Evaluation of Avulsion Potential on Active Alluvial Fans in Central and Western Arizona

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Tiger Wash alluvial fan, western Maricopa County, Arizona

CONTRIBUTED REPORT CR-12-D

June 2012

Arizona Geological Survey

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Arizona Geological Survey Contributed Report CR-12-D

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Executive Summary

An avulsion is the process by which flow is diverted out of an established channel into a new course on the adjacent floodplain. Occurrences of avulsions are what makes an alluvial fans “active.” Avulsions give the alluvial fan the ability to distribute water and sediment over the surface of the landform, which results in a radial “fan” shape. Avulsions influence flood hazards on an alluvial fan landform by changing the location, concentration and severity of flooding on the fan surface.

Avulsions have been observed on several alluvial fans in central and western Arizona. The avulsion history of several fan evaluation sites are documented and described. It is likely that there are other examples of major avulsions in Arizona, 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 central and western Arizona. The cursory data summarized above indicate that it is likely 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 central and western Arizona, and thus it is likely that avulsions will continue to occur in the future.

Review of the literature regarding alluvial fan avulsions identified the following three primary gaps in the knowledge base required to develop a robust methodology for quantifying alluvial fan flood hazards in central and western Arizona:

- Avulsion Frequency. To resolve this knowledge gap, studies of avulsion frequency on active alluvial fans are needed.
- Modeling Methodology. To address the lack of a universally accepted methodology for evaluating avulsion potential, floodplain management agencies should first adopt methodologies that reflect the current understanding of alluvial fan flooding hazards. Subsequent steps include testing such methodologies on alluvial fans in their local area, and vetting the methodology with floodplain management agencies such as FEMA, as well as academic and industry experts.
- Engineering Design Standards. Floodplain management agencies should develop engineering and design guidelines for development on active alluvial fans.

Based on the results of the analyses and information summarized above, a recommended procedure for evaluating the potential for avulsions on active alluvial fans in Arizona 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.
- **Step Two: Geomorphic Analysis**. An evaluation of the surficial geology of an alluvial fan is required. The evaluation should include field observations, surficial mapping of active and inactive surfaces, and assessment of debris flow potential.
- **Step Three: Two-Dimensional Modeling**. Two-dimensional models of the fan surface from the hydrographic apex to the downstream limit of the active alluvial fan should be prepared.
- **Step Four: Sediment Modeling**. The sediment yield at the hydrographic apex should be computed and used to estimate potential deposition along the fanhead channel. Until such time as the available methodologies are improved, detailed sediment transport modeling of the alluvial fan downstream of the hydrographic apex may not provide sufficiently accurate results to justify the effort, and thus is not recommended as part of the recommended avulsion prediction methodology.
- **Step Five: Floodplain Delineation**. The potential for future avulsions should be considered when delineating the floodplain on an active alluvial fan.

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1. Introduction

1.1.Objectives

The objective of this analysis is to determine and quantify how channel avulsions influence flood hazards on alluvial fan landforms. The results are intended to assist floodplain managers, engineers, and planners achieve safe development and regulation of active alluvial fans.

1.2.Importance of Avulsions to Alluvial Fan Flood Hazard Assessment

The occurrence of avulsions is what makes alluvial fans “active.” Avulsions give an 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 landform 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 hydraulics and sedimentation.

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.
- Periodically 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 channels with diminishing capacity.
- Unsteady, rapidly-varied flow conditions.
- High rates of infiltration and flow attenuation across the fan surface.

There are currently no scientifically-valid, widely-accepted engineering standards for evaluation of flood hazards or design of flood mitigation measures on alluvial fans with avulsion potential, although there many fundamental similarities between the methodologies in use or proposed by competent engineers and geomorphologists. 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).

2. Background

2.1. Definition of Avulsion

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 of an avulsive channel change that occurred on the Tiger Wash alluvial fan in western Arizona during the 1997 Hurricane Nora flood is shown in Figure 1. Avulsions are commonly associated with alluvial fan flooding, but are also known to occur on riverine systems and river deltas (Slingerland & Smith, 2004).

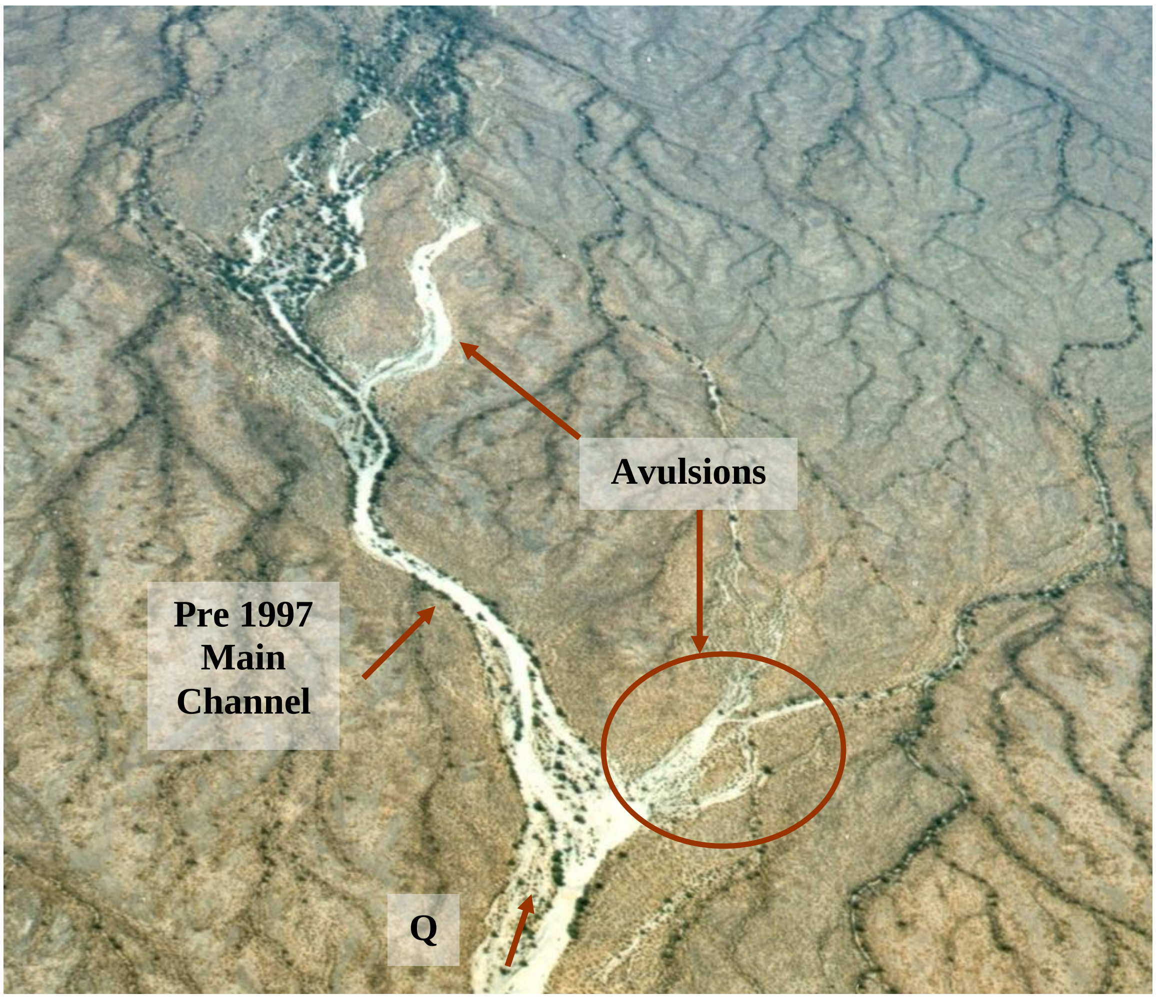

Figure 1. ***Avulsions on the Tiger Wash alluvial fan caused by the 1997 Hurricane Nora flood.***

2.2. Classification of Avulsions

Several investigators (Slingerland & Smith, 2004; Field, 2001; Bryant et. al., 1995) have classified types of avulsions and avulsive processes, as shown in Table 1. In nature, the classifications given in Table 1 exist as a continuum, with no distinct boundaries between end members, and an infinite number of possible combinations of characteristics on any given stream system.

Table 1. Avulsion Terminology & Classification Continuum End Member ←---→ End Member	
Major Avulsion Occurs near the apex Divert > 50% of flow from the parent channel	**Minor Avulsion** Doesn't meet the major avulsion criteria
Full Avulsion All of flow diverted Parent channel abandoned	**Partial Avulsion** Part of flow 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 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 don't return to parent channel

2.3. Other Terminology

Other terms commonly used in discussions of avulsions include the following:

- Avulsion Belt. The entire area of the floodplain affected by avulsions, in which avulsion have occurred in the past.
- Parent Channel. The channel or flow path which existed prior to the avulsive event is called the parent channel. In some cases, the term may apply primarily to the channel reach upstream of the avulsion initiation point.

2.4. Occurrences of Avulsions in Central and Western Arizona

Avulsions have been observed on several alluvial fans in central and western Arizona. It is likely that there are other examples of major avulsions in Arizona, but no comprehensive evaluation of avulsion frequency or occurrences has been made. The avulsion history of Tiger Wash and several other alluvial fan sites are described below.

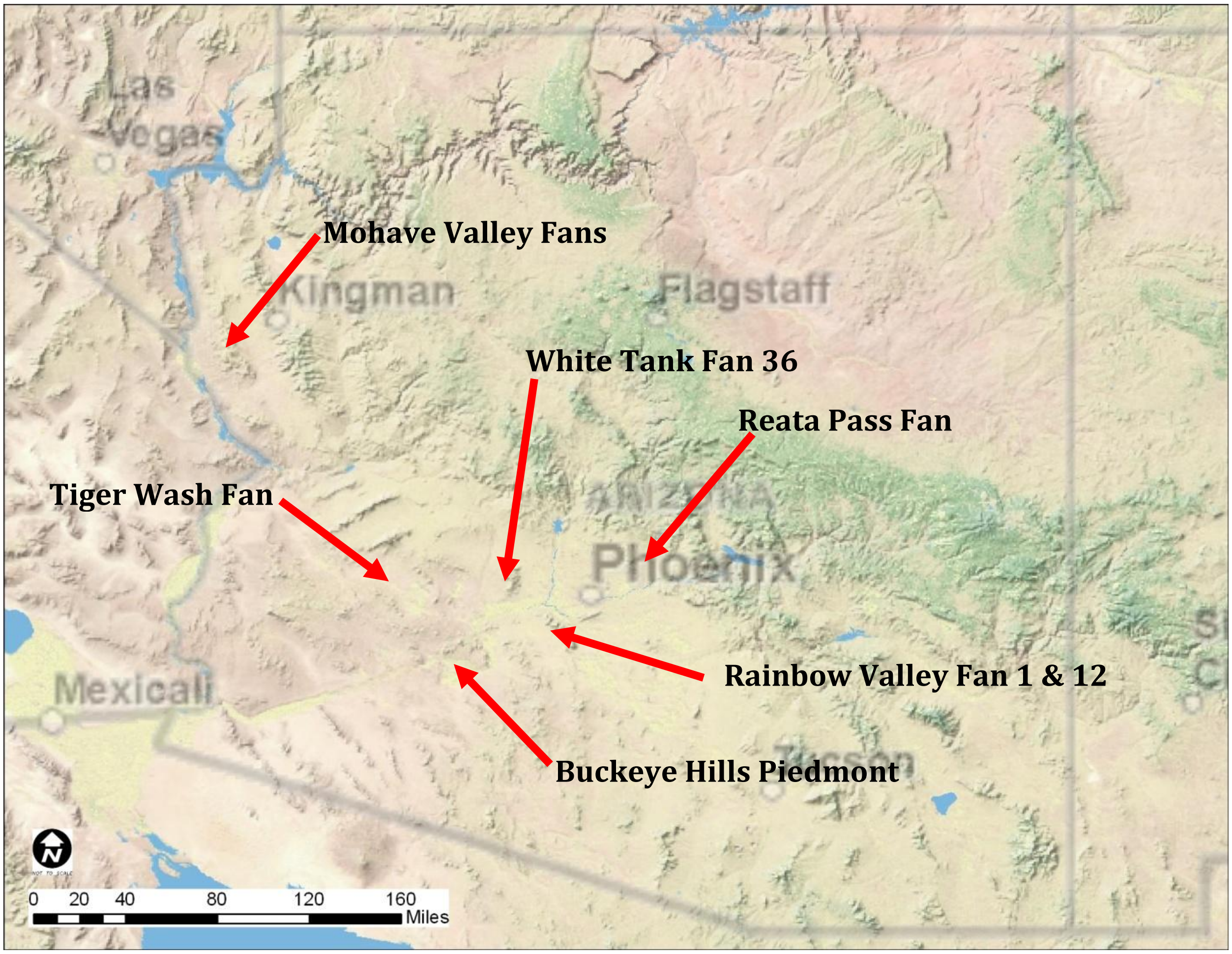

Figure 2. Locations of avulsion study sites in Arizona.

2.4.1. Tiger Wash

The 1997 avulsions on the Tiger Wash alluvial fan are some of the better documented avulsions in the literature (Figure 1). The Tiger Wash fan was evaluated previously in some detail as part of the Flood Control District of Maricopa County's *Alluvial Fan Data Collection and Monitoring Study* (CH2M HILL, 1992), which was completed prior to the 1997 Hurricane Nora flood. After the 1997 flood, the following publications thoroughly evaluated and documented the flood hydrology, avulsive channel change, and sediment deposition on the fan surface:

- JE Fuller/Hydrology & Geomorphology, Inc., 2000, *Approximate Floodplain Delineation Study for Portions of Tiger Wash Piedmont, Technical Data Notebook*, Report to the Flood Control District of Maricopa County, Contract FCD 98-48.

- Pearthree, P.A., Klawon, J.E., and Lehman, T.W., 2004, *Geomorphology and Hydrology of an Alluvial Fan Flood on Tiger Wash, Maricopa and La Paz Counties, West-central Arizona*, Arizona Geological Survey Open-File Report 04-02, 40 p.
- Pelletier, J.D., Mayer, L, Pearthree, P.A., House, P.K., Demsey, K.A., Klawon, J.E., and Vincent, K.R., 2005, An integrated approach to flood hazard assessment on alluvial fans using numerical modeling, field mapping, and remote sensing, *Geological Society of America Bulletin*, Vol. 117, no. 9/10, p. 1167-1180.

Rather than reiterate the information contained in the reports listed above, some of which is discussed in more detail elsewhere in this report, several of the key conclusions regarding the occurrence of avulsions at the Tiger Wash Site are summarized below:

- More channel change occurred on the Tiger Wash fan during one day of flooding in 1997 than in the previous 18,000 days since 1953 (Pearthree et. al., 2004).
- Several moderate-sized floods occurred prior to and after the 1997 event which left no evidence of new avulsions (Pearthree et. al., 2004).
- Based in part on geologic and photographic information collected at Tiger Wash, Field (1994) estimated the recurrence interval of avulsions on alluvial fans in central Arizona at 50 to 650 years.
- Even during the extreme 1997 event, most flood water generally followed the pre-flood channel network (Pearthree et. al., 2004).
- Flood depths greater than 0.6 feet were capable of scouring new channels, but flow depths less than 0.3 foot were not (Pearthree et. al., 2004).
- Streamflow (fluvial) fans have less frequent avulsions than debris flow fans (Pelletier et. al., 2005).
- In the arid west, “rapid” channel change on active alluvial fans occurs on a decadal time scale (Pelletier et. al., 2005).
- Stratigraphic evidence of recent pre-historical (ca. 600 yrs BP) channel avulsions were observed in trench soil profiles, and was corroborated by vegetative evidence (CH2M HILL, 1992).
- Prior to the 1997 flood, of the five Arizona alluvial fans evaluated by Field (1994), the Tiger Wash site had been the most stable (Pearthree et. al., 2004).
- Several types of avulsions were described (Figure 3): (1) two major avulsions that formed long, wide new channels and captured significant percentages of the flood hydrograph (Figure 3B), (2) minor avulsions that scoured small channels on the margins of otherwise active areas (Figure 3D), (3) changes in flow distribution between well-established, semi-permanent distributary flow branches (Figure 3A), and (4) changes in flow distribution in sheet flooding areas (Pearthree et. al., 2004).

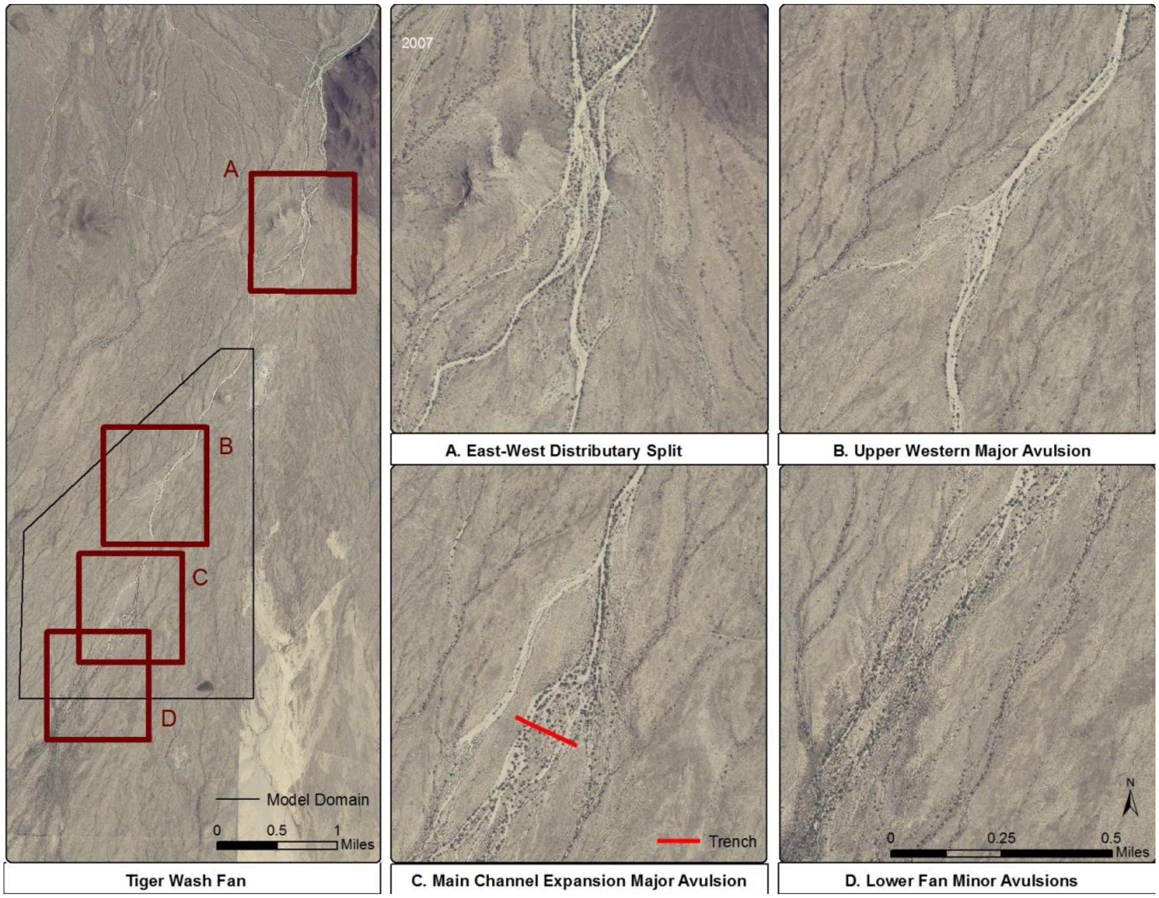

Figure 3. ***Types of avulsions observed on the Tiger Wash alluvial fan in 1997. Trench location in red.***

2.4.2. White Tank Fan 36

The history of avulsions on White Tank Fan 36 has been documented in a number of technical publications and scientific studies, including the following:

- CH2M HILL, 1992, *Alluvial Fan Data Collection and Monitoring Study, Appendix A,* Report to the Flood Control District of Maricopa County.
- Field, J.J., 1994, *Surficial Processes, Channel Change, and Geological Methods of Flood-Hazard Assessment on Fluvially-Dominated Alluvial Fans in Arizona*, Ph.D. Dissertation, Department of Geosciences, University of Arizona, 258 p.
- JE Fuller/Hydrology & Geomorphology, Inc., 2001, *Approximate Floodplain Delineation Study for White Tank Fan (Site 36), Technical Data Notebook*, Report to the Flood Control District of Maricopa County, Contract FCD 99-02.
- Field, John, 2001, "Channel Avulsion on Alluvial Fans in Southern Arizona," *Geomorphology*, Vol. 37, p. 93-104.

Major disruptions of the fan surface of White Tank Fan 36 are thought to have occurred during the August 1951 monsoonal storm which dropped over five inches of rain at Buckeye in a four day period (JE Fuller, 2001). The channel and surficial changes observed near the apex of the fan were different in character than "typical" channel avulsions. In the 1951 flood, a very broad area downstream of the apex, nearly 2,000 feet wide and one mile long, experienced significant changes that included scour and/or deposition of alluvium, removal (or burial) of overbank and channel vegetation, in addition to new channel formation, the more classic behavior of fan avulsions (Figure 4). Aerial photographs bracketing the 1951 event also record a number of minor, local avulsions along some of the small channels that comprise the on-fan drainage network in the lower portion of the fan (Figure 5). These lower fan avulsions consist primarily of relocation of some of the fine-textured distributary branches, probably due to excessive overbank flow that escaped the defined channels, as well as sheet flooding which scoured out new flow paths. Subsequent aerial photographs document that the pre-flood channels were abandoned, filled with sediment, lost their bank vegetation and virtually disappeared. These abandoned channels would be nearly undetectable on recent aerials or in the field if pre-flood aerials or subsurface stratigraphic data were not available. Hydraulic analyses by JE Fuller (2001) indicate that these shallow avulsive channels could have been formed by overbank flows of 1.0 foot depth or less, with velocities in the range 2.5 to 4.0 feet per second.

Interpretation of the soil stratigraphy exposed in test trenches (CH2M HILL, 1992) identified that net aggradation of about three feet occurred over the past 600 years. Despite this level of aggradation, no abandoned channel paths were identified within the recent geologic time period exposed in the trench alignment, even though the trenches were excavated in the area strongly impacted by the 1951 flood. The lack of major channel relocations (classic avulsions[1]) in the area of the trench is probably attributed to very high infiltration rates in the coarse soil materials, and very rapid expansion from the single channel at the apex to highly distributary and sheet flooding conditions immediately downstream of the apex (i.e., no extended linear well-defined major channels exist on the fan surface downstream of the hydrographic apex).

[1] The 1951 "avulsive" behavior consisted of excessive erosion and deposition, rather than relocation of well-defined single channels.

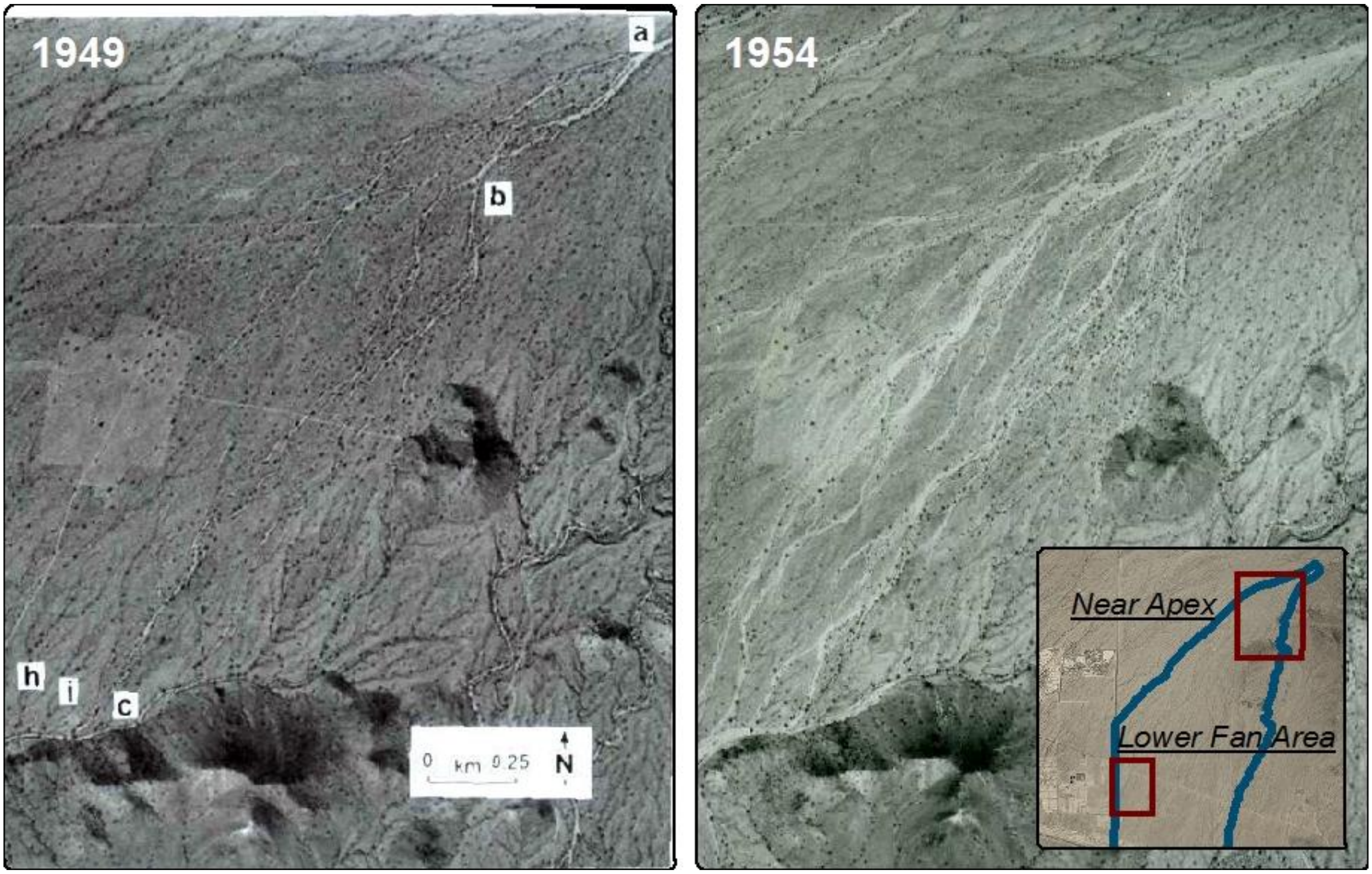

Figure 4. ***White Tank Fan 36, 1949-1954, 1951 Avulsion Near Fan Apex.***

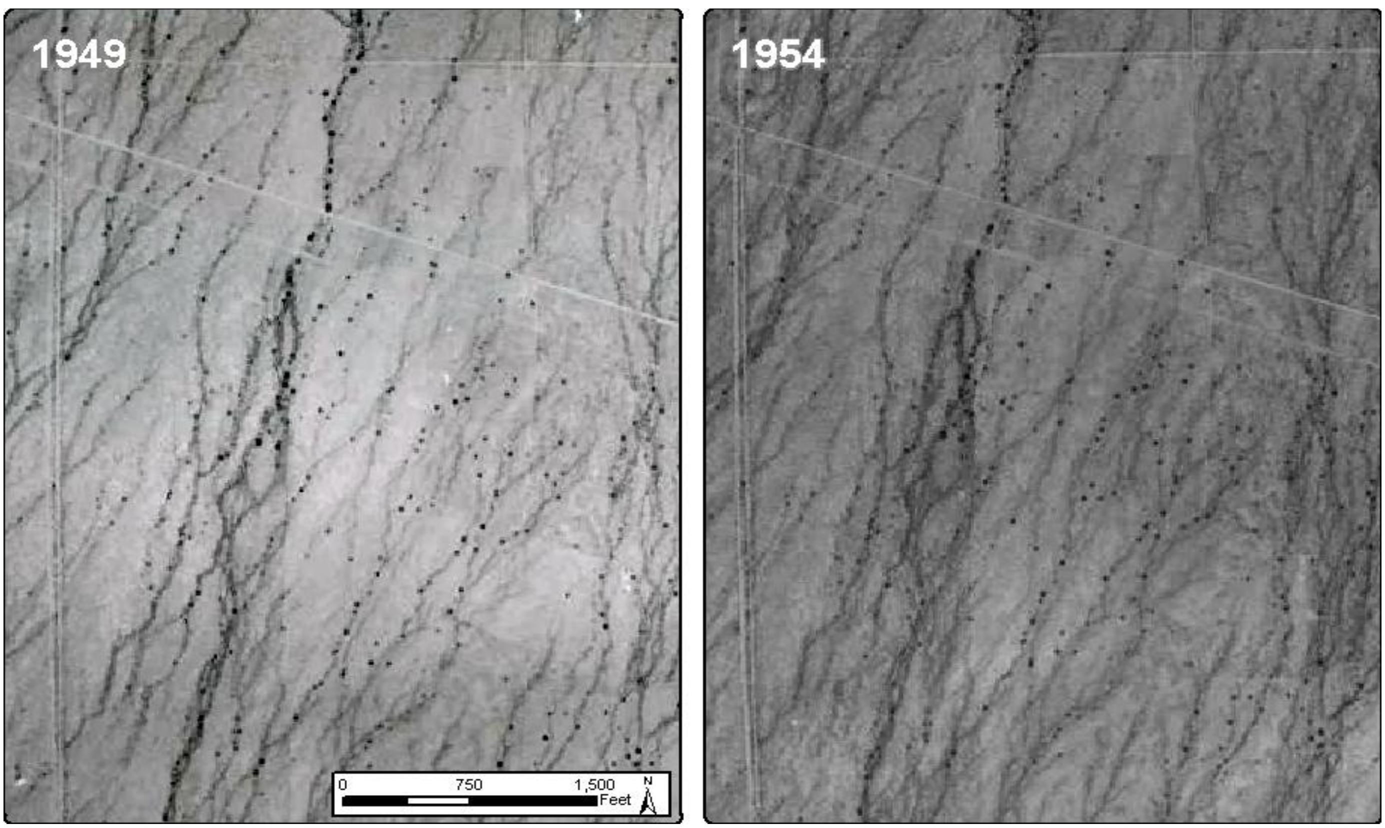

Figure 5. White Tank Fan 36, 1949-1954, Avulsions in Lower Fan Area.

2.4.3. Reata Pass Alluvial Fan

There have been no known major avulsions on the Reata Pass alluvial fan during the 47 year period of record. A comparison of the oldest and most recent aerial photographs is shown in Figure 6. The lack of historical avulsions on the Reata Pass alluvial fan is probably due to two factors. First, there have been no large floods in the period of record. Second, development has obscured and altered the fan surface, and possibly has neutralized some of the potential avulsion mechanisms. If the latter factor is true, it implies that avulsive processes may be hindered or even prevented by development, which in turn indicates that avulsion hazards on low-sloping, fluvially-dominated alluvial fans in Arizona may not be severe. If the former factor is the primary reason avulsions have not occurred, then a significant number of homes may currently be at risk of future flood damage.

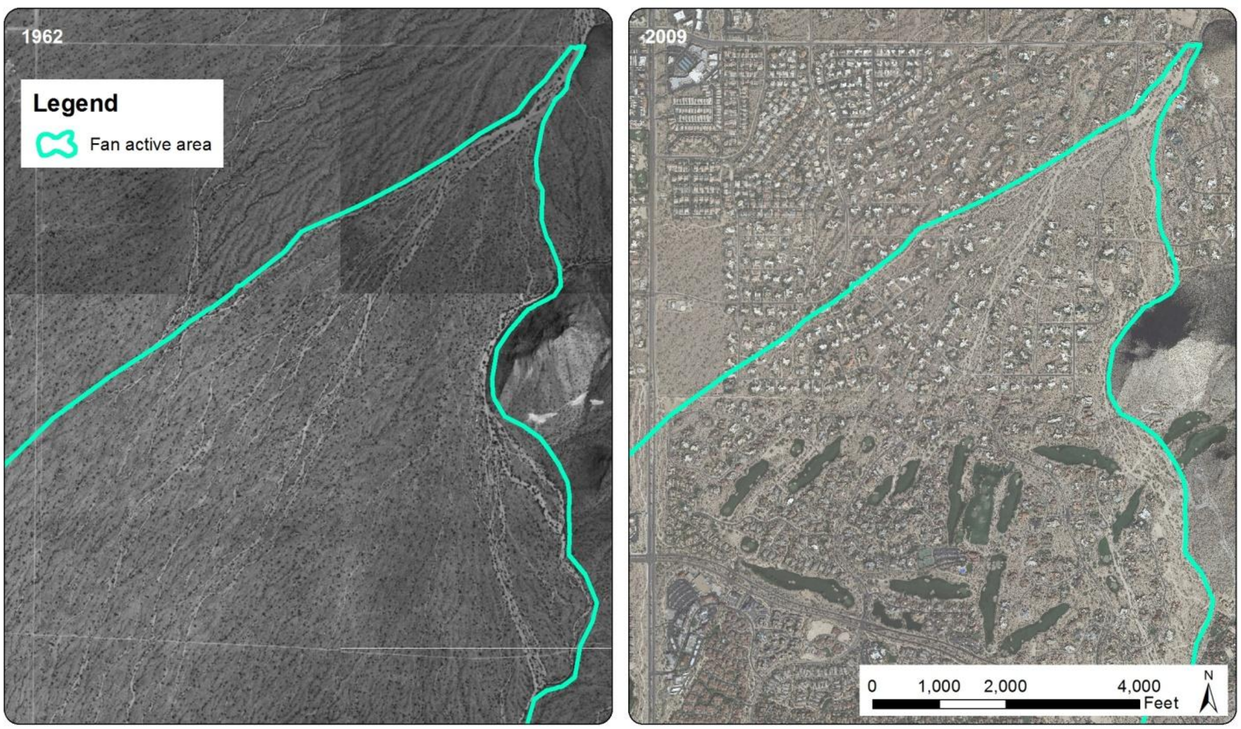

Figure 6. ***Reata Pass Alluvial Fan, 1962-2009.***

2.4.4. Rainbow Valley Fan 1

There has been no systematic evaluation of historical avulsions at the Rainbow Valley Fan 1 site. Simple comparison of 1937 and 2009 aerial photographs (Figure 7) reveals no evidence of any avulsions during the 72 year period of record. The lack of fan avulsions is most likely due to the degree of flow containment along the main flow path. Flow containment limits the frequency and duration of overbank flooding, although a lack of large floods may also be a contributing factor.

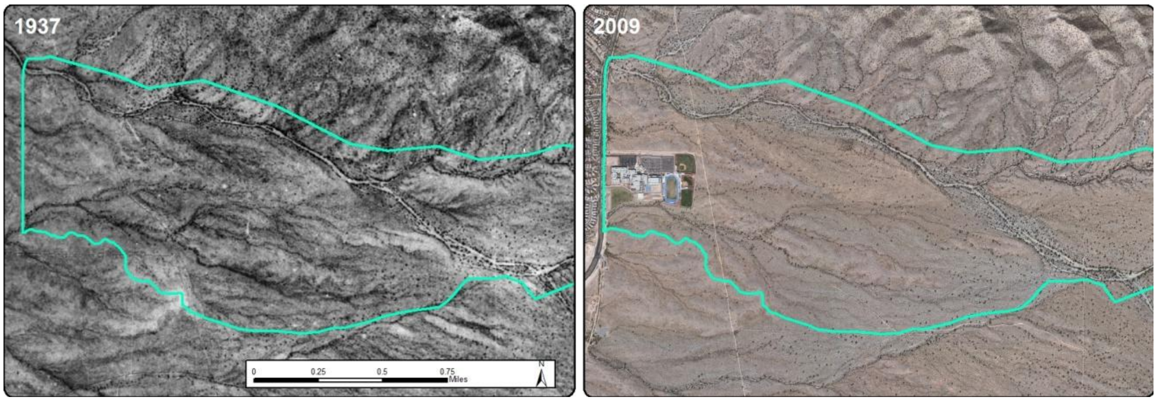

Figure 7. Rainbow Valley Fan 1, 1937-2009

2.4.5. Rainbow Valley Fan 12

There has been no systematic evaluation of historical avulsions at the Rainbow Valley Fan 12 site. However, simple comparison of 1937 and 2009 aerial photographs (Figure 8) reveals both apical and lower fan minor avulsions have occurred during the 72 year period of record. The low resolution of the 1937 photographs precludes detailed description of the avulsions, although this interpretation is consistent with conclusions drawn from trench soil stratigraphy, as reported by CH2M HILL (1992). The CH2M HILL trench profile indicated that while the main channel location had been stable during recent geologic time, several "smaller tributary or distributary abandoned channels that did not correlate with active channels [on the surface] were visible." It was also noted that about three feet of net aggradation had occurred over the past 600-1,000 years at the trench location. The lack of major channel avulsions on this fan is probably attributed to the rapid transition to sheet flooding conditions, very high infiltration rates, and low flood water volume during flows.

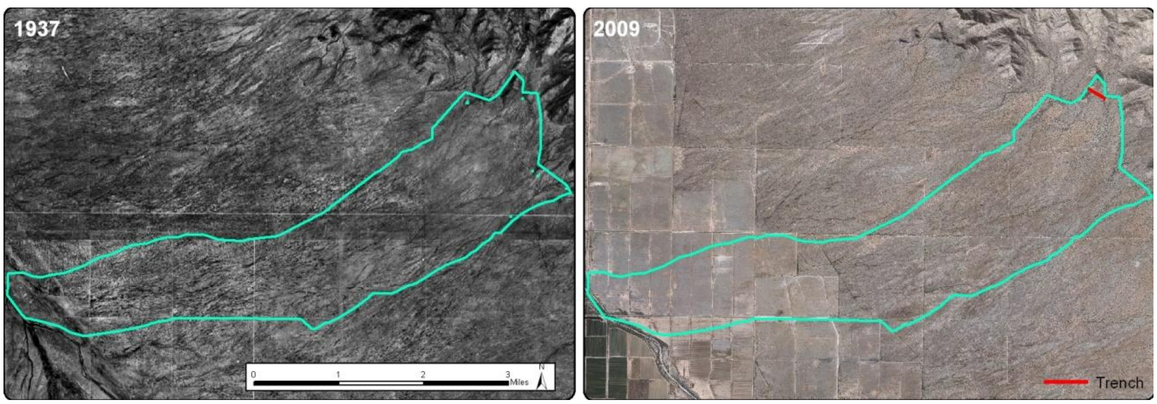

Figure 8. ***Rainbow Valley Fan 12, 1937-2009***.

2.4.6. Buckeye Hills Piedmont

A systematic analysis of changes in channel alignments visible on recent (2010) and historical (1949-1963) aerials was made for the southern Buckeye Hills pediment located in western Maricopa County (Figure 9, Figure 10). While changes in land use dominated most of the piedmont, the locations of a number of potentially avulsive channel changes were identified. In general, the following types of channel changes were observed:

- The same basic pattern channel was observed on the historical and recent aerials.
- Observed channel avulsions consist of new connections between pre-existing distributary channels, minor cutoff channels, and major expansions of existing minor overbank threads.
- Most, but not all, of the avulsions occur in the upper active fan areas near the hydrographic apexes.
- Several minor channel avulsions occurred on lower piedmont.
- Agricultural development altered channel patterns and obscured the record of channel change in many places.

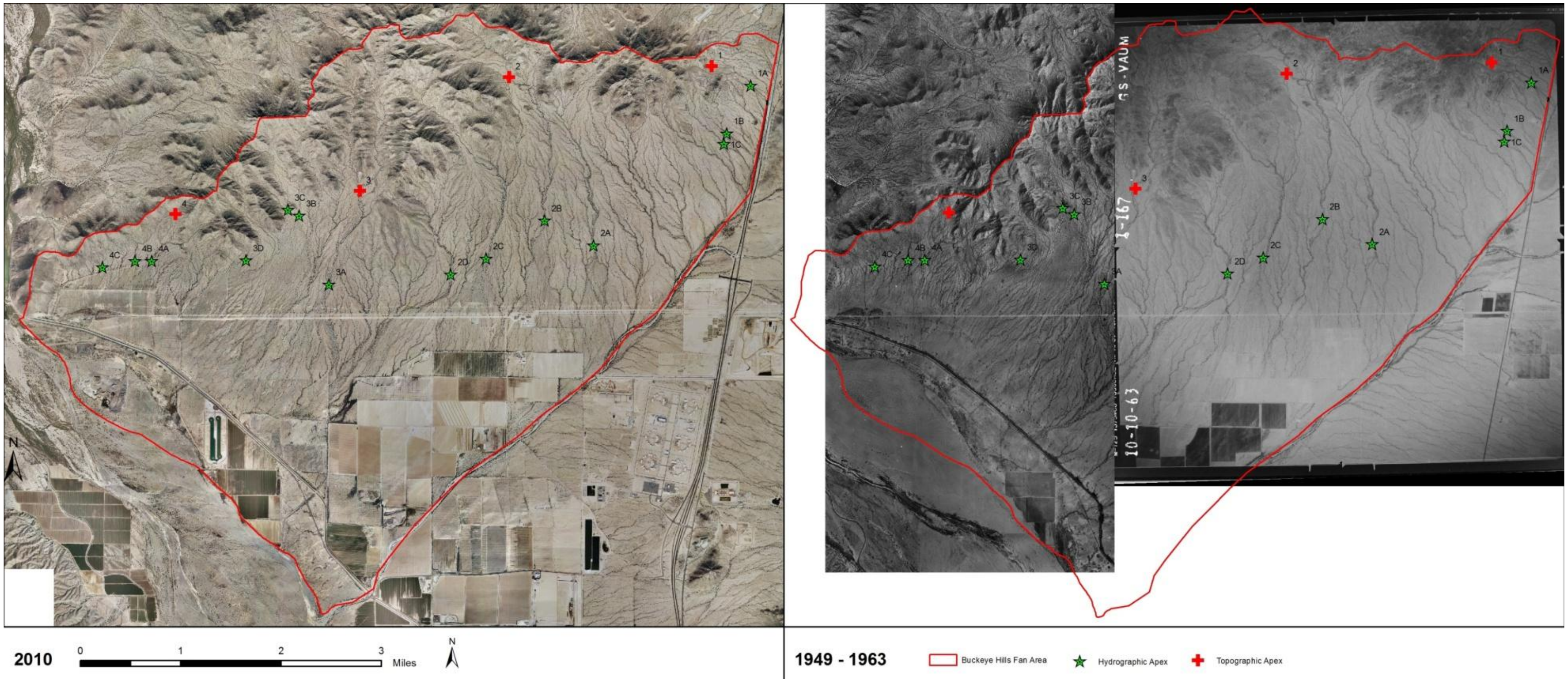

Figure 9. Side-by-side aerial photographs of Buckeye Hills Piedmont study area, 1949-2010.

- Overall, the channel pattern on the Buckeye Hills Piedmont has been very stable. Of the 1,435,071 feet of channel alignment digitized on the historical aerials, only 17,755 feet of new channel segments were identified, which translates to about one percent change during the 47- to 61-year period of record.

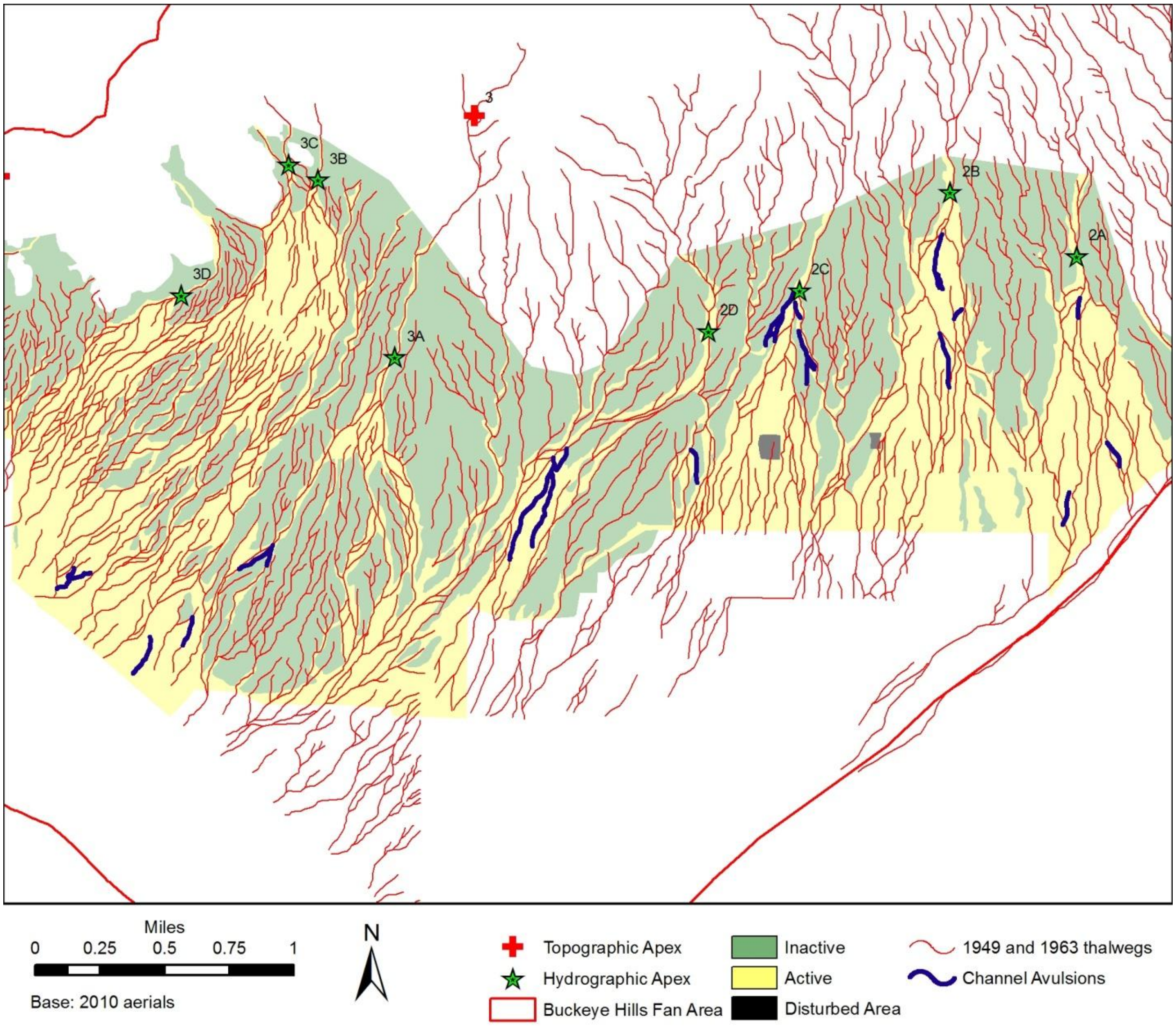

Figure 10. Location of historical avulsions identified on aerial photographs relative to AZGS surficial geology map units (Green -=active; Yellow = inactive).

2.4.7. Summary

Historical records clearly indicate that avulsions do occur on the types of alluvial fans found in central and western Arizona. The cursory data summarized above indicate that it is likely 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.

3. Avulsion Mechanisms

3.1. Past Studies of Avulsions

The topic of avulsive channel change on alluvial fans is not well represented in the scientific literature. The majority of the limited avulsion references found in an extensive literature search are directed at riverine avulsions. Most of the remainder of the avulsion literature either assume a priori the existence of avulsions because the landform is an active alluvial fan, or lack any detailed analysis of avulsion mechanisms, processes, or recurrence interval. The few studies that specifically focus on alluvial fan avulsions can be classified as follows:

- Field based observations. These studies include after-the-fact descriptions of avulsions, some with hypotheses or speculation as to the cause(s) of the avulsive channel change. Field (1996, 2001), examined avulsions in central and southern Arizona, and is the most relevant of the field-based studies. As noted by Field (2001), observations of alluvial fan avulsions have been recorded around the globe in a wide variety of environmental conditions.
- Physical modeling. Some interesting physical model studies of alluvial fan processes have been completed. Although the physical modeling studies were primarily oriented at alluvial fan behavior in general, they make interesting observations about avulsions as an essential element of fan development and evolution. The most relevant of these studies include Hooke (1965; 1967), Schumm et. al. (1987), Bryant et. al. (1995), and Parker et. al. (1998a, 1998b).
- Mathematical modeling. Very limited mathematical modeling of avulsions has been completed. Dawdy (1978) developed a statistical procedure that was intended to account for the effects of channel avulsions on alluvial fan flood hazards, but does not model actual avulsions. Although the Dawdy procedure was the first model adopted by FEMA for alluvial fan floodplain delineations, the methodology has been highly criticized (Fuller, 1990; NRC, 1996; French and Miller, 2012; Fuller, 2012) and is rarely applied today. Other similar formulations (Magura & Wood, 1980; DMA, 1985; Flippin and French, 1994; Heggen and Anderson, 1995) exist, but rely on the rather tenuous and unsupported assumption of random channel movement. Parker et. al. (1998) formulated a mathematical model to describe alluvial fan behavior that shows some promise, but as yet has not gained acceptance outside its initial application, and is probably not applicable to the low-sloped, ephemeral, fluvially-dominated alluvial fan systems found in central and western Arizona. Finally, several new modeling procedures have been developed (Fuller and Pearthree, in press) to identify potential avulsions as well as their flood impacts, as summarized in Section 4 of this report.

In addition to the three types of alluvial fan avulsion investigations listed above, there is a growing body of literature focused on riverine avulsions (c.f., Slingerland and Smith, 1994) in which most authors recognize at least some level of similarity between riverine and alluvial fan avulsive processes. While there may be much that is applicable to alluvial fan avulsions, the following differences between arid-region alluvial fans and perennial riverine systems are noted:

- Fan channels typically lack an alluvial ridge (a.k.a., natural levee) along the channel bank, a feature which is integral in the riverine avulsive process. Because of the lack of an alluvial ridge, the critical slope ratio threshold for riverine avulsions is rarely achieved on alluvial fans, and discharge and sediment deposition are more important causes of avulsions.
- Fans have higher excess sediment supply rates than rivers, increasing the role of sediment supply in causing avulsions.
- Fans in the arid west usually have higher flood ratios (Q100:Q2) than rivers, making the least frequent floods more important in causing avulsions.
- Fans have short, lower volume flood hydrographs, decreasing the amount of geomorphic work that can occur in any given flood, and increasing the amount of time needed to complete an avulsive cycle.
- Flow attenuation over the fan surface can absorb an entire flood hydrograph on many fans in the arid west, which induces sediment deposition and decreases the likelihood of avulsions in the downstream direction.
- Fan planform (shape) is expanding, not linear, resulting in extensive flow attenuation in the downfan direction.
- Fan sediments typically are coarser than riverine sediments, increasing the rate of infiltration and flow attenuation, both in the channel and on the floodplain.
- Fan slopes typically are steeper, increasing flow velocities and stream power (i.e., more erosive) and altering slope ratio characteristics.
- Fan surfaces typically have less organic matter and vegetative cover than rivers, resulting in fewer obstructions on the floodplain and higher floodplain velocities.
- Flood flow over fan surfaces is typically not the result of ground water outflows, with large vertical distances between the surface and the water table.

Because of these differences, methodologies derived from studies of riverine erosion are only partially applicable to alluvial fans, and should be applied with caution to the arid-region alluvial fans in central Arizona.

3.2. Types of Avulsions

All alluvial fan avulsions occur as the result of flow leaving a defined parent channel and entering a floodplain. Slingerland and Smith (2004) classified avulsions into the following types:

- Avulsion by Annexation. For this type of avulsion, an existing floodplain channel is appropriated or reoccupied when overbank flow leaves the parent channel and flows across the floodplain. Avulsion by annexation is sometimes called "second-order avulsions," in contrast to "first order avulsions" which involve channel shifts to entirely new parts of the floodplain (Nanson and Knighton, 1996). If the annexed channels are too small for volume of flow they are usually widened and/or deepened by erosion to contain the discharge. Avulsion by annexation is favored where floodplain aggradation rates are low, sediment supply is low, and some level of channel formation is present on the floodplain.
- Avulsion by Incision. For this type of avulsion, new channels are scoured into the floodplain surface. Flow across the floodplain seeks low ground where a channel

is scoured and/or floodplain flow re-enters a pre-existing channel at some point downstream of the avulsion, and knickpoint erosion works headward creating a new channel. In some cases, the parent channel fills by aggradation after the avulsion occurs, particularly if the parent channel is perched above the surrounding floodplain. Incision avulsions are favored in quick draining floodplains that have steep slopes, sparse vegetation, little lateral relief, erosive soil materials, and/or no significant floodplain obstructions, all of which are conditions that exist on most active alluvial fans in central Arizona.

- Avulsion by Progradation. Avulsions by progradation occur where there is extensive sediment deposition on multi-channeled distributive networks such as anastomosing streams. They typically occur where the avulsive flow is slow moving, and on flat floodplains with dense vegetation or extensive ponding. Sediment deposition on floodplain progrades from parent channel exit point further out onto floodplain as avulsion continues.

All of the avulsion types listed above can be grouped as "overflow" avulsions. Based on extensive field reconnaissance and analysis of historical aerial photographs of alluvial fans in central and southern Arizona, Field (2001) recognized an additional type of avulsion caused by stream piracy. Piracy avulsions have elements of avulsions by annexation, in that an existing floodplain channel is involved, as well as annexation by incision, in that they tend to occur on steep, fast draining floodplain surfaces and new channels can be scoured into the fan surface. For piracy avulsions, headwater erosion from an on-fan drainageway intercepts the parent channel, creating a flow bifurcation. If the pirate channel is steeper than the parent channel, it may divert a high percentage of the runoff, eventually leading to abandonment of the parent channel downstream of the bifurcation. It is likely that headward erosion is not the only process involved, and that overflow from the parent channel also contributes to, or accelerates, the avulsion process. The 1997 Tiger Wash alluvial fan avulsions (Pearthree et. al., 2004) were formed by annexation of the incipient on-fan drainage network, but also included elements of avulsion by incision and progradation. It is likely that combinations of avulsive mechanisms operate in any given historical avulsion.

FEMA (2003) guidelines identify an additional type of avulsion that occurs on alluvial fans. Changes in flow distribution within sheet flooding areas are considered by FEMA to be avulsive (a.k.a., active alluvial fan flooding) because the overall area of inundation changes between floods. FEMA's inclusion of sheet flooding as avulsive behavior differs somewhat from traditional definitions of avulsions in most of the literature, although the historical channel changes observed in the distal mid-fan region of White Tank Fan 36 (See Section 2.4.2) corroborate their interpretation in that avulsions have been documented in areas that FLO-2D modeling indicates are subject only to shallow flooding. FEMA's inclusion of changes in flow distribution as avulsive, without necessarily any accompanying channel change, is not inconsistent with the literature, though most literature sources focus on physical changes in channel location.

3.3. Factors That Cause Avulsions

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 2). 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 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 2. 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 & 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)
• Radial contour pattern	Low radius contours indicate greater avulsive potential (B)
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 (P)
• Flood volume	High flood volume capable of more geomorphic work (P)
• Flood sequence	Sequence of floods important for set-up conditions (F)
• Overbank flooding	Overbank flooding is a necessary condition (SS)
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 (SS)
• Aggradation	Aggradation is a necessary condition (SS)
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, T)
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 need 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	

3.4.Avulsion Processes

The following investigators have developed conceptual models that describe the avulsion process on alluvial fans.

- Field's Five Stage Development Model
- Bryant's Three Phase Development Model
- Schumm's Cyclical Incision Model
- Parker/Whipple Model

These models are briefly described below.

3.4.1. Field's Five Stage Development Model

Based on field work, review of aerial photography, interpretation of stratigraphic profiles exposed in soil trenches, post-flood reconnaissance and mapping in central and southern Arizona, Field (1994, 2001) identified five key stages in development of alluvial fan avulsions (Figure 11). Each of the five stages is characterized by unique channel morphologies:

- Stage 1: On-Fan Channels. In this stage, a distributary channel branch conveys flow from the fan apex (and above) onto the active fan surface. These on-fan channels cover only a small portion of the fan surface. Because of rainfall directly on the fan surface, small dendritic channel networks form in the areas not directly drained by the active distributary (main) channel.[2] These weakly defined channels are considered an incipient drainage network.
- Stage 2: New Channel. During large floods that overtop the parent channel, portions of the on-fan channels that approach the main drainage concentrate overbank flow and are captured. Alternatively, headward erosion of the incipient drainage network may capture the parent channel.
- Stage 3: New Channel Widened. During the flood, the captured flow expands the width of the now-connected avulsive channel, increasing its capacity to divert flow from the parent channel. The channel width adjusts toward a regime width associated with the maximum captured flow rate.
- Stage 4: Aggrading Channel. After the avulsive event, small floods tend to infill the captured channel with sediment and vegetation, decreasing its width and capacity. The infilled channel is more prone to overtop and cause bedload-limited (erosive) sheet flooding, which if concentrated in the on-fan channel network, may initiate headward erosion and additional avulsive captures.
- Stage 5: Abandoned Channel. Depending on the relative bed elevations of the parent and avulsive channel, the flood sequence, and their alignments, one of the channels may be completely filled and abandoned as a low flow conveyance corridor.

In Field's model, large floods are the most effective agents of change, although the sequence of events leading up to an avulsive flood may be important for setting up

[2] Note: Field tends to describe the surfaces outside the main through-channel on a fan as "inactive," but assigns a different meaning than that used in FEMA Appendix G.

conditions conducive to avulsion. Field developed his model from observations on alluvial fans in central and southern Arizona. Field's model is analogous to Slingerland and Smith's (2004) category of avulsion by annexation, which is thought to be more common on floodplains with low aggradation rates (low sediment supply), a consistent finding with observations of alluvial fans in central Arizona made for this study.

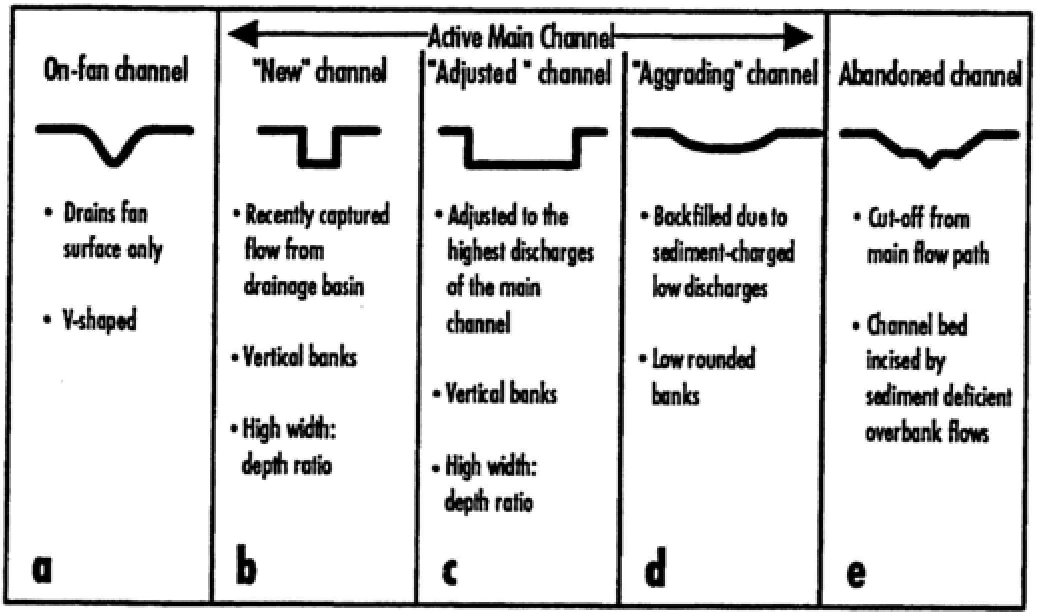

Figure 11. ***Field's five-stages of alluvial fan avulsions.***

3.4.2. Bryant's Three Stage Development Model

Bryant et. al. (1995) used laboratory experiments to theorize that fans typically develop in the following three phases:

- Phase 1: Initial Conditions. More than 50% of the fan surface is covered by sheet flooding, with no defined channels and avulsions. Sediment deposition occurs by sheet flooding processes.
- Phase 2: Fan Growth. As the alluvial fan grows, distinct channels develop, but they are unstable and bifurcate. Sediment deposits form as crevasse splays off the main channel, with less than 50% of flow exiting the parent channel.
- Phase 3: Maturity. In this phase, a single channel is solely responsible for fan deposition. Apical avulsions relocate this channel to other parts of the fan, which then delivers sediment to new parts of the fan surface. A secondary sediment supply comes from the crevasse splays.

In Bryant's model, non-avulsive systems never reach Phase 3, and distribute most of their sediment supply via secondary channels and sheet flooding. While the frequency of channel avulsions is not well documented in central and western Arizona, several researchers (Field, 2001; Pearthree et. al., 2004) have hypothesized that avulsions are at least infrequent, making it likely that much of the sediment delivery on fans in central and western Arizona is accomplished through sheet flooding and secondary channels, rather than by direct avulsion.

3.4.3. Schumm's Cyclical Incision Model

Based primarily on laboratory physical models, with some field verification from alluvial fans in the northern Rocky Mountains, Schumm et. al. (1987) described alluvial fan evolutionary processes that included repeated cycles of channel filling, avulsions and scour. The Schumm model focuses on avulsions along fanhead trenches, which are the defined channels that originate upstream of an alluvial fan apex and continue to the point where the channel pattern becomes distributary. Schumm noted the following two basic patterns in fan sedimentation:

- Deposition at Fan Perimeter. Deposition along the distal margins of an alluvial fan is associated with periods of channelization at the apex and midfan. When defined channels exist in the mid-fan area, they tend to push sediment across the fan surface to the toe, with additional sediment contributed by bank erosion along the channel. Fanhead channel trenches fill slowly, generally filling near the fan toe first, and then progressing up toward the apex. Sediment deposition in the toe area was found to be mostly uniform with time.
- Deposition at Fan Apex and Midfan. When the fanhead trench has been fully backfilled (or prior to its development), deposition on the alluvial fan is widespread and dispersed, but is concentrated near the apex, increasing the fan slope near the apex. Eventually, the apical slope increase causes a fanhead trench to be incised. Deposition in the near-apex zone was found to be highly variable (episodic) with time. The midfan area, which is primarily a transport zone, was generally not subject to either extreme deposition or erosion rates.

Schumm also noted the following modeling results with respect to avulsion processes on an alluvial fan:

- The cycle of fanhead entrenchment, fill, and avulsion to a new location repeats often, regardless of whether a constant or variable discharge was applied to the experimental fan.
- Geomorphic channel changes on the fan are "extreme and dramatically episodic" with very short time periods separating fan deposition from fanhead trenching.
- Fan entrenchment and deposition did not correlate well with fluctuations in sediment yield, particularly at the apex. Specifically,

  > *"Fluctuations in both the location and rate of deposition over the fan surface persisted during period of relatively constant sediment yield. Therefore, it did not appear that the events occurring on the fan were directly controlled by sediment delivery. Similarly, minor fluctuations of sediment yield did not correlate well with periods of fanhead aggradation or incision. Thus, while downfan patterns of alluvial fan sedimentation were controlled by events at the apex, events at the apex were not uniquely controlled by events in the drainage basin."*

- Avulsions tended to occur in the steeper portions of the fan, but there is a transition zone in which the flow path curves from the direction suggested by momentum (straight from upstream) toward the direction of the steepest slope, i.e., the influence of topography increases in the downfan direction. The most stable channel location (fanhead trench) is along the axis of the fan. If the main channel is located off-axis, it will tend to migrate by lateral erosion toward the axis.

- Episodic (variable discharge) fans were very similar in evolution and process to constant discharge fans, except that less lateral migration of trench channels occurred on the episodic fans. Big floods on episodic fans were not the primary agents of change.
- Sites of active deposition are rapidly abandoned, probably because aggradation tends to direct flow away from topographically rising areas.
- On fan as a whole, it was found that: (1) there was a 2% chance of erosion at any given point, (2) if erosion did occur, there was 76% chance of deposition at the point in the following time period, and (3) 63% of sample points experienced "no substantial change" over course of experiment (12,418 measurements) cumulatively during all flow periods.36% experienced deposition.
- Two kinds of fanhead trenches were observed:
  - Shallow, short-term features subject to frequent overflow that were formed by active fluvial processes.
  - Deep, permanent features that were not overtopped, and were formed in geologically stable settings. The deep, permanent channels were formed by changes in geologic processes, such as tectonism or climate change.

Due to potential model scaling issues, Parker (1999) questions whether the physical modeling results like those of Schumm are directly applicable to real-world fans. Certainly, some of Schumm's observations are contrary to observations of real-world fans in Arizona. For example, Field (1994) concluded that large floods were a primary cause of alluvial fan avulsions and that avulsions are rare. In fact, Schumm's experimental fans were much steeper and wetter than alluvial fans in central Arizona. Certainly, the rate of avulsive channel change observed in the experimental fans far exceeds not only the rate of channel change observed on alluvial fans in the study area, but also the frequency of avulsions. Experimental fans in the laboratory typically have near continuous avulsions. Alluvial fans in central Arizona appear to experience avulsions on at least decadal or century time scales.

However, there are several conclusions drawn from Schumm's work that are relevant to avulsions on alluvial fans in Arizona. The apparent independence of avulsion frequency from sediment supply rate on fluvial fans is probably applicable, particularly given the relatively low sediment yields for the low desert mountain watersheds of central Arizona. Schumm's finding regarding the low probability of erosion or deposition at any given point on the fan, even on the highly active experimental fans, probably indicates that most active fan surfaces in central Arizona have a high probability of no significant change during any given year. Finally, Schumm's observation that deep, stable fanhead trenches are relatively permanent features formed and removed by geologic processes that operate outside normal engineering time scales is directly relevant to assessment of alluvial fan flood hazards in central Arizona.

3.4.4. Parker/Whipple Model

Parker et. al. (1998) and Whipple et. al. (1998) used experimental studies and observations of alluvial fans composed of mining by-products and talus to develop theories of fan formation, evolution, and behavior. While their mathematical model assumes the occurrence of avulsion, they do not explicitly model formative mechanisms for avulsions. Some of their findings, however, are relevant to alluvial fans in central Arizona. In particular, they found that the process of sheet flooding is unstable over the long term. In their physical model studies, sheet flooding areas always transitioned to channels after a short flow distance, regardless of what part of the fan was considered. After sheet flooding in the physical models became concentrated into channels, the channels tended to extend up fan via headward erosion. Incised channels formed in this manner had high rates of sediment transport delivered to depositional lobes ("splays"), which also tended to migrate up fan, filling and obliterating the previously incised channels.[3] No evidence of up fan migration of splays during the period of historical record was identified for any of the fan sites considered for this study. This cyclical process occurred at all fan scales and in all parts of the fan. Parker's model is also discussed in more detail in Section 4.4.2 of this report.

3.5. Avulsion Frequency

There have been few published studies of avulsion frequency, and fewer still that are applicable to alluvial fans in central and western Arizona. The following statements summarize the current understanding regarding 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 for 18 fan sites in California and Nevada, none of the test sites had any evidence of avulsions despite the occurrence of very large floods. DMA further reported that the default avulsion coefficient of 1.5 in FEMA's FAN model means that a major avulsion occurs in every other 100-year event.

[3] The described process mimics Bull's (1997) discontinuous ephemeral stream model.

- 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.

3.5.1. Prediction of Avulsion Frequency

The following models have been developed to predict avulsion frequency on riverine systems:

- Jerolmack & Mohrig (2007)
- Tornqvist (2004)
- Slingerland and Smith (2004)

Jerolmack and Mohrig (2007), in a study of riverine avulsions, developed the following equations to predict avulsion frequency:

$T_c = B/V_c$ — Equation 1

$T_a = h/V_a$ — Equation 2

$f(a) = V_a N / h$ — Equation 3

$M = T_a / T_c = (h V_c) / (B V_a)$, — Equation 4

$E = S ((g h B^4)^{0.5}) / Q$ — Equation 5

where:

T_c = time for a channel to migrate a distance equal to its width
B = total channel width
V_c = bank erosion rate.
T_a = time for channel to aggrade amount equal to its depth (h) above the distal floodplain. T_a is an avulsion time scale
V_a = aggradation rate near the channel.
f(a) = avulsion frequency of the stream channel
N = number of active channels
M = Mobility number
  $M >> 1$, very rare avulsions
  $M << 1$, frequent avulsions
E = Parker's stability criterion
  $E << 1$, single channel
  $E > 1$, braided
S = water slope
Q = channel forming discharge

It is possible that Jerolmack and Mohrig's methodology could be applied or modified to predict avulsion frequency on alluvial fans in Arizona. However, it may be difficult to collect the data required to populate their equations (migration times, lateral erosion rates, aggradation rates) without a regional data collection effort, analysis of regional avulsion frequency, and extensive geologic data collection at the site of interest. Interestingly, Jerolmack and Mohrig also found that the type of triggering event is not important for determining the avulsion frequency. In addition, they found that to generate avulsions, the aggradation rate should be high and the lateral movement rate low.

Tornqvist (2004) found that the probability of avulsion could be estimated using the following equation:

$$P(a) = (Q_f/Q_a)^{eQ} * (k_s\ S_{cv} / S_{dv})^{eS} \qquad \text{Equation 6}$$

where:

- Q_f = maximum flood peak in any year
- Q_a = threshold discharge that causes an avulsion
- S_{cv} = local cross valley slope at edge of channel belt
- S_{dv} = local down valley slope near the edge of the channel belt
- k_s = avulsion coefficient, added to reflect required slope ratio, Eqn. 5
- eQ = avulsion discharge exponent
- eS = avulsion slope exponent

For Tornqvist's methodology, Equation 6 is computed at each time step and at each cross section, and then is compared to random number between zero and one. If P(a) is greater than the random number, avulsion occurs. Note that this model is more probabilistic than deterministic. If the ratio of the terms to right in the equation is close to one, the probability of an avulsion increases. The probability of an avulsion increases with the slope ratio and discharge, both of which are intuitively obvious and are supported by numerous field studies. It may be possible to apply this equation to alluvial fans in Arizona, although it would require a significant amount of data from which to calibrate the various parameters. Currently, none of these regional or site-specific data sets exist.

Slingerland and Smith (2004) found that the time rate of the avulsion sequence is dependent on the following factors:

- Parent channel initial depth. A deeper channel requires more time to aggrade to the point of overtopping, or a large recurrence interval flood.
- Flood magnitude. The larger the flood, the higher the avulsion potential.
- Flood sequence. Large floods tend to flush and reset system. Small floods, or extended periods of low flows, tend to aggrade the main channel and set-up conditions conducive to avulsions.
- Proximity of on-fan channels. Nearby avulsive flow conduits increase the probability of forming complete avulsions.
- The ability of bifurcated channels to change their capacities. The stability of the bifurcated channels is a function of:
  - Shield parameter (fluid shear stress: weight of grains/area)
  - Friction coefficient
  - Median grain size
  - Aspect ratio (1/2 width: depth)
  - Water slopes in split channel segments relative to the parent channel
  - Bed elevation differences of parent and new channels at the bifurcation point

- Slope ratio. For suspended load streams (D50<0.4 mm), if the branch slope is greater than five times the slope of the parent channel (or another branch), it will tend to capture all of the flow and abandon the flatter branch. However, such drastic slope differentials are rare on alluvial fans in Arizona.
- For bedload streams with large Shields parameter, water discharge is proportional to the inverse slope ratio.

3.5.2. Avulsion Frequency for Alluvial Fans in Central Arizona

The recurrence interval of avulsions on alluvial fans in central Arizona is not well known. It is known that avulsions do occur on alluvial fans in the region, as documented by several historical accounts summarized in Section 2.4 of this report. Almost all of the causative factors for avulsions listed in Table 2 exist on alluvial fans in central Arizona, and thus it is likely that avulsions will continue to occur in the future. It is also likely that avulsions are relatively rare events, as suggested by Pearthree et. al. (2004), and may have less than a one percent chance of occurrence in any given year (Field, 1994; 2001). Given the importance of the avulsion process to quantifying flood hazards on alluvial fans (See Section 1.2 of this report), it is strongly recommended that a systematic evaluation of avulsion frequency fans be performed in the future.

4. Methods to Predict Avulsions

Historically, the methodologies used to predict avulsion hazards on alluvial fans can be grouped into the following four basic categories:

- Predictions Based on Evaluation of Past Behavior
- Predictions Based on Evaluation of Field Evidence
- Predictions Based on Extrapolation of Physical Model Studies
- Predictions Based on Mathematical Modeling of Fan Processes

Each of these basic categories is discussed below. In addition, the methodologies used to predict channel avulsions in this study are summarized.

4.1. Evaluation of Past Behavior

4.1.1. Comparison of Historical Aerial Photographs

The most reliable way to determine whether a risk of avulsion exists on an alluvial fan is to document evidence of recent historical avulsions. For most of the United States, and all of central and western Arizona, it is relatively easy to find historical aerial photographs that date back to at least the 1950's, and in many cases to the late 1930's.[4] The channel position, geometry, and characteristics identified on historical aerials can be compared to that shown on recent aerials, and the occurrence and nature of avulsions readily determined. Photographic comparisons can either be done over the entire period of record (i.e., oldest to most recent aerial), or can be done using photographs that pre- and post-date a specific significant flood. Examples of this type of photographic comparison are shown in Figure 4 to Figure 8. The aerial photography comparison methodology is robust, cost-effective, and easy to apply, although it is somewhat dependent on the quality of the aerial coverage and the availability of photography near the dates of known floods. In some cases, photographic evidence of an avulsion can become faint or disappear completely over longer time periods, making it possible to miss some types of avulsions if too long a gap between photograph dates is used. In addition, if only the oldest and most recent aerials are used and are assumed to represent the entire history of channel movement during the period of record, the occurrence of multiple avulsions during that time period might be missed.

4.1.2. Interpretation of Soil Stratigraphy

The occurrence of past avulsions can also be identified by examining soil stratigraphy exposed in trenches excavated across a fan surface. Experienced soil scientists and geomorphologists can readily identify stratigraphic features in the soil profile that yield information about the following:

- Former channel deposits that are now below current overbank areas, indicating that the current channels have avulsed away from their former location.
- Overbank deposits below current channels, indicating that the current channels have avulsed into areas that formerly were overbank floodplains.

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[4] In rare cases, channel position comparisons can be made using historical topographic mapping, which may extend the period of record beyond the inception of aerial photography (circa 1930).

- Multiple, stacked sequences of channel and floodplain deposits indicating repetitive avulsion or migration of channels across the fan surface.
- No change in past channel and overbank deposits, indicating a lack of significant avulsions or channel migration.
- Buried soil profiles or surficial features, indicating episodic long-term aggradation of the fan surface, which in turn may imply potential for future channel avulsions.

If datable material is found in the soil profile, then a chronology of channel change can be pieced together which could be used to estimate the frequency of avulsions (or duration of stability). Dating the soil profile can be done using archaeological or historical artifacts, organic material that can be carbon dated, trees with measurable tree rings, pollen samples, or soil development principles. Datable material can also be used to estimate the rate of fan aggradation. On alluvial fans, high rates of aggradation generally correlate to frequent avulsions. Evaluation of soil trenches can be labor-intensive, and may require permits and right-of-entry that can be difficult to obtain. It also requires experience in soil profile interpretation, a skill set that is moderately uncommon. In addition, on large alluvial fans, it may be difficult to sample a representative portion of the fan surface, necessitating extensive extrapolation between trench locations. However, in some cases, investigators may opportunistically take advantage of utility trenching or other construction projects to obtain subsurface soil data.

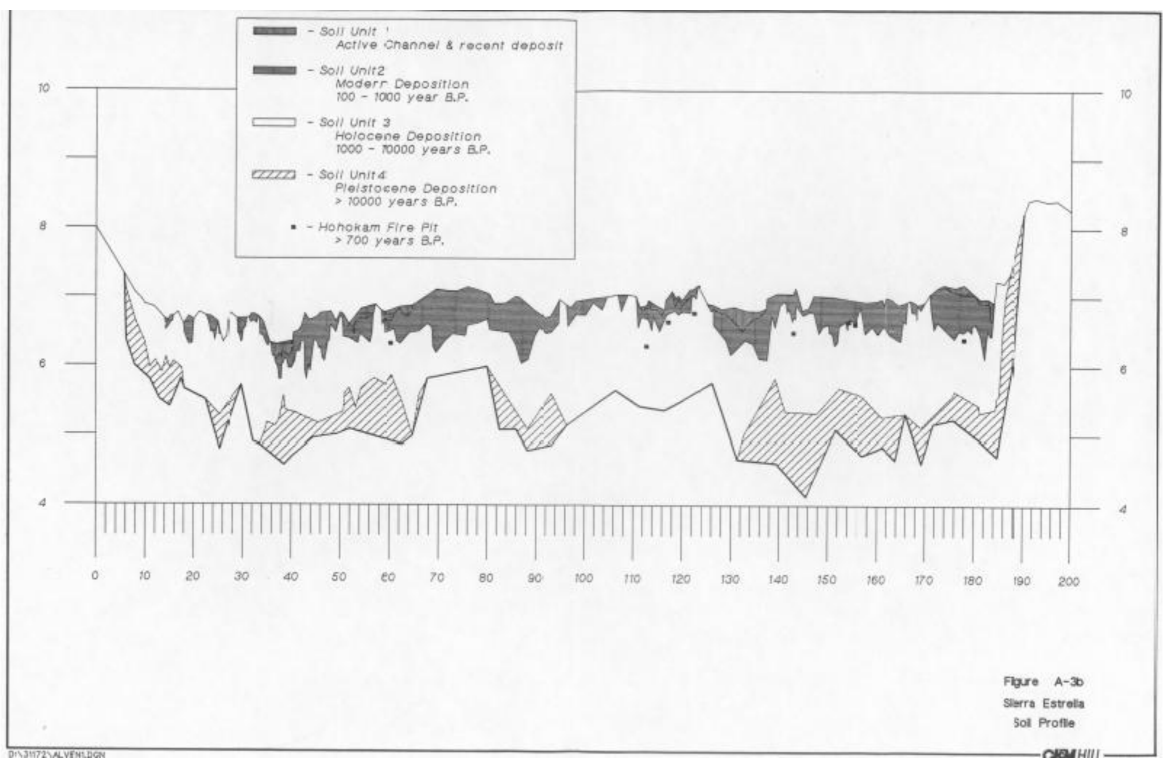

Figure 12. Trench soil profile from Rainbow Valley Fan 12 (CH2M HILL, 1992)

4.1.3. Other Methods

In rare cases, usually if historical avulsions impacted buildings or public infrastructure, there may be written descriptions, news accounts, or photographic records of past avulsions, which represent a third possible source of information about the past behavior of an alluvial fan.

4.2. Evaluation of Field & Map Evidence

The potential for alluvial fan avulsions can also be assessed by observation of existing site conditions in the field. Some portion of the work can be completed in the office through the use of topographic maps and aerial photographs. Types of field evidence that indicate avulsion potential are described below. These types of evidence may be used as indications of past or future avulsion, although any one type of evidence generally should not be considered definitive evidence by itself. These types of indicators are most diagnostic when a suite of indicative characteristics are present at a field site.

4.2.1. Channel Pattern

Beaty (1963) reported that the mere presence of a distributary channel pattern is evidence of past avulsions, although Hjalmarson and Kemna's (1992) study of distributary flow areas in Arizona identified other potential explanations for the formation of channel bifurcations on piedmont surfaces. Historical evidence from the alluvial fans evaluated for this study indicates that the presence of distributary channels on active alluvial fans (as opposed to other types of piedmont surfaces) is at least correlative with past channel avulsions, if not causally related. Other channel pattern evidence of avulsions includes the following:

- Perched, active channels elevated above the surrounding floodplain surface. These types of channels are sometimes difficult to identify in the field, but are readily identified in hydraulic models where more conveyance is available at lower elevations in the overbanks than above the sandy channel bed.
- Abandoned or perched channels disconnected from the active channel network. These types of channels can be identified as abandoned by the types of vegetation on the channel bed, the lack of fresh deposition or erosion, filling by fine-grained (overbank) sediments, or complete infilling of the channel leaving only linear remnants of bank vegetation.
- Underfit channels. These types of channels were formed by expansion in response to large flood flows which no longer are conveyed along that flow path, and can be identified by inset channel features, offset cut banks separated from the currently active channel, and irregular channel geometry.
- Channels with no or poor bank vegetative cover, in stark contrast to channel conditions elsewhere on the fan. These channel types typically indicate very recent formation (avulsion) or expansion, and often have very fresh, vertical cut banks.
- Relict buried channels, sometimes identified by alignments of dead trees only found along channel banks elsewhere on the alluvial fan. In many cases, relict infilled channels can be identified only by trenching and stratigraphic description of the soil profile.
- Erosive lineations in the floodplain apparently caused by overbank flows leaving the active channel network at a discrete point. These features may be more easily identified in aerial photographs than in the field, particularly if some time has passed since the causative event.

- Discontinuous ephemeral stream pattern (repeating chute and splay channel form). Rapid transition from a single, well-defined channel to a highly distributary channel pattern is evidence of net sediment deposition which can result in widely varying flow distributions between floods.
- Aggrading channels. Field evidence of aggrading channels includes low or downstream-decreasing bank heights (in contrast to bank heights elsewhere on the channel system), highly braided channels, and bed elevations that are higher mid-channel than at the margins.

4.2.2. Surface Age

The distribution of geologically young surfaces on the alluvial fan may be evidence of the potential for avulsions. If the youngest surfaces are arrayed in a radial pattern extending outward from the fan apex (i.e., a "fan" shape), the surface was formed by channel avulsions of some type. It would not be possible to form a fan-shaped young surface by stable riverine processes. Riverine floodplains tend to be distributed in a linear pattern roughly parallel to the channel, and contained between higher, older terraces that usually converge in the downstream direction.

The relative age of the surfaces is also indicative of the avulsion potential. Alluvial fans that are subject to very frequent avulsions will have the widest distribution of the youngest surfaces, with little distinction in surface age between the active channels and the floodplain, as well as between younger and older fan surfaces. Less avulsive alluvial fans will tend to have slightly older surfaces and a greater distinction in age between the active channel and the adjacent floodplains.

On active alluvial fans with potential avulsions, "islands" of older surfaces are often inset within the broader areas of younger surfaces. On the most active, avulsive alluvial fans there is usually little or no topographic relief between the younger and (inset) older surfaces. In other cases, the younger surfaces are perched topographically above the older surfaces, making the older surface areas vulnerable to inundation during an avulsion.

The types of field evidence used to estimate surface age on alluvial fans are well documented elsewhere (Birkeland et. al., 1991; FCDMC, 2003; JE Fuller, 1999, 2009; Young, 2010). Therefore, no detailed description of these indicators is provided in this report. Age indicators include such features as desert varnish, desert pavement, surface color, vegetative characteristics, topographic expression, channel pattern development, and soil profile development.

4.2.3. Stratigraphy (Smith et al, 1989).

The occurrence of avulsions on an aggrading landform creates a unique stratigraphic footprint, as described by Smith et. al. (1989). Where deeper stratigraphic information is available, it can be interpreted to estimate the frequency of avulsion as well as the overall rate of avulsion (Smith et. al., 1989; Tornqvist, 2004). However, no such stratigraphic data sets exist for alluvial fans in Arizona. If deep aggregate mines are sited on alluvial fans in the future, it may be possible to obtain such data by inspection of the exposed cut slopes in the mines. The near-surface stratigraphy is also useful for interpreting the more recent history of avulsions, as described in Section 4.1.2 above. Finally, the burial of older surfaces along the margins of the young, active portion of a fan may indicate a type of avulsion that also leaves a distinct stratigraphic pattern, such as varnished pavement surfaces with soil development are covered by younger alluvium.

4.2.4. Topography and Map Analysis

The topography of an alluvial fan can also be used to indicate the potential for avulsions. First, the radial contour pattern is not only one of the key identifying characteristics of the alluvial fan landform, the degree of contour bending is directly proportional to the risk of an avulsion leaving and remaining separated from the parent channel. The greater the degree of contour bending (i.e., lower radius of curvature), the more likely it is that any flooding that overtops the main channel banks will not return to the channel, but will instead find a new path to the toe of the alluvial fan. Second, areas of recent deposition (i.e., young surfaces) tend to be perched topographically above areas that have not received sediment deposition (i.e., older surfaces). Where such topographic inversions exist, they are likely sites for future avulsion since flood water tends to seek out the steepest flow paths. Third, potential flow paths outside the existing channel network can sometimes be identified as continuous low areas by inspecting topographic maps, as described in Section 4.5.7 below. Fourth, lack of topographic relief between the active channel network and the fan floodplain surfaces provides an opportunity for overbank flows that could cause avulsions. Finally, development of an on-fan drainage network provides topographic features that could collect and concentrate overbank flooding and provide sufficient energy for an avulsive channel to form.

4.3. Physical models

Physical model studies of alluvial fans (Hooke, 1967; Schumm et. al., 1987; Parker et. al., 1998) have made significant contributions to understanding alluvial fan processes, including the role of avulsions in alluvial fan evolution. Some of the more important findings relating to avulsions derived from physical model studies include the following:

- Avulsions can occur anywhere between the apex and the toe.
- Avulsions along fanhead trenches occur as cyclical cut and fill processes.
- The occurrence of avulsions is directly related to discharge, but is only weakly correlated to sediment supply.

However, these physical model studies have not directly improved our ability to predict the occurrence or frequency of avulsions on specific, real-world alluvial fans. Constructing a physical model of a specific alluvial fan field site would be cost-prohibitive in most cases, and is probably physically impossible. In general, the physical model studies report observations of avulsion, but do not explicitly evaluate the cause of avulsions. Whipple et. al. (1998) warn that scaling effects in the model study make it difficult to apply the results to fans outside the laboratory.

4.4. Mathematical & Computer Modeling

There have been several attempts to formulate mathematical descriptions of alluvial fan avulsion processes, none of which are particularly useful for predicting avulsions on alluvial fans in central Arizona. These models include the following:

- FEMA FAN Model
- Parker Model
- Riverine Avulsion Models
- Fixed Bed Hydrologic & Hydraulic Models

4.4.1. FEMA FAN Model

The FEMA FAN model (FEMA, 2003) was one of the earliest attempts to generate a mathematical model of alluvial fans flood hazards that incorporated potential avulsions. The probabilistic model is based on a mathematical formulation developed by Dawdy (1978), as well as a number of key assumptions about the behavior of alluvial fans. The FAN model has been extensively criticized in the literature (Fuller, 1990; French, 1992; NRC, 1996; Fuller, 2012) and is prohibited from use by at least one Arizona agency (ADWR, 1995). Some of the key reasons it should not be applied in central Arizona for flood hazard assessments include the following:

- Discharge. The predicted flow depths are based on the assumption that the full apex discharge is not attenuated or supplemented by tributary or on-fan flow sources as the flood traverses the alluvial fan landform. The results of this study, as well as post-flood field observations, indicate that significant flow attenuation occurs during transmission of the flood hydrograph across the fan surface, particularly in central Arizona where flood volumes tend to be small relative to the fan area.
- Random Flow Path. The FAN model assumes that flow is no more likely to follow an existing flow path than to create an entirely new flow path. Historical flood accounts (Pearthree et. al., 1992; Field, 1994; Pearthree et.al., 2004) and extensive two-dimensional modeling of the fan sites described in this study (JE Fuller, 2010) clearly demonstrate that floods are far more likely to follow the existing channel network than create new channels. The net effect of this erroneous random flow path assumption is to significantly underestimate flood hazards along the existing channel network and significantly overestimate flood hazards outside the existing channels.
- Channel Geometry. The FAN model results are derived from an unsubstantiated channel width-depth relationship that was shown to be erroneous on all of the alluvial fans examined by CH2M HILL (1992), and was not supported (or was directly contradicted by FEMA's verification study (DMA, 1985; Fuller, 2012). The FAN model assumed that flow is channelized, either in a single channel or in multiple channels, from the fan apex to the toe, and does not account for flood hazards related to sheet flooding or overbank conditions, which are known to be important components of flood conveyance on central Arizona alluvial fans.
- Topography. The flood hazards predicted by the FAN model do not account for topographic variation (high ground, low ground) across a radial profile of the fan surface, resulting in inaccurate predictions of flow depths, velocities, and inundation areas.
- Inundation Area. The FAN model assumes that all of the active area across a radial contour is equally floodprone. FLO-2D modeling performed for this study, as well as FEMA guidance documents (FEMA, 2003) indicate that not all of the Holocene surface is part of the regulatory floodplain.

- Design Data. The flood depths and velocities generated by the FAN model are not suitable for use in hydraulic design of structures.

For these reasons, it is recommended that the floodplain managers definitively preclude use of the FAN model for flood hazard assessments in Arizona. Additional problems with the FEMA FAN methodology are given in Fuller (2012).

4.4.2. Parker Model

Parker et. al. (1998; Parker, 1999; Whipple et. al., 1998) formulated mathematical descriptions of alluvial fan behavior. While the Parker formulations are intriguing, and probably could be adapted for alluvial fans in central Arizona if sufficient data were available for calibration, they are probably not applicable as currently formulated. The Parker model was developed for steeper fans with much higher sediment inflows and aggradation rates. Furthermore, the models assume the occurrence of avulsions, rather than explicitly modeling them, making their utility for predicting avulsions somewhat limited. Future development and enhancement of the Parker models is worth monitoring for possible future application to alluvial fans in central Arizona.

4.4.3. Riverine Avulsion Models

Some of the more recent mathematical formulations of avulsion risk and behavior on river channels were summarized in Section 3.5.1 above. While these formulations appear promising, they have not yet been evaluated specifically for use on alluvial fans, nor are there currently enough data for alluvial fans in central Arizona from which such an evaluation could be performed.

4.4.4. Fixed Bed Hydrologic & Hydraulic Models

The processes of alluvial fan avulsions occur over time frames that generally exceed a single flood hydrograph. In addition, alluvial fan avulsions inherently involve changes in bed and floodplain elevations, as well as changing channel boundaries on aggrading landforms. Therefore, fixed bed models are not capable of directly generating a realistic process-based simulation of an alluvial fan avulsion. For this reason, FEMA guidance documents (2003) specifically precludes[5] performing floodplain delineations on active alluvial fans with such models, unless they are used in combination with other methods, and unless there is explicit consideration of flow path uncertainty by other means. Nevertheless, because of the limited number of alternatives, the following uses of fixed-bed hydrologic and hydraulic models have a place in assessment of avulsion hazards on alluvial fans:

- Hydrology: HEC-1. JE Fuller (2010) demonstrated that HEC-1 (or any similar lumped-parameter unit hydrograph based rainfall-runoff-routing models) does not adequately model the hydrology of floods downstream of the alluvial fan apex. HEC-1 may be useful for generating flood hydrographs in tributary drainage areas upstream of the fan apex or modeling flow distributions between stable bifurcating channels. On alluvial fans, however, HEC-1 performs poorly in developing and routing the flood hydrograph across broad, shallow floodplains

[5] FEMA, Appendix G, Table G-1; Section G.2.3.4

and poorly defined distributary flow networks, and accounting for infiltration on permeable alluvial surfaces.

- Hydrology: FLO-2D. FLO-2D is a two-dimensional routing model. While FLO-2D cannot explicitly predict or simulate avulsions, a method of accounting for the effect of flow path uncertainty on peak discharges at concentration points downstream of the alluvial fan apex was developed for this study, as described in Section 4.5.4 below. The recommended methodology uses multiple model runs and "virtual levee" scenarios to represent the range of possible discharge variations resulting from avulsions in the most active part of the alluvial fan. FLO-2D offers an additional advantage in that it simultaneously computes the hydrology and hydraulics of flow.
- Hydraulic models. Although fixed bed hydraulic models cannot directly simulate an alluvial fan avulsion because avulsions inherently involve bed elevation changes, it is possible to generate hydraulic data from fixed bed models that can be used to identify conditions conducive to avulsive channel processes. JE Fuller (2010) found that the following model characteristics were found to be important for predicting hydraulic variables related to alluvial fan avulsions:
    - Volume accounting. Because of the extensive attenuation that occurs on alluvial fans in central Arizona, unsteady, volume-accounting models (e.g., FLO-2D) are preferred over steady state models (e.g., HEC-RAS).
    - Two-dimensional flow. Flow over an alluvial fan surface is inherently a two dimensional problem. The most successful simulations will be capable of simulating two-dimensional flow. In most cases, use of one-dimensional models requires unacceptable simplification of the input data.
    - Variable flow depths. The best hydraulic models for alluvial fans are capable of simulating temporally variable conditions ranging from dry surfaces to shallow overland flow to deep channelized flow.
    - Sediment transport. Hydraulic models that compute estimates of scour, deposition, and sediment transport are preferred over water-only models. It is expected that alluvial fan surfaces will be net aggradational over the long term, but that significant amounts of scour may occur locally during single events that will affect water surface elevations and local hydraulic conditions.
    - Flexible output. To understand and predict conditions conducive to avulsion, it is necessary to use a model capable of generating hydraulic variables over a spatially extensive area, at differing time periods, and for both net (model end) and intermediate time periods.

While there are other two-dimensional models available, the FLO-2D model was found to have all of the components and capabilities needed for analysis of alluvial fans in central Arizona. FLO-2D is a physically-based model, combines rainfall and runoff modeling, provides hydrologic and hydraulic data everywhere within the model domain (not just at selected concentration points), is familiar to and frequently used by floodplain manager and engineers in central Arizona, and has been accepted by FEMA for use in hydrologic and hydraulic modeling studies, including alluvial fan floodplain studies, as well as by other local, state, and federal agencies. The model is fully compatible with

GIS-based data sets and technology. The model is capable of simulating infiltration, storage, sediment transport, and flood control structures. It is relatively inexpensive, well-documented, and has a large number of users in central Arizona. Furthermore, the US Army Corps of Engineers (2000), in a study of alluvial fans in California, concluded that FLO-2D was the best available model for floodplain analysis.

4.5. Methods to Predict and Model Avulsions

A number of potential methodologies to predict avulsions on active alluvial fans were explored as part of this study, including the following:

- FLO-2D 100-Year Models
- FLO-2D Mega-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

The methodologies described below attempt 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. Note that sensitivity tests (JE Fuller, 2010) indicate that FLO-2D results are affected by the grid size and the scale of topographic mapping.

4.5.1. FLO-2D 100-Year Models

The FLO-2D model routes a flood hydrograph across a fan surface according to the topographic data and other input parameters coded into the model. The computed distribution of flood water and flow depths on an active fan surface are dictated by the existing channel pattern only to the extent that the existing channels reflect topography and other model input parameters. On many active alluvial fans, the “active” channels, as defined by a sandy bed and bank vegetation, are perched topographically above the surrounding terrain. In other places the channels have aggraded to the point where they no longer have the capacity to convey the volume of flow delivered by upstream reaches. In such situations, FLO-2D distributes runoff to topographically lower areas in the floodplain, thus enabling potential avulsive flow corridors to be identified from plots of flow depths on the fan surface relative to the existing channel locations.

The location of potential avulsive flow paths can be readily identified by careful inspection of plots of FLO-2D modeling results relative to the existing channel network visible on recent aerial photographs. In most cases, FLO-2D predicts that most flood

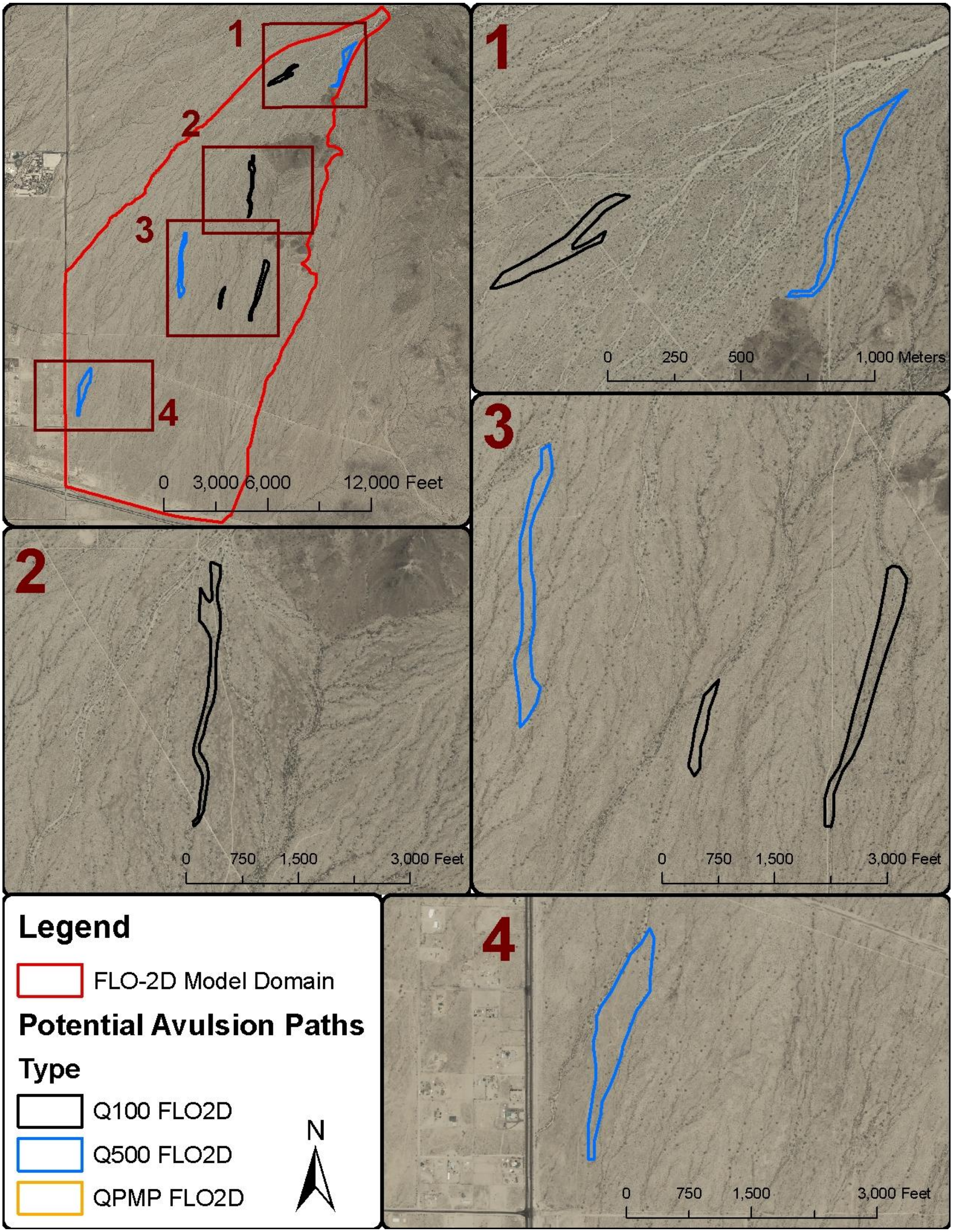

Figure 13. Potential avulsion locations identified from 100-year FLO-2D modeling results for the White Tank Fan 36 site. Black and blue lines indicate avulsions identified from 100- and 500-year results, respectively.

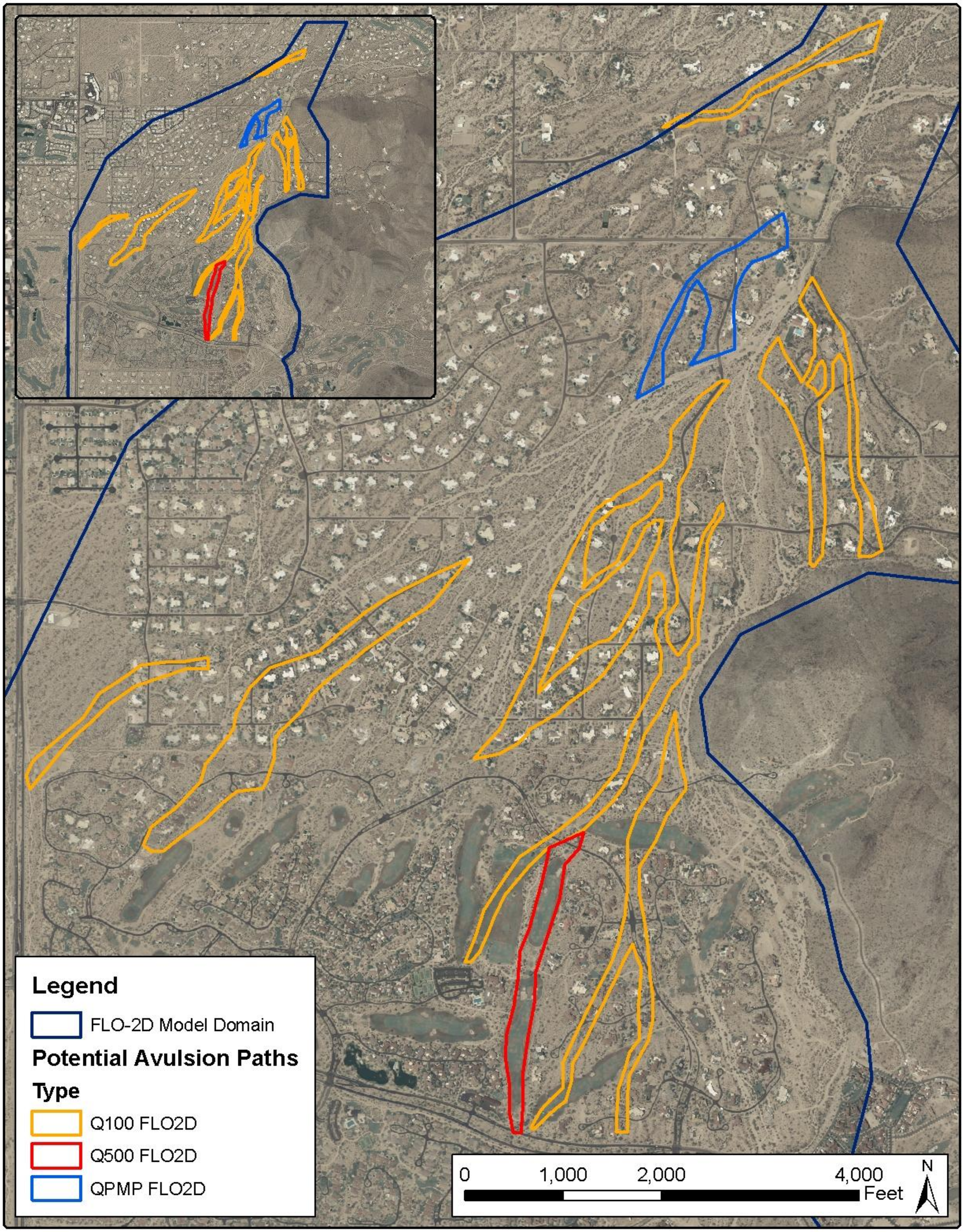

Figure 14. Potential avulsion locations identified from 100-year FLO-2D modeling results for the Reata Pass Fan site. Yellow, blue and red lines indicate avulsions identified from 100-year-, 500-year and PMP results, respectively.

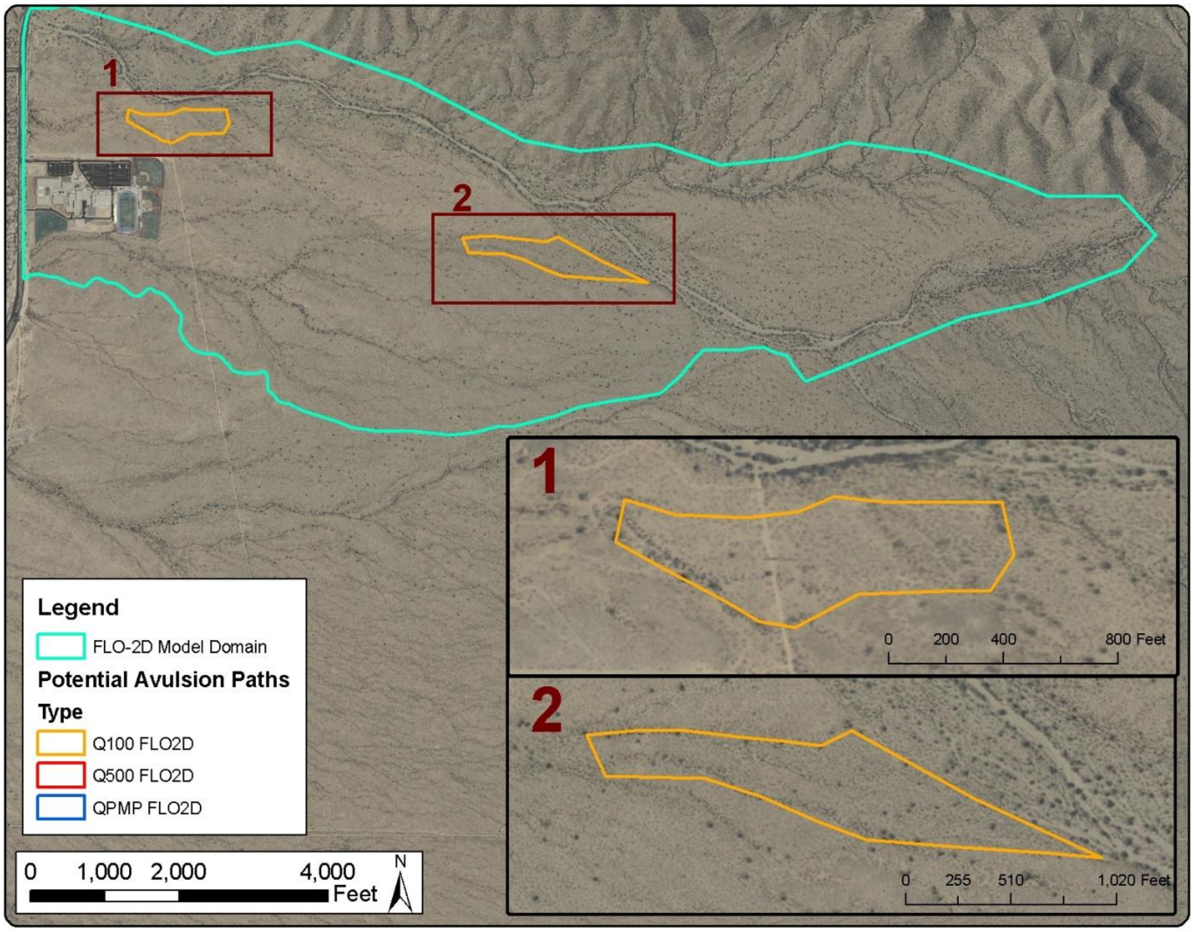

Figure 15. Potential avulsion locations identified from 100-year FLO-2D modeling results for the Rainbow Valley Fan 1 site. Yellow lines indicate avulsions identified from 100-year results.

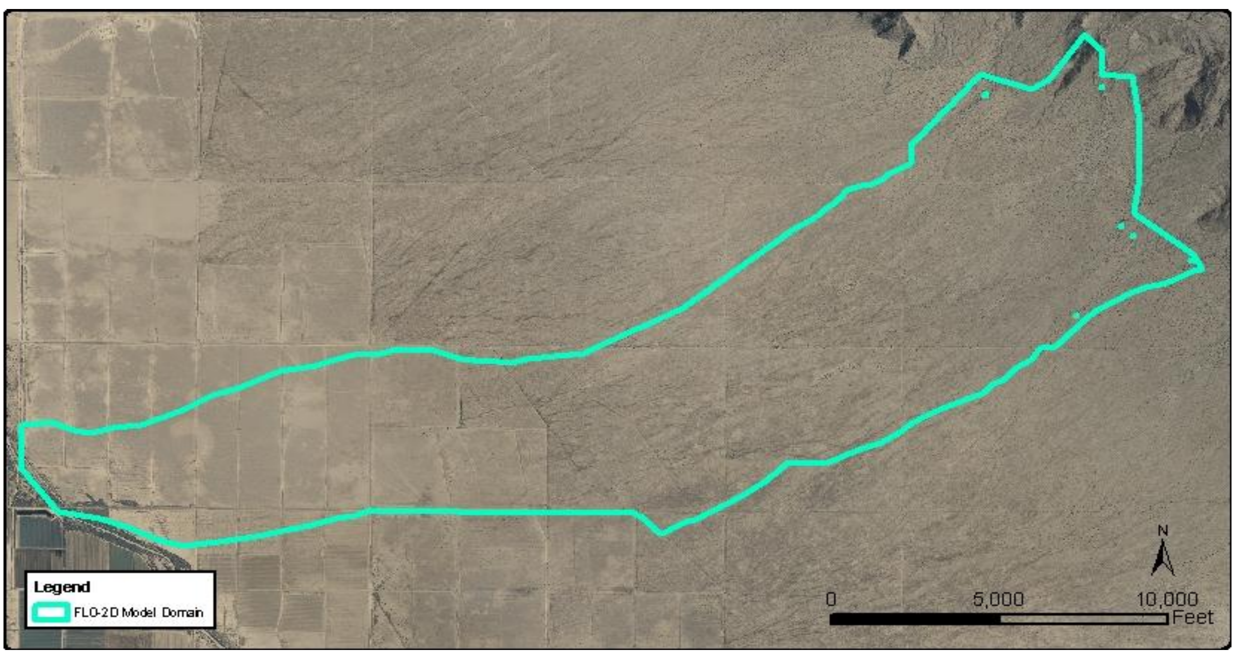

Figure 16. Potential avulsion locations identified from 100-year FLO-2D modeling results for the Rainbow Valley Fan 12 site (NO Avulsions identified).

water will be conveyed via the existing channel network, which is consistent with observations of historical alluvial fan flooding in Arizona (Pearthree et. al., 1992; Field 1994; Section 2.4). In some cases, FLO-2D shows concentrations of flood water outside the existing channel network. Based on field observations published by Pearthree et. al. (1994; 2004), a 100-year 0.3 foot flow depth[6] was used as the lower depth threshold for potential avulsive flow. Potential avulsive flow paths identified using the 100-year FLO-2D models for each of the four alluvial fan analysis sites are shown in Figure 13 to Figure 16.

The following summarize the findings from the modeling illustrated in *Figure 13* to *Figure 16*:

- White Tanks Fan 36
    - Four potential avulsion corridors were identified from the 100-year base model results, with three additional corridors identified for the 500-year event.
    - Only one of the potential avulsion corridors (Q500) was located within 4,000 feet of the hydrographic apex of the alluvial fan. The majority of the potential avulsions were located in the mid- to distal-fan areas. One reason that few potential avulsion corridors were identified near the hydrographic apex is that this portion of the WTF 36 site is covered by a dense distributary channel network, i.e., there are relatively few non-channelized areas in the most active portion of the fan.
    - The potential avulsion corridor located nearest the hydrographic apex is not indicated by crenulations in the 10-foot topography, and thus may represent a more classic type of avulsion (single channel cut into undisturbed floodplain). Note that flows well in excess of the 100-year event, or significant aggradation of the main channel, would be required to exploit this avulsion corridor.
    - One more prominent potential avulsion corridor is located below the secondary apex downstream of the large inselberg on the WTF 36 site. This avulsion follows an incised on-fan flow path, and would likely occur due to piracy.
    - Overall, FLO-2D modeling indicates that most flooding on the fan surface will be conveyed along the existing channel network, especially in mid- to distal fan areas.
- Reata Pass Fan
    - There are numerous interconnected potential avulsive flow paths that are depicted by the 100-, 500-, and PMP FLO-2D modeling results.
    - The presence of a dense network of distributary channels in the western arm of the RPF site precludes identification of avulsive flow paths in that area by this methodology, i.e., there are relatively few non-channelized areas in that portion of the fan.
    - There is a potential avulsive flow path located above what has been traditionally called the hydrographic apex. If the FLO-2D modeling is correct, then the location of the hydrographic apex should be moved

[6] The FLO-2D maximum depth value for each grid cell was used.

upstream, since the hydrographic apex is identified at the point where the fanhead channel loses capacity. This potential breakout is not readily apparent in the topography or aerial photography, and warrants more detailed investigation in the future.
  - There are several prominent potential avulsive flow paths that bisect the “island” of geologically older soils located downstream of the hydrographic apex. Flow through this area may reflect a different mechanism more associated with traditional stream piracy, since the surrounding fan surfaces are more stable than the younger alluvial surfaces elsewhere on the alluvial fan landform.
  - Potential avulsions were only mapped to Thompson Peak Parkway, and are probably only reliably mapped to the upstream limit of the DC Ranch subdivision, because of the impact of development on flow paths below those points.
  - Note that the FLO-2D models of the RPF site were built without accounting for blockage by the numerous homes constructed within the active fan area. Therefore, the FLO-2D models show the natural, not post-development topography and potential flow paths.
  - There is a strong tendency for high flow to inundate surfaces untouched by small floods.
- Rainbow Valley Fan 1
  - Two potential avulsive flow paths were identified from the 100-year FLO-2D base model. Neither of these flow corridors is located at the hydrographic apex.
  - FLO-2D does not predict that runoff enters the overflow corridor located at the apex until flow exceeds the 500-year event, a result that may be evidence of long-term entrenchment of the channel near the apex.
- Rainbow Valley Fan 12
  - The existing drainage network on the RVF 12 site is so fine-textured and the transition to sheet flooding conditions so rapid that most flow paths located more than 1,000 feet from the hydrographic apexes are too small to reliably identify, making comparison with FLO-2D corridors difficult.
  - No avulsive flow corridors were identified using either the FLO-2D 100-year base model or 500-year results.

4.5.2. FLO-2D Mega-Flood Models (Q500 & QPMP)

There is some indication in the literature that avulsions on active alluvial fans in central Arizona are rare (Field, 1994; 2001; Pelletier et. al., 2005; Section 3.5), with recurrence intervals that may exceed the 100-year event. Furthermore, it is likely that large flood volumes are required to perform the geomorphic work necessary to fully form major avulsions. Therefore, FLO-2D modeling results for the 500-year (Q500) and a flood generated from the probable maximum precipitation (QPMP) were compared to the existing channel positions shown on recent aerials to determine if potential avulsive flow paths other than those identified for the 100-year event could be recognized.[7] These so-

[7] Use of the mega-flood hydrographs also addresses potential concern regarding possible over-estimation of loss rates in the 100-year event.

called “mega-floods” provided greater peaks and volumes needed to inundate a greater percentage of the alluvial fan surface. Use of mega-floods is a way to exaggerate the flow conditions and highlight trends that may be less visible from the modeling of smaller, more frequent events. Conversely, if no avulsive flow paths were identified in the mega-floods, then it is more likely that the alluvial fan is not avulsive.

A description of the 500-year and PMP results was provided in Section 4.5.1 above. Some trends of these results are discussed below:

- Most of the 500-year potential avulsive flow paths overlie the 100-year flow paths, although the 500-year flow paths tend to be wider and deeper and convey more discharge than the corresponding 100-year flow paths.
- For the PMP FLO-2D results, the predicted flow nearly inundates the entire Holocene surface, making identification of individual flow paths somewhat subjective.
- Some of the PMP potential flow paths are not significantly deeper than the 100- or 500-year predicted flow depths, indicating that if additional flow is directed at some flow corridors, they simply overflow and the additional flow is shifted to other parts of the floodplain.
- On the WTF 36 site, the FLO-2D PMP model predicts greater flow depths on the southeast side of active alluvial fan surface immediately downstream of the hydrographic apex, possibly indicating a preference for avulsions to occur on that side of the alluvial fan.

An analysis of FLO-2D results was conducted to determine if the 500-year or PMP modeling results could be used as a simpler alternative to the virtual levee scenario methodology. However, the analysis indicated that the results of the mega-flood models and virtual levee scenario models were not equivalent hydrologically or hydraulically, and that there was no known relationship between recurrence interval and avulsion potential. Even if the a floodplain manager’s regulatory interest is limited to the 100-year event, evaluation of the mega-flood FLO-2D model results was useful because the larger discharges accentuated trends that may not have been as evident in the results from the 100-year or more frequent events.

4.5.3. FLO-2D Velocity Zones (water-only models)

For an overbank flow to be avulsive, it must have sufficient energy to erode the floodplain surface and form a new channel. The magnitude of energy required to erode a natural surface is a function of the surface composition, cohesiveness, and ground cover. Data describing the composition, cohesiveness and cover for the alluvial fan surfaces at the four fan evaluation sites are available from the NRCS Soil Survey Maps, and can be verified by field observations. Like most alluvial fan surfaces in central Arizona, all of the four evaluation sites are underlain by relatively non-cohesive sandy, sandy loam, and loamy sand soils, with sparse desert scrub vegetative cover. A variety of investigators have developed relationships between flow velocity and surface erodibility (BUREC, 1974; Neill, 1975; USACE, 1970; 1995), all of which suggest that the alluvial fan surfaces at the four evaluation sites could be eroded wherever flow velocities exceed two feet per second. Floodplain velocities are readily obtained from the FLO-2D results and are plotted in Figure 17 to Figure 20.

Evaluation of the FLO-2D velocity threshold plots in Figure 17 to Figure 20 yielded the following conclusions:

- Any of the colored areas in Figure 17 to Figure 20 could be subject to surface erosion during a 100-year event. These potential erosive velocity zones tend to be very broadly distributed near the hydrographic apexes, but are generally limited to the existing channel network in the mid- and distal fan areas.
- The velocity zone method identified erosive corridors along all of the potential avulsive corridors identified using the base and mega-flood FLO-2D results described above.
- Some of the potential avulsive corridors identified using the base and mega-flood FLO-2D results were shown by the velocity method to have non-erosive velocities.
- The velocity threshold method revealed significant differences in the erosion (and avulsion) potential between the more avulsive WTF 36-RPF sites and the more passive, sheet flooding dominated RVF 12 site.
- On the RPF site, there are numerous homes located in erosive velocity-potential avulsion zones.

Note that the velocity data shown in Figure 17 to Figure 20 are average velocities for each FLO-2D grid cell. Therefore, a 60% downward adjustment of the threshold velocity was made to depict a more accurate maximum channel velocity within each individual grid, as is shown as a separate color in Figure 17 to Figure 20. In addition, the results shown are for the water-only base models and do not reflect inundation of surfaces or alternate distribution of flow that might result from upstream avulsions or sedimentation processes. Further evaluation of this methodology could include composite results from multiple models, or consideration of stream power or shear as a determinative variable. Argett and Wilson (2009) have noted that surfaces may be assumed to be avulsive if the computed overbank stream power or shear equals the values computed for the existing channels.

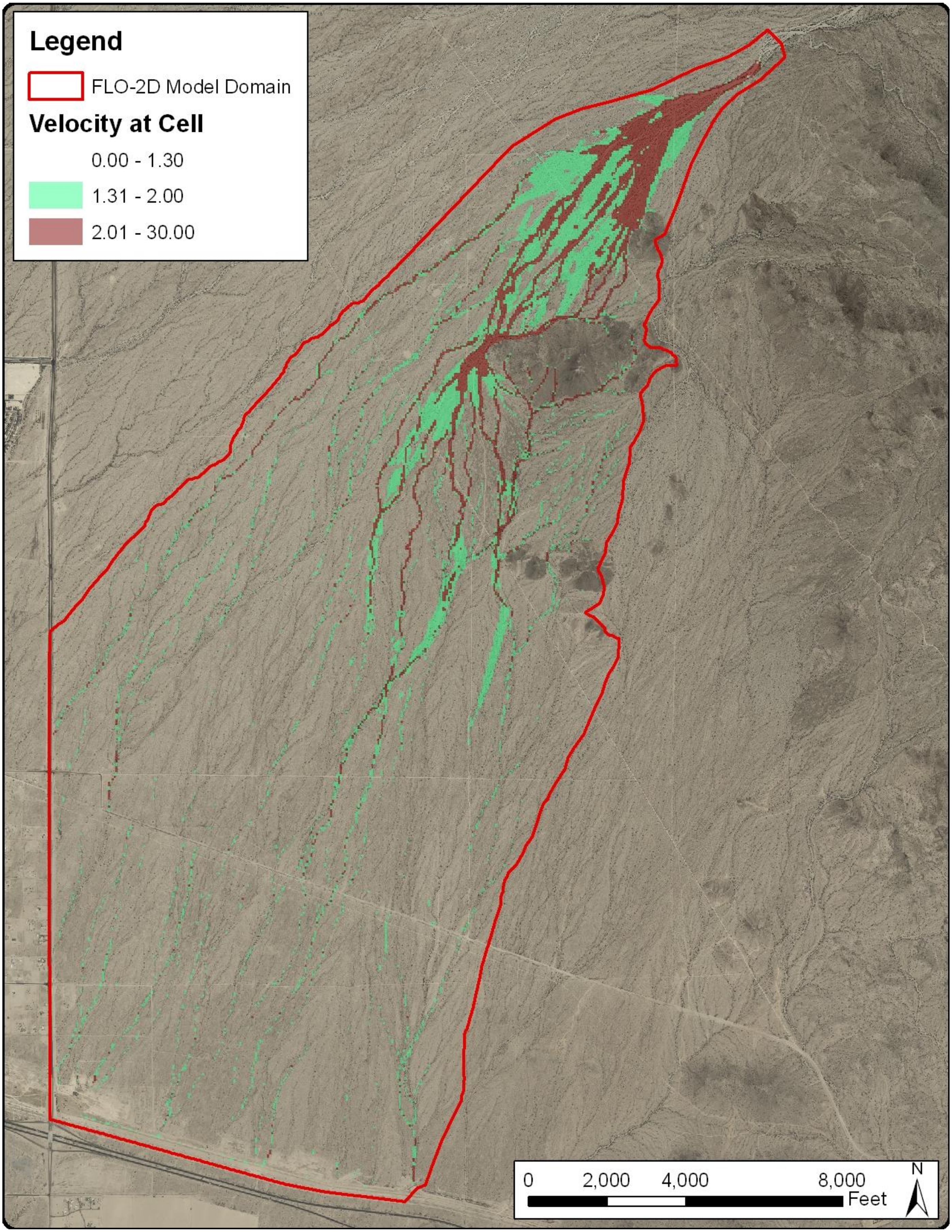

Figure 17. Plot of 100-year FLO-2D velocities greater than the erosive threshold for WTF 36.

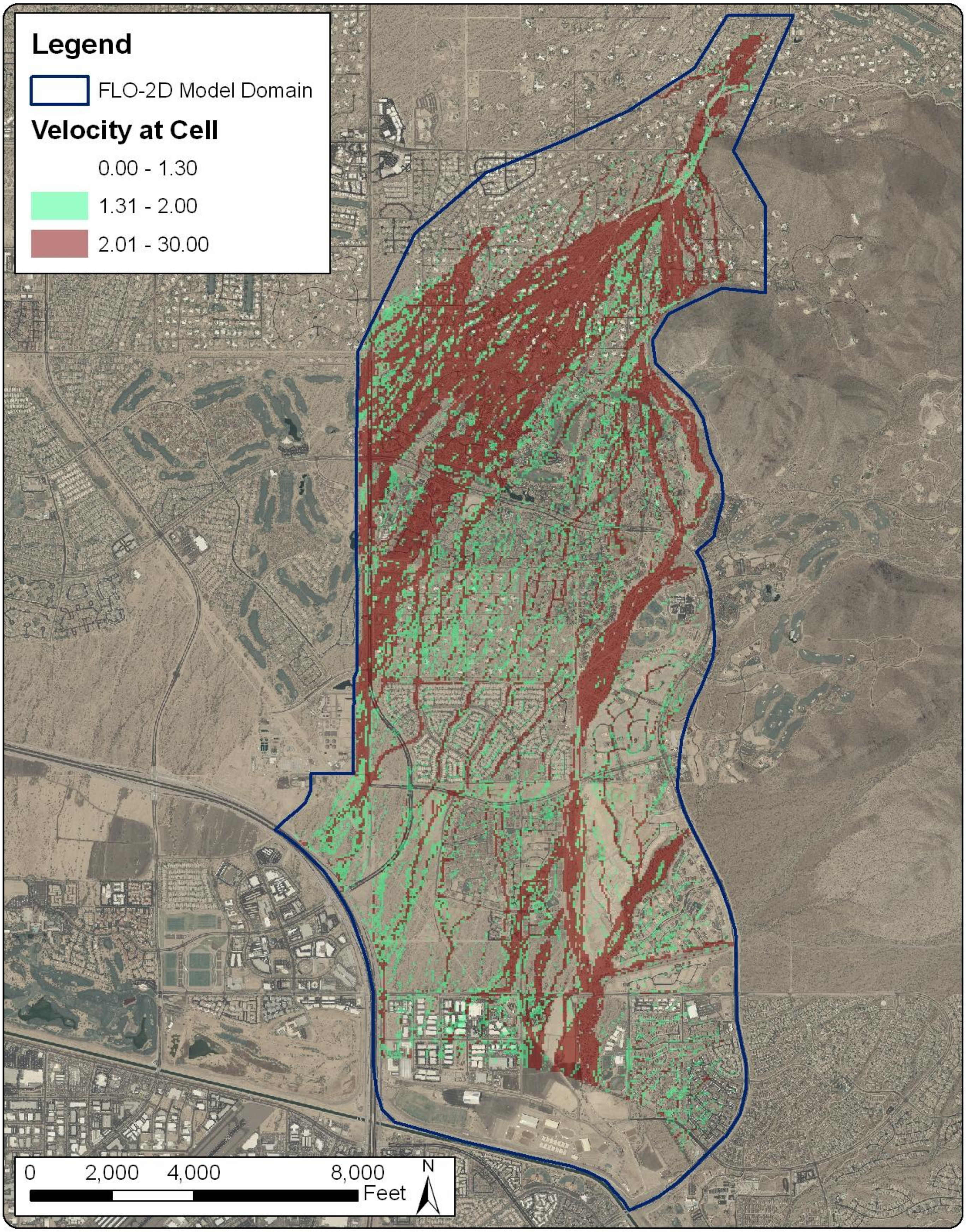

Figure 18. Plot of 100-year FLO-2D velocities greater than the erosive threshold for RPF.

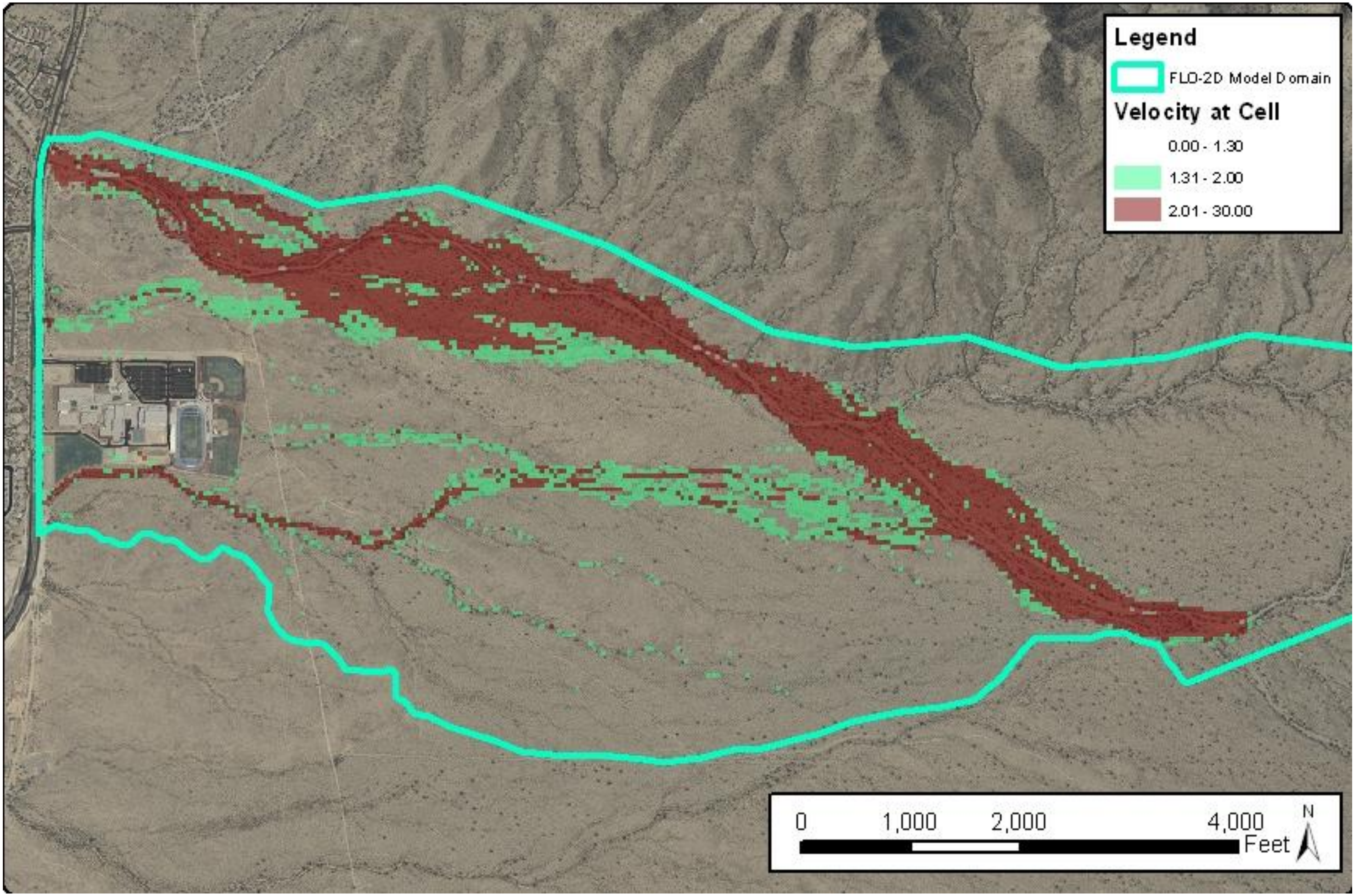

Figure 19. Plot of 100-year FLO-2D velocities greater than the erosive threshold for RVF 1.

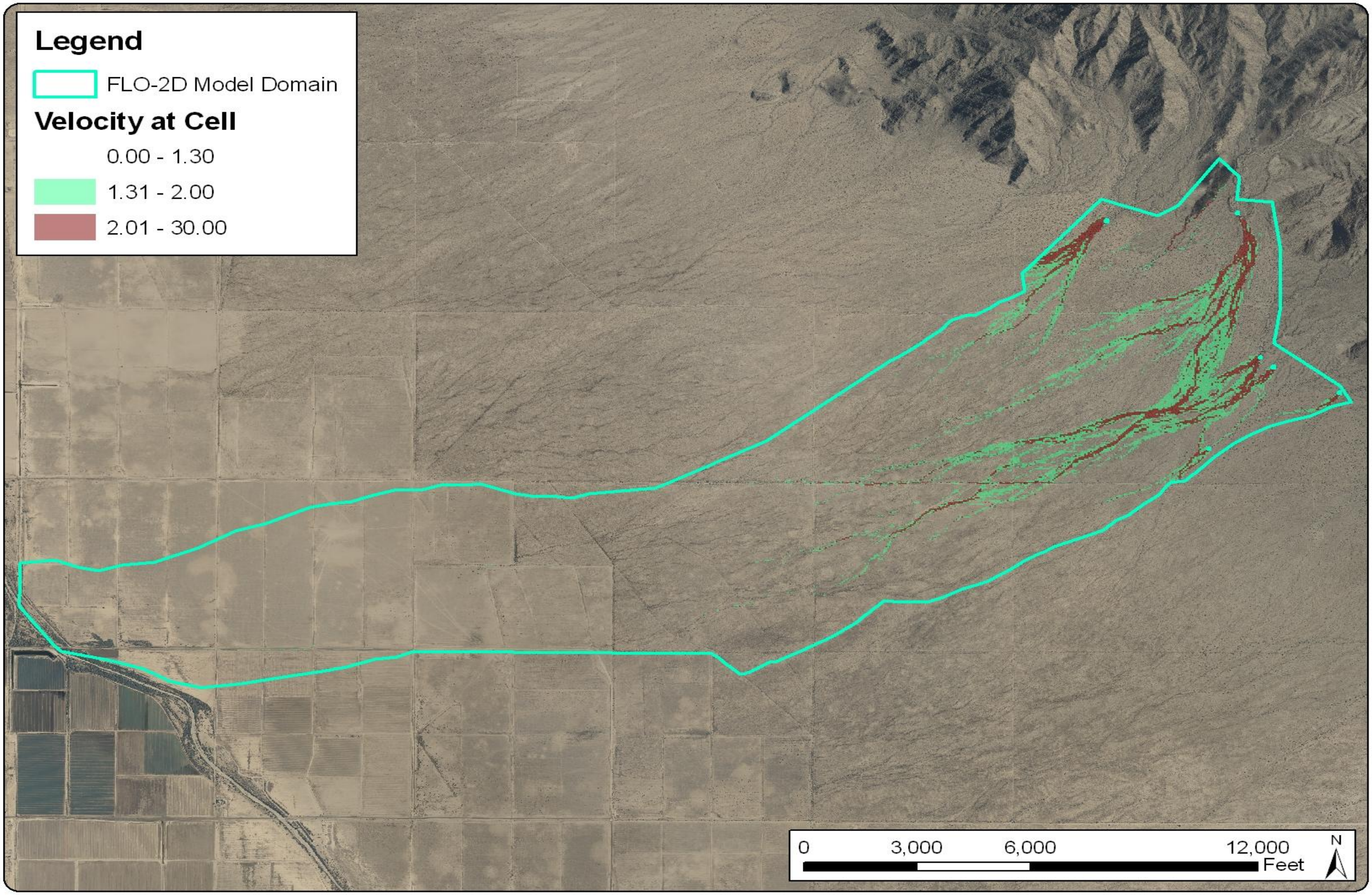

Figure 20. Plot of 100-year FLO-2D velocities greater than the erosive threshold for RVF 12.

4.5.4. BUREC Hazard Classification Zones

The Bureau of Reclamation (BUREC) ACER Technical Memorandum No. 11 includes a series of charts that purport 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. Engineering judgment and field observations indicate that if the flow depth and velocity were sufficient to knock over a small child, it would also be likely to transport the fine- to medium-grained sediment (i.e., erosion) found in the loamy and sandy soils on most active alluvial fans in central Arizona. Therefore, the BUREC (1988, Figure 6) hazards to children chart was selected to identify erosive (and thus potentially avulsive) areas on the four alluvial fan evaluation sites. The BUREC charts subdivide flood hazards into “high” and “low” categories, with an intermediate “judgment” zone between them, as shown in Figure 21. The boundaries of the BUREC 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 22 to Figure 25.

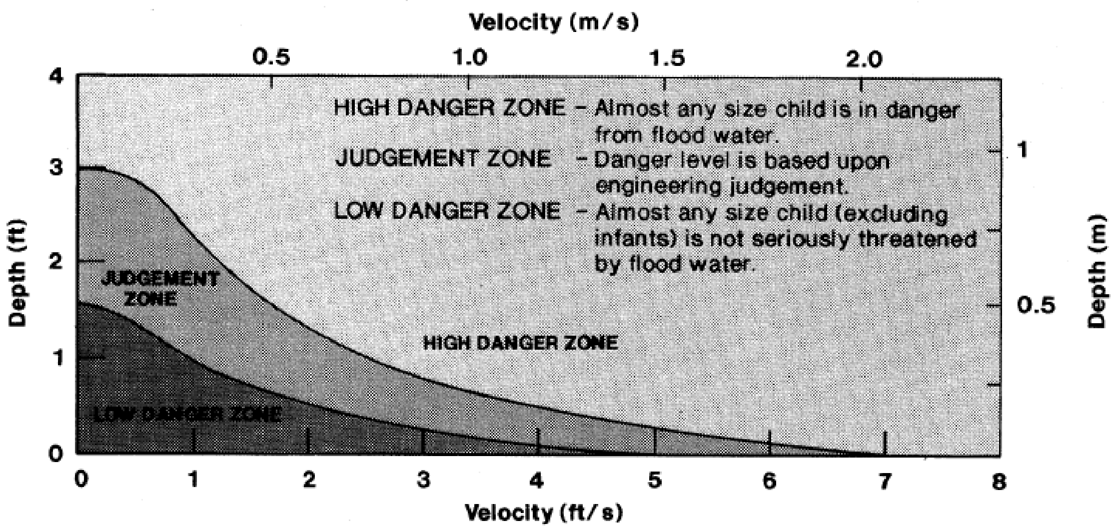

Figure 6. – Depth–velocity flood danger level relationship for children.

Figure 21. USBR ACER Tech Memo No. 11 Figure 6.

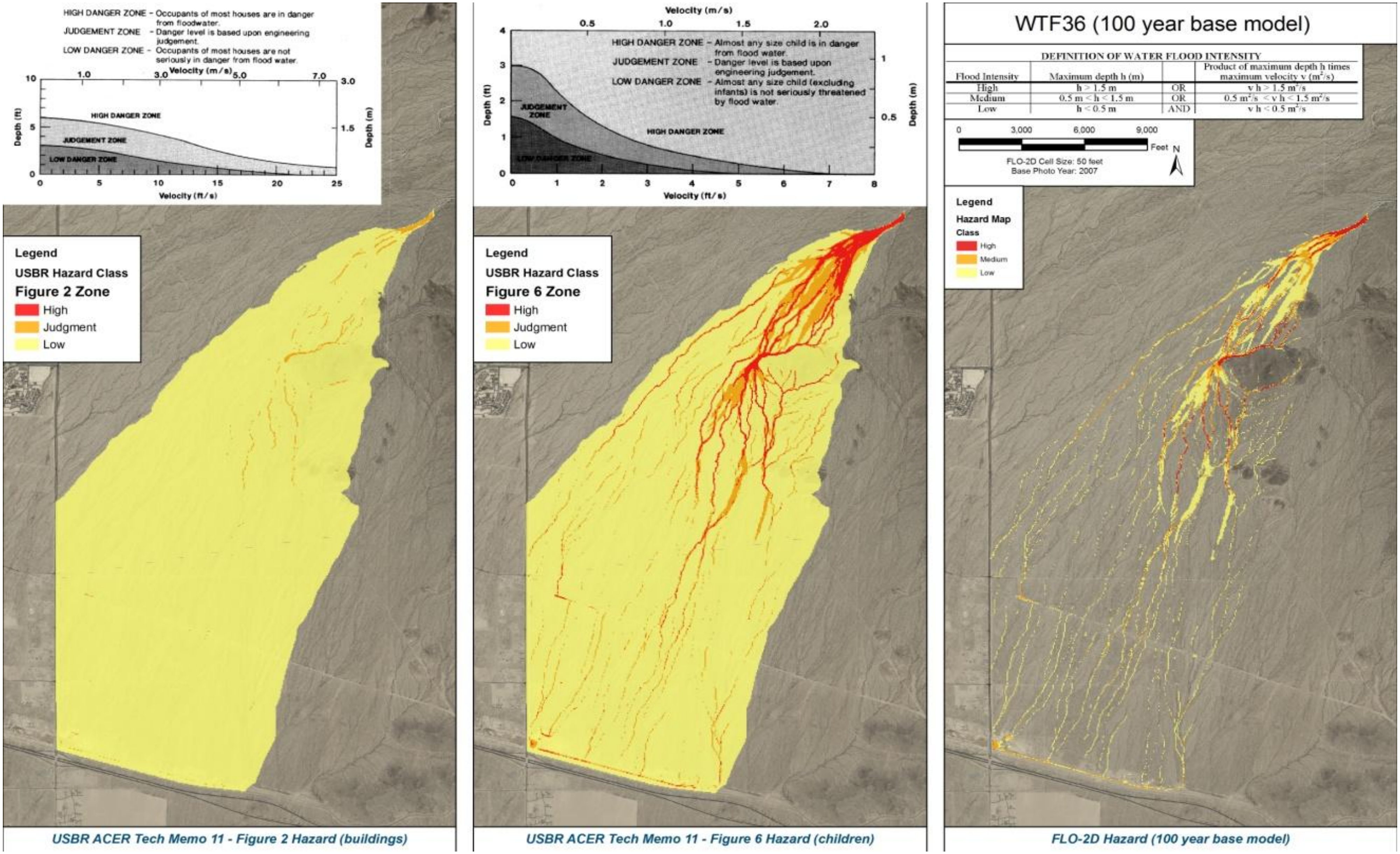

Figure 22. USBR Figure 2 (Buildings on Foundations) and Figure 6 (Small Children) hazard zones, with FLO-2D Hazard Map results for White Tanks Fan 36 FLO-2D base model.

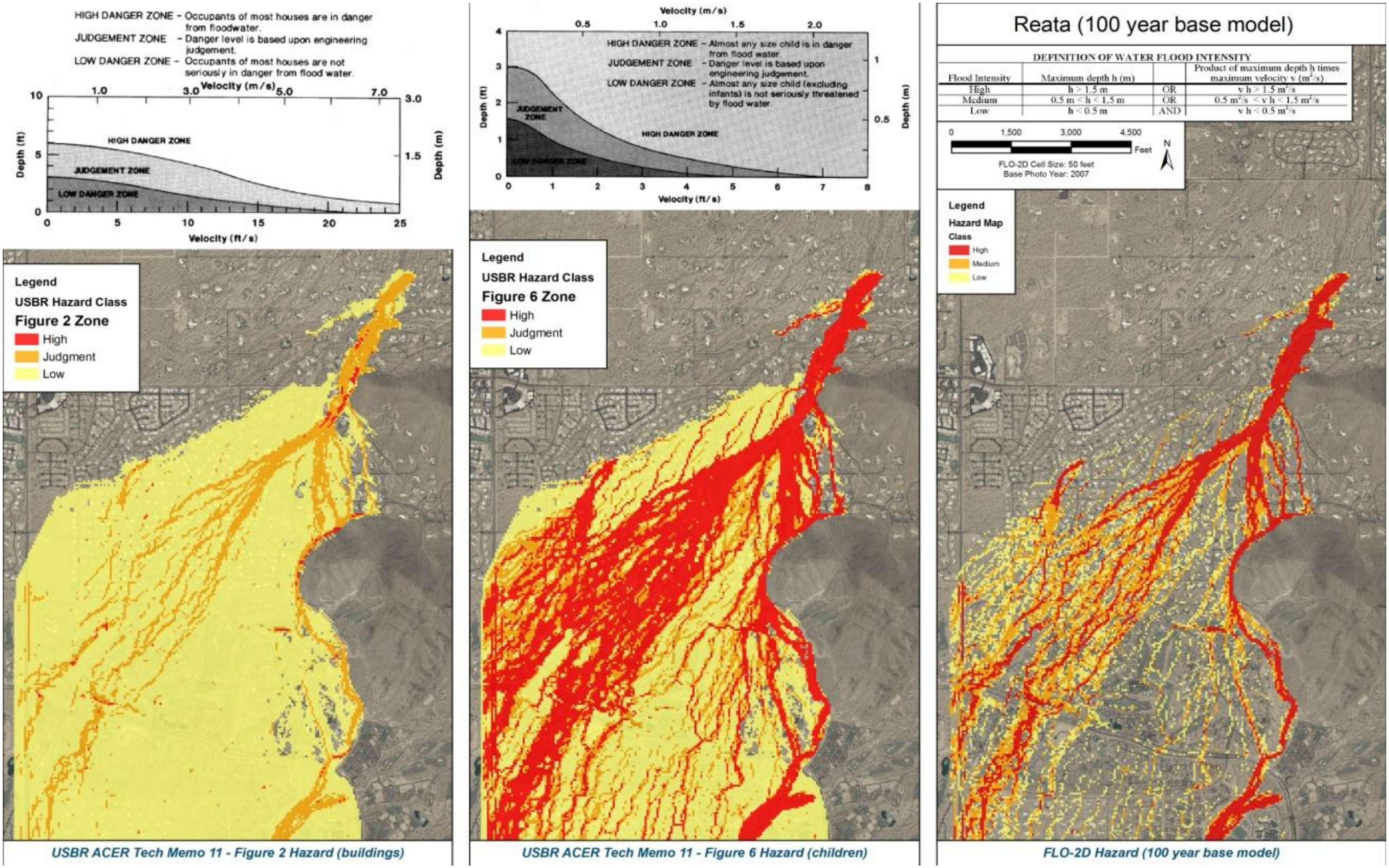

Figure 23. USBR Figure 2 (Buildings on Foundations) and Figure 6 (Small Children) hazard zones, with FLO-2D Hazard Map results for Reata Pass Fan FLO-2D base model

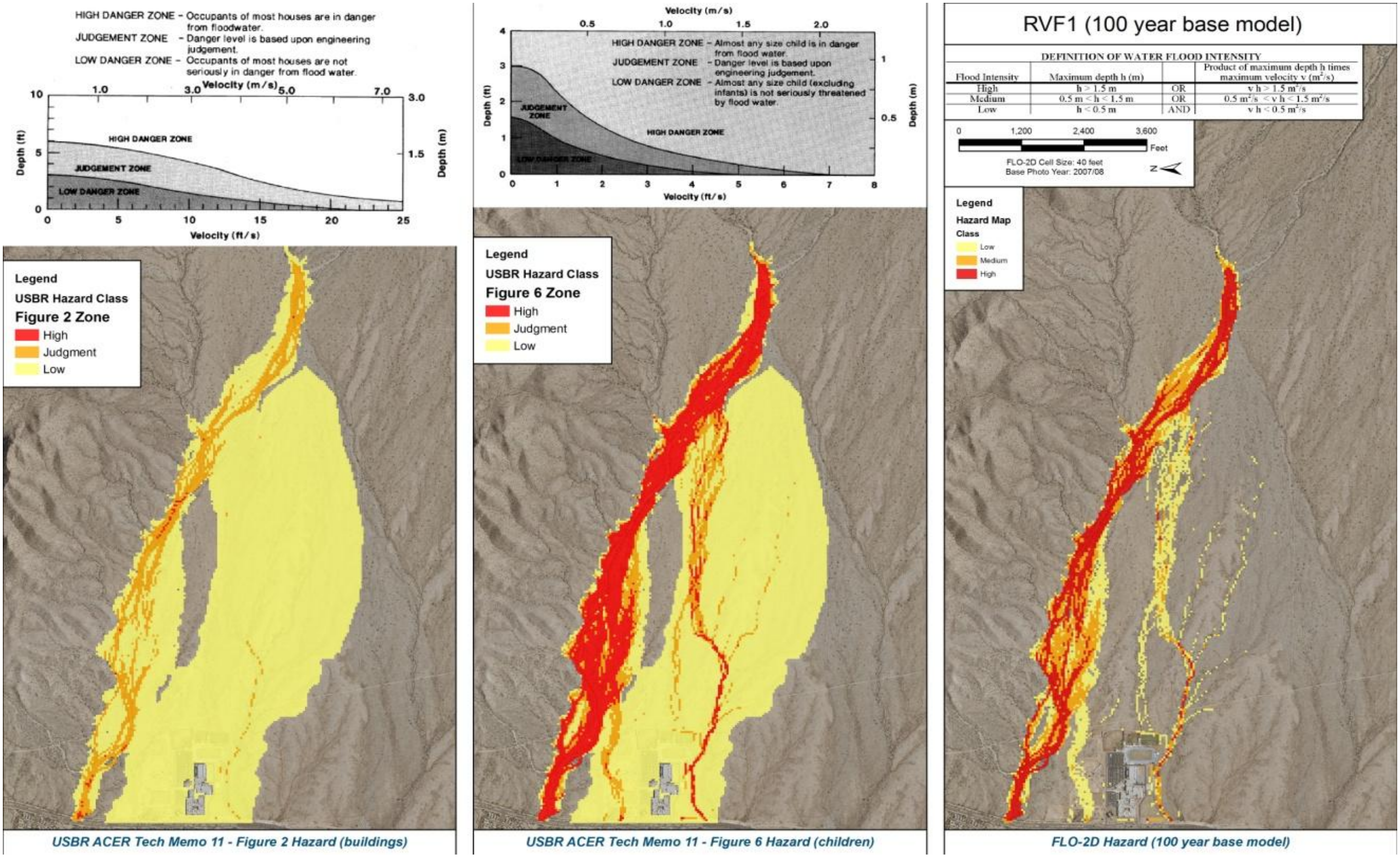

Figure 24. USBR Figure 2 (Buildings on Foundations) and Figure 6 (Small Children) hazard zones, with FLO-2D Hazard Map results for Rainbow Valley Fan 1 FLO-2D base model

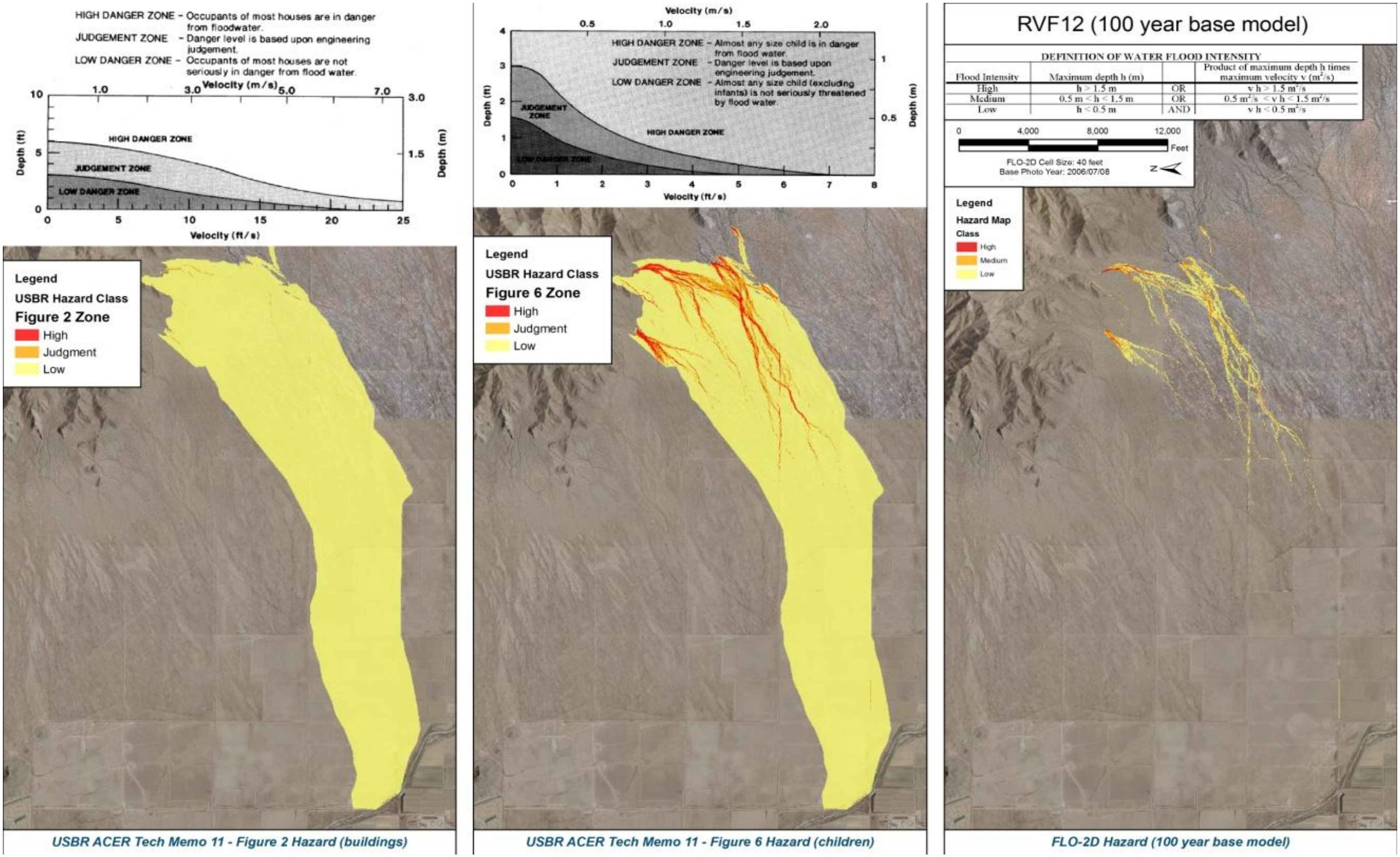

Figure 25. USBR Figure 2 (Buildings on Foundations) and Figure 6 (Small Children) hazard zones, with FLO-2D Hazard Map results for Rainbow Valley Fan 12 FLO-2D base model.

The results of using the BUREC hazard classification charts yielded the following conclusions:

- This methodology of identifying potential avulsion corridors is similar to those summarized above, except that the BUREC method integrates both flow depth and velocity, and it assigns risk to pre-defined categories.
- Like the other avulsion identification methods used, there is a substantial difference in avulsion hazard between the WTF 36-RPF sites (high risk) and the RVF 12 site (low risk).
- The BUREC data indicate that the RPF site has the highest risk of avulsive conditions of the four detailed evaluation sites, probably due to the large 100-year discharge and steep fan slope.

Use of this method to identify potential avulsive flow corridors could be improved by integrating the results of multiple flow scenarios (frequency and virtual levee), and by overlaying the results on aerial photographs to identify zones that do not correspond to the existing channel network.

4.5.5. FLO-2D Channel Blockage Model

Attempts to simulate an alluvial fan avulsion using FLO-2D were made for the WTF 36 site. Because the occurrence of avulsions are related to loss of channel capacity and flow outside the existing channel network, the FLO-2D topographic data input file was manipulated to create a channel blockage that would force channel flow into the floodplain. Blockages were created at three places on the WTF 36 site.

The first blockage (Figure 26) was located on a gradual channel bend immediately downstream of the hydrographic apex, and consisted of a 600-foot long wedge of (simulated) sediment that completely filled the main channel to the elevation of the surrounding floodplain. The objective of the first blockage was to try to force flow onto an early Holocene surface which had a moderately well developed on-fan drainage network that drained away from the rest of the active alluvial fan. In this case, the obstruction did force a portion of the 100-year hydrograph onto the floodplain along a flow path that did not return to the active alluvial fan area. However, even with the main channel entirely blocked and filled, most of the 100-year flood hydrograph continued along the without-obstruction existing flow paths on the active alluvial fan surface.

The second blockage (Figure 27) was located in the most active part of the alluvial fan, at a bend in a well-defined channel, near what appeared to be either a developing or abandoned avulsive flow corridor. In this case, the FLO-2D modeling indicated that runoff simply bypassed the obstruction and continued along the pre-obstruction flow path with minimal changes in flow characteristics downstream. The second blockage was located well within the distributary channel network of the active fan, but in a reach where the individual flow paths were nearly parallel, rather than radiating outward. Lacking alternative flow paths that trended away from the parent channel, flow simply continued downstream parallel to the drainage pattern until it was recaptured by existing channels.

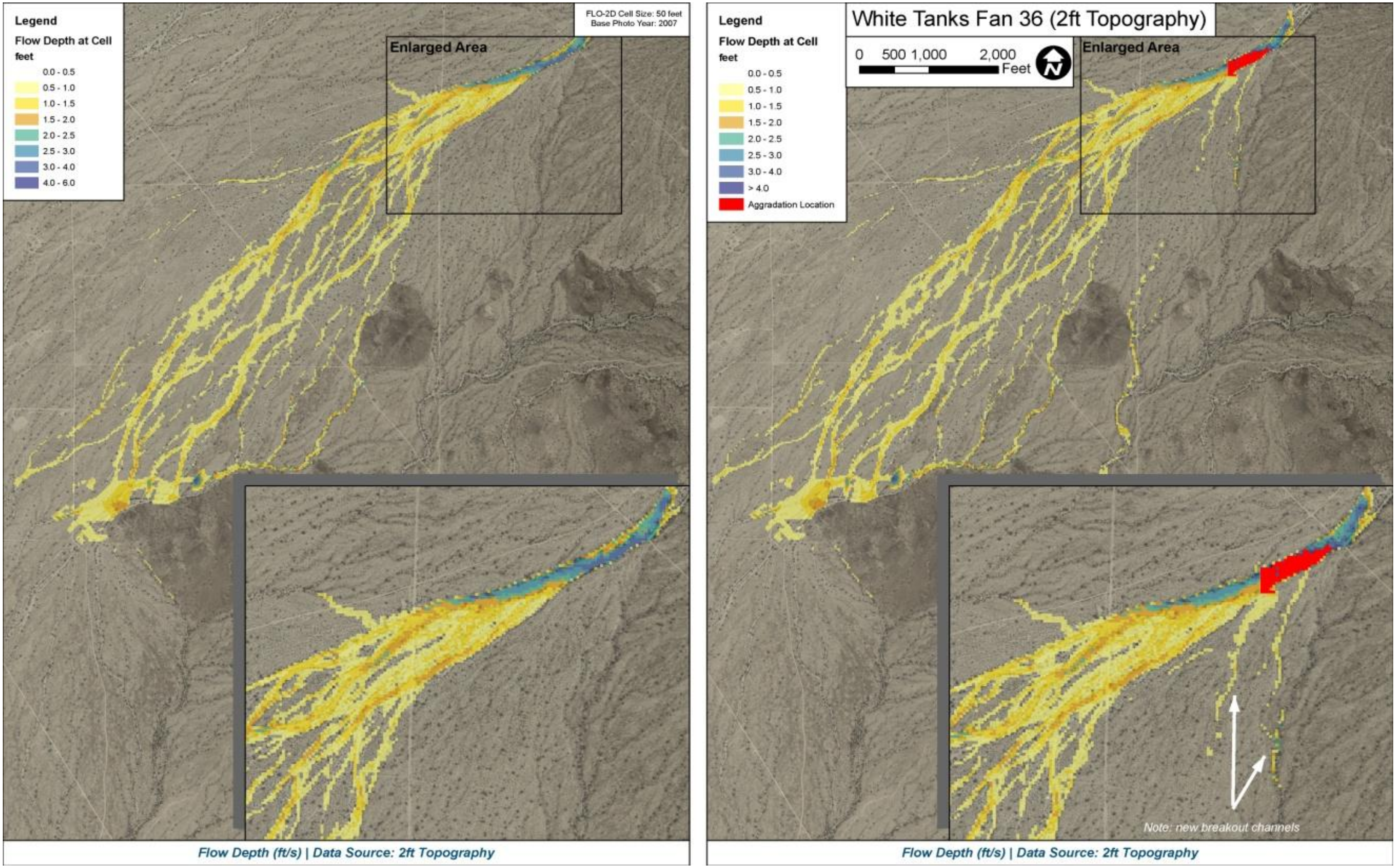

Figure 26. Channel blockage scenario #1 (apex area) for White Tanks Fan 36.

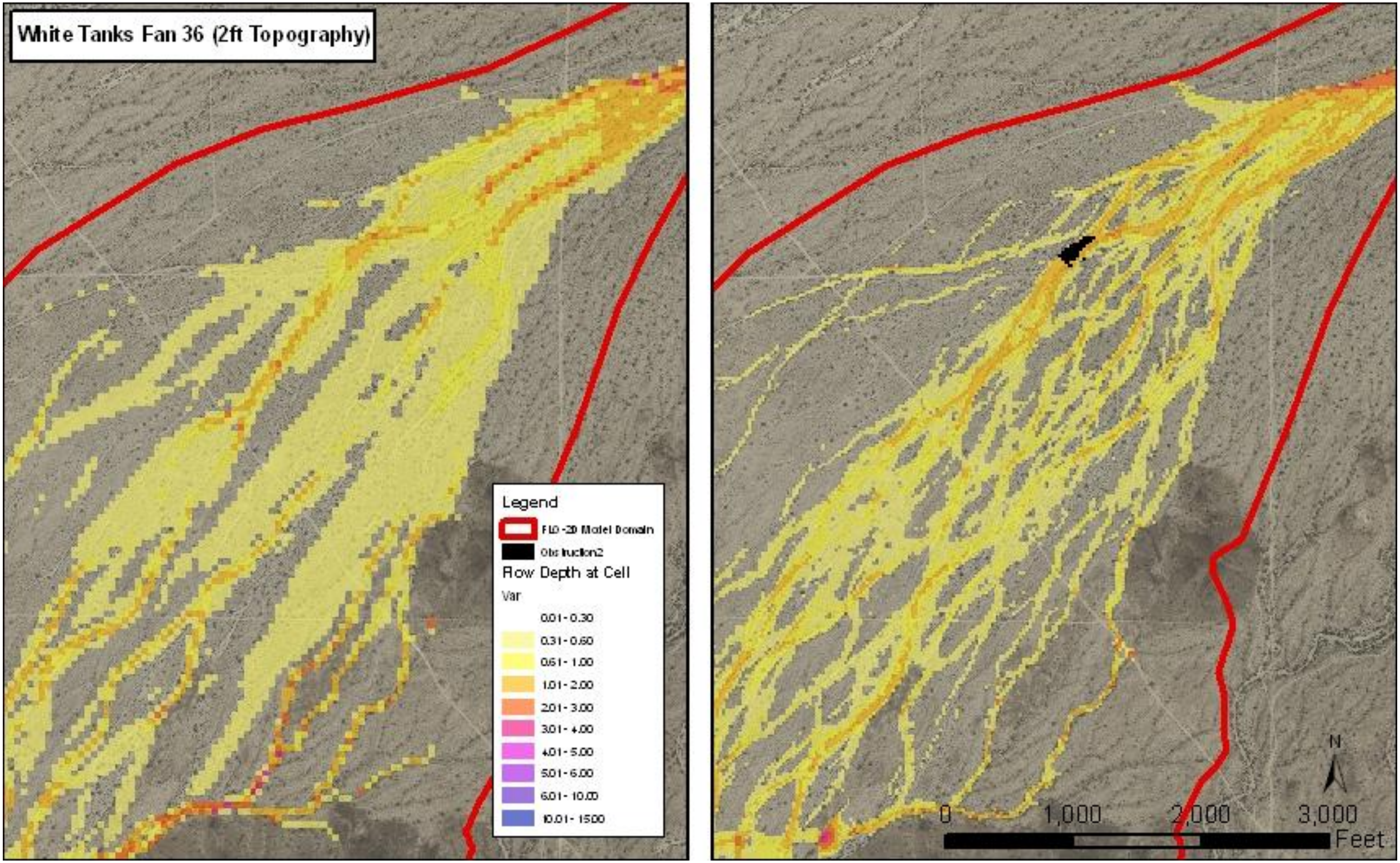

Figure 27. Channel blockage scenario #2 (active fan area) for White Tanks Fan 36.

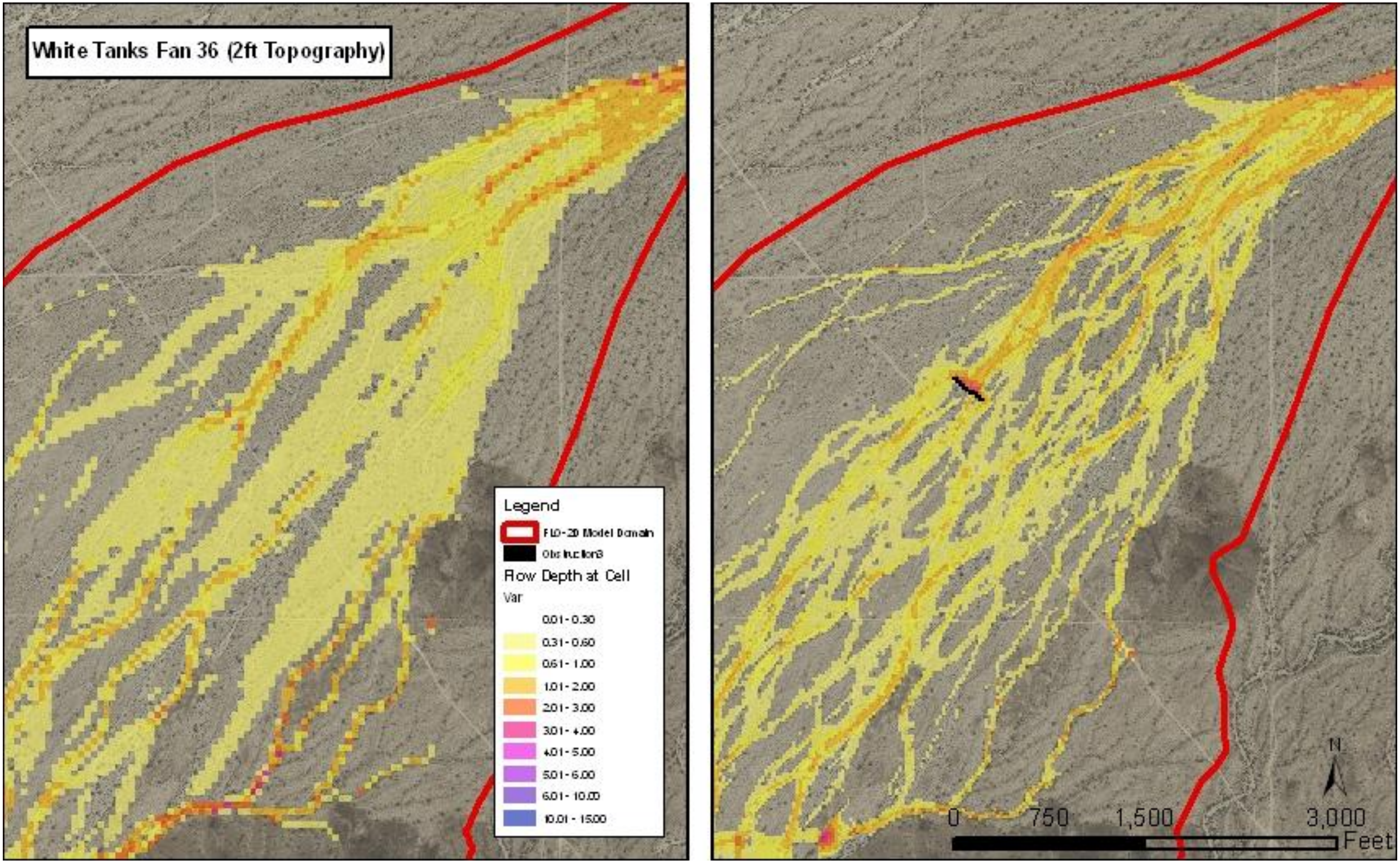

Figure 28. Channel blockage scenario #3 (perpendicular) for White Tanks Fan 36.

The third blockage (Figure 28), was located further downstream than the first and second blockages, in a reach of expanding distributary channels. This blockage consisted of an obstruction of infinite height oriented perpendicular to the primary flow direction, intended to prevent flow from moving directly downstream (i.e., the obstruction could not be overtopped). The FLO-2D modeling results show that flow mounded up along the upstream side of the obstruction until it could flow around it laterally, and then continued along the nearest existing distributary braids.

Based on the results of the scenarios described above, the channel blockage methodology is considered a useful technique for examining the possible impacts of channel obstructions at specific, well-defined locations. The methodology would be somewhat labor intensive if a modeler were to attempt to apply it regionally over a large active alluvial fan, since many model iterations would be required to consider every possible avulsion location. It may also be tentatively concluded from the modeling performed for the WTF 36 site that major avulsions are only likely where the flow diverted from the parent channel is diverted along flow paths that drain away from the pre-avulsive channel network. Channel obstructions due to debris blockage or sediment deposition within the lateral limits of the active distributary portion of the alluvial fan are unlikely to result in major avulsions.

4.5.6. FLO-2D Sediment Models

Two attempts to simulate long-term behavior leading to avulsions on active alluvial fans were made using FLO-2D. 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 isolated 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 algorithms are 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. For this study, the attempts to model surficial changes leading to alluvial fan avulsions using FLO-2D, were found to be unsuccessful and were abandoned in favor of the other methodologies discussed in this report.

Some of the FLO-2D sedimentation modeling results summarized by JE Fuller (2010) which pertain to alluvial fan avulsion processes include the following:

- Differences From Water-Only FLO-2D Models. There were some differences in the predicted flow depths, velocities, and flood hazard zones between water-only and sediment transport FLO-2D models. The differences were generally most pronounced in the highly active areas immediately downstream of the hydrographic apexes, and were less significant elsewhere on the fan surfaces where flow depths, velocities and sediment transport capacities are significantly reduced.

- Small Flood Trends. Since small floods tended to be completed absorbed by infiltration and attenuation, the entire sediment load from these events will be deposited on the inundated portion of the fan surface. Such deposition will tend to reduce channel capacity, induce overbank flooding, and result in overall aggradation, creating conditions potentially conducive to avulsions in subsequent floods.
- Scale of Analysis. FLO-2D sediment model results appear more reasonable when viewed as a large-scale composite of fan behavior, rather than on a single-grid basis.

4.5.7. Topographic Analysis: Avulsive Flow Path Tool

For a fully-developed channel avulsion to occur, flow leaving the parent channel must become and remain hydraulically separated from the parent channel for some measurable distance. In the case where the fan surface elevations and slope are not drastically altered during a flood, the only way a hydraulically separate flow path can exist is if the local ground slope and topography convey flow away from the parent channel. On an idealized alluvial fan with perfectly smooth radial contours, any flow escaping the parent channel would not return since the steepest flow path would be perpendicular to the contours. On many real-world alluvial fans, especially the low-sloping fans in central Arizona, on-fan incipient drainage networks, distributary channels, and other topographic features tend to capture overbank flows and return them to the parent channel network, or at least the broader avulsion belt. Nevertheless, given that avulsions are known to occur on alluvial fans in central Arizona, it was assumed that some avulsive flow paths must exist on local alluvial fans that would direct runoff away from the parent channel network.

An avulsive flow path tool was developed to identify potential overbank flow paths that could serve as avulsive flow corridors. Two variations of the avulsive flow path tool were developed. The more complex version of the tool uses FLO-2D velocity data over the fan surface grid to identify probable flow paths. A computationally similar, but simpler version uses just topographic data, eliminating the need for running the FLO-2D model. For the purpose of this analysis, the FLO-2D modeling grid was used in both model variations as an input to the avulsive flow path tool. Potential locations of flow bifurcations (initiation points for avulsions), such as significant bends in the main parent channel or reaches of limited or diminishing conveyance capacity, were identified using aerial photography, topographic mapping, and field observations. These identified bifurcation points served as the starting point for the avulsive flow path tool computations. The avulsive flow path tool then uses an iterative process, and moves in the downstream direction following the steepest ground slope or largest velocity vector direction obtained from the topographic mapping or previous FLO-2D modeling results. The steepest slope in the eight directions between adjacent grids was estimated using the cell elevations in the FLO-2D topographic data file. The velocity vector direction was obtained from the PMP FLO-2D model run results. The PMP FLO-2D run was used because it provided velocities at the greatest number of cells, i.e., more cells are inundated by the PMP discharge than for smaller floods. Using the directions from steepest slope and velocity distributions, the potential flow paths were tracked from one grid cell to another cell in the downstream direction. These flow paths were then drawn pictorially on top of aerial photography to visualize the potential avulsive paths, as shown in Figure 29.

Once the avulsive flow path model results were overlain on a recent aerial photograph and compared to the existing network of defined channels on the alluvial fan surface, the avulsive flow path model flow paths could be grouped in the following categories:

- Flow along existing defined channels (non-avulsive)
- Flow paths that immediately re-joined existing channel (non-avulsive)
- Flow paths that do not overlie existing channels or rejoin the existing channel network (avulsive)

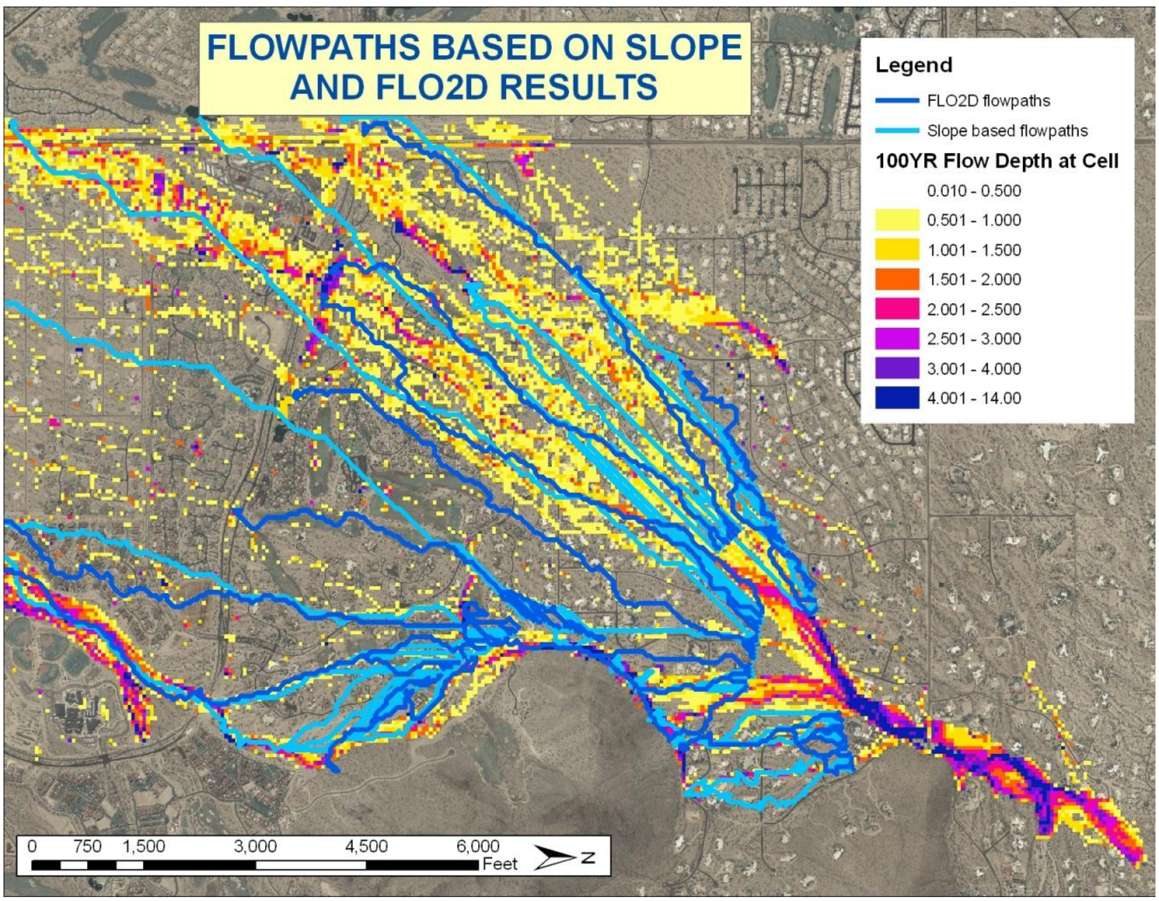

Figure 29. Avulsive flow path tool results for the Reata Pass Fan

The avulsive flow path tool was applied to the Reata Pass Fan (Figure 29). Several key potential avulsive flow paths were identified by the avulsive flow path tool as shown in Figure 30. If flow leaves the parent channel at the possible bifurcation points, and sufficient flow volume leaves the main channel, formation of a new channel is possible along the identified alignment.

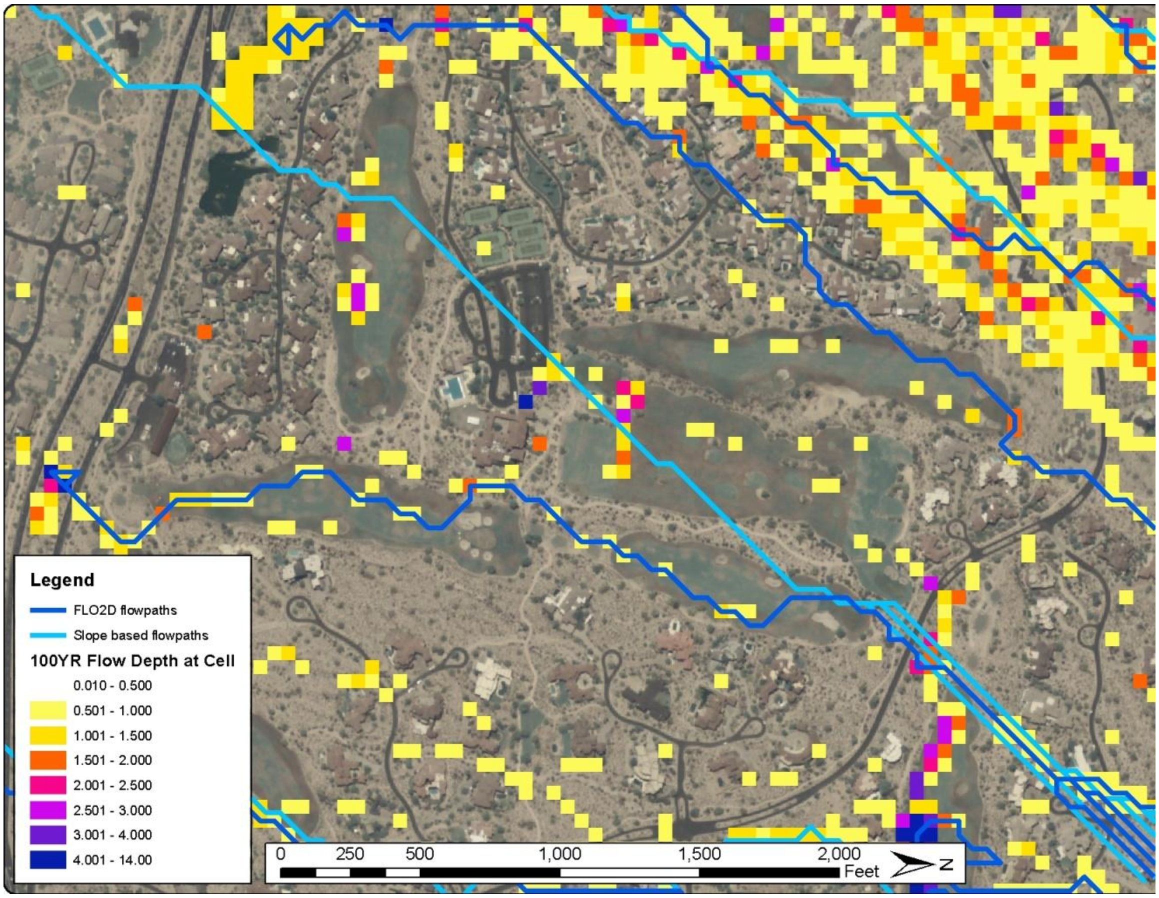

Figure 30. Potential avulsive flow paths on the Reata Pass Fan.

The avulsive flow path tool provides a quick method of identifying potential avulsive flow paths and their impacts. For example, if the avulsive flow path model flow path quickly merges back to the parent channel, the risk of avulsion is probably low and would not significantly impact the overall flow distribution on the fan surface. Conversely, if the potential avulsive flow path deviates significantly from the existing channel network, an avulsion would be more likely to alter downstream hydrology and floodplains. The degree of avulsion hazard may differ depending on the land use, development density, location of flood control structures, discharge peak, volume and duration, soils, and vegetative cover along the potentially avulsive flow path. The avulsive flow path tool may be most applicable as a quick way to identify possible avulsion locations, or as a trigger for additional more sophisticated analyses of the avulsion potential.

4.5.8. Verification: Hindcast of White Tank Fan 36 1951 Flood Avulsions

Large floods occurred at the WTF 36 site in 1951 (JEF, 1999). There is good correlation between the inundation areas visible on the 1953 aerials and the FLO-2D base model results (Figure 31), 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 are 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.[8] 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, 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.

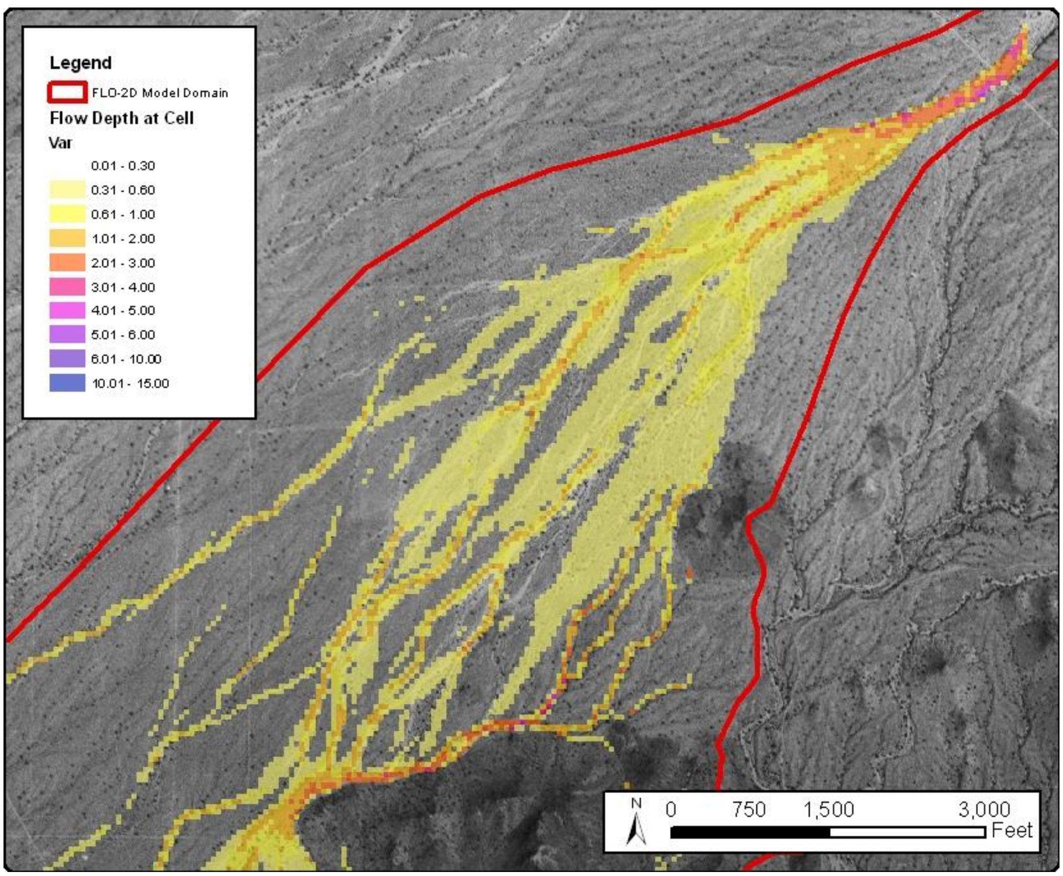

Figure 31. FLO-2D base model results for White Tanks Fan 36 overlain on 1953 post-flood aerial.

[8] Topographic map accuracy or model grid cell size may also be factors.

4.5.9. Verification: Hindcast of Tiger Wash 1997 Flood Avulsions

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. 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 32, 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 a mega-flood discharge like the PMP event, the FLO-2D results did not predict highly erosive flow depths and velocities along the avulsion alignments. Unfortunately, the poor quality[9] of the only available pre-1997 topographic mapping makes it impossible to draw firm conclusions about the ability of FLO-2D to hindcast the historical alluvial fan avulsions on the Tiger Wash Fan.

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

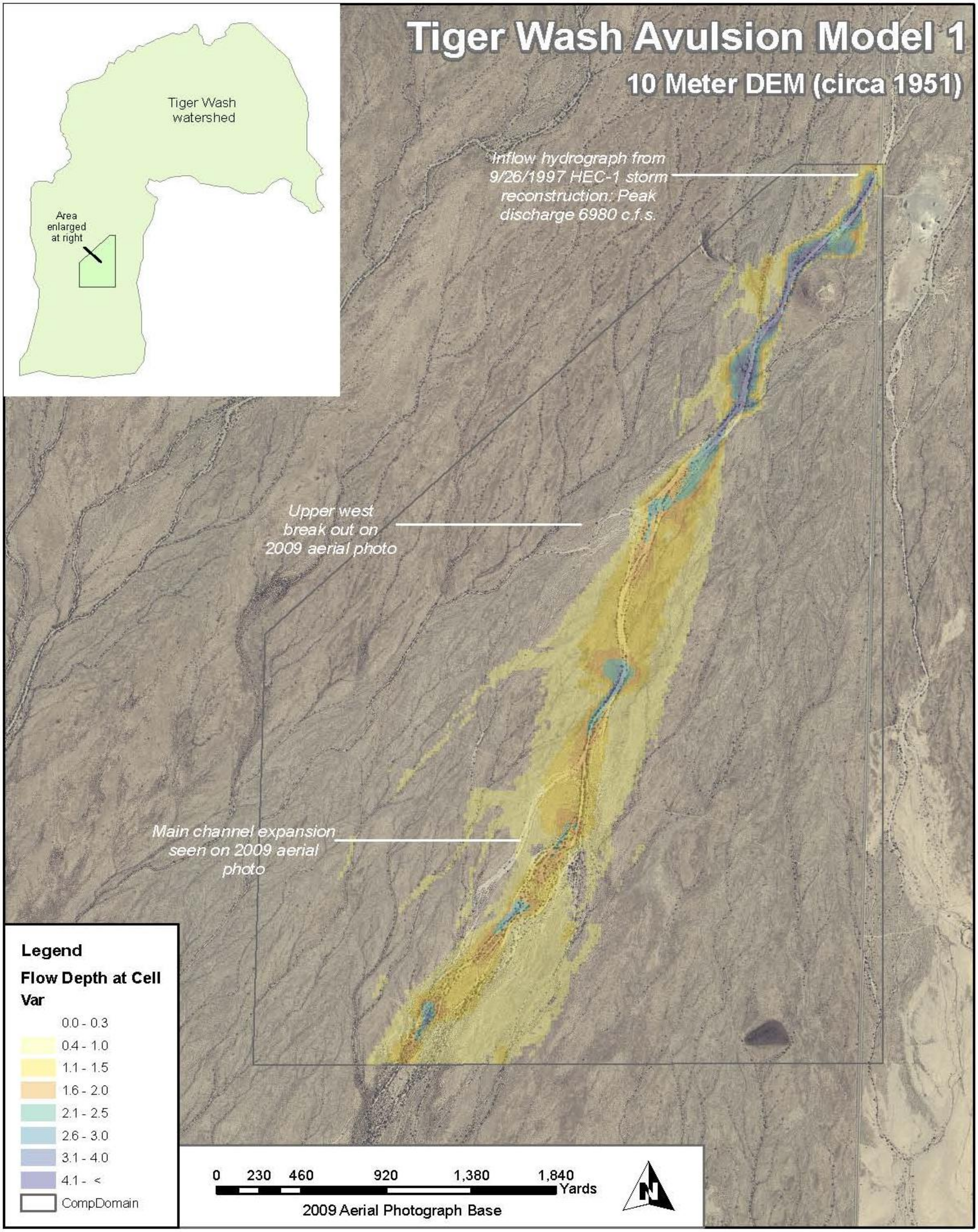

Figure 32. FLO-2D base model results for Tiger Wash Fan overlain on 2007-post-flood aerial.

4.5.10. Virtual Levee Scenario Methodology

The "virtual levee scenario" methodology was originally developed to evaluate the hydrologic impacts of avulsions on concentration points below the apexes of two coalescing active alluvial fans (JEF, 2009). It is important to note that the virtual levee scenario methodology does not explicitly model the mechanics of an alluvial fan avulsion. Instead, it assumes that an avulsion can occur within a user-identified part of the active alluvial fan, that the avulsion will redirect runoff across that portion of fan surface in a manner that only partially reflects the pre-flood topography, and that flow will be conveyed over the non-avulsive part of the fan surface as directed by the surface characteristics and topography. The portion of the active alluvial fan that is subject to potential avulsions is identified by a composite method of two-dimensional modeling, geomorphic landform interpretation, and other techniques described by JE Fuller (2010).

The following guidelines on implementation of the virtual levee scenario methodology are provided:

- Judgment Required. 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.
- Two-Dimensional Modeling. For this study, the FLO-2D model was used. It is possible that other two-dimensional models would also perform adequately.
- 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, fixed-bed, single-hydrograph, base FLO-2D model 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).
- 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 effect 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.
- 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 (or tertiary) apex using the upstream levee combination(s) that delivers maximum flow rates downstream
- 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.

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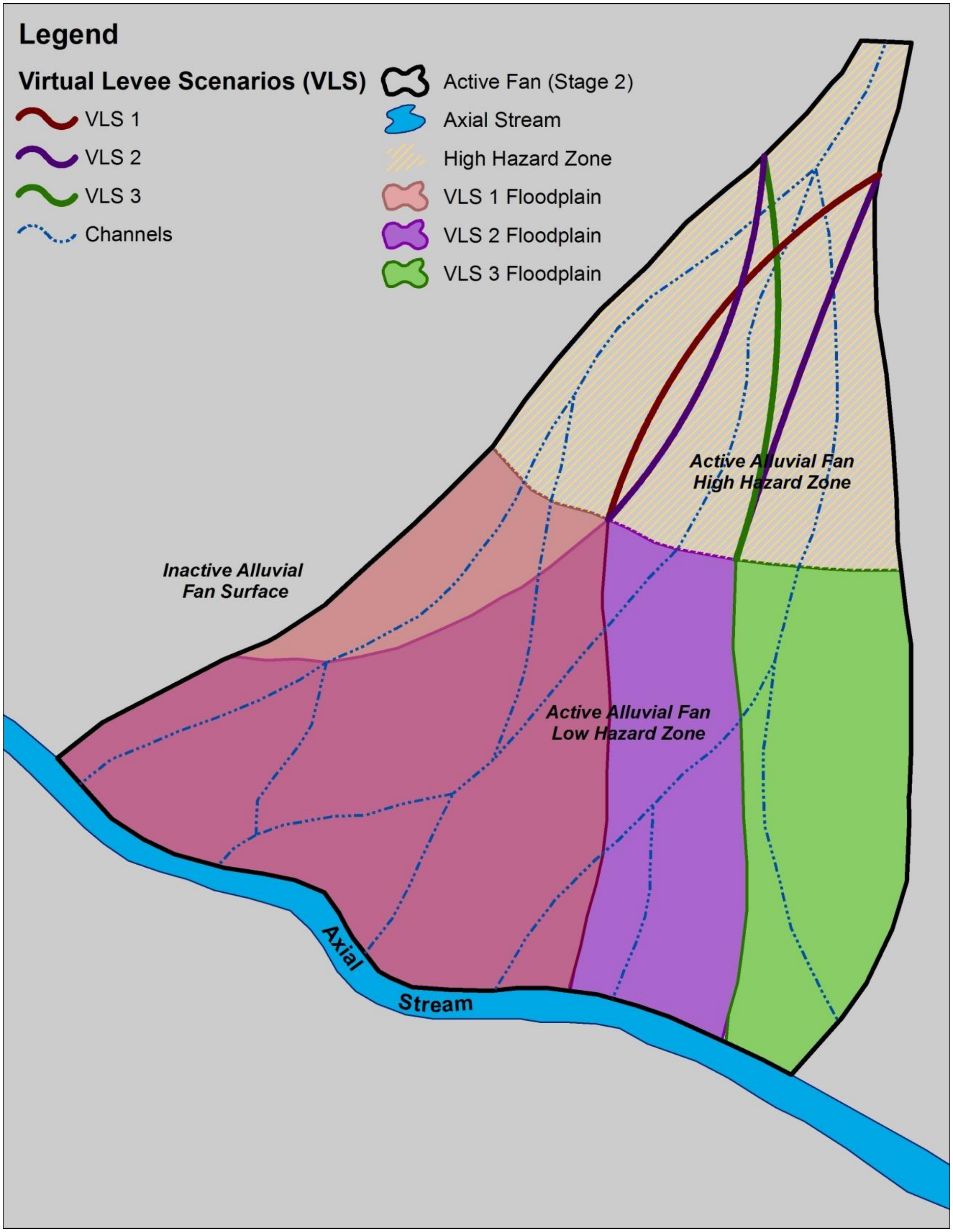

Figure 33. Illustration of virtual levee scenario methodology application.

   - 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 central Arizona, 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

4.5.10.1. Virtual Levee Scenario Models

FLO-2D models applying the virtual levee methodology 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 effect 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 34**):

- 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 this 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.

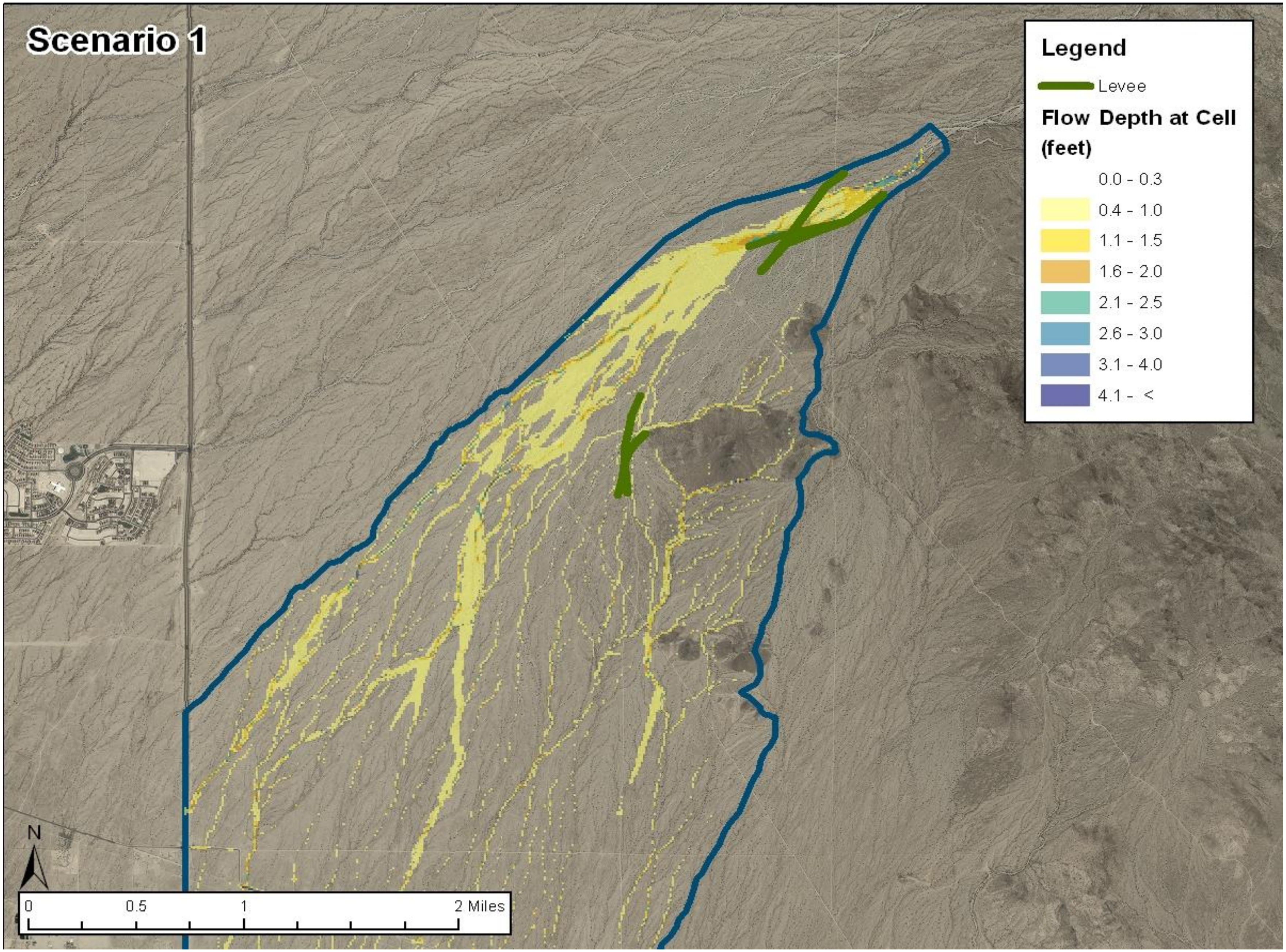

Figure 34. ***Example of virtual levee scenario results for White Tanks Fan 36***

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. 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.

While the virtual levee scenario methodology does not itself predict the occurrence or character of alluvial fan avulsions, plots of FLO-2D modeling results achieved by applying the virtual levee scenario methodology elucidate the possible changes in flow depth and other hydraulic variables (velocity, stream power, etc.) downstream of an avulsion on an active alluvial fan, as shown in Figure 35 to Figure 38. These results indicate that while changes in upstream flow paths (i.e., avulsions) could create changes in flow hydraulics that could also produce minor avulsions in the mid- and lower portions of an active fan, in most cases avulsions near the fan's hydrographic apex have little impact on the predicted flow depths, velocities, and areas of inundation in the mid- to distal-portions of the active alluvial fan. A historically documented example of a minor mid-fan avulsion on the White Tank Fan 36 site was discussed in Section 2.4.2 and shown in Figure 5.

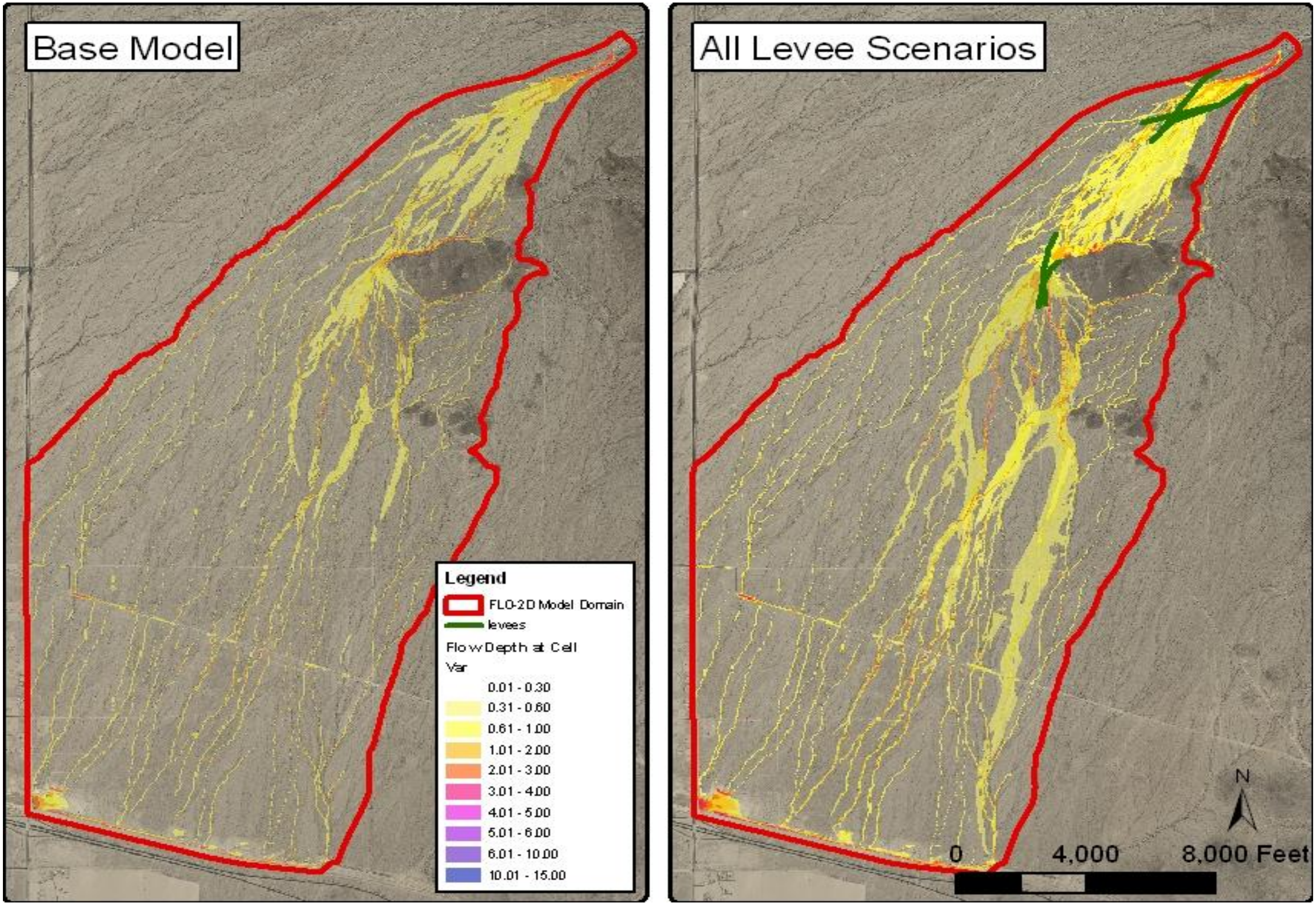

Figure 35. 100-year virtual levee scenario results and virtual levee locations for White Tanks Fan 36

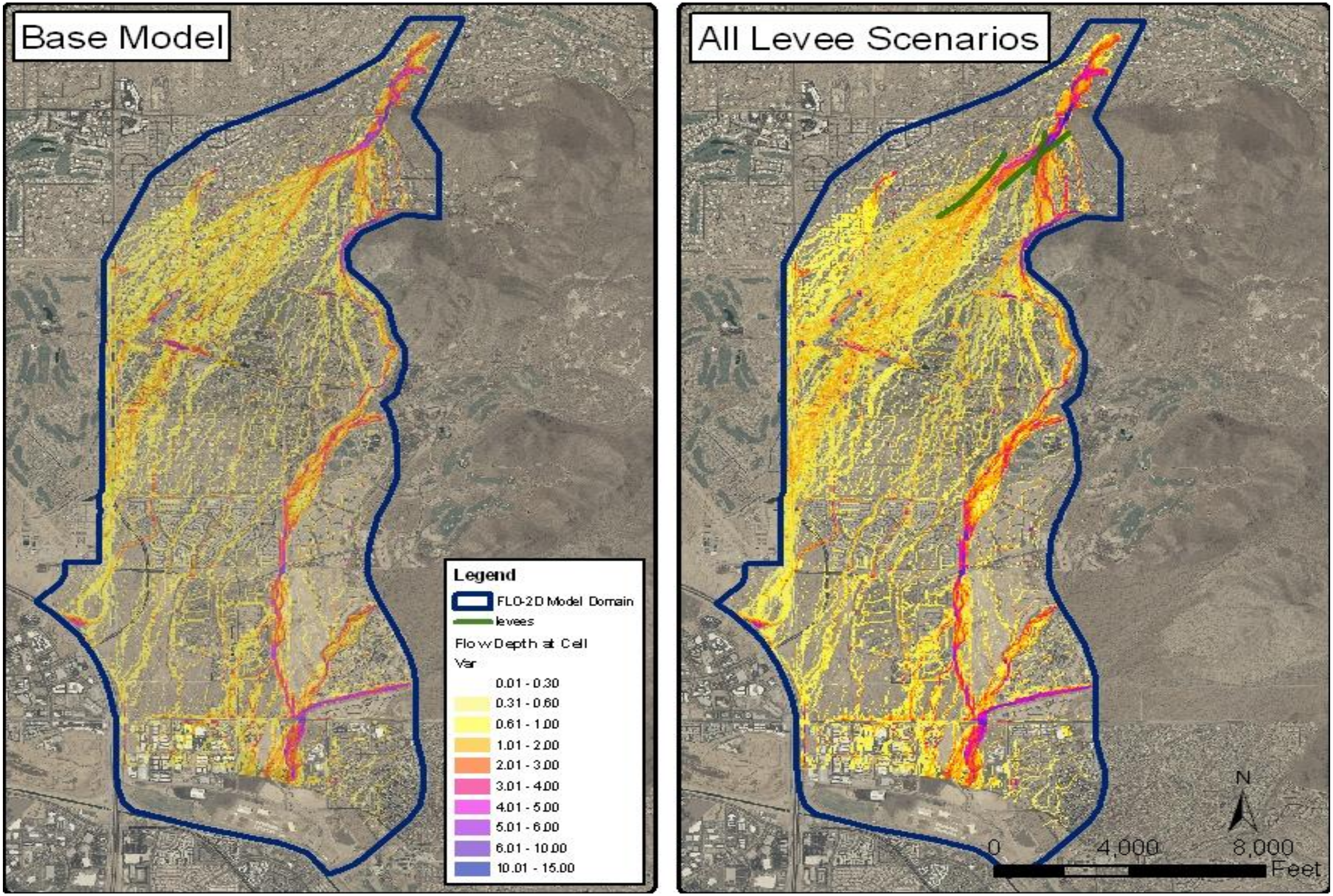

Figure 36. 100-year virtual levee scenario results and virtual levee locations for Reata Pass Fan.

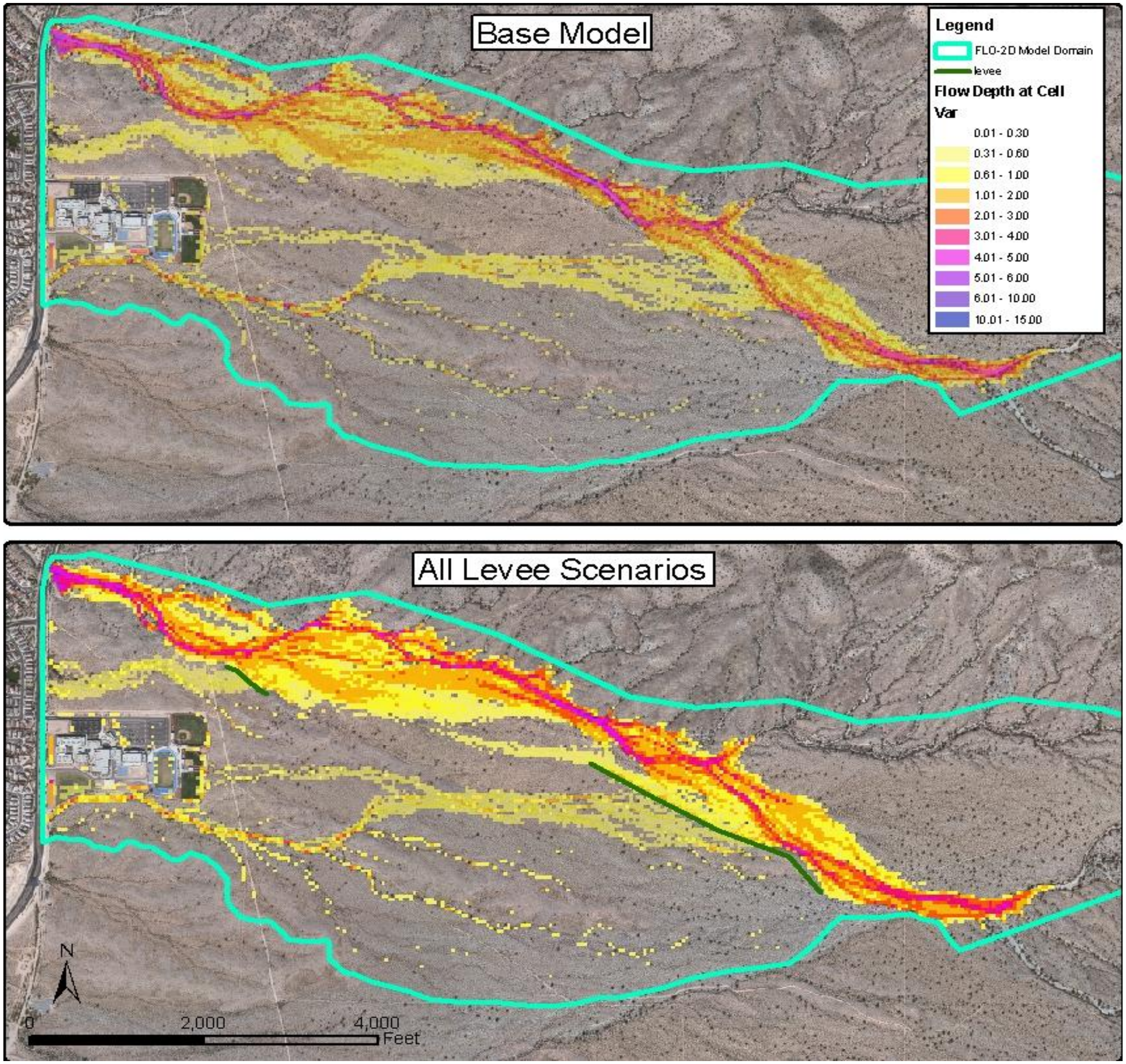

Figure 37. 100-yr virtual levee scenario results and virtual levee locations for Rainbow Valley Fan 1.

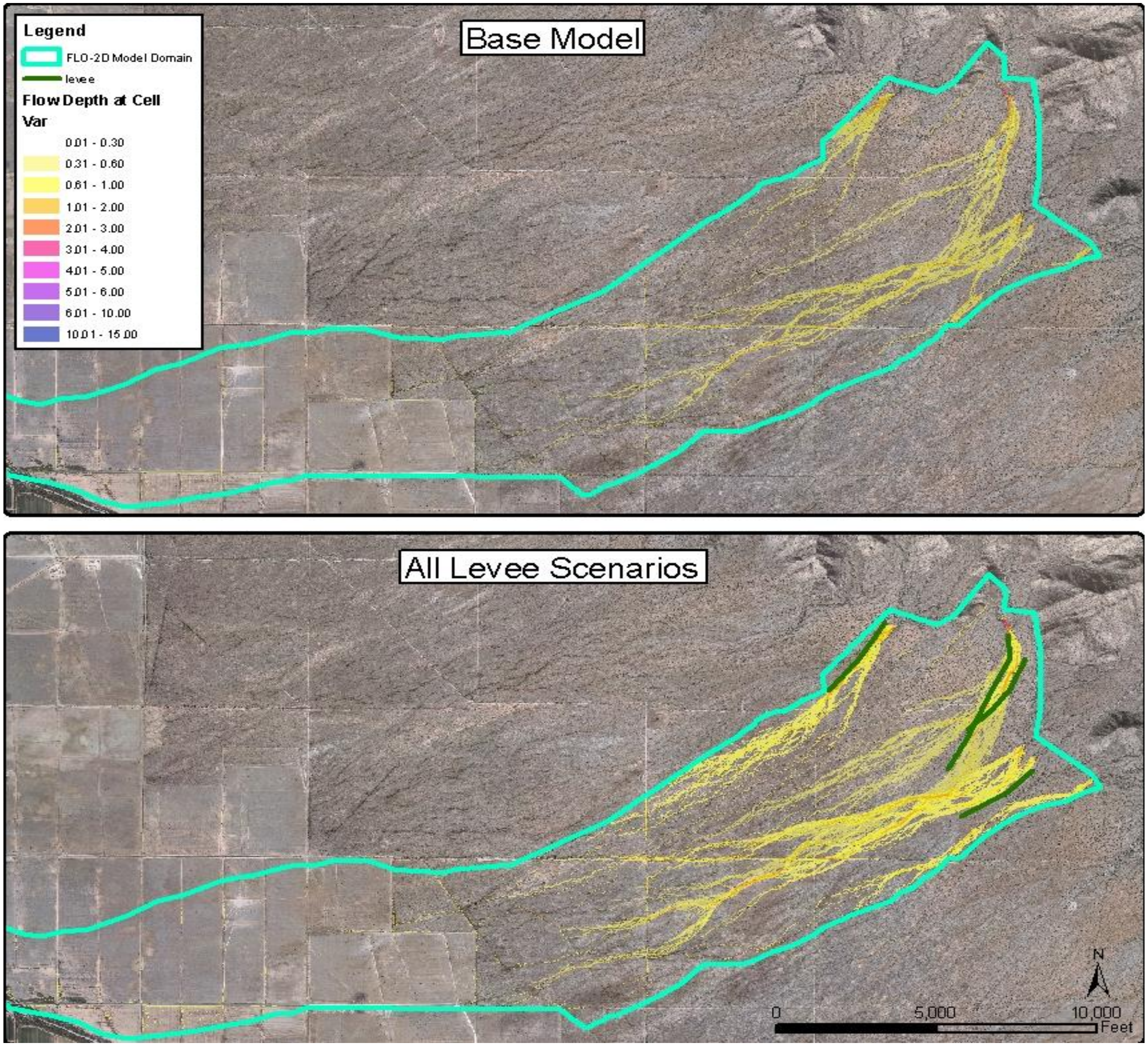

Figure 38. 100-yr virtual levee scenario results and virtual levee locations for Rainbow Valley Fan 12.

4.5.11. Comparison of the Virtual Levee Technique with the FAN Model

Floodplain delineations based on the virtual levee methodology based on FLO-2D modeling and the FEMA FAN model were compared for an active alluvial fan in the Mohave Valley area near Kingman, Arizona (Figure 2). The FAN model was applied using the same base information (10-, 25-, and 100-year discharges) has the FLO-2D modeling effort. FAN also requires a single value for fan slope (0.03 ft./ft.), and roughness coefficient (0.045), and an avulsion factor (1.5). The FAN model generates radial widths which represent transition points between flood depth zones. The FAN-generated widths were used to delineate a floodplain as shown in Figure 39.

The following conclusions can be drawn from resulting floodplain delineations shown in Figure 39.

- AO depth zones generated from the FAN program are less conservative than the depth zones based on the FLO-2D modeling and virtual levee approach.
- Topographic islands identified in the distal portions of the alluvial fan were correctly depicted by FLO-2D modeling, but were ignored by the FAN model.
- The FLO-2D model results were more directly tied to physical characteristics and processes on the alluvial fan.
- The FLO-2D model produced not only depth and velocity estimates, but also generated peak discharge values and other hydraulic parameters that accounted for sources of tributary and on-fan runoff. Because of these additional sources of flow, the FLO-2D based approach identified a 30% higher peak discharge at the toe of the fan than was estimated from the FAN model approach.
- The FLO-2D model identified frequently flooded, active flow corridors within the active fan area and did not assume an equal probability of flooding in channels and on floodplains.

4.5.12. Other Potential Methodologies

It is likely that new techniques for identifying and modeling alluvial fan avulsions will be developed in the future. Some of the more promising techniques include those being developed by Parker et. al. (1998), application of riverine avulsion equations (c.f., Tornqvist, 2004), or physical modeling. FLO-2D evaluation of higher frequency floods, such as a 10-year event, using the techniques outlined above also might be useful for identifying the most likely avulsion locations.

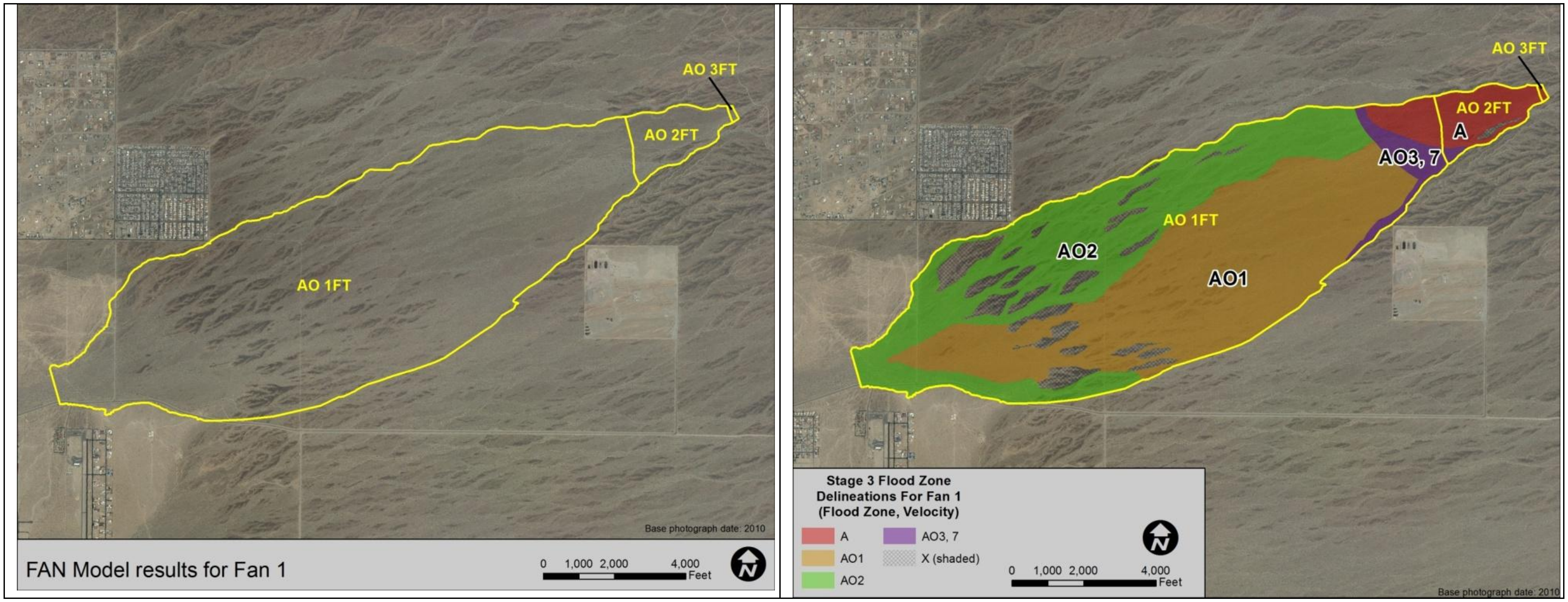

Figure 39. FEMA FAN model-based floodplain delineation (left) vs. FLO-2D based delineation using the virtual levee methodology (right).

4.6. Knowledge Gaps

Review of the literature regarding alluvial fan avulsions identified the following three primary gaps in the knowledge base required to develop a robust methodology for quantifying alluvial fan flood hazards in central Arizona:

- Avulsion Frequency. As indicated below, there are several lines of evidence that suggest that avulsion on fans in central Arizona are rare (Field, 1994). Physical model studies which indicate avulsions are common events (Schumm et. al., 1987) may be misleading due to model scaling issues (Whipple et. al, 1998). However, to date there has been no definitive analysis of avulsion frequency or recurrence interval, in central Arizona or elsewhere.

  Recommendation: The floodplain management community should authorize or conduct a study of avulsion frequency on active alluvial fans, not only in Arizona, but in all areas affected by alluvial fan flooding.

- Modeling Methodology. Identifying past channel avulsions is a rather simple task of observation and documentation. The causative factors leading to avulsions are relatively well known. Several authors have speculated that they may be able to predict likely locations of some avulsions (Field, 2001), but there is currently no accepted method for quantifying such predictions.

  Recommendation: Floodplain managers should adopt the recommended approach presented Section 5 below as a first step toward developing a standard methodology for predicting avulsion potential. Recommended subsequent steps include testing the methodology on alluvial fans in central Arizona, and vetting the methodology with FEMA reviewers and other communities with alluvial fan flooding concerns.

- Engineering Design Standards. Short of designing structures for the full apex discharge and hydraulic conditions, or the "virtual levee" methodology recently developed and applied to fans in central Arizona (JE Fuller, 2009), the standard of practice for design of structures on alluvial fans has not yet been defined.

  Recommendation: Floodplain managers should include engineering and design guidelines for development on active alluvial fans in their locally adopted floodplain ordinances, regulations and design manuals.

5. Recommended Methodology

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 Arizona and geographically similar areas 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 type 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 the potential exists for debris flows to impact that active fan surface, then a detailed debris flow analysis should conducted using the procedures outlined by Youberg (2010), 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 “mega-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. Avulsions should be expected within the high hazard zones on active alluvial fans. 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 to identify potential avulsive flow paths.

- 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 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 is not recommended as part of the recommended avulsion prediction methodology.

- 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.

6. Conclusions

The objective of the avulsion potential evaluation was to determine and quantify how channel avulsions influence flood hazards on alluvial fan landforms in central and western Arizona. This information is to be used to refine methodologies for assessing active alluvial fan flood hazards. The following conclusions can be made from the evaluation summarized in this report:

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- Avulsions Occur on Alluvial Fans in central Arizona. Occurrences of past alluvial fan avulsions are well documented in the literature and are irrefutably demonstrated by comparisons of historical and recent aerial photographs.

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

- 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 analysis of flood hazards on active alluvial fans.

- Methodology. There is no broadly accepted technique for identifying and predicting the location or nature of future avulsions. A five-step methodology for use on alluvial fans in central Arizona has been proposed as part of this study.

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