A Critique of "Alluvial Fan Flooding Methodology: An Analysis"

(DMA Consulting Engineers, 1985, Report to FEMA, Contract EMW-84-C-1488)

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Rocky Canyon, Humboldt River Tributaries (Rye Patch & Oreana)

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A Critique of "Alluvial Fan Flooding Methodology: An Analysis" (DMA Consulting Engineers, 1985, Report to FEMA, Contract EMW-84-C-1488)

By Jonathan Fuller, PE, RG, PH, D.WRE, CFM[1]

FEMA guidelines for floodplain delineations on active alluvial fans allow use the FAN methodology, a stochastic model based on work originally published by Dawdy (1979). In 1985, FEMA contracted with DMA Consulting Engineers (DMA) to perform an analysis of their alluvial fan methodology. FEMA regards the DMA study as the computational link between Dawdy's theoretical model and the FAN program, as well as a verification of the FAN methodology (Lenaburg, 2010). The stated purpose of the DMA report was to evaluate and verify two key assumptions in the FEMA alluvial fan methodology: (1) that the location of a stream path on a fan surface is random, i.e., a channel has an equal probability of occurring anywhere across the fan, and that (2) flow forms its own channel and remains in one channel throughout the flow event, except when a channel avulses (p. 1). [2]

Based on their analysis, DMA reported the following conclusions and recommendations:

(1) The location of the single channels below the canyon mouths on alluvial fans was found to be random (p. 51). Therefore, the assumption of random channel location should continue to be used in alluvial fan flooding analyses (p. 74).
(2) Flow does not remain in a single channel across the entire fan surface (p. 51, 74). Instead, flow over the fan surface occurs in a single channel reach near the canyon mouth, followed by a split channel reach, followed by a braided channel reach which extends to the toe of the fan.
(3) The length of the single channel can be predicted by the ratio of the canyon slope to the fan slope (p. 55, 74).
(4) The width of the single channel can be predicted by the FEMA (Dawdy) equation (p. 55)
(5) The cumulative channel width in the multiple channel region is 3.8 times the width of the single channel (p. 59, 74).
(6) Due to insufficient data, DMA recommended no change in the default avulsion coefficient of 1.5 (p. 61, 75) but did recommend further study of avulsion frequency (p. 75).
(7) Channels on urbanized fans located below well-vegetated watersheds are more stable than channels on undeveloped fans located below poorly-vegetated watersheds (p. 74).
(8) Avulsions are caused by debris flows (p. 75).

Unfortunately, numerous errors, faulty reasoning, and questionable data call into question nearly every one of DMA's conclusions, and undermine the intended "verification" of FEMA's alluvial fan methodology. This paper documents the flaws in the DMA analysis in order to point out the need for a rigorous, scientifically valid evaluation of the FAN methodology. First, general errors that apply comprehensively to the entire DMA study are discussed. Then, errors that apply to each of DMA's conclusions are discussed. Finally, DMA's findings relative to their two stated objectives, random channel paths and self-formed channels, are discussed.

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[2] Cited page numbers refer to the DMA Report, unless otherwise noted.

Overview

DMA's verification study was based on a review of 50 literature sources and analysis at 18 sites[3] (Table 1). The 18 sites were selected because they were identified as alluvial fans, had USGS stream flow gauges or USGS indirect peak discharge estimates, a recent flood, and aerial photographs that pre- and post-dated the flood. DMA's 18 fan sites were located in four Nevada counties and two Southern California counties (Figure 1). All site data appear to have been collected from aerial photographs and USGS 1:24,000 and 1:68,000 scale topographic maps. There is no reference in the DMA report to field visits, geomorphic mapping, ground surveys, or hydrologic and hydraulic modeling for any of the 18 sites.

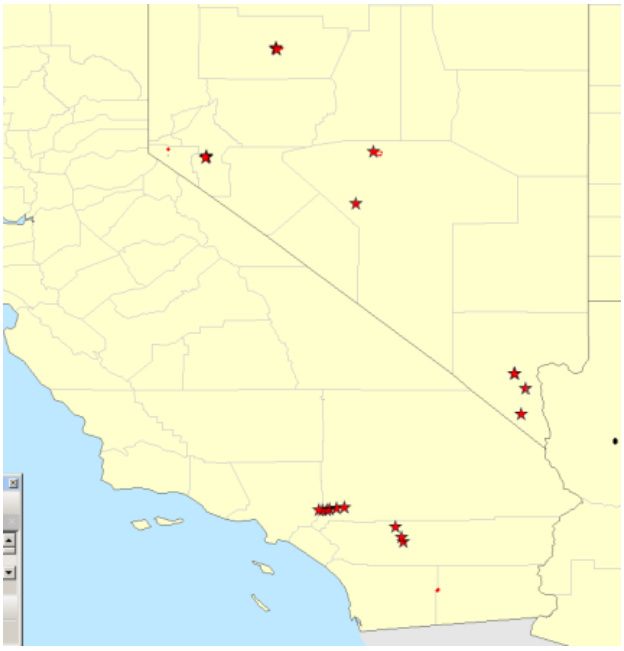

Figure 1. Locations of DMA Alluvial Fan Sites.

Table 1 lists the site names, locations, spatial coordinates and the dates and rates of the historical flood peaks. The spatial coordinates can be used in Google Earth or other GIS-based data services to view aerial photographs and other geographic information for each site.

Table 1. Alluvial Fan Sites Described in the DMA Report

Fan Name	Location	Lat/Long Coordinates	Flood Peak & Date
Northumberland Canyon	Austin, NV	W39°00'44.15" / N116°56'25.41"	7,680 cfs (8-7-1979)
Mason Valley Trib [a]	Mason, NV	W38°57'03.29" / N119°11'59.70"	4,500 cfs (6-30-1970)
Humboldt River Trib	Rye Patch, NV	W40°25'10.56" / N118°15'30.51"	8,940 cfs (5-31-1973)
Rocky Canyon	Oreana, NV	W40°24'33.44" / N118°15'33.58"	14,370 cfs (5-31-1973)
Humboldt River Trib	Oreana, NV	W40°23'49.96" / N118°15'26.86"	6,000 cfs (5-31-1973)
Las Vegas Wash Trib [b]	Henderson, NV	W36°01'20.07" / N115°02'01.05"	1,290 cfs (7-1-1980)
Piute Wash	Searchlight, NV	W35°28'15.25" / N114°56'34.03"	370 cfs (9-11-1976)
San Antonio Wash	Tonopah, NV	W38°18'48.51" / N117°10'15.52"	660 cfs (8-13-1972)
Eldorado Valley Trib	Nelson, NV	W35°48'42.92" / N114°53'20.56"	530 cfs (8-4-1970)
Lytle Creek	Fontana, CA	W34°12'00.25" / N117°26'37.51"	35,900 cfs (1-25-1969)
Day Creek	Etiwanda, CA	W34°10'29.92" / N117°32'31.54"	9,500 cfs (1-25-1969)
Deer Creek	Guasti, CA	W34°10'35.34" / N117°34'15.87"	4,200 cfs (3-2-1938)
Cucamonga Creek	Upland, CA	W34°09'52.11" / N117°38'11.85"	14,100 cfs (1-25-1969)
San Antonio Creek	Claremont, CA	W34°09'52.63" / N117°40'39.87"	21,400 cfs (3-2-1938)
Tahquitz Creek	Palm Springs, CA	W33°48'30.86" / N116°33'20.07"	2,900 cfs (11-22-1965)
Palm Canyon	Palm Springs, CA	W33°34'31.89" / N116°32'14.84"	3,850 cfs (2-6-1937)
Devil Canyon	San Bernardino, CA	W34°12'17.03" / N117°20'05.01"	3,720 cfs (1-25-1969)
Whitewater River	Whitewater, CA	W33°55'31.77" / N116°36'06.69"	42,000 cfs (3-2-1938)

Notes:
a. Two additional nearby ungauged sites, McConnell and Nevada Canyons are described by DMA.
b. An adjacent site, called Las Vegas Wash Tributary Fan A, is also described by DMA.

[3] Eighteen sites are listed in Table 1 of the DMA Report, and three additional sites are described in the text.

General Comprehensive Errors

There are a number of comprehensive errors in the DMA Report that apply to their overall analysis and conclusions. Some of these comprehensive errors are so fundamental that they call into question whether DMA had the requisite expertise in geomorphology and alluvial fan flooding needed to perform the verification study, as well as the credibility of their conclusions regarding FEMA's FAN methodology.

Landform Identification. At least two the 18 sites selected by DMA are not alluvial fan landforms (Table 3). The Piute Wash site (Figure 2) does not have a radial contour pattern, i.e., it does not have the shape of a fan. More importantly, the landform has a well-defined, moderately incised tributary channel pattern indicative of inactive piedmont landforms, and thus exhibits no evidence to suggest a risk of flow path uncertainty. The Eldorado Valley site (See Appendix A) is located at the margin of a broad alluvial plain subject to sheet flooding. It does not have the shape of an alluvial fan, and could be considered an alluvial fan landform in only the broadest sense, although it may have experienced some degree of flow path uncertainty over geologic time scales.

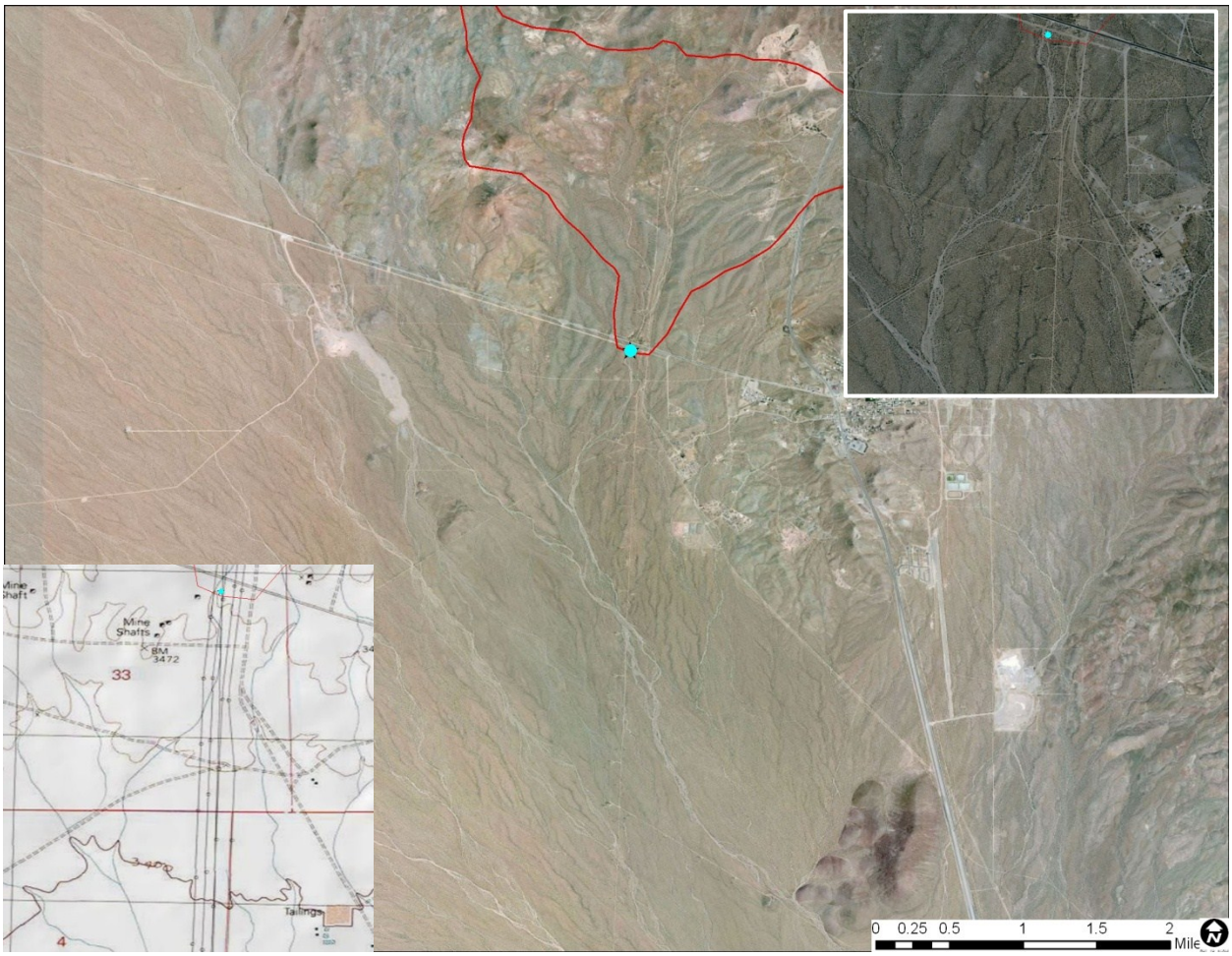

Figure 2. DMA Piute Wash Tributary site, with insets of USGS topographic mapping and an aerial of the "fan" area below the "apex." The site is located on the margins of a broad alluvial plain.

Inactive vs. Active Alluvial Fans. A critical short-coming of the DMA study is that they did not distinguish active alluvial fans from inactive alluvial fan surfaces (Figure 3), a criticism which the National Research Council also noted in regard to the original FEMA alluvial fan methodology (NRC, 1996). Since inactive alluvial fans do not experience flow path uncertainty, the FAN methodology is now applied only on active alluvial fans (FEMA, 2003). Flood hazards along channels on inactive alluvial fans can be adequately analyzed using riverine floodplain delineation techniques because of topographic confinement provided by adjacent inactive fan deposits (NRC, 1996; FEMA, 2003). Inclusion of data from inactive alluvial fan areas for at least 17 of the 18 DMA sites, and up to 50% of the data point clouds the validity of many of DMA's conclusions and creates questions regarding study's applicability to the FAN model.

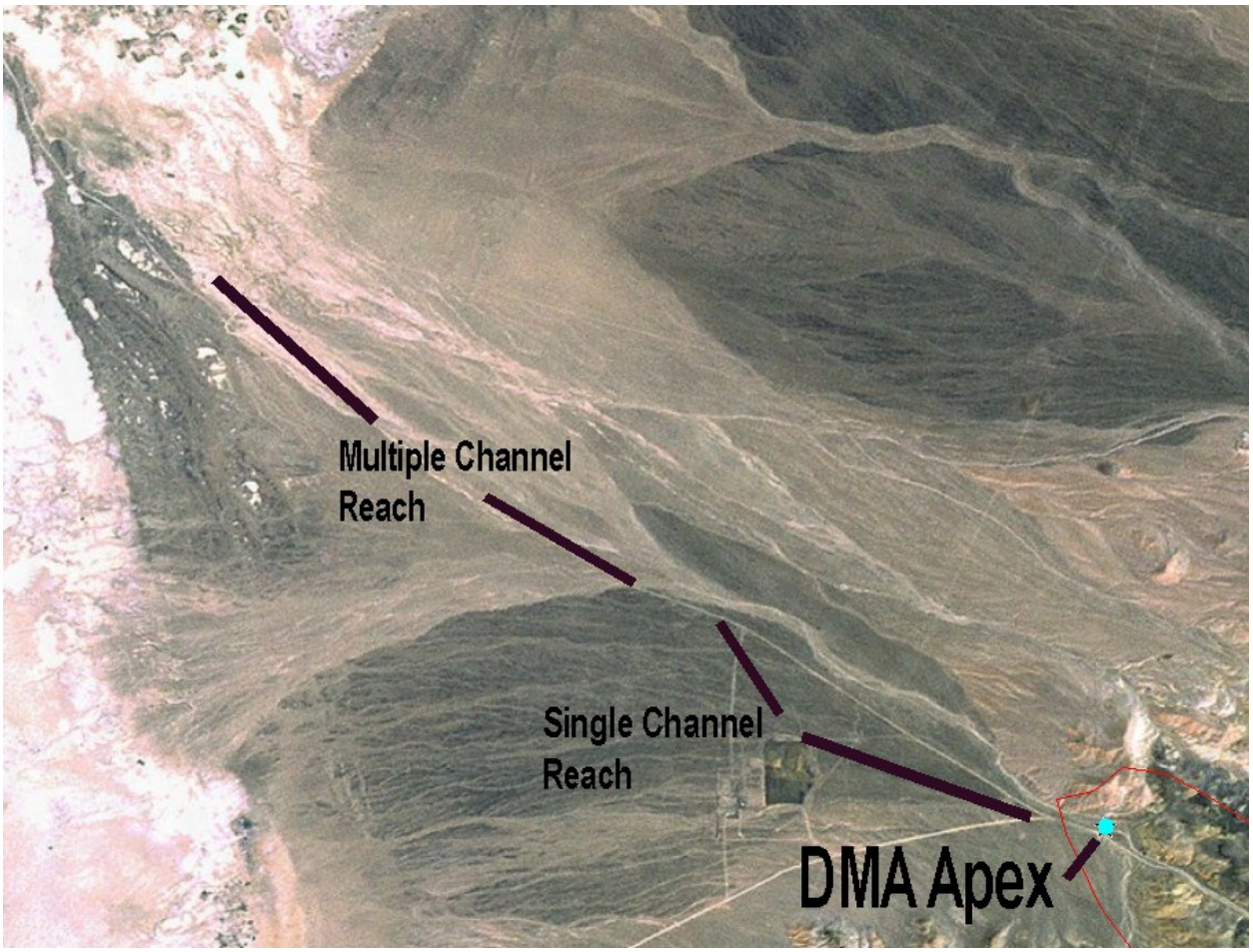

Figure 3. DMA Northumberton Canyon site showing the location of the single channel reach within the inactive fan area upstream of the hydrographic apex.

Geologic vs. Engineering Time Scale. As a consequence of not distinguishing active and inactive fan surfaces, the DMA Report also fails to distinguish processes of fan formation and evolution that operate over geologic time periods (> 10,000 yrs) from flooding processes that operate in engineering time scales (<1,000 yrs). This error not only affects the assumption of ergodicity that DMA relies on to justify their verification of random channel location (discussed below), it underlies their failure to recognize the long time scales over which geologic processes such as alluvial fan evolution occur.

Table 2. Comparison of Fan Data Reported by DMA

	DMA Data[c]						Measured Data					
Fan	Drainage Area (mi2)	Slope			Single Channel		Drainage Area (mi2)	Slope			Single Channel	
		Cyn	Upper Fan	Fan	Length	Width		Cyn	Upper Fan	All Fan	Length	Width
Northumberland Cyn	15.1	0.033	0.033	NR	14500	100-462[a]	19.9	0.038	0.033	0.006-0.033	15800	145-583
Mason Valley Trib	2.6	0.058	NR	0.035	NR	NR	3.3	0.057	0.053	0.053-0.056	860	15-35
McConnell Cyn	NR	NR	NR	NR	NR	NR	2.2	0.105	0.093	0.057-0.093	60	11-27
Nevada Cyn	NR	NR	NR	NR	NR	NR	1.6	0.102	0.067	0.034-0.067	840	12-33
Humboldt River Trib	0.85	0.110	NR	0.071	1060	35-60	1.2	0.116	0.116	0.041-0.166	542	20-60
Rocky Canyon	4.05	0.108	0.058	0.013	1500	NR	5.3	0.111	0.072	0.058-0.072	1220	37-44
Humboldt River Trib	0.76	0.124	0.070	0.02	NR	NR	1.0	0.129	0.079	0.036-0.079	121	19-37
Las Vegas Wash Trib	0.06	0.058	0.050	0.05	3075	68	1.0	0.057	0.048	0.020-0.048	4170	34-73
Las Vegas Trib Fan A	NR	0.061	NR	0.056	3250	183	1.1	0.055	0.055	0.039-0.055	2580	99-230
Piute Wash	3.4	0.016	NR	0.016	10500	90	3.9	0.013	0.013	0.017-0.013	6050	105-210
San Antonio Wash	3.42	0.070	NR	0.053	2250	NR	2.7	0.058	0.049	0.030-0.049	80	90
Eldorado Valley Trib	1.4	0.036	NR	0.036	2000	"wide"	2.6	0.037	0.044	0.038-0.044	2800	93-127
Lytle Creek	46.3	0.031	0.026	0.026	4400	761	52.2	0.032	0.032	0.028-0.032	700	550
Day Creek	11.9	0.149	0.103	NR	2400-3660	268-870	5.7	0.098	0.098	0.057-0.098	Natural channels disturbed by development precluding accurate measurement	
Deer Creek	3.4	0.168	0.109	NR	600	275	4.5	0.140	0.113	0.075-0.113		
Cucamonga Creek	10.1	0.075	0.048	NR	7920	358	12.5	0.099	0.048	0.029-0.048		
San Antonio Creek	26.2	0.055	0.046	NR	8150	276[b]	29.9	0.046	0.040	0.037-0.040		
Tahquitz Creek	43.5	0.111	NR	0.046	2000	NR	20.0	0.078	0.075	0.029-0.075		
Palm Canyon	93.3	0.058	NR	0.055	3825	550	93.1	0.188	0.011	0.015-0.011		
Devil Canyon	5.61	0.085	0.062	NR	1500	216	7.2	0.082	0.065	0.054-0.065		
Whitewater River	57.4	NR	0.034	0.030	880	<640	70.3	0.033	0.026	0.026	5400	370-840

Notes:

a. The channel width reported is the floodplain width. The active, main channels are significantly narrower.
b. 410-810 ft is reported in DMA site description, 276 is listed in DMA Table 2.
c. Fan expansion angle was not verified because that variable is not used in FAN model or any known fan floodplain analysis technique.
d. NR = data not reported.

Table 3. DMA Site Data Summary & Evaluation

	1 North	2 Mason	3 Rye	4 Rocky	5 Oreana	6 LVW	7 Piute	8 SA W	9 Eldor	10 Lytle	11 Day	12 Deer	13 Cuca	14 SA Ck	15 Tahq	16 Palm	17 Devil	18 White
Alluvial fan landform?	Yes	Yes	Yes	Yes	Yes	Yes	No	Yes	No	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Portion of fan active?	Yes	Yes	Yes	Yes	Yes	No	No	Yes	Yes	No	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Portions of fan inactive?	Yes	Minor	Yes	Yes	Yes	Yes	All	Yes	Minor	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
DMA measurements apply to active fan only?	No	Yes NR	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No
Did DMA distinguish topo & hydro apex?	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No
Slope change downfan	Flatter	Flatter	Flatter	Flatter	Flatter	Flatter	Steeper	Flatter	Flatter	Flatter	Flatter	Flatter	Flatter	Flatter	Flatter	Flatter	Flatter	Flatter
Is aerial in Report similar to current aerial?	Very	Can't tell	Yes	Yes	Yes	No	Yes	Yes	Yes	Yes	No	No	No	No	No	No	No	Yes
Has development changed fan since DMA Report?	No	Yes	Yes	Yes	Yes	Yes	No	No	No	Some	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Was fan urbanized at time of DMA report?	No	Yes R,C,M	Minor Rd	Minor Rd,A,C	Minor Rd	Minor Rd	Minor Rd	No	No	Yes M,L,Rd	Yes L	Yes L	Yes L,D,R	Yes L,D,R	Yes D,Rd	Yes L,R,D	Yes L,D,Rd	Minor Rd
Site used in single channel length analysis?	X		X		X	X	X			X	X	X				X		
Site used in random channel analysis?	X		X	X	X	X		X		X	X	X	X	X	X	X	X	X
Site used in FAN method width equation?	X		X			X	X			X	X		X	X		X	X	
Site used in single to multiple channel width?					X	Fan A					X	X						
USGS Gauge Stn # Peak	No info	No info	10335080 8870	10335125 14370	10335150 6000	09419697 1290	19423300	10249135	10248510	11062000	11067000	No gage Day Ck data	11073470	11073200	10258000	10258500	11063680 Dam	102560000 Dams
Does DMA report channel change during flood?	No	No [a]	No	No	No	No	No	No	No	No	Minor	No	No	No	No	No	No	No
Flood Date(s)	8-7-1979	6-30-1970	5-31-1973	5-31-1973	5-31-1973	7-30-1968 7-1-1980	8-4-1970 9-11-1976 8-12-1978	8-13-1973	8-4-1970 6-8-1972	3-2-1938 4-28-1951 1-25-1969	3-2-1938 1-25-1969	3-2-1938 1-25-1969	3-2-1938 1-25-1969 2-25-1969	3-2-1938 1-25-1969	8-31-1954 11-22-1965	2-6-1937 3-2-1938 12-24-1941	3-2-1938 1-25-1969 2-25-1969	3-2-1938 11-22-1965 1-225-1969
Aerial Date: Pre-Flood Post-Flood	no 6-19-1981	10-7-1968 10-25-1972	No 6-23-1973	No 6-23-1973	No 6-23-1973	No 7-4-1980	10-7-1968 No	No 8-29-1973	No 7-24-1973	4-13-1933 3-4-1969	9-8-1935 2-27-1969	9-8-1935 2-27-1969	No 2-27-1969	No 3-10-1938	No 4-20-1959	No 11-5-1940	2-17-1937 3-10-1938	6-8-1936 No
Flood condition d/s hydrographic apex per DMA	Braided Sheet	No channels	Braided Sheet	Channels Braided	Channels Braided	Braided Sheet	Not a fan	Channels	Braided Sheet	Channel Braided	Channel Splits	Braided Sheet	Channel Braided	Channel Split	Channel	Channels Braided	Channel Sheet	Split Braided
Sheet flooding described	Yes	Yes	Yes	No	No	Yes	No	No	Yes	No	No	Yes	Yes	No	No	No	Yes	No

Notes:

a. Text describes "obvious" new channels formed on two adjacent, ungagged fans. No documentation of the "obvious" change was provided and none is visible on aerials.

b. Urbanization codes: R= Reservoir; C=Canal, M= Mine; Rd=Road; A=Agricultural fields; L=Levees; D=Development

Topographic vs. Hydrographic Apex. Because DMA did not distinguish between active and inactive alluvial fans, they similarly miss the differences between the topographic and hydrographic apexes at the fan sites evaluated (Figure 3). The DMA Report consistently identifies the beginning of alluvial fan flooding at the canyon mouth at the mountain front (i.e., the topographic apex), rather than at the point where flow path uncertainty begins (i.e., the hydrographic apex). What DMA describes for some of the sites as the split channel or braided channel reach is actually the active portion of the alluvial fan landform below the hydrographic apex, or the upstream point of active alluvial fan flooding processes. For the latter sites, there was no observed "single" channel on the active portion of the fan.

Geographically-Limited Data Set. The 18 sites selected by DMA represent very limited geographic and geomorphic conditions even within the two states considered. DMA did not include any alluvial fans in arid region states such as Arizona, New Mexico, Oregon, Texas, Washington, or Utah. No coastal region fans from California, Oregon, Washington, or Alaska were considered, nor were alluvial fans from the high mountain states of Colorado, Montana, Idaho, and Utah. Similarly, no humid region alluvial fans were considered, nor were alluvial fans outside the United States. The FEMA FAN methodology is depicted as applicable anywhere within FEMA jurisdiction, but the range of conditions evaluated by DMA does not nearly represent of the range of known alluvial fan types or characteristics.

Sample Size. While there may have been a paucity of sites that met DMA's evaluation criteria (alluvial fan, USGS gauge, aerial coverage bracketing the flood event), the sample size of 18 is too small to support DMA's universal conclusions (channel width, single channel length, etc.), particularly when non-fans, fans altered by urbanization, and inactive fans are removed from the data set. In addition, not all of the sites were used in the analyses on which DMA's conclusions are based, making the effective sample size as small as four sites (Table 3).

Alluvial Fan Flood Processes. The DMA Report does not distinguish between debris flow fans and fluvially-dominated fans, between fans in tectonically active and tectonically stable areas, between portions of fans dominated by channelized, high velocity flow and fan surfaces dominated by sheet flooding, or between fans in different climatic and geologic regimes. The report makes no effort to evaluate the importance of non-channelized flow (sheetflooding), the importance of which has been demonstrated in detailed field investigations of alluvial fan floods and through 2-D modeling. The types and degree of flood hazards differ significantly depending on the types of processes that have occurred on the fan.

Measurement Errors. The DMA study was prepared in a pre-digital world in which access to data was difficult and GIS tools had not yet been invented, but over half of the DMA measurements checked for this report could not be verified or replicated (Table 2). Furthermore, DMA reported single values for key parameters such as single channel width and fan slope, when in fact these parameters varied widely on each fan (Table 2; Also see DMA text and Appendixes).

Disturbed Sites. Nine of the 18 selected sites were already significantly impacted by urbanization at the time of the DMA study (Figure 4; Table 3), making DMA's conclusions about natural channel processes at those sites tenuous at best. Urbanization impacts at the time

of the DMA study included roads, levees, dams, residential development, mass grading, pit mining, mining talus, and large-scale recharge facilities.

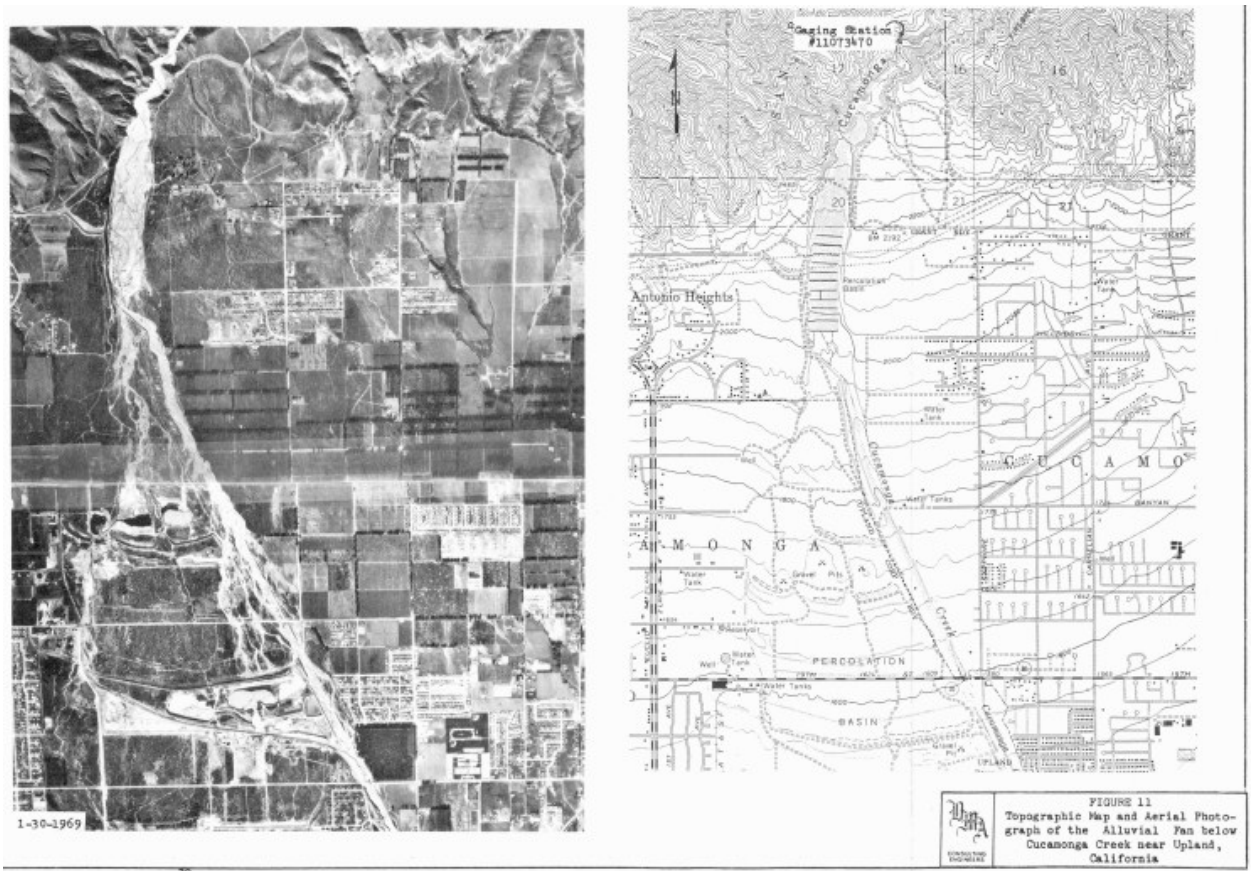

Figure 4. DMA Cucamonga Creek site in southern California showing level of urbanization of the alluvial fan surface.

Lack of Documentation. Most of the measurements reported by DMA could not be replicated (Table 3), because the measurement procedures used were not described in the DMA Report, the locations where measurements were made were not reported or illustrated, or variables were not adequately defined. For example, the fan expansion angle is reported for most sites, but no example showing how this highly variable parameter was measured as a single value was provided. In many cases, no measurements were reported for key parameters (Table 2) with no explanation for the omission. Additionally, the report has no documentation or references for most of the peak discharge estimates attributed to the USGS. Furthermore, the site descriptions discuss channel features and changes, but no photographic or other evidence was provided at any site to document DMA's conclusions. Finally, despite their stated site selection criteria, DMA collected both pre- and post-flood aerials at only six of the 18 sites. It is not clear how DMA supported conclusions regarding flood changes at the remaining 12 sites.

Inaccurate Terminology. DMA describes portions of the alluvial fans as subject to braided or multiple channel flow conditions. While some braiding undoubtedly occurs along some defined flow paths, it is likely DMA was actually referring to distributary channel patterns and/or sheet flooding, which are substantively different from braiding, which is a bed-form condition found in

some riverine channels, and implies a different set of geomorphic conditions than distributary and sheet flooding on active alluvial fan surfaces.

Lack of Peer Review. There is no evidence that DMA's work was peer-reviewed prior to publication. Given how the DMA report has been used to justify application of FEMA's alluvial fan methodology, the lack of a thorough, objective review is disappointing.

Need to Update. All engineering methodologies require periodic review and updates. Our understanding of alluvial fan flood processes, and the tools available for evaluating alluvial fan hazards have significantly improved since the DMA study was completed. Thus, it is likely that the DMA study would have been conducted differently and come to different conclusions if it were completed today.

Errors in Specific Conclusions

DMA listed eight specific conclusions drawn from their analyses. The validity of these conclusions, as well as the analyses used to support them, is discussed below.

Random Channel Location. DMA concluded that the foundational assumption of the FEMA FAN methodology, that the flow path location on an active alluvial fan is random, is justified and should continue to be used in alluvial fan flooding analyses. DMA defined "random channel location" as "[the channel] has an equal probability of occurring anywhere across the fan (p. 1)." DMA justified this conclusion using measurements of the orientation of the "single channel reach" on 15 of the 18 sites (See Figure 17 and Table 2 in DMA).[4] The FEMA FAN methodology assumes that the channel location on an active fan is not only random, it assumes that the distribution of channels is random with a uniform probability distribution across a fan contour.

DMA's methodology of evaluating the random channel location hypothesis consisted of plotting the orientation of the single channel reach relative to the fan limits, as shown in Figure 5. Because the orientation angles of the 15 sites did not cluster around a single value, DMA concluded the position of the channels was random.

There are numerous problems with DMA's analysis and conclusion regarding random channel location. First and foremost, at most sites the reach used to determine channel orientation included the fanhead trench in the inactive portion of the fan, rather than the active portion of the fan downstream of the hydrographic apex. Fanhead trenches are incised into geologically old, stable surfaces which have not changed position for thousands to hundreds of thousands of years. DMA noted that their approach was predicated on the assumptions that the distribution of channels was an ergodic process (p. 53). Since they were in fact measuring the positions of channels incised into older fan deposits, the ergodic assumption does not apply to the chances of the channels shifting to a new position on the fan. If the inactive portions of the fan are considered, the ergodic assumption is at best valid only on long geologic time scales and applies

[4] Three sites were omitted because: (1) no flood channels could be identified on the aerials (Mason Valley), (2) the site was not a "well-defined" alluvial fan (Piute Wash), and (3) the width of the single channel was not well defined (Eldorado Valley).

to the likelihood that a channel will incise in a particular position on a previously unincised alluvial fan. Furthermore, the basic premise that channel orientation is indicative of random channel locations would only be valid if other site-specific explanations for channel orientation, such as geology, valley slope or tectonism, had been eliminated as causative factors. DMA did not consider any other explanations for channel orientation at any of the sites used in their analysis.

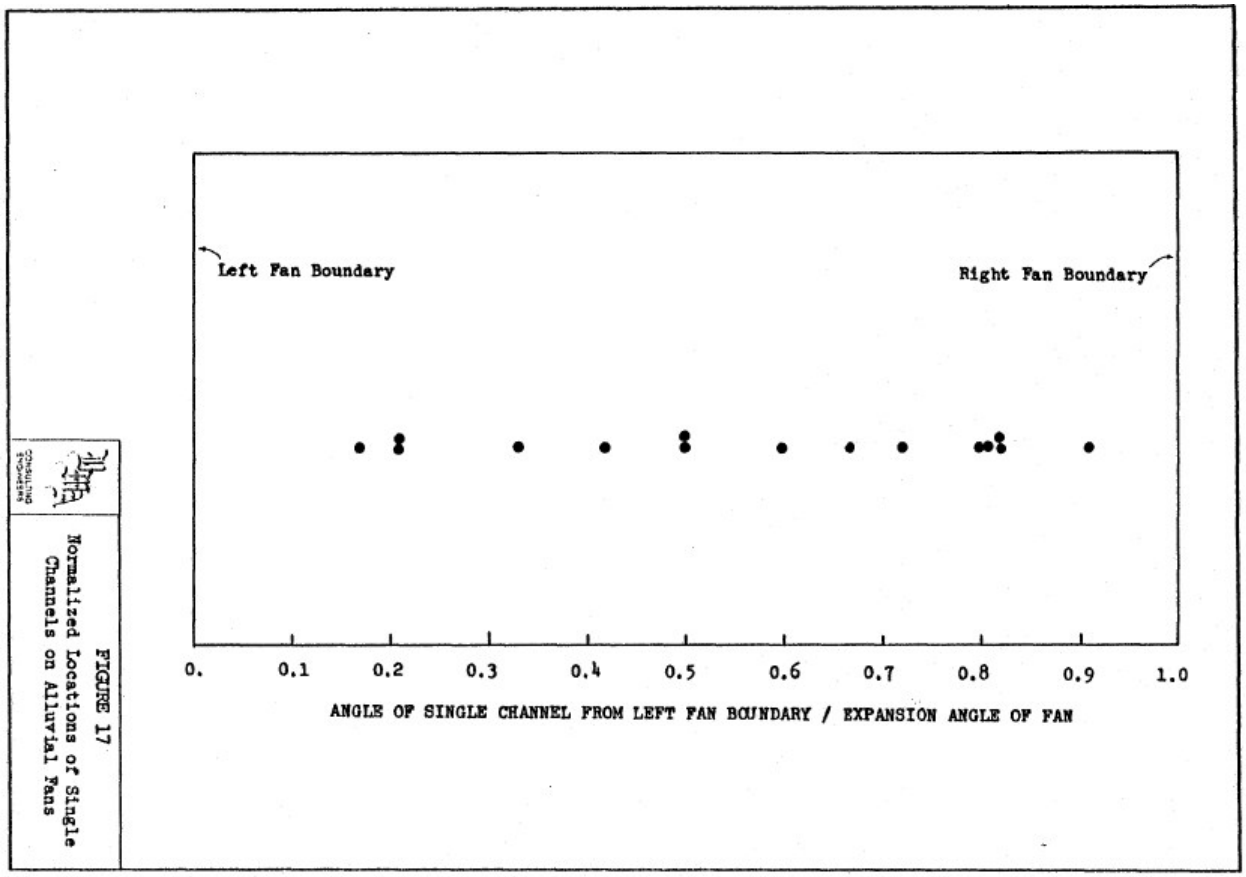

Figure 5. Data from DMA Report used to support conclusion of random channel location.

Second, in their site descriptions, DMA described the channel position as "stable" for almost all of the fans (p. 53). The assumption of random channel locations is incompatible with channel stability. It cannot be both. Third, several of DMA's measurements were made on artificially altered or stabilized channels, which should have been eliminated from the data set. Fourth, even if the other errors are ignored, peer-reviewed work by other investigators who used larger, broader alluvial fan data sets reached the conclusion that there are preferred directions of flow on alluvial fans (c.f., French, 1992) and that there is a high degree of channel pattern resilience during floods on some fans (Pearthree et. al., 1992; 2004). Fifth, DMA reported no significant changes in channel pattern, alignment or width at any of the 18 sites before, during or after the floods described in the study. It is unclear how DMA could conclude that the channel location was random if none of the 18 sites experienced significant changes during the largest known floods. Finally, review of recent aerial photographs of the 18 sites indicates that no significant change in channel alignment has occurred at any of the sites since the DMA study, except where the sites have been altered by urbanization. If channel position at the 18 sites have not changed

over more than 900 years of combined record, it is highly unlikely that the fan channels had an equal probability of developing anywhere across the fan during floods, or over engineering time scales.

At one point in their report (p. 65), DMA phrases their conclusion regarding random channel position as follows: "The present study data base does not provide sufficient evidence to indicate that channel relocations will not occur during the FEMA regulatory 100-year flood." This statement is an example of a classical logical fallacy, i.e., failure to prove the negative does not prove the positive. DMA's unusual phraseology quoted above obscures their actual findings, referenced elsewhere in their report, that the channels they observed on their fan sites were stable at very large discharges, did not experience avulsions, and were not equally likely to be located anywhere within the active fan boundaries during the period of record. Based on the evidence presented in the DMA Report, the only defensible conclusion supported by DMA's data is that channel locations on alluvial fans are relatively stable on engineering time scales, channel avulsions are rare, and that no evidence of random changes in channel positions on fans was found.[5] In short, DMA's data do not support their conclusion.

Single-Split-Braided Channel. DMA concluded that runoff does not remain in a single channel across the entire fan surface (p. 51, 74). DMA observed that flow over the fan surface occurs in a single channel reach near the canyon mouth, followed by a split channel reach, followed by a braided channel reach which extends to the toe of the fan. DMA supported this conclusion using observations of the channel patterns made on aerial photographs and USGS topographic quadrangle maps.

It is likely that DMA's conclusion is at least partially correct for most flows across alluvial fan landforms and active alluvial fan surfaces. However, several potential problems remain. First, DMA's data set of (at most) 18 sites is too limited to justify universal conclusions. Second, as noted above, DMA included the channel in the fanhead trench as part of their description of flooding on the active alluvial fan. Most of the single channel reaches at DMA's sites are not located within the active portions of the alluvial fan areas studied. Third, and more importantly, DMA's conclusion contradicts one of the FAN model's underlying assumptions – that flow across a fan surface is contained within a self-formed channel or multiple channels. DMA correctly observed that below a certain point on the alluvial fan (what DMA should have identified as the hydrographic apex) flow transitions rapidly into multiple channel and sheet flooding conditions in which a significant percentage of flow occurs outside of defined channels. That is, the spatially most dominant flow pattern on active portions of the alluvial fans examined by DMA was not channelized flow, but non-channelized distributary flow and sheet flooding. Finally, DMA sites did not include fans with secondary entrenchment features in which the braided/sheet flooding condition does not necessary extend to the toe of the alluvial fan landform. Examples of fans with secondary entrenchment near their toes are found in NRC (1996).

[5] Obviously, data from other alluvial fan studies by other investigators has documented channel movement, avulsions, aggradation and other processes lead to uncertain flow paths. However, DMA's data set does not support their conclusion regarding random channel locations.

DMA's observation that flooding does not remain in a single channel as it crosses the active fan surface is fundamentally correct, but FEMA realistically implement this finding in the FAN model. Instead, FEMA modified the FAN code to change the single channel geometry to a multiple channel geometry using a 3.8 multiplication factor proposed by DMA (the 3.8 factor is discussed in detail below). However, FEMA did not modify the FAN model to include the hydraulic characteristics and hydrologic consequences of sheet flooding observed at the study sites on the flood depths and velocities predicted by the FAN model.

Length of Single Channel. DMA concluded that the length of the single channel reach can be predicted by the ratio of the canyon slope to the fan slope (p. 55, 74). DMA's conclusion suffers from many of the problems pointed out above: (1) only 10 of 18 sites were used to develop the relationship, (2) many of the slope measurements reported by DMA could not be duplicated, and (3) DMA's single channel reach typically is not on the active portion of the alluvial fan landform. In addition, DMA's data have a correlation coefficient of approximately 0.1, indicating an extremely poor, i.e., non-predictive, relationship between the variables used. DMA's data do not support DMA's conclusion. Note that DMA's proposed relationship between canyon/fan slope and single channel length was never adopted by FEMA for the FAN model or its floodplain delineation methodology.

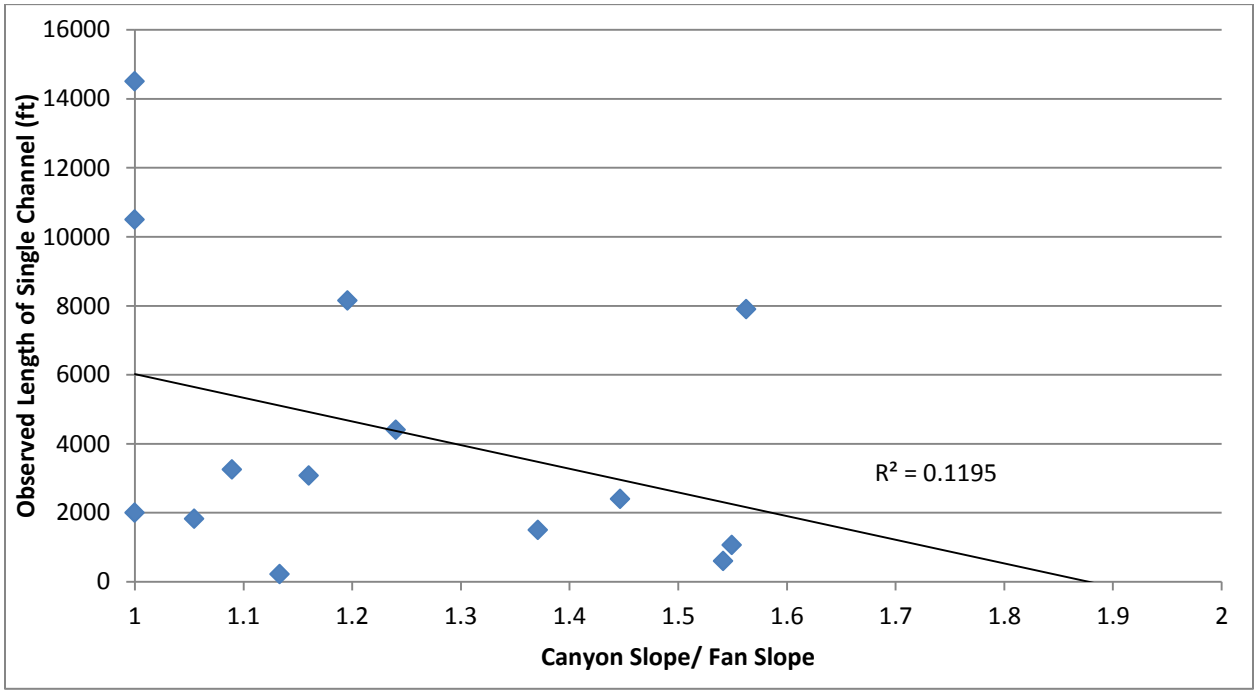

Figure 6. Relationship of observed channel length to the ratio of canyon slope to fan slope (after DMA, Figure 18).

Width of Single Channel. DMA concluded that the width of the single channel can be "reasonably" predicted by the FEMA (Dawdy) equation (p. 55).[6] The channel width (single or multiple channel) is a fundamental element of the FAN model not only because it is directly related to the probability of inundation, but because conveyance of the entire flow within this

[6] Issues with FEMA's channel width equation are discussed in Fuller (2011).

channel is one of the foundational principles upon which the FAN model is constructed.[7] If the channel width cannot be accurately predicted, or if a significant percentage of flooding is not conveyed within the channel, then the FAN model cannot be used to reliably predict flood hazards.

DMA based their conclusion on measurements of channel width at ten of the 18 fan sites. There are numerous problems with DMA's analysis and conclusions, including the following:

- DMA's analysis uses a single value for channel width for each site, when both the text of DMA's site descriptions and the site aerial photographs indicate that there was wide variation in channel widths, even within the fanhead trench reaches. The observed longitudinal variation in channel width below the hydrographic apexes was even greater. While variation in channel width is not surprising, is normal in natural sciences, and can be addressed as part of model uncertainty, the value reported by DMA is not the average of values listed by DMA, nor does DMA state how the reported values were derived.
- The reported DMA width measurements could not be replicated (Table 2), although they are within order of magnitude accuracy.
- The DMA data set included channel width measurements from inactive portions of the fan where there is typically some level of geologic control (e.g., resistant deposits and soils) on channel geometry. Where geologic control exists, the time scale required for channel width adjustments far exceeds the duration of a single flood hydrograph. Therefore, the channels in such reaches will not adjust to peak discharge in the same way as channels on more active portions of fans, particularly on a single flood basis.
- It appears that DMA measured the width of the incised valley floors in the fanhead trench reaches, rather than the bankfull or active channel widths. If an alluvial fan channel is self-formed and the width varies with each discharge, then the width of the sediment transporting portion of the channel (i.e., the active channel) should have been measured, not the floodplain width.
- Although it is not clear in the text, it appears that while DMA measured the valley floor width of the single channels, they measured only the active appearing portions of the channels in the multiple channel reaches (the net width, not the gross width). This practice ignores the width related to the interchange of flow between channel braids which rarely contain an entire flood discharge without overflow.
- It is very difficult to accurately measure the active channel width in braided, split and multiple reaches on aerial photographs, particularly for the scale of photographs available for the DMA study. Many of these channels are too small to appear or be measured on 1:12,000 scale (or less) photographs. Also, overhanging bank vegetation may completely or partially obscure the stream bed and banks, particularly for the smaller channels. Evaluating which channels are "active" is problematic without extensive field verification and/or detailed topographic mapping, neither of which appear to have been available for the DMA analyses.
- Data from only ten[8] of the 18 sites was used, because only "well defined reaches were used for width measurements." DMA's censoring of the available data by removing poorly-defined channels ignored channel conditions at almost half of the sites. DMA

[7] The other key assumption is that flow is critical, which was not addressed by DMA, but is discussed in Fuller (2011).
[8] Two data points for the Day Canyon site were used.

should have recognized the implication of their observation that "channel width could not be measured" at almost half of the sites on the fundamental assumptions in the FAN model, or at least that (defined) channel conditions may not exist on many active alluvial fans.

- DMA notes that no change in channel width was observed on the Day Creek alluvial fan after record floods of 4,200 and 9,500 cfs. DMA attributed this lack of a width adjustment to increased channel depth between the two floods, despite the lack of any physical measurements or direct observations of such a change. If a depth increase had occurred, then DMA should have concluded that FAN model's most basic equation (dw/dd = -200) should be modified to include depth adjustments, or that the corresponding depths generated by the FAN model could be wrong by a factor of two. More importantly, DMA should have recognized that channel width is poorly correlated to the peak discharge of large floods.
- It is important to recognize that DMA by necessity was measuring channel width, not actual flow widths obtained from post-flood observations or mapping. Where such mapping has been performed (Pearthree et. al., 1992, 2004), the portrait of flood inundation is much different than was depicted by simple measurements of dry-weather channels.

There are also numerous problems with DMA's interpretation of the channel width data they reported. First, the predicted channel width was higher than the observed channel width at 80% of the sites considered (Figure 7). From this result, DMA should have concluded that the FEMA equation overestimates channel width, and consequently overestimates the risk of deep inundation. Second, while DMA's data for the 11 sites they include do have a reasonably consistent relationship between predicted and observed width ($R^2 = 0.7$), that relationship is not the relationship proposed by Dawdy. Third, if the remaining sites where no defined channel could be identified (i.e., zero width) are included in the analysis, the portrait of the phrase "reasonably predicts" is significantly different (*Figure 8*). Fourth, the average error of estimate for the ten sites reported by DMA was 31%, with a range from 0 to 86%. While the adjective "reasonably" is a vague term, it is clear that +/- 31% for ten of 18 sites, and for which eight of 18 sites could provide no measurement data at all, does not constitute a "reasonably" accurate prediction.

Based on their data, DMA should have concluded that the FEMA channel width equation could not be verified from the data collected at the test sites, that there may not be a "single channel" reach at many alluvial fan sites, and that channel width is poorly correlated to flood peaks.

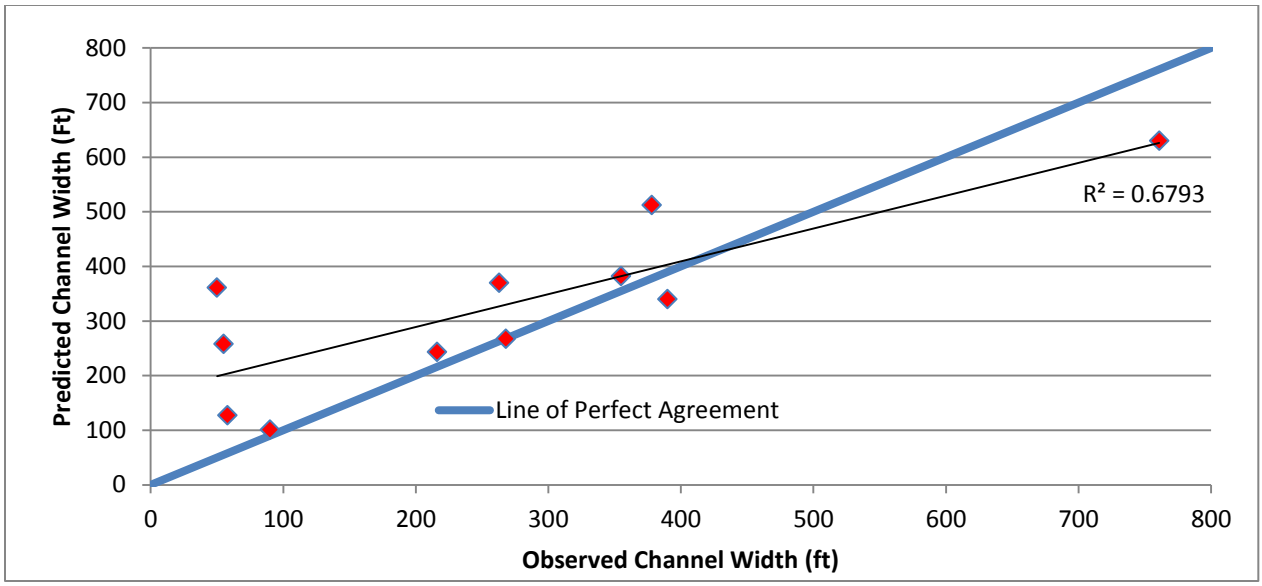

Figure 7. Comparison of observed single channel width to channel width predicted by FEMA FAN equation.

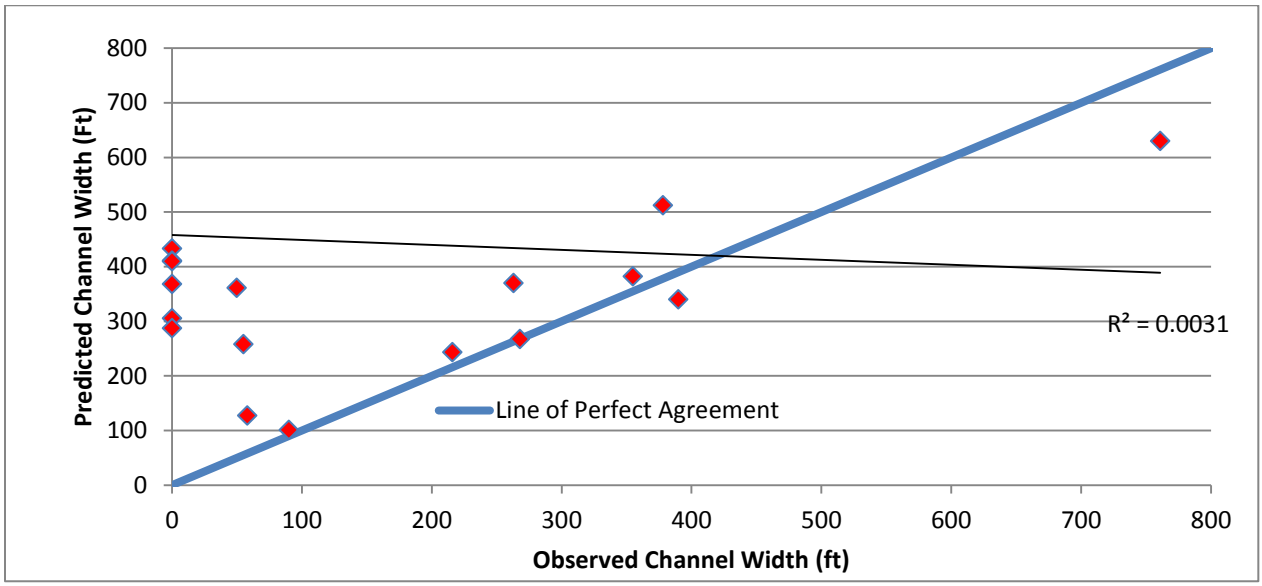

Figure 8. Comparison of observed and predicted channel width with no defined channel data included.

Multiple Channel Cumulative Width. DMA concluded that the cumulative channel width in the multiple channel region is 3.8 times the width of the single channel (p. 59, 74). Based on DMA's conclusion, the 3.8 width factor was coded into the FEMA FAN program and has become part FEMA's floodplain delineation methodology for over 20 years. DMA reached this conclusion by measuring the single and multiple channel widths at four sites (Figure 9), one of which was not in the original 18 sites.

FEMA's adoption of DMA's 3.8 width factor as part of a federally-mandated, universally-applicable methodology is remarkable given the many problems associated with the DMA estimate. The following issues were identified relative to the proposed 3.8 width factor adjustment:

- DMA based the 3.8 width factor on measurements from only four of the 18 sites. Of these four sites, two (Day and Deer Creeks) had been heavily impacted by levee construction and urbanization which constrained the natural channel pattern, two (Deer Creek and Oreana) used gauge data from nearby sites and had no direct observation of recent floods, and one (Day Creek) was observed to experience no change in channel width during the two largest known floods, which varied in magnitude by a factor of two.
- At the majority of the study sites (14 of 18), no relationship between the single channel and multiple channel widths was established. It is unclear why data from the majority of sites was ignored in favor of poor data from a minority of the sites.
- All of the measurement issues described above for DMA's single channel measurements are compounded in their multiple channel width analysis, since their 3.8 estimate is built on the estimate of the single channel width.
- As documented in Appendix A of the DMA report, the actual single to multiple channel width calculations varied from 2.83 to 5.68, indicating significant variance even within the small data set used.
- DMA measured no channels smaller than 15 feet wide in the multiple channel reaches, missing many of the smaller channels visible on modern high resolution aerials.
- DMA did not measure the multiple channel widths all the way to the toe of the four fans used, effectively limiting the small data set even further.
- DMA was unable to distinguish between active, avulsive, and abandoned channels, contaminating the multiple channel width measurements.
- If DMA had measured multiple channel widths in a rigorous manner, they undoubtedly would have found that they vary substantially and generally decrease downstream.
- The DMA site descriptions report the existence of sheet flooding at eight of the 18 sites, including two of the four sites used by DMA, but no width adjustment factor for sheet flooding was proposed.
- The single channel width reported by DMA is the canyon width and includes the floodplain, rather than the main active channel. The multiple channel width includes only the active channels, making the width comparison unequal.

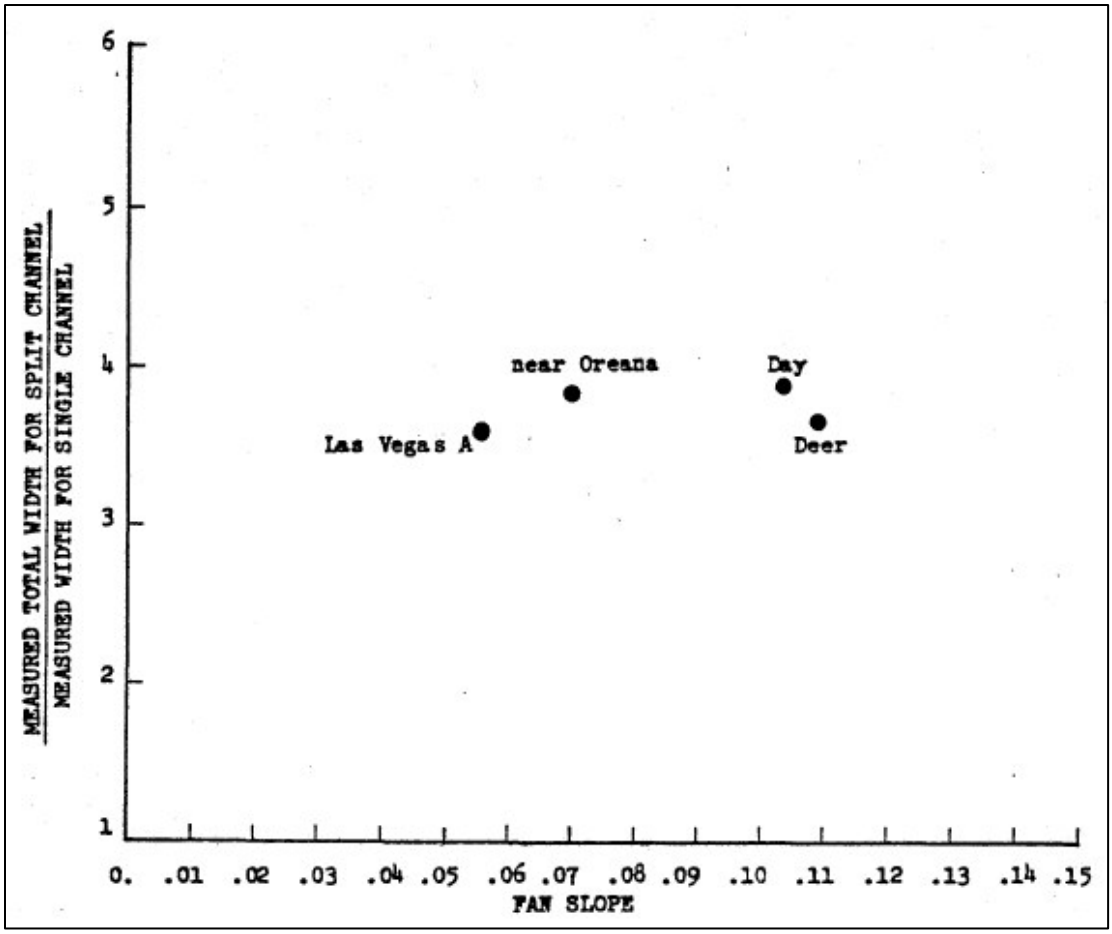

Figure 9. DMA single to multiple channel width data.

DMA did not provide sufficient data to justify their 3.8 width adjustment factor. The majority of the data collected by DMA indicated no definable relationship between the single and multiple channel widths. If presented at all, the 3.8 value should have been described as a crude preliminary estimate in need of further examination using broader, more representative fan channel populations. A more robust conclusion would have been that their data did not support a consistent relationship between single and multiple channel width.

Avulsion Coefficient. DMA concluded that no change in the FAN model avulsion coefficient procedure was justified based on their study, because there was insufficient data to evaluate avulsion frequency (p. 61). DMA recommended that avulsion frequency be studied further.

It is unfortunate that FEMA heeded DMA's recommendation to not change the FAN model avulsion coefficient, but not their recommendation for further study of avulsion frequency. Perhaps if DMA had more carefully considered the data they had collected, they would have reached a conclusion that would have led to more detailed evaluation of avulsion mechanisms and frequency. DMA should have concluded that their study documented no evidence of recent

avulsions at any the 18 study sites[9] during any of the floods studied or in the period of record. The lack of observed avulsions over 900 years of cumulative photographic record should have led DMA to conclude that avulsions are rare events, and that channels may not have an equal probability of relocating to any point within the fan boundaries during individual floods or within normal engineering time scales. A common response to this issue by some floodplain managers has been that the random channel assumption is "conservative" since it assumes that flooding could occur anywhere on the active surface. Careful consideration of this response indicates that if the flood path is in fact not randomly located, then the random channel assumption only results in conservative results in the areas least likely to flood, i.e., the areas outside the existing channel network. For the areas most likely to experience flooding, i.e., the areas within the existing channels, the random channel hypothesis results in non-conservative estimates of flood risk.

It is particularly disappointing that FEMA has never acted on DMA's recommendation to study avulsion frequency, since FEMA regards avulsion as the "main factor" (p. 70) for assuming random channel location on active alluvial fans, and Dawdy himself (1980) invited readers to consider this question in more detail. FEMA continues to provide no guidance on selection of an avulsion coefficient or on the reasonableness of the default value of 1.5 typically used in FAN model applications.

Vegetation and Urbanization. DMA concluded that fan channels on urbanized fans located below well-vegetated watersheds are more stable than channels on undeveloped fans located below poorly-vegetated watersheds (p. 74). This conclusion is not based on any systematic analysis of DMA's site data base, and amounts to little more than an untested hypothesis. It does not recognize the potential effects of wildfire on sediment production and flooding, and also seems to imply that development of active alluvial fans would be beneficial, because it would make the channels more stable. Neither watershed vegetation nor urbanization are parameters in the existing FEMA FAN methodology.

Avulsions are Caused by Debris Flows. DMA concluded that avulsions are caused by debris flows (p. 75). This may well be true, but DMA does not report any observations, occurrences, or evidence of even a single past debris flow or avulsion at any of the 18 sites considered, so the basis of DMA's conclusion is unclear. At the only alluvial fan (not one of the 18 sites) where DMA identified (but did not document) a channel change, no evidence of debris flow was reported by DMA. Furthermore, DMA notes that even on fans subject to debris flow, avulsions may not occur within a normal engineering time scale if debris flows are rare events (p. 9). Thus, DMA's conclusion is without foundation. Curiously, while DMA attributes the cause of avulsions solely to debris flows, current FEMA Guidelines (2003) specifically exclude application of the FAN model to fans subject to debris flows, leaving a knowledge gap regarding the cause of avulsions on fluvially dominated fans.

Factors Affecting Alluvial Fan Floods. DMA concluded (p. 66-67) that alluvial fan floods are affected by the following characteristics: (1) fan slope, (2) man-made structures on the fan, (3) canyon slope above the apex, (4) flood hydrograph – volume, rise time, and duration, (5)

[9] The avulsions referenced in DMA p. 61 were for sites near the Mason Valley alluvial fan, not any of the 18 sites for which data were collected and described by DMA. DMA provided no physical evidence of the alleged avulsions at the other Mason Valley sites.

sediment discharge including debris flow, (6) watershed vegetative cover. Note that none of these factors are included as predictive variables in the FEMA FAN model. A more thorough literature search and analysis by DMA would have identified many more variables that affect alluvial fan flooding, almost none of which are part of the FEMA FAN model input. These variables include watershed characteristics (elevation, slope, cover, fire), soil characteristics (cohesion, size, depth), sediment production rates, bedrock geology (erodibility, type, structure), climate (humid/arid, temperature, precipitation, seasonality), runoff frequency and volume, tributary inflows, on-fan runoff, vegetative cover (fan surface, watershed), fan slope (steepness, segmented, convexity), local topography (relief, incision, slope orientation), man-made structures (watershed, fan, roads, canals, levees), and regional tectonism or subsidence.

Evaluation of the DMA Report Objectives

The stated purpose of the DMA report was to evaluate and verify two key assumptions in the FEMA alluvial fan methodology: (1) that the location of a stream path on a fan surface is random, i.e., it has an equal probability of occurring anywhere across the fan, and (2) that flow forms its own channel and remains in one channel throughout the flow event, except when a channel avulses. With regard to the first objective, which was discussed in detail above, DMA's evaluation reached a conclusion of random channel location based on inappropriate data. They relied primarily on channels that are incised into inactive fan deposits, and thus are not free to change positions on fans during floods. Contrary to their conclusion, DMA's data indicated that channels do not have an equal probability of being located anywhere on the fan surface, and they found virtually no evidence of changes in channel positions on fans during floods. With regard to the second objective, DMA concluded that the FAN model incorrectly assumed that flooding on alluvial fans is conveyed within a single, self-formed channel throughout the flow event and advocated the use of multiple channels with a very specific cumulative width ratio to the single "channel" upstream. Unfortunately, DMA's recommended solution addressed only the single channel aspect of FEMA's flawed assumption, but did not address either the sheet flooding that occurs on all active alluvial fans or the self-formed channel aspect of the question. DMA's recommended adjustment of the single to multiple channel width is scientifically flawed and unsupported by the majority of data they presented.

Conclusions

The following questions regarding the FEMA FAN methodology remain unanswered by the DMA study and should be addressed by a scientifically robust analysis:

- Are channels and/or flood flow paths randomly located on active alluvial fan surfaces within engineering time scales? Or if flow paths are randomly located, it is true that they will take any random flow path during the next flood, or is there an inherent system bias to channel locations on fans?
- What is the frequency of avulsion on active alluvial fans, how can it be determined for individual fans, and how can this information be incorporated into flood risk assessments?
- What are the mechanisms of avulsion and/or flow path uncertainty and how can they be adequately accounted for in flood risk assessments?

- Are flood flows on active alluvial fans conveyed in self-formed channels, and if so, can the geometry and location of these flow paths be accurately predicted? Documentation of recent alluvial fan floods and 2D flow modeling indicate that this assumption is not accurate. Since it is not, what is the nature of conveyance across fan surfaces and how can it best be evaluated?

Because of the limited sample, erroneous treatment of data, unsupported conclusions, and incorrect interpretation of the available data, the DMA study should be rejected as a scientific verification of the FEMA FAN model methodology.

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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.

Appendix A: Aerial Photographs of the DMA Alluvial Fan Sites

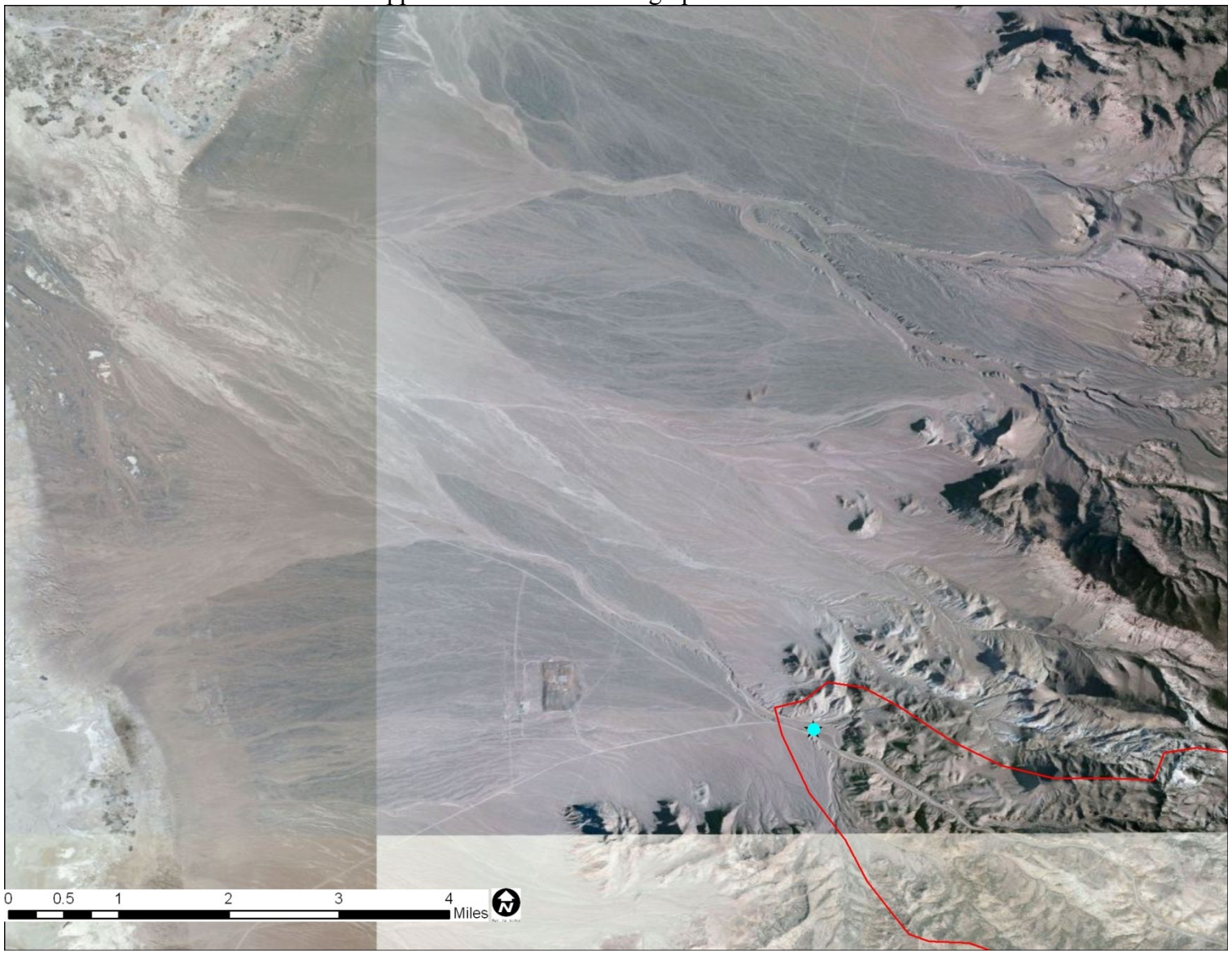

Figure A1: DMA Northumberton Canyon Fan Site.

Figure A2: DMA MasonValley (blue circle) Tributary (McConnell Canyon – south; Nevada Canyon - center) Fan Sites.

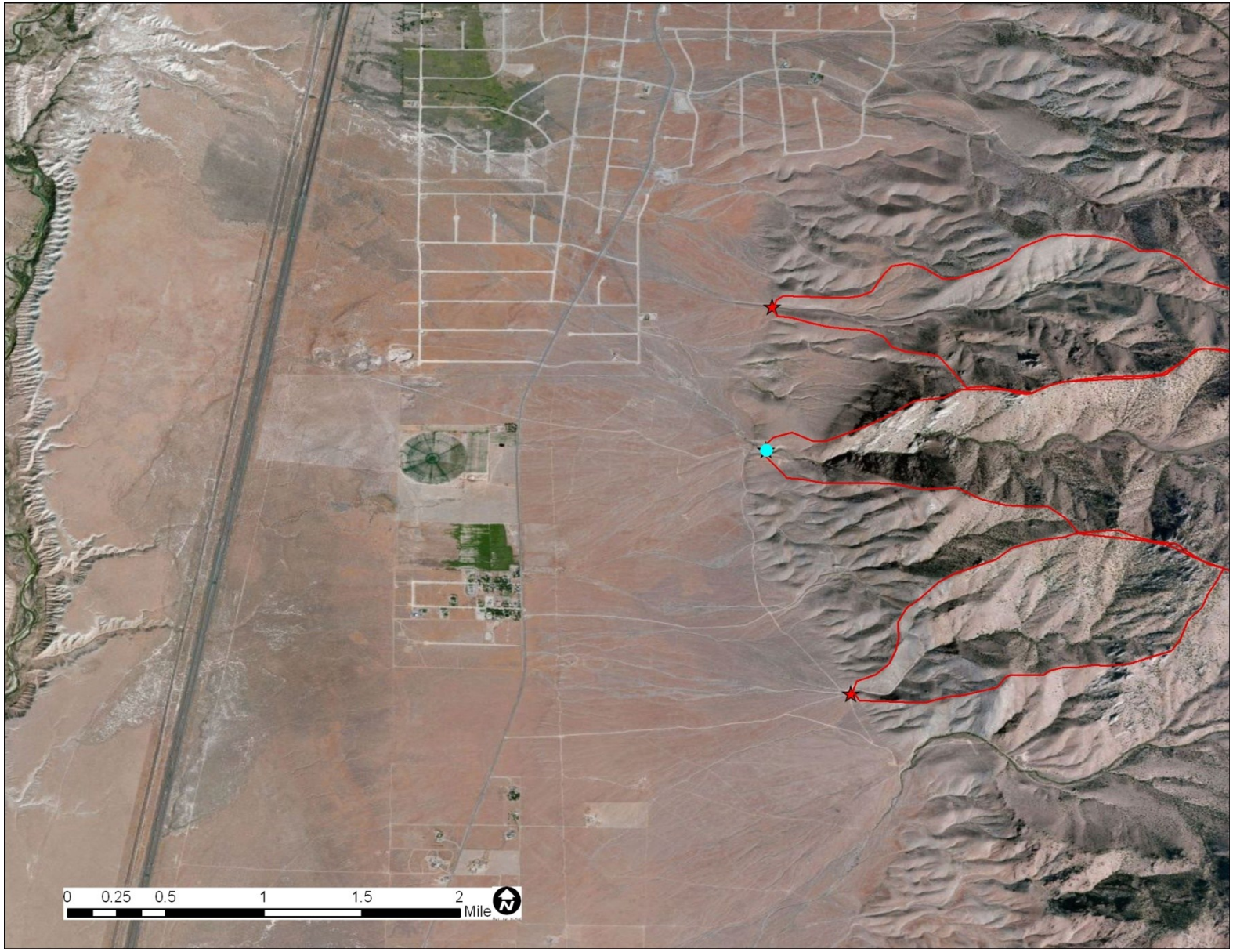

Figure A3: DMA Rocky Canyon (blue circle) and Humboldt River Tributaries (Rye Patch – north; Oreana - south) Fan Sites.

Figure A4: DMA Las Vegas Wash Tributary (Fan A) Fan Site.

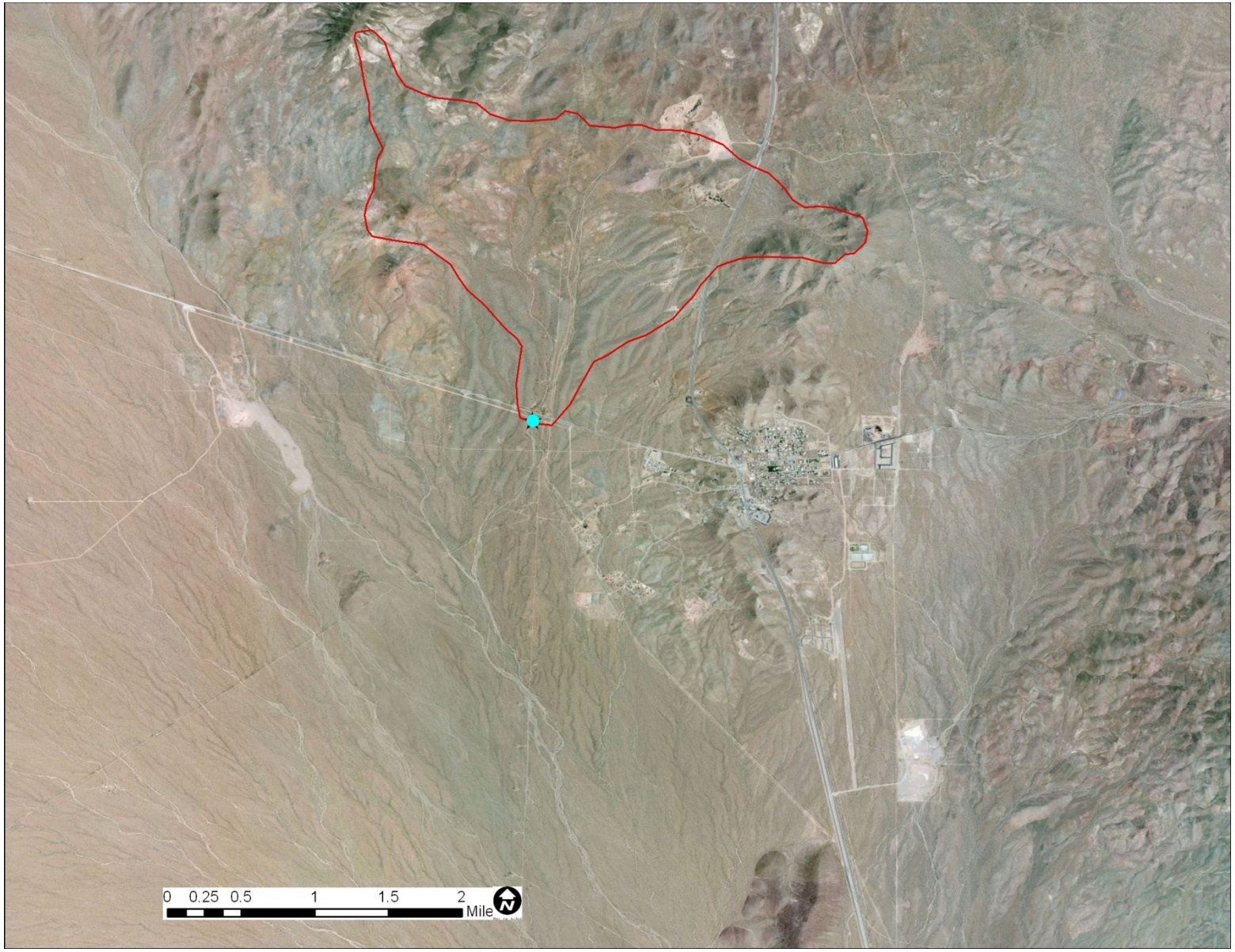

Figure A5: DMA Piute Wash Tributary Fan Site.

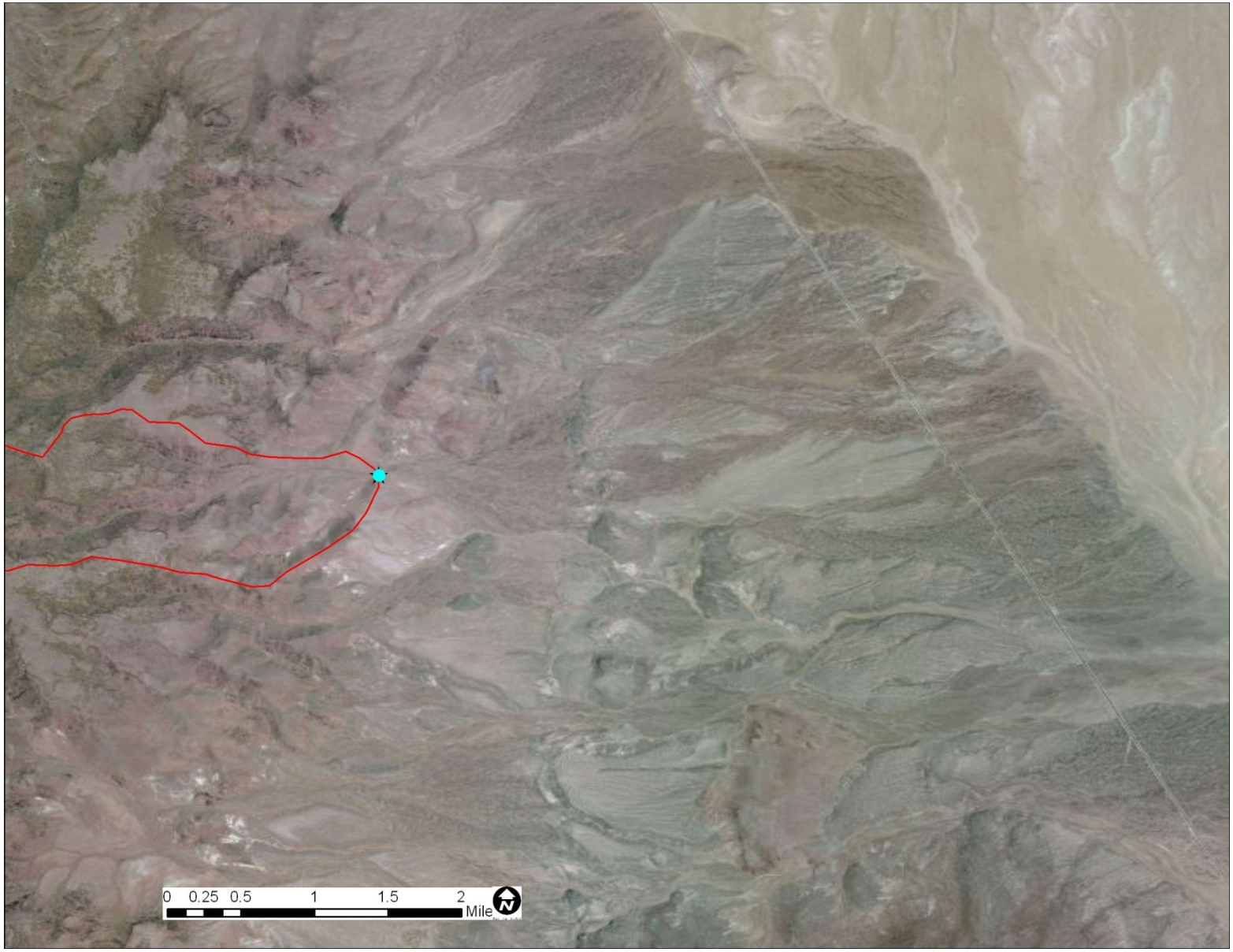

Figure A6: DMA San Antonio Wash Tributary Fan Site.

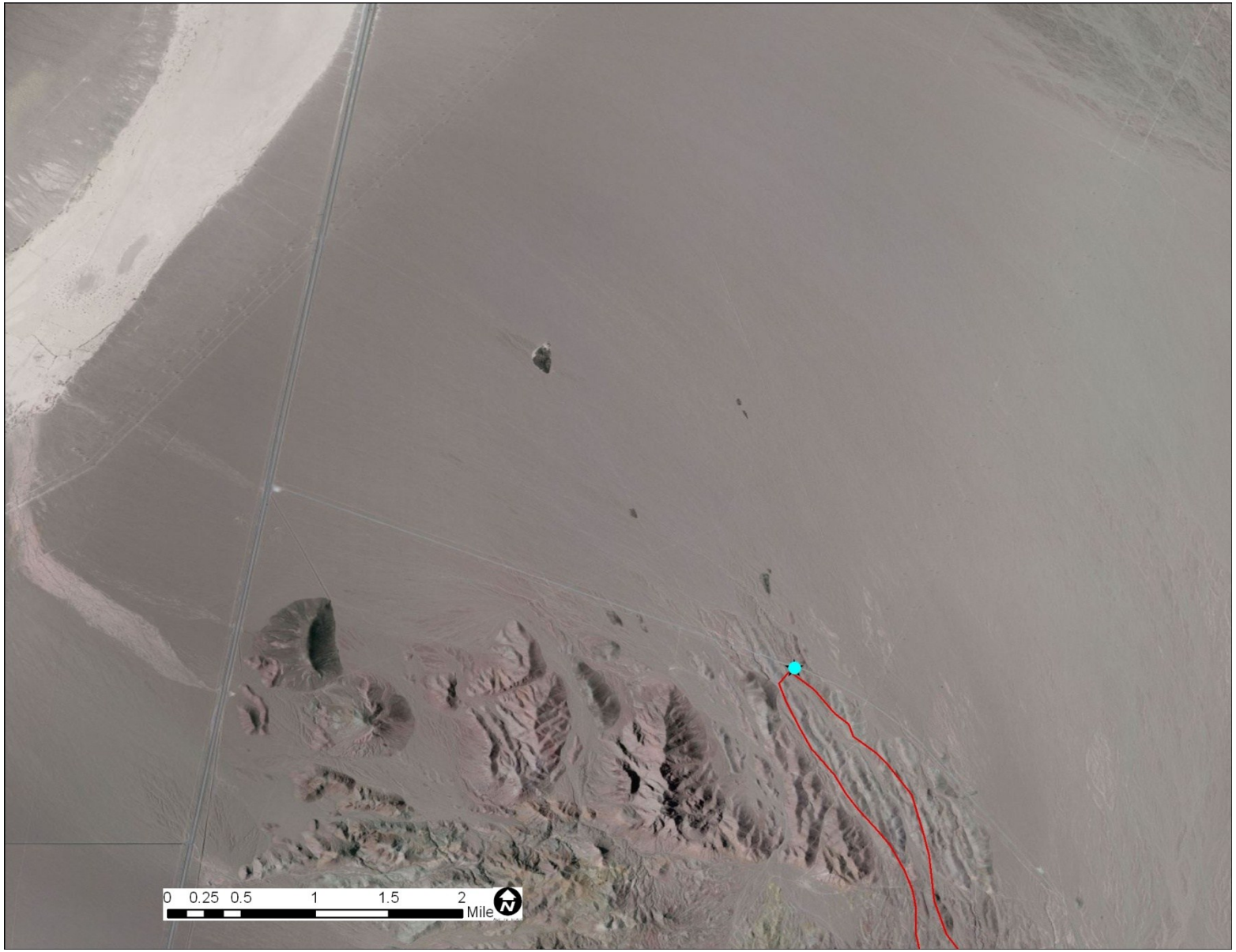

Figure A7: DMA Eldorado Valley Tributary Fan Site.

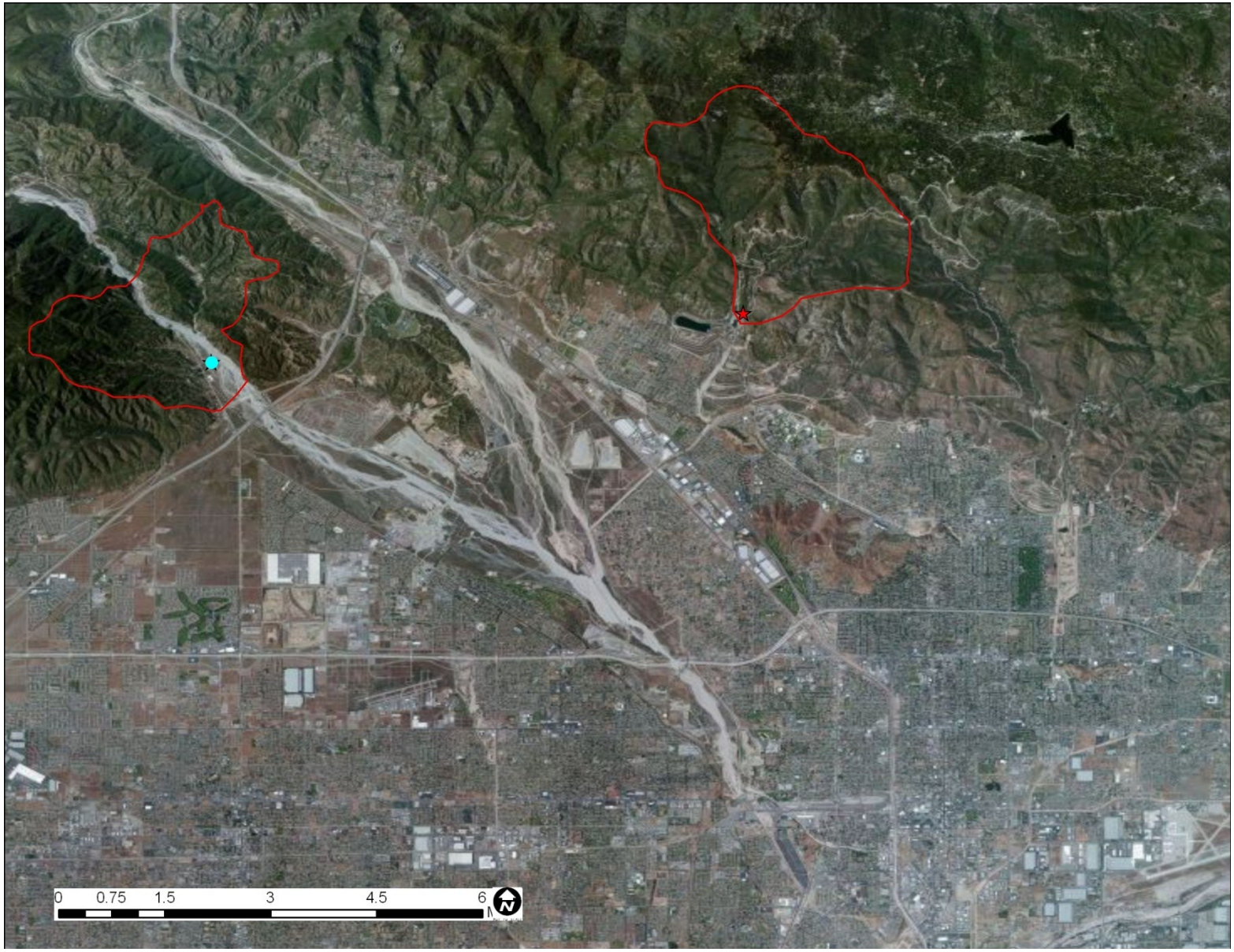

Figure A8: DMA Lytle Creek (western site, blue circle) and Devil Canyon (eastern site, red star) Fan Sites.

Figure A9: DMA Day (eastern site, blue circle) & Deer Creek (western site, red star) Fan Site.

Figure A10: DMA Cucamonga (eastern site, blue circle) and San Antonio Creek (western site, red star) Fan Sites, now urbanized.

Figure A11: DMA Palm Canyon (southern site, red star) and Tahquitz Creek (northern site, blue circle) Fan Sites, now obscured by development.

Figure A12: DMA Whitewater River Fan Site