD 2008C007, Assignment No. 1

Final Report



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Executive Summary

The "Refinement of Methodology: Alluvial Fan Hazard Identification & Mitigation Methods Study" (PFHAM Study) was initiated to develop guidelines and recommendations for regulations that will be used to identify, classify and address flood hazards on alluvial fan landforms in Maricopa County, Arizona. The scope of work for this study called for professional engineering services needed to update and refine the Flood Control District of Maricopa County's (District) current Piedmont Flood Hazard Assessment Manual (PFHAM) methodology, to identify engineering procedures to quantify flood hazards on alluvial fan landforms, to recommend hazard mitigation measures, and to refine landform definitions used in the PFHAM. The methodologies proposed in this report are intended for application to alluvial fans in Maricopa County, Arizona. While the proposed analytical methodologies may be applicable to other types of alluvial fans and uncertain flow path flood hazard areas, such applications are beyond the scope and intent of this report.

The types of alluvial fan flood hazards found in Maricopa County are representative of piedmont surfaces in tectonically inert portions of the semi-arid southwestern United States. Alluvial fan landforms in Maricopa County tend to have relatively low slopes (< 3%) and are dominated by low volume, flash floods. Active alluvial fans make up a small percentage of the alluvial fan landform surfaces in Maricopa County. The active fan areas tend to be located away from mountain fronts, are of limited areal extent, and to be dominated by shallow sheet flooding, except in the zones closest to the hydrographic apexes. Debris flows are not a significant risk for most active alluvial fans in Maricopa County. Avulsions have been documented on several active alluvial fans in Maricopa County, but are thought to occur with relatively low frequency, primarily during large water floods.

To develop the recommended Integrated Alluvial Fan Hazard Assessment Methodology in Maricopa County, the following tasks were completed:

- **Literature Search**. Relevant publications and guidance documents on alluvial fan flooding were researched to identify potential assessment, management and modeling procedures. It was documented that alluvial fans in Maricopa County tend to lie at the low end of the hazard spectrum of fans described in the literature.
- **Historical Analysis**. A review of four active alluvial fans in Maricopa County that had been urbanized over the past 40 years indicated minor sedimentation and maintenance problems, but no flooded homes or failures of structural flood control measures. However, none of the sites has yet experienced a design flood.
- **Surficial Dating Techniques**. A review of geologic dating methods determined that numerical methods are available that would be applicable in Maricopa County, but that a regional dating chronology study would be required to fully implement significantly higher resolution surficial dating.
- **Debris Flow Hazards**. A study of debris flow risk concluded that debris flows are unlikely to affect alluvial fan flooding in Maricopa County. A composite methodology for quantifying debris flow risk was developed for use on local fans.
- **Alluvial Fan Site Analyses**. Four alluvial fan sites, representing a range of typical alluvial fan conditions found in Maricopa County, were selected for more

detailed hydrologic, hydraulic, sediment, and geomorphic analyses. The site analyses were used to formulate the recommended Integrated Alluvial Fan Hazard Assessment Methodology.

- **Hydrologic Modeling**. The following conclusions were derived from the hydrologic modeling analyses:
    - FLO-2D is preferred over HEC-1 for modeling fans and alluvial plains.
    - Significant flood peak attenuation occurs below the hydrographic apex.
    - Use of the apex discharge is overly conservative in the distal fan areas.
- **Hydraulic Modeling**. The following conclusions were derived from the hydraulic modeling analyses:
    - FLO-2D modeling is preferred for modeling fans and alluvial plains.
    - Most fans in Maricopa County are dominated by shallow sheet flooding.
    - High depth and velocity zones are limited in extent on most fans.
    - Unregulated development on alluvial fans will adversely impact downstream areas.
- **Sedimentation Modeling**. The following conclusions were derived from the sediment modeling analyses:
    - No sediment model was identified that adequately depicts alluvial fan sedimentation processes.
    - Single event sedimentation is very low relative to the total active fan area.
    - Long-term sedimentation may impact alluvial fan flooding processes.
    - There is a lack of sediment data needed for development, calibration and verification of alluvial fan sediment models.
- **Avulsion**. The following conclusions were derived from the avulsion analysis:
    - Avulsions are known to occur on fans in Maricopa County.
    - Avulsions occur rarely, but the expected frequency is as yet unknown.
    - A methodology was developed to predict potential avulsion hazards.
    - A methodology, called the virtual levee scenario method, was developed using FLO-2D modeling to simulate the potential impact of avulsions on alluvial fan flood hazards.
- **Flood Hazard Classification**. A methodology was developed to quantify flood hazards on alluvial fans into ultrahazardous, high, moderate and low categories. The method is based on FLO-2D modeling results, assessments of debris flow and avulsion risk, and the 100-year discharge. Portions of active alluvial fan floodplains subject to ultrahazardous "active alluvial fan flooding" would be subject to special FEMA criteria. The remainder of the 100-year flooding on active alluvial fans may be subject to high, moderate, or low hazard are subject to lower, less restrictive development criteria.

Based on the results of the analyses described above, a recommended Integrated Alluvial Fan Hazard Assessment Methodology was developed. The methodology, illustrated in Figure E-1, is a composite of engineering and geomorphic modeling techniques, meets FEMA criteria for evaluation of alluvial fan flood hazards, and consists of the following three steps:

- **Stage 1: Landform Identification**. In Stage 1, it is determined whether a study area lies on an alluvial fan landform, as opposed to a riverine floodplain or alluvial plain landform. Alluvial fan landforms are advanced for Stage 2 analysis.

- **Stage 2: Definition of Active and Inactive Areas**. In Stage 2, the active portions of alluvial fan landforms are distinguished from inactive portions. The active portions of alluvial fan landforms are advanced forward for analysis in Stage 3. Inactive alluvial fan areas can be evaluated using more traditional techniques.
- **Stage 3: Delineation of Regulatory Floodplain**. In Stage 3, the portions of an active alluvial fan that are subject to inundation during a 100-year flood are delineated. The result of the Stage 3 analysis is a regulatory floodplain delineation map and quantified flood hazard information. The floodplain delineation distinguishes ultrahazardous "active alluvial fan flooding" areas subject to the most severe FEMA restrictions, from other less hazardous types of flooding on active alluvial fans and piedmont areas with uncertain flow paths. The less hazardous flood zones include classifications from which appropriate floodplain management strategies can be formulated.

The recommended Integrated Alluvial Fan Hazard Assessment Methodology in Maricopa County was reviewed and endorsed by a "Blue Ribbon Panel" of alluvial fan experts from across the United States and who represented a wide variety of technical, scientific, and regulatory disciplines. The Blue Ribbon Panel recommended that the integrated methodology be applied to a representative alluvial fan in Maricopa County, and submitted to FEMA together with the PFHAM Study documentation as a test case.

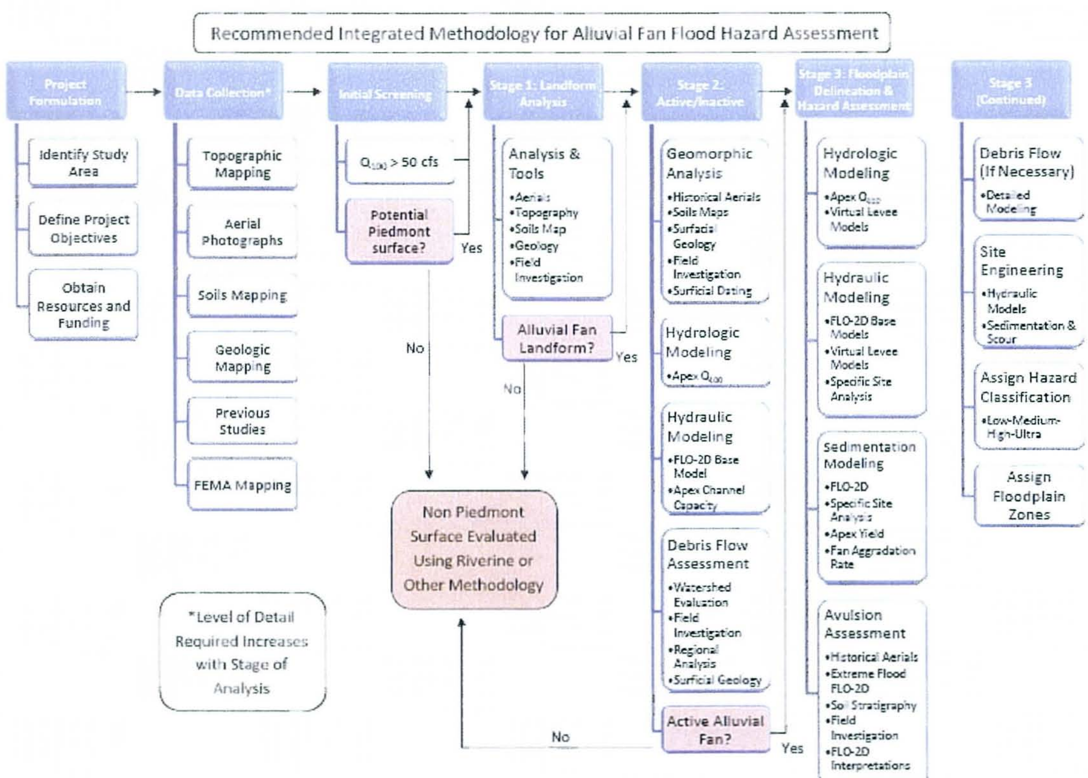

Figure E-1. Decision tree matrix showing the recommended integrated methodology.

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1. Introduction

1.1. Objectives

This study is officially entitled "Refinement of Methodology: Alluvial Fan Hazard Identification & Mitigation Methods." In this report, it is referred to as the "PFHAM Study." The PFHAM study was initiated to develop guidelines and recommendations for regulations that will be used to identify, classify and address flood hazards on alluvial fan landforms in Maricopa County, Arizona.

1.2. Scope

The scope of work for this study called for professional engineering services needed to update and refine the Flood Control District of Maricopa County's current Piedmont Flood Hazard Assessment Manual (PFHAM) methodology, to identify engineering procedures to quantify flood hazards on alluvial fan landforms, to recommend hazard mitigation measures, and to refine landform definitions used in the PFHAM. Specific study tasks are listed in the project scope of services included in Appendix L.

1.3. Applicability

The methodologies proposed in this report are intended for application to alluvial fans in Maricopa County, Arizona. The types of alluvial fan flood hazards found in Maricopa County are representative of piedmont surfaces in tectonically inert portions of the semi-arid southwestern United States. While the proposed analytical methodologies may be applicable to other types of alluvial fans and uncertain flow path flood hazard areas, such applications are beyond the scope and intent of this report.

1.4. Authority

This study was performed under contract FCD 2008C007, Work Assignment #1 by JE Fuller/Hydrology & Geomorphology, Inc. (JEF) on behalf of the Flood Control District of Maricopa County (District).

1.5. Study Participants

The PFHAM study was conducted as a cooperative effort between the consultant team and a special Alluvial Fan Task Force composed of staff from the District's Engineering, Planning, and Regulatory Divisions. State and local agencies with special interest in alluvial fan floodplain hazards also participated in the study. Finally, the results and recommendations of the PFHAM study were peer-reviewed by a "Blue Ribbon Panel" of technical experts from academia, regulatory agencies, and consulting engineering firms.

A complete listing of the study team members is provided in Appendix M.

1.6. Terminology

One of the key findings of the PFHAM study is the importance of precise terminology when discussing alluvial fan flood hazards. This is especially true for the term "alluvial fan." Much of the confusion and controversy about alluvial fan flood hazards stems from miscommunication over what is meant by this term. In this report, unless stated otherwise, the term "alluvial fan" refers to an alluvial fan landform. Alluvial fan landforms are geologic features composed of alluvial deposits that usually have a fan shape. In Maricopa County, alluvial fan landforms are part of a set of landforms developed in the low gradient portion of the fluvially dominated margins of low relief basins and mountain ranges. Use of the phrase "alluvial fan landform" has implications that relate to its formative processes operating over long periods of geologic time, but has no definitive implications regarding flood processes that occur within engineering time scales.

The flood hazard assessment methodologies described in this report apply to "active" alluvial fans, which comprise a minority of the alluvial fan landform surfaces in Maricopa County. The phrase "active alluvial fan" implies a set of processes that have occurred in recent geologic time and which may or may not be operating within relatively short engineering time scales. These "active" fan processes can be inferred from the physical characteristics of the alluvial fan landform. Adding confusion to the phrase "active alluvial fan" is that FEMA has tied specific regulatory requirements, conditions, and inferred flood processes to a vary similar term, "active alluvial fan flooding." In this report, the phrase "active alluvial fan" is used in a geologic sense, and relates to the Stage 2 delineation in the FEMA guidelines. "Active alluvial fan flooding," the phrase which is tied to the most restrictive FEMA regulations, is only applied in Stage 3 of the recommended methodology described in this report.

Finally, an active alluvial fan "floodplain," which is the primary focus of this report, represents only the portion of an active alluvial fan that is at risk of inundation by the one-percent chance flood. A portion of an active alluvial fan floodplain may be subject to "active alluvial fan flooding," as that term is current defined and regulated by FEMA, and is limited to the "ultrahazardous" portions of the 100-year floodplain on an active alluvial fan. The remainder of the 100-year flooding on active alluvial fans may be subject to varying degrees of flood hazards (classified as high-moderate-low in this report), but those flood hazards do not rise to the level of "ultrahazardous." To avoid at least some of the confusion relating to this similar-sounding, but fundamentally different terminology, alternative terminology utilizing terms such as "active piedmont flooding" is proposed as part of the recommended methodology described in Section 3 of this report.

More detailed discussion of terminology and recommended definitions for key terms is provided in Section 3.1 of this report.

2. Summary of Findings

A variety of technical, regulatory, administrative and bibliographic tasks were performed for the PFHAM study, including the following:

- Literature Review
- Evaluation of Historical Development on Alluvial Fan Landforms
- Alluvial Fan Site Evaluations
- Sedimentation Evaluation
- Holocene Dating Techniques
- Debris Flow Potential Assessment
- Avulsion Potential Evaluation

A summary of the findings of each of these tasks is provided in the following paragraphs.

2.1. Literature Review

2.1.1. Alluvial Fan Literature Search

In 2008, JEF performed a specialized literature review for the District under contract FCD2007C051, Work Assignment #1. This literature review focused on the following specific research topics relating to alluvial fans:

- Existing Alluvial Fan Floodplain Delineation Methodologies
- FEMA CLOMR/LOMR[1] Methodologies
- NRC Alluvial Fan Committee Interviews
- Debris Flow Hazard and Risk Assessment
- Frequency of Alluvial Fan Channel Avulsions
- Alluvial Fan Flood Mitigation Measures
- Alluvial Fan Flood Hazard Quantification Methods

For each research topic, separate memoranda were provided to the District and were revised in response to District comments. The literature collected and the memoranda summarizing the findings are included on the DVD attached to Appendix A.

Existing Alluvial Fan Floodplain Delineation Methodologies. The literature research revealed that Maricopa County is one of the few communities to have developed comprehensive alluvial fan floodplain delineation techniques. Existing alluvial fan floodplain delineation methods used in Maricopa County comply with FEMA procedures, as outlined in *Guidelines and Specifications for Flood Hazard Mapping Partners, Appendix G: Guidance for Alluvial Fan Flooding Analyses and Mapping* (hereafter, the FEMA Guidelines; FEMA, 2003). The FEMA Guidelines essentially follow the procedure recommended in the National Research Council (NRC, 1996) report

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[1] CLOMR: Conditional Letter of Map Revision; LOMR: Letter of Map Revision.

Alluvial Fan Flooding. The FEMA Guidelines allow a number of delineation methodologies that include geomorphic methods, one- and two-dimensional fixed bed hydraulic modeling, and composite methods that combine engineering and geologic approaches. Since 1998, Maricopa County has primarily applied a floodplain delineation methodology that relies heavily on geomorphic interpretation. None of the other communities and agencies investigated have adopted alluvial fan management or delineation practices which differ significantly from the FEMA Guidelines, would improve on the existing PFHAM methodology, or offer technical guidance for quantifying flood hazards on fluvially-dominated fans (as opposed to debris flow fans).

FEMA CLOMR/LOMR Methodologies. Review of past alluvial fan CLOMR and LOMR submittals reviewed by FEMA indicated that structural measures are the primary approach to mitigating alluvial fan flood hazards. Few new alluvial fan delineations have been performed since publication of the NRC *Alluvial Fan Flooding* report and subsequent revision of FEMA's Appendix G guidelines. All new alluvial fan floodplain delineations are required to use the three-stage methodology developed by the NRC *Alluvial Fan Flooding* Report.

NRC Alluvial Fan Committee Interviews. Follow-up interviews with the original NRC Alluvial Fan Task Force Committee members revealed the that the members have performed no new research on alluvial fan flood hazard assessment work since publication of the NRC *Alluvial Fan Flooding* report and FEMA's adoption of the Committee's recommended approach. All of the NRC committee members continue to regard their report as ground-breaking work, and consider the report to still be relevant for flood hazard assessment on alluvial fans.

Debris Flow Hazard and Risk Assessment. The debris flow hazard and risk assessment literature search revealed a large body of technical work, primarily from mountainous regions in Europe. Review of the literature indicated that a more focused analysis of debris flow hazards in Maricopa County was warranted. A more locally relevant evaluation of debris flow potential and modeling methodologies was completed as part of the PFHAM study, and is described in Section 2.6 of this report. The PFHAM evaluation concluded that debris flows pose minimal risk to most alluvial fans in Maricopa County.

Frequency of Alluvial Fan Channel Avulsions.[2] Very few studies of alluvial fan avulsion frequency were identified in the literature review. A few examples of historical and recent avulsions on the Tiger Wash alluvial fan, on fans along the western White Tank Mountain piedmont, and on fans in Rainbow Valley are described in reports by the Arizona Geological Survey (AZGS) as well as in related flood study reports previously prepared for the District (e.g., CH2M HILL, 1992; JEF, 1999, 2001). However, no statistical relationships for avulsion frequency on alluvial fans were discovered. Therefore, more detailed evaluation of avulsion frequency, as well as methods of predicting avulsions was authorized as part of the PFHAM study, the results of which are described in Section 2.7 and Appendix I of this report.

[2] The Blue Ribbon Panel (Section 4.7) also recommended more detailed analysis of avulsion frequency.

Alluvial Fan Flood Mitigation Measures. Descriptions of flood mitigation measures for debris flows and landslides are found in some of the European literature sources. Examples of alluvial fan flood mitigation measures from fans in America are summarized in reports by the US Army Corps of Engineers (HEC, 1993; USACE, 2004), and consist of rather standard engineering designs for channels, basins, and diversion structures. FEMA does not currently have engineering details or specific analysis guidelines for design of flood mitigation measures on alluvial fans. The NFIP Regulations (CFR 44, Chapter 1, Part 65.13) require that structural measures on alluvial fans address flow path uncertainty, sedimentation and erosion, debris flow, local inflow and system operations and maintenance, but provide no specific guidance on engineering methodologies, hazard quantification, or design criteria.

Alluvial Fan Flood Hazard Quantification Methods. The District's current version of the PFHAM is essentially a floodplain delineation methodology, and does not specifically address quantification of alluvial fan flood hazards and engineering design. The literature search identified three basic types of alluvial fan floodplain delineation methods: (1) probabilistic models, such as the FEMA FAN model, a.k.a., the Dawdy Method (Dawdy, 1979), (2) geomorphic methods, of which the District's current PFHAM is one, and (3) composite methods that combine elements of the geomorphic method and hydraulic modeling techniques. Because of FEMA's acceptance of the geomorphic method described in the NRC *Alluvial Fan Flooding* report, most new alluvial fan floodplain delineation studies have relied primarily on geomorphic-type delineation techniques. The literature search did identify several methodologies that may be useful for quantifying some elements of alluvial fan floodplain delineation studies and flood hazard assessments. However, none of these methodologies were developed specifically for floodplain management purposes, and none have been formally adopted by regulatory agencies, including FEMA.

2.1.2. Alluvial Fan Characteristics Data Collection

In 2009, JEF performed a specialized literature review for the District under contract FCD2007C051, Work Assignment #4. An analysis of the alluvial fans described in the literature sources collected and catalogued as described in Section 2.1.1 above was completed to document their physical characteristics and to investigate whether the information obtained in the literature search was relevant to alluvial fan flood hazards in Maricopa County. For this assignment, each collected article was reviewed and the individual alluvial fans discussed in each source were described. Excel and GIS databases of the alluvial fan characteristics, including their location, were created. The following data were obtained for each fan site in the literature list:

- Fan location
- Physiographic descriptors such as apex elevation, maximum watershed elevation, approximate climate type and vegetative cover
- Fan slope (landform and channel)
- Watercourse channel bed slope (above the fan apex)
- Watershed drainage area (above the fan apex)
- Distance from the apex to the mountain front
- Fan area below the apex

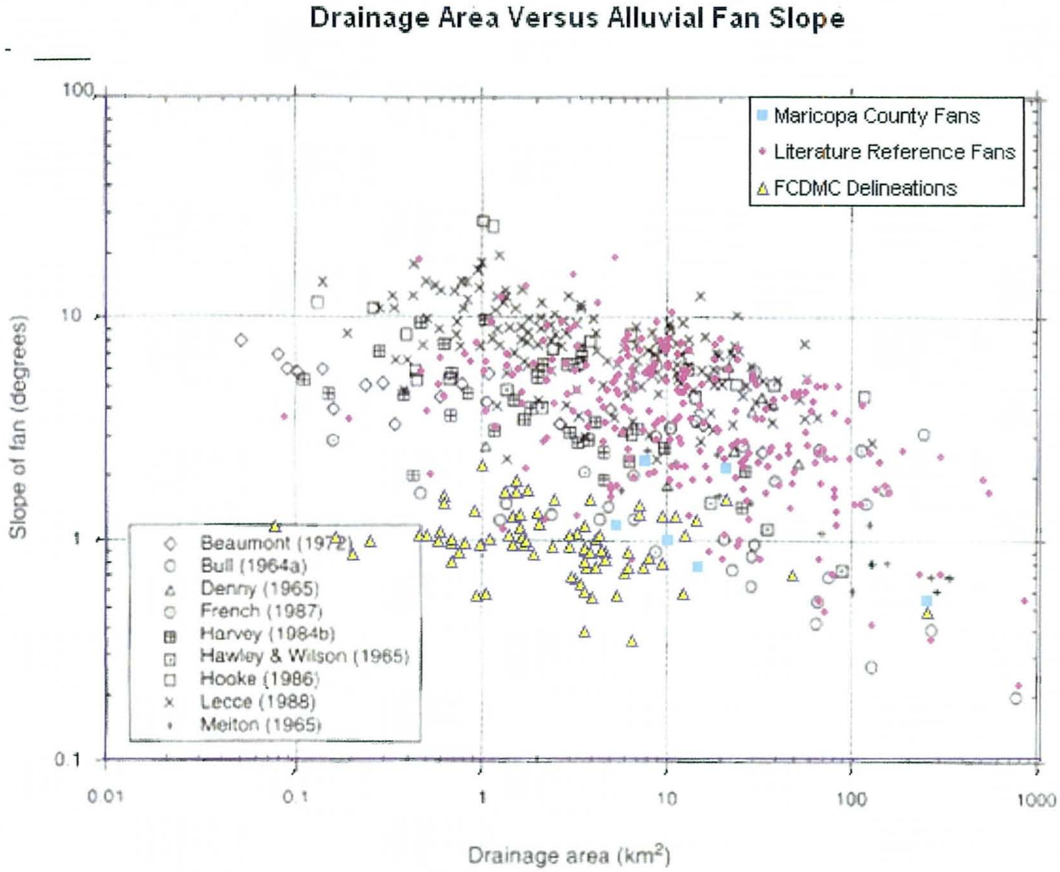

Figure 1. *Plot of fan slope (degrees) vs. drainage area (km2) from Givens (2004) with data from Maricopa County fan sites superimposed (blue squares).*

The following conclusions were drawn from the analysis of the alluvial fans described in the literature:

- Fan slopes ranged from less than one percent to greater than 10 percent. Most of the fans described had slopes greater than 1.7 percent (1 degree).
- Drainage areas ranged from less than one square mile to greater than 75 square miles. Most (67%) of the fan drainage areas described in the literature were less than 10 square miles.
- Fan surface areas ranged from less than 0.5 square miles to greater than 10 square miles. About half (48%) of the fan surface areas were less than one square mile.
- Fan apex elevations ranged from below sea level to above 6,000 feet, with no discernable trend or distribution.
- Most (89%) of the fans are located in arid regions with desert rangeland vegetation, with nearly half of the fans described located in California. Arizona ranked second in the number of fan sites described.
- Approximately 75 percent of the fans have no FEMA floodplain delineation.

Based on this analysis, most alluvial fans in Maricopa County probably lie within, but near the lower end of, the cloud of common values of characteristics for alluvial fans described in the literature, as illustrated in Figure 1. Therefore, the analyses, results, conclusions, and information in the literature sources collected can be assumed to be reasonably relevant to flood hazard assessments on alluvial fans in Maricopa County.

2.1.3. Sheet Flooding Literature Search

There are a range of flow behaviors on alluvial fans, but sheet flooding was found to be of particular importance for piedmont surfaces in Maricopa County. A supplemental literature search task was authorized under contract FCD2007C051, Work Assignment #6, to collect and evaluate sheet flooding literature that might better elucidate alluvial fan flooding issues in Maricopa County. The sheet flooding literature review focused on the following research topics:

- Definition of the term "sheet flooding"
- Defining characteristics of sheet flooding
- Characteristics that distinguish general sheet flooding from alluvial fan sheet flooding
- Flood hazards unique to sheet flooding areas
- Hydrologic and hydraulic modeling tools specifically for sheet flooding areas
- Floodplain regulations or development guidelines for managing sheet flooding areas

One of the key findings of the supplemental literature search was that the term "sheet flow" is used imprecisely in the literature, and that the term "sheet flooding" more accurately describes the natural flood processes that occur on alluvial fans. Therefore, the term "sheet flooding" is used throughout this report and is recommended for use in any future updates of the PFHAM.

Definition(s) of Sheet Flooding. A sheet flood is defined as a broad expanse of unconfined[3] runoff moving downslope (McGee, 1897). Sheet floods have relatively low frequency and high magnitude (Hogg, 1982), while the flow itself is generally shallow and short-lived and has a limited travel distance. Sheet flooding is produced by large discharges, most commonly from high-intensity rainfall, combined with the absence of channelized drainage (Blair & McPherson 1994). The Arizona Department of Water Resources (ADWR) State Standard 4-95 defines types of sheet flooding, which conform to the definition given above. The Maricopa County Floodplain Regulations do not have a definition for sheet flooding (or sheet flow), although the Definitions Section indicates that sheet flooding occurs on portions of alluvial fans.[4] However, it is noted that the defining characteristics listed in the next paragraph may constitute a clearer, more practical definition of sheet flooding than those used above.

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[3] Note that all runoff must be confined in some manner. "Unconfined" is used here to indicate a lack of well-defined flow paths, floodplains, and/or terrains that form obvious lateral boundaries.
[4] See definitions for Alluvial Fan Uncertain Flow Distribution (AFUFD) and Alluvial Fan Zone A (AFZA).

Defining Characteristics of Sheet Flooding. The defining characteristics of sheet flooding include the following:

(1) Flood waters that occur as a broad unconfined sheet
(2) Flat or low slopes, both laterally and longitudinally
(3) Few or no well-defined channels, and a high density of sub-parallel, poorly defined, discontinuous micro-"channels"
(4) Flow conveyed over an unchannelized land surface
(5) Flow depths ranging from several inches (commonly) to several feet (rarely)
(6) Significant loss of flow volume due to infiltration and other abstractions
(7) Ability to transport sediment over large distances on low slopes
(8) Unpredictable flow directions because of low lateral relief, shifting channels, and/or clogging of flow paths by debris or sediment.

Characteristics that Distinguish General Sheet Flooding From Alluvial Fan Sheet Flooding. The literature search did not yield any articles that distinguish general sheet flooding from sheet flooding on an alluvial fan surface. A wide variety of literature sources affirm that sheet flooding does occur on alluvial fans (e.g., NRC, 1995; FEMA, 2003), but none were found that proposed that alluvial fan sheet flooding has characteristics unique to alluvial fans or that are different from sheet flooding on other landforms.

Flood Hazards Unique to Sheet Flooding Areas. No hazards unique to sheet flooding areas were identified in the literature. Sheet flood hazards identified in the literature included: (1) structure inundation (at shallow depths), (2) obscure flow paths that create unconfined flow and uncertain flow distribution, (3) problems resulting from concentration of flow, (4) roadway inundation, (5) under-design of roadway cross drainage structures, (6) erosion and scour, (7) hydrodynamic forces, (8) sediment deposition, and (9) channel avulsion. All of these hazards are also found on other landforms.

Hydrologic and Hydraulic Modeling Tools Specifically for Sheet Flooding Areas. The literature search did not yield any articles about hydrologic or hydraulic modeling tools developed specifically for sheet flooding areas. There are numerous models which can model shallow flooding (e.g., HEC-RAS, FLO-2D, etc.), although none of them were developed specifically to evaluate sheet flooding conditions. The results of the PFHAM study described later in this report indicate that: (1) sheet flooding has a strong two-dimensional component and (2) the rate of hydrograph attenuation is significant in sheet flooding areas. Therefore, the most appropriate hydrologic and hydraulic modeling tools for sheet flooding areas will have the capacity to address two-dimensional flow and hydrograph attenuation.

Existing Sheet Flooding Floodplain Regulations or Development Guidelines. The Maricopa County Floodplain Regulations mention sheet flooding only in the context of alluvial fan flooding, with no specific regulations relating solely to management of sheet flood areas. The Maricopa County Drainage Regulations do not use the terms "sheet flood" or "sheet flow." The Maricopa County Drainage Policies and Standards (2007) reference sheet flooding in Section 3.8.3 (Erosion Hazard Management – Sheet Flow/Unconfined Flow Areas), and recommend minimizing vegetation disturbance and flow concentration, and returning flow to pre-development conditions before exiting a developed property.

Other general guidance for floodplain management in sheet flooding areas was found in ADWR State Standard 4-95 and several local flood control agencies in the southwestern United States. The guidance in the State Standard and from other agencies included recommendations to elevate finished floors, provide scour protection around foundations, elevate or gap fences to allow through flow drainage, set back fences from property lines, align construction parallel to flow (minimizing obstructions), lower building densities, avoid impacts to adjacent properties due to flow concentration, and restrict septic tank placement, as well as general site grading practices.

2.2. Historical Development on Alluvial Fan Landforms

An analysis of historical development on alluvial fan landforms in Maricopa County was performed to assess the successes, failures, and/or drainage problems associated with such development. The historical analysis was intended to gauge the degree of flood hazard severity on alluvial fans in Maricopa County. Four individual site locations (Ahwatukee, Pima Canyon, Reata Wash, and Lost Dog – See Figure 2) were chosen and approved by the District project team. The study site locations were identified using historical and recent aerial photographs, NRCS soils mapping and readily available topographic mapping. The four study sites include areas of dense urbanization (Ahwatukee, Pima Canyon, Reata Pass, Lost Dog), single lot development (Reata Pass), and developments with major structural drainage measures (Ahwatukee, Pima Canyon, Lost Dog). Key site characteristics for the four historical sites are listed in Table 1.

Table 1. Site Characteristics for Historical Alluvial Fan Sites.

Characteristic	Historical Alluvial Fan Sites			
	Ahwatukee	Pima Canyon	Reata Pass	Lost Dog
Watershed area (apex)	1.7 mi2	1.5 mi2	8.1 mi2	2.8 mi2
Watershed slope	8.1 %	7.7 %	12.1 %	4.2 %
Channel Slope				
Upstream of apex	3.8 %	1.6 %	3.4 %	2.5 %
Downstream of apex	1.8 %	1.5 %	3.3 %	2.5 %
Q100 at apex	2778 cfs	2525 cfs	11,900 cfs	5,000 cfs
Fan Profile Shape	Concave up	Concave up	Concave up	Concave up
Max Elevation in Watershed	2586 ft	2555 ft	3880 ft	3,804 ft
Elevation at apex	1350 ft	1310 ft	2185 ft	1,625 ft
Minimum Elevation in fan	1270 ft	1210 ft.	1520 ft	1,440 ft

2.2.1. Ahwatukee Alluvial Fan

The Ahwatukee Alluvial Fan (Figure 3) contained an active alluvial fan before it was urbanized in the 1980s. Prior to its development, the unnamed Ahwatukee Fan wash lost both capacity and definition at its hydrographic apex and the previously channelized flow transitioned to broad sheet flow over the upper fan area. The overall alluvial fan landform remained undeveloped until the 1980s when rapid and dense suburban single-family-unit development occurred over the entire landform. As part of the development

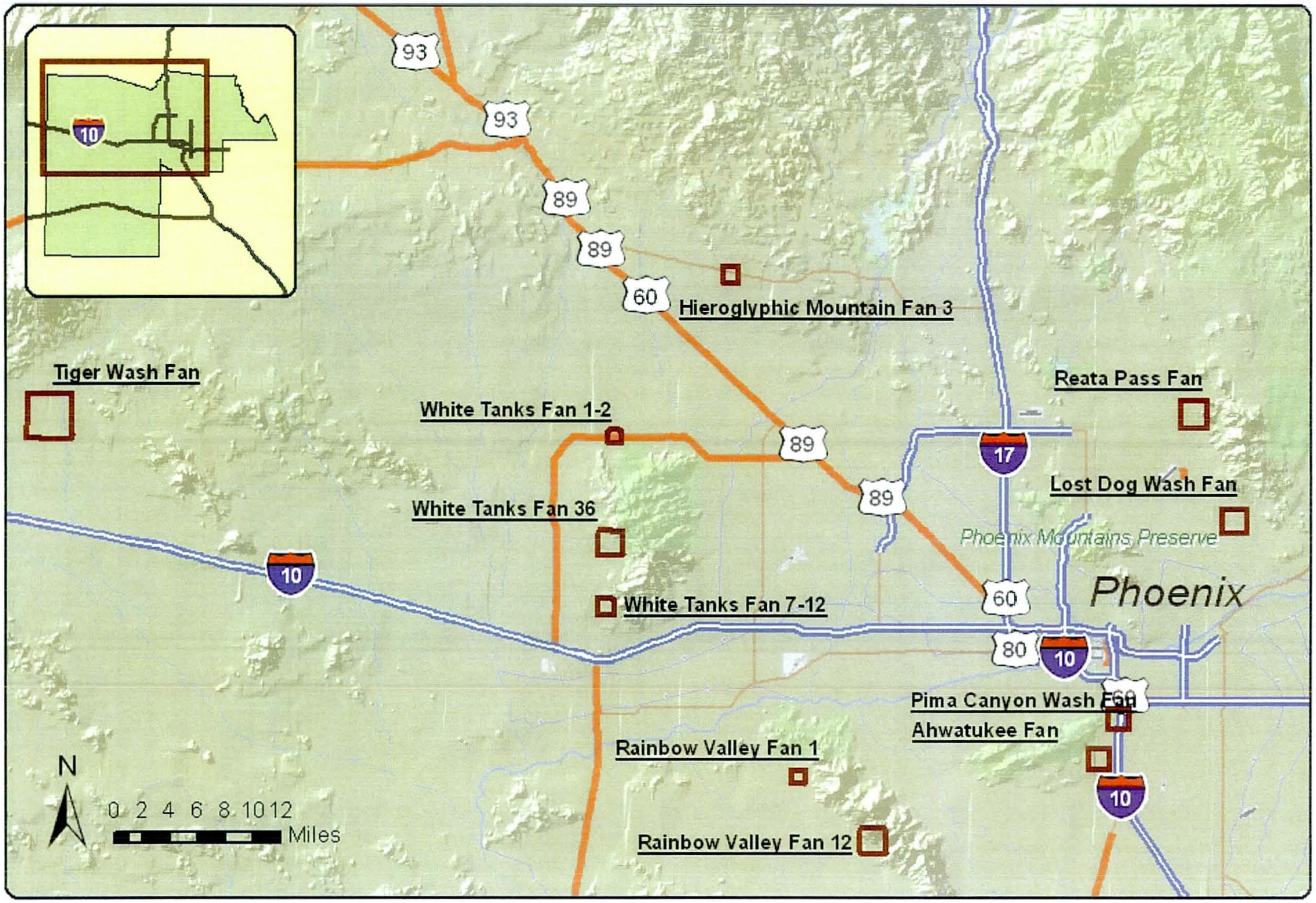

Figure 2. Map showing Maricopa County historical and evaluation fan sites cited in this report.

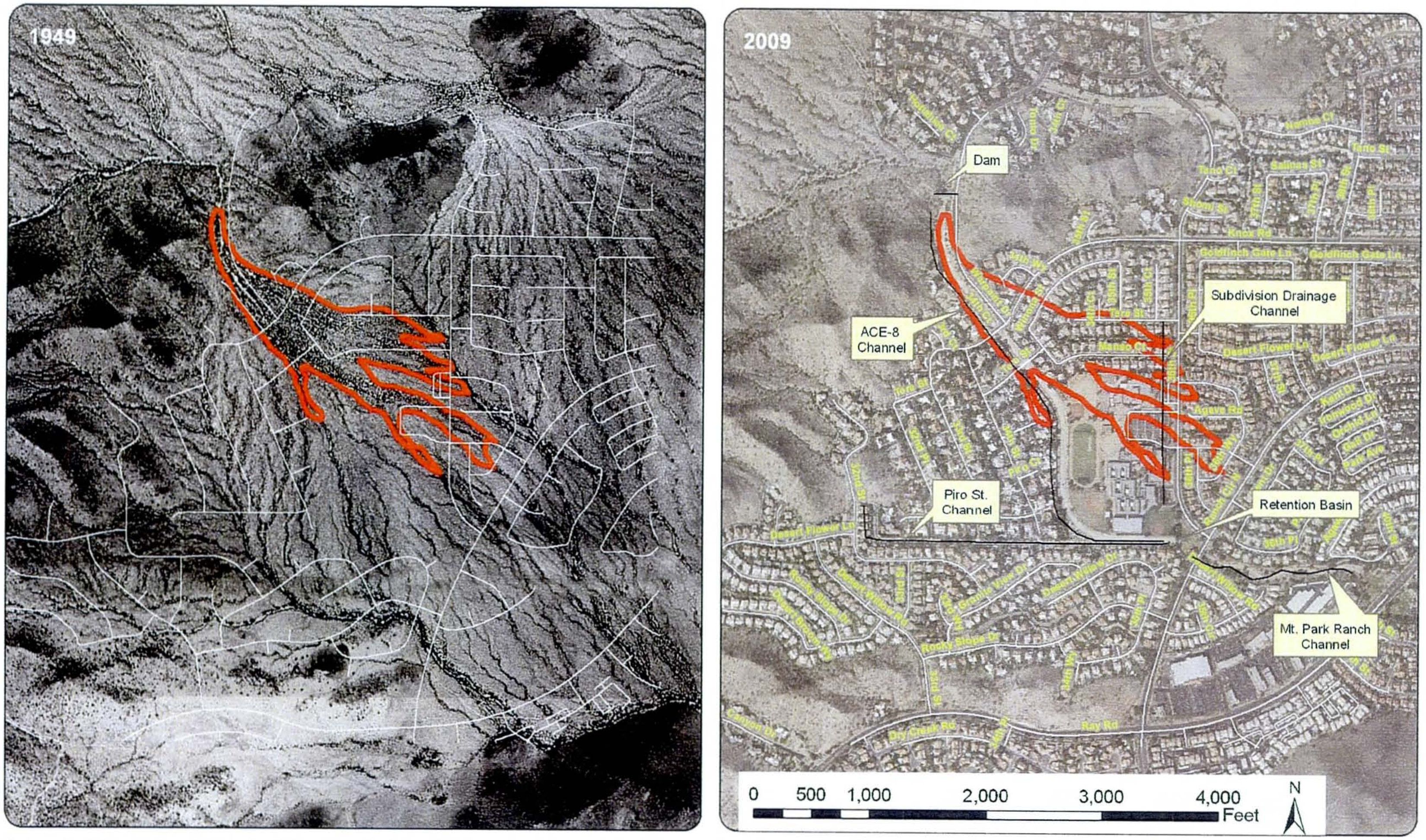

Figure 3. Ahwatukee historical fan site, before (1948) and after development (2009).

*****Note: The aerial base photo for all figures in this report is from 2009 unless otherwise noted in the figure caption.***

drainage plan, flows upstream of the fan apex were detained behind a small, peak-scalping dam. Floodwater exiting the dam was routed to the toe of the alluvial fan via a concrete-lined trapezoidal channel to a small detention basin which drained into a series of rock-lined channels that extended to the toe of the alluvial fan landform.

There is no record that any homes on the Ahwatukee Fan have been damaged by flooding, sedimentation or erosion since construction of the engineered dam-channel flood mitigation system. The concrete-lined channel itself, however, was heavily damaged during a large flood event in 2005, and continues to have on-going issues with damage to the concrete channel lining. Also, some level of sediment deposition occurs in the channel near the dam outlet, as well as in the small detention basin at the downstream end of the concrete channel. Both the sedimentation and the concrete damage have been addressed through routine maintenance by the private homeowners' association which owns the structures. It is likely that these types of sediment and channel maintenance needs will continue indefinitely.

2.2.2. Pima Canyon Alluvial Fan

The Pima Canyon Wash alluvial fan contained an active alluvial fan prior to its urbanization in the late 1980s (Figure 4). The Town of Guadalupe, which is located at the toe of the Pima Canyon alluvial fan, experienced repeated damage to homes and infrastructure from shallow sheet flooding and sediment deposition, dating back to at least the 1930s. Since the 1930s, extensive development has taken place on the fan surface, including the construction of Interstate-10 (1960s) and the Guadalupe Flood Retarding Structure (FRS; 1970s), channelization of Pima Wash (1980s), construction of residential subdivisions and transportation infrastructure (1980s), and development of a golf course (1990s) in the former wash bottom and portions of the active alluvial fan. Since the original construction dates, there has been no record of any flood damage to any home or building on the Pima Canyon alluvial fan, although periodic sediment removal and maintenance is performed by a private homeowners association and golf course maintenance crews.

Development-related flood control improvements on the Pima Canyon alluvial fan have been tested by at least one very large rainfall event in July 2008, which was estimated at about a 350-year rainfall event.[5] The July 2008 storm generated record (though not 100-year) flooding and sedimentation along Pima Canyon Wash and in the Guadalupe FRS. Although record rainfall was recorded on parts of the fan, the actual damage to structures on the fan was minimal. It is likely that flood-related sedimentation and erosion of the main channel of Pima Wash, both in and around the golf course, will continue to occur indefinitely.

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[5] The extreme rainfall in the 2008 event occurred on the fan surface, not the upper watershed. Peak discharges upstream of the fan apex were probably much less than the 100-year peak flow rate. Rainfall intensities in the upper watershed were much less than 100-year levels.

2.2.3. Reata Pass Alluvial Fan

The Reata Pass alluvial fan (Figure 5) is the largest of the four historical sites, and has a large active fan area downstream of its hydrographic apex, as well as a classic fan shape. The earliest urbanization of the fan surface consisted of residential grid style construction on the lower fan landform in the early 1960s. More extensive development of large lot luxury homes has occurred on the upper alluvial fan since the mid-1990s. To date, the largest problem area on the fan has been within the 1960s-style rectangular grid development at the Pima Acres subdivision, where essentially no drainage infrastructure was provided for off-site flows. Elsewhere on the fan, sedimentation has clogged culverts and blanketed dip crossings during small floods, creating a maintenance burden on both the City and the local homeowners' associations. The large lot development on the upper portion of Reata Pass fan preserved much of the natural, distributary drainage patterns of the fan landform, with the natural wash corridors designated and protected by City regulations as environmentally sensitive wildlife habitat.

While no significant flood damages to homes have been reported on the Reata Pass Fan, neither have there been any storm events greater than a 10-year event since development began. Thus, the flood mitigation infrastructure is largely untested. FLO-2D modeling described in Section 2.3.3 and Appendix F of this report indicates that numerous homes on the Reata Pass alluvial fan may be subject to significant flooding during a 100-year event. If large floods occur in the future, they are likely to cause significant damage to flood-prone homes on the most active parts of the upper alluvial fan landform. In addition, it is likely that the existing sediment maintenance problems resulting from small flows will persist indefinitely. Regardless of the future flood potential damage, the short historical record indicates that the current engineering and floodplain management practices have performed adequately, at least with respect to flood damage to homes.

2.2.4. Lost Dog Wash Alluvial Fan

Prior to urbanization between 1997 and 2005, the Lost Dog Wash was located on a small active alluvial fan characterized by unconfined distributary flow downstream (Figure 6) of its hydrographic apex. Lost Dog Wash is now confined to an engineered channel that routes flood water down the western portion of the fan landform, under the 120th Place-Via Linda Road intersection, ending at the Central Arizona Project Canal (CAP). At the CAP, flood water is ponded and routed northwest along the CAP canal. Lost Dog Wash has not had any significant rainfall events since the area was urbanized, and the drainage structures remain substantially untested. However, minimal sedimentation and maintenance concerns are expected in the future, with the possible exception of the ponding and depositional area upstream of the CAP canal, and then only in the event of a large flood.

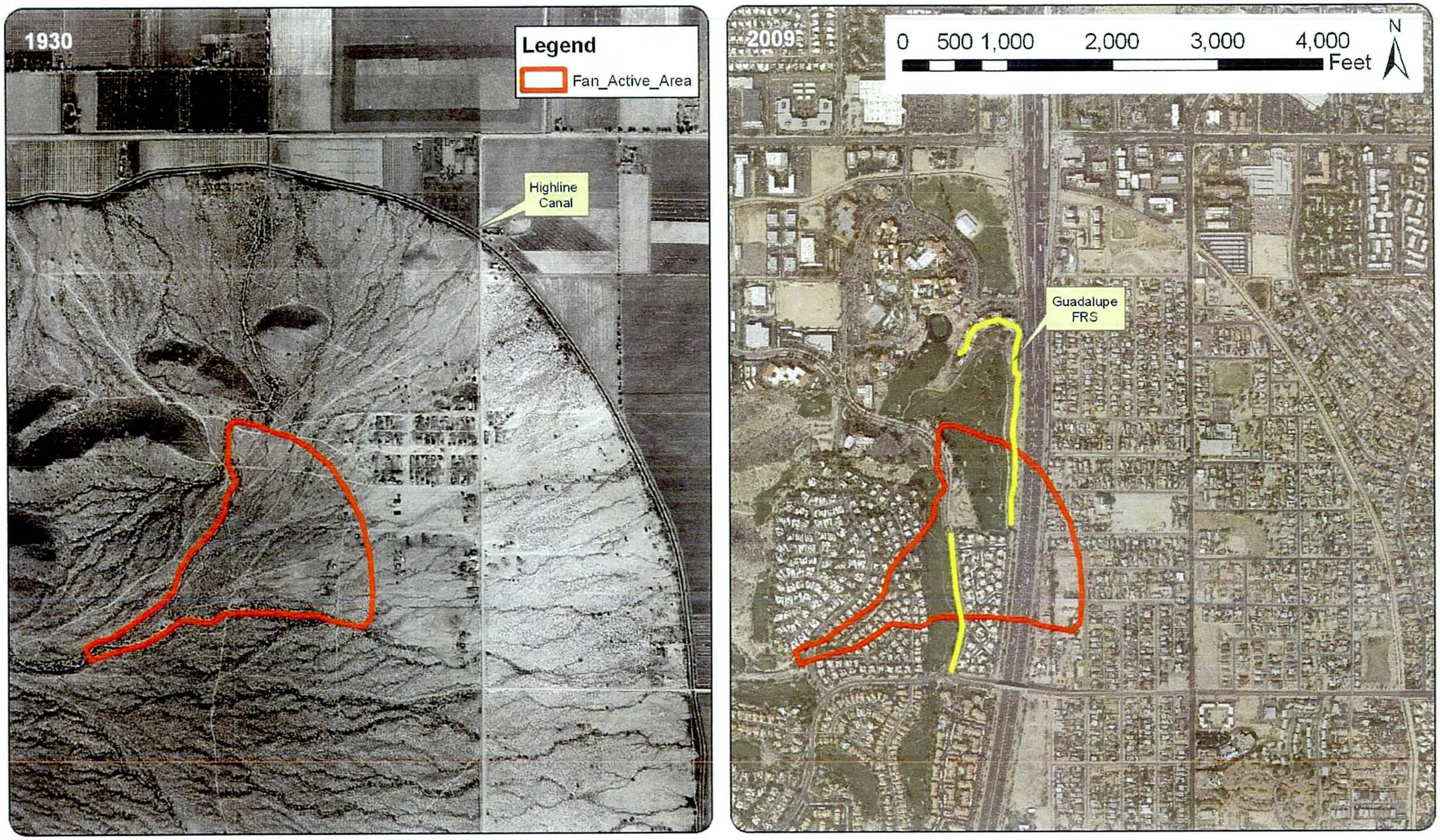

Figure 4 . Pima Canyon historical fan site, before (1930) and after development (2009).

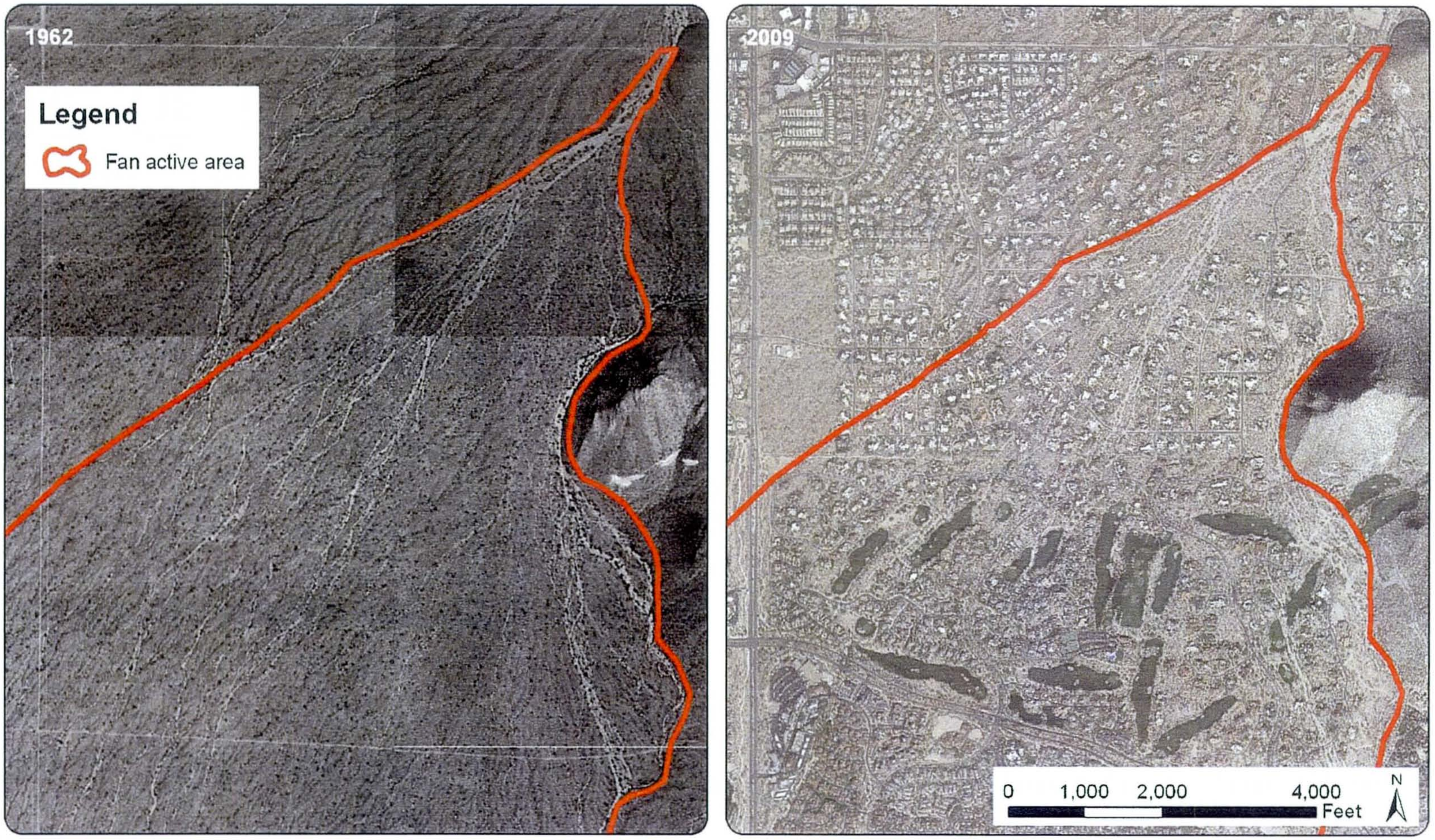

Figure 5. Reata Pass historical fan site, before (1962) and after development (2009).

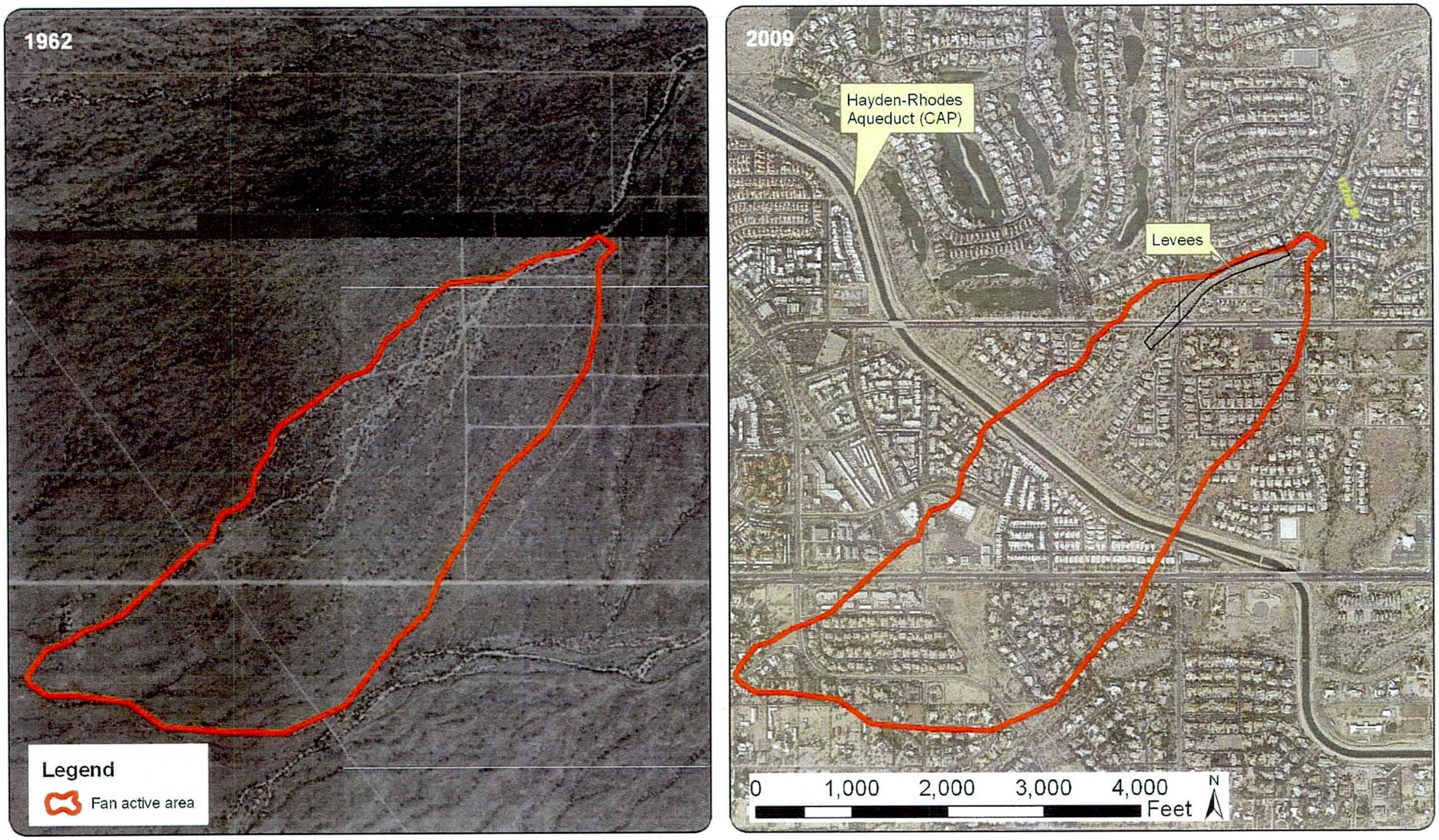

Figure 6. Lost Dog historical fan site, before (1962) and after development (2009).

2.2.5. Summary of Historical Analyses

Based on analysis of the four historical sites, it is concluded that the engineered drainage systems at the four historical alluvial fan study sites have performed adequately during the 20 to 40 year period of record, at least with respect to addressing any flow rate or flow path uncertainty, as well as any sedimentation associated with the now-developed active alluvial fans. Interestingly, there is no record that any of the engineered drainage systems at the four sites explicitly considered alluvial fan flooding as part of the design process. It is likely, however, that drainage engineers were aware of the bifurcating drainage pattern since they took steps to confine flooding to a single channel and/or route it through flood control basins. The range of structural measures used included a peak-scalping detention basin, a concrete-lined channel, an earthen channel with drop structures, mass grading (golf course & development), a regional detention basin (near the fan toe), levees, diversion dikes, culverts, dip crossings, and bridges, as well as some non-structural regulatory measures. Although there has been only one near-regulatory type event on only one of the fans,[6] and the systems remain largely untested, the record indicates the following:

- No homes on the fans have been damaged by alluvial fan flooding in the past 20 to 40 years.
- The structural measures, while they have sustained some damage and required sediment maintenance, have essentially performed their intended function thus far.
- No evidence of adverse impacts from channel avulsions, excessive sedimentation or scour was identified.
- Periodic sediment removal is required, especially near the upper end of the fans, but has not been excessive or beyond the capacity of the HOA's or the local jurisdiction.

Given the episodic and probable low return frequency of fan-altering (avulsive, excessive sedimentation, etc.) flood events, the conclusions listed above should be carefully weighed in light of the short period of record at the four fan sites.

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[6] To date, there is no known systematic evaluation of hydraulic structure performance in Maricopa County from which to determine whether existing design standards result in under or over engineering, either on alluvial fan landforms or on other types of systems subject to flooding. One Blue Ribbon Panel member suggested that such analyses be performed to identify a histogram of the number of features tested by specific recurrence interval events.

2.3. Alluvial Fan Site Evaluations

Four alluvial fan sites in Maricopa County (Figure 2) were selected for more detailed analysis and evaluation of methods for quantifying alluvial fan flood hazards. The following four sites were selected:

- White Tanks Fan 36
- Reata Pass Alluvial Fan
- Rainbow Valley Fan 1
- Rainbow Valley Fan 12

The four sites represent a range of alluvial fans found in Maricopa County, as well as a range of landform slopes, watershed sizes, degree of urbanization, and flow types, as shown in Table 2. Each of the selected sites had available topographic mapping and some type of previous hydrologic modeling prepared for the District or another public agency.

Table 2. Characteristics of Alluvial Fan Evaluation Sites

Site Name	Fan & Watershed Slope (ft/ft)	Watershed Size and Discharge	Type of Urbanization	Flow Types
White Tanks Fan 36	0.022 (fan) 0.097 (watershed)	5.7 mi2 (apex) Q100=2800 cfs 9.9 mi2 (fan)	Rough dirt roads One home site Powerline crossings Future development	Channelized Distributary Sheet Flooding Coalescing
Reata Pass Fan	0.034 (fan) 0.121 (watershed)	8.1 mi2 (apex) Q100=11900 cfs 5.2 mi2 (fan)	Dense residential Large lot residential Dense commercial	Channelized Distributary Sheet Flooding Coalescing
Rainbow Valley Fan 1	0.010 (fan) 0.122 (watershed)	7.2 mi2 (apex) Q100=3900 cfs 1.0 mi2 (fan)	Undeveloped fan area Toe urbanized	Channelized Distributary Sheet Flooding
Rainbow Valley Fan 12	0.018 (fan) 0.210 (watershed)	1.1 mi2 (apex) Q100=1000 cfs 7.0 mi2 (fan)	Undeveloped Powerline crossing Minor agricultural (toe)	Channelized Distributary Sheet Flooding Coalescing

2.3.1. Fan Evaluation Site Descriptions

Brief descriptions of the four alluvial fan evaluation sites are provided in the following paragraphs.

2.3.1.1. White Tanks Fan 36

The White Tanks Fan 36 site (WTF36) is located on the western piedmont slopes of the White Tanks Mountains within the Town of Buckeye in west-central Maricopa County (Figure 7; Table 2). The site was first identified as an active alluvial fan by Hjalmarson and Kemna (1991), and was selected as an alluvial fan data collection site by the District in 1992 (CH2M HILL, 1992). The Arizona Geological Survey (AZGS) has also published a number of studies of the site, including flood hazard mapping (Field and Pearthree, 1992), detailed surficial geology mapping (Field and Pearthree, 1991), and trenching of the active fan surface (Field, 2001). WTF 36 was also included as one of the sites considered in Field's (1994) Ph.D. dissertation on alluvial fan flooding in Arizona. WTF 36 was the site of one of the District's first applications of the PFHAM methodology (JEF, 1999), and was evaluated as part of the District's Sun Valley Area Drainage Master Plan (JEF, 2006) which included detailed HEC-1 hydrologic modeling and drainage infrastructure planning tasks.

The hydrographic apex of the WTF 36 site is located significantly downstream of the geologic mountain front of the White Tanks Mountains. At the hydrographic apex, the drainage pattern rapidly transitions from an incised, well-defined channel on the upper piedmont to a highly distributary channel on the active alluvial fan surface. Distributary flow then rapidly transitions to sheet flooding within about one mile of the hydrographic apex. Downstream of that point, shallow sheet flooding conditions persist over most of the rest of the alluvial fan landform. Smaller, secondary hydrographic apexes also occur in the lower and distal parts of the WTF 36 site. In the lower portions of the fan, on-fan runoff apparently becomes more dominant, as indicated by the incipient dendritic drainage pattern on the fan surface.

Flood runoff from the site drains toward the Buckeye Flood Retarding Structure #1 (FRS), which truncates the alluvial fan landform and serves as the downstream limit for this study. There is no gauged record of flooding or rainfall for the WTF 36 site, although the District's Alluvial Fan Data Collection and Monitoring Study (CH2M HILL, 1992) paleoflood analysis indicated that the maximum flow preserved in the geologic record was approximately 2,000 to 4,000 cfs. Analysis of historical aerial photographs indicates that a very large avulsive flood occurred between 1949 and 1953 (JEF, 1999), probably as a result of extreme rainfall in August 1951, as recorded at a nearby station in Buckeye (Figure 8).

At present, the WTF 36 site is mostly undeveloped, with the exception of one rural homestead located approximately one mile downstream of the main hydrographic apex, and an area of rural development located at the extreme southwestern tip of the alluvial landform just upstream of the Buckeye FRS #1. However, prior to the current economic recession, most of the WTF 36 area was slated for residential construction as part of several large master planned communities. It is likely that the WTF 36 will be fully built out within two decades.

The WTF 36 site was selected for this study because there is general consensus from a variety of investigators that it includes an active alluvial fan, it may well be the most well-studied alluvial fan landform in Maricopa County, it has an existing PFHAM delineation that was approved by FEMA, it has experienced a historical avulsive flood event, and because it is likely to be developed in the near future.

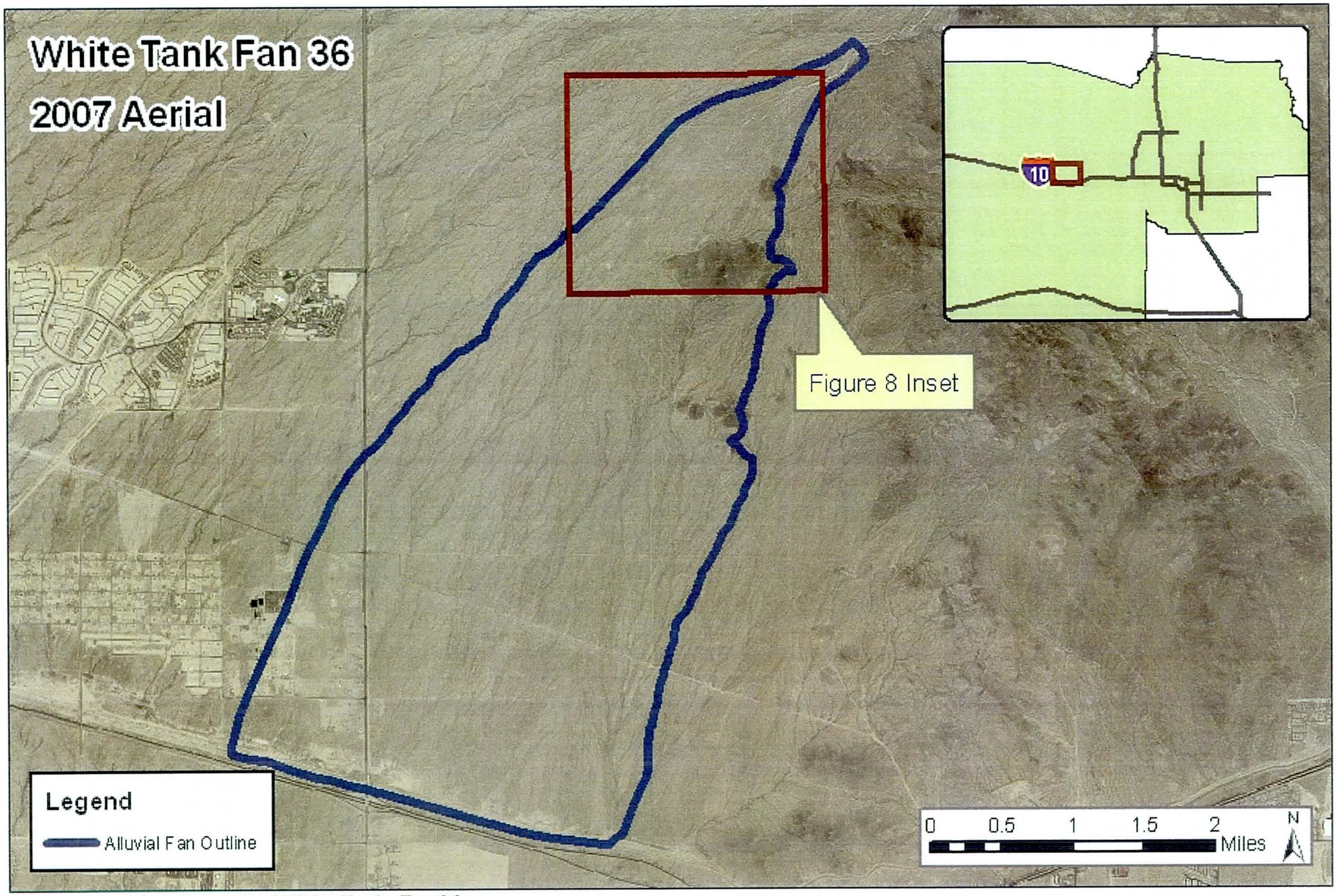

Figure 7. Aerial photograph of White Tanks Fan 36.

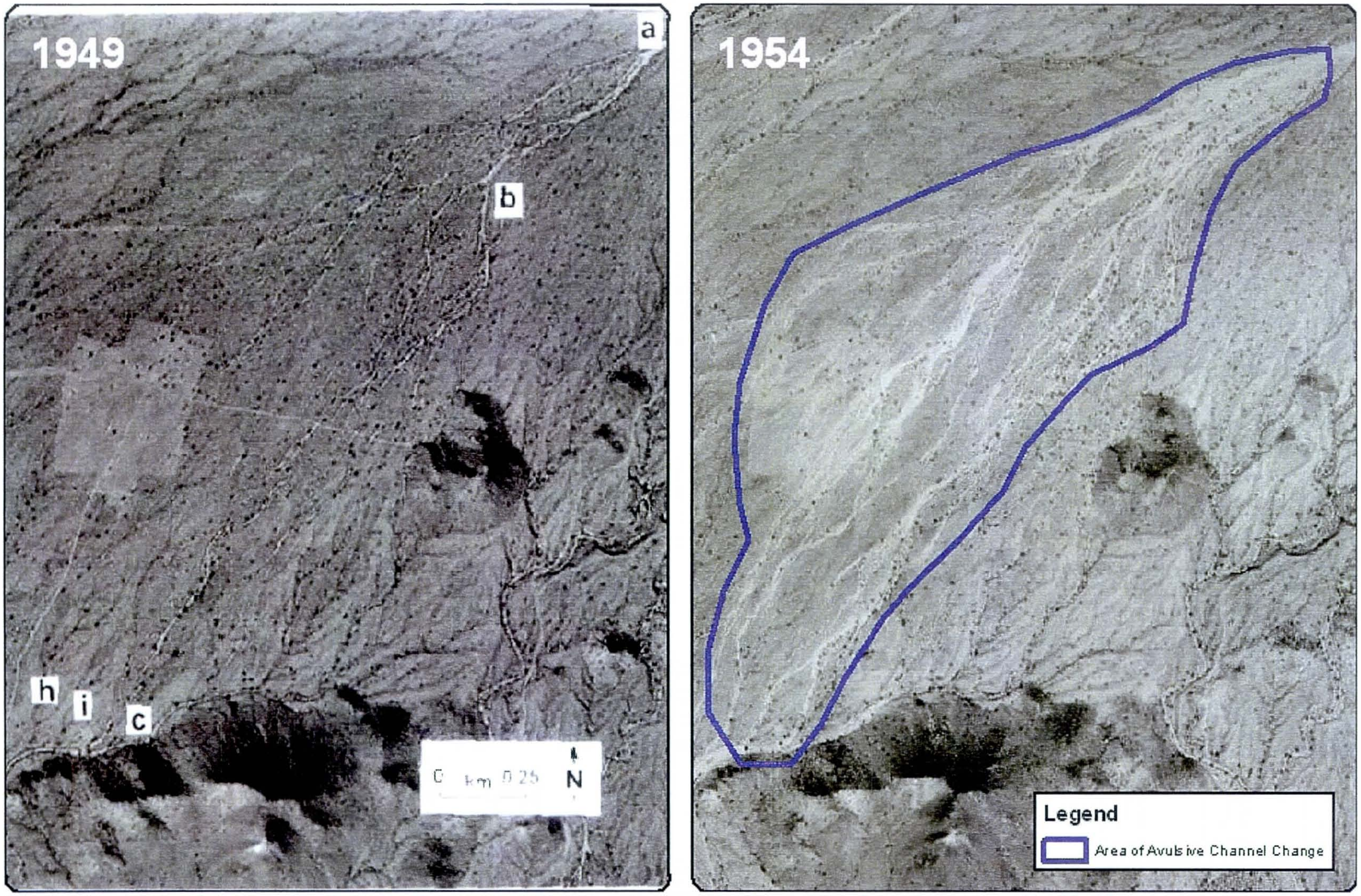

Figure 8. Aerial photographs of White Tanks Fan 36, 1949-1954, showing area of 1951 avulsive channel change outlined in blue.

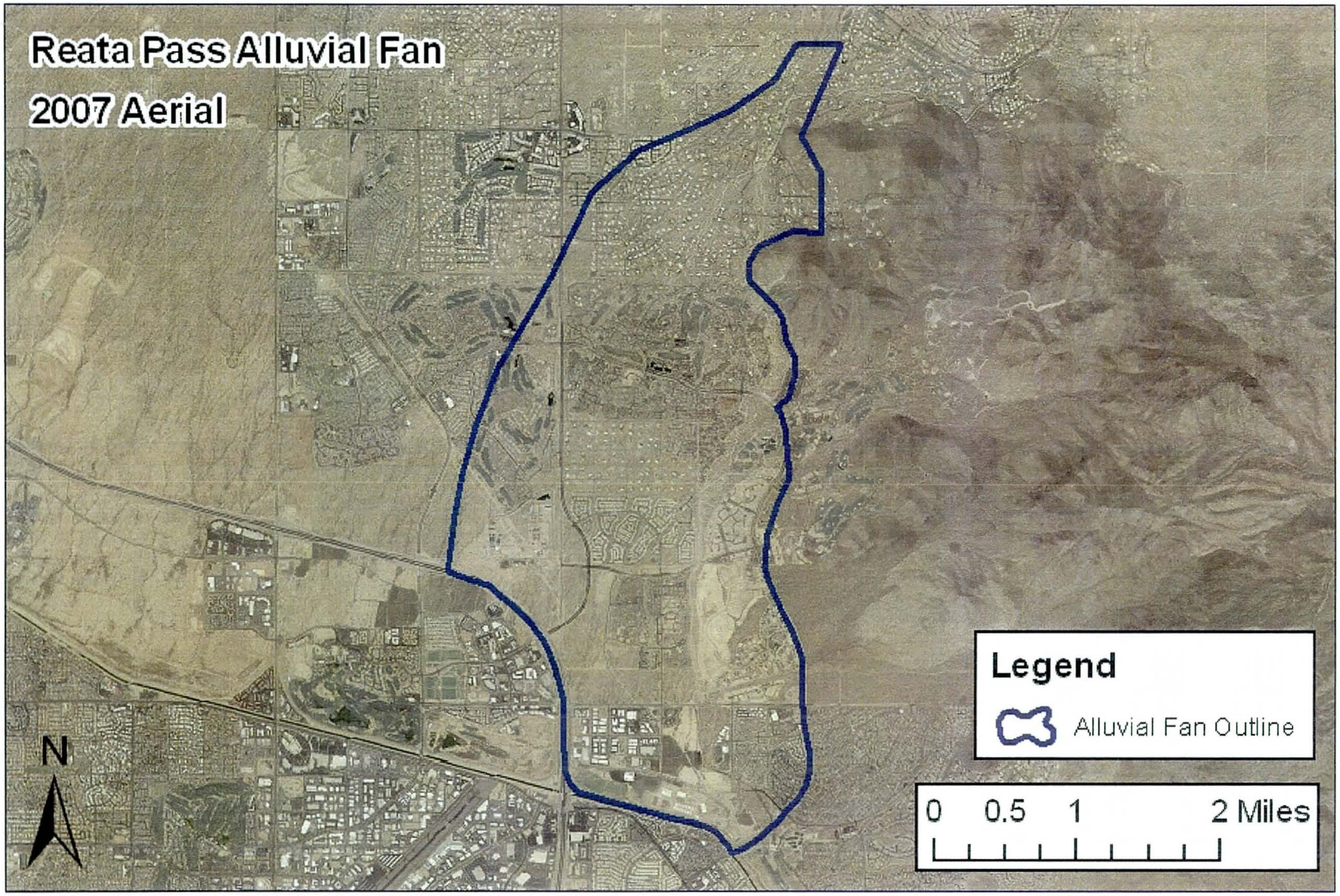

Figure 9. Aerial photograph of Reata Pass Alluvial Fan.

2.3.1.2. Reata Pass Alluvial Fan

The Reata Pass Fan site (RPF) is located on the western piedmont slopes of the McDowell Mountains within the City of Scottsdale in northeastern Maricopa County (Figure 9; Table 2). The site was identified as an alluvial fan as part of a FEMA floodplain delineation in the 1980s, and was delineated using the FEMA FAN model (a.k.a., the Dawdy Method). The City of Scottsdale previously proposed major structural improvements to mitigate alluvial fan flooding hazards on the RPF site as part of their Desert Greenbelt Project, but the project has never been constructed. There have been several HEC-1 hydrologic modeling studies that analyzed the RPF site (See Appendix D). Geologic mapping of the area has been performed (Christensen, 1976), as well as a geomorphic landform classification (Rhoads, 1986) which identified portions of the site as an active alluvial fan. The RPF site was also selected as one of the historical alluvial fan sites described in Section 2.2 of this report.

The hydrographic apex of the RPF site is located quite close to the geologic mountain front of the McDowell Mountains. At the hydrographic apex, the drainage pattern rapidly transitions from an incised, well-defined channel leaving the mountain canyons to a system of distributary channels that cross the upper alluvial fan surface. Near the mid-fan area, the natural distributary flow pattern probably transitioned to sheet flooding, but is now obscured or confined by recent urbanization. Several secondary hydrographic apexes also occur along the eastern margin of the RPF site where significant tributary systems exit the McDowell Mountains and debouche onto the piedmont.

Flood runoff from the RPF site drains south toward the Central Arizona Project (CAP) canal levee, which impounds upstream runoff, truncates the alluvial fan landform, and serves as the downstream limit for this study. Since 2001, the District has maintained a streamflow gauge near the hydrographic apex of the RPF alluvial fan, as well as several other ALERT monitoring stations in the vicinity. No significant floods at the RPF site have been captured by the District's ALERT system, nor is there any evidence of large floods visible in the historical aerial photographs, which date back to 1953.

There are several styles of development on the RPF site. Near the hydrographic apex, development consists of luxury homes on large lots, with paved roads and at-grade crossings. Most of the defined flow paths are not obstructed by development, allowing some level of distributary flow to continue. Near the upper mid-fan area, a large master planned residential golf community has been constructed that includes structural flood control measures such as flow collection systems, diversion structures, detention basins, and bridge/culvert crossings. Further south, there is a mixture of older, large-lot subdivisions that lack adequate drainage infrastructure and newer, dense residential development with traditional flood control measures.

The RPF site was selected for this study because it is one of the larger, steeper alluvial fan landforms in Maricopa County, it has a large 100-year discharge and correspondingly large flood velocities and depths, it has been urbanized by a variety of development styles, it has an existing FAN model delineation that was approved by FEMA, and because of the risk of future flood damage to existing development by alluvial fan flooding.

2.3.1.3. Rainbow Valley Fan 1

The Rainbow Valley Fan 1 site (RVF1) is located on the western piedmont slopes of the Sierra Estrella within the City of Goodyear in western Maricopa County (Figure 10; Table 2). The site was identified as a possible active alluvial fan as part of the Rainbow Valley ADMP (JEF, 2010). The Arizona Geological Survey (AZGS) has also published detailed surficial geology mapping (Pearthree et. al., 2004). There is a current FEMA-approved riverine floodplain delineation for the lower portion of the alluvial fan landform.

The hydrographic apex of the RVF 1 site is located well downstream of the geologic mountain front of the Sierra Estrella. At the hydrographic apex, the main channel drainage pattern becomes slightly more braided, but does not change drastically. The apex consists of potential high-flow overflow onto a potentially active fan surface which appears to be subject shallow sheet flooding. The lower portions of the RVF 1 alluvial fan site consist mostly of older, inactive surfaces into which the more active upstream portions flow.

Flood runoff on the RVF 1 site drains east toward and through the Estrella master-planned community, although any alluvial fan flooding characteristics end upstream of Estrella Parkway. There is no gauged record of flooding or rainfall for the RVF 1 site. Analysis of historical aerial photographs revealed no evidence of avulsive channel change between 1939 and 2010. At present, the RVF 1 site is undeveloped.

The RVF 1 site was selected for this study because is represents one end member of the range of alluvial fan landform types common in Maricopa County, that of a potentially active area that could easily be confused with a riverine floodplain. In fact, the RVF 1 site has elements of both riverine and alluvial fan flooding, depending on the recurrence interval considered and type of sedimentation trends that occur along the existing main channel. The RVF 1 site also an existing FEMA-approved riverine floodplain delineation, and is located upstream of existing dense development that was apparently designed without consideration of potential upstream alluvial fan flood hazards.

2.3.1.4. Rainbow Valley Fan 12

The Rainbow Valley Fan 12 site (RVF 12) is located on the western piedmont slopes of the Sierra Estrella within the Cities of Goodyear and Avondale, as well as unincorporated Maricopa County (Figure 11; Table 2). The site was first identified as an active alluvial fan, and was selected as an alluvial fan data collection site by the District in 1992 (CH2M HILL, 1992). The Arizona Geological Survey (AZGS) has also published detailed surficial geology mapping (Pearthree et. al., 2004) and soil descriptions based on trenching of the active fan surface (CH2M HILL, 1992). The RVF 12 site was evaluated as part of District's Rainbow Valley Area Drainage Master Plan (URS, 2010) which included detailed HEC-1 hydrologic modeling and drainage infrastructure planning tasks.

As evaluated for this study, the RVF 12 site consists of a bajada composed of a number of previously identified hydrographic apexes that coalesce on the alluvial fan landform.

The hydrographic apexes that comprise the RVF 12 site are located immediately downstream of the geologic mountain front of the Sierra Estrella. At the hydrographic apexes, the drainage pattern rapidly transitions from an incised, well-defined channel on the upper piedmont to extensive sheet flooding conditions. This transition occurs via small ephemeral distributary channels. Shallow sheet flooding conditions persist over most of the rest of the alluvial fan landform until it merges with the alluvial plain of Waterman Wash, the axial stream within the Rainbow Valley.

Flood runoff from the site drains toward the geologic floodplain of Waterman Wash, which forms the lower limit of the toe of the alluvial fan landform. The District has operated a system of precipitation, weather, and streamflow gauges at the RVF 12 site since it was identified in their Alluvial Fan Data Collection and Monitoring Study (CH2M HILL, 1992). A paleoflood analysis conducted for that study indicated that the maximum flow preserved in the geologic record was less than 1,000 cfs. Analysis of historical aerial photographs revealed no evidence of avulsive channel change between 1939 and 2010, although soil trench analyses indicate that significant aggradation and minor channel movement has occurred near the hydrographic apex over the past 600 years (Appendix I). At present, the RVF 12 site is undeveloped in the upper fan area, although the toe of the alluvial fan landform has a history of grading associated with irrigated agricultural uses.

The RVF 12 site was selected for this study because of the District's history of flood data collection at the site, its inclusion as an alluvial fan site in previous District studies, the presence of coalescing alluvial fans, the large component of sheet flooding, the proximity of the fan apexes to the mountain front, and the gradual transition from the active fan area to an axial stream.

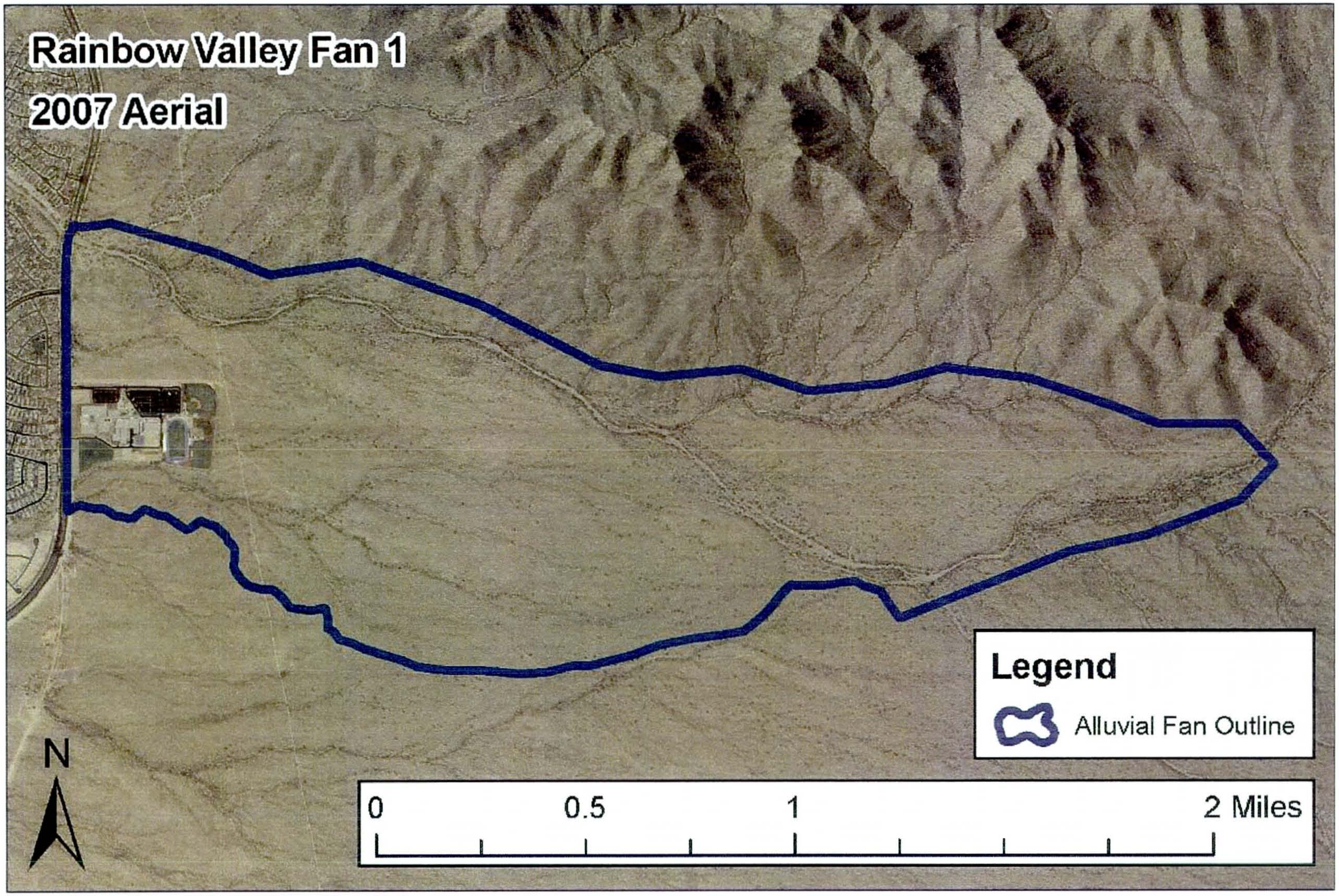

Figure 10. Aerial photograph of Rainbow Valley Fan 1.

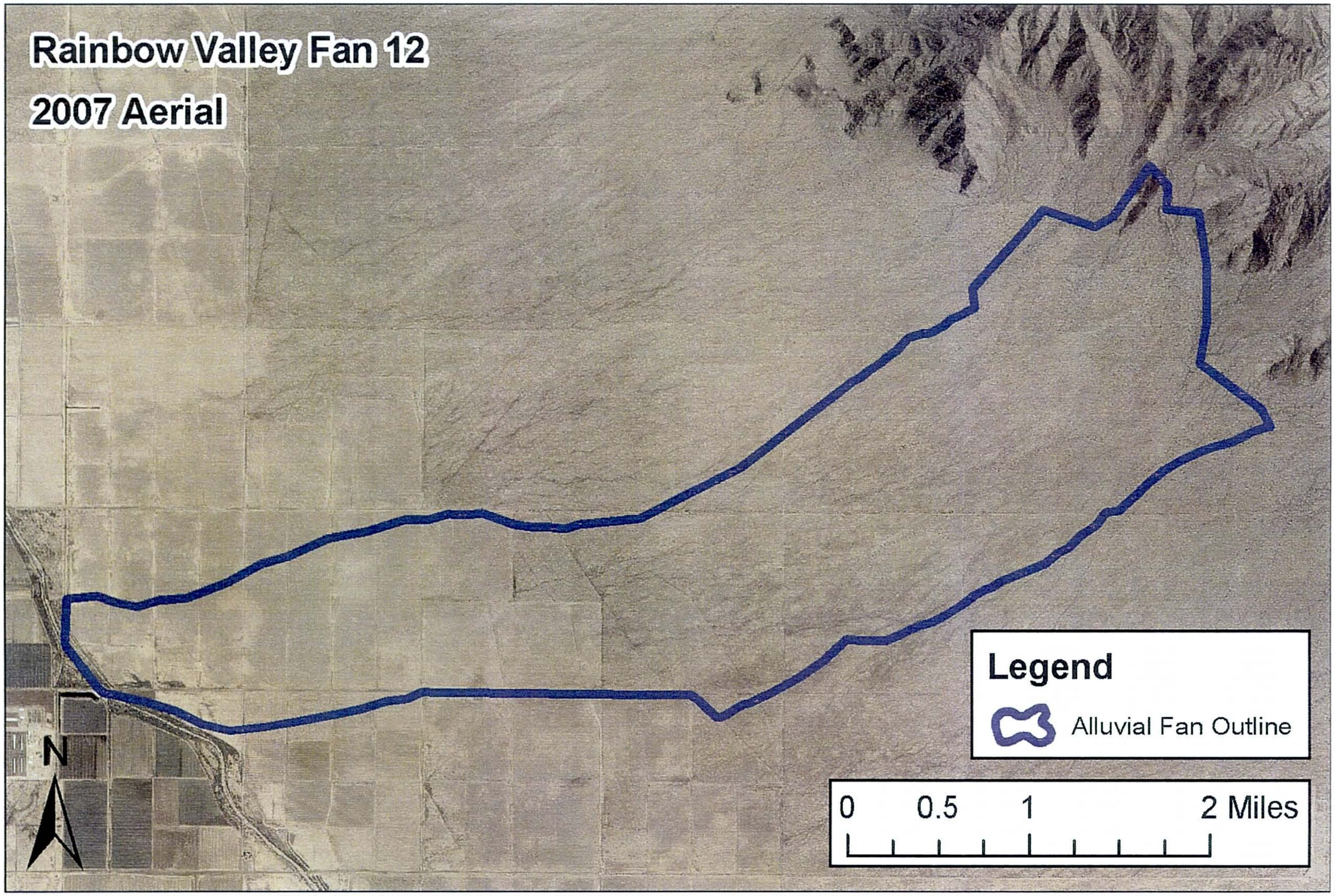

Figure 11. Aerial photograph of Rainbow Valley Fan 12.

2.3.2. Hydrology

The objective of the hydrologic modeling tasks of the PFHAM study was to recommend hydrologic methods for estimating flood hydrographs and peak discharges at concentration points on, or downstream of, an active alluvial fan (hydrographic) apex, in sheet flow areas, and on coalescing fans. Hydrologic modeling tasks performed for the PFHAM study included the following:

- Evaluation of existing hydrologic models provided by the District
- Development of new HEC-1 hydrologic models for each fan site
- FLO-2D modeling of each fan site

2.3.2.1. HEC-1 Modeling

Because of disparities in HEC-1 modeling techniques in the watershed models provided by the District, new HEC-1 models were developed for each of the four fan evaluation sites. The HEC-1 models were coded using current District modeling guidelines, as outlined in the District's *Drainage Design Manual for Maricopa County: Hydrology* and described in Appendix E. For the portions of the watersheds upstream of the hydrographic apexes, the modeling process was no different than any other hydrologic modeling project in Maricopa County. However, there were a number of challenges in applying the HEC-1 model downstream of the hydrographic apexes due to the distributary flow pattern and extensive areas of sheet flooding. Some of the HEC-1 modeling challenges included the following:

- Flow splits. Channel bifurcations must be hard-coded into the HEC-1 model. The percent of flow distributed between channel branches must be determined by a hydraulic rating or engineering judgment. Even if sufficient topographic data are available from which to make a reasonable estimate of the flow division in the channels, uncertainty regarding flow delivered outside the main channel makes such estimates tenuous at best. Furthermore, small changes in bed elevations, vegetative density, channel geometry or roughness may render even the most precise estimates inaccurate in subsequent floods.
- Flow path uncertainty. HEC-1 is not capable of changing the flow distribution to account for channel avulsions, unless multiple models with varying split distributions are used. Traditionally, flow splits on active alluvial fans have been modeled by assuming that the entire apex discharge could flow down any flow path (i.e., all flow paths receive the entire apex discharge). Alternatively, the model could be coded to over-account for flow between branches to provide a less-conservative estimate, by directing a less-than-100% portion of the apex discharge into each routing reach. For example, 70% of the apex flow could be diverted into a binary flow bifurcation, resulting in 140% of the apex discharge in the combined channels. However, no guidance is available from which to establish an appropriate over-accounting value (e.g., 70% vs. 60%). Furthermore, the latter approach does not conserve flow volume, and becomes increasing difficult to apply if multiple splits are encountered as flow traverses the fan surface.
- On-fan subwatersheds. Because active alluvial fans have distributary channel patterns, topographically indistinct drainage divides, and extensive sheet flooding

areas, it is difficult to accurately delineate watershed boundaries below the hydrographic apex. Some of the major data input values for HEC-1 presume that the subbasin area is well defined (basin area, length, time of concentration). In addition, HEC-1 does not allow flow to cross drainage boundaries except at concentration points.

- Concentration points. Discrete concentration points are difficult to identify in distributary and sheet flooding areas. On all of the active alluvial fans evaluated for the PFHAM study, the on-fan areas had either distributary characteristics with numerous flow paths or sheet flooding areas with no obvious concentration point. HEC-1 concentration points were assigned using either engineering judgment or at distinct geographic features such as road alignments.
- Channel routings. Normal depth routing reaches defined using a traditional eight-point cross section inadequately depict the storage that occurs in distributary and sheet flooding areas in which flow zones may be thousands of feet wide with very shallow average depths.
- Influence of manmade features. On developed fans, it is likely that distributary flow and sheet flooding are diverted, stored, or otherwise altered in complex ways by spatially distributed manmade features such as grading for home construction or roads (either perpendicular or sub-parallel to primary flow direction). It is not possible to model such features in detail in a lumped parameter model like HEC-1 without making simplifying assumptions regarding the impact of these features.

2.3.2.2. Two-Dimensional Modeling

Two-dimensional hydrologic modeling was performed using the FLO-2D computer model. FLO-2D is a volume conservation flood routing and physical process model that routes rainfall-runoff and flood hydrographs over unconfined flow surfaces or in channels using the dynamic wave approximation to the momentum equation.[7] It can be used for delineating flood hazards, regulating floodplain zoning or designing flood mitigation. The model will simulate river overbank flows, but it can also be used on unconventional flooding problems such as unconfined flows over complex alluvial fan topography, split channel flows, mud/debris flows and urban flooding. It has a number of components to simulate street flow, buildings and obstructions, sediment transport, spatially variable rainfall and infiltration, floodways and many other flooding details. Predicted flow depth and velocity between the grid elements represent average hydraulic flow conditions computed for a small timestep (on the order of seconds). Typical applications have grid elements that range from 25 ft to 500 ft on a side and the number of grid elements is unlimited. FLO-2D is on FEMA's list of approved hydraulic models for both riverine and unconfined alluvial fan flood studies.

FLO-2D models were prepared for each of the four alluvial fan evaluation sites. FLO-2D modeling techniques are described in more detail in Appendix F and Section 2.3.3 of this

[7] More information on the FLO-2D model is available at www.flo-2d.com. Although the FLO-2D model was used for this study, the District will allow use of any two-dimensional model that meets the criteria and that has the capabilities required to perform the analyses outlined in this report. The rationale for selecting the FLO-2D model is provided in the following discussion, as well as in Sections 2.3.2.3 and 2.3.3.

report. With respect to the hydrologic modeling aspects of FLO-2D, the approach consisted of several elements. First, a computation domain was identified that bracketed the limits of the alluvial fan landform from the hydrographic apex to the toe. Second, an inflow hydrograph computed using HEC-1 was input at a point far enough upstream of the hydrograph apex to assure that flow was adjusted to the ground terrain before it passed the apex. Third, NOAA Atlas 14 point rainfall depths were used for simulating on-fan rainfall. The current FLO-2D code does not areally reduce point rainfall depths with increasing drainage area. Given the relatively small size of the fan watersheds, and the fact that applying the NOAA 14 point rainfall depths directly would be conservative with respect to runoff rate, the lack of aerial reduction was considered insignificant for the purposes of the fan evaluations. Finally, FLO-2D rainfall loss rate methodologies used were identical to those used in the HEC-1 modeling.

2.3.2.3. Comparison of HEC-1 and FLO-2D Hydrologic Modeling

Comparison of the HEC-1 and FLO-2D modeling results revealed a number of key findings, as described in the following paragraphs.

Peak discharges. There are major differences in peak discharges computed using FLO-2D and HEC1, particularly for watersheds located on piedmont surfaces subject to shallow distributary flow and sheet flooding. Differences between HEC-1 and FLO-2D discharges for each of the four alluvial fan evaluation sites are shown in Table 3 to Table 6. The causes of these differences are the subject of on-going studies by the District (Loomis, 2010), but are most likely due to differences in unit hydrograph development (HEC-1 is based on unit hydrograph theory, FLO-2D is not), use of lumped (HEC-1) versus distributed (FLO-2D) modeling parameters, treatment of rainfall losses, computation of infiltration losses, and hydrologic (HEC-1) versus hydraulic (FLO-2D) routing technique.

Table 3. Comparison of HEC-1 and FLO-2D Peak Discharges: White Tanks Fan 36

Cross Section	HEC-1 Discharge (cfs)	FLO-2D Base Discharge (cfs)	Percent Difference	FLO-2D: No Infiltration (cfs)	Percent Difference
10	2842	2802	-1%	3024	6%
1020	767	538	-30%	577	-25%
1050	938	921	-2%	979	4%
10100	1137	1150	1%	1254	10%
20	699	35	-95%	60	-91%
33	740	14	-98%	0	-100%
43	754	12	-98%	0	-100%
50	745	18	-98%	31	-96%
60	709	41	-94%	19	-97%
80	923	58	-94%	122	-87%
100	1010	1615	60%	2107	109%
110	776	101	-87%	237	-69%
140	544	349	-36%	475	-13%
140110	136	90	-34%	137	1%
140150	408	256	-37%	327	-20%
160	1209		-100%	95	-92%

Table 4. Comparison of HEC-1 and FLO-2D Peak Discharges: Reata Pass Fan					
Cross Section	HEC-1 Discharge (cfs)	FLO-2D Base Model Discharge (cfs)	Percent Difference	FLO-2D Model: No Infiltration (cfs)	Percent Difference
60	11913	13119	10%	12884	8%
280	750	4450	493%	4721	529%
240	786	172	-78%	6	-99%
130	1599	417	-74%	397	-75%
120130	1660	2737	65%	2979	79%
110140	1734	2013	16%	2248	30%
150	2372	443	-81%	246	-90%
140150	2431	377	-84%	264	-89%
110120	2601	3129	20%	3041	17%
250	3683	716	-81%	240	-93%
260	3685	230	-94%	6	-100%
90	3693	2090	-43%	1959	-47%
270	3806	369	-90%	149	-96%
60110	4646	4713	1%	4659	0%
60170	4765	5120	7%	4947	4%
170180	5460	2816	-48%	3410	-38%
180	5504	1989	-64%	2884	-48%
330	6485	8050	24%	8237	27%

Table 5. Comparison of HEC-1 and FLO-2D Peak Discharges: Rainbow Valley Fan 1					
Cross Section	HEC-1 Discharge (cfs)	FLO-2D Base Model Discharge (cfs)	Percent Difference	FLO-2D Model: No Infiltration (cfs)	Percent Difference
xs30	3889	3763	-3%	3828	-2%
xs40	4149	3739	-10%	4042	-3%
xs60	661	172	-74%	133	-80%
xs30-60	1	332	33100%	342	34100%

Table 6. Comparison of HEC-1 and FLO-2D Peak Discharges: Rainbow Valley Fan 12					
Cross Section	HEC-1 Discharge (cfs)	FLO-2D Base Model Discharge (cfs)	Percent Difference	FLO-2D Model: No Infiltration (cfs)	Percent Difference
xs60	884	871	-1%	824	-7%
xs90	1070	159	-85%	198	-81%
xs70	1264	73	-94%	126	-90%
xs80	1185	13	-99%	18	-98%
xs120	2281	49	-98%	73	-97%
xs130	2189	16	-99%	51	-98%

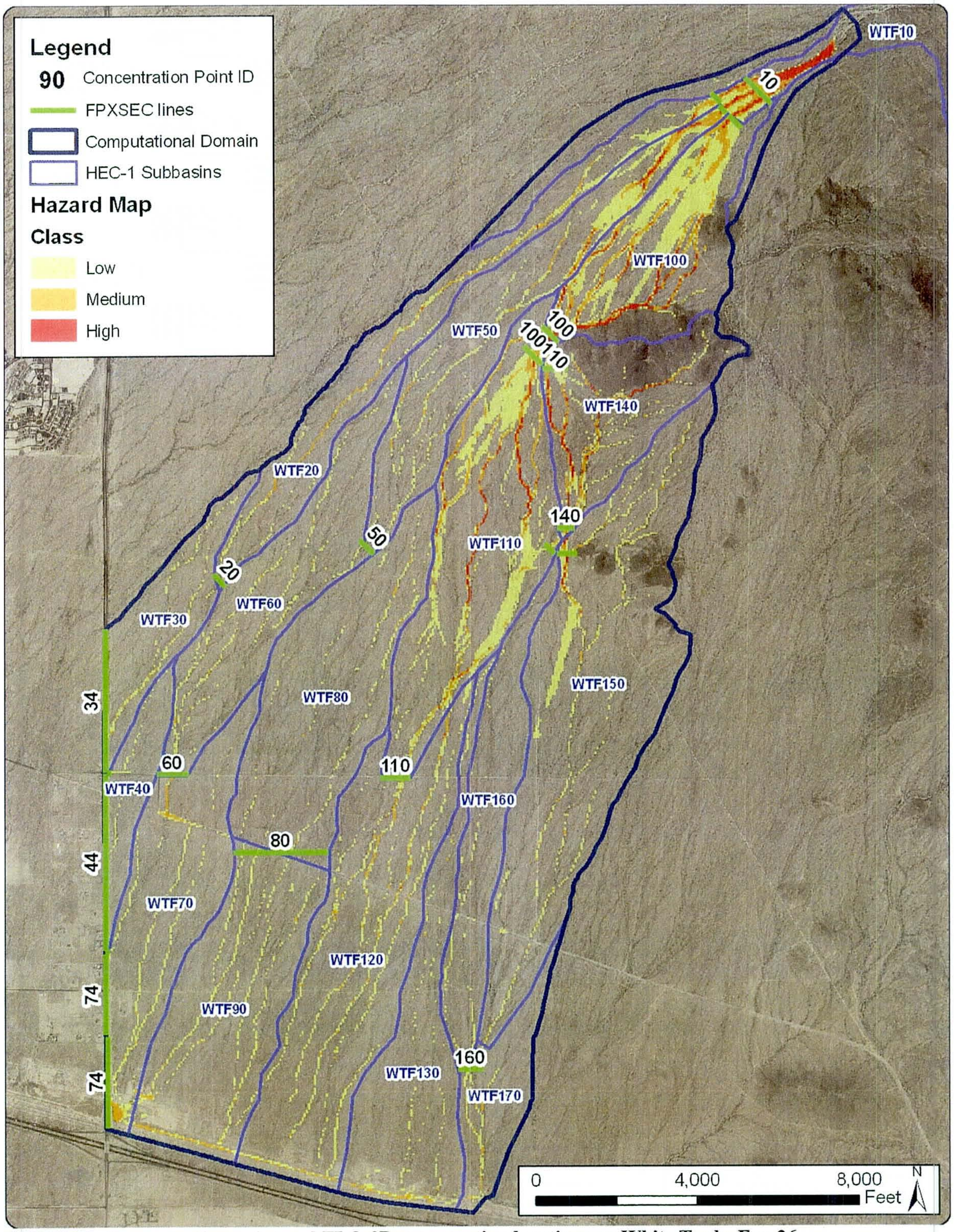

Figure 12. Concentration point and FLO-2D cross section locations on White Tanks Fan 36.

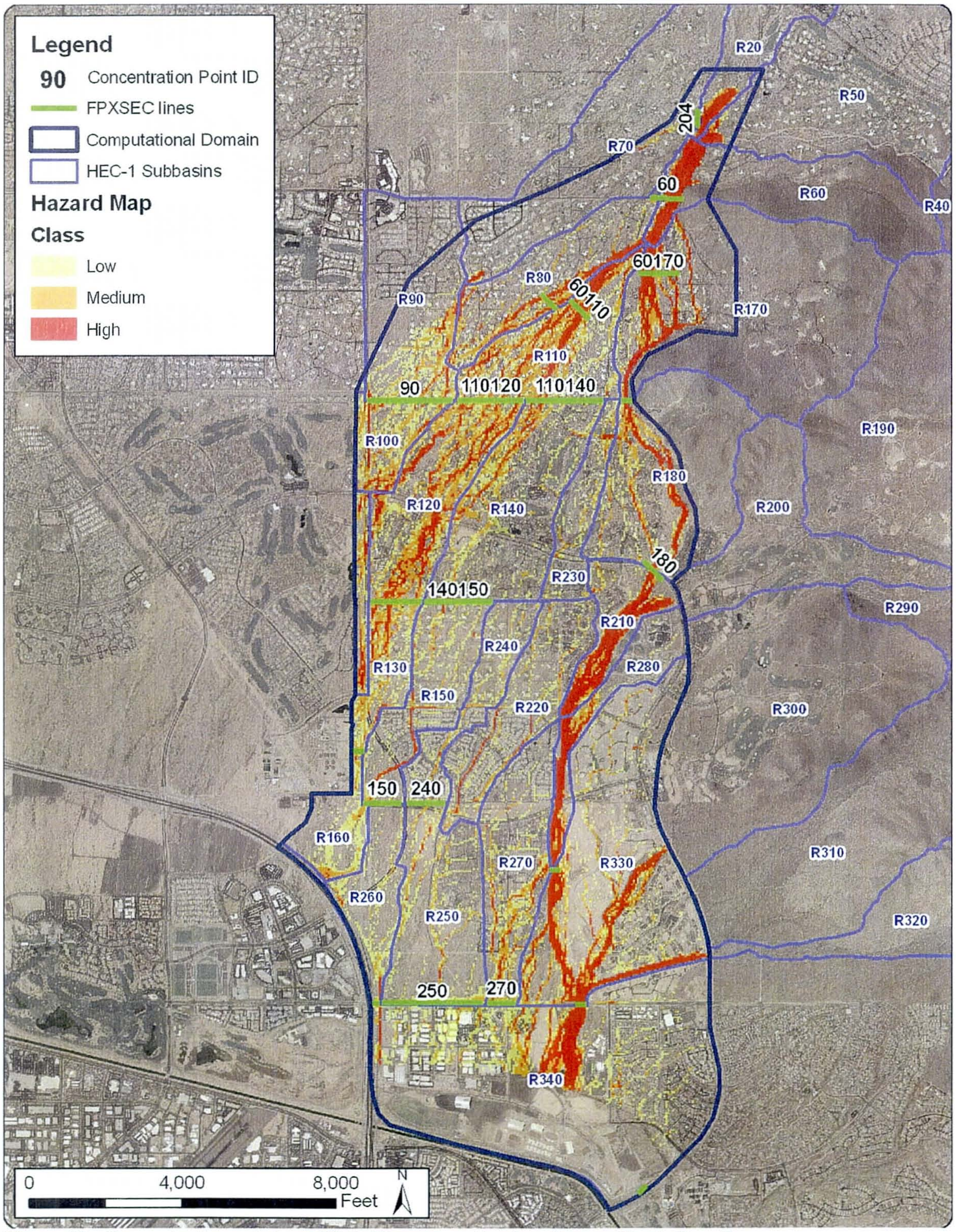

Figure 13. Concentration point and FLO-2D cross section locations on Reata Pass Fan.

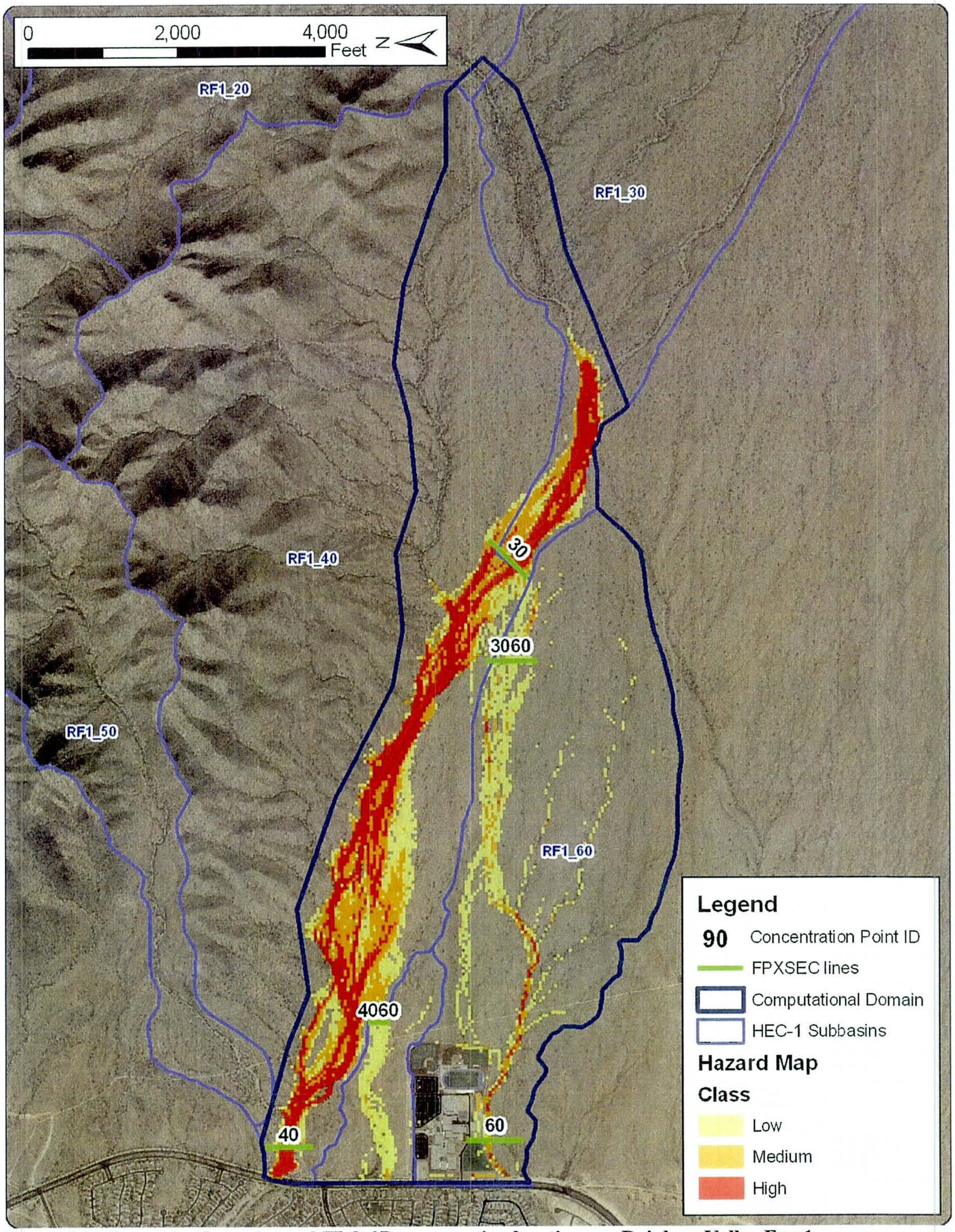

Figure 14. Concentration point and FLO-2D cross section locations on Rainbow Valley Fan 1.

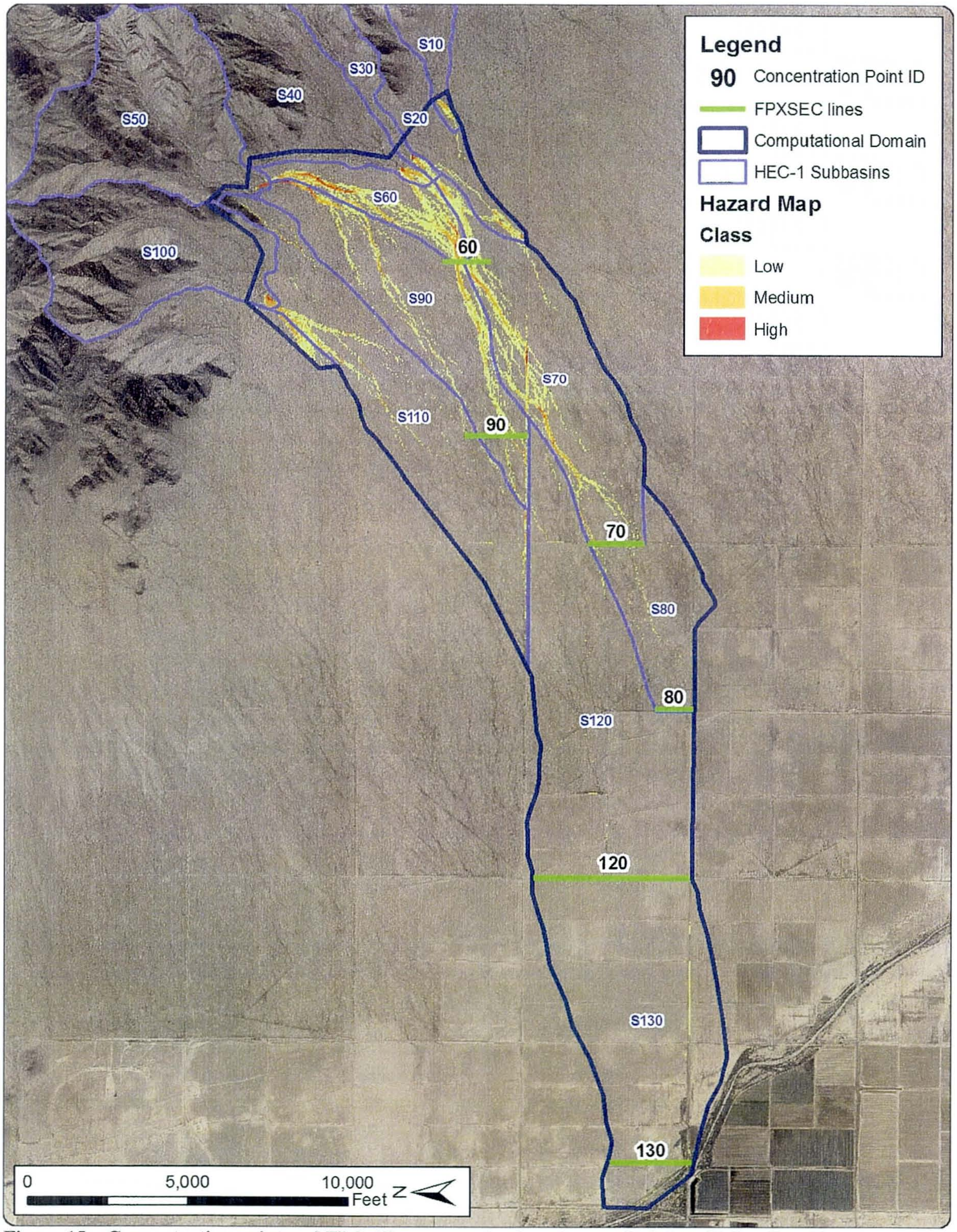

Figure 15. Concentration point and FLO-2D cross section locations on Rainbow Valley Fan 12.

Data requirements. Interestingly, the improved modeling capabilities of FLO-2D compared to HEC-1 do not come at an increased modeling cost or data requirements. The same topographic, rainfall, and soils data are used in both models. FLO-2D may require less data input in that vegetative cover type and density, time of concentration estimates, land use information, sub-watershed delineations, and channel routing parameters may not require explicit data sets. Additionally, FLO-2D offers the capability to include better resolution topographic and geographic data well beyond the lumped-parameter capabilities of HEC-1 that would further improve the FLO-2D model results.

Re-infiltration.[8] HEC-1 applies loss rates only to rainfall, and assumes that all of the "rainfall excess" become runoff at a downstream concentration point. FLO-2D computes rainfall losses similarly to HEC-1, but also continues to compute losses as the "rainfall excess" moves downstream across the land surface, if the ground storage and infiltration capacity has not been met at the time runoff crosses a grid element. This difference alone results in significant differences in the flow volume reaching any concentration point. For the purposes of this report, the continued infiltration of surface runoff as it moves across a land surface has been termed "re-infiltration" to distinguish it from the initial infiltration that occurs as an element of rainfall losses.

Flow peak attenuation. One of the most important findings of the PFHAM study is that significant attenuation of the peak discharge at the hydrographic apex occurs as the flood hydrograph crosses the surface of active alluvial fans in Maricopa County. Use of the peak discharge at the hydrographic apex may over-estimate the peak discharge at any point along the toe of the alluvial fan by up to two orders of magnitude. This finding is based primarily on FLO-2D modeling results, but is consistent with post-flood observations of alluvial fans, in which widespread (i.e., non-channelized) flood inundation floods (Pearthree et. al., 1992; 2004) and large flood peaks that completely dissipated before leaving the fan surface were observed (French and Miller, in press) Significant attenuation is also consistent with the geomorphic character of the drainage system on active alluvial fans in which net channel capacity decreases in the down-fan direction (CH2M HILL, 1992). Additional FLO-2D models coded with no re-infiltration showed similar attenuation across the active fan surface.

Flow attenuation on active fan surfaces is caused by three primary factors. First, on alluvial fans in Maricopa County the acreage of the active alluvial fan area may far exceed the watershed area upstream of the hydrographic apex. These extensive land surfaces are inundated and available for storage of flood water, resulting in high rates of flow attenuation. Second, most of the flooding on active alluvial fans in Maricopa County occurs as shallow sheet floods or distributary flow. The areas subject to high velocities and depths are relatively limited and are located near the hydrographic apex. Outside the limited high hazard zones, shallow flooding moves at relatively slow velocities increasing both the storage time and opportunity for (re)infiltration. Third, active alluvial fans in

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[8] "Re-infiltration" is a form of transmission loss. The term re-infiltration is preferred in this context to distinguish it from losses that occur only along defined flow paths.

Maricopa County typically are composed of permeable sand and/or gravel, which are capable of absorbing large volumes of flood water.

Advantages of FLO-2D modeling. FLO-2D offers a number of advantages over HEC-1 for hydrologic modeling of active alluvial fans. First, there is no need to delineate subwatershed boundaries in poorly-defined distributary and sheet flooding areas. Runoff is accumulated based on site topography and flow hydraulics without regard for pre-conceived basin divides. Furthermore, runoff can flow in different directions at different flow rates and depths, depending on specific site conditions. Second, runoff can leave the model space anywhere along the modeling domain boundary, not just at specific concentration points. Third, the model can generate peak discharges and hydrographs anywhere within the model domain, rather than just at specific concentration points. Fourth, flow does not have to collect at concentration points in FLO-2D but can exit as unconfined sheet flooding, distributary flow along multiple channels or be stored at intermediate ponding areas. Fifth, intermingling of flow along undefined boundaries between coalescing alluvial fans is easily modeled and addressed. Sixth, the flow hydrology and hydraulics are computed concurrently, avoiding any disconnect (and additional labor) between single-focus models. Seventh, routing of a flow hydrograph is inherent in the model code, eliminating the need for estimated hydrologic routing parameters or averaged hydraulic routing cross sections. Eighth, watershed parameters can be entered as distributed characteristics over a relatively small grid size, rather than lumped and averaged over large subbasins, allowing much finer resolution of input data. Ninth, modeling elements can be entered anywhere within the modeling domain, rather than just at pre-determined concentration points and computational nodes. Most importantly, FLO-2D results fit the anecdotal and behavioral expectations of the engineering and geosciences communities better than the HEC-1 results. Therefore, it is the conclusion of the study, that FLO-2D is far superior to HEC-1 for modeling piedmont drainage systems.

Development impacts. As a consequence of the loss of the high rates of flow attenuation that occurs on undeveloped active alluvial fans, unregulated development on active fan surfaces is likely to have major adverse impacts on flow rates at adjacent downstream properties. Development impacts on flooding are likely to include loss of natural flood storage areas, loss of runoff infiltration surfaces, increased runoff volume from constructed or disturbed surfaces, increase runoff frequency from impervious areas, accelerated flow travel times over developed surfaces, concentration of previously unconfined flow, introduction of non-natural runoff sources (over-watering, spillage, etc.), and increased antecedent moisture due to irrigation.

If unregulated development only eliminated the natural flow storage and infiltration areas on an active alluvial fan, a number of adverse consequences would be likely. First, the peak discharge reaching downstream properties is likely to be at or nearer the flow rate at the hydrographic apex. Second, when the increased peak discharges reach distal portions of the fan that lack defined channels, increased overbank flooding and/or erosion of new channels is likely. Third, sediment that was previously stored on the active fan surface will be transported downfan and deposited in areas that previously received little or no sediment deposition. In effect, the fan apex will be translated downstream to a point below the developed portion of the fan. Therefore, it is critical that development on active alluvial fan surfaces be appropriately managed.

Flow path uncertainty. A methodology to account for the impact of flow path uncertainty on peak discharge was developed for use on active alluvial fans in Maricopa County. This methodology, called the "virtual levee scenario" technique, the mechanics of which are described in more detail in Section 2.3.3, as well as in Appendixes F and I of this report. The virtual levee scenario methodology simulates the possible impact of an avulsion on the flood hydrology and hydraulics of an active alluvial fan using an artificial (virtual) levee coded into the FLO-2D model. A series of FLO-2D models (scenarios) such virtual levees that direct flow along potential avulsive flow paths with in the most active portion of an alluvial fan, changing the rate and distribution of flow in the portions of the alluvial fan located downstream of the virtual levees. The maximum computed flow rate and hydraulic characteristics at any given point derived from all of the virtual levee scenarios are then used for floodplain delineation and engineering design. The virtual levee scenario methodology thus accounts for flow path uncertainty within the active parts of the alluvial fan, while not ignoring the important processes of flow attenuation downstream of the hydrographic apex. The virtual levee scenario methodology was developed in conjunction with staff from the District's Engineering Division, and was successfully applied to estimate peak discharges below the fan apex for the White Tanks Fan 1-2 floodplain delineation (JEF, 2009).[9]

The virtual levee methodology offers a number of advantages over other traditional hydrologic modeling techniques on active alluvial fans. First, the method explicitly accounts for flow path uncertainty by considering multiple flow paths that could occur if runoff were redirected along potential avulsive channels in the high hazard portion of an active alluvial fan. Second, the method provides a reasonable technical basis (avulsion) for any over-accounting of the apex hydrograph. Third, the method is based on physical processes identified by geomorphic and hydraulic evaluation of an active alluvial fan (Appendix I). Fourth, the method combines engineering and geomorphic analysis techniques, providing opportunities for verification of quantified results. Fifth, the hydrologic elements allow for flow attenuation both within the channelized portion of the alluvial fan and across the shallow sheet flooding and distributary flow portions of the alluvial fan. In summary, the virtual levee method provides a conservative, but not overly conservative estimate of peak discharge at any point on an active alluvial fan downstream of the hydrographic apex.

2.3.2.4. Hydrologic Modeling Conclusions

Based on the results of the hydrologic modeling evaluation performed for the PFHAM study, the following hydrologic modeling recommendations are proposed:

- Two-dimensional modeling is recommended for all hydrologic modeling below the hydrographic apex of active alluvial fans in Maricopa County.

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[9] The Fan 1-2 study is currently under review by FEMA.

- The District should develop two-dimensional hydrologic modeling guidelines that specifically address:
    - Point rainfall depths
    - Loss rate parameters
    - Limits on re-infiltration volume
    - Pre- and post-processing tools for modeling coalescing alluvial fans
- Hydrologic modeling upstream of the hydrographic apex should be completed as dictated by current District modeling guidelines and standards. Based on the findings of this study, it is recommended that the District develop guidelines for using FLO-2D to model watersheds upstream of the hydrographic apex, particularly for small watersheds or where tributary inflows to the active fan surface occur over broad areas, rather than at discrete concentration points.
- The virtual levee methodology should be used to estimate conservative peak discharges, flood hazard areas, flow depths, and water surface elevations for all areas located downstream of an active alluvial fan apex.

2.3.3. Two-Dimensional Hydraulic Modeling

Two-dimensional hydraulic modeling was performed using the FLO-2D computer model.[10] The objective of FLO-2D modeling of the four alluvial fan sites was to evaluate FLO-2D for use as a tool to quantify flood hazards on active alluvial fans in Maricopa County. To this end, over one hundred separate FLO-2D models were prepared for the four alluvial fan evaluation sites, as well as for several additional alluvial fans in Maricopa County. The following types of FLO-2D models were prepared for the study:

- 100-Year Base Models
- Multiple Frequency Models
- Model Sensitivity Runs
- Encroachment Impact Models
- Flood Hindcast Models
- Avulsion Scenario Models
- Virtual Levee Scenario Models
- Sediment Transport Models

A complete list of the FLO-2D models prepared and evaluated for this study is shown in Table 7. A description of the specific FLO-2D input data and modeling procedures used is provided in Appendix F of this report. Plots of FLO-2D depths, velocities and hazard zones for all of the types of FLO-2D runs are grouped and shown together in Figure 16 to Figure 22. Descriptions of each of the types of FLO-2D runs, as well as some of the key conclusions drawn from them, are provided in the following paragraphs.

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[10] Although the FLO-2D model was used for this study, the District will allow use of any two-dimensional model that meets the criteria and that has the capabilities required to perform the analyses outlined in this report.

Table 7. FLO-2D Models Prepared for the PFHAM Study								
Model Description	**WTF 36**	**RPF**	**RVF 1**	**RVF 12**	**WTF 1-2**	**H3**	**WTF 7-12**	**TW**
Base Model (Q100)								
With re-infiltration	x	x	x	x	x	x	x	x
No on-fan re-infiltration	x	x	x	x			x	
No on-fan rainfall	x	x	x	x				
Detailed topography	x				x			
Finer grid size	x							
Multiple channel option	x							
Multiple Frequency								
Q2	x	x	x	x				
Q10	x	x	x	x				
Q50	x	x	x	x				
Q500	x	x	x	x			x	x
QPMP	x	x	x	x			x	x
Virtual Levee Scenarios	5	3	3	2	7		3	
Fan Area Encroachment	X							
Known Flood Hindcast	1951							1997
Avulsion Scenarios								
Channel obstruction	x							
Extreme flood	x	x	x	x				x
Sediment Transport								
Q100	x	x	x	x	x			
Q500	x	x	x	x				
Q50	x	x	x	x				
Q10	x	x	x	x				
Q2	x	x	x	x				
Q100 – fine D50	x							
Q100 – average D50	x							
Q100 – coarse D50	x							
Q100 – Ackers/White		x						
Q100 – Englund/Hansen		x						
Q100 – Woo		x						
Q100 – Yang		x						
Q100 – Zeller/Fullerton		x			x			
Q100 – clear water inflow		x						

Key:
WTF 36: White Tanks Fan 36 | WTF 1-2: White Tanks Fan 1-2 | WTF7-12: White Tank Fan 7-12
RVF1: Rainbow Valley Fan 1 | RPF: Reata Pass Fan | H3: Hieroglyphic Mtns Fan 3
TW: Tiger Wash Fan | RVF12: Rainbow Valley Fan 12 | *(H3 modeling by PACE)

Table 8. FLO-2D modeling parameters.	
Rainfall	NOAA 14 Point Rainfall Values No rainfall in upstream HEC-1 subbasins overlap areas
Rainfall Losses	Green-Ampt loss rate methodology Initial abstraction, percent vegetative cover, imperviousness based on land use types ARF based on land use type
Topographic Data	Grid elevation from center of grid using Gaussian average tool Elevations built in ArcGIS TIN using 3d Analyst 10-ft topo (White Tanks) from District 2-ft topo (Reata, Rainbow) from District & Scottsdale
FLO-2D Parameters	N-values based on land use Limiting Froude No. = 0.95 per FLO-2D manual guidance for fans Shallow n-value = 0.112 (extrapolates to 0.040 at 3 ft depth) TOL = 0.001 DEPTOL = 0.05 WAVEMAX = -0.25
Modeling	50-ft grid size

2.3.3.1. 100-Year Base Model

The FLO-2D base models simulated the hydrology and hydraulics of the 100-year event on each of the alluvial fan evaluation sites. In addition, 100-year modeling results were considered from the White Tank Mountain Fan 1-2 Floodplain Delineation Study (JEF, 2009), White Tanks Mountain Fan 7-12 Floodplain Delineation Study (JEF, 2010), Hieroglyphic Mountain Fan 3 FLO-2D Modeling Study (PACE, 2010), and the Tiger Wash Alluvial Fan (see Appendix I). The base condition models were used as a standard of comparison to all other FLO-2D models, and were the primary source of 100-year hydraulic data. The following are some of the conclusions drawn from the FLO-2D 100-year base model results shown in Figure 16 to Figure 22:

- Distributary Flow Pattern. The flow pattern below the hydrographic apex makes a rapid transition from a confined, straight-braided single channel pattern to a highly distributary channel pattern. The distributary pattern persists over the entire alluvial fan landform, although in the mid- to distal-fan regions it becomes progressively intermingled with an incipient dendritic or parallel pattern that appears to have developed to convey on-fan runoff.
- Sheet Flooding. Most of the active alluvial fan surfaces are inundated by relatively shallow flow depths broadly distributed over the fan surface. Sheet flooding is probably the dominant type of flooding on any of the active alluvial fan surfaces considered.
- Flow Attenuation. The hydrograph attenuation described in Section 2.3.2 is due in part to the distribution of flow over the fan surface in distributary channels and sheet flooding areas. This distribution of flow allows for extensive flood storage, opportunities for infiltration, and low velocity flow over the fan surface, all of which create opportunities for flow attenuation.

- Low Depth and Velocity. The predicted 100-year flow depths and velocities are relatively low[11] over the vast majority of the fan surface. Areas of low velocity are conducive to sediment deposition and net long-term aggradation, which is not surprising, since it is a defining characteristic of an active alluvial fan.
- Limited High Hazard Zone.[12] As a consequence of predicted low flow depths and velocities, the high hazard zones are spatially limited, generally to small areas immediately below the hydrographic apexes.
- On-Fan Drainage Pattern. FLO-2D modeling predicts that most of the 100-year flooding is conveyed along the existing distributary channel pattern, with only a few minor exceptions noted in Section 2.7 and Appendix I.
- Inundation Limits. In no case did the FLO-2D modeling indicate that the 100-year flood completely inundates the Holocene surface, nor is it likely that a single 100-year flood would inundate the entire active portion of the alluvial fan landform. This finding is consistent with post-flood inundation mapping (Pearthree et. al. 1992, 2004) as well as the findings of other authors cited in the literature search (Pelletier et. al., 2004, French and Miller, in press).
- Anthropomorphic Impacts. The presence of roads and other structures on the fan can alter natural flow paths and create new, artificial channel alignments (e.g., Figure 19).

The FLO-2D base models indicate that flooding at fan evaluation sites is not conveyed via a single channel and that the flow paths locations are relatively predictable if floods occur with minimal sediment transport and relatively unchanging topography.

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[11] Note that the reported flow depths and velocities are average values for the FLO-2D grid cell. Maximum depths and velocities may be somewhat higher if more detailed topographic information were used.
[12] Computation of "hazard" shown in Figure 16 to Figure 22 is based on default FLO-2D methodology. The recommended hazard assessment methodology is discussed in more detail in Section 2.3.3.9.

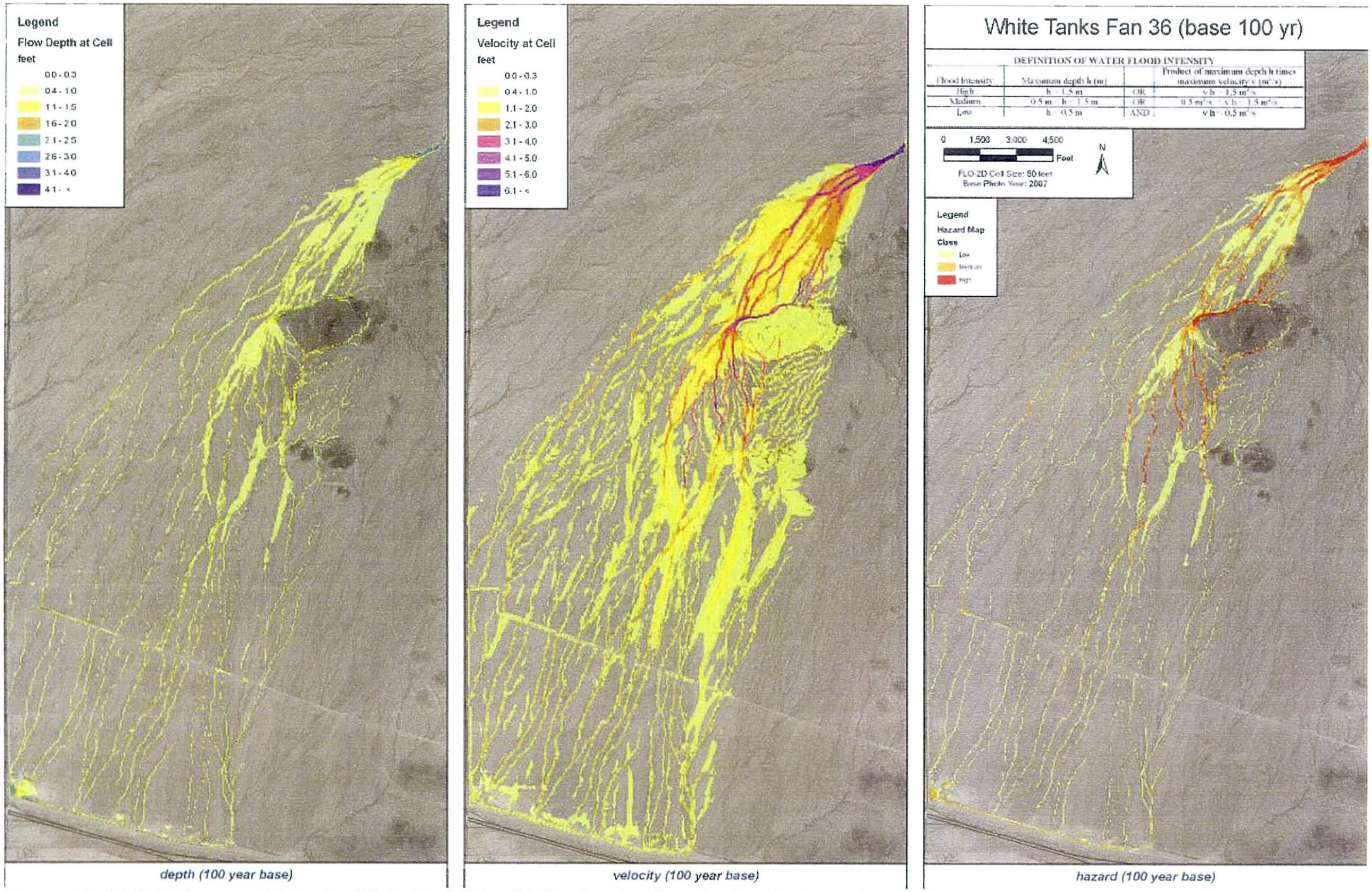


Figure 16. FLO-2D base model for the White Tanks Fan 36 site showing flow depth, velocity, and hazard.

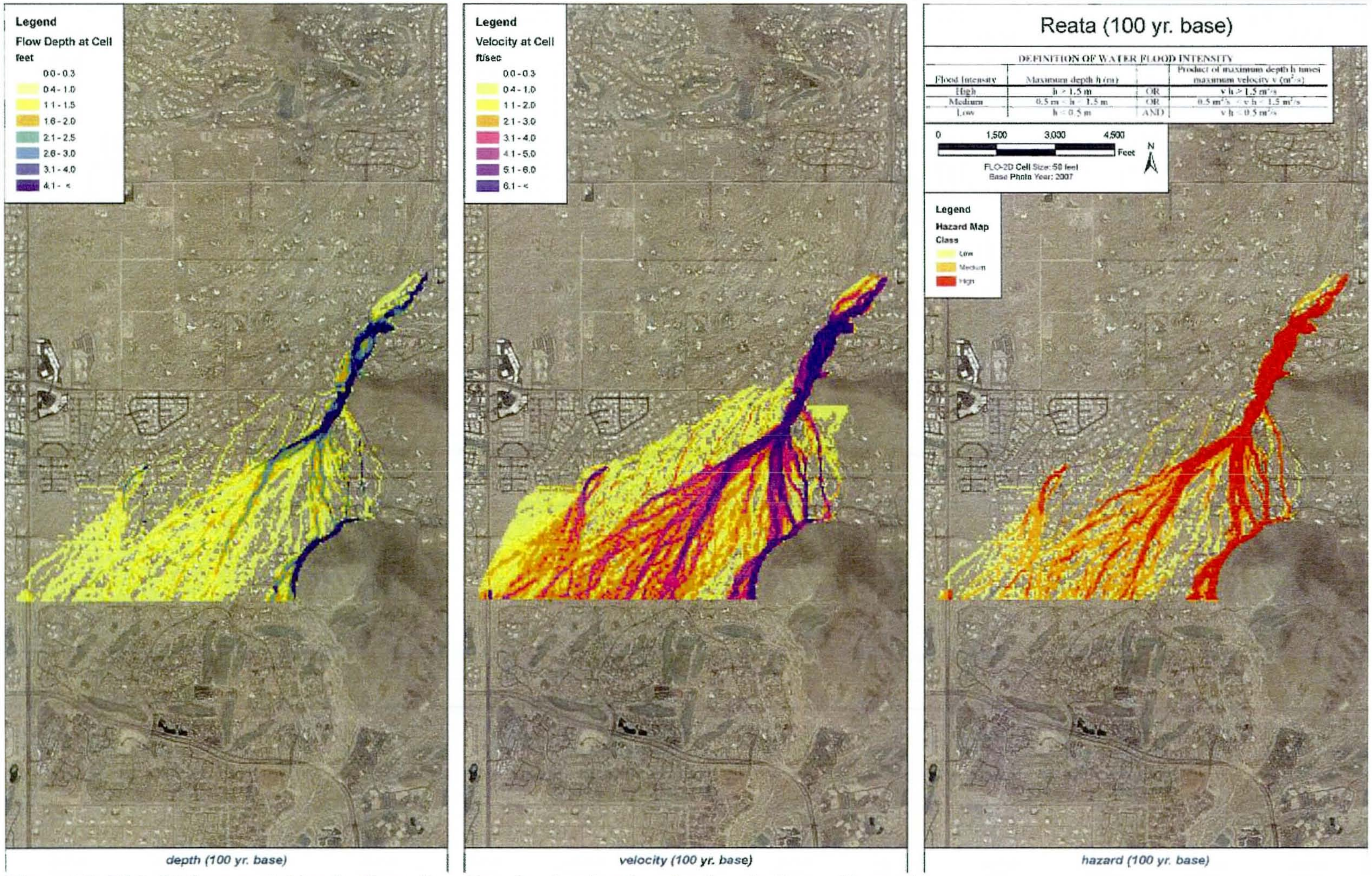


Figure 17. FLO-2D base model for the Reata Pass Fan site showing flow depth, velocity, and hazard.

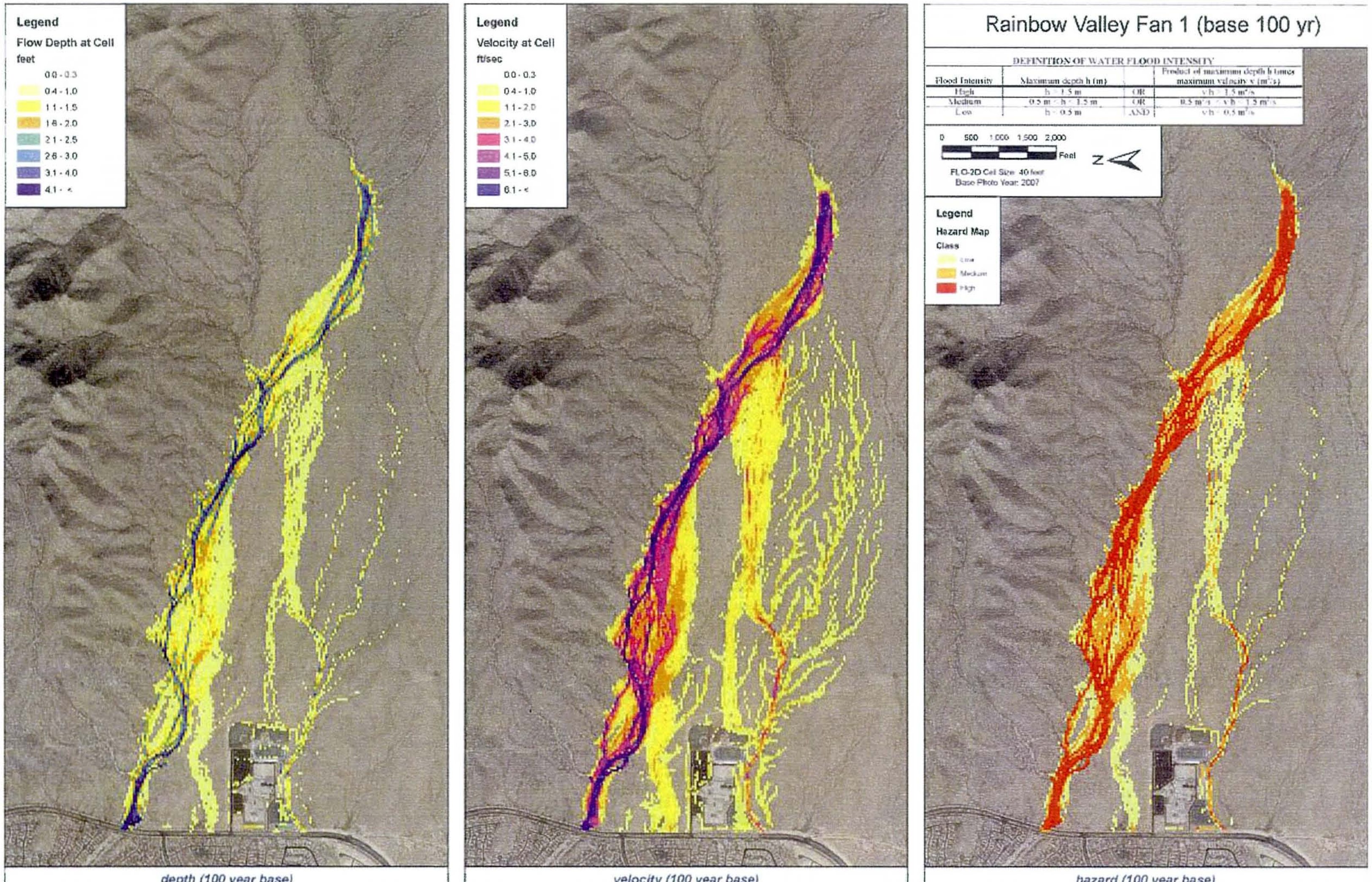


Figure 18. FLO-2D base model for the Rainbow Valley Fan 1 site showing flow depth, velocity, and hazard.

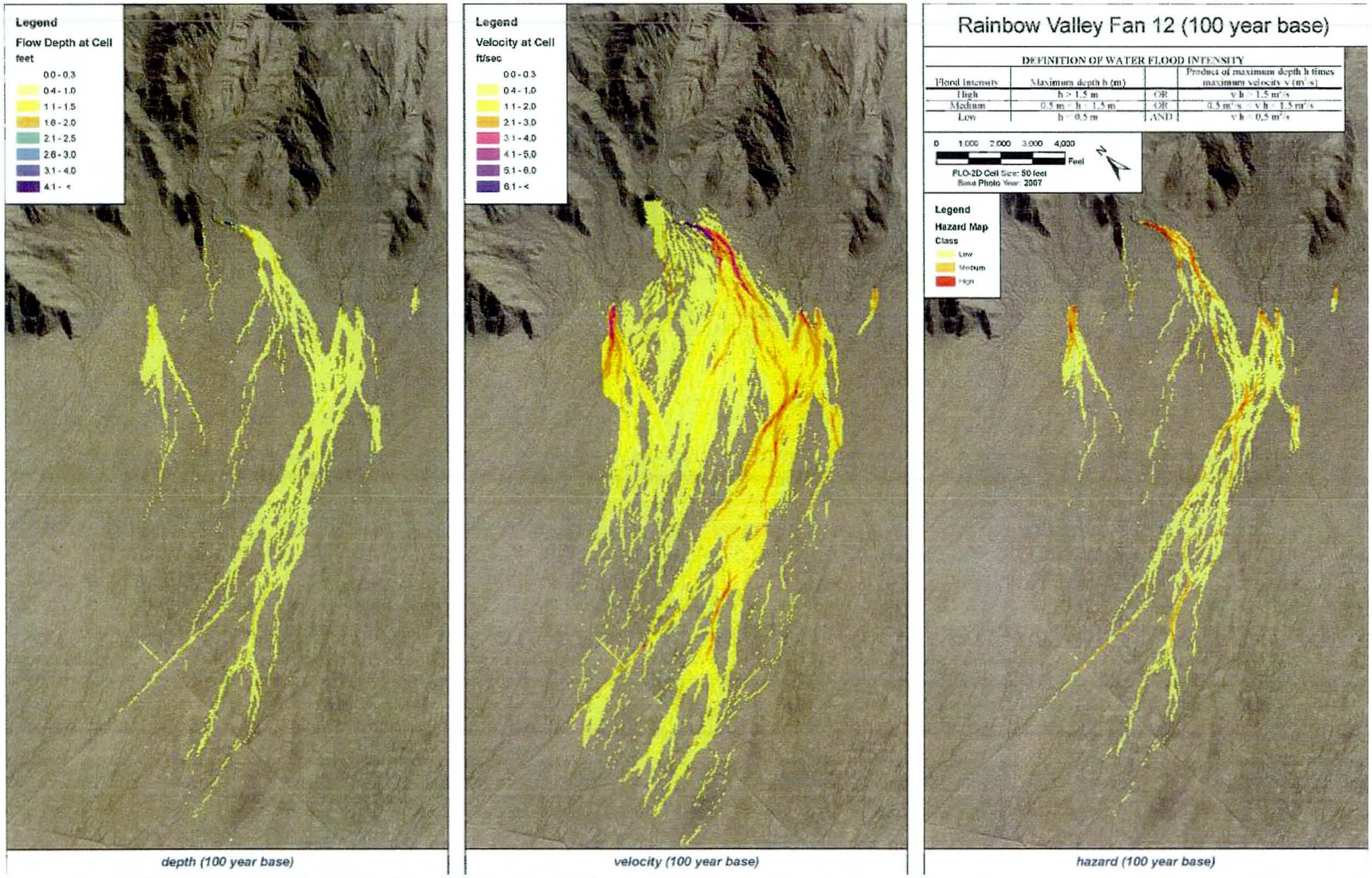
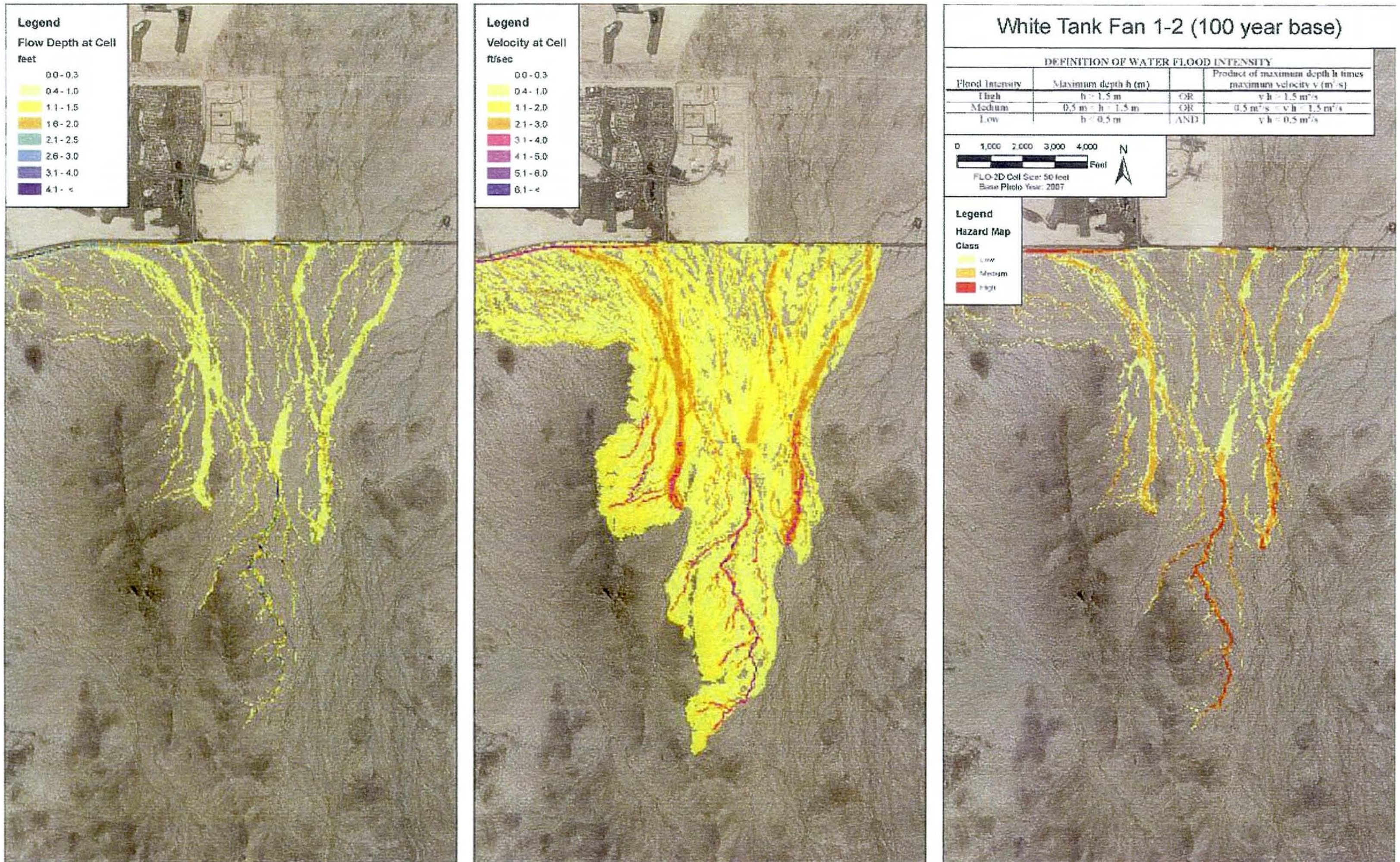


Figure 19. FLO-2D base model for the Rainbow Valley Fan 12 site showing flow depth, velocity, and hazard.



depth (100 year base) | velocity (100 year base) | hazard (100 year base)

Figure 20. FLO-2D base model for the White Tanks Fans 1-2 site showing flow depth, velocity, and hazard.

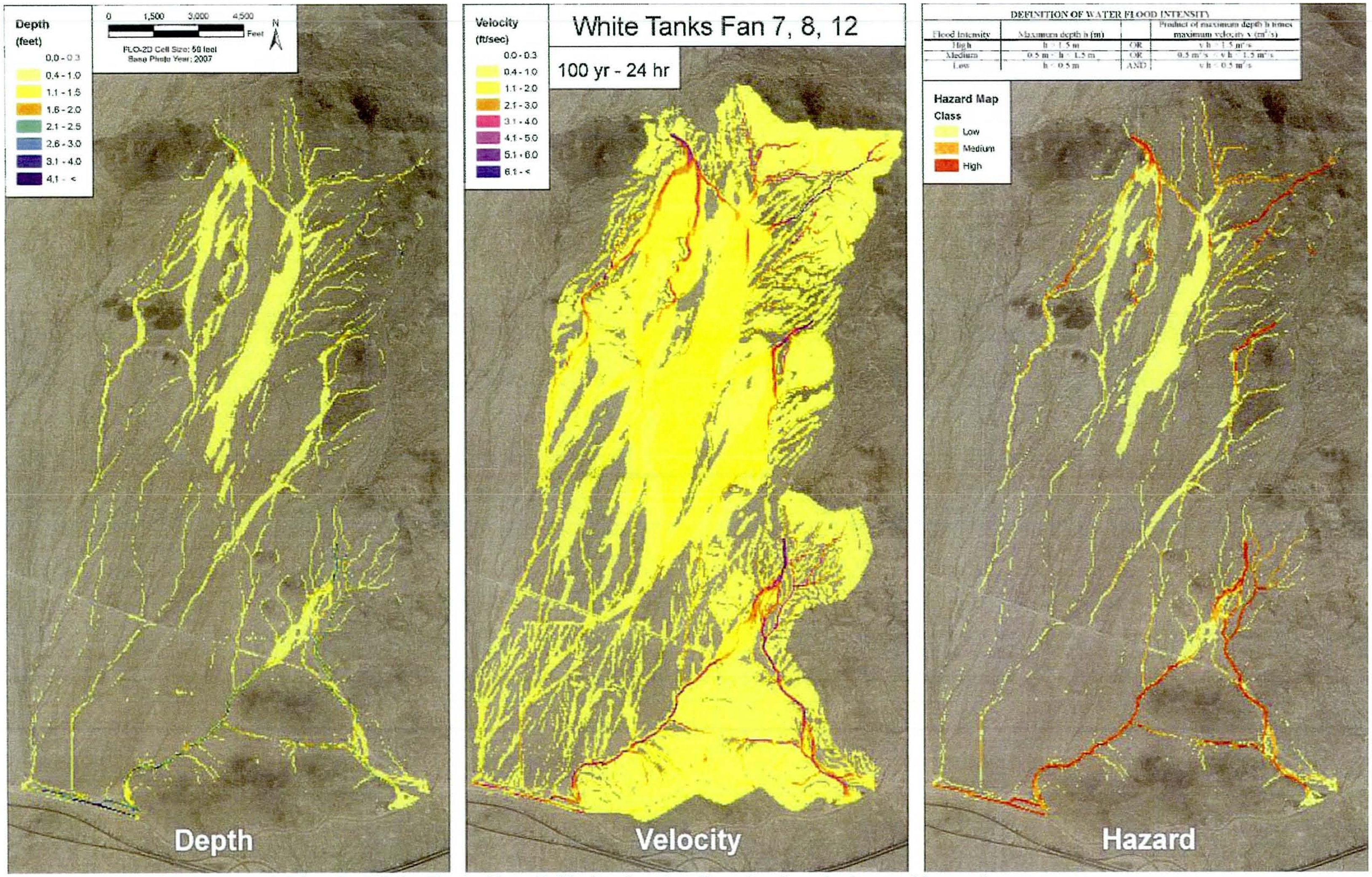


Figure 21. FLO-2D base model for the White Tanks Fans 7-12 site showing flow depth, velocity, and hazard.

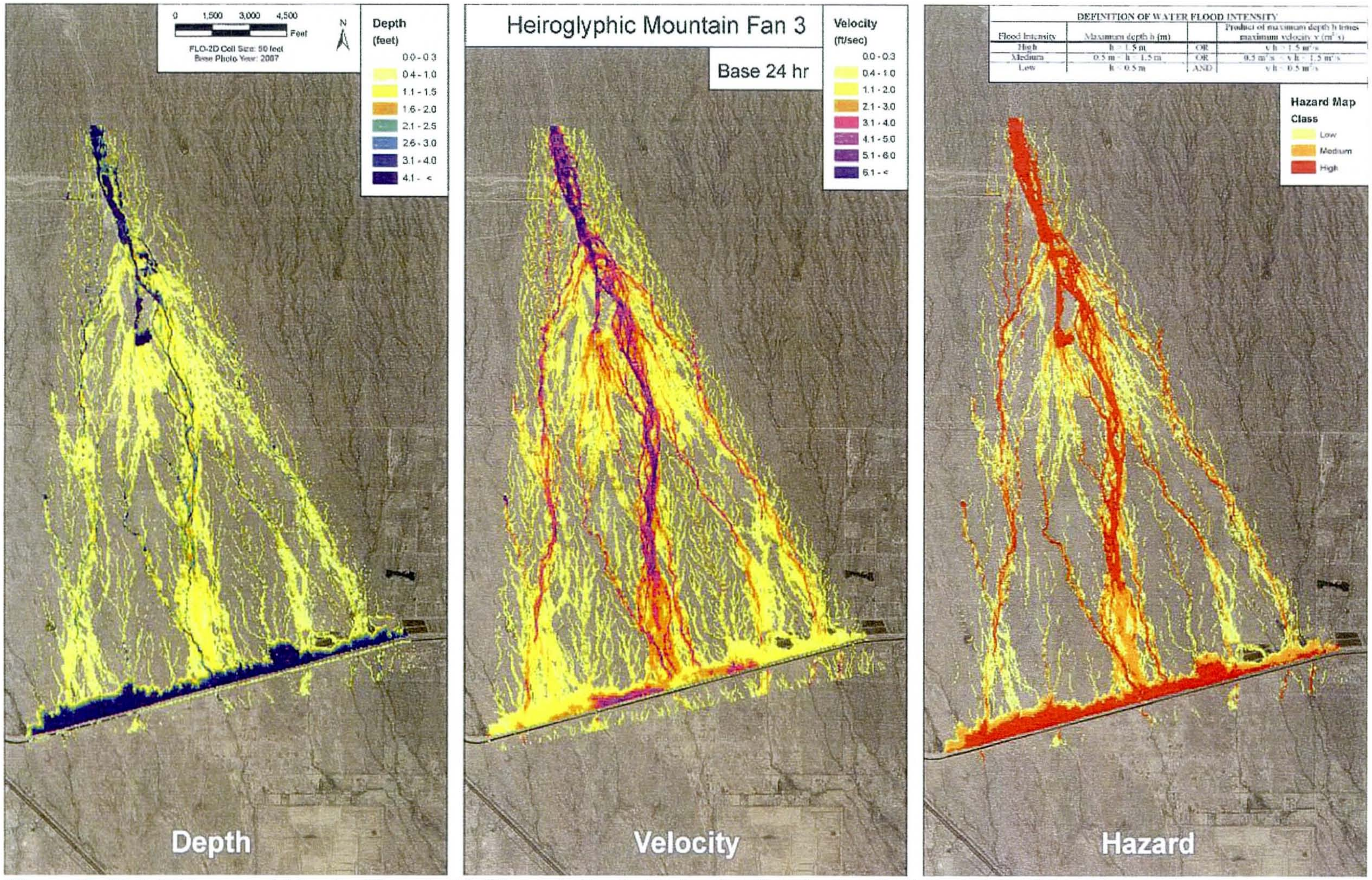


Figure 22. FLO-2D base model for the Hieroglyphic Mountain Fan 3 site showing flow depth, velocity, and hazard.

2.3.3.2. Multiple Frequency Models

Additional FLO-2D models were prepared for the four evaluation sites using 2-, 10-, 50-, and 500-year hydrographs. FLO-2D models also were prepared using probable maximum precipitation (PMP)[13] rates to simulate the potential behavior of an extreme flood event (>Q500) on the fan surface. The multiple frequency models were used to assess differences in potential impact to alluvial fan processes and hazards between large (infrequent) and small (frequent) floods. The following are some of the conclusions drawn from the FLO-2D multiple frequency model results shown in Figure 23 to Figure 26:

- Flow Pattern Similarity. Not surprisingly, FLO-2D results indicate that large floods inundate more of the fan surface, and at greater depths and velocities than small floods. However, despite the differences in depth and inundation, the overall pattern of flow inundation was nearly identical for large and small events. Regardless of flood magnitude, FLO-2D predicts that most flow occurs in distributary channels or as shallow sheet flooding.
- Extreme Floods. FLO-2D modeling indicates that the PMP event inundates nearly all of the Holocene surfaces at the four evaluation sites (Figure 27), particularly in the upper active fan areas. However, some surfaces in the mid- and distal-portions of the fan were not inundated, even at PMP flow rates. Therefore, the PMP FLO-2D runs may be useful for identifying non-floodprone surfaces within active portions of an alluvial fan. In addition, PMP (and 500-year) modeling results also help elucidate potential avulsive flow corridors, as described in Section 2.7.
- Flow Attenuation. The smallest floods tend to be completely attenuated on the active fan surfaces, and do not reach the fan toes. It can be assumed that if the flood water does not leave the fan surface, the entire sediment load (in those small events originating above the hydrographic apex) will be deposited on the fan surface. Furthermore, if the smaller, more frequent floods originating above the hydrographic apex do not reach the toe of the fan, then the drainage patterns in the lower fan areas are most likely the result of on-fan runoff alone. On-fan runoff events may transport sediment downfan, or in some cases, off the active fan surface.

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[13] The PMP rainfall depths and distributions were obtained from HMR 49 (NOAA, 1984).

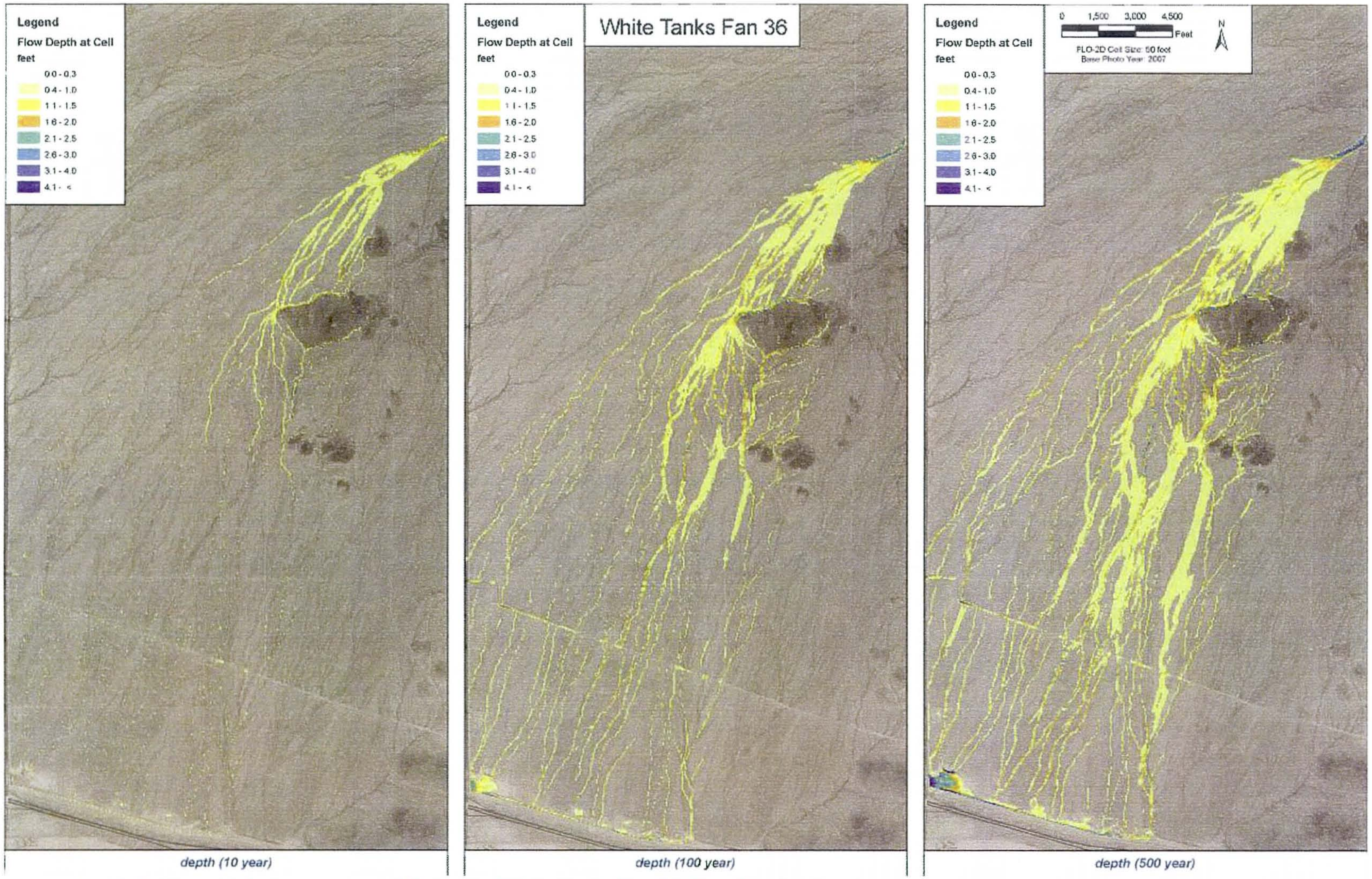


Figure 23. FLO-2D multiple frequency models for the White Tanks Fan 36 site - flow depth only.

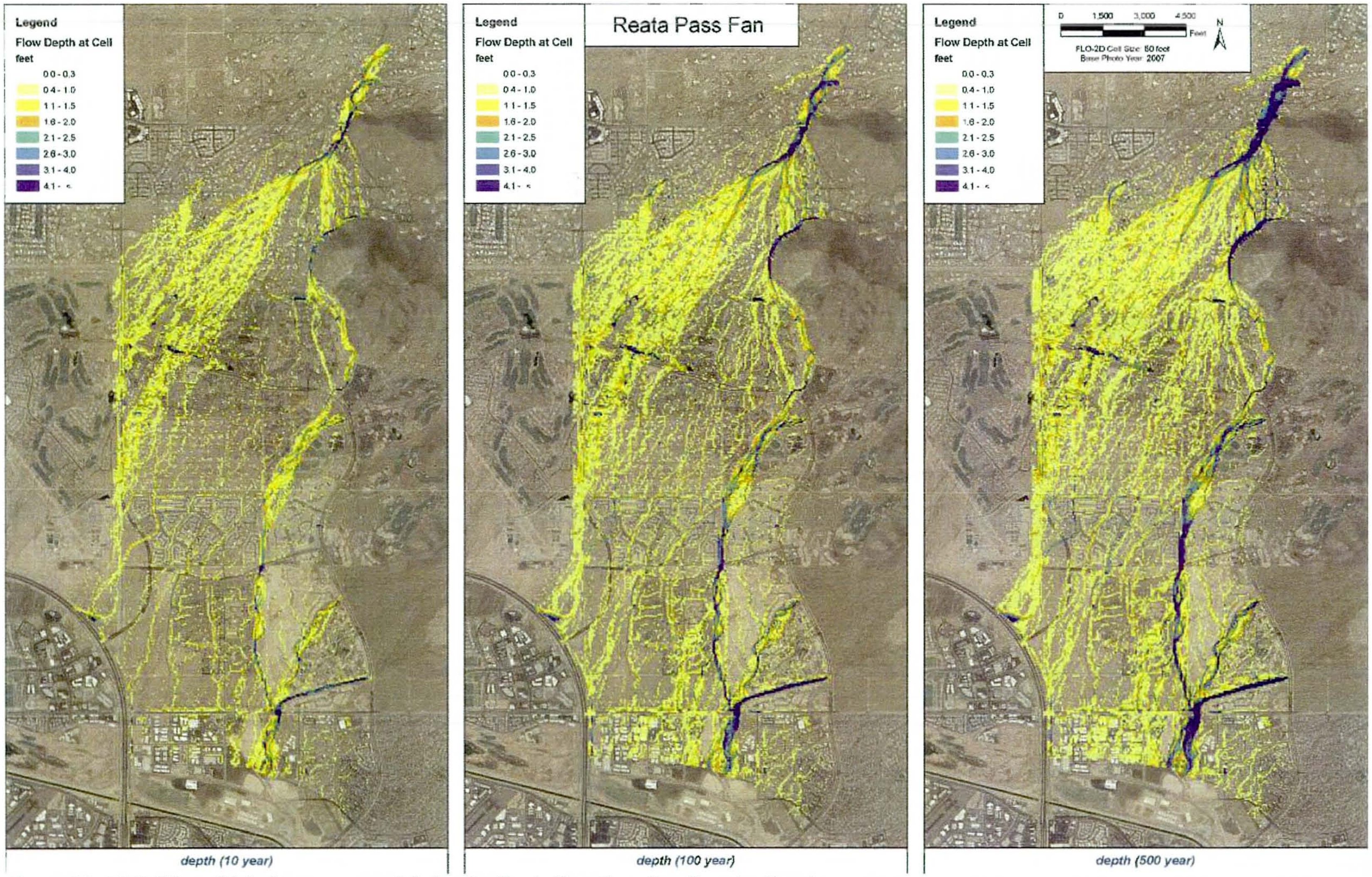


Figure 24. FLO-2D multiple frequency models for the Reata Pass Fan site - flow depth only.

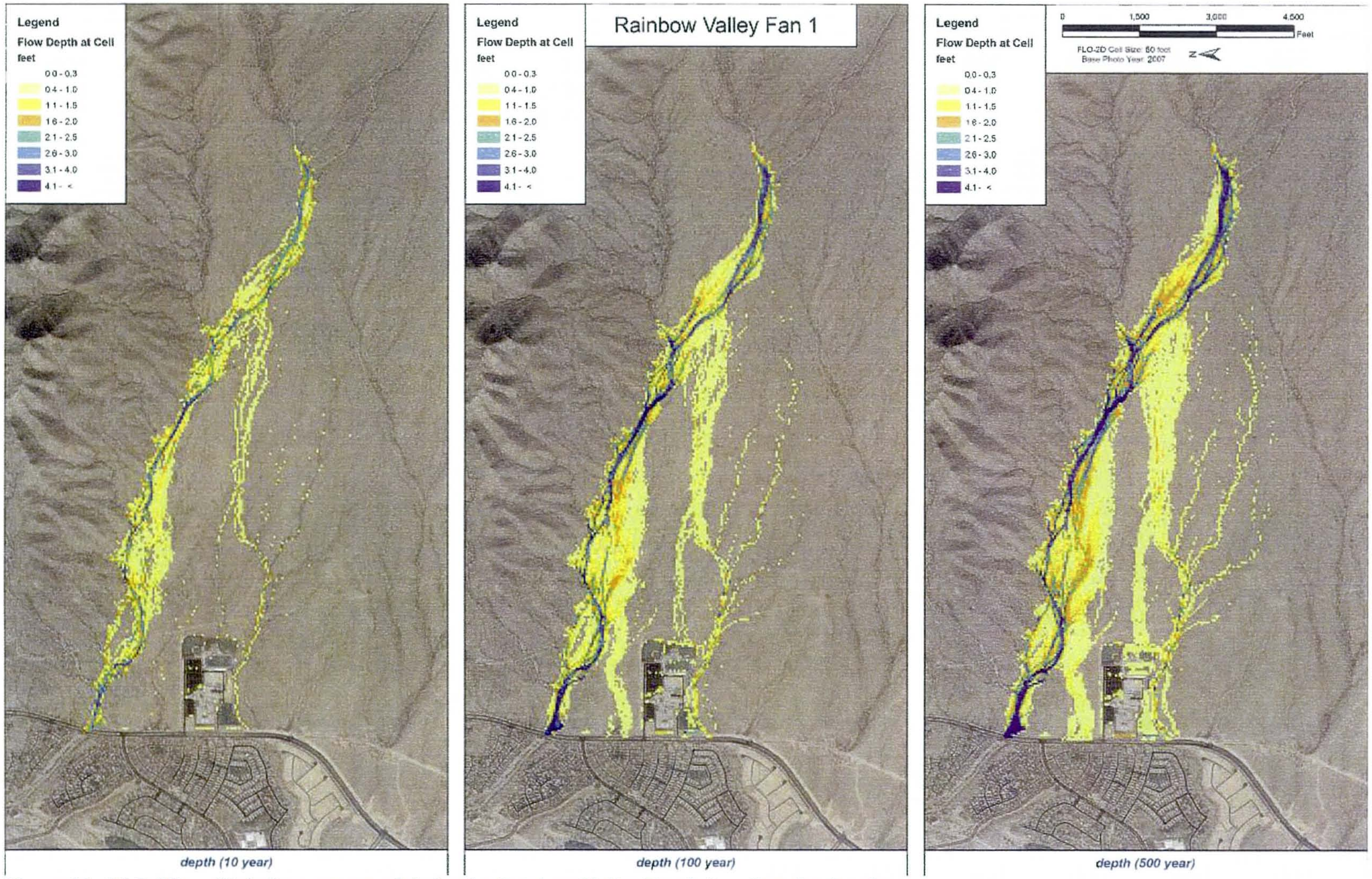


Figure 25. FLO-2D multiple frequency models for the Rainbow Valley Fan 1 site - flow depth only.

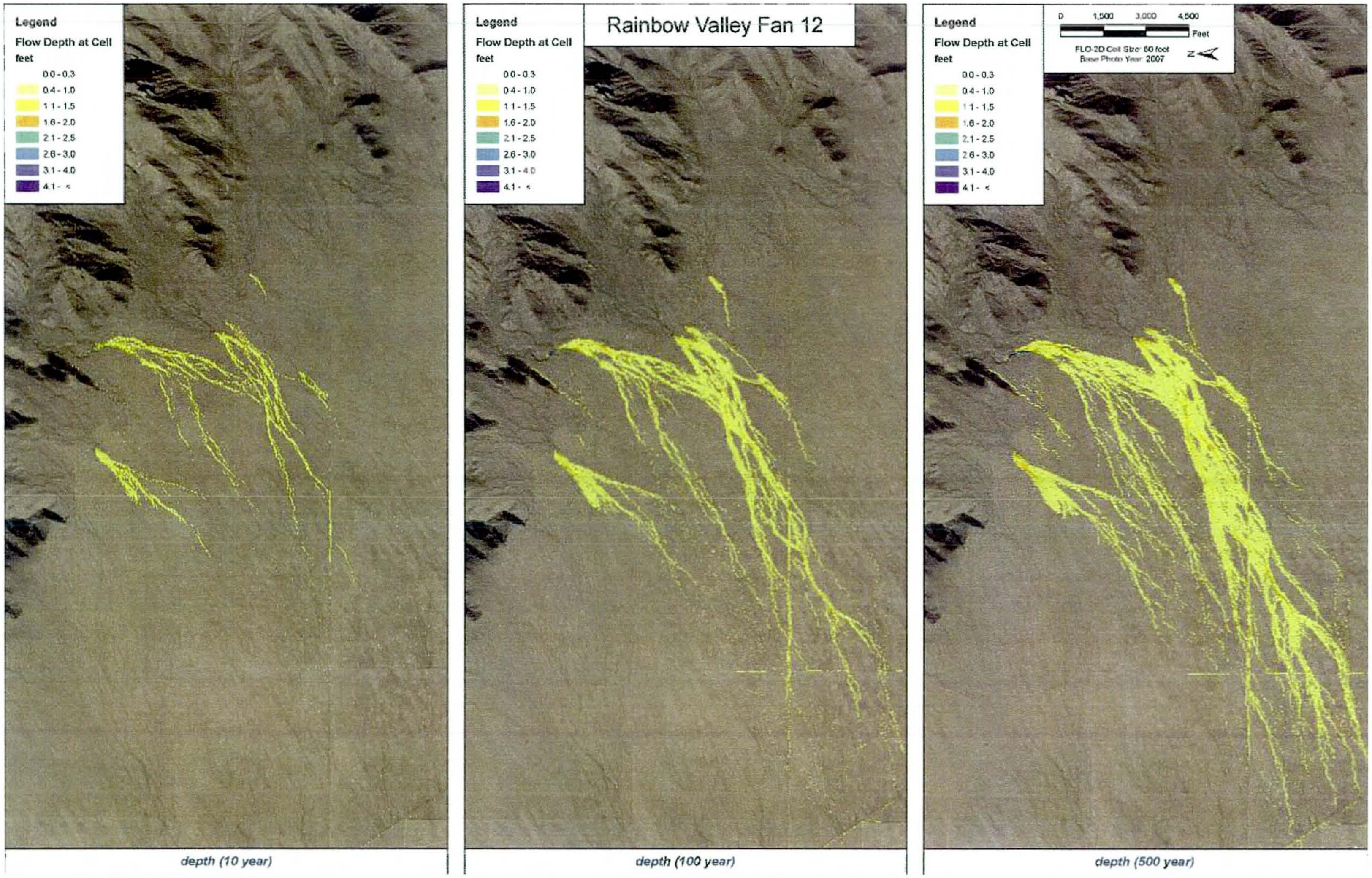


Figure 26. FLO-2D multiple frequency models for the Rainbow Valley Fan 12 site - flow depth only.

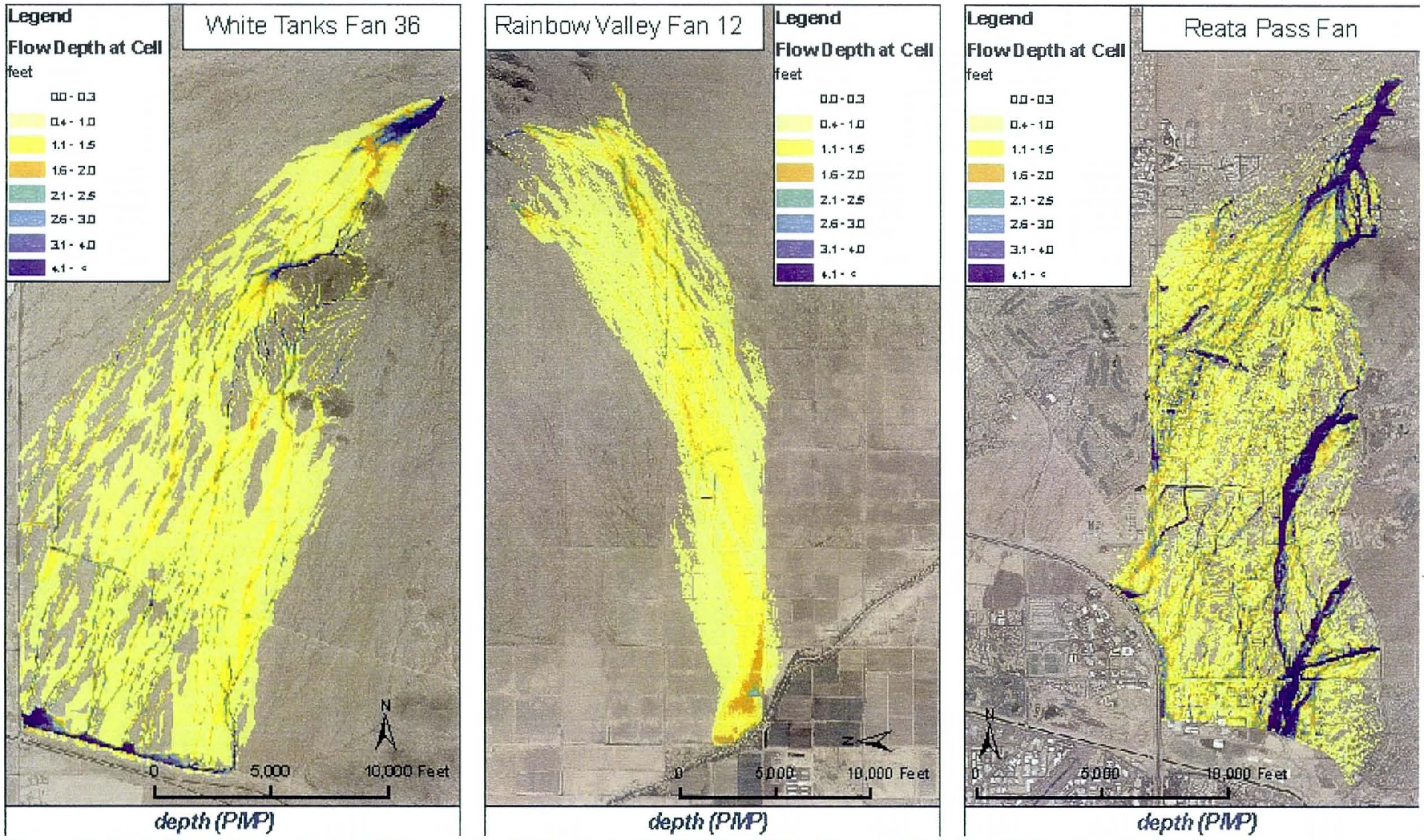


Figure 27. FLO-2D model results for PMP event for White Tanks Fan 36, Reata Pass Fan, and Rainbow Valley Fan 12.

2.3.3.3. Model Sensitivity Runs

A number of model sensitivity runs were prepared to evaluate the accuracy of the FLO-2D results. The following are some of the conclusions drawn from the FLO-2D model sensitivity results shown in Figure 28 to Figure 31:

- Multiple Channel Option (Figure 28). The multiple channel option in FLO-2D was developed to recognize that flow over the sheet flooding portions of a fan surface may occur in fine-textured, self-formed channels that might not be well-expressed using a coarse FLO-2D grid. The FLO-2D multiple channel option allows the model to develop a regime channel for routing the hydrograph through a grid cell. More detail on the modeling procedures are available in the FLO-2D user's manual (FLO-2D, 2010). Accordingly, use of the FLO-2D multiple-channel option in the WTF36 base model increased the volume of runoff delivered to the toe of the fan, increased the rate at which flow travelled across the fan, and increased the overall area of inundation on the fan surface. These results indicate that the multiple-channel option should be carefully evaluated prior to finalizing the recommendations for the proposed PFHAM methodology.
- Grid Size (Figure 29). Compared to the 50-foot grid used in the FLO-2D base model, use of a 25-foot grid size increased the resolution of the FLO-2D results, resulted in inundation of more land within the active area, and facilitated identification of more channelized flow paths, as well as potential avulsive flow corridors within the active area. Therefore, it was concluded that use of a smaller grid results in more accurate depiction of flood conditions. It is noted that smaller grid sizes can significantly increase the model run times for large alluvial fans, and that selection of the appropriate grid size requires experience, engineering judgment, and knowledge of site conditions. In cases where the topographic data resolution is poor, use of a smaller grid system may not be justified. In this study, modeling performed using 40- and 50-foot grid cells was found to achieve the study goals. More guidance on grid size selection is available in the FLO-2D User's Manual, and will be provided (and supplemented with District guidelines) in the revised PFHAM document, after the completion of this study.
- Topographic Data (Figure 30). Similarly, use of 2-foot topographic data in the WTF 36 site FLO-2D model increased the resolution of the predicted inundation area relative to the 10-foot topographic data used in the base models. In all cases, use of the most detailed topographic data available is recommended. Where more detailed topographic mapping is available, the smallest possible grid size relative to run time should be used to optimize the modeling results.
- No Infiltration and On-Fan Rainfall (Figure 31). To test the validity of the high rates of flow attenuation predicted by FLO-2D, additional models were prepared in which no on-fan rainfall was simulated and the infiltration option was turned off. These changes did not significantly change the FLO-2D results, leading to the conclusion that the levels of predicted flow attenuation are due primarily to the extensive storage volume available on the inundated portions of an alluvial fan relative to the flood volume, and the slow rate of hydrograph progression downfan at low depths and velocities across the fan surface.

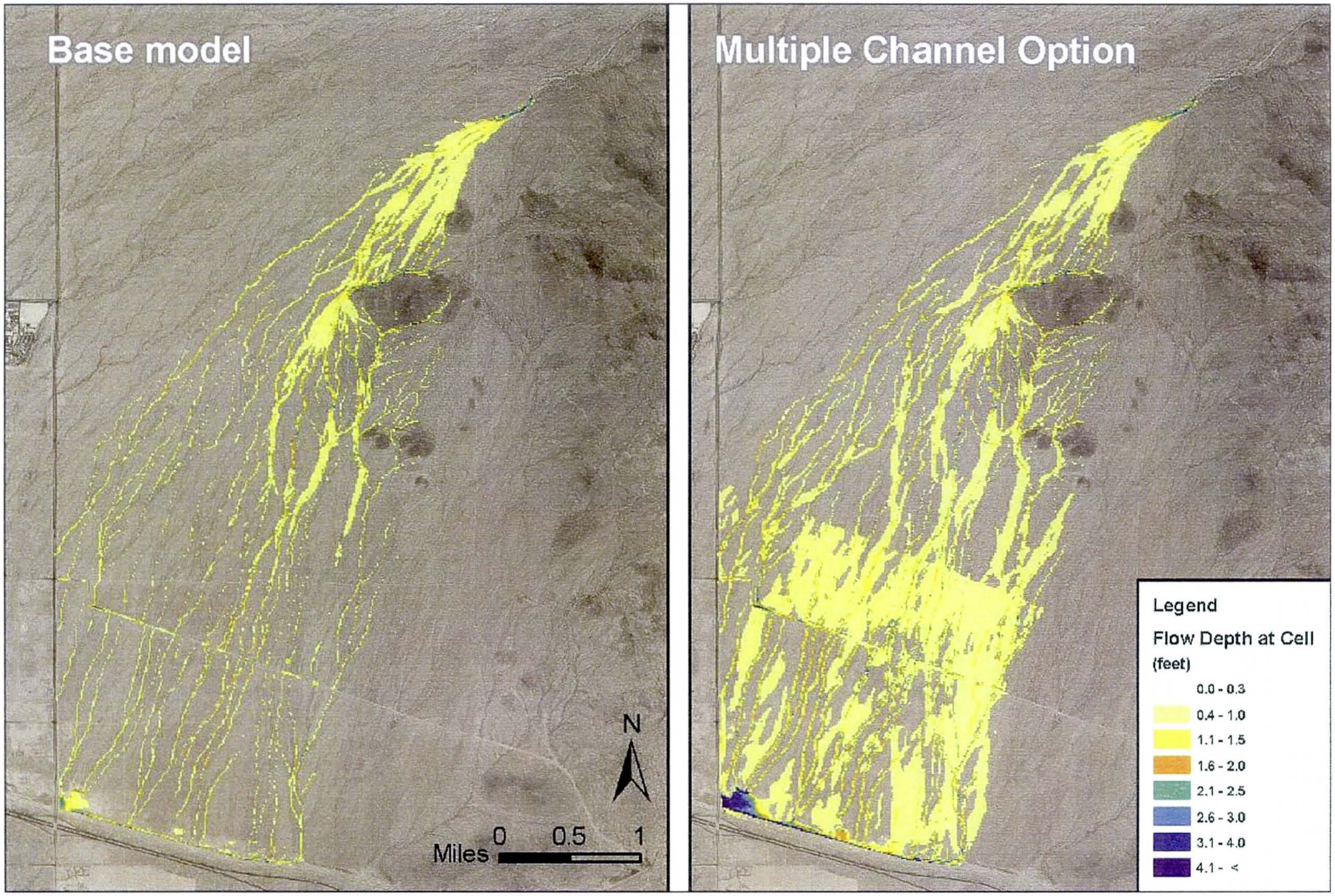


Figure 28. FLO-2D results for White Tanks Fan 36 – multiple channel vs. base model (Q100).

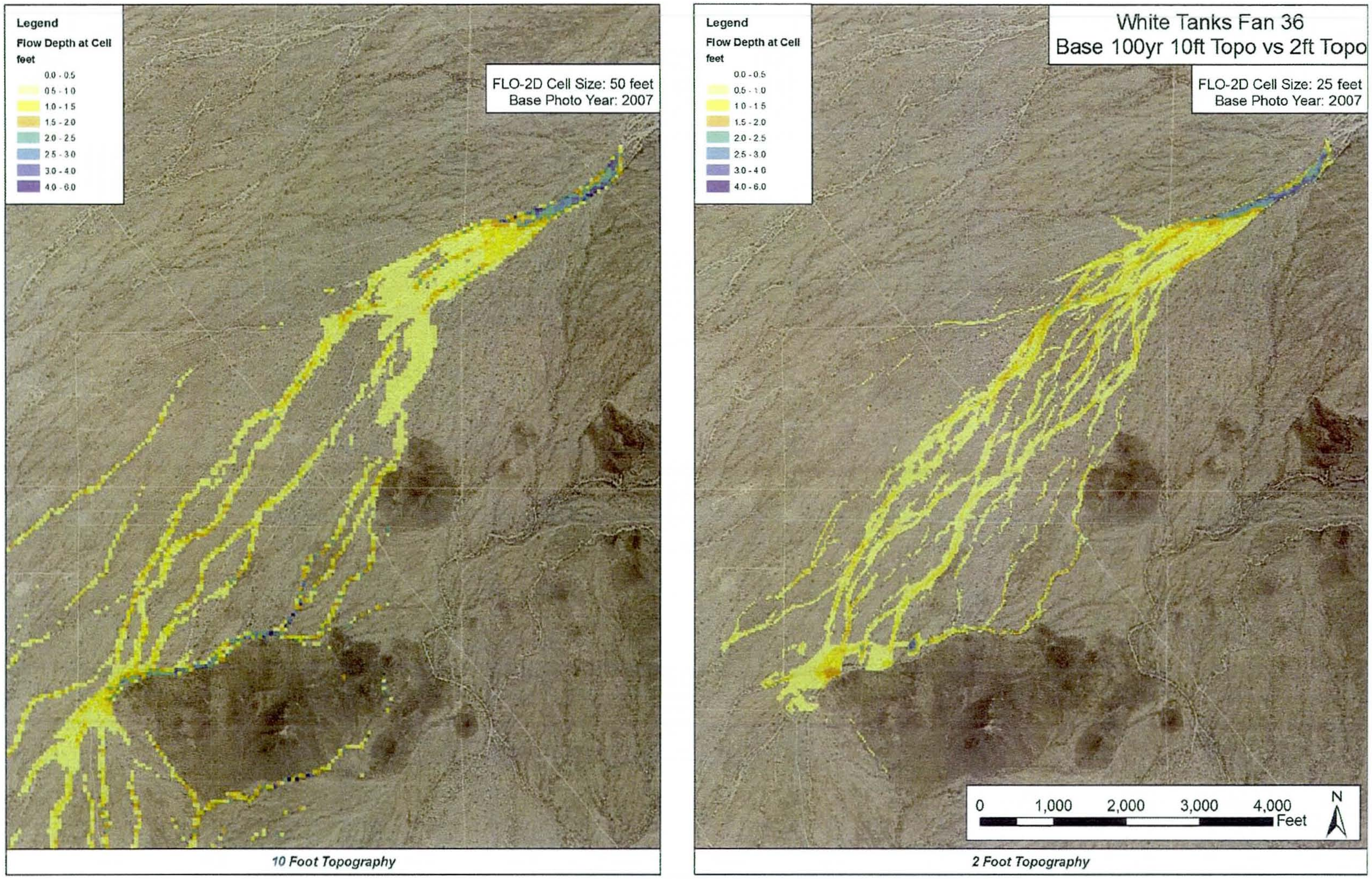


Figure 29. FLO-2D results for White Tanks Fan 36 – 25-ft vs. 50-ft. grid size (Q100).

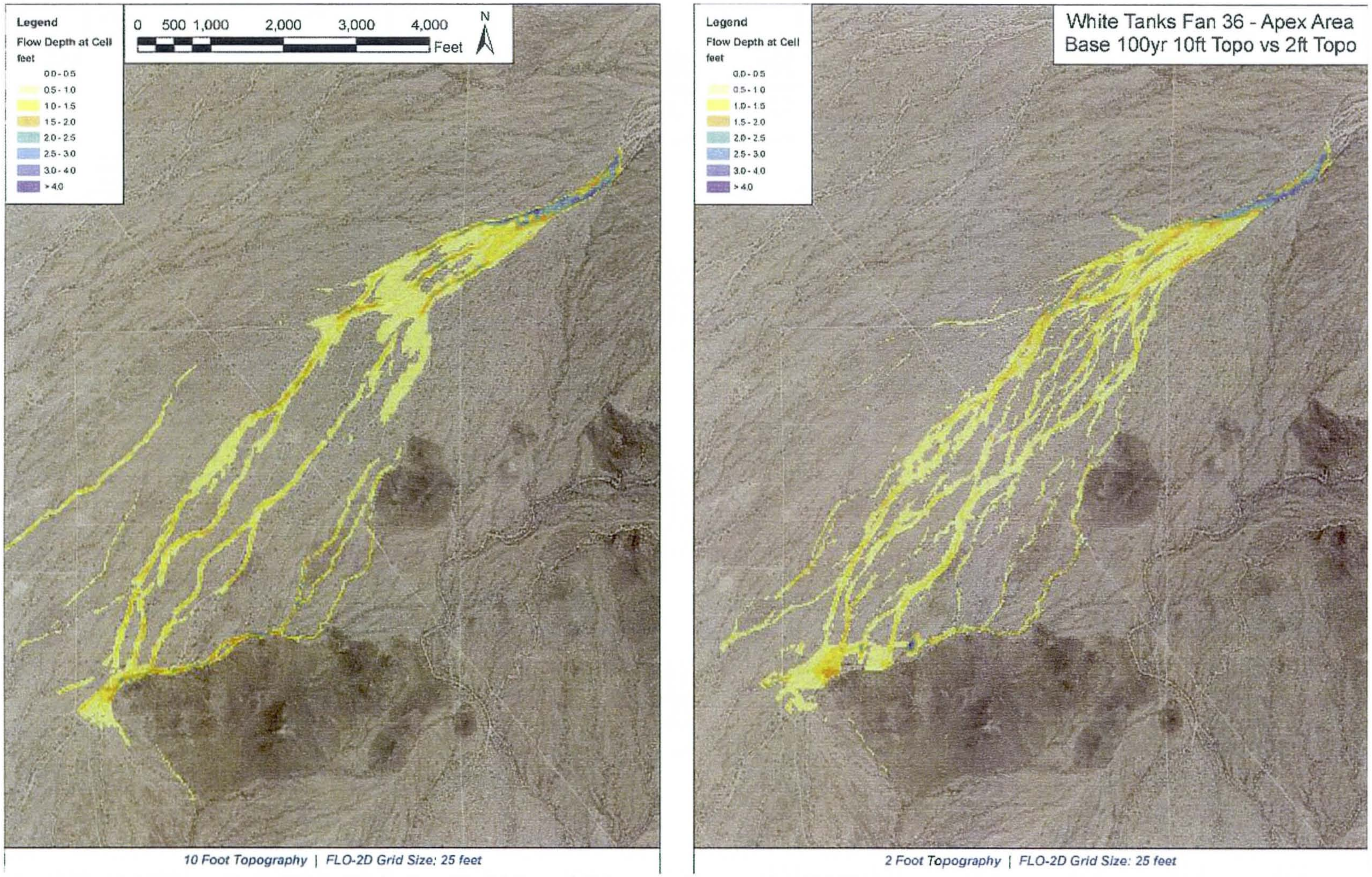


Figure 30. FLO-2D results for White Tanks Fan 36 – 10 ft. vs. 2 ft topographic mapping (Q100).

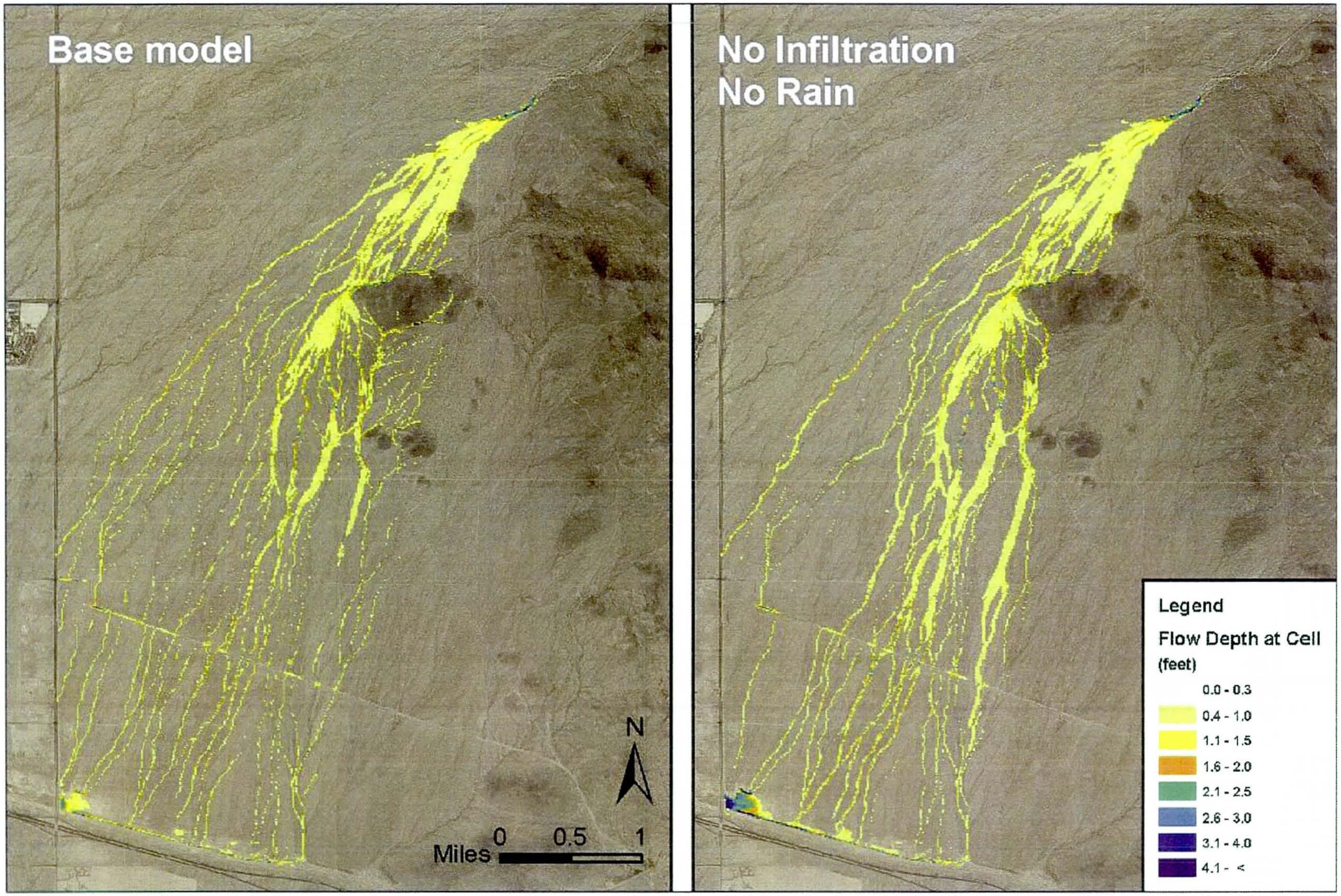


Figure 31. FLO-2D results for White Tanks Fan 36 – no infiltration and on-fan rainfall vs. base model (Q100). Similar results were obtained for the other fan evaluation sites (see Appendix F)

2.3.3.4. Encroachment Impact Models

A FLO-2D model simulating the impact of encroachment by development of the active alluvial fan was prepared for the WTF 36 (Figure 32) and RVF 12 (Figure 33) sites. To simulate the potential impact of encroachment by development on the active fan surface, the high hazard portion of the upper fan area was blocked, leaving only a conveyance channel that mimicked the width of the channel above the hydrographic apex. This approach was used to simulate the hydrologic and hydraulic impacts of protecting the developed area from flooding from upstream sources. The developed areas were allowed to generate runoff that was conveyed downstream, but no runoff from upstream sources was allowed to enter the simulated developments.

The encroachment impact models demonstrated that, as expected, loss of natural attenuation areas on the active fan surface resulted in adverse increases in peak discharge, flood depth, and flood velocity on downstream properties, as well as diversion and concentration of natural flows. Other potential adverse impacts of encroachment include changes in sediment delivery rates to areas below the encroachment, scour and headcutting along channels not adjusted to the new supply of flood water and sediment, and cutting off flow to riparian corridors formerly supplied by now-obstructed distributary channels. The alteration of the natural flow distribution may be particularly problematic since the mid- and distal-portions of the fans tend to lack any well-defined significant flow corridors.

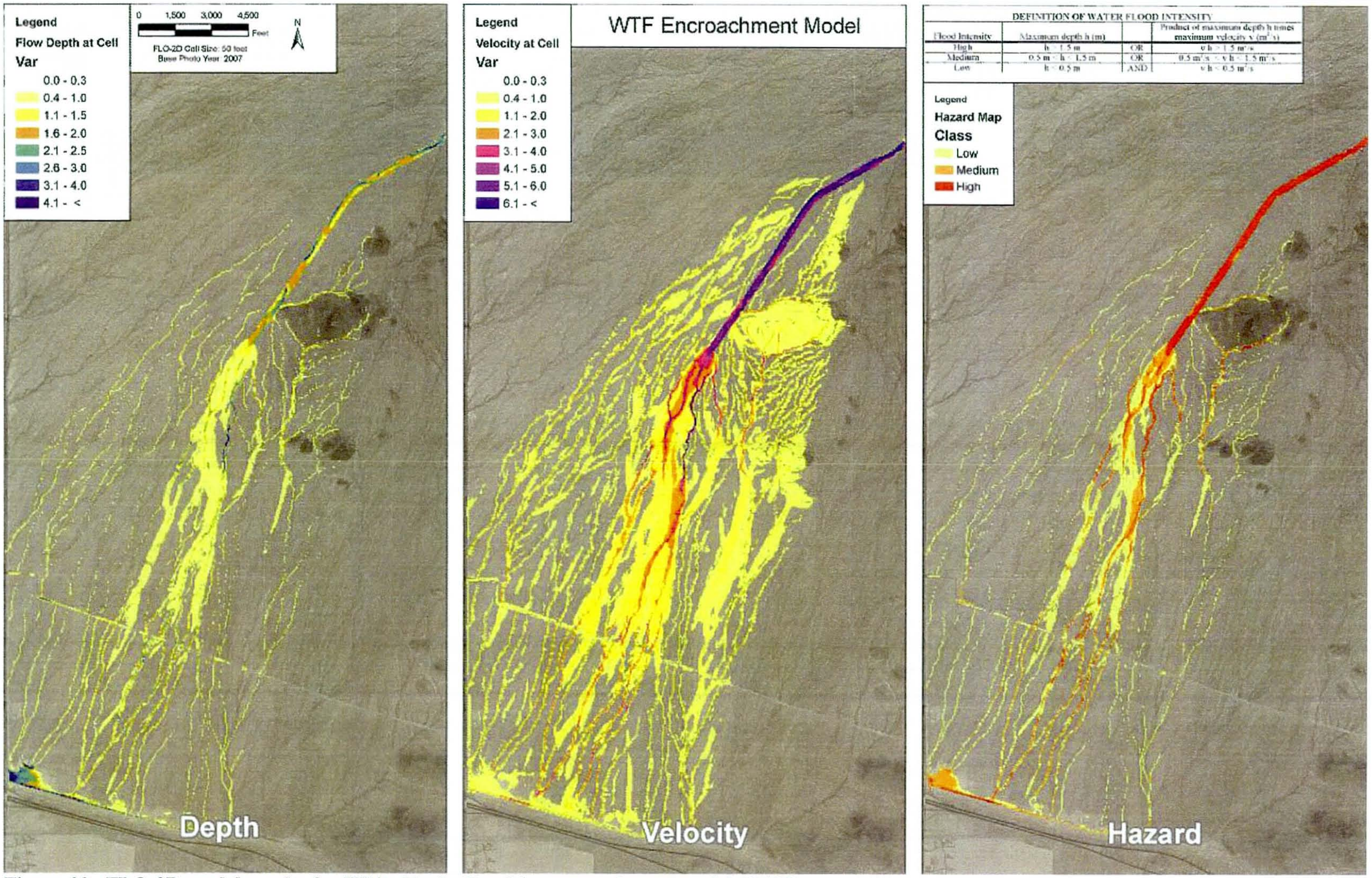


Figure 32. FLO-2D model results for White Tanks Fan 36 – encroachment model (Q100).

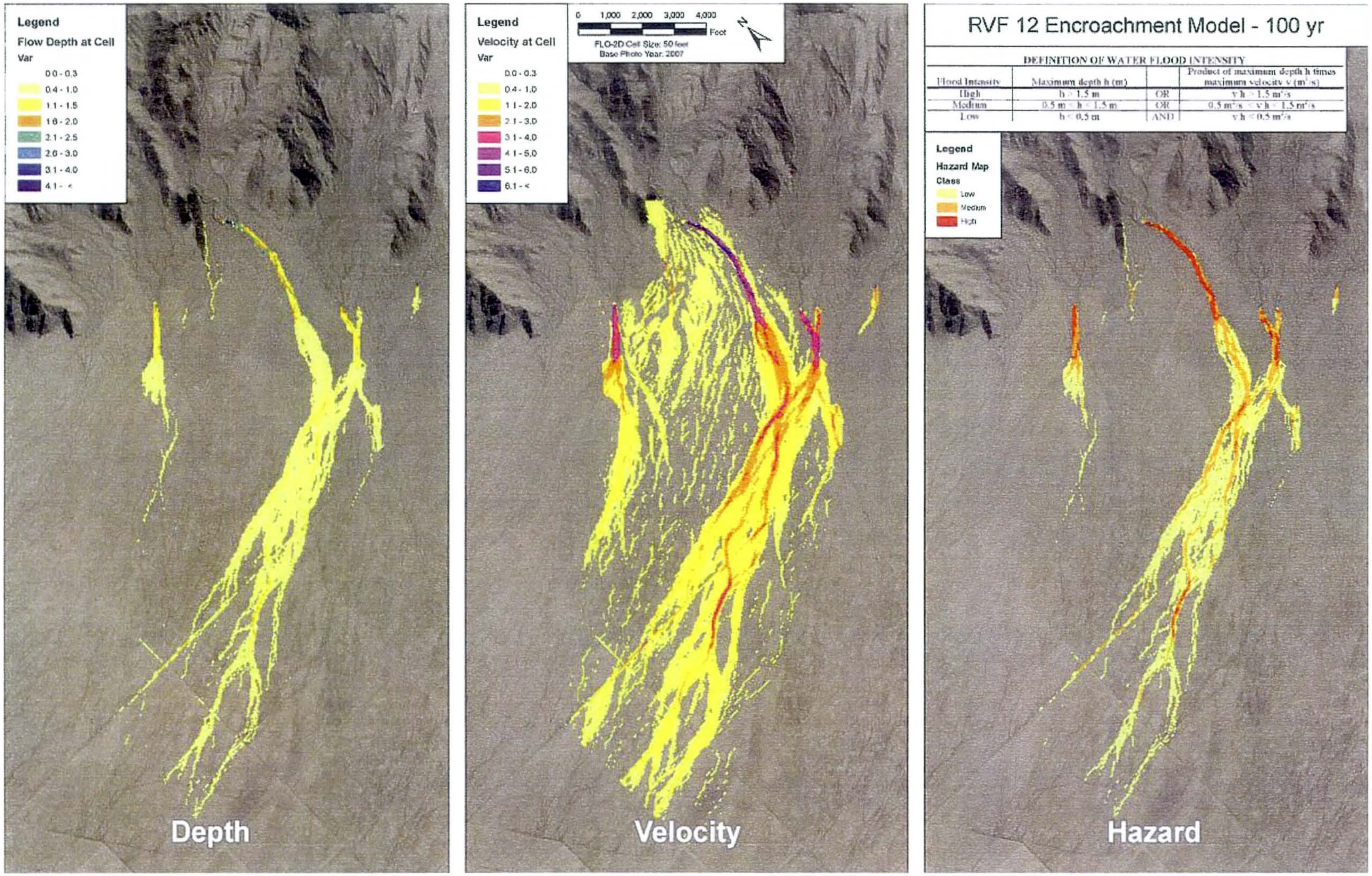


Figure 33. FLO-2D model results for Rainbow Valley Fan 12 – encroachment model (Q100)

2.3.3.5. Flood Hindcast Models

Large floods occurred at the WTF 36 site in 1951 (JEF, 2000) and on the Tiger Wash alluvial fan in 1997 (Pearthree et. al., 2004). For the WTF 36 site, there was good correlation between the FLO-2D base model inundation area relative to flood evidence visible on the 1953 aerial photographs. For the Tiger Wash alluvial fan, neither the reconstructed 1997 hydrograph (Pearthree et. al., 2004), nor the 500-year FLO-2D inundation area adequately inundated areas of known avulsions, indicating that the cause of the Tiger Wash avulsions was due to more than just simple water flooding processes. Conclusions drawn from the FLO-2D flood hindcast model results are summarized below.

White Tanks Fan 36 (Figure 34). There is good correlation between the inundation areas visible on the 1953 aerials and the FLO-2D base model results, indicating that the overall topography of the WTF 36 site has probably not changed significantly since the 1951 flood. However, there are a number of differences between the 1951 and FLO-2D base model inundation areas. First, there a several readily identified channels visible on the 1953 aerials that are not shown as flooded in either the 100- or 500-year FLO-2D results. These channels have either aggraded since they were exploited in the 1951 flood, or other parts of the fan surface have changed sufficiently to re-direct flow away from them. Second, some avulsive flow corridors along the northern margin of the active fan area near the hydrographic apex identified from the FLO-2D modeling results do not appear to have been inundated during the 1951 flood. These potential avulsion corridors picked up by the FLO-2D model either did not exist as topographic lows in 1951 or changes in ground elevations near the apex since 1951 now direct flow towards them. Third, avulsions in the distal portion of WTF 36 occurred in areas shown by FLO-2D modeling to have extremely low flow depths and velocities. Finally, it is known that the 1951 event flooded portions of the Town of Buckeye and was one of the reasons for construction of the Buckeye FRS#1. However, the FLO-2D base models indicate that relatively little flow reaches the Buckeye FRS. Therefore, either the 1951 event was larger than a 100-year event (either by peak or volume), other sources contributed to the flooding in Buckeye, and/or the FLO-2D model is over-estimating losses on the fan surface. Given the results of the multiple channel modeling, it is likely that at least part of the difference is due to over-estimated losses in the FLO-2D base models.

Tiger Wash (Figure 35 and Figure 36). The 1997 Hurricane Nora flood on Tiger Wash resulted in at least two major channel avulsions as well as inundation of significant portions of the alluvial fan surface. Because the 1997 flood reached the ponding area upstream of the Central Arizona Project (CAP) canal, the event provided an opportunity to test whether the default FLO-2D modeling parameters accurately predicted flow losses on the fan surface. As shown in Figure 35, initial FLO-2D modeling predicted much less ponding at the CAP than was observed, indicating that FLO-2D is probably over-estimating the routing losses on the fan. Note that this study firmly concludes that significant hydrograph attenuation occurs on alluvial fans (See Section 2.3.2 of this report). The rough verification exercises summarized above merely indicate that the initial base modeling procedure may require minor adjustments to decrease the predicted rates of attenuation.

To attempt to hindcast the occurrence and locations of the 1997 avulsions, FLO-2D models were also prepared using pre-1997 topographic mapping and the 1997 flood hydrograph estimated by Pearthree et. al. (2004), a 100-year inflow hydrograph, a 500-year inflow hydrograph, and a hydrograph based on PMP rainfall. As shown in Figure 36, the FLO-2D results do not clearly predict the location of the 1997 avulsions. For the estimated 1997 hydrograph, the FLO-2D results indicate that the areas where avulsions occurred were inundated by flows less than 0.3 feet deep. Even for an extreme flood discharge like the PMP event (Figure 37), the FLO-2D results did not predict highly erosive flow depths and velocities along the avulsion alignments. Unfortunately, the poor quality[14] of the only available pre-1997 topographic mapping makes it impossible to draw firm conclusions about the ability of FLO-2D to predict alluvial fan avulsions.

[14] The only available pre-1997 topography was a USGS 10 meter DEM from circa 1951.

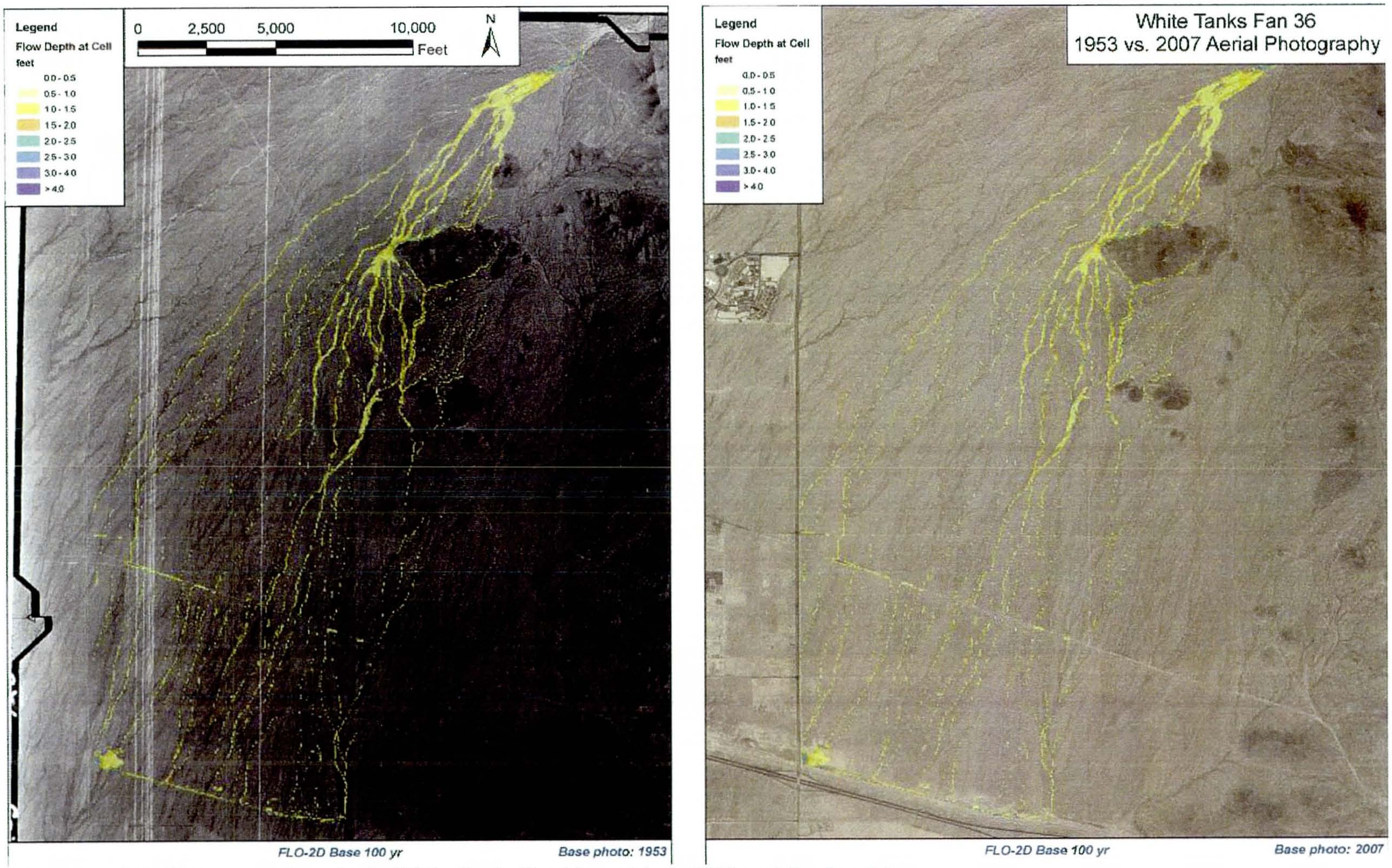


Figure 34. FLO-2D base model results for White Tanks Fan 36 overlain on 1953 post-flood aerial.

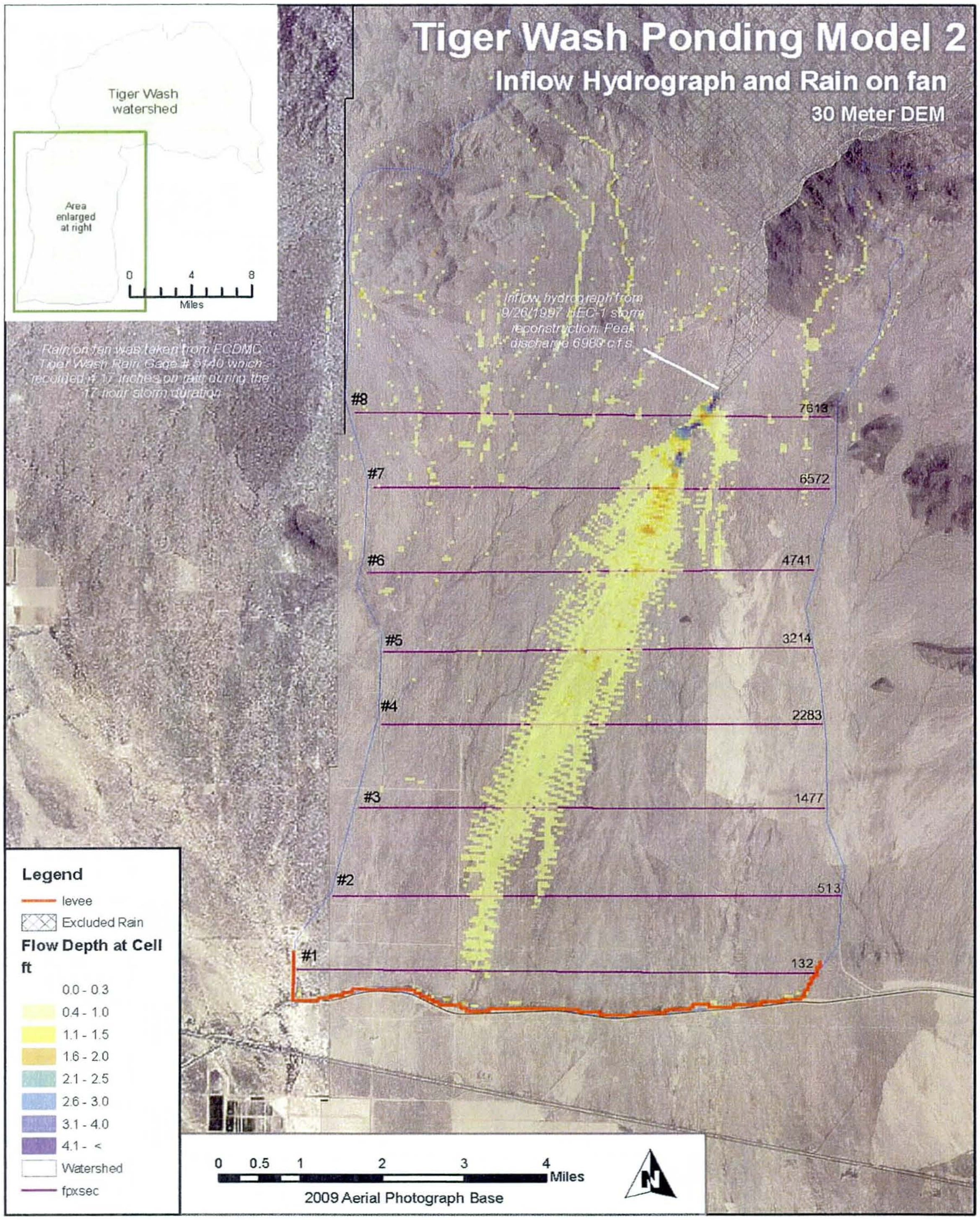


Figure 35. FLO-2D 1997 flood model of entire fan landform to CAP ponding area.

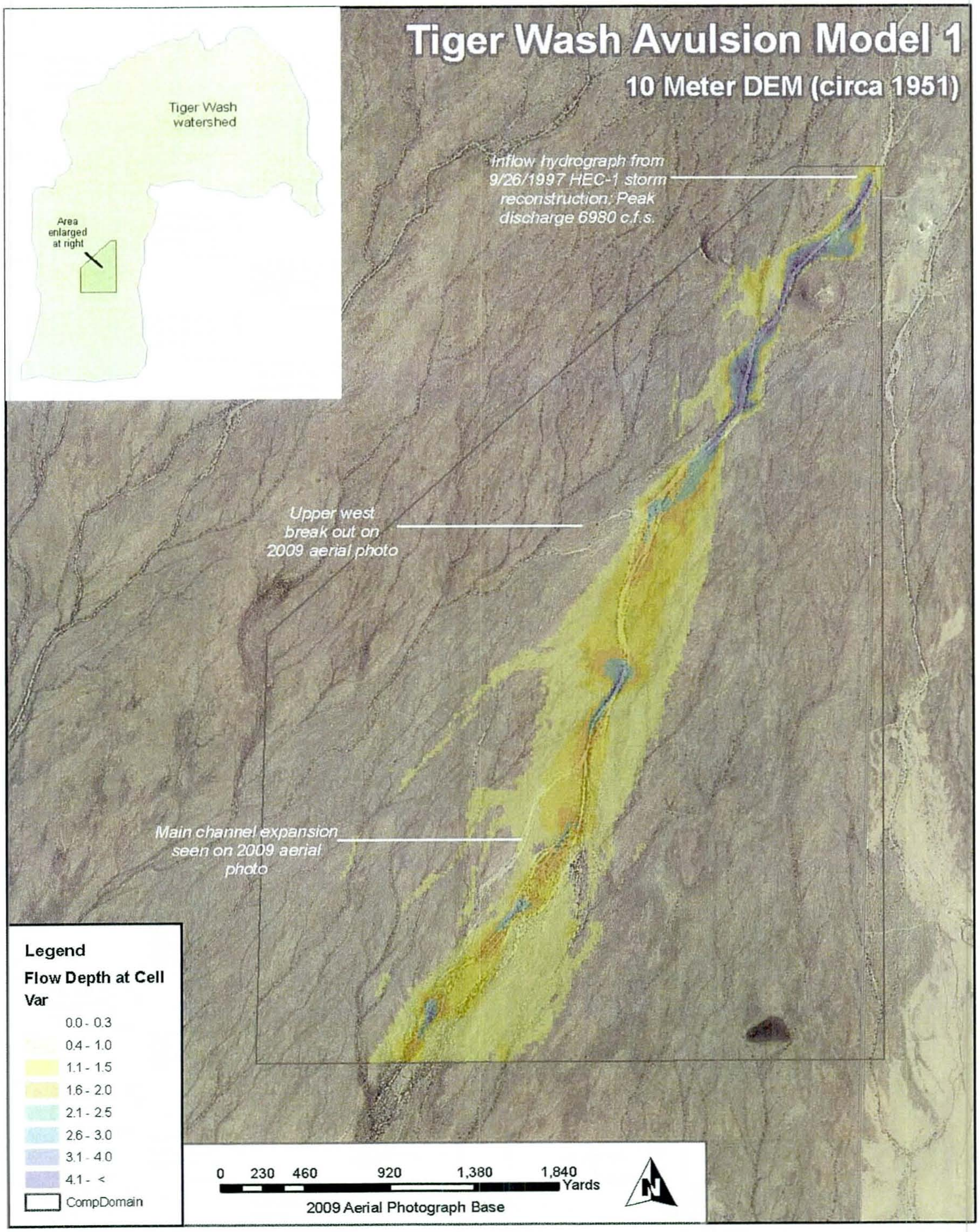


Figure 36. FLO-2D base model results for Tiger Wash Fan overlain on 2007-post-flood aerial.

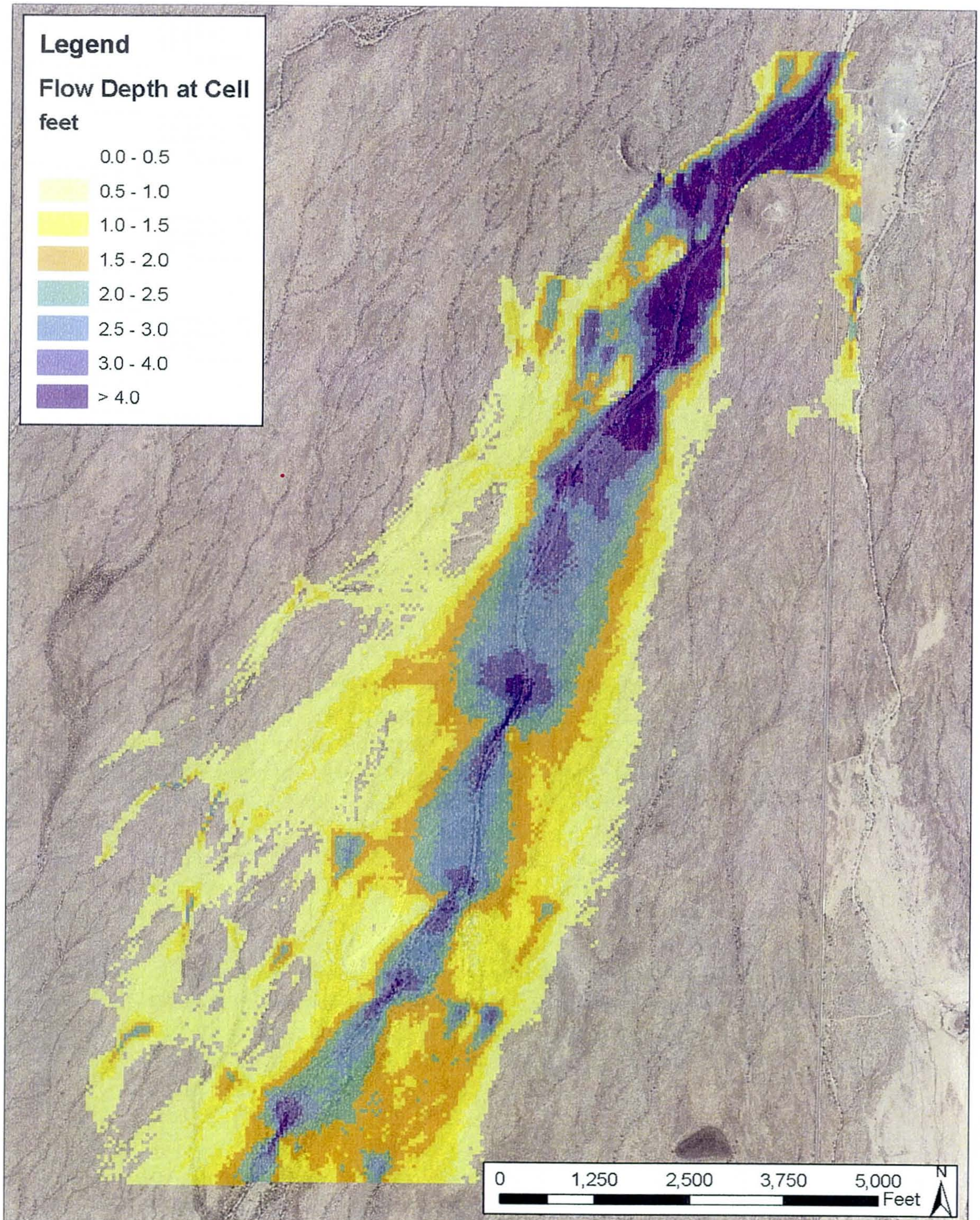


Figure 37. Tiger Wash Q500 FLO-2D modeling result

2.3.3.6. Avulsion Simulation Models

Several types of FLO-2D models were prepared to simulate the affects of channel avulsions in the active fan area. These models included runs for the WTF 36 site in which the main channel was blocked at likely sediment deposition points or channel bends to force flow into the floodplain, and use of hydraulic data from 100-year and extreme flood FLO-2D runs from all four evaluation sites to identify potential avulsive corridors (i.e., areas of high flow depths and velocity that do not correspond to existing channel locations). The results of the avulsion scenario models are described in more detail in Section 2.7 and Appendix I of this report. The following conclusions were drawn from the FLO-2D avulsion modeling results shown in Figure 38 to Figure 40:

- Channel Blockage (Figure 38). For all of the trials for the WTF 36 site, blockage of a well-defined channel forced flow out of the main channel into the floodplain. The blockages were simulated by raising the grid elevations to match the channel bank and overbank ground elevations. However, for most of the trials, FLO-2D predicted that all of flow returned to the main channel immediately downstream of the blockage. Only where the fan sloped steeply away from main channel at the blockage point (i.e., where the radial contours had a shorter arc length) did flow leave the parent channel and flow along a new alignment. However, even where flow did not immediately return to the main channel, it was quickly captured and conveyed along other existing channels on the fan surface.
- Avulsion Flow Path Tool (Figure 41). FLO-2D results were used as part of the avulsive flow path methodology (formerly called the slope-walk method) for identifying potential avulsive flow corridors. The avulsive flow path methodology uses FLO-2D velocity vectors and steepest slope paths to identify potential flow corridors outside the existing channel network on a fan surface. The tool does not specifically model the avulsion process, but instead identifies flow paths that might direct flow away from existing channel alignments if overbank flow were to occur. As currently formulated, the avulsive flow path tool differs from other drainage path identification tools in that it works in the downstream direction and utilizes FLO-2D hydraulic result vectors to identify potential flow paths. This methodology is described in more detail in Appendix I.
- Flow Corridor Identification (Figure 39). As described in Section 2.7 and Appendix I of this report, FLO-2D depth, velocity and hazard results for the 100- and 500-year floods were compared to the existing channel pattern visible on recent aerial photographs. Since FLO-2D routes flow along topographic lows, subject to momentum and energy conservation principles, areas where FLO-2D predicts significant conveyance that do not correspond to existing defined channels were hypothesized to be potential avulsive flow corridors. Examples of such potential avulsive corridors were identified at the four fan evaluation sites.
- Perched Channel Identification (Figure 40). FLO-2D results were also used to identify channels visible on recent aerial photographs for which the model predicted no inundation. These results were hypothesized to represent channels that were perched above the surrounding terrain and that were therefore candidates for avulsive abandonment.

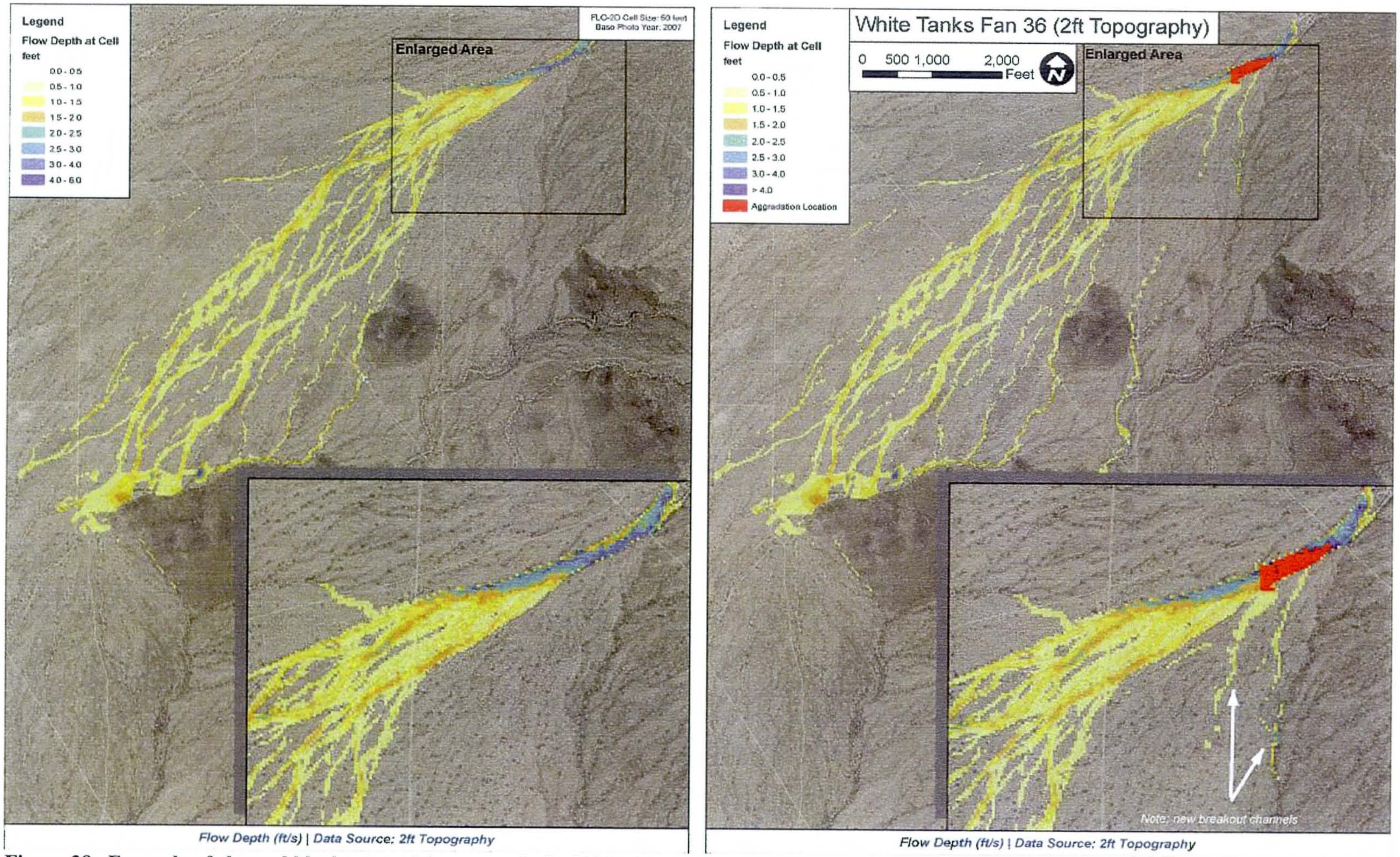


Figure 38. Example of channel blockage avulsion scenario for White Tanks Fan 36.

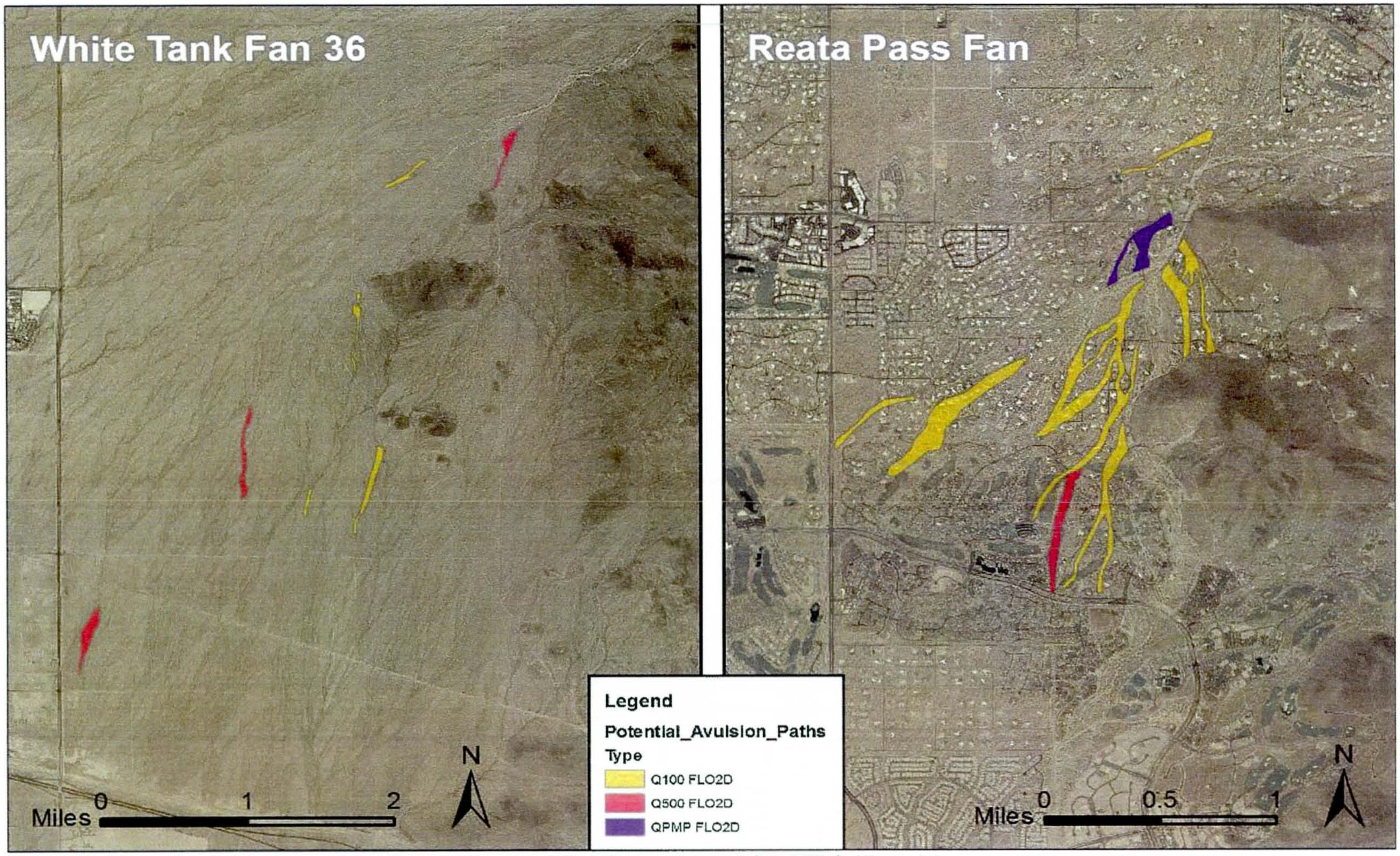


Figure 39. Example of potential avulsive flow corridor identified from a extreme flood FLO-2D model.

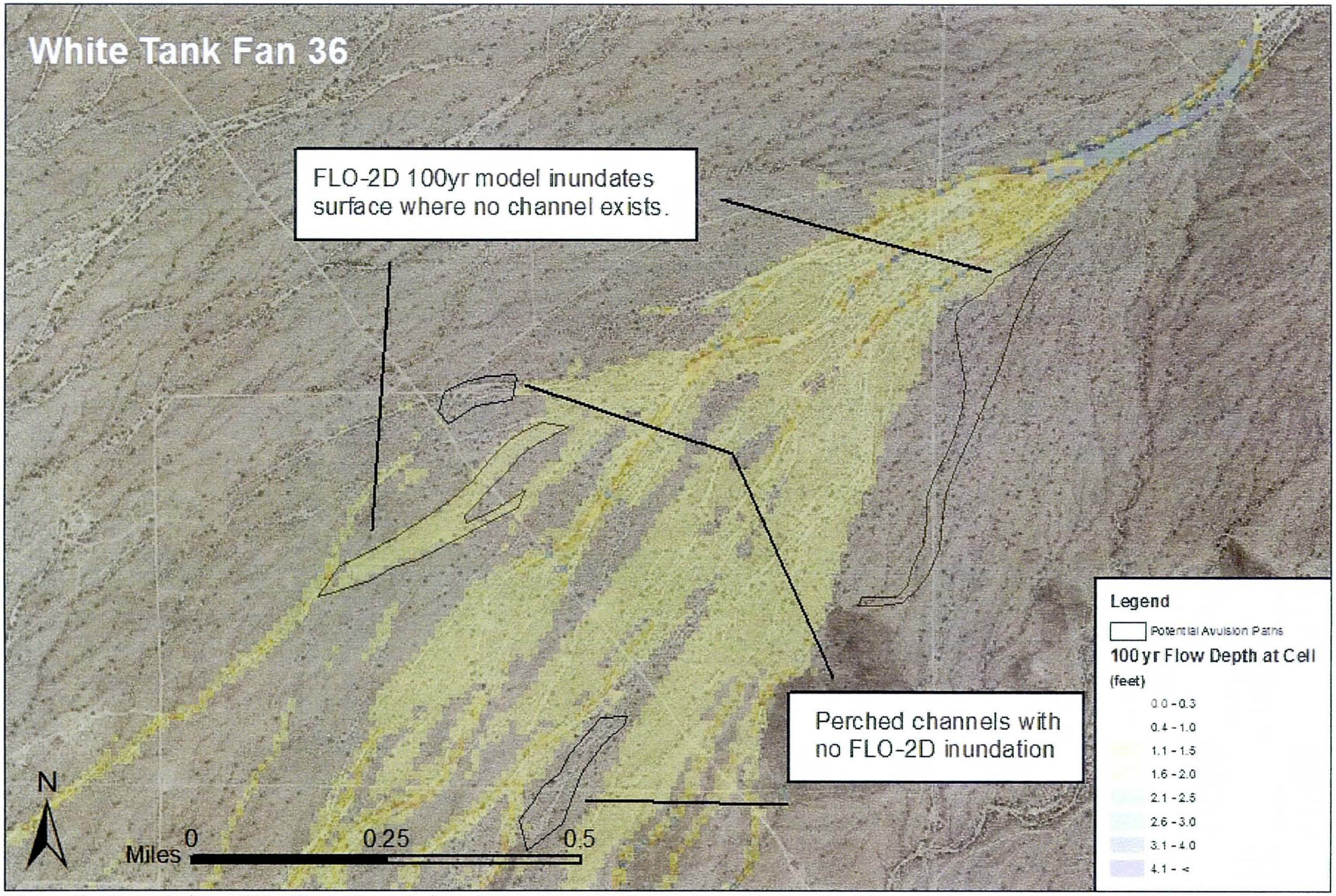


Figure 40. Example from White Tanks Fan 36 of perched channel ripe for avulsive abandonment.

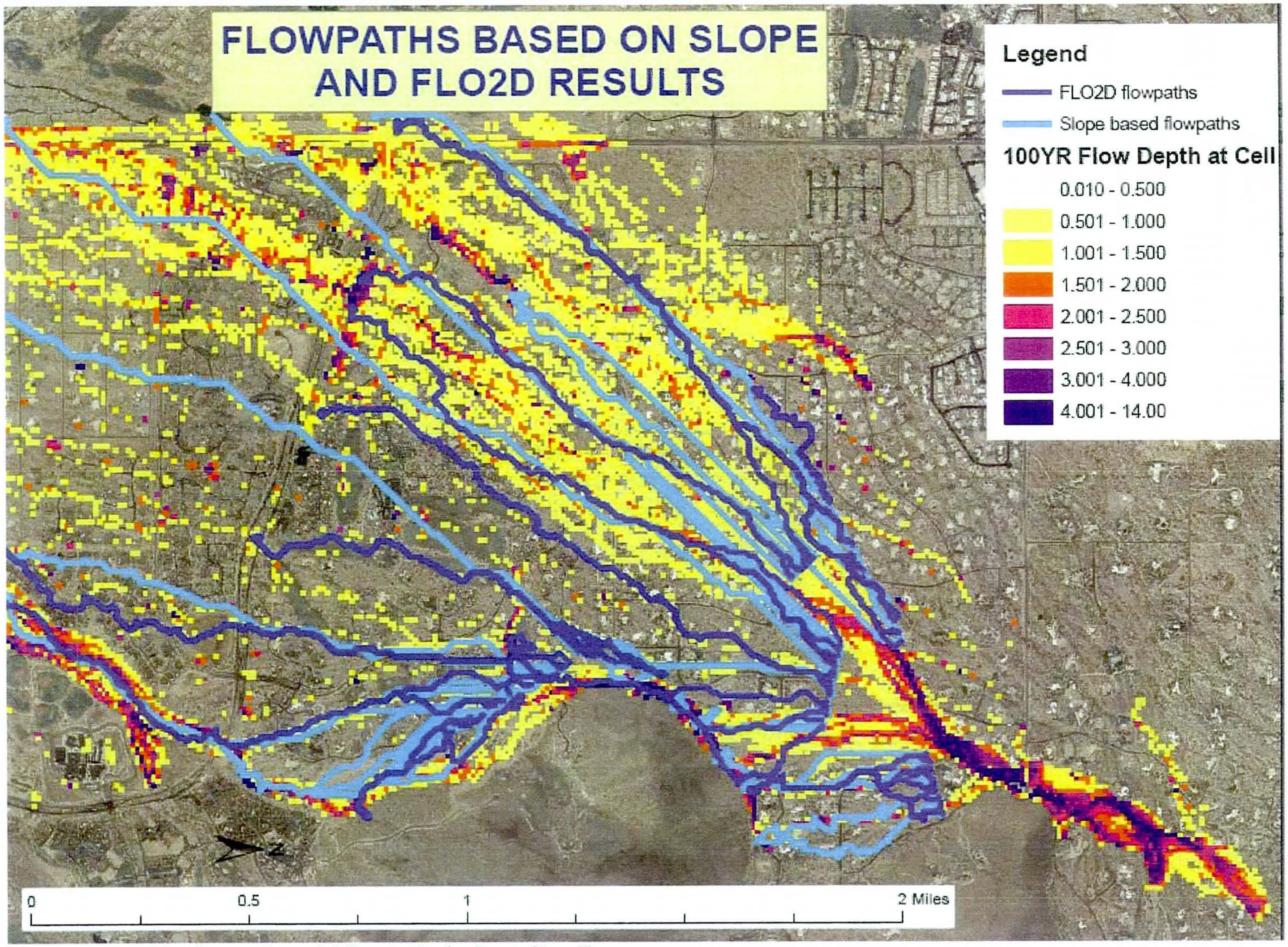


Figure 41. Avulsive flow path model flow paths for Reata Pass Fan

2.3.3.7. Virtual Levee Scenario Models

FLO-2D models applying the virtual levee methodology, as described in Section 2.7 and Appendix I of this report, were prepared to simulate the possible impacts of avulsions on flood hydrology and hydraulics on the active fan, to distinguish active and inactive parts of the alluvial fan landform, and to identify what portions of the active alluvial fan are subject to one percent chance flooding. The virtual levee scenario methodology does not attempt to model the avulsion process explicitly, but instead attempts to simulate the possible affect on downstream hydrology and hydraulics of an avulsion by forcing flow toward specific parts of the fan using "virtual" levees coded into the FLO-2D input file. The following are some of the conclusions drawn from the virtual levee scenario FLO-2D modeling results (Figure 42):

- Upper Fan Areas. For the portion of the alluvial fan in which the virtual levees are placed, FLO-2D results should be used with caution. There is some potential for flow to "pile up" along the levees, particularly where the levee alignment is more oblique than parallel to the primary flow direction. However, since the virtual levees are typically placed in the portion of the fan most likely to experience sedimentation aggradation, scour and avulsion, water-only FLO-2D depth predictions are already less reliable than on other, less hazardous portions of the fan.
- Mid-Fan Areas. The impact of the virtual levees is expressed most strongly in the mid-fan areas immediately downstream of the virtual levee footprint. Differences in flow depths and velocities between the base model and virtual levee models were greatest in this region. The maximum (worst-case) depths and velocities from all scenarios probably best represent the flood hazard in this region.
- Distal-Fan Areas. One of the more important results from the PFHAM study is that regardless of the virtual levee scenario modeled, flow in the distal portions of the fan is relatively unchanged. That is, flow returns to a shallow sheet flooding condition near the toe of the fan regardless of how it is re-routed by avulsions near the apex of the fan. This interpretation is not only supported by the FLO-2D modeling results, but also by geomorphic interpretation of channel geometry and spacing in the distal fan areas.

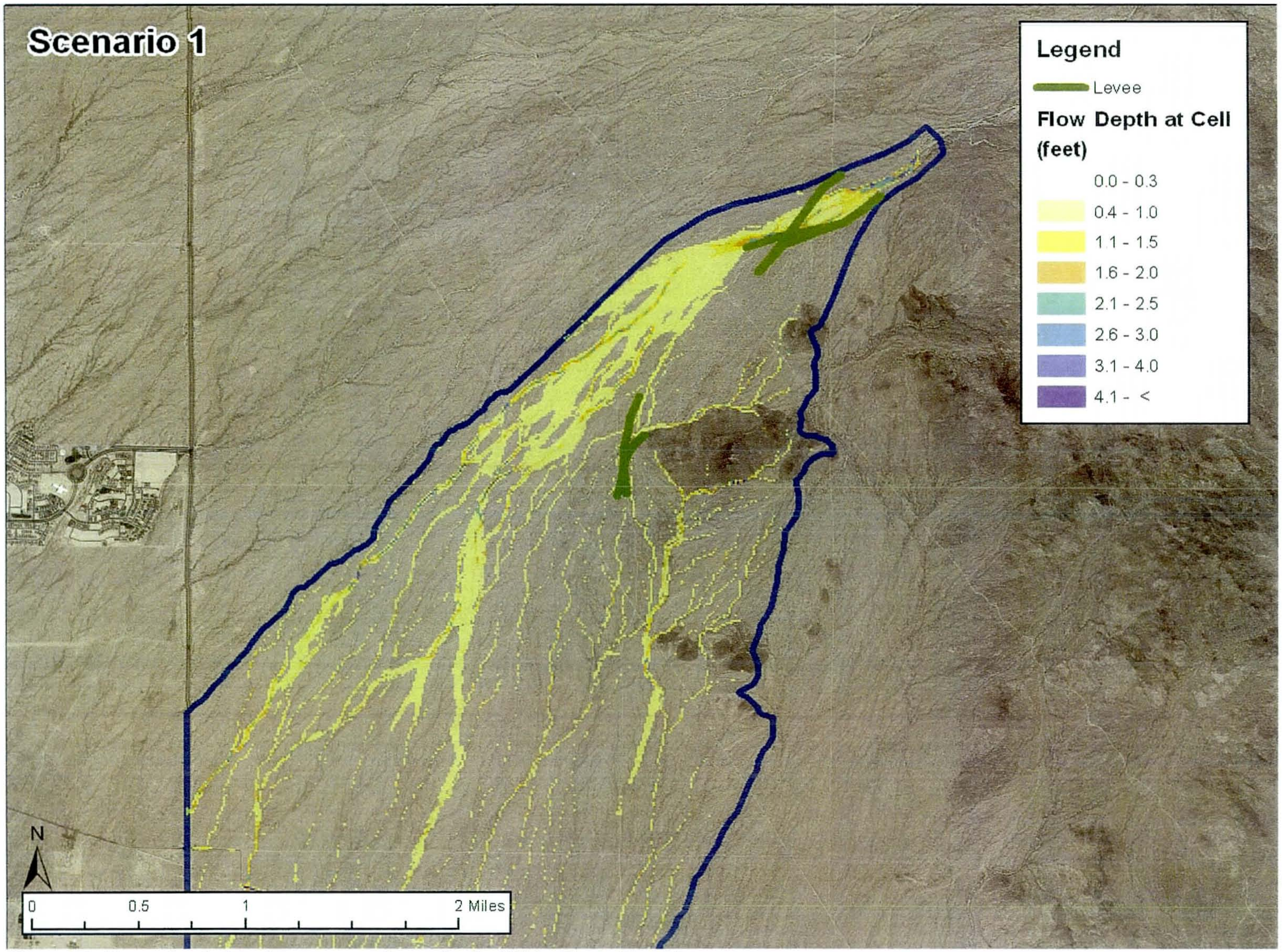


Figure 42. Example of virtual levee scenario results for White Tanks Fan 36

2.3.3.8. Sediment Transport Models

FLO-2D sediment transport models were prepared for each of the four alluvial fan evaluation sites, as described in Section 2.4 below.

2.3.3.9. Flood Hazard Zone Classification

One of the District's primary goals for the PFHAM study was to quantify the level of flood hazards on active alluvial fans. Several established hazard classification methodologies were considered and evaluated and the following were selected for application to the four alluvial fan evaluation sites:

- USBR (1988) Flood Danger Level (Figure 2, Building Foundation)
- USBR (1988) Flood Danger Level (Figure 6, Small Children)
- FLO-2D Default Method (FLO-2D, 2007; Fieberger, 1997)

It is noted that after initially selecting the flood hazard classification method described in this section, the District decided to abandon this approach in favor of relying solely on FLO-2D depths. Therefore, the methodologies described in the following paragraphs are provided for reference only, and as documentation of work products prepared in this study.

USBR Flood Danger Level Charts. The Bureau of Reclamation (USBR) ACER Technical Memorandum No. 11 includes a series of charts that are intended to depict flow hazards downstream of dams. These charts relate flow depth and velocity to hazards to buildings on foundations, mobile homes, motor vehicles, adult pedestrians, and children. The two end members of these categories of flood hazards were quantified for the four alluvial fan test sites for the PFHAM study – hazards to buildings on foundations (USBR, 1988 - Figure 2) and hazards to children (USBR, 1988 - Figure 6). The USBR charts subdivide flood hazards into "high" and "low" categories, with an intermediate "judgment" zone between them, as shown in Figure 43 and Figure 44.

The boundaries of the USBR hazard zones on the Tech Memo No. 11 figures were approximated using a polynomial function, and the resulting equations were applied to the FLO-2D output for each grid cell in the 100-year base model results for each alluvial fan evaluation site. The corresponding hazard zones were then determined for each cell from the function results (e.g. above or below the lines), and were plotted using ArcGIS. The results for each site are shown in Figure 45 to Figure 48.

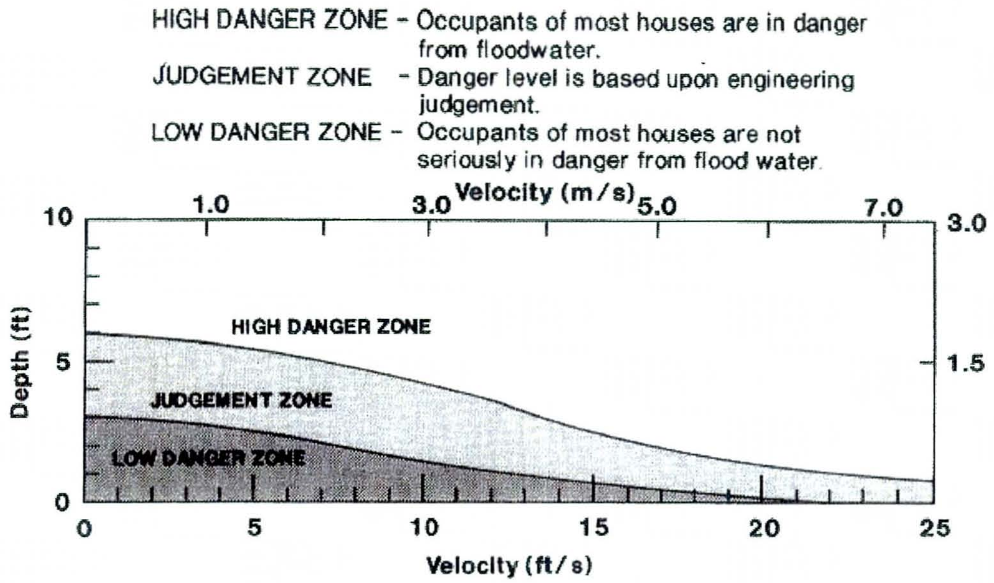


Figure 2. – Depth–velocity flood danger level relationship for houses built on foundations.

Figure 43. USBR ACER Tech Memo No. 11 Figure 2

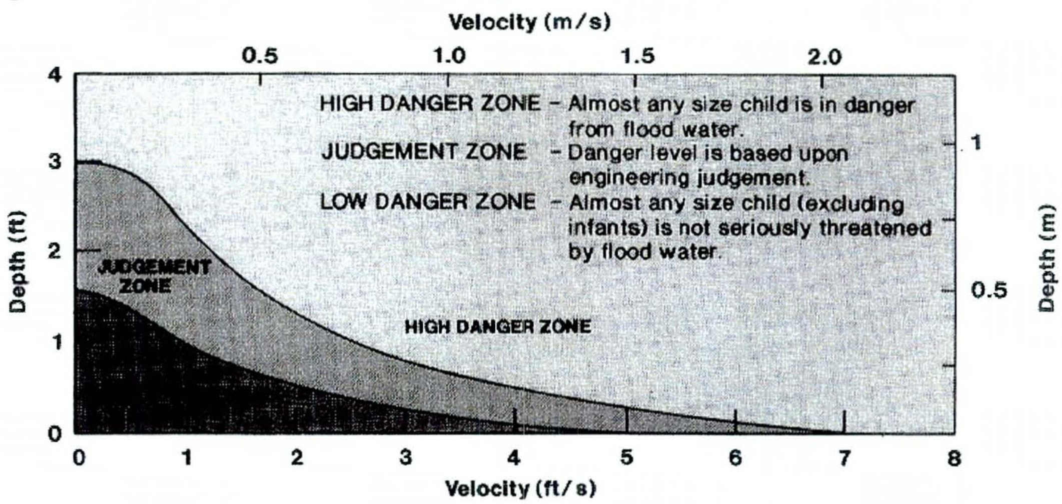
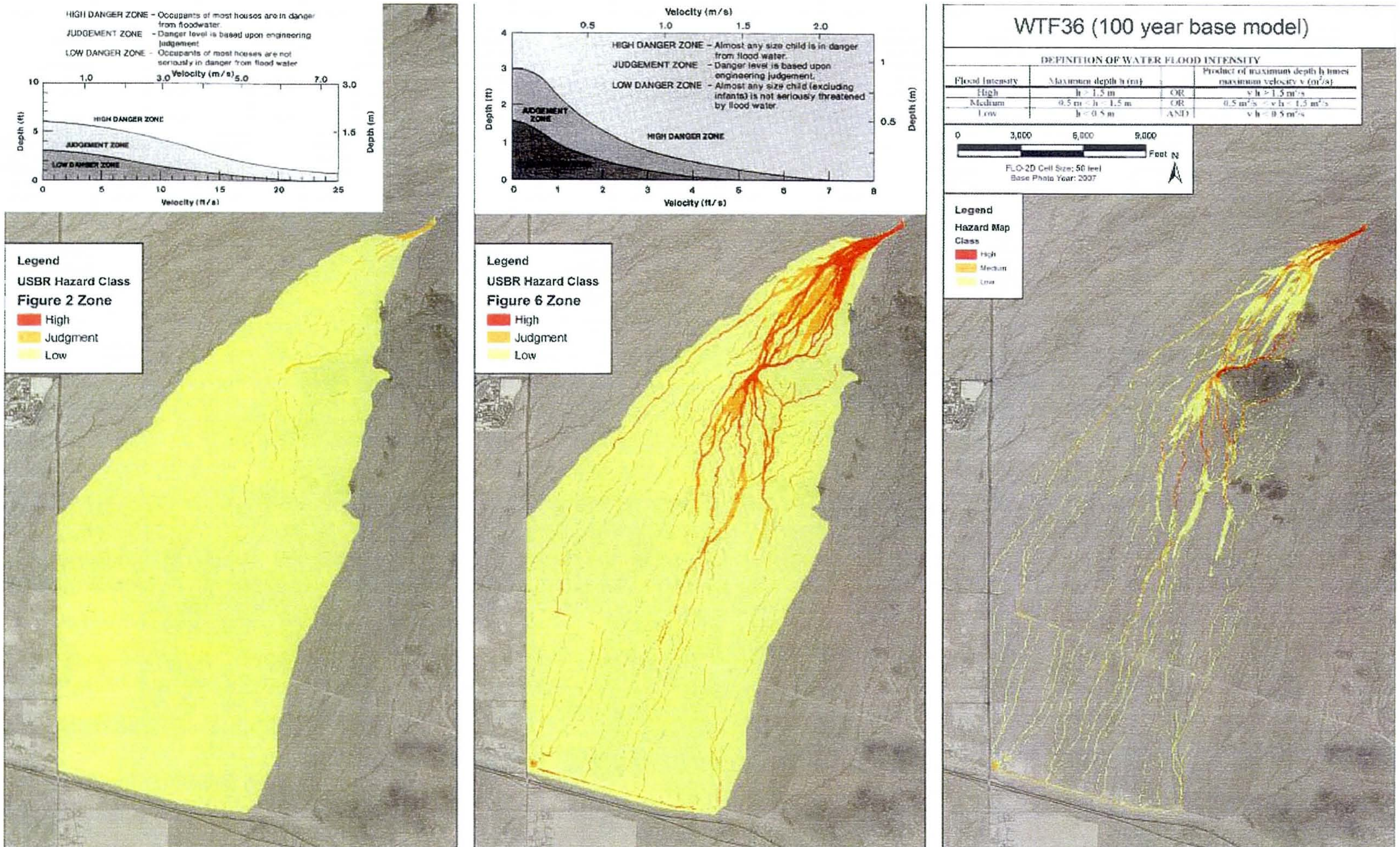


Figure 6. – Depth–velocity flood danger level relationship for children.

Figure 44. USBR ACER Tech Memo No. 11 Figure 6.



USBR ACER Tech Memo 11 - Figure 2 Hazard (buildings)

USBR ACER Tech Memo 11 - Figure 6 Hazard (children)

FLO-2D Hazard (100 year base model)

Figure 45. USBR Figure 2 (Buildings on Foundations) and Figure 6 (Small Children) hazard zones, with FLO-2D Hazard Map results for White Tanks Fan 36 FLO-2D base model.

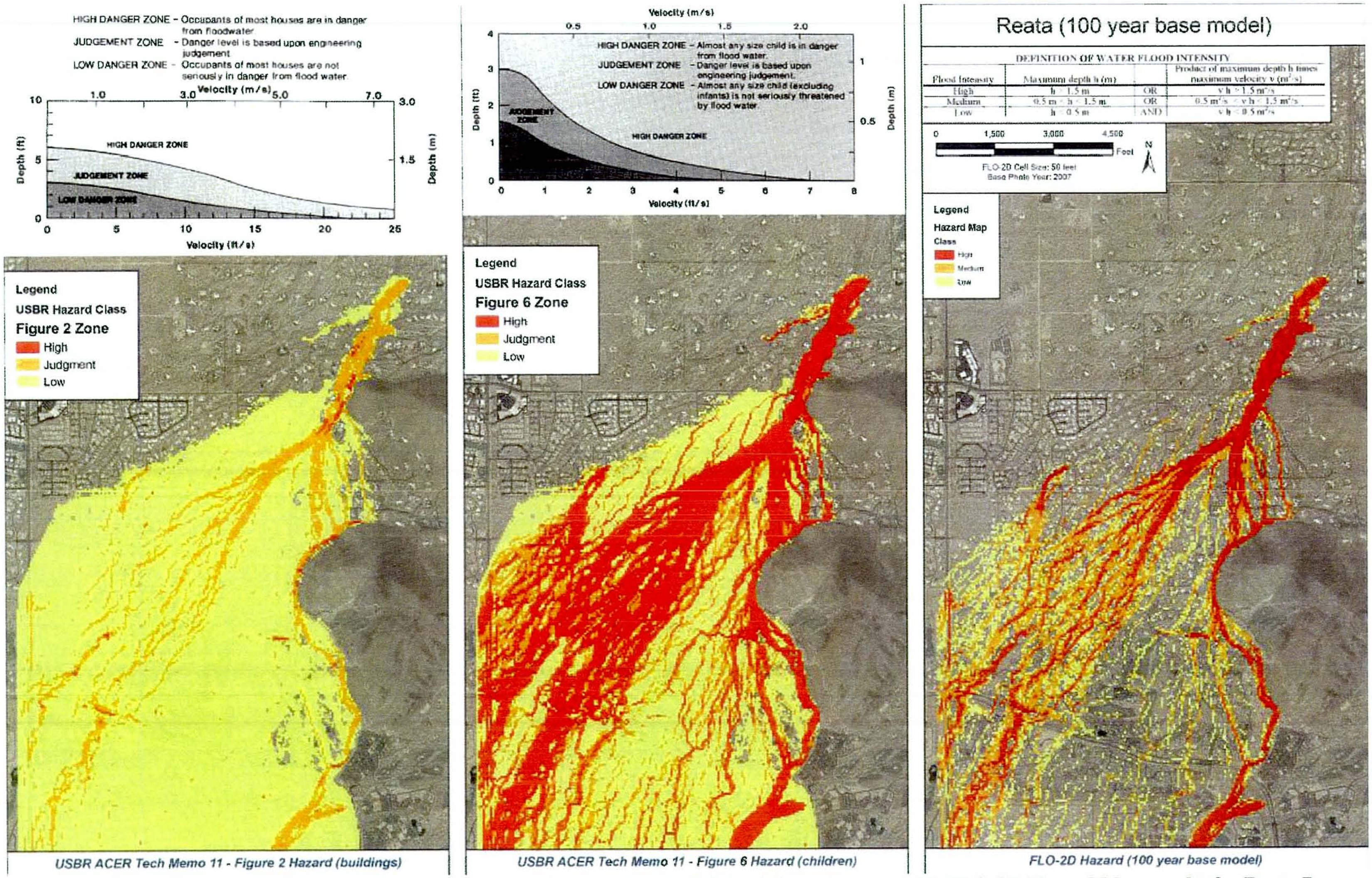


Figure 46. USBR Figure 2 (Buildings on Foundations) and Figure 6 (Small Children) hazard zones, with FLO-2D Hazard Map results for Reata Pass Fan FLO-2D base model.

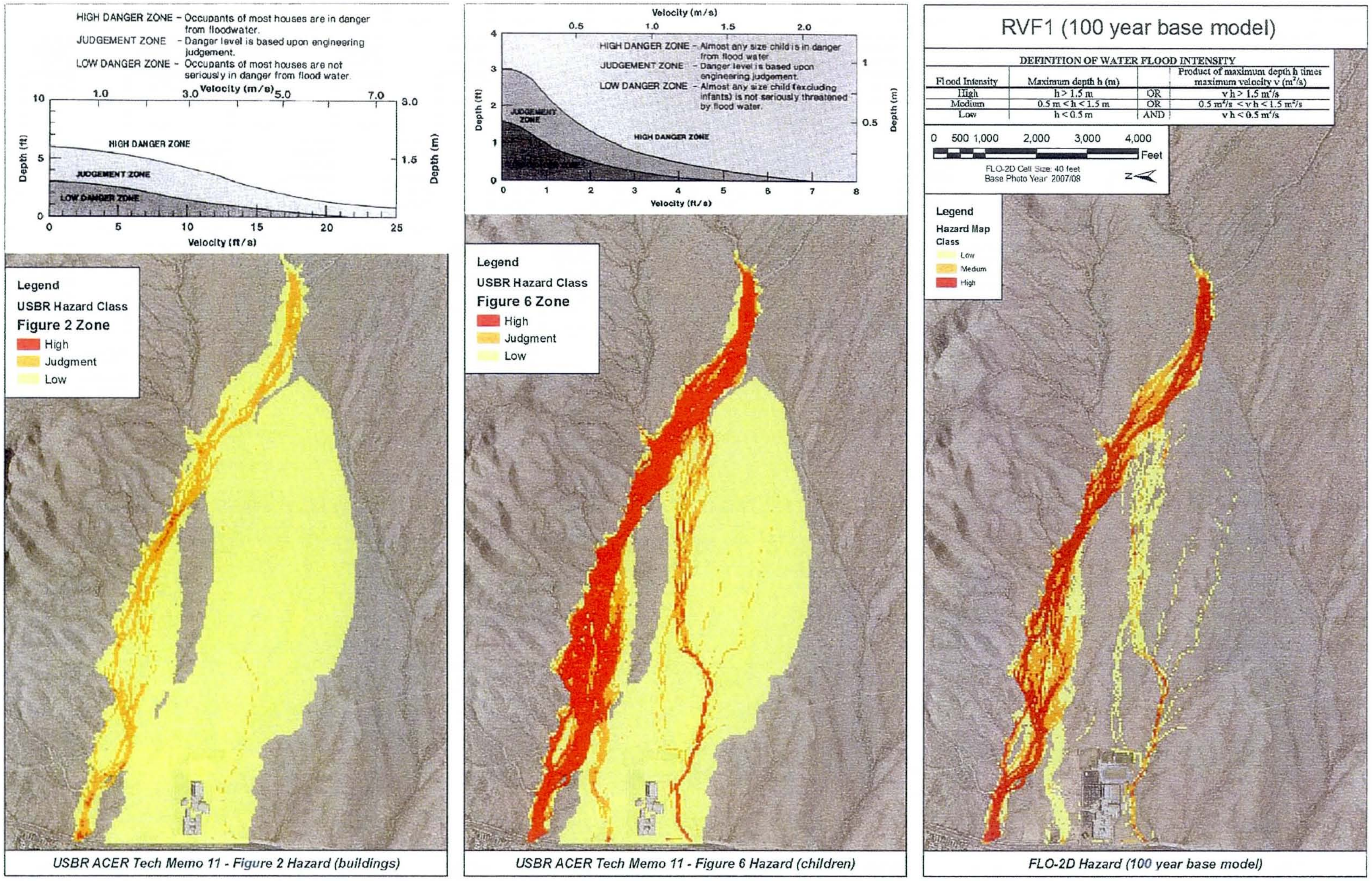


Figure 47. USBR Figure 2 (Buildings on Foundations) and Figure 6 (Small Children) hazard zones, with FLO-2D Hazard Map results for Rainbow Valley Fan 1 FLO-2D base model.

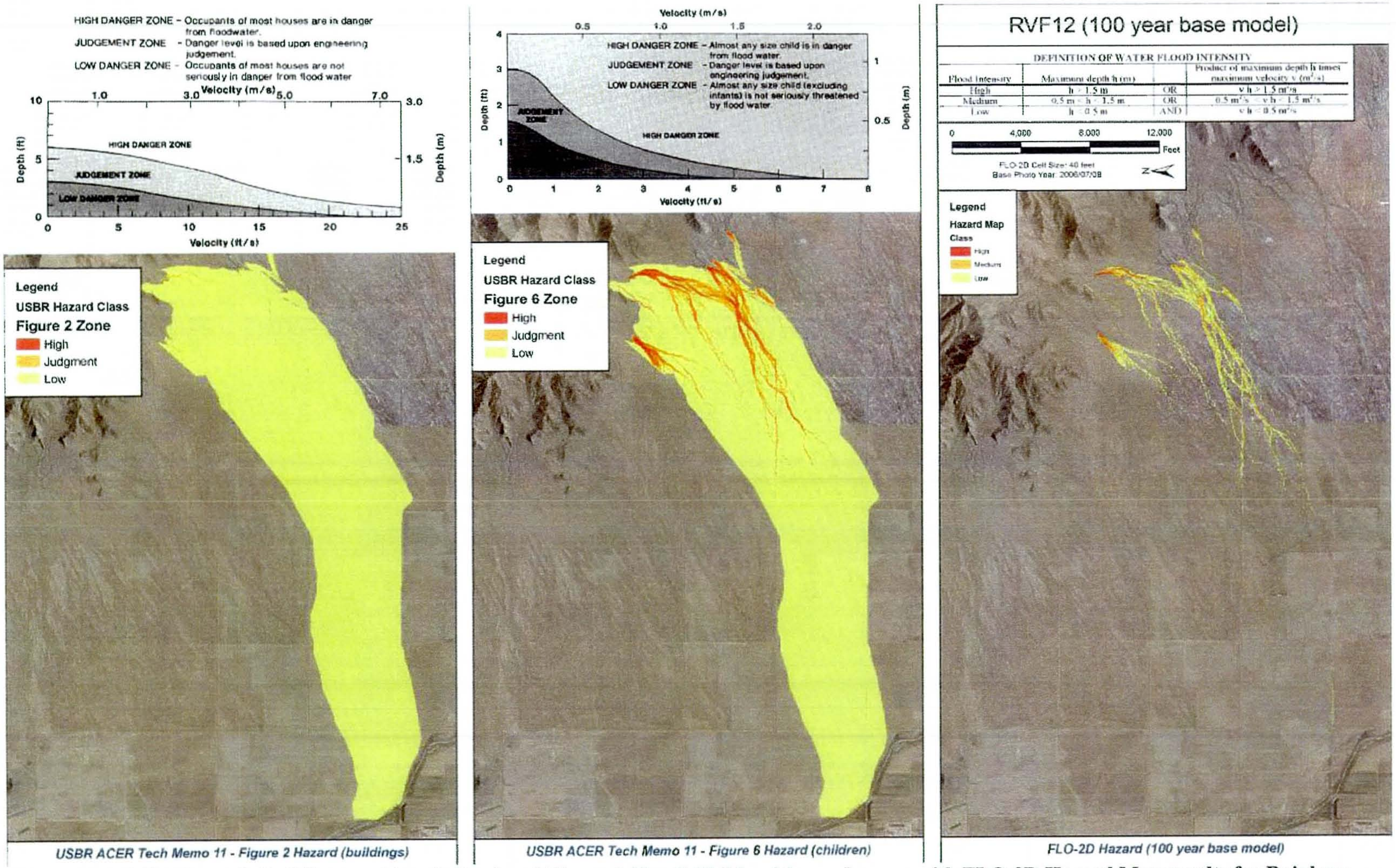


Figure 48. USBR Figure 2 (Buildings on Foundations) and Figure 6 (Small Children) hazard zones, with FLO-2D Hazard Map results for Rainbow Valley Fan 12 FLO-2D base model

FLO-2D Mapper Hazard Classification. The "Hazard Map" classifications as presented in the FLO-2D Mapper program (FLO-2D, 2007) were computed for the 100-year base models. The FLO-2D hazard classifications are based on work by Fieberger (1997) and have been used by a variety of regulatory agencies worldwide. In addition, a composite or combination hazard classification was also computed by combining the 10-, 100-, and 500-year FLO-2D base model results using the frequency-weighting procedure illustrated in Figure 49 and described in Table 9 and Table 10, as well as in the FLO-2D user's manual. The results of the FLO-2D methodology for each fan site were shown in Figure 45 to Figure 48.

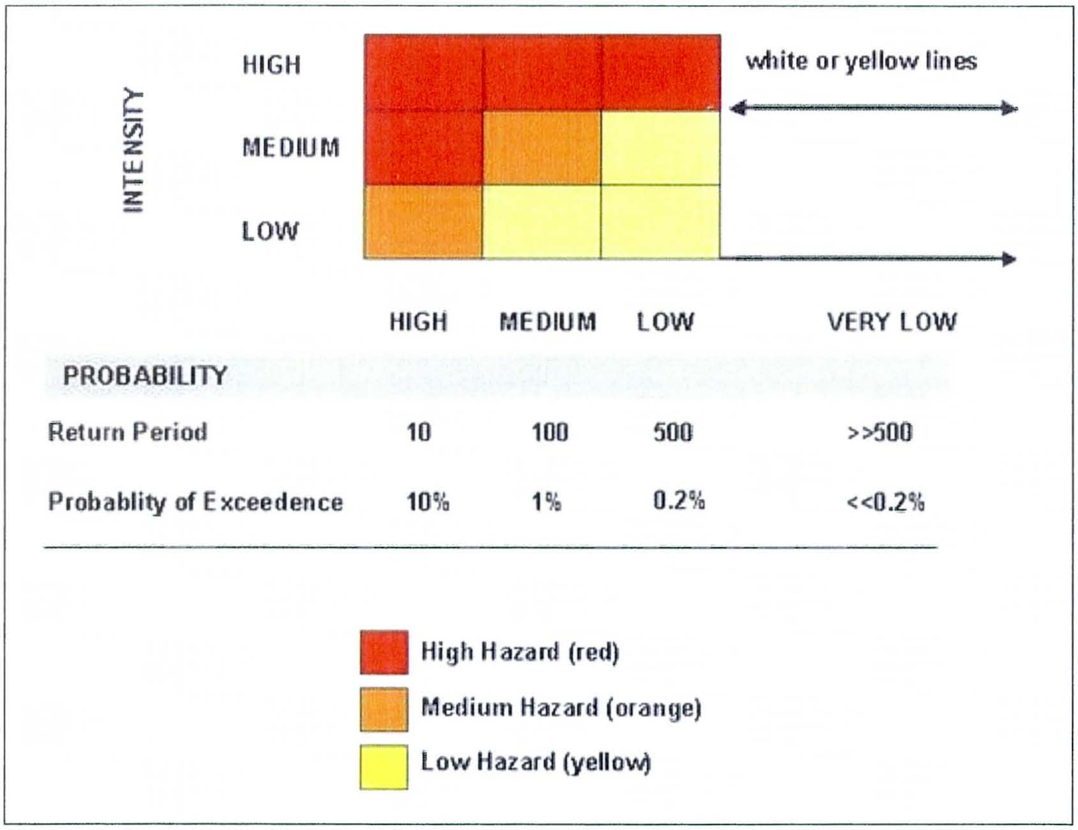


Figure 49. FLO-2D frequency-weighted hazard classification system

Table 9. FLO-2D Hazard Classification descriptions

Flood Hazard Definition		
Hazard Level	Map color	Description
High	Red	Persons are in danger both inside and outside their houses. Structures are in danger of being destroyed.
Medium	Orange	Persons are in danger outside their houses. Buildings may suffer damage and possible destruction depending on construction characteristics.
Low	Yellow	Danger to persons is low or non-existent. Buildings may suffer little damages, but flooding or sedimentation may affect structure interiors.

Table 10. FLO-2D Hazard Classification computational basis

Definition of Water Flood Intensity			
Flood Intensity	Maximum depth h (m)		Product of maximum depth h times maximum velocity v (m^2/s)
High	h > 1.5 m	OR	v h > 1.5 m^2/s
Medium	0.5 m < h < 1.5 m	OR	0.5 m^2/s < v h < 1.5 m^2/s
Low	0.1 m < h < 0.5 m	AND	0.1 m^2/s < v h < 0.5 m^2/s

Conclusions. As expected, the USBR Figure 6 hazard classification (Figure 44) produces the largest extent of hazards on all four example fan sites, because it has the lowest thresholds for the hazard classifications of the three methods considered. The USBR Figure 6 hazard threshold was determined to be the most appropriate for application in Maricopa County for several reasons. First, engineering judgment and field observations indicate that such flow depths and velocities are were sufficient to transport the fine- to medium-grained sediment (i.e., erosion) found on most active alluvial fans in Maricopa County. Second, the USBR Figure 2 was determined to be too high a threshold since significant property damage could occur long before flows exceeded the threshold to damage a building with a solid foundation. Third, District staff strongly recommended use of hazard classification methodology that had been developed by the federal government, in order to provide more credibility. However, District staff also preferred the frequency-weighted approach used by the FLO-2D Mapper. Therefore, the District PFHAM team decided to use the FLO-2D frequency-weighting procedure (Q10-Q100-Q500), but use USBR Figure 6 thresholds to categorize the low-judgment-high hazard classifications. District staff will work with FLO-2D Software, Inc. under a separate contract to modify the FLO-2D code to include the USBR curves as an alternative to the default methodology. Finally, as a result of the recommendations of the PFHAM Blue Ribbon Panel (Section 4.7, Appendix J), the USBR Figure 2 (Buildings) hazard classification will also be used in the recommended integrated methodology, as part of the method for identifying the "ultrahazardous" portion of an alluvial fan.

Subsequent to preparation of the draft report, the District elected to not use the USBR-based hazard classification in favor of direct use of flow depths from the FLO-2D modeling tasks.

2.3.4. Normal Depth Modeling

The PFHAM study found that normal depth modeling, e.g. HEC-RAS is not an appropriate method for hydraulic evaluation of flood hazards within active alluvial fan floodplains, except in certain specific situations, such as local site analyses, as described later in this report (Sections 3.3.2 and 4.4). Normal depth modeling has the following deficiencies when applied on active alluvial fan floodplains:

- Horizontal water surface elevation. A normal depth rating assumes that the water surface within a cross section is horizontal, and that all flows within the cross section are hydraulically connected. Post-flood observations reveal that flows on an active fan surface often have multiple disconnected flow paths across a given contour, each with its own water surface elevation and hydraulic characteristics.

- Cross section alignment. Active alluvial fans typically have a radial contour pattern with perched and/or abandoned flow paths and floodplains. It would be very difficult to correctly align a cross section to accurately reflect the flow distribution across an active fan surface. Failure to correctly align the cross section would inaccurately distribute flow into the lowest part of the section.
- Topographic containment. Active alluvial fans typically have relatively planar surfaces, resulting in inadequate topographic containment at the margins of any given cross section.
- One-dimensional flow. Field observations and FLO-2D modeling prepared for this study indicates that alluvial fan flooding has a strong two-dimensional component. A normal depth rating assumes flow is one dimensional.
- Continuity. Flow reaching any given part of a cross section of an active alluvial fan is highly dependent on the distribution of flow between upstream distributary channels and sheet flooding areas. A normal depth rating does not take into account the distribution of flow in upstream areas.
- Fixed-bed model. A key characteristic of active alluvial fan floodplains is changing topography due to scour, erosion and sediment deposition. Normal depth models typically do not consider mobile-bed or bank hydraulics.
- Flow path uncertainty. A normal depth rating is not capable of evaluating the potential affect of channel avulsions or flow distribution changes on the fan surface, and thus is not appropriate for a whole-fan analysis.

Despite the deficiencies listed above, a normal depth hydraulic analysis may be appropriate for a single site if the following conditions exist:

- Design discharge. A design discharge must be provided by the methods recommended in this report. The discharge used should correctly reflect any uncertainty in the flow rate reaching the site where the normal depth rating is to be applied.
- Site-specific analysis. A normal depth rating may be appropriate where it is used to generate hydraulic data for a specific localized channel reach. A normal depth analysis is not appropriate for fan-wide evaluations.
- Detailed topography. A normal depth rating may provide more accurate hydraulic data if more detailed topographic data are available for a specific site or channel reach on an alluvial fan than was used in a whole fan model, such as FLO-2D.
- Apex channel. A normal depth rating is appropriate for estimating the capacity of a defined channel at or above the hydrographic apex.

2.3.5. Fan Site Evaluation Conclusions

The following conclusions are supported by the hydrologic and hydraulic modeling performed for the four alluvial fan evaluation sites:

- Two-Dimensional Modeling. Two-dimensional modeling is the preferred method for evaluating the hydrology and hydraulics of alluvial fans. For the PFHAM study, the FLO-2D model was selected as the best available model, a finding which is consistent with the findings of other agencies (USACE, 2000). However, any two-dimensional model that has the same capabilities as FLO-2D would be acceptable for the purposes of floodplain delineation and flood hazard identification.

- Flow Attenuation. Attenuation of the hydrograph peak is an important process on active alluvial fans in Maricopa County. Therefore, use of the full apex discharge at any point other than the hydrographic apex is unnecessarily conservative and is not supported by the scientific analyses conducted as part of the PFHAM study. In many cases, the degree of flow attenuation is such that many small floods are completely stored on the fan surface, never reaching the toe, and resulting in deposition of the entire sediment load on the fan. The following are also noted with respect to flow attenuation:
  - Antecedent moisture condition. With increased antecedent moisture, the degree of rainfall losses and re-infiltration is likely to decrease compared to a dry antecedent condition. However, given the very high degree of flow attenuation computed for the "no-infiltration" sensitivity models, antecedent moisture condition is not likely to be a significant factor relative to the volume of flow storage provided on the fan surface. Also, if the FLO-2D results are compared HEC-1 results, the conclusion that flow attenuation is an important process on active alluvial fans is still supported. The District intends to provide specific guidance on the recommended antecedent moisture condition.
  - Storm sequence. Sequencing of back-to-back storms produces the same conditions as discussed above for antecedent moisture.
  - On-fan precipitation. The occurrence of on-fan precipitation was included in the FLO-2D simulations and did not affect the conclusion that significant flow attenuation occurs on active alluvial fan surfaces, although it is intuitively obvious that more attenuation is likely if no on-fan precipitation occurs.
  - Local (non-apex) inflow sources. The occurrence of local inflows to the fan surface was included in several of the FLO-2D simulations and did not significantly affect the degree of flow attenuation predicted.
- Sheet Flooding. Large portions of active alluvial fans in Maricopa County are affected only by shallow sheet flooding with minimal flow depths, flow velocities, and aggradation rates. The majority of the land area on the active alluvial fans specifically evaluated for this study is dominated by shallow sheet flooding. The extent of sheet flooding is both a cause and result of significant flow attenuation that occurs on active alluvial fans.
- 100-Year Inundation. Not all of the active portions of the alluvial fan sites will be inundated by the 100-year flood in a single event.
- Flood Hazard Zone Classification. Flood hazard zones on alluvial fans in Maricopa County can be classified using a frequency-weighted technique based on USBR (1988) hazard classification charts and FLO-2D hydraulic data.
- High Hazard Zones. On active alluvial fans in Maricopa County, high hazard zones are limited in extent and are generally limited to the region immediately downstream of the hydrographic apex. The extent of the high hazard zones is a function of fan slope, drainage area, and discharge.

- Modeling Results. FLO-2D depth and velocity output represent average values for the grid size used in the model. Therefore, some interpretation of results is necessary to determine design data for specific sites that may not be well represented by the grid elevations. In these cases, site specific step-backwater modeling is recommended to obtain structure design data.
- Modeling Guidelines. The accuracy of topographic data may affect the modeling results. Use of the best available topographic mapping is recommended. In some cases, the county-wide 10-foot mapping may not produce sufficiently accurate results. In addition, the FLO-2D grid size used also affects the model output. The use of the finest grid size feasible with respect to model run time and topographic data is recommended.
- FLO-2D Grid Size. The modeler should chose a grid size that reflects required model precision, model run time, topographic data precision, and unique site characteristics. For this study, 40- to 50-foot grids achieved adequate results.

2.4. Sedimentation Evaluation

The objectives of the PFHAM study sedimentation analysis were to quantify how sediment delivery, transport and deposition across an active alluvial fan surface can be quantified, and how sediment processes influence flood hazards on alluvial fan landforms in Maricopa County. The sedimentation evaluation consisted of the following two elements: (1) sediment yield, and (2), sediment transport modeling.

2.4.1. Sediment Yield Analysis

Sediment yield to the hydrographic apex of each of the four alluvial fan evaluation sites was computed using the District's sediment yield methodology described in Chapter 11 of draft *Drainage Design Manual for Maricopa County: Hydraulics*. Calibration, verification, or evaluation of District's sediment yield methodology was not included in the scope of services for this study, and the methodology was applied per the District guidelines. The computed sediment yields for the four evaluation sites are shown in Table 11. To relate the computed sediment yields to potential fan aggradation, Table 11 also lists an estimate of the active alluvial fan area and the resulting deposition during a 100-year design flood as well over a 100 year time period. The active fan acreage is a rough estimate based on visual inspection of an aerial photograph and the default FLO-2D hazard zones (high and moderate). It is unlikely that all of the sediment yield would be deposited in the high hazard zone, nor is it likely that deposition would be uniform over the entire active area. Furthermore, at least some of the deposited material would be transported or removed during subsequent floods. Nevertheless, the rough prediction indicates that the estimated sediment yield to the fan apex is probably insignificant for the 100-year flood, but may be of consequence over longer planning periods on some parts of an active alluvial fan.

The District's sediment yield methodology estimates the sediment load delivered from the upper-watershed to the alluvial fan apex. The load delivered to the fan apex is transported across or deposited on the alluvial fan surface. The rate of deposition is a function of the transport capacity, as expressed by hydraulic data and site conditions. Sediment delivered to unchannelized floodplains may deposit on the fan surface if runoff is stored or infiltrates into the soil. If it is assumed that sediment transport occurs primarily in the channels and high depth-velocity overbank areas, and that sediment deposition primarily occurs in shallow, overbank areas, an estimate of fan deposition can be made by combining the sediment yield estimates with FLO-2D hydraulic data, as described in Appendix F of this report. Using this approach, sediment deposition was estimated for the 2-, 10-, 50- and 100-year events by using FLO-2D results. The estimated sediment deposition volumes were then probability-weighted by recurrence interval to estimate the average annual sediment deposition. The results indicated that average annual sediment deposition would be less than 0.01 foot for most of the fan surface, with slightly larger values in areas adjacent to the significant wash corridors. When compared with stratigraphic interpretations of trench profiles from the WTF 36, RVF 12, and Tiger Wash site (CH2M HILL, 1992), the data indicated recent sediment deposition rates at the trench locations of 0.005 ft/yr, 0.003-0.005 ft/yr, and 0.005-0.03 ft/yr, respectively.

Table 11. MUSLE Sediment Yield to Fan Apex & Simplistic Projection of Deposition Rates

Fan Site	100-Year (AF)	Average Annual (AF)	Active Fan Area (Ac)	Potential Deposition (ft)	
				100-Yr Flood	100 Year Period
WTF 36	34.2	4.9	>185	< 0.2	< 2.6
RPF	49.7	7.0	>250	< 0.2	< 2.8
RVF 1	33.9	4.9	>115	< 0.3	< 4.3
RVF 12	14.6	2.1	>110	< 0.1	< 1.9

2.4.2. Sediment Transport Modeling

Sediment modeling was performed using FLO-2D. The modeling evaluation found that FLO-2D performed the sediment transport calculations adequately, and that the model is the best available for the purposes of quantifying flood hazards on active alluvial fans in Maricopa County. FLO-2D was used to investigate the following aspects of sediment transport on alluvial fans:

- Multiple Frequency Models
- Sediment Gradation
- Sediment Inflow
- Sediment Transport Functions
- Series of Events
- Comparison to Water-Only Models

The sediment transport modeling effort is summarized in the following paragraphs. For the purposes of the sediment transport analyses, the 100-year model with the Zeller-Fullerton transport function was considered the "base" model. All sensitivity models were evaluated relative to this base model.

2.4.2.1. Multiple Frequency Models

FLO-2D models were prepared for the 2-, 10-, 50-, and 100-year events. Not surprisingly, FLO-2D modeling indicates that smaller events impact smaller areas, similar to the results of the without-sediment runs described in Section 2.3.3.2 above. Also, smaller events not only inundated a smaller percentage of the fan surface, but more of the flow was attenuated or infiltrated on fan surface (Figure 50). Therefore, it is likely that a

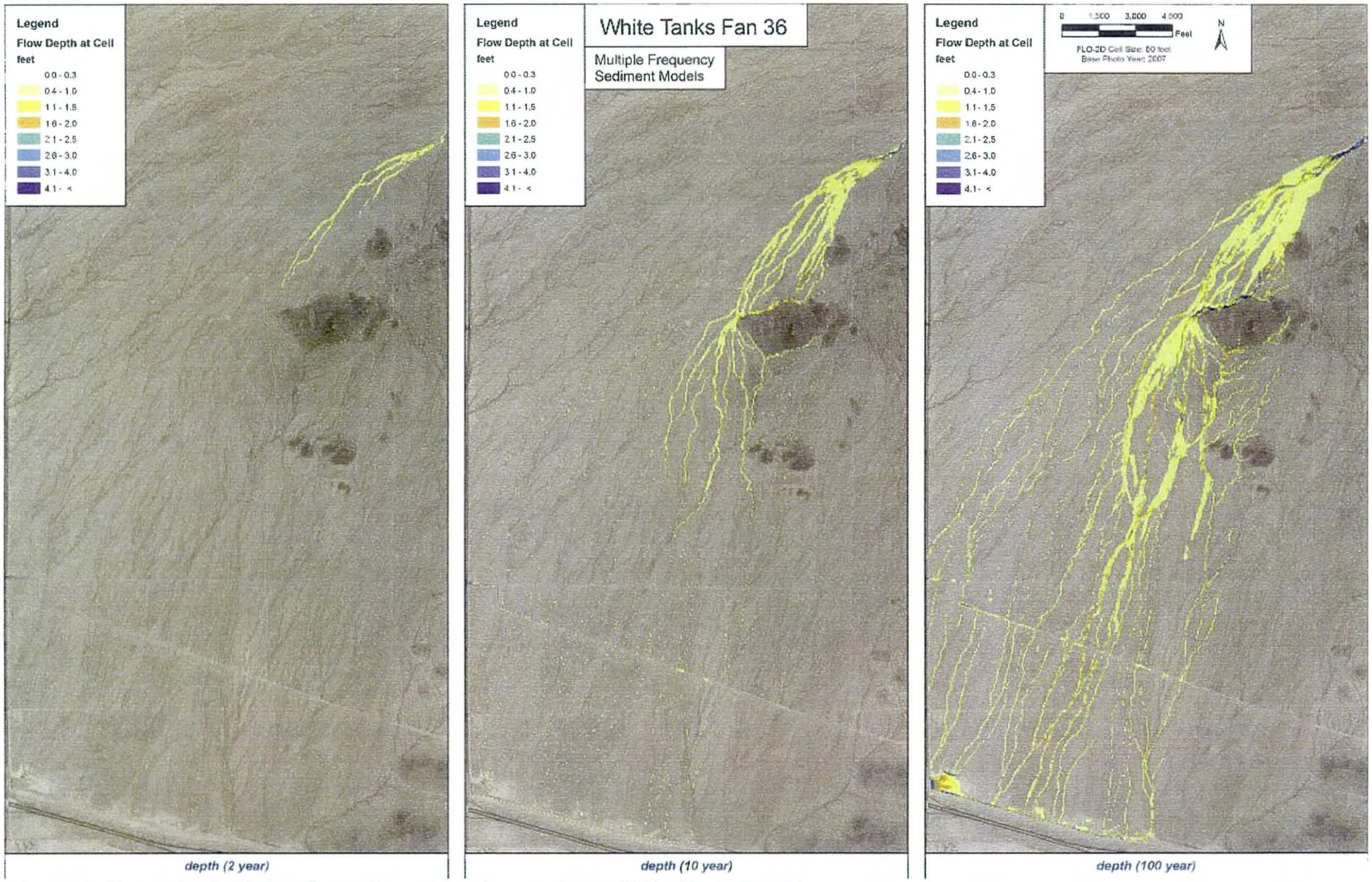


Figure 50. Plots of FLO-2D flow depths for multiple frequencies for White Tanks Fan 36.

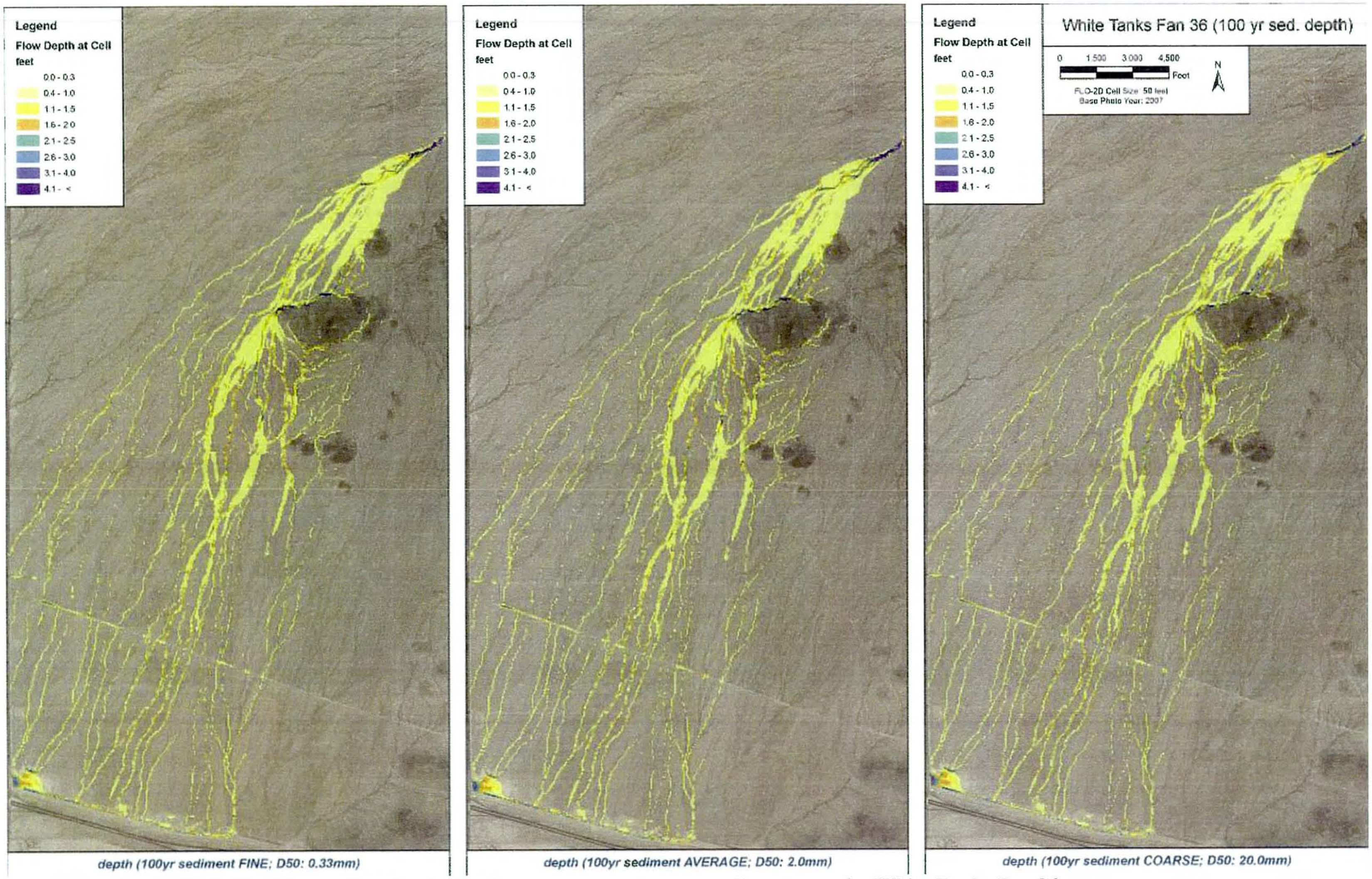


Figure 51. Plots of FLO-2D 100-year flow depths for fine, average, and coarse sediment runs for White Tanks Fan 36.

higher percentage of the sediment load delivered by the frequent events is deposited on the fan surface, possibly creating conditions more conducive to avulsion in subsequent larger floods. The water-only simulations of large floods such as the 100- and 500-year events could be interpreted to identify possible alternate (avulsive) flow-paths that could be exploited in rare floods, as described in Section 2.7 below.

2.4.2.2. Sediment Gradation

A variety of FLO-2D sediment runs were made to test the model's sensitivity to sediment size. The model results indicated that sediment size does impact the predicted flow hydraulics, scour and deposition, although the overall area of inundation was essentially identical to water-only modeling (Figure 51). In general, use of a finer sediment size resulted in greater predicted scour along the main watercourses, and overall larger high and moderate hazard zones. Use of a coarser sediment distribution resulted in lower net bed elevation changes. Given that the current formulation of FLO-2D only allows a single sediment distribution for the fan area, the selection of the appropriate sediment distribution should be made to reflect the purpose of the modeling as well as the specific area of concern within the fan boundaries. Use the distribution for the area of concern.

2.4.2.3. Sediment Inflow

The impact of available sediment supply at locations upstream of the apex was investigated by comparing the clear-water inflow simulations with equilibrium sediment inflow simulations. The results indicated that overall, the fan areas immediately downstream of the apex are not affected by the sediment inflow rate, as long as the model domain extends far enough upstream of the apex for the sediment transport rate to normalize before it reaches the fan. The only impact due to sediment inflow occurs immediately below the sediment inflow location. Therefore, the inflow locations were intentionally located further upstream of the apex so that such impacts diminish as the flow approaches the apex and the area of interest on the fan surface. The hazard delineations obtained from either approach were very similar, leading to the conclusion that sediment inflow impacts are minimal and can be addressed by shifting the inflow location further upstream from the areas of interest.

2.4.2.4. Sediment Transport Functions

Sensitivity to the sediment transport function used by FLO-2D was investigated by testing different sediment transport equations in the Reata Pass Fan models. Various sensitivity-type simulations were performed using the Zeller-Fullerton, Yang, MPM-Woo and Englund-Hansen equations. The results indicate a high sensitivity of the hazard zones to the transport equation used, as shown in Figure 52. The Zeller-Fullerton appears to predict the most reasonable results based on the following:

- Standard of Practice – for other types of sediment transport analyses, the District has recommended using the MPM and/or Zeller-Fullerton equations. The ADWR Manual also uses the Zeller-Fullerton equation.
- Engineering Judgment – lacking data for calibration or verification, the engineer must rely on experience and judgment to select the best results.

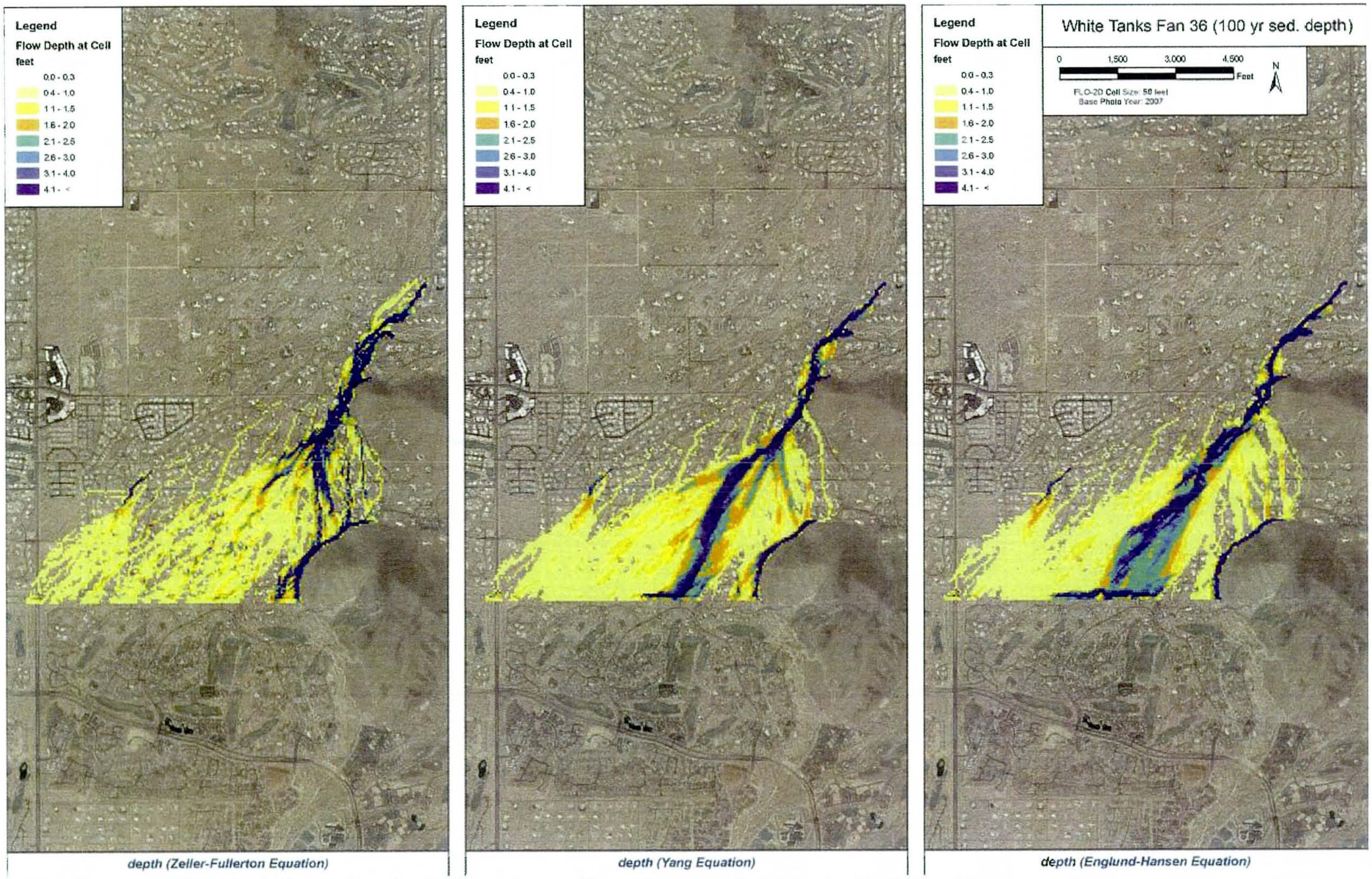


Figure 52. Plots of FLO-2D 100-year flow depths for various sediment transport functions for Reata Pass Fan.

It is recommended that the District continue to explore sediment transport modeling options for alluvial fans and to develop data for model verification. Dr. O'Brien15 notes that all of the available equations were developed for riverine, not alluvial fan, modeling

2.4.2.5. Series of Events

Two attempts to simulate long-term behavior of active alluvial fans were made using the FLO-2D model. The first attempt consisted of probability-weighting the results of 2-, 10-, 50- and 100-year models and projecting the average annual result over a long planning period. Unfortunately, this approach resulted in predictions of unrealistically excessive scour and deposition in some locations (e.g., greater than 25 feet). Future use of this methodology may be possible if subroutines are developed to cull out unrealistic results through an area-weighting or local averaging procedure. The second attempt consisted of running a series of flood hydrographs back-to-back in the model. However, since the FLO-2D model processing time is already slowed considerably by inclusion of sediment transport modeling, the addition of even longer duration flows caused the model to slow to the point where it was no longer practical. As computers get faster in the future and the FLO-2D algorithm is improved, it is more likely that a two-dimensional modeling based approach can be used to predict long-term behaviors in addition to single event models.

2.4.2.6. Comparison to Water-Only Models

Comparison of the flow rates from water only and sediment FLO-2D models at index cross sections on the fan surface indicated only minor differences (Table 12). Therefore, use of water only models probably results in acceptable estimates of peak discharge. Differences in predicted flow depths between water-only and sediment models are illustrated in Figure 53 to Figure 62. The FLO-2D modeling results indicate that there are differences in predicted flow depths and hazard levels caused by consideration of sediment transport. The greatest differences tend to occur near the hydrographic apexes in the high hazard zones. Further downfan, the differences are less significant, and are generally less than one foot. Note that the overall area of inundation is not significantly different between water-only and sediment models, but the predicted depths within those zones have some differences. At this time, there are insufficient data from which to conclusively judge the accuracy of the sediment modeling results.

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[15] Email to Jon Fuller on 7/18/10.

Table 12. Comparison of FLO-2D 100-year discharge estimates for water-only and sediment models.				
Site	FLO-2D Water Only		FLO-2D Water & Sediment	
	Q (cfs)	Vol (AF)	Q (cfs)	Vol (AF)
White Tanks Fan 36				
Section 10	2802	339	2861	345
Section 1020	538	81	313	25
Section 1050	921	103	1164	165
Section 10100	1150	125	1084	118
Section 20	35	11	50	9
Section 33	14	2	22	2
Section 34	0	0	0	0
Section 43	12	2	14	2
Section 44	0	0	0	0
Section 50	18	4	23	5
Section 60	41	7	49	9
Section 74	0	0	0	0
Section 80	58	13	65	19
Section 100	1615	157	1758	180
Section 100110	934	86	1162	114
Section 100140	532	54	413	45
Section 110	101	19	203	40
Section 140	349	59	276	52
Section 140110	90	10	101	22
Section 140150	256	51	234	32
Rainbow Valley Fan 1				
Section 30	3763	429	3549	424
Section 40	3739	481	2831	470
Section 60	172	26	115	20
Section 30-60	332	25	246	13
Section 40-60	207	10	163	8

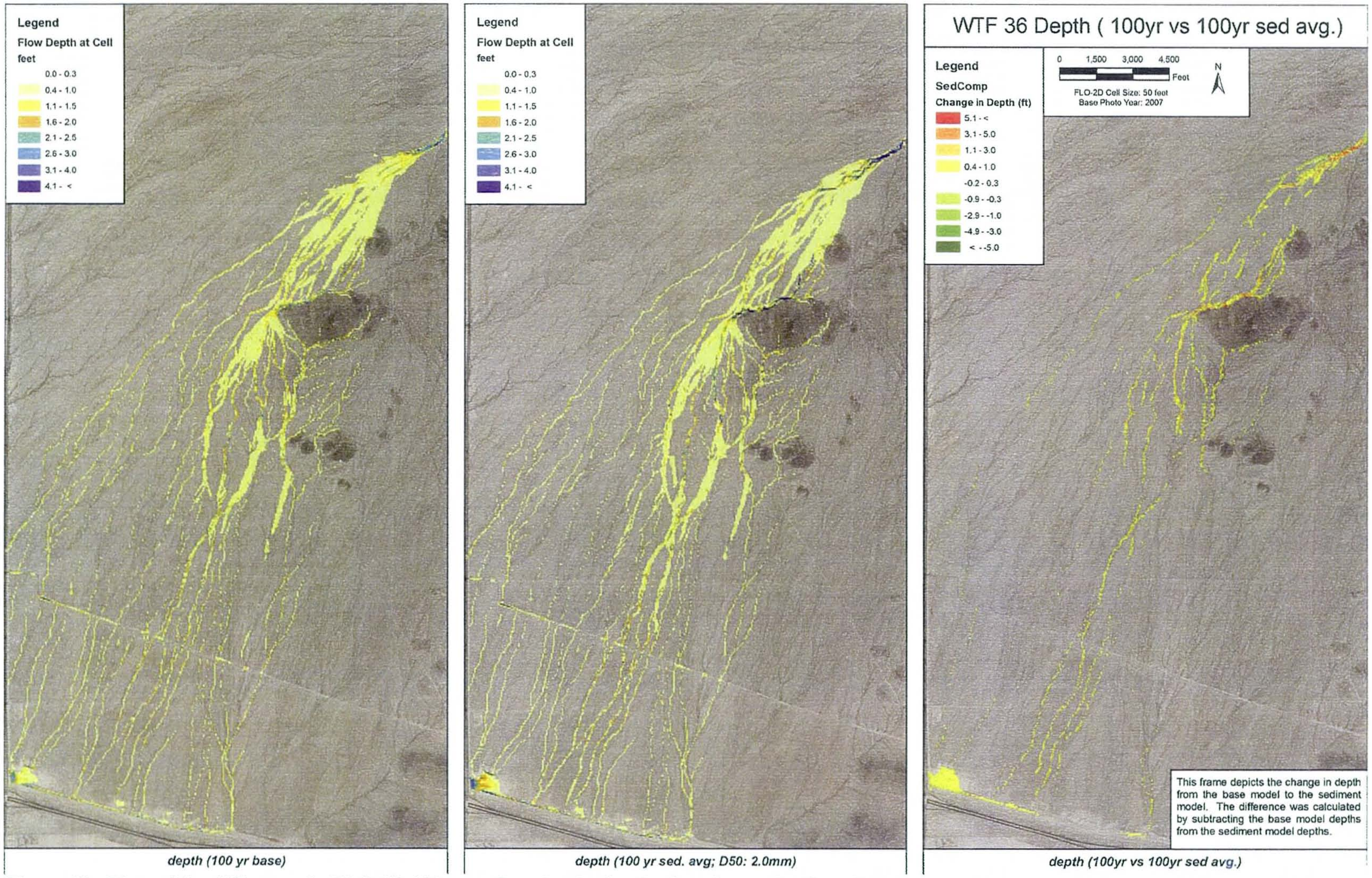

Figure 53. Plots of the difference in FLO-2D 100-year flow depths for the four fan evaluation sites.

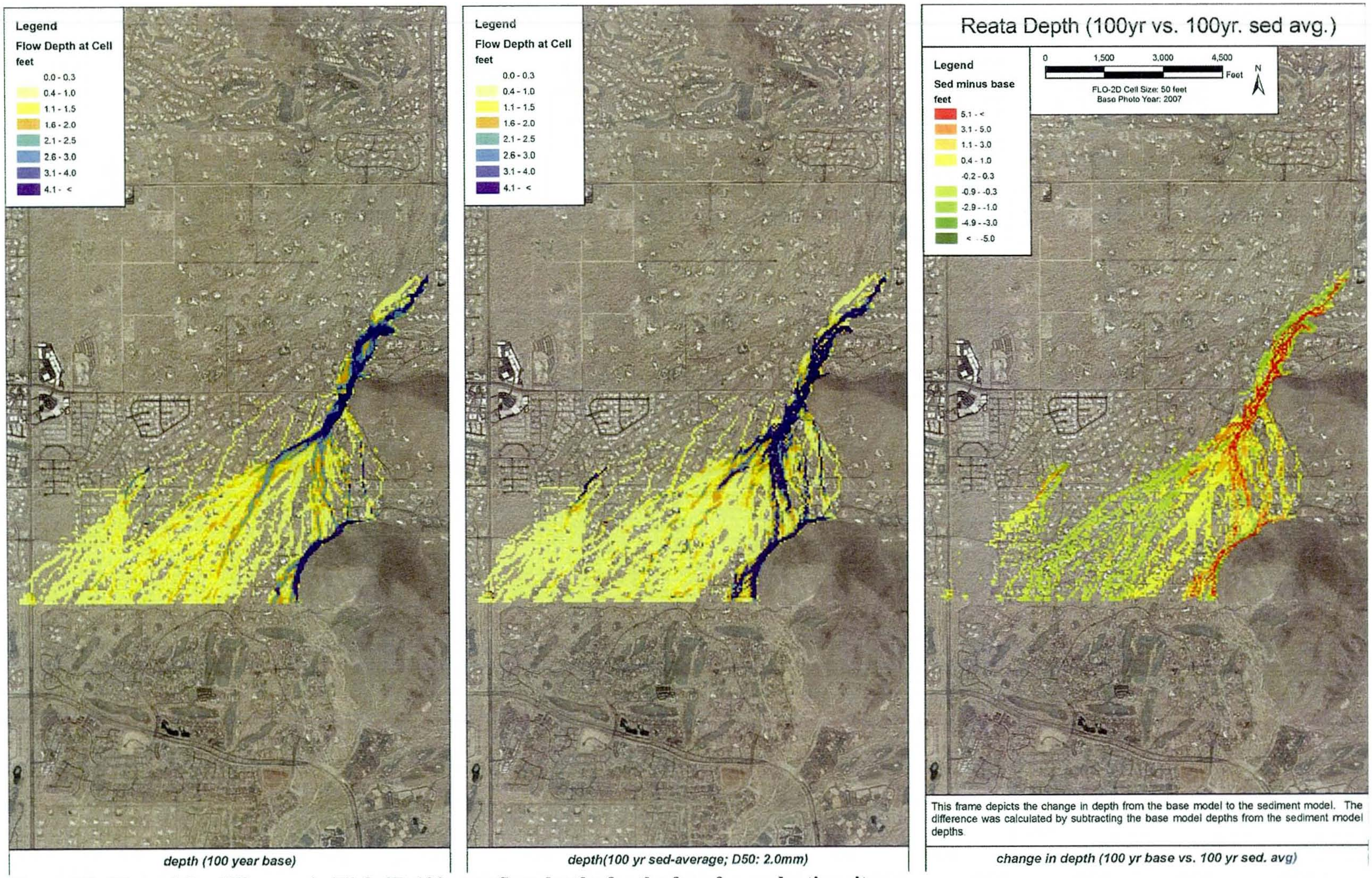

Figure 54. Plots of the difference in FLO-2D 100-year flow depths for the four fan evaluation sites.

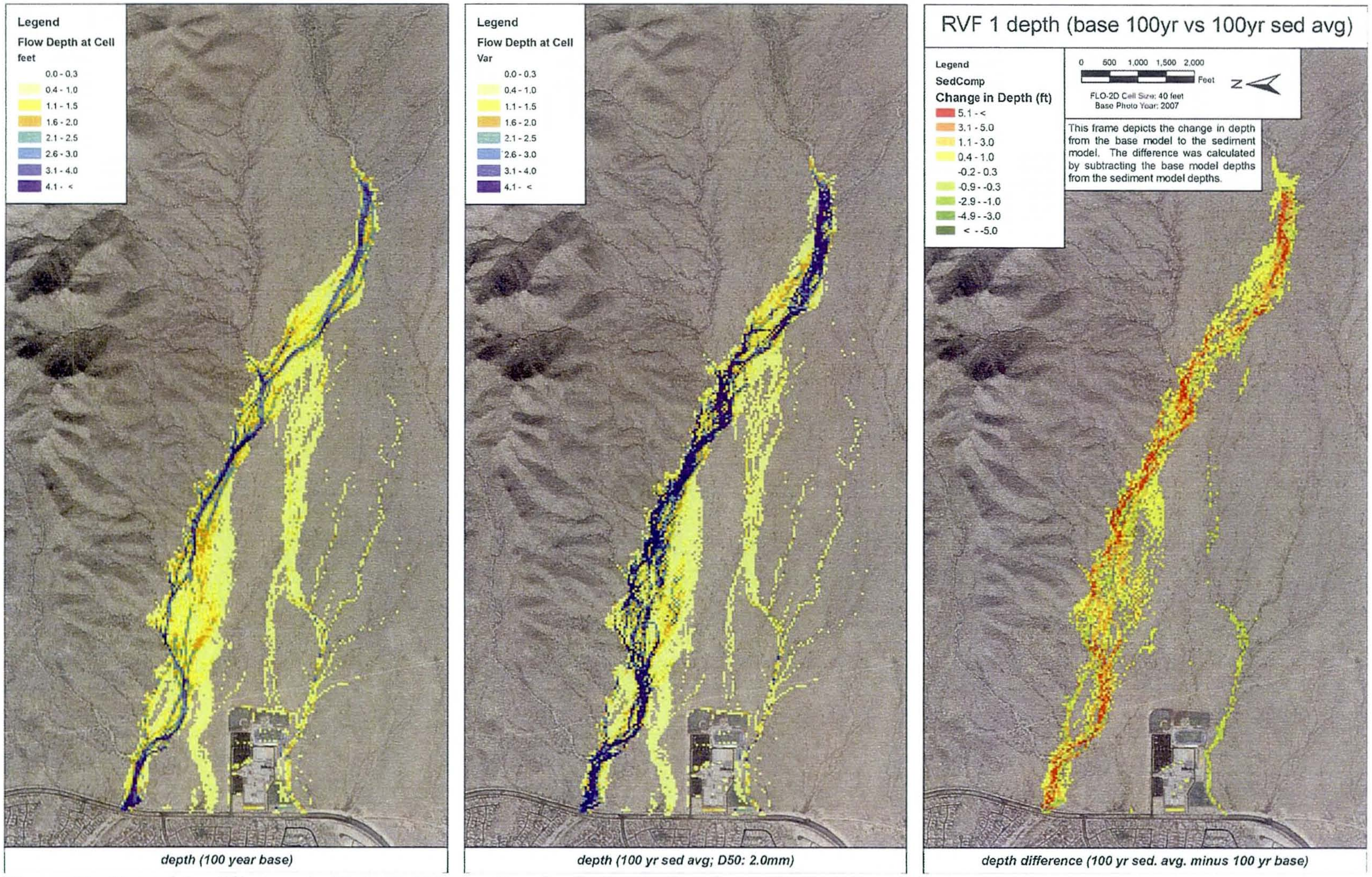

Figure 55. Plots of the difference in FLO-2D 100-year flow depths for the four fan evaluation sites.

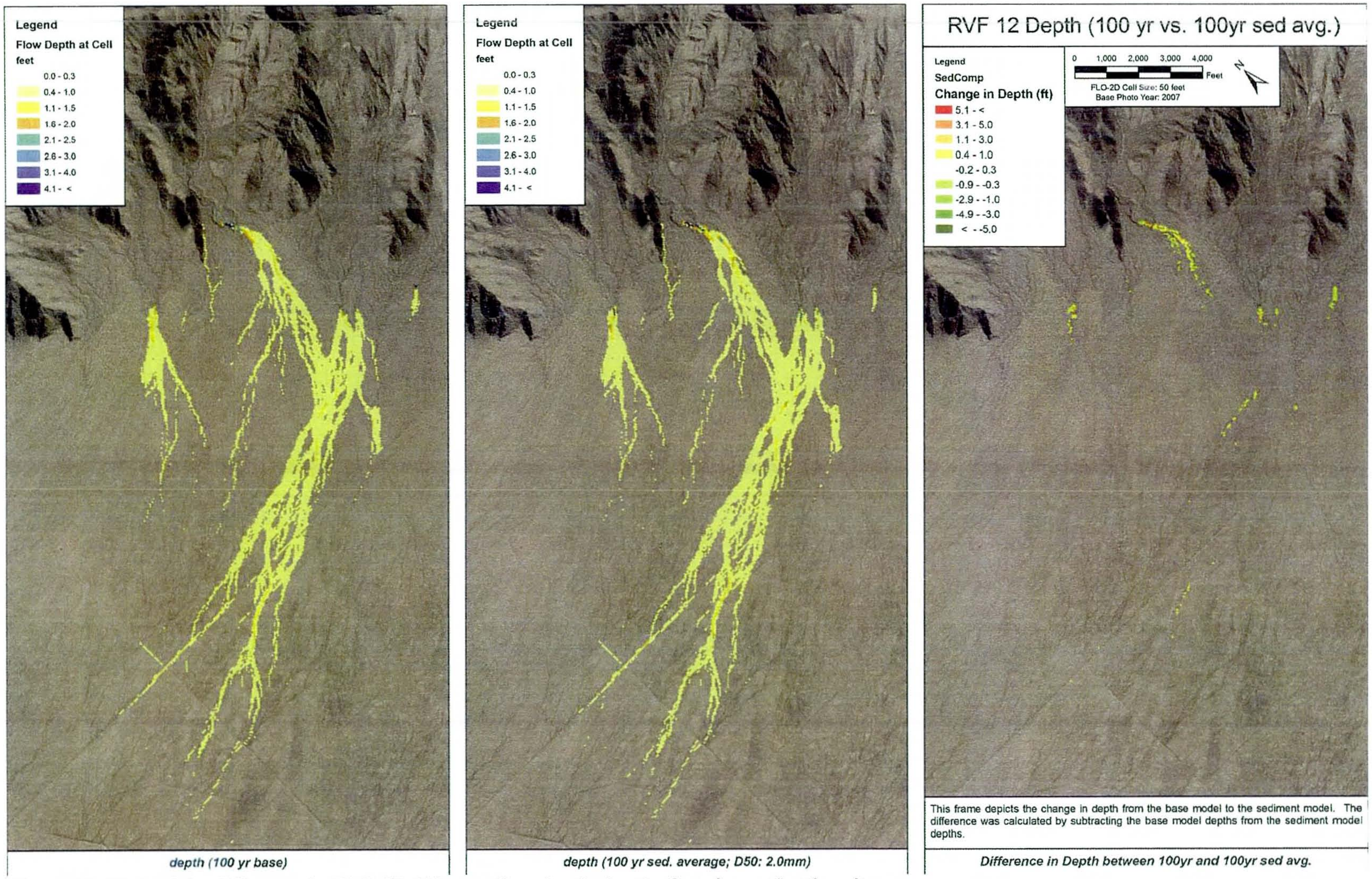

Figure 56. Plots of the difference in FLO-2D 100-year flow depths for the four fan evaluation sites.

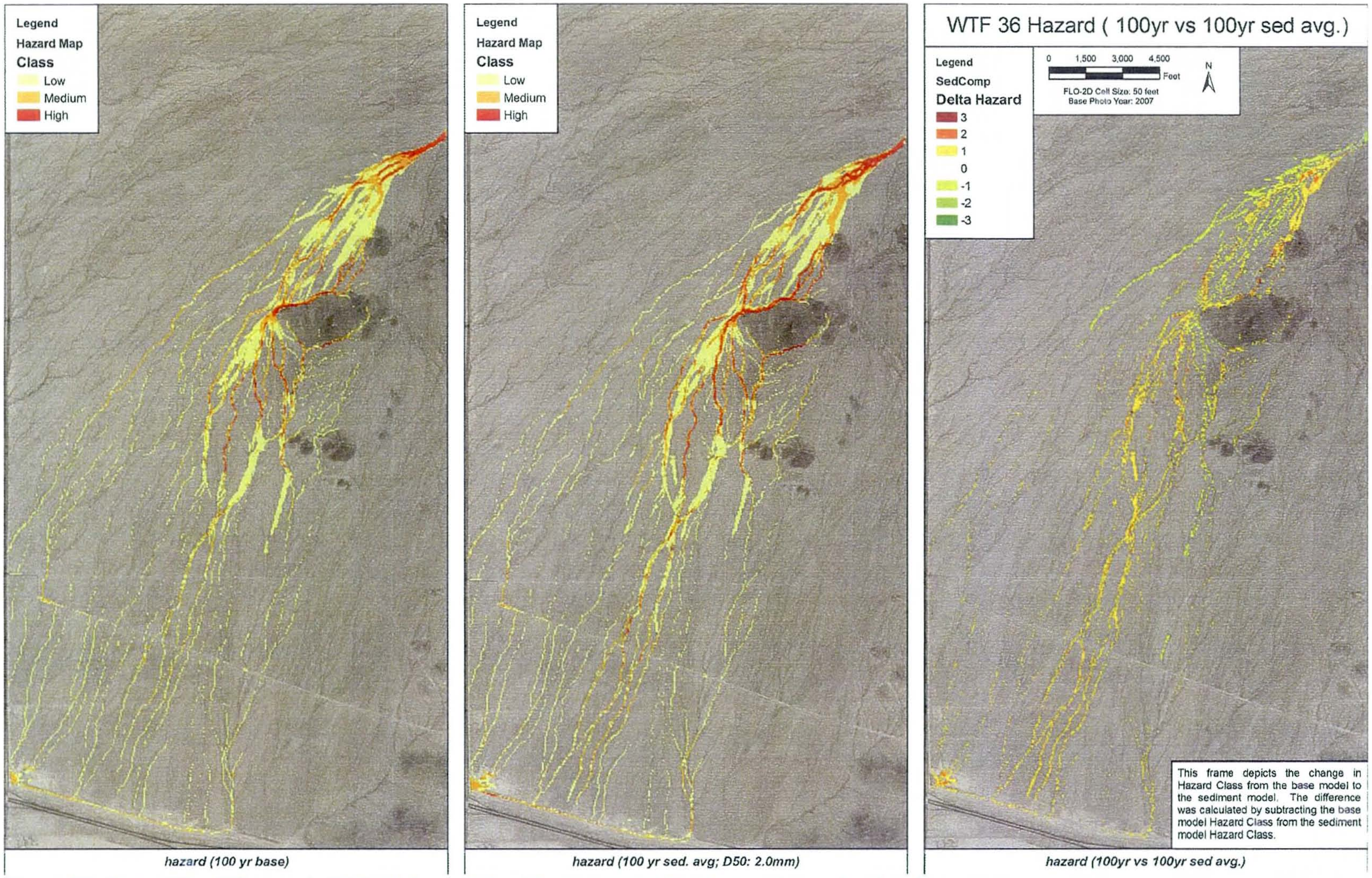

Figure 57. Plots of the difference in FLO-2D hazard classification (Q100) for the four fan evaluation sites.

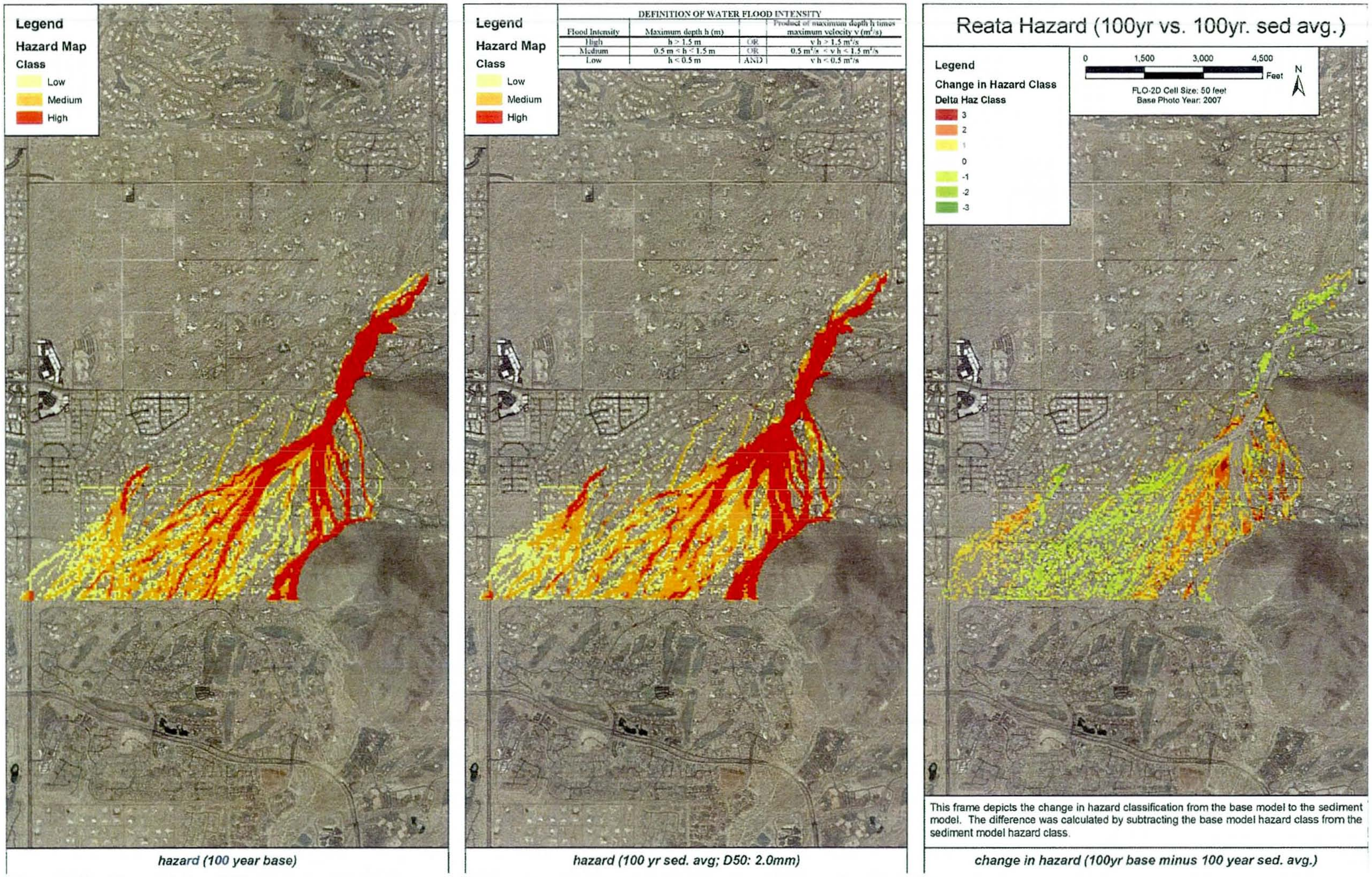

Figure 58. Plots of the difference in FLO-2D hazard classification (Q100) for the four fan evaluation sites.

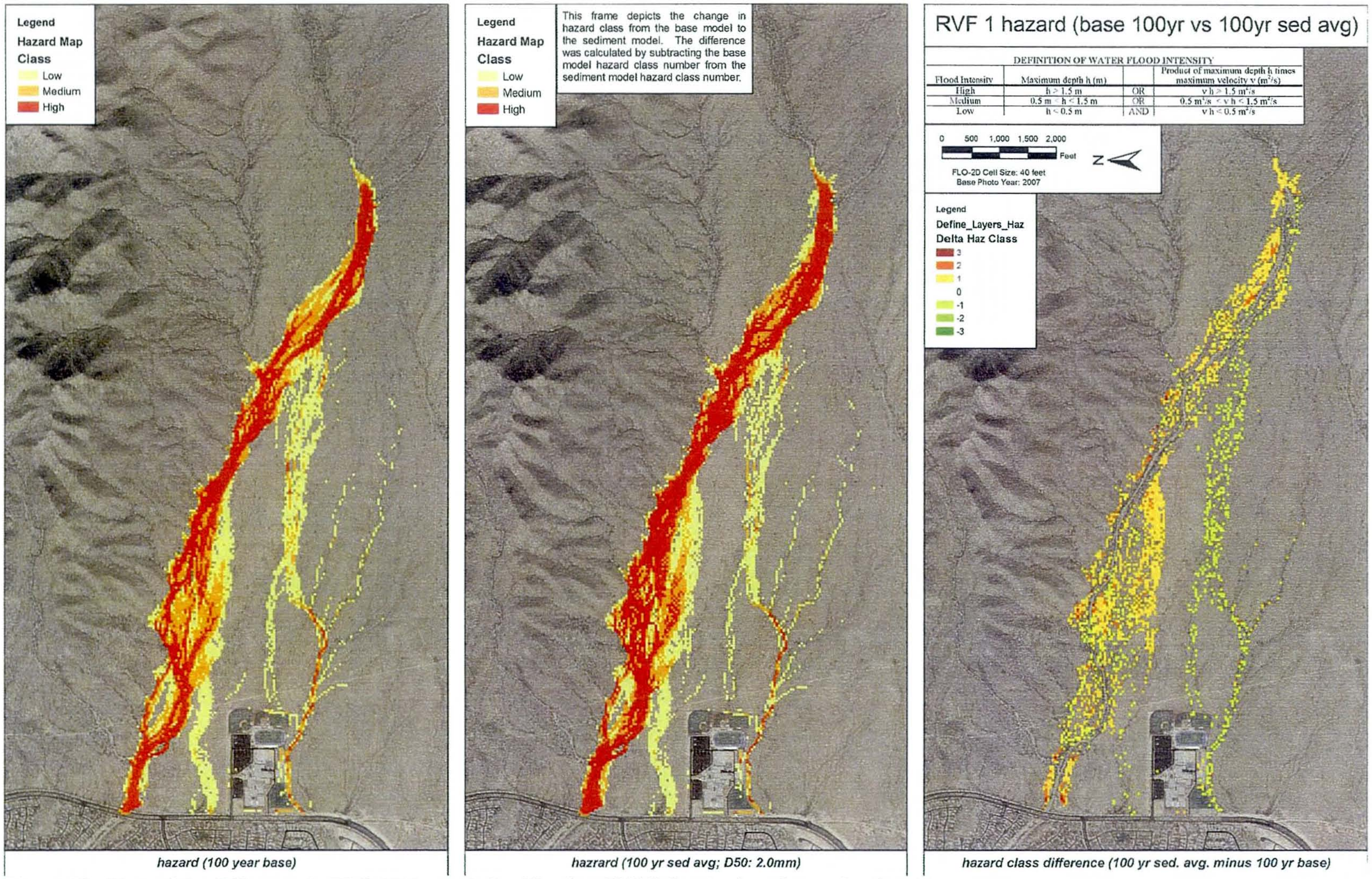

Figure 59. Plots of the difference in FLO-2D hazard classification (Q100) for the four fan evaluation sites.

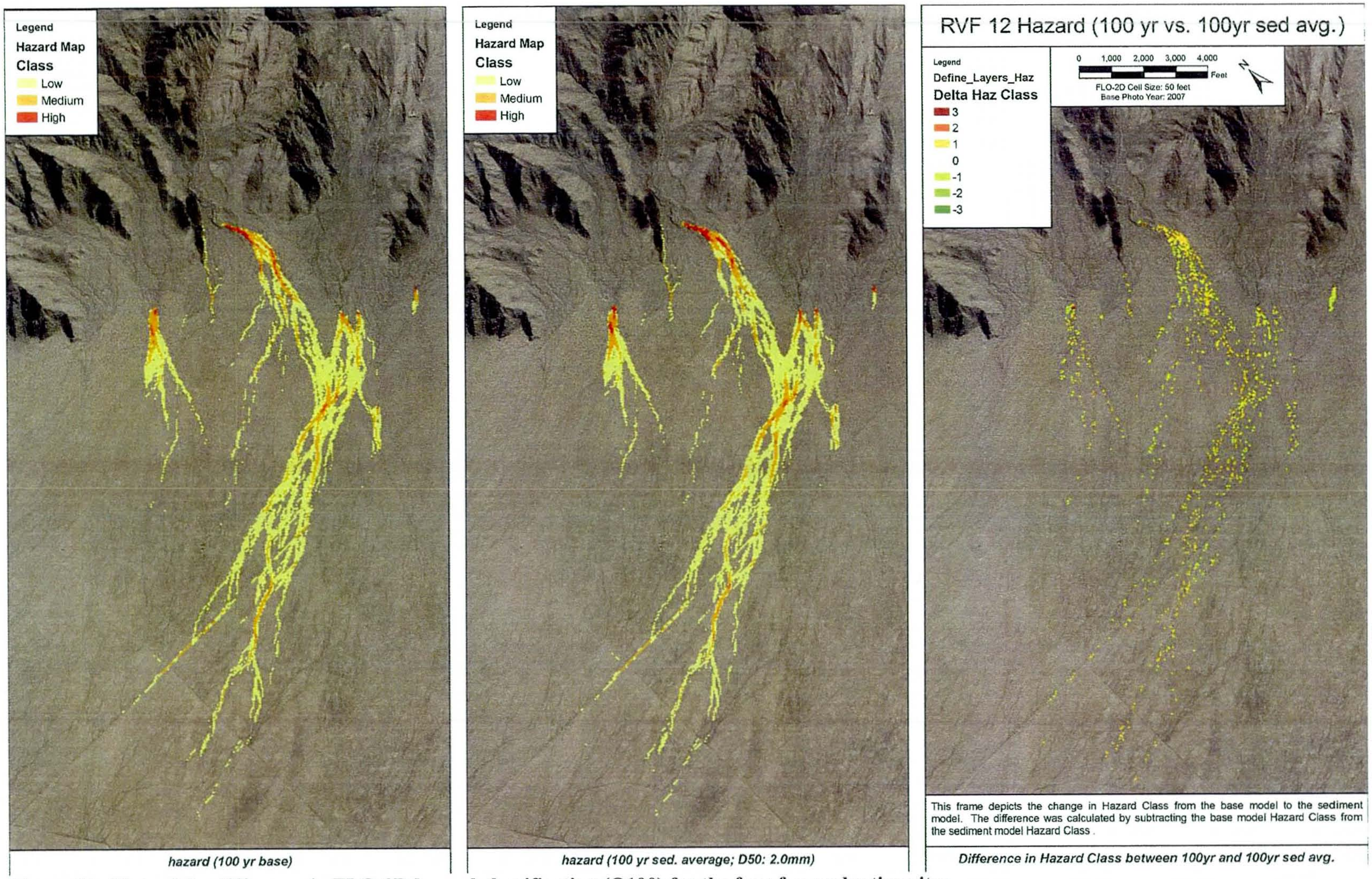

Figure 60. Plots of the difference in FLO-2D hazard classification (Q100) for the four fan evaluation sites.

2.4.3. Conclusions

Conclusions drawn from the sedimentation evaluation of the four alluvial fan sites included the following:

- Frequent floods, such as the 2- to 10-year events, induce channel changes which may not be significant on a single event basis, but may have important cumulative impacts, particularly when large, rare floods occur. However, long-term cumulative sediment impacts are difficult to simulate using any available modeling tool, including FLO-2D.
- The impact of the sediment supply was not found to be significant if the sediment inflow point was placed sufficiently upstream of the area of concern. Clear-water inflow and sediment laden inflow models resulted in nearly identical results for the areas downstream of the fan apex.
- Modeling results reinforce the importance of accurate, detailed topography and appropriate grid size when performing FLO-2D modeling on alluvial fans.
- FLO-2D is highly sensitive to the transport function used. The Zeller-Fullerton was judged to predict the most reasonable results, but more investigation and model calibration is recommended.
- The upstream sediment supply was found to have a minor impact on fan topography, at least for single flood events.
- Use of sediment transport subroutines slows the FLO-2D model considerably.

In order to enhance the effectiveness of the two-dimensional sediment transport models, further calibration of sedimentation results to measurements is needed. Presently, there is lack of data to verify the adequacy of the models to predict reliable results from a qualitative as well as a quantitative point of view. The collection of such data may be difficult and expensive.

2.5. Holocene Dating Techniques

An assessment of Holocene[16] surficial dating techniques was completed to demonstrate how landform surface age estimates can be used in the evaluation of alluvial fan flood hazards in Maricopa County, Arizona. Surface age estimates are used to help identify active (young) and inactive (old) portions of alluvial fan landforms, and are a major component of the Stage 2 PFHAM methodology. Detailed geomorphic mapping of alluvial fan surfaces combined with surface age estimates reveal the degree of flood hazards by identifying the most recently active flooding areas. Geomorphic mapping and application of relative dating methods (surface morphology, degree of soil and desert pavement development, vegetation type and density, carbonate content and structure) should be performed prior to applying any numerical dating techniques. A more detailed discussion of Holocene dating techniques as applied to alluvial fans in Maricopa County is presented in Appendix G.

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[16] The Holocene Epoch consists of the past ~10,000 years of earth history. Some of the dating techniques described extend into the Pleistocene Epoch (> 10,000 yrs before present), though the focus of this report is only on the more geologically recent Holocene dates.

The dating techniques considered included relative, numerical, and correlative methods, but the evaluation focused on methodologies that could provide better age-resolution of Holocene surfaces. The following methodologies which are considered applicable to alluvial fan landforms in Maricopa County were evaluated:

• Optically Stimulated Luminescence (OSL)	(Numerical)
• Radiocarbon (C-14)	(Numerical)
• Cosmogenic Nuclides (CND)	(Numerical)
• Thorium-Uranium (Th-U)	(Numerical)
• Varnish Micro-Lamination (VML)	(Correlative)
• Pedogenesis	(Relative)
• Rock weathering	(Relative)
• Surface Morphology	(Relative)
• Gully diffusion	(Relative/Correlative)
• Palynology	(Correlative)
• Archaeology	(Correlative)

Of the dating techniques listed above, the OSL and radiocarbon dating methods were found to be the most applicable numerical dating methods for dating alluvial fan sediments on fan landforms in Maricopa County. CND and VML are the most applicable methods for estimating surface ages. VML is a correlative method which should be evaluated further for application in Maricopa County. The types of dating techniques considered, as well as their resolution and age ranges are shown in Figure 61.

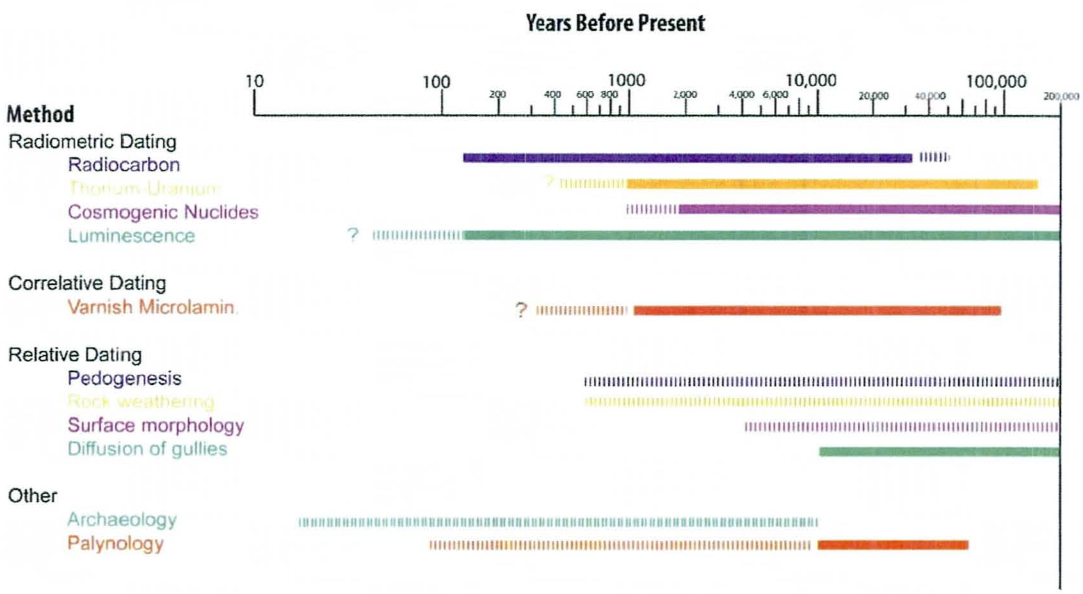

Figure 61. Dating techniques and age-resolution available for use on alluvial fans in Maricopa County.

While relative, numerical and correlative dating methods can be used to date Holocene alluvial fans in Maricopa County, accurately estimating the ages and establishing a chronology of alluvial fan development in Maricopa County will require a multi-step approach which relies on several methodologies. Relative dating methods are always an important first step, and are used to generate a contextual geomorphic interpretation, as well as detailed maps that define the physical framework of the alluvial fan system. The relative dating results provide a basis for evaluating what type of material and surface to sample and what dating methods would be most useful. Numerical dating methods should always be coupled with relative age indicators. If numerical ages are obtained from alluvial fan sediments and surfaces like those found in Rainbow Valley or Tiger Wash, then indirect dating techniques like VML, weathering rind thickness measurements, surface roughness and degree of soil formation can be calibrated from those same sediments and surfaces. When relative dating methods have been calibrated at several sites within Maricopa County, a regional chronology of fan and surface development could be constructed that would apply throughout Maricopa County. The process of constructing a regional chronology could take several years to complete, and would require the involvement of several types of dating and surficial geology experts. It may be possible to complete this task using research staff from Arizona Universities in conjunction with the Arizona Geological Survey. Once completed, it would provide useful guidelines in the PFHAM for dating and delineating young alluvial fan surfaces.

2.5.1. Conclusions

This study concludes that there are methods for quantifying surface age that are applicable to alluvial fans in Maricopa County. OSL and AMS radiocarbon dating methods are the most applicable numerical dating methods for dating alluvial fan sediments on fan landforms in Maricopa County. Cosmogenic nuclide dating and varnish microlamination correlation are the most favorable methods for estimating surface ages. Varnish microlamination (VML) is a correlative method and should be evaluated further in Maricopa County. It is recommended that a combination of relative and numerical methods be applied, in conjunction with conventional surficial mapping techniques, to most accurately determine surface age on alluvial fans in Maricopa County. It is further recommended that a regional chronology be constructed so that more cost-effective relative dating techniques can be used to determine correlative ages.

2.6. Debris Flow Potential Assessment

An assessment of the potential for debris flows to influence alluvial fan flood hazards in Maricopa County was conducted as part of the PFHAM study. Specifically, the assessment evaluated and recommended methods for determining potential debris flow occurrence and run-out onto alluvial fan flood hazard areas. Other debris-flow hazard issues such as expected magnitude, frequency, or direct impacts on developments located at the base of steep slopes (Péwé, 1978) are not directly addressed in this report. A more detailed discussion of the debris flow assessment is provided in Appendix H.

Debris flows are unsteady, non-uniform, very poorly sorted sediment slurries that are generated when hillslope soils become saturated and fail. While there is some evidence that debris flows have occurred in Maricopa County on very steep slopes of mountainous watersheds, there are no documented cases of historic debris flows impacting flood hazards on any mid-piedmont alluvial fans within the County. Based on known general characteristics of debris-flow behavior, as well as on the specific climatic and geologic conditions in Maricopa County, the expected recurrence interval for debris flows in Maricopa County, even in the mountainous areas, probably exceeds 1,000 years. Furthermore, because of the regional physiography and watershed characteristics, it is likely that future debris flows will have low volumes because of limited sediment supplies, will travel only short distances from their point of initiation due to their coarse sediment composition and low clay content, and that most will not reach the active areas of alluvial fans, particularly the fans that are located well away from the mountain front.

Based on the PFHAM study requirement to develop a method for assessing potential debris-flow impacts on alluvial fan flooding, the following steps are recommended for detailed evaluations of debris flows on specific alluvial fan landforms in Maricopa County:

- Step One: Initial Assessment of Alluvial Fan
- Step Two: Geologic Reconnaissance
- Step Three: Debris-Flow Runout Hazard Modeling

<u>Step One: Initial Assessment</u>. The first step in the recommended approach is to select a fan of interest and determine if the alluvial fan is adjacent to or distant from the mountain front. If the alluvial fan is distant from the mountain front, it is highly unlikely that debris flows will impact alluvial fan flooding. Thus, there is no need to proceed with further assessment of debris flow impacts on the alluvial fan floodplain. If the alluvial fan is adjacent to the mountain front, then the next step is a geologic reconnaissance to determine if debris flows have occurred in the basin of interest, and if any debris flow deposits are found on the fan.

<u>Step Two: Geologic Reconnaissance</u>. The second step in the recommended approach is geological reconnaissance. Geologic reconnaissance of the watershed and alluvial fan, especially near the fan apex, will confirm the presence or absence of debris-flow deposits, and provide details of the basin and piedmont conditions that will be useful for calculating and evaluating potential debris-flow volumes. Geologic mapping will provide data regarding minimum number of deposits, relative ages, and travel distances of past debris flows. If debris-flow deposits are not found in the watershed or on the alluvial fan, it is not a debris-flow producing basin, and no further debris flow hazard evaluation is warranted. If debris-flow deposits are in found in the basin and/or on the fan, then the deposits should be geologically mapped. Detailed field mapping of young debris flow deposits at and below canyon mouths can provide real data to help constrain estimates of debris flow volumes and runout distances using the procedures outlined in Youberg and others (2008). This field-mapping step is critical to realistically assess the potential impacts of debris flows on alluvial fan flooding under modern climatic conditions. If debris-flow deposits are found on the alluvial fan then additional modeling will be required to assess the potential impacts to alluvial fan flooding hazards.

Step Three: Modeling. The third step, if deemed necessary based on the results of step two, is to model various debris-flow volumes using LAHARZ[17] as shown in Figure 62. The first phase of the recommended LAHARZ methodology uses the lahar function, where deposition zone begins at the apex of the active fan area. Various flow volumes should be modeled, in half order-of-magnitude increments, to estimate potential volumes required to emplace debris-flow deposits at the farthest distance the youngest deposits (late Holocene to modern) were mapped. Debris-flow maps will provide the basis for determining potential deposition zones and modeling flow volumes. Results from LAHARZ can also then be used to identify potential hazard zones on alluvial fans.

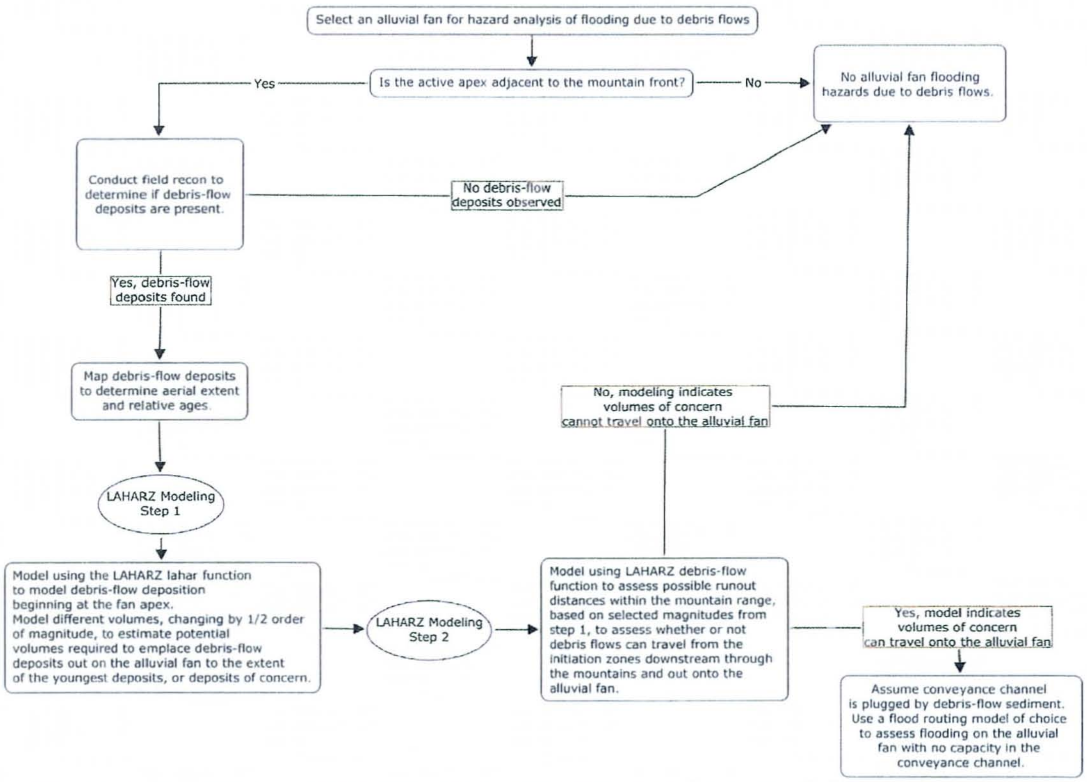

Figure 62. Flow chart showing recommended steps to evaluate the potential for debris flows to impact alluvial fan flooding.

Once the potential debris flow volumes have been estimated, a geologic analysis of material available is required. For example, if the model indicates 100,000 cubic yards of material are required to emplace debris-flow deposits on the active fan surface, then that volume can be compared to the average depths of hillslope soils, as well as to the material volume stored in upstream channels. The sediment production rate should also

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[17] LAHARZ (Schilling and Iverson, 1997; Griswold and Iverson, 2008) is an empirical area-volume model. It is a GIS-based runout prediction model originally developed for volcanic-related debris flows (lahars) and recently revised to predict runout distances for non-volcanic debris flows and rock avalanches (Griswold and Iverson, 2008). It uses an empirical approach based on observations that the debris-flow inundation area is proportional to flow volume raised to the 2/3 power (Schilling and Iverson, 1997).

be compared to the required volume to determine if the basin can produce enough material to reach the modeled volumes. If sufficient sediment material is available, then the second phase of LAHARZ modeling should be conducted using the debris flow function.

The purpose of the second phase of LAHARZ modeling is to determine if debris flows produced in the basin can actually travel to the alluvial fan. Deposition zones for this phase will be based on field- and GIS-derived data, such as minimum contributing area and slopes, channel gradients, and soils data, if available. The second phase of modeling will take several iterations, as the modeler will need to consider the effects of coalescing debris flows. If the modeling indicates that debris flows cannot reach the alluvial fan, then it is unlikely that debris flows will impact alluvial fan flooding. If the modeling indicates that debris flows can reach the fan, then the assumption that the conveyance channel can become blocked with sediment should be made, at which point more traditional distributary alluvial fan flooding models (e.g., FLO-2D) can be applied. The greatest impact debris flows may have on flooding is to block existing channels with sediment, forcing the following floods onto other areas on alluvial fans.

Application of debris-flow runout models like LAHARZ will provide hazard information regarding potential travel distances, as well as the volumes required to reach those distances. It should be noted that these methods will not provide any information to quantify frequency-magnitude relationships or the actual risk of debris-flow occurrence or expected volumes. Initiation modeling to evaluate the likelihood of debris-flow occurrence would require significant resources in terms of time commitments to set up and run the models, and collect field data with which to calibrate the models. In addition, these models need debris flow inventories for calibrating model results. Because no such inventory currently exists for Maricopa County, one would have to be developed by qualified personnel. Without such an inventory, initiation modeling is not recommended.

Model results from LAHARZ should be locally validated and calibrated with debris-flow data from Maricopa County. LAHARZ has been calibrated using the limited data set from southeast Arizona to model the 2006 debris flows in the Santa Catalina Mountains with reasonable success. It may be possible to test LAHARZ in Maricopa County on alluvial fans with young debris-flow deposits by making generalized assumptions regarding location of debris-flow initiation, and volume estimates. The 2006 southern Arizona debris flows may act as a proxy for initiation locations and volumes. If results from these tests are satisfactory, LAHARZ can be considered ready to use in Maricopa County. Otherwise, additional calibration LAHARZ coefficients will have to be developed from newer debris flows as they occur, or other modern debris flows in Arizona that have not yet been studied in detail.

2.6.1. Conclusions

This study concluded that debris flows are unlikely to impact regulatory flood hazards on alluvial fans in Maricopa County for two primary reasons: (1) they occur so infrequently or, (2) when they do occur they do not runout far enough to reach the hydrographic apex of the alluvial fan. Nevertheless, as directed by the project scope of work, a three-step procedure for evaluating debris flow potential and hazards was developed for use on piedmont surfaces in Maricopa County.

2.7. Avulsion Potential Evaluation

The objective of the avulsion potential evaluation was to determine and quantify how channel avulsions influence flood hazards on alluvial fan landforms in Maricopa County. This information is to be used to refine the Integrated Alluvial Fan Hazard Assessment Methodology that may be used in future revisions of the Flood Control District of Maricopa County's (District) Piedmont Flood Hazard Assessment Manual (PFHAM). The results of the avulsion potential evaluation are described in detail in Appendix I.

An avulsion is the process by which flow is diverted out of an established channel into a new course on the adjacent floodplain (Slingerland & Smith, 2004). Avulsions divert flow from one channel into another, leading to a total or partial abandonment of the previous channel (Field, 2001; Bryant et. al., 1995), or may involve simple flow path shifts in a braided or sheet flooding system (Slingerland & Smith, 2004). An example from Maricopa County of avulsive channel change that occurred on the Tiger Wash alluvial fan during the 1997 Hurricane Nora flood is shown in Figure 63. Avulsions are commonly associated with alluvial fan flooding, but are also known to occur on riverine systems and river deltas (Slingerland & Smith, 2004). Some of the terminology associated with alluvial fan avulsions is shown in Table 13.

The occurrence of avulsions is what makes an alluvial fan "active." Avulsions give the alluvial fan the ability to distribute water and sediment over the surface of the landform, which results in the radial "fan" shape. Avulsions influence flood hazards on an alluvial fan landforms by changing the location, concentration and severity of flooding on the fan surface. That is, an area not previously inundated by flooding (or inundated only by shallow flow) may in a subsequent flood become the locus of flood inundation, sediment deposition, and/or erosion. If an alluvial fan has no risk of avulsion, flood hazard delineation and mitigation become much simpler engineering problems, consisting only of modeling two-dimensional flow and/or normal riverine hydraulic and sedimentation issues.

The occurrence of major avulsions in an alluvial fan drainage system introduces the following complications into an engineering analysis of the flood hazard:

- Uncertain and changing flow path locations, during and between floods
- Continually changing channel and overbank flow path topography
- Inundation and/or sedimentation hazards in previously unflooded areas
- Uncertain and changing flow rate distribution for areas downstream of avulsions
- Uncertain and changing watershed boundaries for areas downstream of avulsions
- Aggrading, net depositional land surfaces and channel with diminishing capacity
- Unsteady, rapidly-varied flow conditions
- High rates of infiltration and flow attenuation across the fan surface

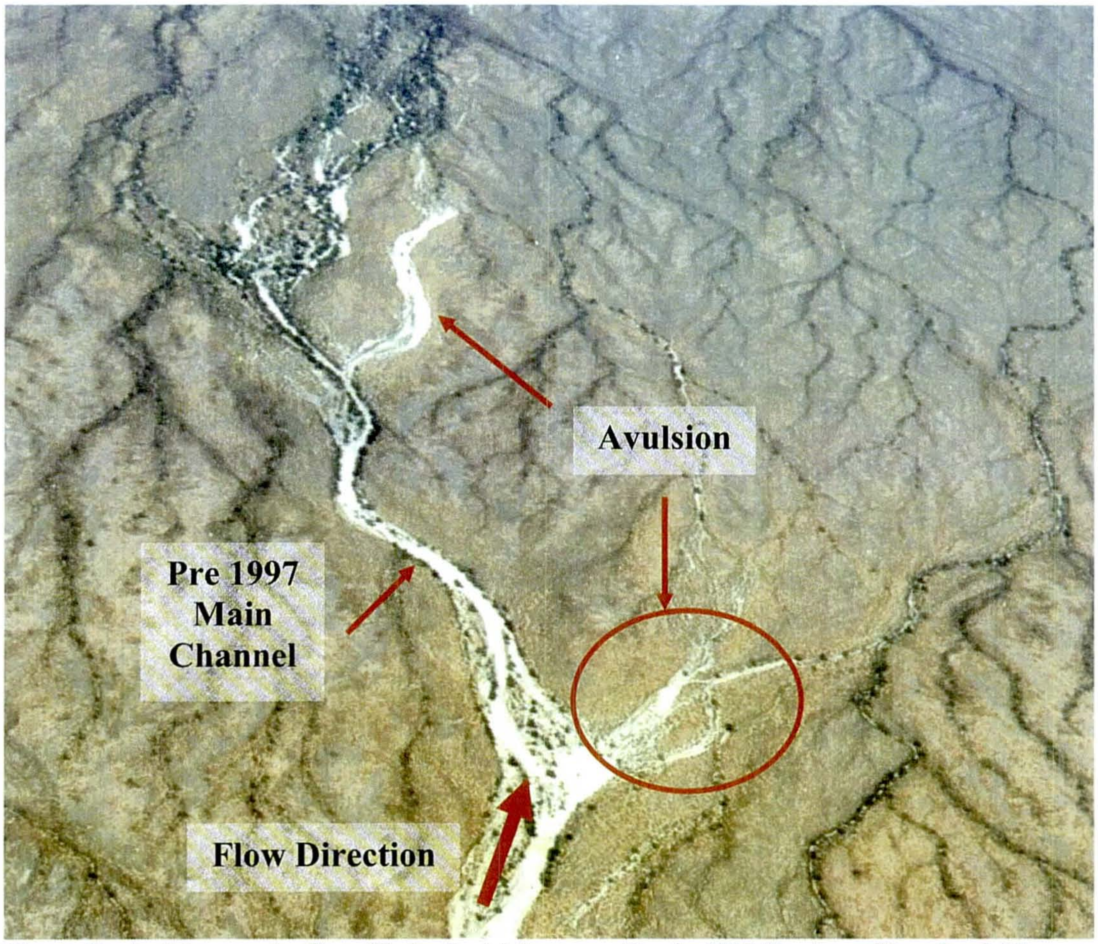

Figure 63. ***Avulsions on the Tiger Wash alluvial fan caused by the 1997 Hurricane Nora flood. View looking southwest across active fan surface.***

Table 13. Avulsion Terminology & Classification Continuum End Member ←-------------------------------→ End Member	
Major Avulsion Occurs near the apex Diverts > 50% of flow from the parent channel	**Minor Avulsion** Does not meet the major avulsion criteria
Full Avulsion All of flow is diverted Parent channel abandoned	**Partial Avulsion** Part of flow is diverted Parent and avulsive channel coexist
Nodal Avulsion Recurring at fixed point, e.g., a fan apex	**Random Avulsion** Occurs anywhere along an active channel system
Local Avulsion Avulsive channel rejoins parent downstream	**Regional Avulsion** Large scale event Affects all of system downstream of origin
Abrupt Avulsion Full avulsion occurs in single event	**Gradual Avulsion** Avulsion completed over decades or more
Anastamosing Avulsions return to parent downstream	**Distributary** Avulsions do not return to parent channel

Most importantly, there is a lack of appropriate engineering standards for evaluation of flood hazards or design of flood mitigation measures on alluvial fans with avulsion potential. Despite the importance of avulsions to the assessment of flood hazards on alluvial fans, the causes and frequency of avulsions have not been extensively studied (Slingerland & Smith, 2004).

Avulsions have been observed on several alluvial fans in Maricopa County, including some of the four fan evaluation sites selected for the PFHAM study. The avulsion history of the four PFHAM fan evaluation sites and Tiger Wash are documented and described in Appendix I. It is likely that there are other examples of major avulsions in Maricopa County, but no comprehensive evaluation of avulsion frequency or occurrences has been made. Historical records clearly indicate that avulsions do occur on the types of alluvial fans found in Maricopa County. The data available indicate that avulsions are relatively rare events, and that they are often associated with the occurrence of large floods. However, further documentation of the avulsion history of local alluvial fans is warranted to better assess the recurrence interval and frequency of avulsions. Almost all of the known causative factors for avulsions exist on alluvial fans in Maricopa County, and thus it is likely that avulsions will continue to occur in the future.

While there is much yet to be understood about avulsion prediction, avulsion frequency, and avulsion mechanics, there is general consensus about many of the factors that are conducive to forming avulsions (Table 14). Because of the number of variables that affect the occurrence of avulsions, accurate prediction of their occurrence may always elude modelers. Similarly, any given avulsion may be caused to some degree by a large number of variables.

Other important considerations in assessing the cause of alluvial fan avulsions include the following:

- Aggradation is a necessary condition for riverine avulsions (Slingerland & Smith, 2004). Most avulsions occur on aggrading landforms or channels.
- Overbank flooding is a necessary condition (Slingerland & Smith, 2004) for avulsions. Therefore, avulsions tend to occur during large floods (Wells & Dorr, 1987; Field, 2001; Pearthree, 2004). However, not all large floods cause avulsions (Pearthree et. al., 1992; Whipple et. al., 1998; Field, 2004), even if conducive set up conditions exist (Tornqvist & Bridge, 2002).
- It is important to distinguish between the set-up conditions (those conducive to avulsion) and the triggering event (e.g., a flood, debris blockage, or bank failure).
- The radial topographic pattern is evidence that avulsions have occurred (Beaty 1963). Avulsions on alluvial fans will tend to be directed toward topographically lower areas, i.e., slopes steeper than the parent channel, in areas that haven't received recent sediment deposition (Hooke 1967).

Table 14. Physical Variables Which Affect Alluvial Fan Avulsions	
Factor	**Comments**
Fan Physiography	
• Fan Slope	Steeper fans experience more frequent avulsions (P)
• Floodplain morphology	Size and configuration of invaded flood basin (SS)
• Floodplain vegetative cover	Affects conveyance and resistance (SS, M)
• Erosion resistance	Less cohesive floodplain soils more prone to avulsion (SS)
• Presence of existing channels	Overbank flows exploit on-fan flow paths (SS, F)
• Wide, unobstructed floodplain	Open conveyance more conducive to avulsions (SS)
• Drainage area	Large drainage area generates higher peaks and volumes (P)
Discharge	
• Size and duration of avulsion	Large, long overbank flows form more complete avulsions (SS)
• Flood magnitude	Large peaks after proper set-up condition (SS, F)
• Frequency	Floods are of limited duration, avulsions at finite rate (SS)
• Flood ratio	High flood ratio watersheds prone to high overbank floods
• Flood volume	High flood volume capable of more geomorphic work (P)
• Flood sequence	Sequence of floods important for set-up conditions (F)
Channel Pattern	
• Outside of bends	Avulsions more likely on outside of bends (SS, F)
• Sheet flooding	Avulsions likely in sheet flooding areas (F)
• Splays	Avulsion likely in braided channel splays (F)
• Near channel tributaries	Piracy more likely when channels close to parent (F)
Sediment Transport	
• Sediment partitioning	Between parent and avulsion affects closure rate (SS)
• Suspended sediment	Initial overflow high in water column, is sediment deprived (F)
• Bed material load	Occurs on channel bottom, deep avulsions only (SS)
• Small floods aggrade	Results in set-up conditions, loss of capacity (F)
• Total supply	More sediment supply, more frequent avulsions (SS)
• Debris flow potential	Avulsions common on debris flow fans
Breach Geometry	
• Avulsion vs. parent bed elevation	Sediment distribution affected, rate of completion (SS, F)
Slope	
• Downstream vs. cross slope	If slope ratio > 5 avulsion will occur (SS)
Channel Conditions	
• Low bank height; channel depth	Low bank height causes overbank flow (F, SS)
• Aggrading	Main channel aggradation lowers capacity (SS)
• Debris blockage	Lowers capacity (SS, F)
• Bed elevation vs. overbank	Overbank flow needed for avulsion (SS)
• Bank vegetation	Increases channel stability, leads to aggradation (SS, S)
• Height of alluvial ridge	Inversely related, higher ridge when overtopped avulses (SS)
• Bank stability	Directly related (M, S)
Allogenic Factors	
• Change in sediment supply	Increased sediment supply increases avulsion risk (S)
• Change in water supply	Increased water supply increases avulsion risk (S)
• Change in base level	Initiates regional aggradation or degradation (S)

References:
SS = Slingerland & Smith, 2004 F = Field, 1994; 2001 S = Southamer, 2007
M = McCarthy et. al., 1992 P = Pearthree et. al, 2004 M = Mohrig, 2000

There have been few published studies of avulsion frequency, and fewer still that are applicable to alluvial fans in Maricopa County. The following statements summarize the current understanding of avulsion frequency:

- Field (1994) estimated a 50 to 650 year return period for avulsions at five active alluvial fan sites in central and southern Arizona. His estimates were based on interpretation of historical and recent aerial photographs, post-flood inundation mapping, interpretation of soil trench profiles, and limited radiocarbon dating of organic material from two sites.
- Kesel and Lowe (1987) estimated an avulsion recurrence interval of several hundred years for humid region alluvial fans, based on radiocarbon dates.
- Parker et. al. (1998), Whipple et. al. (1998), Schumm et. al. (1987), and Hooke (1967) found that avulsions occurred rapidly and continuously in physical modeling studies of alluvial fans.
- Pelletier et. al. (2005) noted that rapid avulsions occur on a decadal time scale, with a lower frequency on fluvial fans compared to debris flow fans.
- Pearthree et. al, (1992) found that 13 of 19 off-channel soil pits on the Tortolita piedmont near Tucson, Arizona had channel deposits that could be at least tentatively interpreted as evidence of past avulsions.
- DMA (1985), in their verification analysis of FEMA's FAN model (Dawdy, 1978), determined that avulsions occurred on 18 sites in California and Nevada. However, inspection of their records as part of this study indicates that as few as two of the 18 sites had solid evidence of avulsions. DMA further reported that the avulsion coefficient of 1.5 in FEMA's FAN model means that a major avulsion occurs in every other 100-year event.
- Slingerland & Smith (2004) report avulsion frequency ranges from 28 years on the Kosi River in India to 1400 years on the Mississippi River, but that rates may be less in glacial outwash streams and more on non-aggrading rivers.

A number of methodologies to predict avulsions on active alluvial fans were explored as part of this study, and are summarized in more detail in Appendix I. These methodologies attempted to identify two types of avulsive characteristics: (1) non-channelized portions of an active fan surface in which formation of an avulsion is likely, or (2) portions of the existing channel network that are ripe for being abandoned by avulsive processes. The results of these analyses were verified by comparing their predictions to conditions observed in the field and on aerial photographs, as well as by comparing their results to channel changes observed during known avulsive floods on White Tanks Fan 36 and the Tiger Wash alluvial fan. The following methodologies were applied to the four alluvial fan evaluation sites:

- Interpretation of Historical Aerial Photographs
- Field Methods for Identifying Avulsions
- FLO-2D 100-Year Models
- FLO-2D Extreme Flood Models
- FLO-2D Depth-Velocity Zones
- FLO-2D Hazard Classification
- FLO-2D Virtual Levee Scenarios
- FLO-2D Sediment Transport Models

- FLO-2D Channel Blockage Models
- Topographic Analysis: Avulsive Flow Path Models

Based on the results of the analyses and information summarized above, the recommended procedure for evaluating the potential for avulsions on active alluvial fans in Maricopa County consists of the following steps:

- Step One: Historical Analysis. The most reliable means of determining if an alluvial fan is subject to avulsions is to identify evidence of historically recent avulsions. Documentation of past avulsions can be completed by comparing channel locations and conditions on historical and recent (or pre- and post-flood) aerial photographs. In addition to the presence of historical avulsion, the extent, location on the fan surface, and types of avulsions should be described and related to the flood history.

- Step Two: Geomorphic Analysis. An evaluation of the surficial geology of the alluvial fan should be conducted that includes field observations, surficial mapping of active and inactive surfaces, and assessment of debris flow potential. If possible, the geomorphic analysis should include interpretation of stratigraphic data from subsurface soil profiles to estimate fan aggradation rates and occurrence of channel sediments outside the existing channel corridors. If debris flows have the potential to impact that active fan surface, then a detailed debris flow analysis should be conducted using the procedures outlined in Section 2.6 and Appendix H, prior to proceeding to Step Three.

- Step Three: FLO-2D Modeling. FLO-2D models of the fan surface from the hydrographic apex to the downstream limit of the active alluvial fan should be prepared. At minimum, FLO-2D models for the 100-year base condition and a 500-year "extreme flood" should be prepared. Potentially avulsive flow corridors can be identified by overlaying 100- and 500-year FLO-2D flow depths and velocities and hazard classification zones over a recent aerial photograph and identifying disparities from the existing channel network. For specific sites where concerns about avulsion exist, channel blockage FLO-2D models can be prepared to estimate overflow frequency and behavior. Finally, FLO-2D modeling results should be used to prepare an avulsive flow path model analysis.

- Step Four: Sediment Modeling. The sediment yield at the hydrographic apex should be computed and used to estimate potential deposition along the fanhead channel. The sediment yield values should be used to help identify the location of the hydrographic apex as the point where flow is no longer contained in a single channel, and where alluvial fan flooding begins. At some point in the future, improvements in sediment transport modeling tools for alluvial fans may progress to the point which such modeling will improve our ability to predict alluvial fan avulsions. Until such time, detailed sediment transport modeling of the alluvial fan downstream of the hydrographic apex should be used only to identify broad sedimentation trends and likely locations of single-event sediment deposition or possible changes in flow distribution on the fan surface.

- Step Five: Floodplain Delineation. The potential for future avulsions should be considered when delineating an active alluvial fan floodplain. To this end, the virtual levee scenario method results should be incorporated into the predicted inundation limits.

The avulsion analysis task identified the following three primary gaps in the knowledge base required to develop a robust methodology for quantifying alluvial fan flood hazards in Maricopa County:

1. Avulsion Frequency. To resolve this knowledge gap, the District should conduct a study of avulsion frequency on active alluvial fans in Maricopa County, as recommended by the Blue Ribbon Panel.
2. Modeling Methodology. To address the lack of a universally accepted methodology for evaluating avulsion potential, the District should adopt the recommended methodology presented in this report as a first step. Subsequent steps include testing the methodology on alluvial fans in Maricopa County and vetting the methodology with FEMA.
3. Engineering Design Standards. The District should include engineering and design guidelines for development on active alluvial fans in the updated PFHAM.

2.7.1. Conclusions

The objective of the avulsion potential evaluation was to determine and quantify how channel avulsions influence flood hazards on alluvial fan landforms in Maricopa County. This information is to be used to refine the Integrated Alluvial Fan Hazard Assessment Methodology that may be used in future revisions of the District PFHAM methodology. The following conclusions can be made from the evaluation summarized in this report:

- Avulsions Occur on Alluvial Fans In Maricopa County. The occurrence of past alluvial fan avulsions on alluvial fans in Maricopa County is well documented in the literature, by past District studies, and by aerial photographs.
- Avulsion Frequency. The frequency of avulsions on alluvial fans in Maricopa County is not well known, although it is likely that avulsions are relatively rare events. A systematic study of avulsion frequency is strongly recommended. If avulsions are found to be sufficiently rare, avulsions could be eliminated from the recommended integrated methodology, greatly simplifying the required analyses. If avulsion frequency is better quantified, it can be more precisely evaluated.
- Avulsions Affect Flood Hazards on Alluvial Fans. When avulsions occur, they change the distribution of flood peaks and volumes downstream, lead to extensive erosion of the fan surface, and redistribute areas of sediment deposition. Consideration of avulsion impacts should be included in any revisions the District's PFHAM methodology.
- Methodology. There is no broadly accepted technique for identifying and predicting the location or nature of future avulsions. A multi-step methodology for use on alluvial fans in Maricopa County has been proposed as part of this study

3. General Recommendations

3.1. Recommended Definitions of Terms

One of the key findings of the PFHAM study is the importance of using terminology precisely when discussing alluvial fan flood hazards. This is especially true for the term "alluvial fan." Because of the high potential for miscommunication when dealing with regulatory agencies, it is strongly recommended that the current NFIP and FEMA definitions be used for the terms listed in Table 15. This approach will also assure conformity with the rest of the floodplain management community. However, the District should work with FEMA in conjunction with other affected communities to improve FEMA definitions and guidance, where needed.

3.1.1. Definition of Alluvial Fan

The PFHAM scope of services calls for "clear administrative guidance based on technical definitions of what is an alluvial fan." Within the floodplain community, there is near universal agreement that an alluvial fan landform can be defined or identified by the following three criteria:

- Composition. An alluvial fan is a sedimentary deposit composed of alluvium.
- Morphology. An alluvial fan has the shape of fan.
- Location. Alluvial fans are usually located at mountain front or topographic break.[18]

The three criteria listed above are technically sufficient to allow any competent investigator to be able to identify an alluvial fan landform. Unfortunately, there is not universal agreement on how to identify an <u>active</u> alluvial fan. The differences in opinion on how to define an active alluvial fan stem mostly from the floodplain management consequences of delineating an area as an active alluvial fan floodplain. Absent the NFIP insurance regulations for development in areas subject to alluvial fan flooding (e.g., elevation on fill is normally insufficient to remove the insurance requirement), there is general agreement on the defining characteristics of an active alluvial fan. The key characteristics of active alluvial fans include the following:

- Location on an alluvial fan landform
- Flow path uncertainty
- Net depositional environment
- Geologically young surface where flooding is possible

Disagreements over what constitutes an active alluvial fan come primarily from the third aspect of the NFIP definition of active alluvial fan flooding: "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." The key (and most perplexing) term in the quoted portion of the NFIP definition is "ultrahazardous."

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[18] See NRC (1996; cf p. 55 and Examples, p. 83-125) for further discussion of what constitutes a topographic break.

Table 15. Existing FEMA Definitions of Key Terms		
Term	**NFIP or FEMA Definition**	**Comments**
Alluvial Fan	An alluvial fan is a sedimentary deposit located at a topographic break such as the base of a mountain front, escarpment, or valley side, that is composed of streamflow and/or debris flow sediments and has the shape of a fan, either fully or partially extended. (FEMA Appendix G, p. G-6)	This is the definition of the alluvial fan landform. The definition in the Maricopa County Floodplain Regulations uses the old NFIP definition.
Active Alluvial Fan	The term active refers to that portion of an alluvial fan where deposition, erosion, and unstable flow paths are possible. If flooding and deposition have occurred on a part of an alluvial fan in the past 100 years, clearly that part of the fan can be considered to be active. (FEMA Appendix G, p. G-8)	It is recommended that the District work with FEMA to clarify contradictory language in the FEMA Guidelines regarding the defining criteria for active alluvial fans.
Alluvial Fan Flooding	Alluvial fan flooding means flooding occurring on the surface of an alluvial fan or similar landform which originates at the apex and is characterized by high-velocity flows; active processes of erosion, sediment transport, and deposition; and, unpredictable flow paths (44 CFR, Part 59.1)	This is the only definition currently in the NFIP Code of Federal Regulations.
Active Alluvial Fan Flooding	An active alluvial fan flooding hazard is indicated by the following three related criteria: 1) Flow path uncertainty below the hydrographic apex; 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; 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. (FEMA Appendix G, p. G-2)	This definition closely parallels the "active alluvial fan hazard" definition in the Maricopa County Floodplain Regulations. "Active alluvial fan flooding" applies only to the ultra-hazardous portions of the floodplain of an active alluvial fan. Part 65.13 conditions apply to ultrahazardous areas.
Active Alluvial Fan Floodplain	The extent of the 1-percent-annual-chance (100-year) flood within any floodprone area on an active alluvial fan identified during Stage 2. (FEMA Appendix G, p. G-11)	Only a portion of the active alluvial fan is within the regulatory floodplain.
Inactive Alluvial Fan	For a given area of the alluvial fan, if the situations described in Subsection G.2.2.1 do not exist, then the area is considered inactive and not subject to the deposition, erosion, and unstable flow path flooding that builds alluvial fans. (FEMA Appendix G, p. G-9)	This definition basically states that inactive fans are those that do not meet the definition of active, i.e., inactive = not active.
Inactive Alluvial Fan Flooding	Inactive alluvial fan flooding is similar to traditional riverine flood hazards, but occurs only on alluvial fans. (FEMA Appendix G, p. G-2)	Flooding on inactive alluvial fans can be addressed using riverine modeling techniques. Stable distributary flow areas may require fixed-bed 2d modeling.

Table 16. Definitions of Key Terms Not in FEMA Guidelines		
Term	**NFIP or FEMA Definition**	**Comments**
Alluvial Plain	Not defined in NFIP or FEMA Appendix G. Defined in PFHAM Glossary as "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."	Note that alluvial plains can occur on alluvial fan landforms, or may be a unique landform type. See discussion below regarding District interpretation of alluvial plain.
Uncertain Flow Path Flooding	A broad category of flooding in which the location of channels and/or the distribution of flooding across a landform cannot be known with certainty.	See NRC (1996)
Sheet Flooding	Any broad expanse of unconfined runoff moving downslope.	See Section 2.1.3 & Appendix C
Distributary Flow Areas	Any landform on which the drainage pattern consists of channels that split, divide, or branch in the downstream direction.	May be stable (flow paths not subject to avulsion) or unstable (uncertain flow path).
Mountain Front	A line defined by the intersection of the steep sloping bedrock mass of a mountain range with the flatter sloped piedmont.	The alluvial fan landform topographic apex is usually located at mountain front.
Re-Infiltration	The continued infiltration of surface runoff as it moves across a land surface, as distinguished from the initial infiltration that occurs as an element of rainfall losses.	Term defined for use in this report. See Section 2.3.2.
Major Avulsion	A major avulsion occurs near a hydrographic apex and has the potential to divert more than 50% of the flow from the parent channel.	See Section 2.7 and Table 13

Unfortunately, the guidance in FEMA Appendix G does little to clarify the intended meaning of "ultrahazardous." On the one hand, the definition states that active alluvial fan flooding reaches a level of hazard so great that elevation on fill cannot mitigate it. On the other hand, FEMA Appendix G (p. G-11) states the following, "Because such sheetflows [near the toe of the fan]...follow unpredictable flow paths, they are classified as active alluvial fan flooding." It is hard to reconcile the characteristics of sheet flooding (shallow, low velocity) found on much of the four alluvial fan sites in the PFHAM study with an ultrahazardous condition for which elevation on fill would not mitigate the risk.

The FEMA Guidelines further complicate the definition of "active alluvial fan," stating that an active alluvial fan may include older alluvial fan surfaces where areas upstream could lead to sheet flood across the surface (p. G-9, 3rd bullet), or parts of the alluvial fan where flooding and deposition have occurred in the past 1,000 years (p. G-8). Comparison of these criteria to riverine conditions is problematic since elevation on fill is considered a reliable means to mitigate flood risk in shallow, low velocity riverine floodplains (and even in deep, high velocity riverine floodplains).

The resolution to these apparently contradictory definitions may be found in the difference between the terms "active alluvial fan flooding" and "active alluvial fan." The NFIP only defines "active alluvial fan flooding," which refers to the actual floodplain delineation (i.e., Zone A determined during Stage 3 of the delineation process). The term "active alluvial fan" is described in FEMA Appendix G and refers to the second stage of the floodplain delineation process. An active alluvial fan, per se, is not regulated by

FEMA. Active alluvial fan flooding, which may occur on a portion of the active alluvial fan, is regulated by FEMA, and consists of the portion of the floodplain that has "ultrahazardous" conditions. Therefore, there must be parts of an active alluvial fan that are subject to a one percent risk of inundation that are not ultrahazardous and thus not subject to "active alluvial fan flooding." This interpretation is consistent with the conclusion of the NRC Report (1996), as well as the opinions of the members of the NRC Alluvial Fan Committee who participated in the PFHAM Blue Ribbon Panel (See Section 4.7 and Appendix J).

To resolve the question regarding definition of active alluvial fans, it is recommended that the District take the following actions:

- FEMA Coordination. The District should work with FEMA to clarify apparent contradictions in FEMA Appendix G guidance. Specifically, differences between "active alluvial fans" and "active alluvial fan flooding" should be clarified. One potential avenue for FEMA coordination is the Association of State Floodplain Managers (ASFPM) Arid Regions Committee White Paper (ASFPM, 2010) recommending improvements to FEMA Appendix G. The District should participate in and support the ASFPM effort, and encourage the Arizona Floodplain Management Association (AFMA) and other local communities to do so as well.
- District Definition. The District should make an affirmative statement that active alluvial fan flooding applies only to the areas of ultrahazardous flood conditions on an active alluvial fan. That is, there are portions of active alluvial fans that are not subject to ultrahazardous flood conditions, and these areas should be distinguished as such.
- Quantify Ultrahazardous. The District should use the USBR Figure 2 hazard classification criteria, as outlined in Sections 2.3.3.9 of this report to define the portions of the active alluvial fan that are subject to ultrahazardous flood conditions.
- Inactive Alluvial Fan. The District should continue use the FEMA Appendix G definition of the term "inactive alluvial fan." Efforts to re-define "inactive" will create confusion in the Stage 2 delineation, as well as potential roadblocks for FEMA approval of the recommended methodology.

3.1.2. Definition of Alluvial Plain

The District also has concerns regarding definition of alluvial plains, and would like clear guidance on how to distinguish active alluvial fans from alluvial plains. Alluvial plains can occur on piedmont and alluvial fan landforms, but are most commonly identified along river corridors. There is also an alluvial plain landform that is transitional in character (as well as spatially) between alluvial fan landforms and riverine alluvial plains. While it is relatively easy to distinguish riverine alluvial plains from piedmont landforms, these transitional alluvial plains are not easily distinguished from alluvial fan landforms as there is generally an irregular, gradational boundary between the alluvial fan and the piedmont alluvial plain. Normally, smaller alluvial plain surfaces that occur on the piedmont are considered part of the alluvial fan landform, as indicated by the last part of the PFHAM definition[19] of alluvial plain.

Some of the defining characteristics of alluvial plains include the following:

- Smooth or gently undulating terrain
- Dominated by unconfined, non-channelized flow, which may consist of sheet flooding or shallow overbank flooding
- Uniform vegetative characteristics
- Lack of well-defined channels or flow paths
- Fine-grained sediment substrate
- Non- or marginally erosive velocities
- High rates of flow attenuation due to extensive floodplain storage and infiltration
- Parallel rather than radial contour pattern
- Location far enough from a mountainous watershed that the dominant flow originates on the alluvial surface itself, though some contribution of runoff from a distant mountainous watershed is possible

Note that some of the characteristics listed above also apply to some alluvial fans. In practice, there is a very gradual transition from an active alluvial fan to an alluvial plain on a piedmont landform for which no clear demarcation may exist. FEMA Guidelines indicate that sheet flooding on an alluvial fan landform is alluvial fan flooding. Therefore, the occurrence of sheet flooding is not a reliable diagnostic characteristic for distinguishing alluvial fans and alluvial plains.

This study evaluated ways to demarcate a boundary between an alluvial plain and an alluvial fan landform both in Stage 1 and Stage 2 of the delineation process. While this can easily be done at Stage 1 for boundaries between riverine alluvial plains and alluvial fan landforms, it would be problematic in Stage 2 when attempting to demarcate an active alluvial fan from an alluvial plain on an alluvial fan landform. If the motivation for making this distinction in Stage 2 is to minimize the area that could be classified as subject to "alluvial fan flooding," as that term is currently defined by FEMA, then the approach outlined in Section 3.1.1 above may circumvent the need for such a distinction. If not, there are a number of challenges to delineating a physical boundary between alluvial plains and active alluvial fans on alluvial fan landforms, including the following:

- There is no established regulatory procedure for making such a distinction.
- Descriptions of the two features in the literature are not precise enough to eliminate subjectivity in such a delineation.
- Alluvial plains and the toes of active alluvial fans have similar characteristics (sheet flooding, planar topography, parallel and distributary drainage paths, etc.)
- It is clear from the literature that neither alluvial plains nor active alluvial fans are identified based solely on slope. While alluvial plains typically have flat slopes (< 2%), alluvial fans described in the literature have slopes ranging from far less

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[19] PFHAM Glossary: An alluvial plain is 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 (p. 164).

than 1% to well above 10%. By itself, slope is not a diagnostic feature for distinguishing alluvial plains and alluvial fans.

As the District completes more alluvial fan floodplain delineations and collects more data, it may be possible to define measurable characteristics that can be used to distinguish active alluvial fans from alluvial plains in Maricopa County. Possible parameters for consideration include developing a relationship describing the geometric change of slope in the downfan direction, measurements of drainage density, or other forms of contour analyses. At this time, sufficient data do not exist.

Because of the similarities between active alluvial fans and alluvial plains located downstream of active alluvial fans, it is recommended that the proposed integrated methodology be applied to both feature classifications. The similarities include the following: (1) both are subject to uncertain flow paths, (2) both are subject to uncertain flow rate, and (3) neither is subject to ultrahazardous flood conditions.

3.2. Recommended Design Frequency

The 100-year (1%) design frequency is recommended for regulation of alluvial flood hazards in Maricopa County for the following reasons:

- FEMA Standard. The 100-year event is firmly established in federal regulations as the standard of design for floodplain management. Deviation from the federally-mandated minimum criteria would require broad political support. NFIP member communities are allowed to adopt more stringent standards.[20]
- Maricopa County Standard. The 100-year event is the standard of regulation and design for all other types of floodplains in Maricopa County. This study has documented that although alluvial fan flooding hazards are different than riverine floodplain hazards, they are not so hazardous as to require a different design standard. The unique aspects of alluvial fan flooding in Maricopa County can be addressed by applying the integrated technical approach outlined in this report.
- Maricopa County Cities and Towns. Use of a higher design standard may complicate District involvement with the regulatory policies and flood control planning with other Maricopa County incorporated communities.
- State of Arizona Criteria. No other community in Arizona currently regulates anything other than the 100-year event. All of the ADWR State Standards are based on the 100-year flood.
- Regulatory Authority. It is not clear whether the State of Arizona's floodplain management enabling legislation would allow Maricopa County to use a higher design standard without action by the State Legislature. This matter should be discussed with the District's legal counsel.
- Technical Criteria. While there are hazards that are unique to alluvial fan floodplains in Maricopa County, no technical bases were identified that would justify raising design standards for alluvial fans. Attempts to replace some of the recommended procedures with 500-year and PMP-based floods were found to inadequately depict the flood hazard.

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[20] The State of California recently adopted a 200-year standard of design for levee floodplains.

- Debris Flows. Some communities in North America and Europe regulate debris flow hazards using a 200-year or higher design standard. However, the PFHAM study determined that debris flows were not a significant risk for alluvial fan flooding in Maricopa County. Therefore, for the few instances in which there is a risk of debris flow, a site-specific analysis of those hazards using the procedures outlined in this report is recommended.
- Distributary Flow Areas. No technical basis for applying a different design standard for distributary flow floodplains was identified during the course of this study. The 100-year event is recommended as the standard of design.
- Risk-Based Analysis. As an alternative to the 100-year design standard, the District could follow the lead of some federal agencies and move toward risk-based design. Risk-based analysis of alluvial fan flooding is already one of the approved methodologies listed in the FEMA Guidelines (2003, Appendix G, Table G-1).

It is recommended that the District follow FEMA guidance for selecting the regulatory design standard for alluvial fan flooding. Currently, the 100-year event is the standard of design.

3.3. Engineering Tools for Alluvial Fan Flood Hazard Assessment

Task item 2.9.3.1 of the PFHAM study scope of work requires that a matrix or list of engineering tools and methodologies be recommended for assessing the type and degree of flood hazards on alluvial fans landforms in Maricopa County. The recommended engineering tools matrix is shown in Table 17 below. Note that Table 17 only lists the engineering tools, as directed by the District scope of work. Other tools may exist and may be added to the list in the future. A brief outline of how the recommended engineering tools listed in Table 17 can be applied is described in the following paragraphs. The description of the recommended Integrated Alluvial Fan Hazard Assessment Methodology in Maricopa County, that incorporates all the engineering, geomorphic, and other tools, is provided in Section 4.

Table 17. Recommended Engineering Tools for Alluvial Fan Flood Hazard Assessment

Discipline	Recommended Engineering Tool		
	Active Alluvial Fan	**Alluvial Plain**	**Inactive Alluvial Fan**
Hydrology	FLO-2D	FLO-2D	Current District Hydrology Manual
Hydraulics Whole Fan Local Site	 FLO-2D HEC-RAS	 FLO-2D HEC-RAS	 Current District Hydraulics Manual
Sediment Transport Whole Fan Local Site	 FLO-2D HEC-RAS, HEC-6	 FLO-2D HEC-RAS, HEC-6	 Current District Hydraulics Manual
Debris Flow	LAHAR-Z	Not applicable	Not applicable
Surficial Dating	Optical Stimulated Luminescence Cosmogenic Nuclide	Radiocarbon – AMS Varnish Microlamination	
Avulsions	FLO-2D Avulsive Flow Path Tool Sediment Yield (District)	FLO-2D	Not applicable

Note: FLO-2D was selected for use in the PFHAM study (See Section 2.3.3). However, any two-dimensional model with similar or superior capabilities may be used.

3.3.1. Hydrologic Modeling

The recommended engineering tool for hydrologic modeling of active alluvial fans and alluvial plains in Maricopa County is FLO-2D. Upstream of the hydrographic apex and on inactive alluvial fans, the current District modeling practices should be followed. HEC-1 or other lumped parameter, unit hydrograph flood routing models are not recommended for active parts of alluvial fans. There may valid reasons to select FLO-2D for modeling the entire watershed, as well as for the active alluvial fan area, but that decision should be coordinated with the District prior to beginning the modeling effort. A few of the reasons for using FLO-2D to model the hydrology of areas above a hydrographic apex might include: (1) better representation of spatial variation in watershed parameters, (2) simplification of the modeling process – use of one model instead of multiple models, (3) better accounting for attenuation and infiltration in low-sloping watersheds with poorly defined flow paths, (4) deficiencies in the unit-hydrograph approach for generating runoff in low-sloping watersheds with poorly defined flow paths, (5) presence of stable distributary or sheet flooding areas upstream of the hydrographic apex, and (6) presence of multiple poorly defined watersheds that contribute runoff to the active alluvial fan area downstream of the hydrographic apex.

In addition, the following special conditions should be considered for active alluvial fans:

- Virtual levee scenario method. The virtual levee scenario method should be used to estimate peak discharge at all points downstream of the hydrographic apex. Use of the full apex discharge is not recommended for design purposes. The maximum discharge from the cumulative virtual levee scenarios should be used for design purposes.
- Coalescing alluvial fans. Where one or more active alluvial fans coalesce, combination of discharges from adjacent fans should be estimated using the virtual levee scenario method.
- Future conditions. For planning studies, future condition discharges should be estimated by applying full-build out of the fan surface with normal retention requirements and whatever current District (or local community) development policies exist at that time.
- Flood conveyance corridor. For planning purposes, it may be useful to identify a flow corridor that could be used to convey upstream and local runoff from the hydrographic apex to the toe of the alluvial fan landform.
- Sheet flooding areas. Where runoff is expected to occur as unconfined sheet flooding, peak discharge estimates should reflect the total flow reaching the upstream boundaries of a site, or flow across the entire sheet flooding area, rather than the point discharge at a single concentration point or grid cell.
- Model sensitivity. Given the potential for uncertainty in hydrologic modeling, it may be necessary to run a number of modeling scenarios with different input parameters to build confidence in the final predicted results.

Other hydrologic modeling recommendations were provided in Section 2.3.2.4 of this report.

3.3.2. Hydraulic Modeling

The recommended engineering tools for (water-only) hydraulic modeling on active alluvial fans and alluvial plains are FLO-2D and HEC-RAS. The scenarios in which each model should be used are summarized in Table 18. In general, FLO-2D should be used for overall modeling of the fan surface, including estimation of peak (design) discharges. HEC-RAS should be used to estimate hydraulic parameters in individual channels at specific sites in most circumstances. The District employs this same division of hydraulic modeling tools in the highly distributary channel networks near the Rio Verde area in northern Maricopa County. However, if the District submits a floodplain delineation to FEMA with the Zone AE designation, the FLO-2D model results must be used to set finished floor elevations, per FEMA guidance. Additional freeboard should be provided to account for potential sediment deposition (aggradation), as discussed in Section 3.3.3 below.

Table 18. Selection of Hydraulic Modeling Tools

Modeling Scenario	Recommended Tool
Design Discharges	FLO-2D – virtual levee scenario method
Flow Distribution over Active Fan Surface	FLO-2D
Flow Distribution over Alluvial Plain	FLO-2D
Water Surface Elevations at Building Site	HEC-RAS* Use FLO-2D discharge Include sediment deposition
Hydraulic Design Data (depth, velocity, etc)	HEC-RAS Use FLO-2D discharge
Notes: * Unless delineation submitted as Zone AE. See text above for discussion.	

HEC-RAS (or any similar model) is preferred over FLO-2D for site-specific hydraulic analyses where the following conditions exist:

- The modeling reach has fine-textured topography that cannot be readily defined by grid-based topographic data. If HEC-RAS is used, topographic data and cross section spacing should be coded into the model in a manner that accurately portrays the subtleties of the local terrain.
- Flow is primarily one-dimensional and gradually-varied flow conditions exist.
- A single design discharge (steady flow) reasonably approximates flow conditions.
- Flow is conveyed in a relatively well-defined natural or engineered channel.
- The modeling reach is short enough that flow volume conservation is not a factor.

FLO-2D is preferred for the following types of hydraulic modeling exercises on active alluvial fans and alluvial plains:

- Determining flow hydraulics in broad sheet flooding areas
- Modeling of the entire alluvial surface
- Identifying preferred, alternative or avulsive flow corridors
- Identifying low relief "islands" within the active fan (use extreme flood discharges)
- Estimating impacts of development in active fan attenuation areas

3.3.3. Sedimentation Modeling

A variety of tools are recommended for sedimentation modeling on active alluvial fans and alluvial plains. First, prediction of sediment yield to the hydrographic apex should be completed using the procedures outlined in the District's Hydraulics Manual. Similarly, the District's Hydraulics Manual lists specific methodologies for the computation of scour that should be used in channel and site design. The PFHAM study did not identify any reasons to replace any of the District's currently approved methodologies for scour and sedimentation. Second, use of FLO-2D and HEC-RAS should be partitioned in a similar manner as described above for hydraulic modeling (Section 3.3.2). FLO-2D should be used in broad scale surface analyses, and HEC-RAS should be used for site-specific evaluations that meet the conditions listed above. Where sediment continuity modeling is needed, HEC-6 or HEC-6T is recommended.

The sediment modeling tasks performed for the PFHAM study led to the conclusion that FLO-2D results are sensitive to the transport function selected, and that sediment transport will affect the single event maximum flow depths and velocities, at least in the high hazard zones near the fan apex. Long-term sediment deposition and scour may similarly impact hydraulic conditions in the high hazard zone over longer planning periods. The study also identified the need to further refine the sediment modeling routines in FLO-2D and to collect data for calibration of its application to alluvial fans. Based on the results summarized in this report, use of the Zeller-Fullerton sediment transport equation is recommended, at least until more data are available from which to make a more refined evaluation.

For site specific analyses in the ultra-hazardous and high hazard portions of active alluvial fans, the District's current guidelines should be applied to estimate the potential for long-term aggradation at a proposed development, and the estimated deposition should be added to the water surface elevations as freeboard.

3.3.4. Surficial Dating

The recommended methodologies listed in Table 17 probably are better classified as quantitative geologic techniques, rather than engineering tools, but are described in this section because they are numerical techniques. These geomorphic dating tools may be used to better refine estimates of surface age, and therefore may inform on the degree of alluvial fan activity, as well as help distinguish between active and inactive alluvial fan surfaces. A combination of relative and numerical methods may be applied where more detailed age resolution is needed, in conjunction with conventional surficial mapping techniques, to most accurately determine surface age on alluvial fans in Maricopa County. OSL and AMS radiocarbon dating methods are the most applicable numerical dating methods for dating alluvial fan sediments on fan landforms in Maricopa County. Cosmogenic nuclide dating and varnish microlamination correlation are the most favorable methods for estimating surface ages. Varnish microlamination (VML) is a correlative method and should be evaluated further in Maricopa County. As noted in Section 2.5 and Appendix G, the recommended quantitative dating techniques have varying degrees of precision, and would be improved by development of a regional dating chronology for Maricopa County.

3.3.5. Debris Flow Assessment

This study concluded that debris flows are unlikely to impact regulatory flood hazards on alluvial fans in Maricopa County for two primary reasons: (1) they occur so infrequently or, (2) when they do occur they do not runout far enough to reach the hydrographic apex of the alluvial fan. Nevertheless, to complete the project scope of work a three-step procedure for evaluating debris flow potential and hazards was developed for use on piedmont surfaces in Maricopa County in the event that a debris flow hazard is identified at a specific fan site.

For evaluation of debris flow hazards, the recommended engineering tool is the LAHAR-Z model, as described in Section 2.6 and Appendix H. Again, this study found that it is unlikely that debris flows will impact flood hazards on active alluvial fans in Maricopa County. Furthermore, use of the LAHAR-Z model is recommended only after completion of more foundational analyses in the recommended multi-step process.

3.3.6. Avulsion Assessment

Two engineering tools are recommended as part of the assessment of avulsion potential on active alluvial fans: (1) FLO-2D and (2) an avulsive flow path tool, both of which are discussed in more detail in Section 2.7 and Appendixes F and I. A variety of FLO-2D modeling scenarios are used to help predict the location and occurrence of avulsions, including the following: (1) 100-year base models, (2) extreme flood models, (3) hazard classification models, (4) sediment models, and (5) channel blockage models. The avulsive flow path tool uses topographic data and FLO-2D flow vector data to identify potential avulsive corridors, as defined by slope and conveyance, which are located outside the existing channel network.

3.3.7. Limitations of the Geomorphic (Only) Approach

The overall recommendation of the PFHAM study is for a methodology that integrates engineering and geomorphic techniques to achieve a more robust, comprehensive analysis of flood hazards on active alluvial fans. The existing PFHAM methodology follows the lead of the NRC (1996) and FEMA Appendix G in relying heavily on geomorphic methodologies for delineating alluvial fan floodplains. However, over-reliance on geomorphic interpretation alone may result in the following weaknesses:

- Urbanized Alluvial Fans. It is difficult to apply geomorphic assessment techniques on urbanized alluvial fans for several reasons. First, urbanization obscures many of the natural landscape feature used to support a geomorphic assessment. Second, grading of the natural topography often accompanies urbanization, changing the natural distribution, rate and volume of runoff. Third, road and building construction typically obstructs, diverts and alters natural flood and sediment transport processes. Finally, urbanization usually alters the natural balance of sediment and water supply, resulting in significant changes to the pre-development stream morphology. Therefore, in urbanized or developing areas, it is more important to include engineering methodologies in the overall assessment procedures.
- Quantitative Results. As currently formulated, the geomorphology-based PFHAM methodology does not provide quantitative engineering data needed for

design of structures, implementation of structural flood control measures, and performance of standard floodplain management tasks such as setting safe finished floor elevations. Note that the existing PFHAM methodology was originally intended primarily for alluvial fan hazard zone delineation, not development of engineering design data.

- Subjectivity. While there are varying degrees of subjectivity in all types of engineering analyses, there is a relatively high degree of applied judgment inherent in the geomorphic methodologies in the current PFHAM manual that has complicated its implementation.
- Expertise. Use of geomorphic methodologies requires special training, extensive field experience, and understanding of natural surficial processes that are outside the practice of many civil engineers. Therefore, any methodology that relies solely on geomorphic expertise will be difficult to implement among practitioners without such skill sets.

3.4. Flood Hazard Classification Matrix

3.4.1. Flood Hazard Zones on Alluvial Fans in Maricopa County

Based on the results of the PFHAM study tasks, the project team was able to reach consensus and definitively conclude the following with respect to classification of flood hazards on alluvial fans in Maricopa County:

- Ultrahazardous Levels. It is possible, though unlikely, that there may be ultrahazardous flood zones that meet FEMA's criteria for "active alluvial fan flooding" on small portions of some alluvial fans in Maricopa County.
- Conveyance & Uncertain Flow Path Flooding. On alluvial fans in Maricopa County, there are areas characterized by channelized flow, higher flow depths and velocities, and uncertain flow paths which typically have higher flood hazards.
- Sheet Flooding & Ponding. On alluvial fans in Maricopa County, there are areas of relatively low flood hazards dominated by sheet flooding.
- Engineering Tools. There are engineering tools, such as FLO-2D, that are capable of predicting areas of high and low hazards on alluvial fans.
- Geomorphic Tools. There are geomorphic tools that are capable of identifying areas of high and low hazards on alluvial fans.
- Integrated Approach. The best way to evaluate alluvial fan flooding hazards is an approach that integrates engineering and geomorphic tools.
- Key Variables. There is a relatively small set of variables that are most important for predicting the degree of flood hazards on alluvial fans in Maricopa County.
- Floodplain Management. Floodplain management restrictions and guidelines for development on alluvial fans should reflect the degree of flood hazard.

Based on the criteria listed above, the District decided to use the hazard classification scheme described in Section 2.3.3.9 of this report as the basis for evaluating avulsion potential in alluvial fan flooding areas, and elected not to use the USBR hazard classification curves in the final recommended procedure. The final hazard classification selected by the District is based on FLO-2D estimates of flow depth, as summarized in Table 19, and the following additional criteria:

- 100-Year Discharge. If the 100-year peak discharge is less than 50 cfs, Maricopa County Floodplain Regulations dictate that the floodplain is not regulatory. Below the hydrographic apex of an active alluvial or on an alluvial plain, the 100-year discharge is measured as flow along individual defined channels or the sum of flow approaching the upstream boundary as sheet flooding.
- Debris Flow. All areas subject to debris flow hazards are deemed ultrahazardous zones, regardless of other criteria. The recommended procedures for identifying debris flow risk are outlined in Section 2.6 of this report.
- Avulsion. Portions of active alluvial fans at risk of major avulsions are considered high or ultrahazardous zones. The recommended procedures for identifying avulsion risk are outlined in Section 2.7 of this report. The following avulsion characteristics are used in Table 19:
    - Major avulsions occur near a hydrographic apex in areas of high flow depths and velocities, involve major channel relocations or formation of significant channels, or have the capability of diverting 50 percent or more of the hydrograph, and are often caused by excessive sediment deposition.
    - Minor avulsions occur in distal or medial portions of the active fan area, divert smaller parts of the parent channel flow, involve formation of new distributary linkages (as opposed to abandoning the parent channel), or occur in areas of medium or low flow depths and velocities, and are often caused by piracy or erosion.
    - Frequent avulsions occur with a less than 50-year recurrence interval.
    - Infrequent avulsions occur with a 50- to 200-year recurrence interval.
    - Rare avulsions occur with a greater than 200-year recurrence interval.
- Multiple Criteria. In the unlikely event that the criteria in Table 19 indicate different hazard levels, the highest hazard level should be used.

Table 19. Recommended Hazard Zone Classification Criteria (Applies only if Q100 > 50 cfs and FLO-2D Depth > 0.3 ft)

Hazard Level	Ultra-Hazardous (Active Alluvial Fan Flooding)	Areas of Conveyance & Uncertain Flow Paths	Areas of Sheet Flooding
Risk of Debris Flow	Yes	No	No
Avulsion Characteristics	Major - Frequent	Major – Infrequent Minor - Frequent	Minor - Infrequent Minor - Rare

Notes:
1. If the apex 100-year discharge is less than 50 cfs, the floodplain is non-regulatory, and no delineation is required.
2. If the 100-year depth from FLO-2D modeling is less than 0.3 ft, the floodplain is non-regulatory, and no delineation is required.

The following variables known to affect the severity of alluvial fan flooding were considered for use in Table 19 but were ultimately abandoned, for the reasons explained below:

- Fan Slope. The slope of the alluvial fan surface is both the result of and cause of the degree of flood hazard on alluvial fans. In general, steep alluvial fans are more hazardous than low-sloped alluvial fans. However, there are no widely accepted slope thresholds published in the literature or in practice that can be used to classify alluvial fan flooding hazards.

- Flow Depth. Flow depths in all of the plots of FLO-2D results in this report use depth category thresholds of 0.3 feet, 0.6 feet, and 1.0 feet (and above) because of technical references indicating that flows less than 0.3 feet deep tended to be non-erosive (i.e., non-avulsive). On that basis, flow depth was considered as one of the categories for the hazard zone classification criteria in Table 19. However, FLO-2D plots of discharge indicate that in some cases, areas of shallow flow (< 0.3 ft) may still convey discharges well in excess of the County's 50 cfs threshold. Also, it is noted that the FLO-2D depths reported represent averages over the grid cell width, and may underestimate actual maximum flow depths in channels smaller than the grid size. Therefore, to avoid discounting very real flood hazards associated with (predicted) low FLO-2D depths, use of depth alone as a criteria was initially discontinued. However, the District decided that flow depth shall be used as part of the FEMA floodplain classification.
- Watershed Area. In general, alluvial fans with large watersheds tend to have large peak discharges, which in turn result in more severe flood hazards. However, watershed area per se is not a factor for determining flood hazard. It is the flood discharges the watershed produces that affect flood hazard levels.
- Peak Discharge. Alluvial fans with large peak discharges tend to have higher hazard levels than alluvial fans with small peak discharges. However, it is really the flow depths and velocities which define the hazard, not the discharge alone. That is, a large discharge spread over a wide area at shallow depth is normally less hazardous than that same discharge when concentrated in a defined channel.
- Stream Power & Shear Stress. These variables definitely impact the ability of flooding to transport sediment, but for the purposes of assessing broad hazard classifications, they are adequately captured by evaluating flow depth and velocity.
- Distance from Apex. The degree of flood hazard generally decreases with distance from the hydrographic apex. However, no consistent relationship between flood hazard and distance from the apex was observed in the field, in post-flood observations, or in FLO-2D modeling results.
- Sediment Yield. Fans with high sediment yields to the fan apex tend to be more vulnerable to avulsions, and thus may have higher flood hazards. However, difficulties in predicting sediment yield, as well as sediment transport on active alluvial fans, make use of this variable problematic, at least using the currently available technology. The impacts of sediment delivery are adequately captured in the debris flow potential and avulsion analysis.
- Channel Capacity. Stream channels with low capacity (relative to the flow rate and sediment supply) on active alluvial fans are more prone to overflow and cause avulsions, and thus may be more hazardous than fans with higher capacity channels. However, channel capacity is adequately captured by the FLO-2D modeling used to establish the USBR hazard classifications. Channel capacity is also a factor in the avulsion potential analyses. Note that channel capacity is one of the key factors in identifying the location of the hydrographic apex.

The PFHAM study scope of work Task 2.9.2 requires that a "flood hazard classification matrix based on engineering parameters" be developed to distinguish the degree of alluvial fan flood hazards. A draft flood hazard classification matrix was presented to the District PFHAM task force at a brainstorming meeting on April 21, 2009. The original intent of the flood hazard classification matrix was to identify specific measurable or predictable characteristics indicative of the degree of flood hazard, such as flow depth, velocity, fan slope, stream power, shear stress, debris flow potential, watershed size, distance from the hydrographic apex, sediment transport capacity, flood frequency, avulsion potential, surface age, sediment yield, historical channel movement, and channel capacity.

In addition, the District identified the following necessary characteristics for the flood hazard classification matrix:

- Be simple, concise, implementable, and understandable
- Be usable by "journeyman" engineers and regulators
- Provide unambiguous regulatory guidance
- Contain specific criteria for defining hazards
- Support responsible and appropriate regulation
- Provide mitigation guidance
- Provide reliable, repeatable quantitative measures that address uncertainty
- Be technically supportable
- Include tools for different types of alluvial fan flooding hazards

The District PFHAM team also outlined a general description of what might constitute high and low hazard levels on alluvial fan floodplains in Maricopa County, as summarized in Table 20. While the descriptions of the characteristics listed in Table 20 are broadly informative, they are qualitative, and do not meet the District's goal of quantifying flood hazards on alluvial fan. Ultimately, while the highly detailed draft flood hazard classification matrix concept was used to guide the investigations summarized in Section 2 of this report, the final version evolved into the more simplified form shown in Table 19 for the following reasons:

- Variables. The large numbers of variables that affect the degree of flood hazard on active alluvial fans make application of a matrix too complicated and impractical.
- Precedent. No published information was identified that clearly and definitively categorized the degree of hazard relative to many of the specific variables considered.
- Consensus. The project team was unable to reach consensus on how to classify many of the variables as to the degree of hazard.
- Results. The results of the technical analyses performed for the PFHAM study pointed toward a more feasible way to classify flood hazards on alluvial fans in Maricopa County, as presented in Section 3.4.1 and Table 19.

Table 20. General Characteristics of High and Low Hazards on Alluvial Fan Floodplains in Maricopa County		
Characteristic	**Areas of Conveyance & Uncertain Flow Path Zones**	**Sheet Flooding & Ponding Zones**
Velocity	High	Low
Sediment Transport Capacity	High	Low
Channel Stability	Low	High
Debris Flow Risk	High	None
Drainage Area	Large	Small
Fan Slope	Steep	Flat
Distance from Mountain Front	Short	Long
Roads & Development	Affect Flooding	No Effect on Flooding
Danger to Life	Yes	No
Danger to Property	Yes	Some
Ease of Management	Difficult	Normal
Elevation on Fill Adequate	No	Yes
Sheet Flooding	No	Yes
Flood Control Measures	Regional	Site
Floodway	Yes	No

Discussion of how the hazard classification is incorporated into the overall recommended methodology is provided in Section 4.4.

3.5. Recommended Design Guidelines

Development on active alluvial fans should be designed so that structures are not damaged by the regulatory flood and so that it has no adverse impacts to adjacent properties. That is, development on active alluvial fans should be held to the same development standards in any other type of floodplain in Maricopa County. Because some flood hazards are unique to active alluvial fans, the flood hazard analyses techniques for hydrology, hydraulics, sedimentation, debris flow, avulsion, and floodplain delineation described above (Sections 3.3 and 4) should be applied, as outlined in Table 17 and Table 24. Some additional design guidelines for development on active alluvial fans include the following:

- Design Discharge. The 100-year event should be used as the standard of design, as discussed in Section 3.2 above. When determining adverse impacts, a range of discharges (Q2-Q10-Q100) should be considered to assure that impacts to adjacent properties do not occur either in frequent floods or the regulatory flood.
- Debris Flow Hazards. Debris flows are not a risk factor for the vast majority of alluvial fans in Maricopa County. However, if steep alluvial fans near mountain slopes vulnerable to mass movement are identified in Maricopa County, the portions of the alluvial fans vulnerable to debris flow impacts should be managed as ultrahazardous flood zones, and major engineered flood control mitigation measures should be mandated prior to any development.
- Analysis Required. In the areas of conveyance, uncertain flow paths, sheet flooding and ponding, no development should occur without a detailed engineering analysis that uses the flood hazard assessment methodologies described above, and that is sealed by an applicable Arizona registrant.

- Conveyance Corridors.[21] For large active alluvial fans where development is expected to occur, the District should identify conveyance corridors with sufficient right-of-way to convey flood discharges from the hydrographic apex to a downstream watercourse with sufficient capacity, and/or detention basin sites required to reduce peak discharges to meet downstream conveyance limits. Identification of conveyance corridors is fundamentally a planning activity, rather than a floodplain delineation task.
- FEMA Criteria. For development in mapped active alluvial fan floodplains,[22] the County has traditionally required that the FEMA floodplain be changed through the CLOMR/LOMR process. To revise a FEMA floodplain for an area subject to active alluvial fan flooding, the requirements of 44 CFR, Part 65.13 must be met, which include the following:
    - Elevation on fill alone *generally* (emphasis added) is not sufficient to revise a FEMA active alluvial fan floodplain delineation. Typically, major structural flood control measures are required.
    - Engineering analyses must be prepared that address the potential for erosion, scour, deposition, sediment, debris flow, and local inflow.
    - An operations and maintenance plan underwritten by a public agency is required for any structural flood control measures relied on to alter an active alluvial fan floodplain.
- Operations and Maintenance. Any structural measures relied on for flood control should have well-documented operations and maintenance plan that demonstrate continued safe functioning of the flood protection measures.
- Sheet Flooding Zone. Development in sheet flooding areas of active alluvial fans and alluvial plains may be allowed if the following criteria are met:
    - Runoff enters and leaves the developed area in the same manner as in pre-development conditions. This requirement may mean that a portion of some lots remain undeveloped.
    - Finished floors for single lot homes are elevated 2 feet above the 100-year water surface elevation.
    - Drainage openings are provided in any wall or obstruction of flow sufficient to prevent capture of sheet flooding and ponding that will adversely impact a structure.
    - Fill pads that may be impacted by off-site runoff should be protected against scour and erosion.
- Single Lot Development. The District should develop rules of development for single lot construction using the Rio Verde ADMP regulations as a template. Implementation of single lot development guidelines for active alluvial fans may require revision of the County Floodplain Regulations and/or development of a County-wide Area Drainage Master Plan for active alluvial fan areas.

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[21] Through-flow corridors are existing well-defined channels on active alluvial fans that convey flow from an active area toward the toe of the alluvial fan landform. Conveyance corridors may or may not follow existing through-flow corridor channels.

[22] The District intends that only the ultra-hazardous areas be subject to NFIP Part 65.13 criteria. Other (non-ultra-hazardous) parts of an alluvial fan floodplain would be subject to the NFIP Part 65.10 criteria.

- Performance assessment. The District should systematically monitor the performance of flood control measures constructed on active alluvial fans to provide feedback for refining and upgrading their design guidelines.

3.6. Recommended PFHAM Refinements

One of the primary objectives of the PFHAM study was to "make recommendations for updating the PFHAM."[23] Actual revision of the PFHAM, if necessary, will be completed by the District in the future. General recommendations for analyzing and quantifying flood hazards on active alluvial fans have been made throughout this report, and are summarized in Section 5 below. Recommendations specific to the PFHAM manual are provided in the following paragraphs.

3.6.1. Definitions

The definitions of terms used in the PFHAM Manual should be consistent with the definitions used in FEMA guidelines and NFIP regulations, as discussed in Section 3.1. The District should work with FEMA, ASFPM, AFMA, and other local communities to improve FEMA description and definition of an active alluvial fan (See Section 3.6.5).

3.6.2. Stage 1 Refinements

The following recommendations apply to the Stage 1 methodology as described in the existing PFHAM:

- Focus on Alluvial Fan Landforms. The PFHAM Stage 1 methodology should focus on distinguishing alluvial fan landforms from non-alluvial fan landforms. Identifying relict fans and pediments should be part of the Stage 2 (Active / Inactive) analysis.
- Simplify. Identification of alluvial fan landforms should be a relatively simple task that requires a minimal level of effort. The Stage 1 methodology should be simplified to the three basic criteria: composition, morphology, and location.
- Fan Boundaries. The guidelines for delineating the boundaries of alluvial fan landforms should be improved, particularly with respect to the following:
    - Identifying the toe of alluvial fan landforms
    - Identifying the boundaries of coalescing alluvial fans (bajada)
    - Identifying the topographic apex along embayed mountain fronts
- Alluvial Plains. Techniques for distinguishing alluvial plain landforms[24] from alluvial fan landforms should described, and examples should be provided. Note that because many alluvial plains are subject to flow path uncertainty due to unconfined sheet flooding, some of the floodplain analysis techniques for active alluvial fans described in this report may be more applicable than traditional riverine modeling techniques. Separate (Stage 3) floodplain delineation techniques for alluvial plains should be developed, perhaps as a separate chapter in the PFHAM.

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[23] PFHAM Study Scope of Work, Task 1.1.2.

[24] As opposed to alluvial plain surfaces on alluvial fan landforms, identification of which is part of the Stage 2 analyses.

- Countywide Delineation. The District should perform a Stage 1 landform delineation for the entire County, or at least the potentially developable lands within the County. This exercise could be completed with minimal effort, would provide valuable information on where alluvial fan flood hazards exist, and would be useful for District drainage master planning studies. The Stage 1 delineation could be incorporated into the floodplain information GIS available on the District's website.

3.6.3. Stage 2 Refinements

The following recommendations apply to the Stage 2 methodology as described in the existing PFHAM:

- Active/Inactive. The PFHAM should be written using the active-inactive terminology used by FEMA, the NFIP, and most other floodplain management agencies. The terms "stable/unstable" carry connotations related to development and are typically not used to describe undisturbed natural systems.
- Inactive Fans. Detailed discussion of types of inactive fans (relict, inactive, etc.) is unnecessary. Since the methodology currently only describes floodplain delineation techniques for active alluvial fans, the PFHAM Stage 2 methodology should focus on identifying active alluvial fans. Anything that is not an active alluvial fan simply falls out of the PFHAM process, and requires little, if any, detailed description. Any distinction between an inactive alluvial fan and relict alluvial fan is more of an academic exercise, and may not be relevant for floodplain delineation purposes, since both can be evaluated using delineation methodologies described in other District manuals.
- Stable Distributary Flow Areas. Criteria for distinguishing stable distributary flow areas from active alluvial fans should be developed and described. Guidelines for delineating flood hazards (Stage 3) on stable distributary flow areas also should be developed (See Section 3.6.5).
- Pediments. The discussion of pediments in the Stage 2 PFHAM methodology should be rewritten or removed. Pediments are geologic landforms characterized by sloping planar surfaces underlain by shallow or exposed bedrock. Pediments may have stable tributary drainage patterns (inactive), stable distributary drainage patterns (inactive), or small inset active alluvial fan floodplains (active). The presence of shallow bedrock, although interesting from a geologic perspective, may not affect surface flooding if it is buried by more than a meter of unconsolidated alluvium. Therefore, the PFHAM Stage 2 methodology should focus on whether active or inactive flooding occurs on a pediment, rather than on identification of the pediment itself. If there are unique floodplain characteristics on pediments that are substantively different from those on active or inactive alluvial fans, the recommended process for delineating such hazards should be discussed in a separate chapter of the PFHAM.
- Debris Flows. A discussion regarding debris flow potential on alluvial fans in Maricopa County should be added to the PFHAM, as well as a description of the recommended methodology to perform debris flow assessments for specific study areas where debris flow potential exists. When documenting the level of alluvial

fan activity (Stage2), the potential for debris flows is an important consideration for FEMA.

- Approximate vs. Detailed Method. A description of the recommended approximate and detailed Stage 2 methodologies should be added to the PFHAM.
- Countywide Delineation. The District should consider performing an approximate method Stage 2 delineation for the entire County. This exercise could be completed with a moderate effort, would provide valuable information on where active alluvial fan flood hazards exist that require special analysis techniques, and would be useful for District drainage master planning studies. The Stage 2 delineation could be incorporated into the floodplain information GIS available on the District's website.

3.6.4. Stage 3 Refinements

The following recommendations apply to the Stage 3 methodology as described in the existing PFHAM:

- Methodology. The existing PFHAM Stage 3 description should be rewritten to include the composite engineering and geomorphic methodologies outlined in this report, including both approximate and detailed methods.
- Flood Hazard Zones. The Stage 3 methodology should result in at least the following types of flood zones on active alluvial fans (See Table 19):
    - Ultrahazardous zone (may not occur on all fans in Maricopa County)
    - Areas of conveyance and uncertain flow paths
    - Areas of sheet flooding
    - Riverine through-flow corridors
- Active Alluvial Fans Flood Zones. The District needs to evaluate the local administrative zones for relationship to how they are currently administered.

Table 21. Hazard Classification vs. Floodplain Delineation Zone Designation

Hazard Classification	Detailed PFHAM Method	Approximate PFHAM Method
Ultra-Hazardous FIRM Panel FCDMC Work Map	 Zone A (Alluvial Fan) Administrative Floodway AFAN	 Zone A (Alluvial Fan) Administrative Floodway AFAN
Areas of Conveyance and/or Uncertain Flow Paths FIRM Panel	AE	Zone A (unnumbered)
Areas of Sheet Flooding & Ponding FIRM Panel	AE or AO1, Shaded X	Zone A
Riverine / Through-Flow FIRM Panel FCDMC Work Map	AE	Zone A

- Terminology. As recommended by some members of the Blue Ribbon Panel, the District may wish to consider different terminology for portions of active alluvial fans that does not meet the recommended ultrahazardous criteria, and thus does not meet the NFIP definition of "active alluvial fan flooding." For example, shallow or moderate depth uncertain flow path flooding on an active alluvial fan could be called "active piedmont flooding" or "uncertain flow path flooding." It is recommended that the District conduct additional coordination efforts with FEMA and FEMA technical reviewers to determine whether this approach has merit or would achieve the intended outcome.

3.6.5. General Refinements

In addition to the recommendations for each of the three stages of the PFHAM, the following general recommendations are made for the PFHAM:

- Examples. The example studies provided in the PFHAM (Chapter 5) should be updated to illustrate the integrated analysis techniques described in this report, and should closely follow the three-stage process outlined in the PFHAM.
- Appendixes. The existing PFHAM appendixes should be provided in a separate document to reduce the file size. Appendixes which contain copies of reports available elsewhere should be removed and simply listed in the bibliography.
- Alluvial Plain Chapter. The District should consider adding a new chapter to the PFHAM which describes how the recommended flood hazard assessment techniques described in this report could be applied to floodplain delineations on alluvial plains.
- Stable Distributary Flow Chapter. The District should consider adding a new chapter to the PFHAM which describes how to identify stable distributary flow areas, as well as the recommended method for estimating design discharges, hydraulic data, and floodplain limits on stable distributary flow areas.
- Pediment. If further analysis indicates that pediments have flood hazards that are substantively different from active alluvial fans, inactive alluvial fans, alluvial plains, and stable distributary flow areas, the District should consider adding a new chapter to the PFHAM specifically oriented at pediment surfaces.
- Debris Flow Assessment. A description of how to apply the recommended debris flow assessment technique to the Stage 3 delineation, for both approximate and detailed approaches should be added to the revised PFHAM.
- Sediment Modeling. A detailed description of how to incorporate the recommended sediment yield and sediment modeling approaches to estimate potential fan aggradation rates, impact on avulsion, fan activity, and flood hazards should be added to the revised PFHAM. In general, the sediment yield is used to predict the average fan aggradation rate, and the 100-year FLO-2D model results are used to: (1) identify potential avulsive flow paths, (2) determine differences in flow distribution and extent from the 100-year water-only FLO-2D models, and (3) identify area of more rapid sediment accumulation trends (or scour).
- Geotechnical Testing. Additional guidance on more detailed geotechnical testing such as erodibility measurements (cohesion, soil strength, material size, etc.) that could potentially be used to supplement more detailed Stage 3 analyses should be added to the revised PFHAM.
- FEMA Coordination. The Integrated Alluvial Fan Hazard Assessment Methodology described in this report is consistent with current FEMA guidelines and regulations. However, there are some possible differences in how some FEMA officials have traditionally interpreted their guidelines, as well as some needed clarifications of FEMA guidance. Therefore, it is recommended that the

District continue to work with staff from FEMA Region IX and FEMA headquarters to coordinate the findings of this study with ongoing efforts to update FEMA alluvial fan delineation and management practices. Specific coordination efforts should focus on the following:

  - Recognize that there are different types of active alluvial fans, such debris flow fans and fluvial fans.
  - Recognize that portions of active alluvial fans are subject to differing degrees of hazard, such as debris flows, channelized flow, avulsions, and sheet flooding.
  - Clarify terminology in Appendix G, specifically for that relating to characteristics of active alluvial fans and active alluvial fan flooding.
  - Improve technical guidance for delineating active alluvial fan floodplains.
  - Improve technical guidance for engineering support of CLOMR/LOMR requests on active alluvial fan flooding areas.
  - Recognize the importance of flow attenuation and infiltration on active alluvial fans.
  - Recognize the occurrence and importance of sheet flooding on active alluvial fans.
  - Recognize the need for continued training on alluvial fan methodologies.
  - Identify improvements in the alluvial fan review process to assure consistency and thoroughness.
  - Recognize the need to quantify the risk of avulsion on active alluvial fans.

- Engineering Analyses. The PFHAM should be expanded to include guidelines for engineering analysis of specific development sites. The current PFHAM is oriented primarily at floodplain delineation and does not directly address the types of analyses required to remove a site from an alluvial fan floodplain using structural methods, or how to design flood control mitigation measures in active alluvial fan floodplains.

4. Recommended Integrated Methodology

Revision of the existing PFHAM Manual is not part of the current PFHAM study scope of work. However, Task 2.9.3.2 of the PFHAM study does require preparation of a "decision tree that maps the engineering, investigation, and analyses required for flood hazard assessment and mitigation on alluvial fans." The recommended methodology represents the decision tree, also shown in Figure 64, which was developed using the following goals and assumptions:

- Quantified Flood Hazards. The recommended methodology should be (and is) based on engineering principles that are able to quantify the level of flood hazard on alluvial fan landforms.
- FEMA Guidelines. The methodology should be compatible with NFIP requirements (44 CFR, Chapter 1, Part 65.13) and FEMA Guidelines (Appendix G). The proposed integrated method is fully compatible with the composite methodology described in the FEMA Appendix G Guidelines.
- Maricopa County. The methodology is intended for use only in Maricopa County, Arizona. Application of the recommended methodology in other geographic areas may be possible, but was not specifically investigated as part of this study.

4.1. Methodology Overview

An overview of the recommended Integrated Alluvial Fan Hazard Assessment Methodology in Maricopa County is presented below. The outline follows the three-stage process developed in the NRC (1005) Report and adopted in FEMA Appendix G (2003), which can be summarized as follows:

- **Stage 1: Landform Identification**. In Stage 1, it is determined whether a study area lies on an alluvial fan landform, as opposed to a riverine floodplain or alluvial plain landform. Only alluvial fan landforms are advanced forward for analysis in Stage 2.

- **Stage 2: Definition of Active and Inactive Areas**. In Stage 2, the active portions of an alluvial fan landform are distinguished from inactive portions. Only the active portions of alluvial fan landforms are advanced forward for analysis in Stage 3.

- **Stage 3: Delineation of Regulatory Floodplain**. In Stage 3, the portions of an active alluvial fan that are subject to inundation during a 100-year flood is delineated. The result of the Stage 3 is a regulatory floodplain delineation map.

Identification of a study area as an alluvial fan landform (Stage 1) or an active alluvial fan (Stage 2) does not dictate any special requirements by FEMA. FEMA jurisdiction only extends to those areas delineated within the 100-year floodplain (Stage 3). The recommendation integrated methodology is illustrated on the decision tree shown in Figure 64.

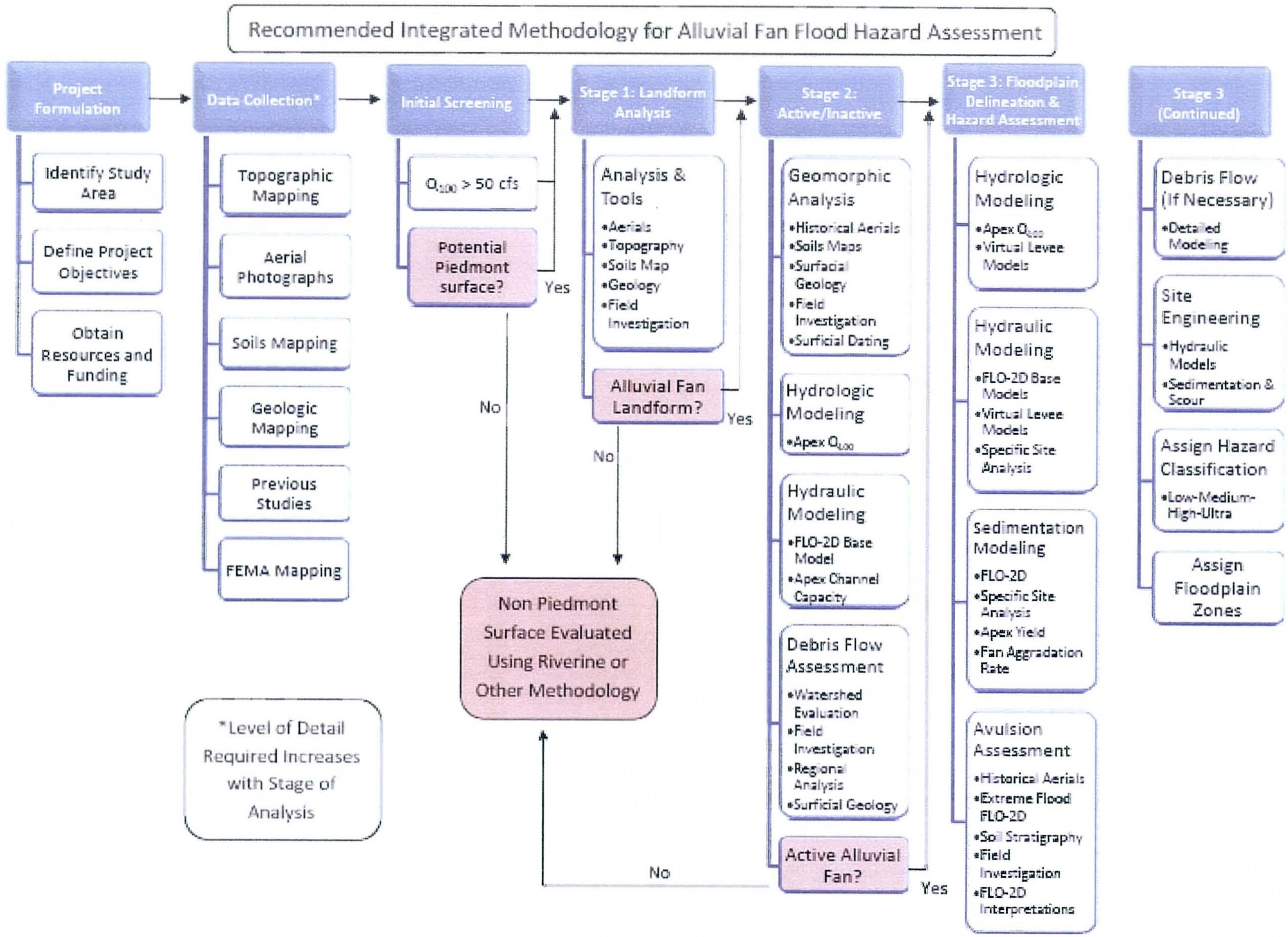

Figure 64. Decision tree illustrating the recommended Integrated Alluvial Fan Hazard Assessment Methodology for alluvial fans in Maricopa County.

4.2. *Stage 1: Landform Identification*

In the Stage 1 analysis, alluvial fan landforms are distinguished from other landform types. Other landform types that may occur in Maricopa County include mountains, riverine alluvial plains, piedmont alluvial plains, and riverine floodplains. The methodologies and tools required for a Stage 1 analysis are listed in Table 22. Suggested modifications to the existing PFHAM Manual Stage 1 procedures are provided in Section 3.6. Alluvial fan landforms are identified using the three basic criteria: (1) composition, (2) morphology, and (3) location.

Table 22. Overview of Stage 1 Methodology.
GOAL: IDENTIFY LANDFORM TYPE

Methodology	Tools
Interpretation of Aerial Photographs	Recent aerial photographs
Interpretation of Topographic Maps	USGS quadrangle maps (or other source)
Interpretation of Geologic Maps	Surficial or bedrock geologic maps
Interpretation of Soils Maps	NRCS soil survey map
Field reconnaissance (optional)	

As indicated in Table 22, the Stage 1 analysis is relatively straightforward, and can be completed by interpretation of aerial photographs, topographic maps, soils and geologic maps, and field reconnaissance. None of the elements of a Stage 1 evaluation can be readily quantified given the existing data sets for alluvial fan landforms in Maricopa County. Furthermore, use of additional numerical analyses, if any could be developed, would probably unnecessarily complicate the Stage 1 evaluation, which is intended to be a preliminary screening that generally should be accomplished with a minimal effort and resources. If a landform is identified as an alluvial fan landform in Stage 1, then it is advanced for a Stage 2 analysis. Other non-fan landforms can be evaluated using traditional floodplain delineation tools which are described in other Maricopa County manuals.[25]

4.3. *Stage 2: Definition of Active & Inactive Areas*

In the Stage 2 analysis, the active portions of an alluvial fan landform are distinguished from inactive portions. Definitions of active and inactive alluvial fans are discussed in Section 3.1 above. The recommended integrated methodology for Stage 2 includes an approximate and detailed approach, as shown in Table 23. The approximate method approach relies primarily on geomorphic techniques and is best applied where a coarse, non-quantified Stage 2 delineation is acceptable. The detailed method incorporates all of the approximate method techniques, but also includes a base two-dimensional model, as well as more detailed or quantified geomorphic, soils and geotechnical analyses. The detailed Stage 2 methodology requires a higher level of effort and expertise than the approximate method, and is therefore recommended in areas where finer distinctions between active and inactive areas are warranted, such as where the boundary between

[25] Note that some members of the Blue Ribbon Panel suggested that the recommended integrated methodology would probably be applicable to other landform types where flow path uncertainty exists.

active and inactive is not obvious and finer resolution delineation would eliminate the need for a detailed Stage 3 application.

Table 23. Overview of Stage 2 Methodology GOAL: IDENTIFY ACTIVE & INACTIVE PORTIONS OF ALLUVIAL FAN LANDFORMS	
Methodology	**Tools**
Approximate Method (Geomorphic)	
Interpretation of Aerial Photographs	Recent aerial photographs
Interpretation of Topographic Maps	USGS quadrangle maps (or other source)
Interpretation of Geologic Maps	Surficial or bedrock geologic maps
Interpretation of Soils Maps	NRCS soil survey map
Field Reconnaissance	Field equipment, maps and aerials
Debris flow potential assessment	Expertise in field, aerial & map interpretation
Surficial geologic mapping	Expertise in soils & geomorphology
Estimate apex channel capacity	Manning's equation, other hydraulic modeling
Estimate apex 100-year discharge	Regression equation, other hydrologic modeling
Detailed Method (Composite of Engineering & Geomorphology)	
All approximate method tools	See above
Hydraulic/hydrologic modeling	FLO-2D - may be simplified base model
Detailed soils mapping	Expertise in soil description & classification Trenching equipment
Detailed surficial geologic mapping	Expertise in geomorphology Field mapping tools
Detailed topographic mapping	Low contour interval mapping
Numerical surficial dating	Expertise in sampling & dating techniques AMD, VML, CND, TLD Access to specialized dating laboratories
Geotechnical testing of soil characteristics	Erodibility & resistance sampling equipment Expertise in geotechnical engineering Access to specialized testing laboratories
Debris flow potential evaluation	Expertise in field, aerial & map interpretation Expertise in slope stability & geomorphology

The objective of the Stage 2 analysis is to identify active and inactive portions of the alluvial fan landform. Therefore, the level of effort for each analysis type listed in Table 23 should be limited to the level required to achieve the objective. For example, at Stage 2, it is sufficient to determine that a risk of debris flow exists for the alluvial fan landform in question. It is not necessary to quantify the extent of the debris flow hazard, the potential runout distance, or potential flow volume. Similarly, FLO-2D models conducted for the Stage 2 analysis may be somewhat less refined than the FLO-2D modeling required for the Stage 3 hazard assessment. Thus, what might appear to be a duplication of effort between Stages 2 and 3 is actually a scaled level of effort that reflects the different objective of each stage of analysis. Likewise, the use of engineering analyses is incorporated into both the approximate and detailed Stage 2 methodologies, although the level of engineering analysis increases significantly for the detailed Stage 2 approach.

Descriptions of how to apply many of the recommended Stage 2 delineation techniques are provided in the existing PFHAM, and thus are not repeated in this report. A brief description of how the following methods that are listed in Table 23, but are not discussed in detail in the existing PFHAM, is provided below:

- Approximate Methods.
    - Debris Flow Assessment. Steps One and Two of the recommended methodology described in Section 2.6 and Appendix H of this report should be applied. Any areas found to be potentially subject to debris flow risk should be considered active.
    - Apex 100-Year Discharge. The 100-year discharge at the (potential) hydrographic apex may be estimated using any of the procedures outlined in the District Hydrology Manual. The 100-year discharge is then used as part of the analyses to define the location of the hydrographic apex.
    - Apex Channel Capacity. The channel capacity at the hydrographic apex may be estimated using Manning's equation. The channel just upstream of the hydrographic apex should contain the 100-year discharge, including any applicable freeboard to account for potential sediment deposition and/or sediment bulking. The hydrographic apex can then be defined using the channel capacity modeling in conjunction with surficial geology to demonstrate flow containment (lack of flow path uncertainty).
- Detailed Methods. The following detailed Stage 2 methods are similar to the approximate methods, but use more detailed, less generalized information, or are performed at a smaller scale:
    - Debris Flow Evaluation
    - Detailed Soils Mapping
    - Detailed Surficial Mapping
    - Detailed Topographic Mapping

  The following tools are unique to the detailed Stage 2 methodology:
    - FLO-2D Modeling. A base 100-year FLO-2D model can be used to generate rough estimates of the transition from channelized to sheet flooding, high depth and velocity zones versus shallow, low velocity zones, and the extent of inundation over the alluvial fan landform. Extensive interpolation and extrapolation of the FLO-2D results will be required to assure that the impacts of flow path uncertainty, avulsion, and sedimentation are not overlooked by use of a single event, single recurrence interval model. That is, one should avoid over-reliance on the Stage 2 FLO-2D results alone. The base FLO-2D model results can also be used to distinguish topographically low, older surfaces that can be flooded from topographically elevated older surfaces that can safely be considered inactive.
    - Numerical Surficial Dating. In some cases it may be beneficial to apply higher resolution numerical dating techniques (See Section 2.5 and Appendix G) to create a more refined geomorphic surfaces map. Surfaces not flooded for long time periods (> 1,000+ yrs) may be considered inactive, if hydraulic modeling also indicates that are not at risk of inundation.
    - Geotechnical Testing. In some cases geotechnical testing of soils may yield information that helps distinguish active and inactive surfaces. Such geotechnical information may include soil erodibility, cohesiveness, soil profile development, or sediment size.

If a portion of an alluvial fan landform is identified as an active alluvial fan in Stage 2, then it is advanced for Stage 3 floodplain delineation. Inactive alluvial fan floodplains identified in Stage 2 can be evaluated using traditional floodplain delineation tools described in other Maricopa County manuals.

4.4. Stage 3: Floodplain Delineation and Hazard Assessment

In Stage 3, the portion of an active alluvial fan that is subject to inundation during a 100-year flood is delineated. In conjunction with the floodplain delineation, a hazard assessment is performed for use in engineering design and analysis. The bulk of the work performed for the PFHAM study is reflected in the recommended Stage 3 methodologies. Like the Stage 2 methodology, the recommended integrated Stage 3 methodology includes an approximate and detailed approach, as shown in Table 24.

Table 24. Overview of Stage 3 Methodology
GOAL: IDENTIFY ACTIVE ALLUVIAL FAN FLOODPLAIN LIMITS

Methodology	Tools
Approximate Method (Geomorphic)	
Use of Stage 2 active area boundary	See Table 23 tools (approximate or detailed) Engineering judgment
Flow depth estimates	Manning's ratings (apex & fan surface)
Debris flow assessment	If debris flow potential exists, use detailed methods Field and map reconnaissance, surficial mapping
Detailed Method (Composite of Engineering & Geomorphology)	
Hydrologic modeling	FLO-2D below hydrographic apex FLO-2D or HEC-1 above hydrographic apex
Hydraulic modeling	FLO-2D 100-year base model 10-, 50-, 500-, PMP water only model Sediment transport model (100-yr) Virtual levee scenario models
Sediment modeling Sediment yield Sediment transport on fan surface Estimate 100-year deposition Estimate long-term deposition	 Current District Hydraulics Manual guidelines FLO-2D (100-yr) Sediment yield, FLO-2D Sediment yield, FLO-2D, soil trench descriptions
Debris flow potential assessment	Field and map reconnaissance Historical debris flow assessment Surficial geologic mapping Regional debris flow evaluation LAHAR-Z modeling
Avulsion analysis	FLO-2D – 100-yr, 500-yr, sediment, channel blockage, hazard classification Avulsive flow path tool Aerial photo interpretation & historical analysis Surficial geology interpretation Field investigation Topographic map evaluation Soil trench stratigraphy
Engineering Analysis of Development Sites (Not Floodplain Delineation)	
All analyses listed above Hydraulic modeling of site features Sedimentation analysis of site features	 HEC-RAS HEC-6, District Hydraulics Manual methods

The approximate method approach relies primarily on geomorphic techniques and is best applied where a coarse, non-quantified Stage 3 floodplain delineation is acceptable. In general, an approximate method Stage 3 delineation will be similar in extent to limits of the Stage 2 active alluvial fan delineation. Therefore, the approximate Stage 3 delineations are likely to be more conservative in extent than a detailed Stage 3 delineation.

The detailed method incorporates most of the approximate method techniques, but also includes more sophisticated hydrologic, hydraulic, and sediment transport modeling, as well as modeling of debris flows and avulsions where needed. The detailed Stage 3 method may also require more detailed field investigation and more detailed topographic mapping. The detailed Stage 3 methodology requires a much higher level of effort and expertise than the approximate method, and is therefore recommended in areas where quantitative data are needed for floodplain management or engineering design purposes that justify the increased investment of labor and capital.

Use of engineering analyses is incorporated into both the approximate and detailed Stage 3 methodologies, although the level of engineering analysis increases significantly for the detailed approach. The portion of any active alluvial fans identified as within the 100-year floodplain is delineated using the procedures outlined above. Areas of an active alluvial fan that are outside the 100-year floodplain limits are not under FEMA or District jurisdiction. Recommendations for assignment of alluvial fan floodplain zones are discussed in Section 3.6.4.

Descriptions of how to apply many of the recommended Stage 3 delineation techniques are provided in the existing PFHAM, and thus are not repeated in this report. A brief description of how the following methods that are listed in Table 23, but are not discussed in detail in the existing PFHAM, is provided below:

- Approximate Methods.
    - Debris Flow Evaluation. Where evidence of debris flows are identified in the Stage 2 analysis, the detailed Stage 3 method should be used.
    - Flow Depth Estimates. Coarse estimates of depth made using the full apex discharge and Manning's equation can be used to verify geomorphic-based floodplain delineations and estimates of the limits of the high hazard zones, as well as to identify the transition from channelized flow above the hydrographic apex to uncertain flow path flooding below the hydrographic apex.
- Detailed Methods.
    - Debris Flow Evaluation Step Three of the recommended methodology described in Section 2.6 and Appendix H of this report should be applied. Any areas subject to debris flow risk should be considered ultrahazardous zones.
    - Hydrologic Modeling. See Section 2.3.2.
    - Hydraulic Modeling. See Section 2.3.3. The results of the FLO-2D modeling should be composited and interpolated to provide a reasonable

depiction of the potential flood hazard, considering avulsions, sedimentation, flow path uncertainty, and normal flow across the fan surface.

    - Sediment Modeling. The results of the sediment modeling support the floodplain delineation in the several ways. First, estimates of the average annual and 100-year sediment yield can be distributed over the active fan surface using the methodologies described in Appendix F to determine the relative magnitude of potential aggradation. Where potential aggradation is minimal relative to the flow depths predicted, it can be assumed to not affect water surface elevations. Second, the distribution and extent of predicted flow depths from a sediment-enabled FLO-2D model can be compared to the FLO-2D base and virtual levee scenario models to identify potential impacts of sediment on flood hazards, and the floodplain delineation adjusted according to account for the differences. Third, areas of high predicted scour or deposition can be included as factors for identifying high hazard zones and flow conveyance corridors. Fourth, the sediment model results can be included in the avulsion risk analysis as described in Section 2.7 and Appendix I of this report.
    - Avulsion Analysis. The floodplain delineation should envelop all areas potentially subject to flooding due to avulsions. Predicted 100-year flow depths and/or water surface elevations should be a composite of the maximum depths predicted by all the 100-year FLO-2D models prepared for the site. Some interpolation and extrapolation of the virtual levee scenario results, base models, other avulsion models, and sediment models will be necessary to composite the modeling results appropriately.

4.5. Virtual Levee Scenario Methodology

The virtual levee scenario methodology is a key element of the recommended Integrated Alluvial Fan Hazard Assessment Methodology in Maricopa County. The virtual levee scenario methodology is required to address the flow path uncertainty element of the hazard analysis. A discussion of the virtual levee scenario methodology is provided in Section 2.3.2.3 (p. 38), and more detailed information about its application in the PFHAM modeling exercises was provided in Sections 2.3.3.7 and Appendix F. Because of its importance to the recommended integrated methodology, the following cursory guidelines on implementation of the virtual levee scenario methodology are provided:

- Not a Cookbook. Because of the unique hazards associated with flooding and sedimentation on active alluvial fans, implementation of the virtual levee scenario methodology requires engineering judgment, modeling finesse, and a thorough understanding of the dynamics of flooding on alluvial fans in Maricopa County.
- Foundational Analyses. The following analyses should be completed prior to beginning the virtual levee scenario modeling:
    - Stage 2 Analysis. Active and inactive areas should be delineated, as well as areas of flow path uncertainty and potential avulsion

- Base FLO-2D Model. The results of a preliminary base FLO-2D model completed in Stage 2 can be used to help identify channelized and sheet flow zones, as well as areas of potentially high flow depth and velocity.
    - Geomorphic Assessment. The most active surfaces, areas of channelized flow, high velocity areas, and surfaces with the youngest soils should be identified as potentially avulsive areas to be covered by virtual levees.
    - Avulsion Analysis. A full avulsion potential analysis should be essentially complete prior to beginning the virtual levee scenario modeling. This includes interpretation of historical aerial photographs (to identify past avulsions and likely avulsion areas such as bends or piracy points), as well as a range of FLO-2D models up to extreme discharge models (to identify high depth/velocity zones, perched or abandoned channels, and overbank flow concentrations), as described in Section 2.7 and Appendix I.
- Preliminary Avulsion Hazard Area. It is useful to outline a preliminary avulsion hazard area based on the composited results of the foundational analyses listed above. The virtual levees should extend from a point of full flow containment upstream of the hydrographic apex to the downstream limit of preliminary avulsion hazard area to simulate the affect of possible avulsions within the ultrahazardous and high hazard zones.
- Levee Modeling. The overall objective of virtual levee modeling is to force flooding in directions that would simulate avulsions, and to estimate a maximum (reasonable) delivery of routed flow to concentration points in the lower fan area. The number, geometry, and alignment of the virtual levees should be selected to achieve those objectives. In addition, the following apply:
    - Levee Length. The virtual levees should extend from a point of full flow containment upstream of the hydrographic apex and extend downstream to the beginning of the sheet flooding area (shallow depth in FLO-2D results). The levees should extend across the entire preliminary (and final) ultra- and high hazard zones.
    - Number of Levee Scenarios. The number of virtual levee scenarios modeled depends on level of detail required, the number of obvious existing or potential avulsive flow paths, whether there are coalescing adjacent fans to be considered, the number of concentration points being evaluated, and other site-specific factors. Engineering judgment and coordination with affected regulatory agencies is recommended.
    - Alignment. The virtual levees should be aligned at moderate angles to the fan axis so that they do not cause a significant "pile up" of flow in the model results.
    - Drainage Pattern Interpretation. The existing condition drainage pattern on the active (and inactive) surfaces downstream of the hydrographic apex(es) can be used to provide clues as to the number and alignment of virtual levees needed. At minimum, flow should be directed at the primary existing flow corridors defined by the drainage network.
    - Coding. The virtual levees should be coded to not overtop or fail.

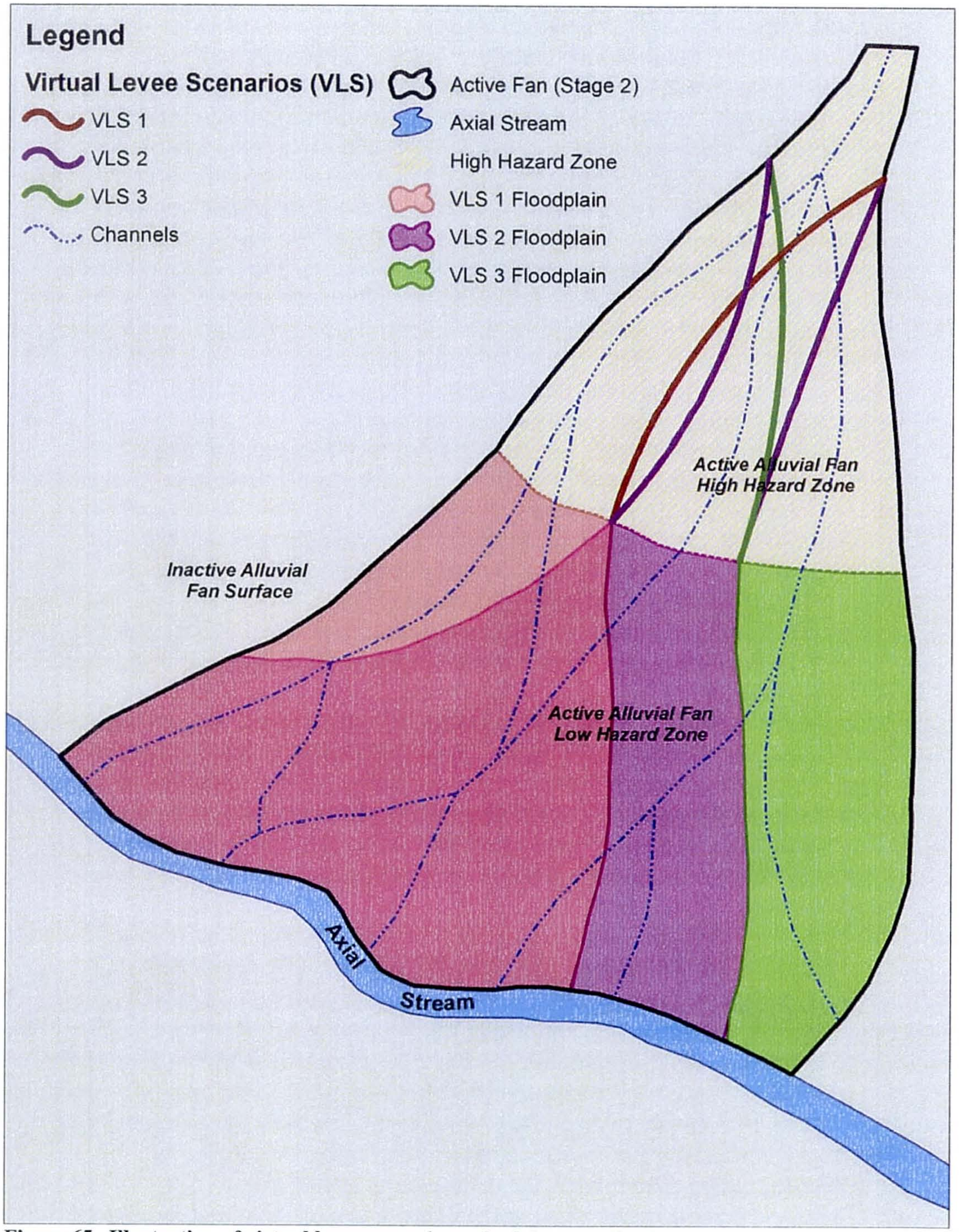

Figure 65. Illustration of virtual levee scenario methodology application.

- Model Iteration. After the initial virtual levee scenarios are modeled, the results may dictate that additional iterations are required, particularly if the FLO-2D results appear to contradict the preliminary avulsion hazard area delineation.
- Secondary Apex. If multiple apexes exist on the alluvial fan, the virtual levee scenario modeling should be repeated for each secondary apex using the upstream levee combination(s) that deliver maximum flow rate to secondary apex
- Hazard Delineation. In the simplest case, the maximum depth at each grid cell from a combination of virtual levee scenario runs can be used as the regulatory flood depth. In most cases, however, delineation of the flood depths from the virtual levee scenario modeling results will require interpolation and extrapolation of FLO-2D output, at least for the high hazard zone, to produce a reasonable depiction of the hazard. Outside the high hazard zone, it is likely that the virtual levee scenario results will have similar depths regardless of the upstream scenario. The following also may apply:
    - Pile-Up. Avoid mapping the "pile up" depth against the virtual levees, which should be easy to identify by its location and alignment, as well as the depth relative to surrounding grid cells.
    - Islands. Avoid mapping islands of low or high hazard that are significantly different than surrounding grid cells, unless they are topographically or geomorphically justified.
    - Uniformity. Interpolated depths should be laterally uniform near the hydrographic apex, with increasing lateral variation possible in downfan direction.
- Conservative Results. If properly modeled, the virtual levee scenario produces somewhat conservative flood depths, particularly given the (probable) low frequency of avulsion on fans in Maricopa County, as well as the fact that actual avulsions do not completely divert the entire hydrograph along a particular alignment. The method requires application of engineering judgment and understanding of alluvial fan flood processes to assure that the results are reasonable.

4.6. Integration of Stage 3 Results for Floodplain Delineation

The recommended integrated methodology does not produce a single, definitive model output file from which a floodplain delineation can be automated. Therefore, some engineering judgment will be required to synthesize the results from the various elements of the recommended Stage 3 methodology listed in Table 24. In most cases, the results won't necessarily all coincide perfectly, and will thus require some integration. The following general guidelines may be useful when integrating the results:

- When delineating flood zones, err on the side of public safety.
- Consider the consequence of an error in mapping when drawing zone limits.
- Be mindful of the uncertainty in each of the methodologies used.
- Results with the least uncertainty may be most reliable.
- Weight documented historical evidence of flooding over theoretical results.
- Allow for application of engineering judgment and experience.

4.7. Blue Ribbon Panel Review of the Recommended Methodology

The recommended integrated methodology was presented to a panel of experts (the "Blue Ribbon Panel") for peer review. The Blue Ribbon Panel meeting was held at the Flood Control District of Maricopa County on June 2-3, 2010, and was facilitated by District staff. The Blue Ribbon Panel consisted of experts from a variety of engineering, scientific, and regulatory disciplines associated with alluvial fan flood hazard assessment. In general, the Blue Ribbon Panel endorsed the recommended methodology. A detailed summary of the Blue Ribbon panel meeting and a list of the panelists are provided in Appendix J.

The Blue Ribbon Panel concluded the following with regard to the recommended Integrated Alluvial Fan Hazard Assessment Methodology:

- The methodology as proposed in the draft report (May 25, 2010 version) was reasonable, defensible, and scientifically sound.
- The proposed methodology may have applicability to similar fan areas elsewhere in the semi-arid west, but it should be adopted specifically for Maricopa County.
- The proposed methodology should be applied on a local alluvial fan and sent to FEMA as a test-case delineation (with documentation) for review and approval.
- The 100-year flood should be used as the basis of engineering design and floodplain delineation on alluvial fans in Maricopa County.
- Two-dimensional modeling is strongly recommended for alluvial fan flood hazard assessment.
- Flow attenuation is a key process on alluvial fans in Maricopa County and should be accounted for the methodology.
- The virtual levee scenario is an important and necessary component of the proposed methodology.
- The proposed hazard assessment methodology (BUREC Figure 6, FLO2D depth-velocity, frequency-weighted) is acceptable. Depth and velocity are the best variables for assessing the hazard level, if uncertainty is addressed through the virtual levee scenario method.
- Avulsions are a key process for alluvial fan flooding hazards. Avulsion methodology should distinguish between major avulsions, minor avulsion and simple lateral channel erosion. Recent occurrence of avulsions may preclude formation of new avulsions in the near term.
- The recommended avulsion risk assessment methodology is acceptable.
- The slope-walk method is a useful tool.[26]
- "Active alluvial fan flooding" refers to an ultrahazardous flooding condition characterized by very high velocities and flow depths, active transport of boulder-sized sediment, high avulsion potential, rapid aggradation, and debris flow potential. New terminology, such as "piedmont active flooding," may be needed to address uncertain flow path flooding on active alluvial fans that is not ultra-hazardous.

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[26] The name of the slope-walk method was changed to "avulsive flow path method" at the request of District staff.

- There is no known physical characteristic that could serve as the minimum threshold of concern to identify alluvial fan landforms or the potential for alluvial fan flooding. Hazards can be quantified based on the flow depths and velocities predicted by the proposed methodology
- There is no need to quantify the Stage 1 delineation process using variables such as minimum slope, velocity, etc.
- Some quantification of flood hazards is needed in the Stage 2 delineation process. Flow depth and velocity estimates are needed to identify "active alluvial fan flooding" as defined by FEMA.
- Alluvial fans in Maricopa County are not unique, though they differ from steep alluvial fans bounding tectonically active mountain ranges. The fans in Maricopa County are typical of alluvial fans formed near tectonically inactive mountain ranges in semi-arid climates.
- Areas on active fans outside the 100-year floodplain should be designated as having some hazard potential, but should not be mapped as part of the FEMA floodplain
- Development in low hazard areas on alluvial fans is acceptable as long as it is adequately regulated for impacts to adjacent areas. High hazard areas should be regulated with higher restrictions. Policies to prevent loss of attenuation (downstream impacts) should be developed.
- There are significant problems with the Dawdy Method (FAN model).
- FEMA's current plan to revise the NFIP provides a rare window of opportunity for also revising the FEMA Appendix G methodology to incorporate the recommendations of the PFHAM study.
- There is a need for high quality topographic mapping when performing floodplain delineations.

The Blue Ribbon Panel also voiced the following concerns and recommendations regarding alluvial fan flood hazard assessments:

- "Point-in-time" modeling may not adequately characterize long-term fan behavior and flood risks because fan processes evolve dynamically over time. Because we do not yet have the ability to reliably predict how those processes will change the landscape or impact other functions such as flow attenuation over time, a composite methodology (combining engineering and geomorphic techniques) is needed.
- The recommended integrated methodology would be improved if clarification of mechanics of virtual levee scenario methodology – length of levees, orientation, number of scenarios, approach at secondary apexes, etc. – were provided.
- The District should endeavor to determine avulsion frequency on alluvial fans in Maricopa County.
- The District should work to document infiltration parameters on alluvial fans. The values used in the PFHAM Study modeling need verification.
- If and when large floods occur on alluvial fans in Maricopa County, they should be thoroughly documented & studied, and compared with proposed methodology.

- The District should develop and provide documentation on how "risk" is quantified by the proposed methodology. This documentation of risk will be important for FEMA approval.
- When an application of the recommended integrated methodology is submitted to FEMA for review and approval, the methodology should be characterized in RiskMAP language.
- Additional work should be done to clarify which sediment transport function produces best results.
- The District should explore the definition of hazard level relative to no-build zones and/or floodways. No-build zones could be based on hazard classification as well as the "ultrahazardous" areas, but also could be incorporated into zoning overlays.

Additional information on the Blue Ribbon Panel meetings is provided in Appendix J.

5. Summary of Recommendations

The following paragraphs reiterate and summarize the recommendation of the PFHAM study presented earlier in this report.

5.1. Definitions

The following recommendations were made with respect to terminology:

- Sheet Flooding. The term "sheet flooding" is preferred over "sheet flow."
- FEMA Definitions. Current NFIP and FEMA definitions relating to alluvial fan flooding should be used wherever possible (Table 15). Where necessary, the District should work with FEMA in conjunction with other affected communities, to improve FEMA definitions and guidance.
- Active Alluvial Fan Flooding. The District should make an affirmative statement that the term "active alluvial fan flooding," as defined in the NFIP, applies only to the areas of ultrahazardous flood conditions on active alluvial fans. The District should use the hazard classification criteria outlined in Sections 2.3.3.9 and 3.4 of this report to define the term "ultrahazardous" with respect to alluvial fans.
- Inactive Alluvial Fans. The District should use the FEMA Appendix G definition of the term "inactive alluvial fan."

5.2. Hydrology

The following recommendations were made with respect to hydrologic analyses of alluvial fans:

- Two-Dimensional Modeling. Two-dimensional modeling is recommended for all hydrologic modeling below the hydrographic apex of active alluvial fans in Maricopa County. The recommended engineering tool for hydrologic modeling of active alluvial fans and alluvial plains in Maricopa County is FLO-2D.
- Virtual Levee Scenario. The virtual levee scenario method should be used to estimate peak discharge at all points downstream of the hydrographic apex. Use of the full apex discharge is not recommended for design purposes. The maximum discharge from the cumulative virtual levee scenarios should be used for design purposes.
- Coalescing Alluvial Fans. Where one or more active alluvial fans coalesce, a combination of discharges from adjacent fans should be estimated using the virtual levee scenario method.
- Future Conditions. For planning studies, future condition discharges should be estimated by applying full-build out of the fan surface with normal retention requirements and whatever current District (or local community) development policies exist at that time.
- Conveyance Corridors. For planning purposes, it may be useful to identify a flow corridor that could be used to convey upstream and local runoff from the hydrographic apex to the toe of the alluvial fan landform.
- Sheet Flooding. Where runoff is expected to occur as unconfined sheet flooding, peak discharge estimates should reflect the total flow reaching the upstream

boundaries of a site, or flow across the entire sheet flooding area, rather than the point discharge a single concentration point or grid cell.

- Modeling Guidelines. The District should develop two-dimensional hydrologic modeling guidelines that specifically address:
    - Point rainfall depths
    - Loss rate parameters
    - Limits on re-infiltration volume
    - Pre- and post-processing tools for modeling coalescing alluvial fans
- Above Apex. Hydrologic modeling upstream of the hydrographic apex should be completed as dictated by current District modeling guidelines and standards. Based on the findings of this study, it is recommended that the District develop guidelines for using FLO-2D to model watersheds upstream of the hydrographic apex, particularly for small watersheds or where tributary inflows to the active fan surface occur over broad areas, rather than at discrete concentration points.
- Flow Attenuation. Attenuation of the hydrograph peak is an important process on active alluvial fans in Maricopa County. Therefore, use of the full apex discharge at any point other than the hydrographic apex is unnecessarily conservative and is not supported by the scientific analyses conducted as part of the PFHAM study. In many cases, the degree of flow attenuation is such that many small floods are completely stored on the fan surface, never reaching the toe, and resulting in deposition of the entire sediment load on the fan.
- Design Frequency. The 100-year (1%) design frequency is recommended for regulation of alluvial flood hazards in Maricopa County.

5.3. Hydraulics

The following recommendations were made with respect to hydraulic analyses of alluvial fans:

- Model Selection. The recommended engineering tools for (water-only) hydraulic modeling on active alluvial fans and alluvial plains are FLO-2D and HEC-RAS. The scenarios in which each model should be used are summarized in Table 18. For the PFHAM study, the FLO-2D model was selected as the best available model, a finding which is consistent with the findings of other agencies (USACE, 2000). Any two-dimensional model that has the same (or better) capabilities as FLO-2D would be acceptable for the purposes of floodplain delineation and flood hazard identification.
- FLO-2D. FLO-2D is preferred for the following types of hydraulic modeling exercises on active alluvial fans and alluvial plains:
    - Determining flow hydraulics in broad sheet flooding areas
    - Modeling of the entire alluvial surface
    - Identifying preferred, alternative or avulsive flow corridors
    - Identifying low relief "islands" within the active fan (use extreme flood discharges)
    - Estimating impacts of development in active fan attenuation areas
- HEC-RAS. HEC-RAS may be used for evaluation of channel capacity near the hydrographic apex as part of the methodology for identifying the hydrographic

apex location. In addition, HEC-RAS (or any similar model) is preferred over FLO-2D for site-specific hydraulic analyses where the following conditions exist:

    - The modeling reach has fine-textured topography that cannot be readily defined by grid-based topographic data. If HEC-RAS is used, topographic data and cross section spacing should be coded into the model in a manner that accurately portrays the subtleties of the local terrain.
    - Flow is primarily one-dimensional and gradually-varied flow conditions exist.
    - A single design discharge (steady flow) reasonably approximates flow conditions.
    - Flow is conveyed in a relatively well-defined natural or engineered channel.
    - The modeling reach is short enough that flow volume conservation is not a factor.

- Further Research. The District should continue to investigate improvements in FLO-2D modeling techniques as applied to active alluvial fans and alluvial plains in Maricopa County. Specifically, the use of the multiple-channel option in FLO-2D and the effect of topographic resolution should be explored.
- Modeling Results. FLO-2D depth and velocity output represent average values for the grid size used in the model. Therefore, some interpretation of results is necessary to determine design data for specific sites that may not be well represented by the grid elevations. In these cases, site specific step-backwater modeling is recommended to obtain structure design data.
- Modeling Guidelines. The accuracy of topographic data may affect the modeling results. Use of the best available topographic mapping is recommended. In some cases, the county-wide 10-foot mapping may not produce sufficiently accurate results. In addition, the FLO-2D grid size used also affects the model output. The use of the finest grid size feasible with respect to model run time and topographic data is recommended.
- Sheet Flooding. Large portions of active alluvial fans in Maricopa County are affected only by shallow sheet flooding with minimal flow depths, flow velocities, and aggradation rates. Most of the land area on the active alluvial fans specifically evaluated for this study is dominated by shallow sheet flooding. The extent of sheet flooding is both a cause and result of significant flow attenuation that occurs on active alluvial fans.

5.4. Sediment Transport

The following recommendations were made with respect to sediment transport analyses on alluvial fans:

- Modeling Tools. A variety of tools are recommended for sedimentation modeling on active alluvial fans and alluvial plains.
    - Sediment Yield. Prediction of sediment yield to the hydrographic apex should be completed using the procedures outlined in the District's Hydraulics Manual.
    - Scour. The District's Hydraulics Manual lists specific methodologies for the computation of scour that should be used in channel and site design.

- Model Selection. Use of FLO-2D and HEC-6 should be partitioned in a similar manner to that described above for hydraulic modeling (Section 3.3.2). FLO-2D should be used in broad scale surface analyses, and HEC-6 should be used for site-specific evaluations that meet the conditions listed above.

- Further Research. The District should conduct additional research on calibration of FLO-2D sediment modeling results and sediment transport functions for use on active alluvial fans.

5.5. Debris Flows

The following recommendations were made with respect to debris flow analyses on alluvial fans:

- Risk. The PFHAM study concluded that the risk of debris flow impact on flood hazards on most alluvial fans in Maricopa County is much less than one percent. In the vast majority of cases, no detailed investigation of debris flow potential will be needed. For the few cases of possible concern, a recommended methodology was developed.
- Methodology. Based on the District's goal of assessing debris-flow potential to impact alluvial fan flooding, the following steps are recommended for detailed evaluations of debris flows on specific alluvial fan landforms in Maricopa County:
    - Step One: Initial Assessment of Alluvial Fan
    - Step Two: Geologic Reconnaissance
    - Step Three: Debris-Flow Runout Hazard Modeling
- Engineering Tools. For evaluation of debris flow hazards, the recommended engineering tool is the LAHAR-Z model, as described in Section 2.6 and Appendix H. Use of the LAHAR-Z model is recommended only after completion of more foundational analyses in the recommended multi-step process.

5.6. Avulsions

The following recommendations were made with respect to avulsion risk assessment on alluvial fans:

- Methodology. The recommended method of evaluating avulsion potential on active alluvial fans in Maricopa County consists of the following multi-step process (Section 2.7):
    - Step One: Historical Analysis.
    - Step Two: Geomorphic Analysis.
    - Step Three: FLO-2D Modeling.
    - Step Four: Sediment Modeling.
    - Step Five: Floodplain Delineation.
- Engineering Tools. Two engineering tools are recommended as part of the assessment of avulsion potential on active alluvial fans: (1) FLO-2D and (2) an avulsive flow path tool, both of which are discussed in more detail in Section 2.7 and Appendixes F and I. A variety of FLO-2D modeling scenarios are used to help predict the location and occurrence of avulsions, including the

following: (1) 100-year base models, (2) extreme flood models, (3) hazard classification models, (4) sediment models, and (5) channel blockage models.

- Avulsion Frequency. The frequency of avulsions on alluvial fans in Maricopa County is not well known, although it is likely that avulsions are relatively rare events. A systematic study of avulsion frequency is strongly recommended.

5.7. Surficial Dating

The following recommendations were made with respect to dating of alluvial fan surfaces:

- Regional Chronology. This study recommends that a combination of relative and numerical methods be applied to most accurately determine surface age on alluvial fans in Maricopa County. It is further recommended that a regional chronology be constructed so that more cost-effective relative dating techniques can be used to determine correlative ages.
- The recommended methodologies listed in Table 17 are better classified as quantitative geologic techniques, rather than engineering tools. These geomorphic dating tools can be used to better refine estimates of surface age, and therefore may inform on the degree of alluvial fan activity, as well as help distinguish between active and inactive alluvial fan surfaces.

5.8. Policy

The Consultant recommended use of flood hazard zone classifications to determine floodplain zones; however, the District after careful consideration, has directed that floodplain management policies follow the current FEMA practice and be based on depth of flow.

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