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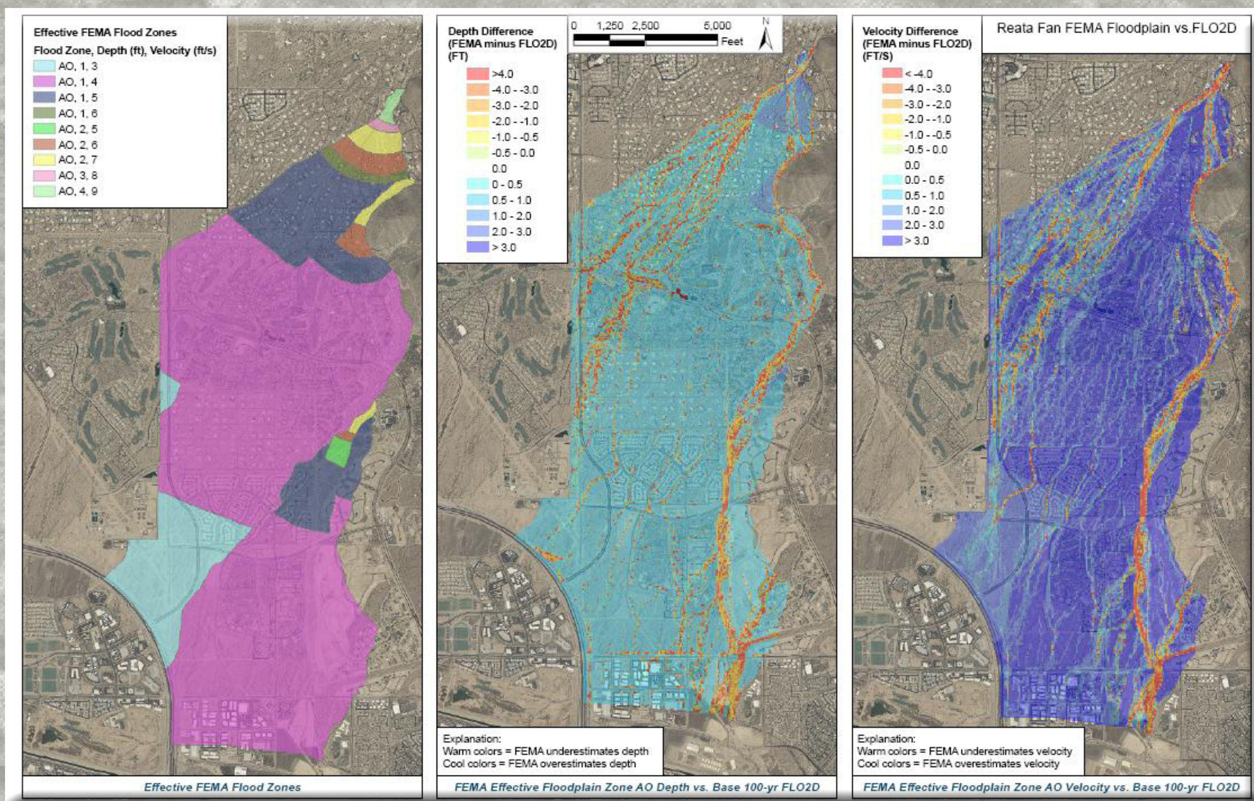

Reata Pass Fan, Scottsdale, Arizona, showing differences between FEMA FAN results and FLO2D mapping of flood depths.

THEORETICAL AND PRACTICAL DEFICIENCIES IN THE FEMA FAN METHODOLOGY

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Theoretical and Practical Deficiencies in the FEMA FAN Methodology

By Jonathan Fuller[1]

The FAN model, developed by the Federal Emergency Management Agency (FEMA, 1990) was one of the earliest attempts to generate a mathematical model of alluvial fan flooding that incorporated the impact of channel avulsions on flood risk. The FAN model implements a methodology for delineating alluvial fan flooding hazards first proposed by Dawdy (1979), and later modified by FEMA based on recommendations made by DMA (1985).[2] The FEMA FAN methodology has been criticized in the literature (McGinn, 1979; Burkham, 1988; French, 1987, 1992; Fuller, 1990; NRC, 1996) since its inception, but remains a key component of FEMA's floodplain delineation guidelines for alluvial fans (2003). Reaction to the FEMA methodology by floodplain managers has been mixed. The FAN model is specifically prohibited from use by at least one public agency with floodplain management authority (ADWR, 1995), but use of the FAN model for floodplain delineation on alluvial fans is mandated by a number of communities in Southern California. The Association of State Flood Plain Managers recently called on FEMA to update its fan modeling guidelines to reflect new mapping tools and more current thinking about alluvial fan flooding, although no specific recommendations regarding the FAN model itself were made in their paper (ASFPM, 2011). This paper outlines some of the key deficiencies in the FEMA FAN model in order to demonstrate the need for moving beyond the simplistic, outdated FAN model to more sophisticated, verifiable methodologies that better reflect the current understanding of alluvial fan flood processes.

Description of the FAN Model

The FAN model is based on a mathematical formulation first published by Dawdy (1978). After a series of catastrophic alluvial fan floods and debris flows in Southern California in the 1970's, FEMA correctly recognized that riverine floodplain delineation techniques did not adequately depict the flood hazard on active alluvial fans, and adopted Dawdy's equations in an attempt to better depict flood risks associated with non-riverine processes such as avulsions, changing flow paths, high rates of sediment transport, and net aggradation. Dawdy theorized that that flood channels on alluvial fans were self-formed, that they stabilized at a specific width/depth ratio, that they flowed at critical depth, and that they could relocate to any portion of the fan. Based on these hypotheses, Dawdy proposed what essentially amount to the following regime equations:

$$W = 9.5\, Q^{0.4} \qquad \text{Eq'n 1}$$
$$D = 0.07\, Q^{0.4} \qquad \text{Eq'n 2}$$
$$dW/dD = -200 \qquad \text{Eq'n 3}$$

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[2] In this paper, the terms "FEMA alluvial fan methodology" and the "FEMA FAN model" are used interchangeably, though in fact there are slight differences.

Where: Q = peak discharge (cfs) conveyed in the channel
W = flow width (ft.) in a self-formed channel that conveys Q,
D = flow depth (ft.) in a self-formed channel that conveys Q, and
dW/dD = rate of channel width change with respect to channel depth.

Once the flow depth and width for a given flow rate are estimated using Dawdy's equations, the probability of inundation at any given point on the fan surface for any depth can be computed by comparing the computed flow width to the radial width of the alluvial fan surface. More specifically, the radial width of the fan surface, where the probability of depth and velocity thresholds equal to 1.0, 2.0, 3.0, etc., can be computed. These radial widths can then be plotted as boundaries between flood risk inundation zones (See Figure 2).

FEMA applied Dawdy's equations directly in a number of alluvial fan floodplain delineation studies in the 1980's, and then developed the FAN model (1990), a DOS-based software package that uses Dawdy's basic equations, as well as a modification proposed by DMA (1985), to predict regulatory flow depths and velocities on alluvial fans.[3] In 2003, in response to a National Research Council Committee Report (NRC, 1996), FEMA revised their alluvial fan floodplain delineation guidelines to help assure that the FAN model be applied only to highly active, conical, fluvial fans (not debris flow fans), but has not updated the FAN model itself since 1990.

FAN Model Input

The FAN model requires minimal input. For the most basic applications, only the 2-, 10-, and 100-year peak discharge estimates at the hydrographic apex and an avulsion coefficient[4] are required to generate results. If the user believes that a "multiple channel" reach exists on the alluvial fan,[5] then a single Manning's n value and a value for fan slope which apply to the entire fan surface are also required. The user must also identify the location of the hydrographic apex[6] and the lateral boundaries of the active portion of the alluvial fan to be able plot the results of the FAN model output, but these data are not required as FAN model input. FEMA guidelines (2003) provide basic information on how to identify the active fan boundaries and the location of the hydrographic apex.

FAN Model Output The FAN model output is rudimentary, consisting of tables that list flow depths[7] and velocities with corresponding discharges and contour widths (Figure 1).

[3] Note: French (1987) attributes the first computer code for the FAN model to Harty (1982).
[4] The avulsion coefficient depicts the frequency of avulsion on the fan. In most cases, the default avulsion coefficient of 1.5 is used. FEMA (1990, 2003) offers no specific guidance on how any other avulsion coefficient would be selected. DMA (1985) reports that an avulsion coefficient of 1.5 means that a channel avulsion occurs in every other 100-year event.
[5] The default assumption in the FAN model is that flooding is conveyed and contained in a self-formed single channel that extends from the hydrographic apex to the toe of the fan.
[6] FEMA (2003) defines the hydrographic apex as "the highest point on the alluvial fan where there exists physical evidence of channel bifurcation and/or significant flow outside the defined channel."
[7] The FAN model actually uses depths associated with the energy grade line (total energy) rather than the hydraulic grade line (water surface elevation), as shown in Figure 1.

It is up to the modeler to manually plot the depth and velocity contour widths on a map of the alluvial fan to complete the flood hazard map (Figure 2). As seen in Figure 1, the FAN model produces a table that lists a series of decreasing depths and velocities. Note that the predicted depths and velocities shown in Figure 1 do not decrease because of peak flow attenuation, change in flood channel geometry, change in slope or other flood processes occurring on the active fan surface, they decrease because the radial width of the active fan is assumed to increase. If the radial width of the fan does not increase, the mapped depths and velocities will not change in the downstream direction. Any resemblance to field observations of decreasing depths and velocities during fan flooding is coincidental, since the FAN model assumes no flow losses on the fan surface, nor does it account for on-fan precipitation or tributary inflows.

SINGLE-CHANNEL REGION

ENERGY (FT)	DEPTH (FT)	DISCHARGE (CFS)	PROBABILITY OF DISCHARGE BEING EXCEEDED AT THE APEX BY:		WIDTH (FT)
			Q	$1.0521\ Q^{1.0125}$	
0.5	0.3	49	1.00000	1.00000	40118
1.5	1.0	756	0.99744	0.99885	40072
2.5	1.7	2712	0.73347	0.80776	32406
3.5	2.3	6288	0.23565	0.31720	12726
4.5	3.0	11787	0.04425	0.07679	3081

VELOCITY (FT/SEC)	DEPTH (FT)	DISCHARGE (CFS)	PROBABILITY OF DISCHARGE BEING EXCEEDED AT THE APEX BY:		WIDTH (FT)
			Q	$1.0521\ Q^{1.0125}$	
3.5	0.4	68	1.00000	1.00000	40118
4.5	0.6	238	1.00000	1.00000	40118
5.5	0.9	649	0.99901	0.99954	40100
6.5	1.3	1496	0.94804	0.96869	38862
7.5	1.7	3059	0.66588	0.74849	30028
8.5	2.2	5719	0.28296	0.37242	14941
9.5	2.8	9974	0.07701	0.11975	4804
10.5	3.4	16451	0.01421	0.02537	1018

Figure 1. Example of FAN model output for the single channel region of an alluvial fan (from FEMA, 1990).

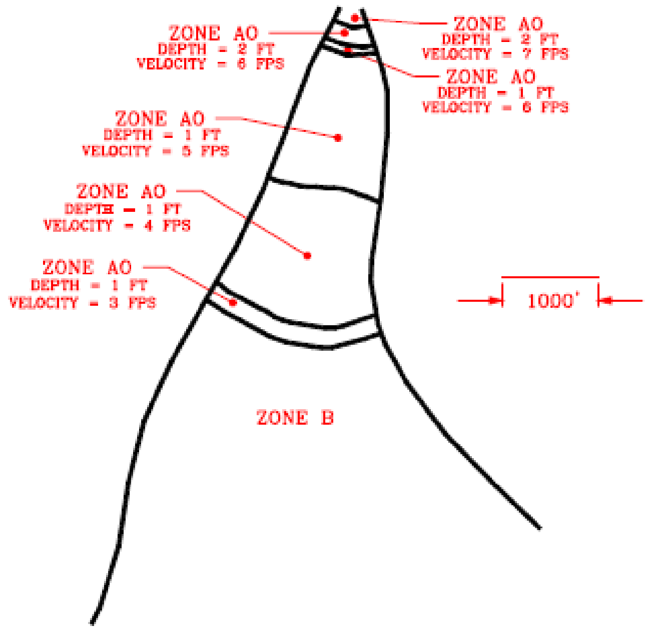

Figure G-4. Flood Insurance Risk Zones Respective to Figure G-3

Figure 2. Application of FAN model output (from FEMA, 2003) by manual plotting FAN output. AO Zones represent the regulatory floodplain. Zone B is not a regulatory floodplain.

FAN Model Applicability

FEMA (2003) guidance indicates that the FAN model may be used to generate regulatory floodplains for alluvial fans with the following characteristics:

- Active alluvial fans (not inactive fan floodplains)
- Fluvial fans (not debris flow fans)
- Fans with unstable flow paths
- "Highly" active, conical fans

FEMA (1990, 2003) does not identify any other geographic, geologic, hydrologic or process-related restrictions to applying the FAN model. It is critical to recognize that the FAN methodology is not applicable to debris flow fans or debris flow events on active alluvial fans. The methodology is applicable only to water floods on active alluvial fans that have the characteristics listed above. Therefore, the discussion in this paper is primarily directed at how the FAN methodology is applied on fluvially-dominated active alluvial fans.

FAN Model Assumptions

All models are based on a set of assumptions, and have limitations and an expected range of applicability. The FAN model is no exception. Table 1 lists the FAN methodology assumptions and limitations that are acknowledged by FEMA (1990, 2003). Table 2 lists assumptions and limitations that are implicit in the FAN model, but that are not formally stated in FEMA documentation.

Table 1. FAN Model Assumptions Reported by FEMA		
	Description	**Comment**
#1	Floods are conveyed in a rectangular channel.	Disputed
#2	Floods are conveyed at single channel flowing at critical depth, or in multiple channels flowing at normal depth.	Disputed
#3	The total width of multiple channels is 3.8 times the single channel width.	Disputed
#4	During a flood, the rectangular channel self-adjusts until the change in width divided by the change in depth equals -200.*	Disputed
#5	There is an equal probability of flood inundation along any single contour within the active alluvial fan surface.**	Disputed
#6	The 2- through 500-year peak discharges at the apex can be adequately defined.	Not Disputed
#7	Peak discharges at the apex are independent of peak discharges in any other year.	Accepted
#8	The probability density function of the apex discharge follows a log Pearson III (LP3) distribution.	Not Disputed
*FEMA (2003) notes that the width/depth and probability distribution assumptions can be modified, but that "the FAN program does not readily accommodate these adjustments." FEMA does not provide any instructions on how to make such adjustments outside the model. **A corollary to this assumption is that the degree of flood hazard is equal for all points equidistant from the fan apex. Note: "Not Disputed" means that the existence of disagreements regarding this assumption are recognized, but are not addressed in this paper.		

Table 2. FAN Model Assumptions Not Reported by FEMA		
	Description	**Comment**
#9	The peak discharge at the apex can be used to derive channel geometry anywhere from the fan apex to the toe of the fan, i.e., no significant attenuation of the peak flow rate occurs as the flood crosses the alluvial fan surface (no transmission losses). On-fan precipitation and tributary inflows do not significantly affect flood hazards within the active fan limits.	Disputed
#10	The geometry of channels on the fan surface are not significantly impacted by on-fan rainfall/runoff, sediment size, fan slope, soil cohesion, bank or floodplain vegetation, sediment supply, watershed conditions, climate, flow duration, hydrograph shape, flow frequency, channel infiltration, or regional geology, i.e., channel geometry can be adequately predicted using only the peak discharge of any given flood. That is, the behavior of flood flows is largely a function of location below the fan apex.	Disputed
#11	There is no significant variation in flood hazard processes that would affect predicted flow depth or velocity between fans in any climatic and geographic region of the United States.	Disputed
#12	The predicted geometry of the multiple channel equation adequately depicts the depths, velocities and inundation limits of the sheet flooding portion of the alluvial fan.	Disputed
#13	Channels on active alluvial fans are highly unpredictable in location, but reliably predictable in their geometry.	Disputed
#14	The frequency of avulsion can be described by an "avulsion coefficient," a measure of the average avulsions per event.	Disputed
#15	Fans are composed of highly erodible materials, subject to rapid alteration and channel geometry changes during floods.	Disputed
#16	Local relief is small (5-10 ft.), except above the fan apex, and does not impact the distribution or character of flooding on the active fan surface.	Disputed
#17	Flows do not spread evenly over the entire surface of an active alluvial fan in a single flood.	Accepted
#18	All portions of an active fan are subject to potential flood hazard regardless of location.	Accepted

The validity of a model's assumptions controls the validity of the modeling results, as well as the model's ability to depict real-world conditions. Even though a model may have no computational or mathematical errors in its formulation or computer code, if the model assumptions are invalid, the model may have no practical utility. In this paper, Assumptions #1 to #5, and #9 to #16, are shown to be unfounded or are contradicted by field observations, flume experiments, other mathematical models, or other published data. Assumptions #6 and #7 are standard hydrologic modeling assumptions made for many floodplain delineations studies, and are not questioned here, though some investigators have noted the implications on uncertainty, as well as the impact of the LP3 skew coefficient on #6 (Zhao & Mays, 1993). While some investigators question the validity of Assumption #8 for some watersheds in some areas (Reich & Renard, 1990; Grindeland et. al., 1990), the effect of use of the LP3 distribution on the results of the FAN model probably is minimal relative to other errors, and was not addressed in this paper. Assumptions #17 and #18 are consistent with field observations and other published data.

Previous Published Criticism of the FAN Model

Criticism of the FAN model and FEMA's alluvial fan methodology is not new, and in the past has been directed at the following elements of the FEMA methodology:

- The assumption of equal probability of inundation along contours is not justified (McGinn, 1980; Burkham, 1988; Fuller, 1990; French, 1992a; 1992b; O'Brien and Fuller, 1992; Zhao and Mays, 1993; Cazanacli et. al., 2002).
- The assumption of self-formed equilibrium channels is inappropriate (McGinn, 1980; Burkham, 1988; French, 1984; 1987; Fuller, 1990).
- The application of universal, rather than site-specific, regime geometry equations approach is inappropriate (French, 1984; 1986; 1987; Mays and Mushtaq, 1993; Xu et. al, undated).
- The derived regime equations are incorrect (French, 1987), undocumented (Grindeland et. al., 1990; Fuller, 1990); or unverified (Burkham, 1988; O'Brien and Fullerton, 1991; Mays and Mushtaq, 1993; Hjalmarson, 1994; Xu et. al., undated), or all three (Fuller, 2011).
- A transition zone between the single and multiple channel portions of the fan is needed (Xu et. al., undated).
- The effect of development, such as roads, flood control structures, canals, housing is not accounted for (French, 1987; Grindeland et. al., 1990; Fuller, 1990).
- The effect of local relief on predicted flood hazards is not properly accounted for, and often exceeds predicted depths (Grindeland et. al., 1990; Fuller, 1990; Mays & Mushtaq, 1993; Cazanacli et. al., 2002).
- Topographic, geologic, hydrologic, and/or hydraulic conditions are ignored (French, 1987; Grindeland et. al., 1990; O'Brien and Fuller, 1992; Baker et. al., 1990).
- Flow attenuation over the fan surface is not accounted for (French, 1987; Dawdy et. al., 1989; Grindeland et. al., 1990; Fuller, 1990; Mays and Mushtaq, 1993; Hjalmarson, H.W., 1994).

- The FAN model has been applied to alluvial fans that are not active (PCFCD, 1986; Mays and Mushtaq, 1993; NRC, 1996).
- There is no clear relationship between flood magnitude and area of inundation (Cazanacli et. al., 2002).
- Impacts from sediment bulking are not addressed (Grindeland et. al., 1990),
- Use of the LP3 distribution is inappropriate (Grindeland et. al., 1990).
- Key differences between engineering and geologic time scales and their impact on modeling assumptions are not recognized (Fuller, 1990; French, 1992b; O'Brien and Fuller, 1992; French et. al., 1993).
- The role of sheet flooding[8] on fans is ignored (Fuller, 1990).
- The impact of on-fan tributary drainages and on-fan precipitation on flood peaks is ignored (Fuller, 1990; Mays and Mushtaq, 1993).
- There is a general lack of, or erroneous, model verification (O'Brien and Fullerton, 1991; Mays and Mushtaq, 1993; Hjalmarson, 1994; Xu et. al. undated; Fuller, 2011).
- The methodology is based on invalid or over-simplified assumptions (Baker et.al., 1990; Fuller, 1990; Grindeland et. al., 1990; French and Fuller, 1992).
- The methodology is poorly documented (Fuller, 1990).
- The predicted widths, depths, and velocities are not expected to occur on any fan at any time, except on the average (Dawdy et. al., 1989).
- The model results are not accurate on the lower part of the fan (Dawdy et. al., 1989).
- The model produces significantly different results than physically based models (Mays and Mushtaq, 1993; Fuller, 2010; 2011) and post-flood observations of flood depths and inundation limits (Pelletier et. al., 2004; Fuller, 2011).
- The model does not predict the 100-year discharge on the fan surface (Mays and Mushtaq, 1993).
- Application of the methodology leads to floodplain management problems (Fuller, 1990).
- The methodology does not address flood hazards resulting from mud and debris flow (French, 1987; Mays and Mushtaq, 1993; Fuller, 2011).
- The resulting floodplain delineation is not conservative (Flippin, 1992; O'Brien and Fuller, 1992; Fuller, 2011).
- The model is overly simplistic and ignores key watershed physiographic, geologic, hydrologic, climatic, and site specific factors known to affect flooding on active alluvial fans (Fuller, 2011).
- Is not sensitive to local topography, changes in roughness, slope, on-fan runoff or tributary flows onto the fan (Fuller, 2011).
- Is not appropriate for fans that are not highly active, conical, or urbanized (Fuller, 2011).

In addition, a number of other investigators have used the model for floodplain delineations, but recommended changes in the model formulation to better represent

[8] Sheet flooding is defined in ADWR, 2011.

flood hazards (Magura and Wood, 1980; Theilman, 1980; French, 1987), such as inclusion of uncertainty techniques in the depth estimation procedure (Xu et. al., undated), or application of a theoretical upper limit for the energy depth near the hydrographic apex (Xu et. al., undated). French (1987) used and modified the FEMA methodology, but noted the lack of acceptable alternatives at that time. Indeed, the lack of alternatives formally accepted by FEMA probably has contributed to the persistence of the FAN model in the floodplain management community.

Problems with FAN Model Foundation

There are numerous deficiencies in the theoretical basis of the FEMA FAN model. This is not to say that the probability formulations are incorrectly computed or that the program has coding flaws. Instead, the primary problem with the FAN model is that it is based on principles and formulas that do not reflect the reality of alluvial fan flood processes, or at least for which there is no evidence to prove that they do. These flaws are discussed individually in the following paragraphs, but stem from several fundamental misconceptions about the nature of flooding on fluvially-dominated alluvial fans, as summarized in **Table 3**. It is important to note that many of the assumptions in the initial formulation of the FAN model were made of necessity, in the face of outstanding need and a general lack of scientific data. The objective of the following discussion is not to second guess decisions made 30 years ago, but to highlight the need to revisit the model foundation in light of the current state of the art.

Table 3. Fundamental Misconceptions Regarding the Nature of Alluvial Fan Flooding Inherent in the FAN Methodology

FAN Methodology Characterization	Scientific Characterization
Flooding confined in channels – single or multiple	Flooding is not confined in channels over much of the fan
Distinct transition from single to multiple channels	No distinct transition, patterns may repeat cyclically
Sheet flooding not modeled	Sheet flooding dominates some distal fan surfaces
Flood peaks do not attenuate over fan surface	Extensive peak attenuation occurs
Channel avulsions are frequent & unpredictable	Channel avulsions are rare & partially predictable
Excessive sedimentation negates effect of topography	Water flood sedimentation is moderate or localized. Local topography effects water flood characteristics Debris flow deposition is less sensitive to topography
Entire active fan surface is ultrahazardous	Level of hazard varies over active fan surfaces Distal active areas, shallow flooding may be low hazard
Existing channel network irrelevant for flow distribution	Existing channel network important for flow distribution

Random Flow Path (Assumptions #5, 13). The primary purpose of the FAN model is to incorporate flood hazards associated with flow path uncertainty on alluvial fans (FEMA, 1990). FEMA interprets flow path uncertainty to mean that "flooding is no more likely to follow an existing flow path than to create an entirely new flow path" (FEMA, 1990). Early documentation for the FAN model likened the occurrence of flood paths on an active alluvial fan to the successive rolling of iron balls down a rigid cone (FEMA, 1990). That is, the probability of flood inundation is equal along any radial contour through the fan within the limits of the active portion of the alluvial fan. FEMA's approach equates any flow path uncertainty as synonymous with completely random channel locations (Dawdy, 1981).

Given the importance of the random flow path assumption in the FAN model, it is a legitimate scientific question to ask on what evidence FEMA concluded that channels on active fans are randomly located. Certainly, there is a wealth of scientific literature documenting channel movement during the evolution of alluvial fans over geologic time scales (c.f., Hooke, 1965; Schumm et. al, 1987). However, knowing that alluvial fan flow paths change over time is not equivalent to knowing that such movement is random, or that such change cannot be predicted. The FAN model implies that random channel movement occurs over the engineering time scales within which its floodplain delineations are applicable. While Dawdy's (1979) original formulation did not cite a single technical reference or data set to support his random channel hypothesis, FEMA (1990) has relied on a study performed by a FEMA contractor (DMA,1985) to provide the requisite verification. To verify the random channel location hypothesis, DMA measured the orientation of the "single channel reach" on 15 of 18 sites represented as alluvial fan landforms, found a broad range of channel orientations relative to the mountain front, and concluded that flow path locations on alluvial fans are random with a uniform probability distribution.

There are a number of serious flaws in the DMA study (Fuller, 2011), and their analysis of "random" channel position is no exception. Most significantly, many of the channel orientations measured by DMA were for fanhead trenches in the inactive portions of the alluvial fan landforms, not channel reaches within the active fan areas where random channel movement might actually occur. DMA's site descriptions and comparisons of historical aerial photographs for their test sites contradict their conclusion of random channel orientations, since they recorded no observations of actual channel avulsions during or after the very large floods allegedly recorded at each site.[9] In fact, DMA's site descriptions refer to channels at many of the sites as "stable." In some cases, what DMA described as evidence of past (pre-dating the photographic record) avulsions was simply a pre-existing distributary channel bifurcation that has since remained has essentially unchanged throughout the 50+ year period of record. The DMA study provided no evidence of any significant channel movement, avulsions or "random" behavior of any defined channel on any time scale appropriate for floodplain delineation. Thus, their conclusion was unwarranted and misrepresents their data. In their defense, DMA (1985) did acknowledge and recommend that more study of avulsion frequency was needed, a recommendation that has not yet been implemented by FEMA.

Contrary to DMA's conclusion and the FAN model's underlying premise, there are numerous lines of evidence that indicate that flow paths on active alluvial fans are not randomly located, at least within engineering time scales. Post-flood inundation mapping of historical floods (Pearthree et. al., 1992; Field, 1994; Pearthree et.al., 2004) indicated that the channel patterns during several large alluvial fan floods demonstrated a high degree of spatial stability during the period of record, and tended to preferentially exploit the existing channel network rather than form new channels. Field (1994) estimated a recurrence interval of 50 to 650 years for avulsions on active alluvial fans in central and southern Arizona. Similarly, the perseverance of drainage networks over long historical

[9] One of DMA's site selection criteria was that the fan had experienced a recent large, documented flood.

periods as observed on historical and recent aerial photographs for fluvial fans[10] indicates that avulsive channel movement is rare, rather than frequent. Cazanacli et. al. (2002) concluded from scaling factor analyses in physical modeling studies that movement over the most active fans occurs over time periods extending from hundreds to thousands of years. FEMA's recommended avulsion coefficient of 1.5 further argues for rare, rather than frequent channel movement, since they state that their default value of 1.5 means that avulsions occur in every other 100-year event, i.e., that no avulsions occur in the other events. Physical model studies (Hooke, 1965; Schumm et. al., 1987; Parker et. al., 1998; Cazanacli et. al., 2002) also reveal some degree of predictability to alluvial fan channel behavior. Dawdy (1981) himself admitted that the assumption of uniform distribution of channels across a contour was "somewhat arbitrary" and invited readers to provide quantitative evidence to the contrary. Finally, extensive two-dimensional modeling of active alluvial fans in central Arizona (JE Fuller, 2010) predicts that low flow depths and velocities dominate large portions of many active fan surfaces, indicating that the most frequent flows and large portions of the even the largest floods lack the stream power to initiate or complete avulsions.

Another line of evidence that flow paths on active alluvial fans are not spatially random comes from the study of the physical processes of alluvial fan flooding. For example, it is well known that flood water seeks out topographically lower ground. Therefore, avulsions are more likely to occur where low ground exists outside the existing channel network (Schumm et.al, 1987; Pearthree et.al, 1992). These conditions may exist due to channel aggradation above the surrounding floodplain, or where on-fan drainages have formed channels in which overbank flows can concentrate (Pearthree et.al., 2004). JE Fuller (2010) cites a number of physical conditions conducive to avulsions, without which the risk of avulsion can be reasonably set aside. These conditions include net aggradation of the fan surface, conveyance of significant flooding outside the defined channel network, presence of set-up conditions such as channel deposition or blockage, the occurrence of a triggering event such as a large flood, the availability of alternative conveyance corridors which often are steeper and hydraulically disconnected from the pre-flood parent channel network. Since many of these conditions can be identified from field observations or hydraulic modeling, areas of likely avulsions can be predicted, and thus are not completely random.

While our current understanding of fan flood processes makes it obvious that some level of flow path uncertainty exists on active alluvial fans, that does not necessarily imply that there is an equal degree of probability of inundation along any given topographic contour. That is, semantic arguments aside (c.f., Dawdy, 1981), "uncertain" does not equate to "random," at least in a pragmatic sense. The standard established by FEMA (2003) for identifying active alluvial fan flooding is that "the uncertainty cannot be set aside" for reasonable depiction of the flood hazard. Most alluvial riverine systems have some level of flow path uncertainty, either in their location (avulsion) or geometry (bed and bank erosion), but that uncertainty is routinely set aside for flood hazard delineations. All of the available field, historical and laboratory evidence suggests that flooding on active

[10] Recall that the FAN model is not intended for debris flows on fans.

fluvial alluvial fans is more likely to follow the existing channel network than to create a new flow path, indicating that there is a serious flaw in the FAN model formulation.

The net effect of this flaw in the FAN model is to underestimate flood hazards along the existing channel network and overestimate flood hazards outside the existing channels. That is, the areas most likely to be flooded (the channels) are shown by the FEMA methodology to be less hazardous than they really are, and the areas least likely to be inundated (interfluves and floodplains) are shown to be more dangerous than reality. An example of this principle is provided in

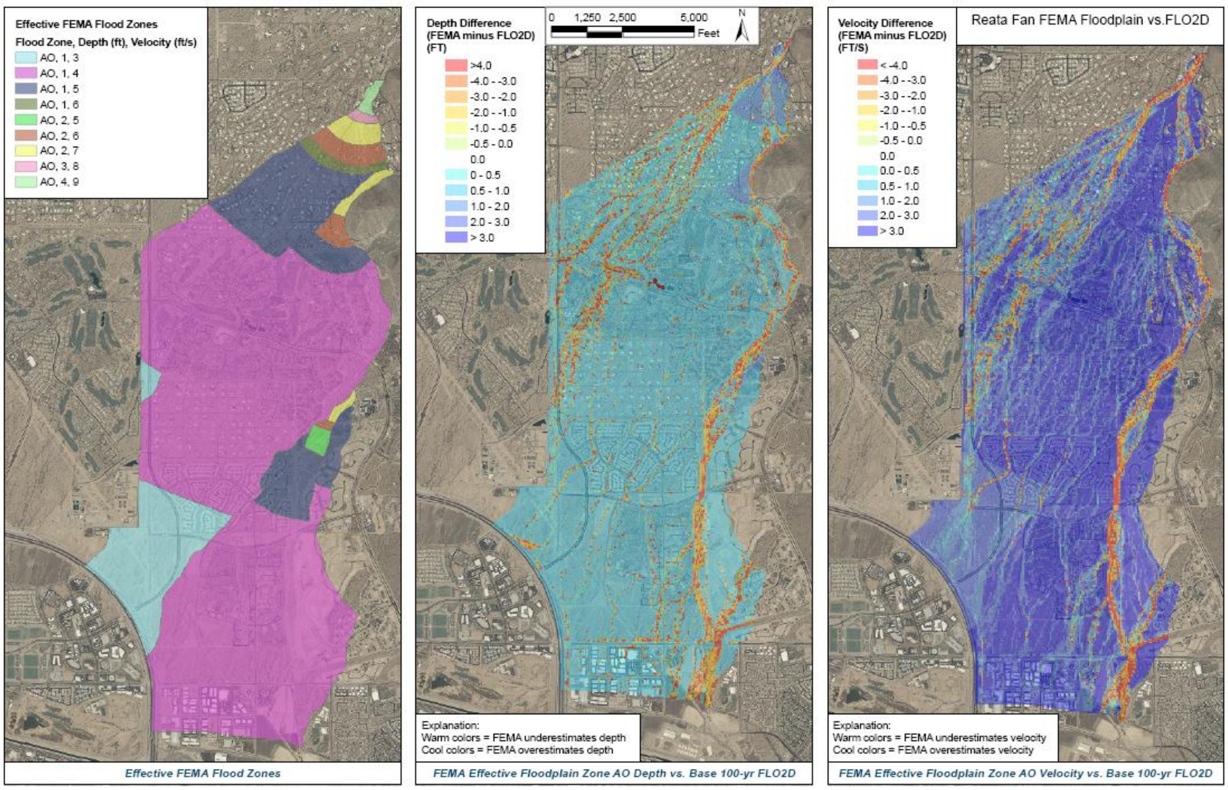

Figure 3, which was taken from JE Fuller (2010). In this example, flood depths along channels are under predicted by as much as four feet relative to a physically-based model, and overestimated by as much as three feet in overbank areas. In the example shown in

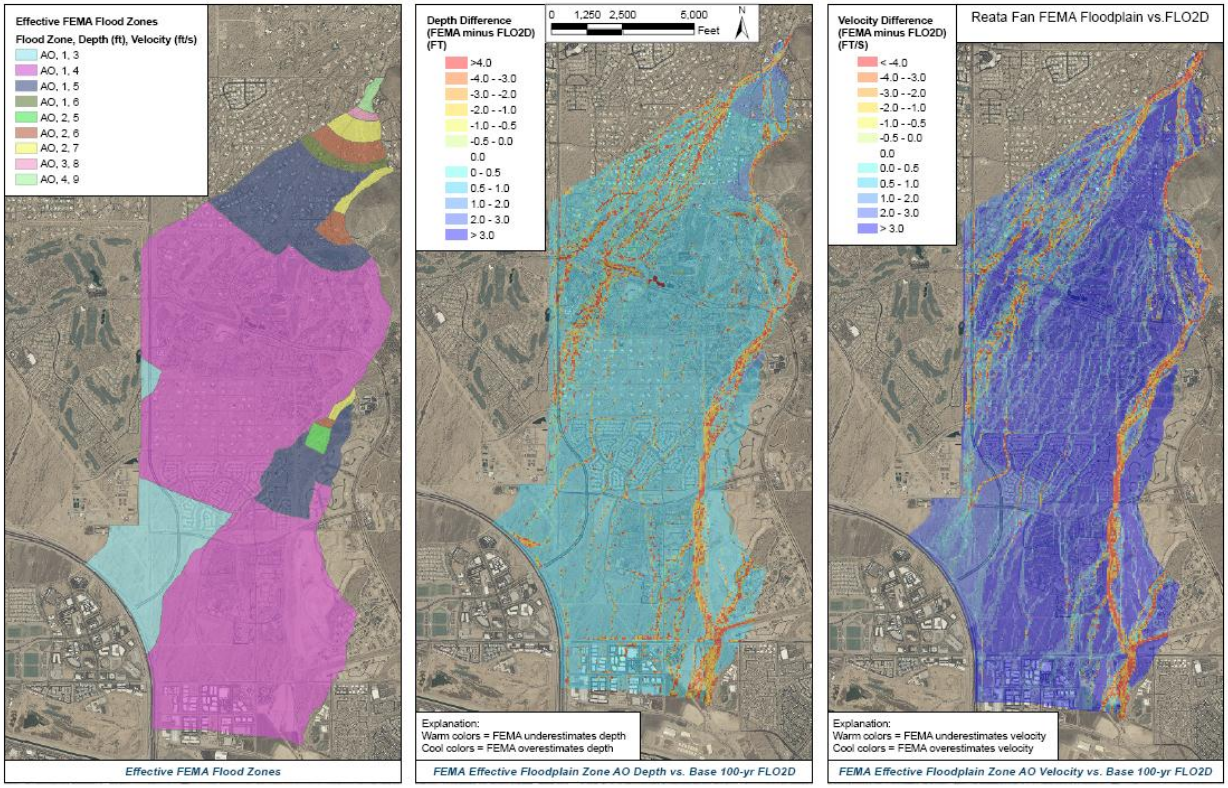

Figure 3, there have been no recorded avulsions or significant channels changes over the 60 year period of photographic records.

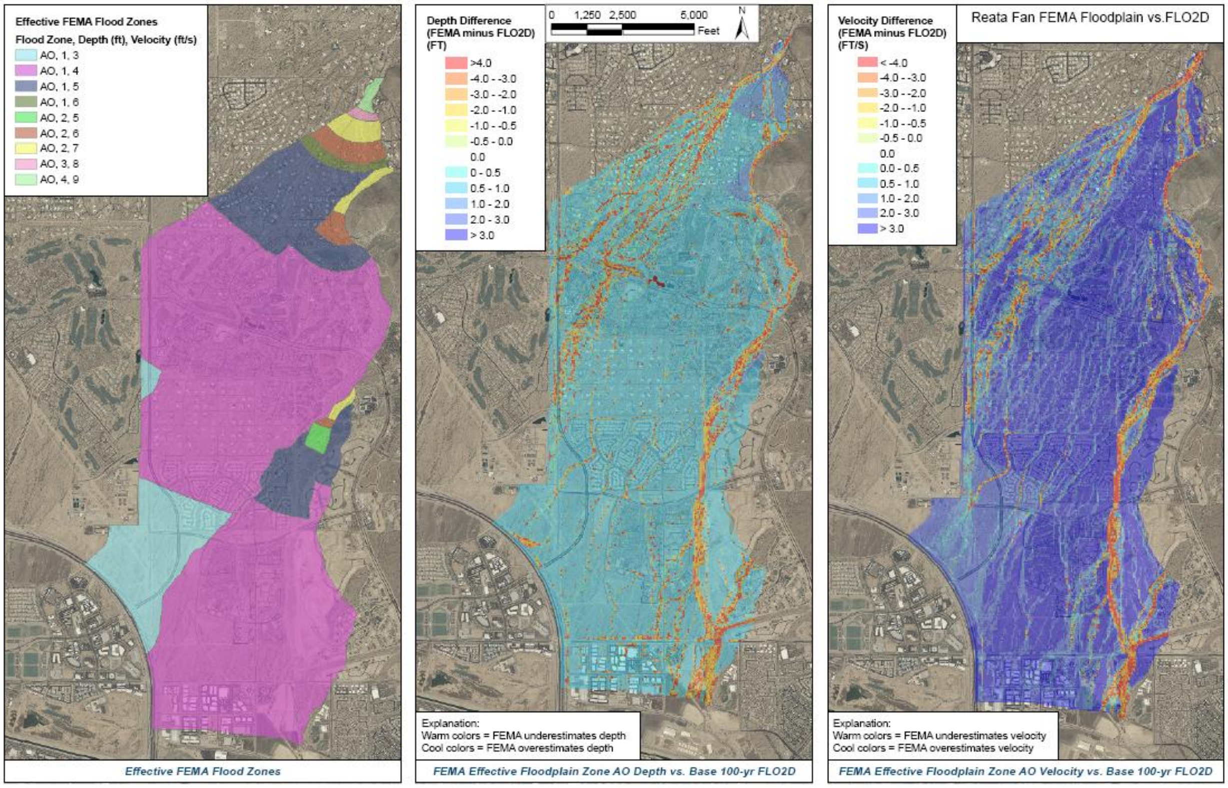

Figure 3. Reata Pass Fan, Scottsdale, Arizona, showing differences between FEMA FAN results and FLO2D mapping of flood depths.

Self-Formed Channel (Assumptions #2, 13). The FAN model predicts flood depth using the premise that all of the flood flow on the alluvial fan is conveyed in a self-formed channel sized to carry the peak discharge at the hydrographic apex (FEMA, 2003). While there is universal agreement that alluvial channels shape their own boundaries to some degree, the extension of this principle to the peak discharge of a 100-year flash flood in an ephemeral stream on an aggrading landform is problematic. Even for perennial stream systems with low flood ratios, there is disagreement about the frequency of channel forming discharges and considerable scatter in the data (Rosgen, 1996; Hedman and Osterkamp, 1982). Unlike the FAN model formulation, the channel geometry in all other applications of hydraulic geometry and regime equations (Rosgen, 1996; Leopold and Maddock, 1953; Blench, 1951) is predicted from a dominant discharge, not the peak discharge of a rare flood. One would expect the scatter for dominant discharge on alluvial fan channels to be even wider than for riverine systems, although it is unclear whether any such analyses have ever been published. Certainly, no research exists that indicates that alluvial channels adjust to contain the peak of the 100-year discharge. Floods on most active alluvial fans are probably too short in duration for the alluvial channels to fully (and predictably) adjust to an average discharge, let alone the peak discharge which may not last for more than a few minutes.

A second major problem with the FAN model's reliance on self-formed channels to convey runoff is that it does not account for runoff that is conveyed across fan surfaces <u>outside</u> of channels. Indeed, it is the lack of confinement that is probably most responsible for any flow path uncertainty on active alluvial fans. Post-flood inundation mapping, observations and photographs of fan floods, laboratory studies, and geomorphic interpretations all indicate the importance of non-channelized flow in alluvial fan flooding and fan evolution. (Hooke, 1965; Schumm et. al., 1987; Pearthree et. al., 1992; 2004). Non-channelized flow includes sheet flooding, flow between distributary channels, overbank flow, and floodplain storage. Studies by the Arizona Geological Survey (Pearthree et. al,1992; 2004) indicate that the most spatially dominant form of flooding for mapped floods in southern and central Arizona occurred outside of the defined channel network. The defined channel network includes those channels that are hydraulically connected to the apex, as well as the channels developed on the surface of the active fan due to on-fan precipitation. By contrast, the FAN model is formulated assuming all of the flooding on an active alluvial fan occurs within a self-formed channel that originates at the apex.

The FAN model's reliance on the occurrence of self-formed channels also creates a self-contradictory conundrum. If the self-formed channel is shaped to contain the full discharge delivered to them, there can be no overbank flows outside the channel. If there are no overbank flows, then by what process do the avulsions that lead to random channel locations occur? Suggesting that avulsions occur due to locally non-erosive channel boundaries or channel blockage by sediment or debris violates the model's assumptions of self-adjustment and containment of flow. That is, while these processes do occur on active fans, they are not consistent with the model assumptions. If there is no random channel behavior, there is no need to apply the model. Conversely, if the peak discharge is not fully contained in the self-formed channel, how can the self-formed channel geometry be predicted as a function of the peak discharge? More importantly, if flooding is not contained in the self-formed channel, how can the FAN model compute the probability of inundation from the fan contour width?

The consequence of this flaw in the FEMA FAN model is to undermine its computational framework. Either channels contain the full discharge and no avulsions occur, and hence flow paths are not uncertain, or channels do not contain the full discharge and the FAN model's estimates of flow width, depth and inundation frequency are erroneous.

Channel Geometry (Assumptions #1,2,3,10,12, 13). The FAN model assumes that flood flow on active alluvial fans is conveyed in a self-formed, rectangular channel with predictable dimensions such that "the change in width divided by the change in depth equals -200" (FEMA, 2003). Use of this equation in the FAN model leads to the conclusion that for every 100-year discharge rate, there is a single corresponding value of channel width and depth that applies to the entire fan site regardless of any other site variable or condition. The fundamental problems with the FAN model channel geometry equations can be categorized as follows, each of which is discussed in the following paragraphs:

- Source of channel geometry equation
- Verification of stable width/depth ratio
- Uniform geometry over entire fan surface
- Critical depth in single channels

- Normal depth in multiple channels.
- Single to multiple channel adjustment

Source of Equation. The FAN model width-depth equation (dW/dD=-200) was attributed by Dawdy (1979) to a personal communication from Boyd Lare, a U.S. Army Corps of Engineers (USACE) scientist working on a portion of the Embudo Canyon fan in Albuquerque, New Mexico. The original equation used by Lare was never documented in any published USACE report,[11] although Lare and Eyster (undated) authored an unpublished report that uses the equation dD/dW = 0.005, which is the reciprocal of Dawdy's equation. Lare and Eyster's unpublished report describes the equation as a width-depth criterion, selected (not derived) as a threshold after which width increases have marginally decreasing impacts on depths, as computed using Manning's equation. Lare and Eyster's width-depth criteria were based on "field experience and floods of record," though no details on either were provided. Lare and Eyster note that unique width-depth curves should be developed and "analyzed independently" wherever channel conditions on the fan change, i.e., the equation may not even be applicable over a single fan surface. Their width-depth equation was not presented either as indicating stable channel geometry or as a lateral limit on inundation. Magura and Wood (1980) confirm that Lare's width/depth equation was not intended to be universally applied, and should be replaced with a more locally representative equations. Since the USACE equation was never formally published or peer-reviewed, its source, the data on which it was based, or the range of conditions tested remains unknown. Use of Lare's site specific width/depth ratio as a universally-applicable equation far exceeds its intent and derivation.

Verification of Stable Width/Depth Ratio. There is no verifiable physical or theoretical basis for the width/depth equation used in the FAN model. Even the most cursory of field observations indicates that alluvial fan channels do not have a regular, predictable geometry over an entire surface of a single fan, let alone between fans in widely varying geographic settings. The FAN model width/depth ratio was shown to be erroneous on all of the alluvial fans in central Arizona examined by CH2M HILL (Figure 4; 1992). The authors of extensive laboratory model studies of fan evolution report no such universally consistent relationship (Hooke, 1965; Schumm et. al., 1987; Parker, 1998a), but instead note the variation in channel geometry and flow conditions over the length of their fans. In contrast, DMA (1985) concluded that the FEMA equation "reasonably" predicted channel widths. Fuller (2011) outlines twelve serious flaws in the DMA study that undermines their conclusion regarding channel geometry, including measurement errors, data censoring, incorrect landform interpretation, inclusion of data from inactive and urbanized alluvial fans, and misrepresentation of their results. In fact, DMA's data had a correlation coefficient close to zero, which should have led DMA to conclude that the FEMA width/depth equation could not be verified.

[11] A search of USACE, FEMA and NTIS library databases yielded no relevant published references for the Boyd C. Lare and G.L. Eyster, the authors of the USACE equations, as cited in Magura and Wood (1980).

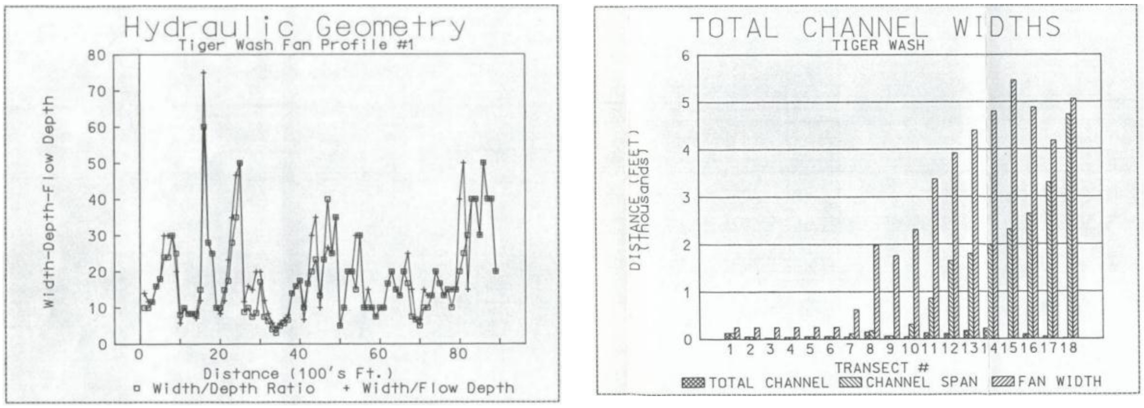

Figure 4. Field measurements of channel width-depth ratio and total channel width for Tiger Wash Fan, Arizona (CH2M HILL, 1992) showing no consistent relationship over the fan surface.

Uniform Geometry Over the Entire Fan Surface. Several lines of evidence contradict FEMA's use of a constant width/depth ratio over the entire fan surface:

- Observations and measurements of channel geometry demonstrate that channel geometry changes drastically across the surface of a fan (CH2M HILL, 1992 – See Figure 4 above; Pearthree et. al., 1992; 2004; Bull, 1997). Uniform channel geometry is not a viable hypothesis for active alluvial fans, except perhaps as a crude approximation within a small portion of a single fan.
- Laboratory studies of fan evolution document rapidly changing channel geometry over the fan surface (Hooke, 1965; Schumm et. al., 1987).
- Discharge in any given channel is not constant over the fan surface (JE Fuller, 2010; French, 1987; Dawdy et. al., 1989; Grindeland et. al, 1990; Pearthree et. al., 1992; 2004; Blainey & Pelletier, 2008), although the FAN model assumes that to be the case. If the discharge is known to change over the fan surface, then there is no reason to expect the channel width and depth to be constant.
- Active alluvial fans are aggrading landforms. It is unclear how a fan channel would maintain a constant geometry in an environment of net aggradation, even if the aggradation rate were slow on recent time scales.
- Few active alluvial fans have constant slopes. If no flow attenuation occurs, as formulated in the FAN model, but the slope changes, why would we expect the width/depth ratio to remain unchanged?

Critical Depth in Single Channels. The FAN program computes flood risk zones using critical depth for the 100-year discharge. Neither Dawdy (1979) nor FEMA (1990. 2003) cite a single technical reference, field measurement, physical modeling study, or other data set to support this assumption. Dawdy asserts that critical flow conditions represent the "most efficient movement of water and sediment down the fan," a hypothesis which requires establishment of equilibrium conditions. The likelihood of equilibrium conditions being established during a flood in an active alluvial fan channel is very low. In contrast, Grant (1997) demonstrated that unconfined flow over steep non-cohesive surfaces is slightly supercritical. Regardless, there are several problems with the critical depth assumption beside the lack of supporting documentation:

- Soil characteristics. Unless the alluvial fan is completely composed of cohesionless erodible materials, areas of greater resistance will exist that could allow reaches of super- or sub-critical flow to occur.
- Slope. Alluvial fans range in slope from much less than 1% to greater than 15%. It is unlikely that flow on the steepest alluvial fans consistently remains at critical depth throughout the full range of flows, or that flow on very flat fans is not subcritical.
- Discontinuous Ephemeral Stream Model. Bull (1997) documented a repeating pattern of incised and depositional zones, reminiscent of laboratory observations of fan channel evolution by Schumm et. al. (1987). Given the wide variation in channel geometry, it is unlikely that critical depth is maintained within the entire fluvial system, particularly as the stream channels evolve temporally and spatially, through sediment deposition, scour and avulsion.

Normal Depth in Multiple Channels. The FAN program computes flood risk zones using normal depth for flow in the multiple channel region of the fan. The multiple channel option was not part of Dawdy's original formulation, but was added to the FAN model based on a recommendation in the DMA study (1985). DMA and FEMA provide no explanation of why self-formed single channels on fans would flow at critical depth, but self-formed multiple channels would not.

Single to Multiple Channel Adjustment. The FAN model computes channel width in a "multiple channel reach" using a 3.8 adjustment factor first proposed by DMA (1985). The existence of a multiple channel reach on a particular fan is identified by the user of the FAN model. FEMA guidance implies that some active fans are subject only to flow in single channels, since the multiple channel feature is presented as an option in the FEMA methodology. The DMA value was derived from rather measurements at (only) four of DMA's 18 alluvial fan sites, two of which had already been urbanized, and one of which experienced no measurable channel change during the two largest floods in the record. None of the DMA measurements could be duplicated from their data. The single channel width measurements were made in part above the hydrographic apexes of the DMA sites on inactive fan surfaces, and the multiple channel widths were not sampled over the entire fan surface, and varied by more than 100 percent even within DMA's limited data set. DMA did not include any flow widths measurements in the extensive areas of sheet flooding on their test sites. A more thorough critique of the DMA study is provided in Fuller (2011).

Given the lack of theoretical and empirical data supporting the FEMA channel geometry equation, it is astonishing that this element of the methodology was approved by a federal agency for widespread use, particularly since it was intended to map "ultrahazardous" flooding areas. There is much more theoretical and empirical evidence that alluvial rivers are self-formed to some predictable geometry (Leopold & Maddock, 1953) than there is for active alluvial fan channels, yet FEMA does not allow delineation of riverine flood hazards using hydraulic geometry equations. In short, the theoretical and physical basis of the width/depth ratio used by the FAN model to predict flood depths and velocities is tenuous at best, and lacks any scientific basis at worst. It seems clearly implausible that channels whose location is so unstable that they are "no more likely to follow the existing flow path as form a new one," have geometric characteristics so reliably predictable that they can be described by a single, universally applicable equation. Verification of the channel geometry and single to multiple channel adjustment factor would be relatively simply scientific analysis which is long overdue. The consequence of this deficient equation is to undermine the basic foundation of the FAN model, and make its results unreliable.

Discharge (Assumption #9). The FAN model flow depths and velocities over the entire fan surface are computed using only the peak discharges at the hydrographic apex of the alluvial fan. None of the following are accounted for in discharge used by the FAN model:

- Tributary inflows below the hydrographic apex
- Runoff generated on the fan surface below the hydrographic apex
- Hydrograph attenuation through storage, routing or infiltration
- Sediment bulking of water discharges

Post-flood field observations (CH2M HILL, 1992; Pearthree et. al., 1994; 2004; Fuller (2011), two-dimensional modeling of gaged fan floods (JEF, 2009; 2010; 2011) and geologic investigations (Blainey and Pelletier, 2008) indicate that significant flow attenuation occurs as the flood hydrograph moves across the fan surface, particularly in the arid west where flood volumes tend to be small relative to the fan area. Dawdy (1989) also acknowledged the potential for infiltration and storage on fans. In some cases, entire flood hydrographs passing the apex were observed to have completely attenuated before reaching the toe of the fan (CH2M HILL, 1992; Fuller, 2011). Ignoring on-fan attenuation is regarded as a conservative error by some floodplain managers (CVWD, 2009), but if it is overly conservative, may lead to takings claims, as well as unnecessary expenditures for oversized public infrastructure. Furthermore, ignoring flow attenuation discounts the impacts of urbanization of fan areas which will lead to adverse flood impacts downstream of development. Hydrograph attenuation is accounted for in every other type of floodplain delineation, and should be even more relevant for alluvial fan floods, since runoff is broadly distributed at low depths over highly permeable alluvial surfaces. Conversely, FAN's failure to account for tributary inflows and on-fan runoff are not conservative errors, and ignore what can be significant sources of runoff, particularly on the lower portions of fans.

Avulsion Factor (Assumption #14). The default avulsion factor in the FAN model is 1.5, which reportedly means that an avulsion will occur in every other base flood event (DMA, 1985). If avulsions do not even occur in every 100-year event, then the assumption of random channel location in engineering time becomes more questionable, and the assumption that any flood is "no more likely to follow an existing flow path as form a new path" (FEMA, 1990) is invalid. While it is possible to enter different values for the avulsion coefficient in the FAN model, FEMA provides no direction on what values would be appropriate or how to go about estimating an avulsion coefficient.

Furthermore, FEMA (1990) attributes avulsions to sudden sediment deposition, debris blockage, or undercutting and bank failure. It is not clear how such sediment deposition could occur in a self-formed equilibrium channel of constant geometry and discharge, i.e., what would induce sediment deposition if there is no change in velocity, channel dimensions, or discharge? Furthermore, undercutting and bank failure lead to lateral erosion, not avulsion, and result in increased channel capacity which should lessen the potential for avulsions.

Topography (Assumption #16). The flood hazards predicted by the FAN model do not account for topographic variation (high ground, low ground) on the fan surface. In fact, no topographic data are needed to apply the FAN model methodology. Not needing topographic data is an advantage for expediency, but a significant disadvantage in terms of accuracy. The consequences of omitting topographic data include the following:

- In the single channel portion of an alluvial fan, the FAN model results are insensitive to even order of magnitude differences in slope. If the discharges and fan boundaries are the same, the FAN model will predict the same flood depths and velocities for fans of 0.1, 1.0, and 10.0 percent slopes.
- Moderate lateral relief along a radial arc through the fan surface, even in the sheet flooding portion of an alluvial fan, has no impact on predict flood depths, flow distribution, or inundation limits.
- Local topographic relief, which may exceed the predicted flood depths by a factor of two or more, does not affect the FAN model results.
- The lateral boundaries of the fan cannot be defined based on hydraulic containment without separate, more detailed analyses.

Ignoring local topography by the FAN model is often justified by pointing at the assumed potential for sedimentation, erosion or avulsions. However, as pointed out elsewhere in this paper, the actual effect of sedimentation and frequency of avulsions are essentially unknown. There is ample field and modeling evidence that topography affects flooding on fluvial fans, and therefore should be considered in flood hazard assessments.

Geomorphic Characteristics Not Considered (Assumptions #11, 15). Another flaw in the FAN model stems from what it does not consider. Flood hazards on active alluvial fans reflect the watershed and soil characteristics, bedrock geology, climate, weathering and sediment production rates, runoff frequency, fan topography, runoff volume, vegetative cover, watershed and fan slope, sediment cohesion, sediment size, constructed features on the fan or in the watershed, and regional tectonism, none of which are variables in the FAN program. The FAN model predicts flood depths and velocities only as a function of peak discharge. Therefore, if two fans in drastically different geographic settings have the same peak discharges and shape, the predicted flood risk zones will be identical, which is clearly untenable.

Manning's N Value. The FAN model allows input of a single Manning's n value to compute normal depth in the multiple channel region of the alluvial fan. No spatial or temporal variation in Manning's N is permitted by the FAN model, regardless of the size of the fan surface, the characteristics of the channel network, or the distribution of channelized, braided or sheet flooding conditions. Given that flow characteristics in the multiple channel region are computed using normal depth, the flow depth is strongly correlated to roughness. It is highly unlikely that a single Manning's n value adequately represents the entire flooded portion of fan surface. Therefore, the depths predicted by the FAN model are likely to be rather crude estimates. Use of a single Manning's n value for any other fluvial system would not be accepted by FEMA, so it is unclear why it accepted for the ultrahazardous conditions thought to exist on active alluvial fans.

Slope. The FAN model allows input of a fan slope value to compute normal depth in the multiple channel region of the alluvial fan. Examinations of fan profiles by many investigators (c.f., Bull, 1964) indicate that most fans do not have a uniform slope from their apex to the toe. Therefore, flow depth estimates made using the FAN model are likely to be little more than rough approximations where slope varies over the fan surface. Furthermore, if avulsions were to occur frequently as hypothesized by the FAN model, the avulsive flow paths are likely to have steeper slopes than their parent channels (Hooke, 1967; JE Fuller, 2010).

FAN Computer Program Issues. The FAN software package is outdated, and reflects 20-year old technology (e.g., the User's Manual notes that the program is available for purchase on 5.25-inch floppy disks). It is DOS based, and uses command line data entry. Users often experience model crashes on many newer operating systems. The various model components have to be run in a specific order, not described in the model documentation, or the program fails. The current code allows only a single run at a time and data have to be manually re-entered on the command line for each iteration. There is no graphical output of the results, and there is no GIS interface to aid in production of flood maps.

Modeling Gap. FEMA Guidelines (2002) dictate that the FAN model is not appropriate for debris flow fans or urbanized fans, and should only be used on "highly active, conical fans." Many current FAN-based FEMA delineations have been done on fans subject to debris flows, that have been urbanized, or that are not highly active and conical. FEMA currently has no approved methodology for assessing flood hazards on urbanized and debris flow fans, leaving a gap in the allowable methodologies for the most hazardous types of fans with the most potential for flood damage.

Problems with Application of the FAN Model

Even if the FAN methodology lacked the flaws outlined above, floodplain managers would still have problems with application and use of the model results. Fuller (1990) lists the following floodplain management concerns raised by one Southern Arizona community:

- Delineation of Zone B floodplains at the toe of wide fans. Zone B floodplains carry no development restrictions or mandatory flood insurance requirements, placing the floodplain management burden on local officials. The Zone B designation also tacitly encourages development on the toes of fans, thereby eliminating many of the most practical options for whole-fan flood control measures.

- Delineation of velocity zones on FEMA Flood Insurance Rate Maps (FIRM). Velocity zones are not regulated under the NFIP and serve no apparent floodplain management purpose. The regime velocities shown on the FIRM are not suitable for design and may mislead local officials and homeowners.
- Delineation of radial flood depth zones that ignore local topography and existing channel networks. It is difficult for local officials to explain to landowners how low lying property has the same flood risk as adjacent land elevated 4-5 feet above it.
- Delineation of flood depths and velocities on FIRM that are not suitable for hydraulic design. The regime, probability-weighted depths and velocities shown on the FIRM may be significantly less than actual 100-year flood depths of water floods that will occur along the existing channel network.
- Mitigation by elevating homes on fill is generally not allowed. It is difficult for floodplain managers to justify disallowing elevation on fill where the FIRM indicates regulatory flood depths of one foot and velocities less than three feet per second.

While it may be argued that FEMA developed the FAN model methodology only for undeveloped active alluvial fans, the end result of the model is creation of a Flood Insurance Rate Map (FIRM). The sole purpose of an insurance map is to determine insurance rates for development. Therefore, FEMA must have at least anticipated that areas mapped using the FAN methodology would eventually be urbanized, even if they were undeveloped at the time of the delineation.

Other local flood control agencies and citizen groups have also cited the following regulatory concerns regarding floodplain delineation produced using the FAN methodology:

- Abrupt, whole foot increment, transitions in AO flood depth zones create issues where these boundaries fall within a single development site.
- Use of energy grade depths may violate NFIP regulations which mandate use of 100-year water depths for floodplain delineations.
- Definition of AO1 zones as depths between 0.5 and 1.5 feet, when NFIP regulations only address flood depths greater than 1.0 feet.
- The NFIP as a whole uses existing floodplain and watershed conditions as the basis of floodplain delineation, but alluvial fan methodology is based on depiction of flood hazards over long time periods and future channel alignments.

Floodplain delineations based on the FAN methodology have resulted in numerous appeals, and at least one law suit filed against FEMA. In contrast, several communities in Southern California (CVWCD, San Diego County) are satisfied with the FAN methodology and require its use for floodplain delineation and design of flood mitigation measures. Clearly, floodplain management works best where it is based on sound, scientifically-defensible methodologies.

Conclusions

A model only "works" if it accurately represents the processes and system it was developed to mimic. FEMA's FAN model was developed because "by 1979, FEMA recognized that standard procedures for evaluating riverine flood risks could not be used to evaluate flood risks attendant to alluvial fan flooding." That is, FEMA correctly recognized that riverine models did not accurately represent the flood processes on active alluvial fans, and that a new type of model was needed. In assessing that need, FEMA identified the following key processes for alluvial fan flooding:

- Occurs on an alluvial fan or similar landform highly susceptible to erosion
- Originates at an apex
- Characterized by high velocity flows
- Has active processes of erosion, sediment transport and deposition
- Associated with flash flooding
- Has unpredictable flow paths

Of the key processes above listed by FEMA, only unpredictable flow paths are truly unique to active alluvial fans. Most mountain and piedmont stream systems experience flash floods, high velocity flows, erosion, sediment transport and erosion during floods. Distributary, anastomosing and sheet flooding systems have apex points, and may or may not be located on alluvial fans. The FAN methodology does not explicitly recognize the following processes that are associated with alluvial fan flooding:

- Debris and mud flow
- Two-dimensional flow
- Distributary flow patterns
- Sheet flooding
- Avulsion (a mechanism of flow path uncertainty)
- Aggradation (net deposition)
- Flow attenuation

Of the alluvial fan flooding characteristics listed above, flow unpredictability is the only characteristic explicitly addressed by the FAN methodology. This paper demonstrates that even the FAN model's representation of flow path unpredictability does not adequately depict real flow path uncertainty processes on actual alluvial fans. The FAN model is overly simplistic, narrowly focused, and based on principles that don't reflect the current understanding of alluvial fan flooding processes. The FAN methodology may have been a good first step at the time it was initially proposed. However, our understanding of active alluvial fan flood processes has evolved considerably since 1979, as have the available tools from which to assess alluvial fan flood hazards. At best, the FAN methodology applies to a very narrow range of fans with specific characteristics which may rarely occur in nature, and even then is only a rough approximation of the hazard.

An update of the current formulation of the FAN methodology is needed, if for no other reason than to provide a tool for analysis of flooding on fans subject to debris flows and fans that have been fully or partially urbanized, two conditions that carry the greatest degree of flood hazard. It is time that the FAN model be re-evaluated, verified, and upgraded to reflect current capabilities, needs, and floodplain management goals. Until such time as the re-evaluation occurs, we recommend that the FAN methodology not be used for floodplain delineation and flood hazard management. There are better tools for considering flow path uncertainty and alluvial fan flood hazards.

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