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FLOOD HAZARD ASSESSMENT ON ALLUVIAL FANS: AN EXAMINATION OF THE METHODOLOGY

by

Richard H. French

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EXECUTIVE SUMMARY

The purpose of this report is to present the results of a critical examination assumptions and mehtodology recommended by the Federal Emergency Management Agency (FEMA) to assess flood hazard on alluvial fans.

The conclusions reached in this report are as follows. First, the assumption that a flow on an alluvial fan has an equal probability of crossing any point on a given contour seems to be a very conservative assumption; however, from the viewpoint of flood hazard analysis this assumption is for the present acceptable. Second, given the data from the Nevada Test Site, it would appear that the assumption that fans have critical to supercritical slopes is acceptable. However, validity of this assumption is dependent on the third assumption regarding channel width and depth. Third, the present methods of estimating channel width and depth on alluvial fans seem to be invalid. However, it must be noted that at the present time there does not seem to be a superior method available. Therefore, for the present, the three assumptions indicated above should be accepted, but the unquantifiable errors present in these assumptions must be recognized. Fourth, the specific flood hazard evaluation procedures recommended by FEMA are not valid in some cases because they are based on the assumption that sufficient records exist to do a standard peak flow analysis. It is not obvious that for much of the Southwest this is a valid assumption since sufficient data are not available. Fifth, the validity of the implied assumption that debris flows present no risk can only be assessed after a location on a fan relative to the intersection point has been established. It must also be recognized that the location of the intersec-

tion point may change dramatically even on an engineering time scale. Thus, it is concluded that the current methods of flood hazard assessment on alluvial fans are not adequate given the current and projected economic value of structures and development on alluvial fans in the southwestern United States.

Given the above comments, at least three areas of basic and applied research can be identified. First, there is a need to understand how alluvial fans develop on a geologic time scale. Previous laboratory studies and the models should be carefully studied and a new program incorporating co-ordinated physical and numeric model studies with field verification of the results must be designed.

Second, numeric models capable of estimating the location and size of channels formed by unsteady, high Froude number flows in alluvial fill must be developed. Although it may be possible to modify currently available models to accomplish this goal, field and laboratory verification of the results will be required.

Third, in areas where there are not adequate stream gaging records, techniques which are superior to the regional method of peak flood flow analysis and the envelope curve method must be developed. If this is not possible, then error limits on these methodologies must be developed and the error estimates carried through the subsequent calculations. Further, if the regional or envelope curve methodologies are used, then a technique of estimating a hydrograph shape must be developed for use in routing the flow across the fan and estimating sediment transport.

FLOOD HAZARD ASSESSMENT ON ALLUVIAL FANS: AN EXAMINATION OF THE METHODOLOGY

INTRODUCTION

Although alluvial fans are common features of the landscape throughout the world, especially in arid and desert regions, the hydraulic processes which formed these features and continue to modify them are but poorly understood from the viewpoint of hydraulic/water resources engineering. An improved, quantitative understanding of hydraulic processes on alluvial fans is crucial for two reasons. First, the recognition and assessment of the hazard that flash floods can pose to structures located on alluvial fans is seriously deficient relative to the ability of the engineer to assess the flood risk to structures located in the vicinity of perennial rivers. To a large extent, this situation exists because until recently there has been a general lack of economic development in desert areas; and therefore, there is a relatively short historical record of flood damage to structures on alluvial fans. With the development of major urban areas and hazardous and radioactive waste management sites in the Southwestern United States on alluvial fans, there is both an increasing need and interest in developing rational and reliable techniques for assessing the hazards floods pose to these facilities. Second, in many arid and desert areas alluvial fans are an important source of groundwater; and further, recharge to many groundwater basins is through alluvial fan deposits. A better understanding of the hydraulic processes that form alluvial fans would aid the water resources engineer and hydrogeologist in estimating aquifer parameters and/or interpreting well-logs and aquifer tests in arid areas.

The study of hydraulic processes on alluvial fans is difficult both because of a lack of data and because it requires an understanding of geology, geomorphology, and hydraulic engineering. Further, much of the geological literature regarding alluvial fans is qualitative rather than quantitative; and much of the literature of hydraulic engineering regarding the behavior of alluvial channels is not applicable to the type of alluvial channel found on fans. Finally, it should be mentioned that the seriousness of flooding on alluvial fans is less related to the absolute magnitude of the flood than is the case with the flooding of perennial rivers and more related to the quickness and ferocity of the event; see for example Imhoff and Shanahan (26). The erratic hydraulic behavior of these events on alluvial formations is also a matter of great concern and current interest.

The purpose of this treatise is to present general descriptive information regarding alluvial fans from the geologic literature and some quantitative data from alluvial fans on the Nevada Test Site in Southern Nevada, which both lends credence to and casts doubt on many of the assumptions engineers and geologists have made about hydraulic processes on alluvial fans. This report focuses specifically on concepts important in flood hazard evaluation as delineated by the Federal Emergency Management Agency, Anon. (2). It should be noted that other methodologies of flood hazard analysis are used by other agencies; see for example Magura and Wood (36), Christensen and Spahr (15), and Squires and Young (47).

ALLUVIAL FANS: GEOLOGIC DESCRIPTION

Although many definitions of alluvial fans can be found in the literature; see for example Anstey (3), Bull (10), and

Rachocki (41), there is general agreement that an alluvial fan is a fan or cone-shaped deposit of sediment found at the base of some mountain fronts. While alluvial fans are found in humid areas, they are primarily features associated with arid climates. Rachocki (41) attributed the abundance of fans in arid regions to excellent preservation rather than unusually favorable conditions for formation.

Alluvial fans are formed by water transporting debris from intermountain canyons into adjacent valleys. A reasonable scenario for alluvial fan formation might be as follows. Debris accumulates along the flanks of mountains due to weathering; and when an intense precipitation event occurs, the accumulated debris is transported downslope in an intermountain canyon. At the point where the canyon enters the valley - the apex of the fan - the widening of the flow results in a decrease of its debris carrying capacity, and the debris is deposited at the apex and downslope from it. Through time, a series of depositional events cause the fan to aggrade and give it its characteristic shape. It should be noted that fans form because of base-level fall of the depositional area relative to the source area. Erosional base-level falls tend to result in temporary, thin fans, while tectonic base-level falls tend to result in the prolonged accumulation of thick fans.

The transport of material on alluvial fans can take place as either stream or debris flow. Streamflow is believed to be the more important mechanism in areas where annual precipitation is high, Hooke (24 and 25); and Blissenbach (6), based on an examination of field observations, also suggested that the relative importance of debris flow to streamflow deposition increased with decreasing average precipitation. However, it must be recognized that debris flow deposits are commonly sorted and stratified by subsequent streamflow; that is, the evidence of debris flow is continously destroyed. Thus, one explanation of the observations of Blissenbach is that on fans in areas of higher precipitation there is less evidence of debris flows because the evidence of past debris flows has been modified beyond recognition. Hooke (24 and 25) attributed the formation of debris flows to intense episodic rainfall, unconsolidated fine material, sparse vegetative cover, and reasonably steep slopes. This view was supported by Bull (10) and Beaty (4); however, none of these investigators provide quantitative threshold limits on these causative factors. Beaty (4) and Hooke (24) have asserted that in the White Mountains of Nevada and California spectacular episodes of debris flow deposition (catastrophes) interspersed with periods of quiescence have been primarily responsible for building the fans. It should be noted that this assertion contradicts the commonly accepted hypothesis that by far the greater share of geomorphic work is accomplished by the relatively frequent event of moderate magnitude rather than catastrophic events; see for example Wolman and Miller (53). Although Wolman and Miller (53) supported their hypothesis of normalism with elementary analytic computations, the engineer cannot ignore the eyewitness accounts and the physical evidence of catastrophic flow events on alluvial fans in the twentieth century. Finally, the characteristics of the fan source material is also an important factor in determining whether stream or debris flow is the primary process in building the fan. The studies of Hooke (24) demonstrated that an abundance of silt and clay is necessary for a debris flow. For example, in Eastern California where the fan source areas are quartzite and dolomite, there is little evidence of debris flow. However, on fans where the source material is granitic rocks containing feldspars which decompose to form clays, debris flows appear to be responsible for much of the deposition.

A common characteristic of alluvial fans is the entrenchment of a channel near the fan apex - a geomorphologic feature termed the fanhead trench. Channel entrenchment occurs when erosion rather than deposition occurs near the apex. Bull (10) noted that the fanhead trench is not always a permanent feature and distinguished between temporary and permanently entrenched channels. Bull (10) termed trenches which were less than 50 ft (15 m) below fan surfaces exhibiting no visible soil profile as temporary. In contrast, channels entrenched as much as 165 ft (50 m) below fan surfaces having old soil profiles were termed permanent. Laboratory observations, Hooke (24 and 25), suggest that channel incision at the fanhead is the result of the alteration of debris and stream flows. Further, even when a fanhead channel is deeply entrenched, debris flows may either exceed the channel depth, resulting in the deposition of material on the fan surface above the intersection point or blocking the original channel and causing a new channel to be formed.

A second characteristic of alluvial fans which should be noted is that the slope of major channels on many fans is less than the slope of the adjacent fan surface. This results in channels which are deeper upstream and grow shallower in the downstream direction until they merge with the fan surface at a place known as the intersection point. This point is also a locus of deposition, and the material found in this location is usually coarser than the average material found in the channel. It is also in the vicinity of this point that most debris flows will terminate. Field observations indicate that in general most deposition near the fanhead was caused by debris flows while at the toe of the fan deposition is the result of streamflow.

Alluvial fans are depositional features which can be active for long periods of time. Although the rates of deposition on large fans may seem very low when averaged over the entire fan surface, the amount of material deposited on a portion of the fan by a single flow event may be many times the average rate for the fan as a whole. Many of the large alluvial fans in the Southwestern United States are believed to be of Pleistocene age. Bull (9) put a tentative age of 600,000 years on the Arroyo Ciervo Fan in the San Joaquin Valley of California. This fan, which is 700-900 ft (200-300 m) thick, has a calculated average accretion rate which ranges from 0.11 to 0.70 ft (0.03-0.2 m) per decade for various parts of the fan. Beaty (4) dated the Milner Creek Fan in the White Mountains of Nevada and California at 700,000 years. This fan contains an estimated 2.9 x 10^{10} ft^3 (8.2 x 10^8 m^3) of material and is apparently growing at the rate of 0.25-0.50 ft (0.08-0.15 m) per thousand years. French and Lombardo (22), using geologic evidence from twelve drill holes, assigned a tentative age of 7 million years to three fans in the northern part of Frenchman Flat on the Nevada Test Site. These fans have an average thickness of 1,600 ft (490 m); and thus, the calculated average rate of accretion is 0.23 ft (0.07 m) per thousand years.

Given the rather low estimated average rates of fan growth, it would appear that structures sited on fans are reasonably safe. This is far from the truth. Blissenbach (6) and Bull (8) have measured debris flows with apex to toe thicknesses of 20 ft (6 m). Alluvium deposited by streamflow may range from a fraction of a foot to several feet. Anstey (3) reported on the destructive nature of an alluvial fan flash flood in Death Valley which, while depositing as much as 4 ft (1.2 m) of alluvium in some areas, eroded channels up to 6 ft (1.8 m) deep in other parts of the fan. During this event, boulders up to 6 ft (1.8 m) in diameter were moved. Although the average rate of fan growth in geologic time is low, it cannot be assumed that catastrophic flow events do not occur. The engineer must further realize that he and the geologist have time scales that are orders of magnitude apart. While the engineer considers time scales of hundreds of years, the geologist commonly uses time scales on the order of thousands to millions of years. This difference in time scales can be a significant impediment to understanding and effective communication when flood hazard and the average rate of fan growth are discussed. For example, since alluvial fans are by definition on a geological time scale depositional features, the engineer would be inclined to believe that a hazardous or radioactive waste site on such a surface would be safe since the waste could only be buried deeper. However, this could be a very dangerous misconception, because in an engineering time frame the alluvial fan may be either a depositional or an erosional feature.

ALLUVIAL FANS: HYDRAULIC PROCESSES

From the viewpoint of hydraulic engineering and flood hazard evaluation, the following primary assumptions are usually made regarding alluvial fans; see for example Dawdy (18 and 19) and Anon. (2):

1. Flows only rarely spread evenly across the surface of a fan. In general, a flood flow across a fan will initially be concentrated in an identifiable, temporary channel or will be confined to a specific portion of the fan. These initial flows are prone to lateral migration and/or sudden relocation to almost any other portion of the fan during a single extreme flow event.

2. For a majority of fans, critical slope; and hence critical flow is the norm.

3. Channels formed on the face of the fan are shaped by the flow itself. If supercritical flow occurs, the channel banks will erode so that a wider channel is formed and the flow will return to a critical state.

Two crucial assumptions are also tacitly implied. First, given a specific location, a flood-discharge frequency distribution can be determined using a rational and accurate method; see for example, Anon. (1). Second, debris flows do not present a flood hazard to facilities on alluvial fans.

At this point, these basic assumptions will be examined from the viewpoint of determining their validity since they are crucial to any flood hazard analysis. The first assumption implies that fans are created and modified by what might be termed a random process. In fact the U.S. Federal Emergency Management Agency, Anon. (2), assumes that a channel caused by a flood event is equally likely to cross a contour of the fan at any point or

$$p(x|f) = T/W_c \qquad (1)$$

where $p(x|f)$ = conditional probability that given flood f occurs point x on a specified contour will be hit, T = channel width, and W_c = alluvial fan width at point x. In fact, the assumption of random fan growth seems to be valid although a few individuals have argued against it; see for example McGinn (37). To some degree, the validity of this assumption depends on the time scale considered. Over short periods of time, flow events on both laboratory and natural fans are localized, Hooke (24 and 25). However, over longer periods of time, the locus of deposition must shift to yield uniform deposition over the entire fan surface. For example, Price (40), using a geologic time scale, developed a random walk simulation of alluvial fan deposition. The primary justification for the development of this model was not the evaluation of flood hazard but to add to the understanding of alluvial fans from the perspective of a potential groundwater source. This model produces a record of the form and character of the different deposits making up an alluvial fan and allows the geohydrology of the fan to be related to the processes which led to its formation. The Price model describes the fan in terms of a Cartesian network of nodes. The probability that a streamflow will go from one node to one of the surrounding nodes is proportional to the gradient between the nodes - thus suggesting that as a series of events takes place deposition and erosion are random. However, Price (40) noted that once a stream flows in a given direction it tends to continue in this direction. Thus, in in the probabilistic framework of this model, a stream has a tendency to move straight ahead rather than to the right or left unless certain conditions are met; such as flow upgradient because of a channel blockage. Because this model simulates the development of an alluvial fan on a geologic time scale and in a generic fashion, its treatment of alluvial fan hydraulic processes is very elementary.

In view of the existing, albeit limited evidence, the assumption that a flood flow has an equal probability of crossing a fan contour at any point is conservative. An alternative hypothesis was suggested by French and Lombardo (22). In Figure 1, an idealized fan is shown spreading out in a conical shape between two boundaries which cannot be crossed by a flood event. It is assumed that the points on line AB which connects the apex of the fan and the lowest point in the watershed are the most likely to be hit by a flood event. Points lying off line AB are less likely to be hit depending on their position with respect to AB. Quantifying these assumptions

$$p(x|f) = \frac{T}{W_c} \left(1 - \frac{\theta}{\Gamma} \right) \qquad (2)$$

where θ and Γ are angles defined in Figure 1. The validity of Equation 2 is supported by field observations. First, the central portion of alluvial fans is generally higher than other parts because of greater deposition on the central portion. Second, in examining present day channel deviation from the medial radial line of seventy-five fans, Bull (8) found that approximately two-thirds of the channels were within thirty degrees of the medial position and only three channels had a deviation of more than fifty degrees. These field observations are summarized in terms of the probability of a specified degree of deviation in Figure 2. (Note, the medial radial line on an alluvial fan is by definition the straight line from the fan apex to the toe, positioned so that the fan is split into approximately two equal areas.) Thus, at present, risk of a specified point on an alluvial fan being hit by a specified flood given by either Equations (1) or (2) appears to be acceptable and conservative.

The second primary assumption is that the slope of the fan is such that critical flow will occur. While it is true that the qualitative literature available demonstrates that alluvial fans have steep slopes in comparison to perennial streams and rivers, there has been in the past no quantitative justification of this assumption. Recall that, by definition, the critical slope is one on which uniform or normal flow occurs at critical depth. The normal velocity of flow is given by the Manning equation or

$$u = \frac{1.49}{n} R^{2/3}\sqrt{S} \qquad (3)$$

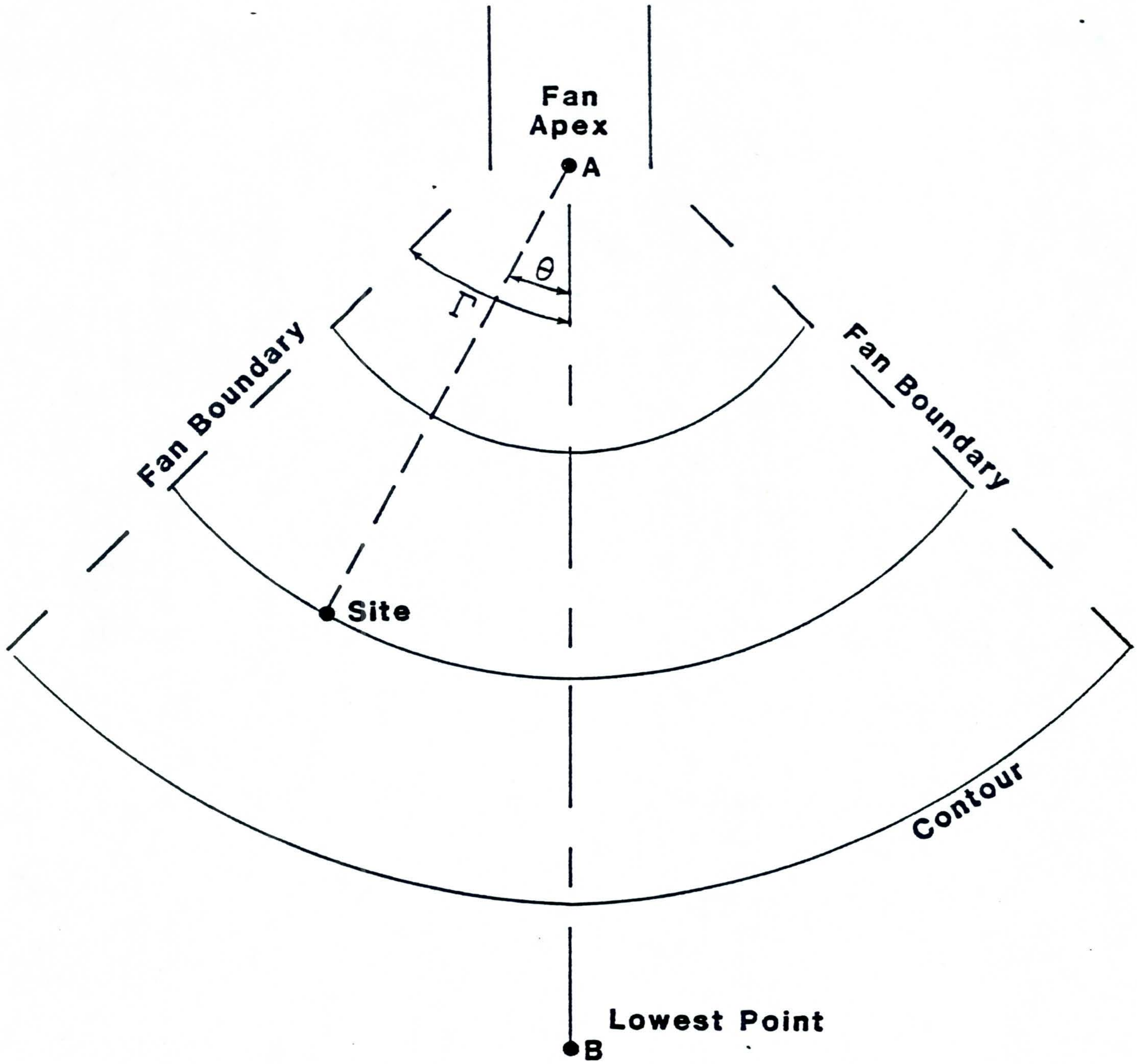


FIGURE 1: Schematic of an idealized alluvial fan.

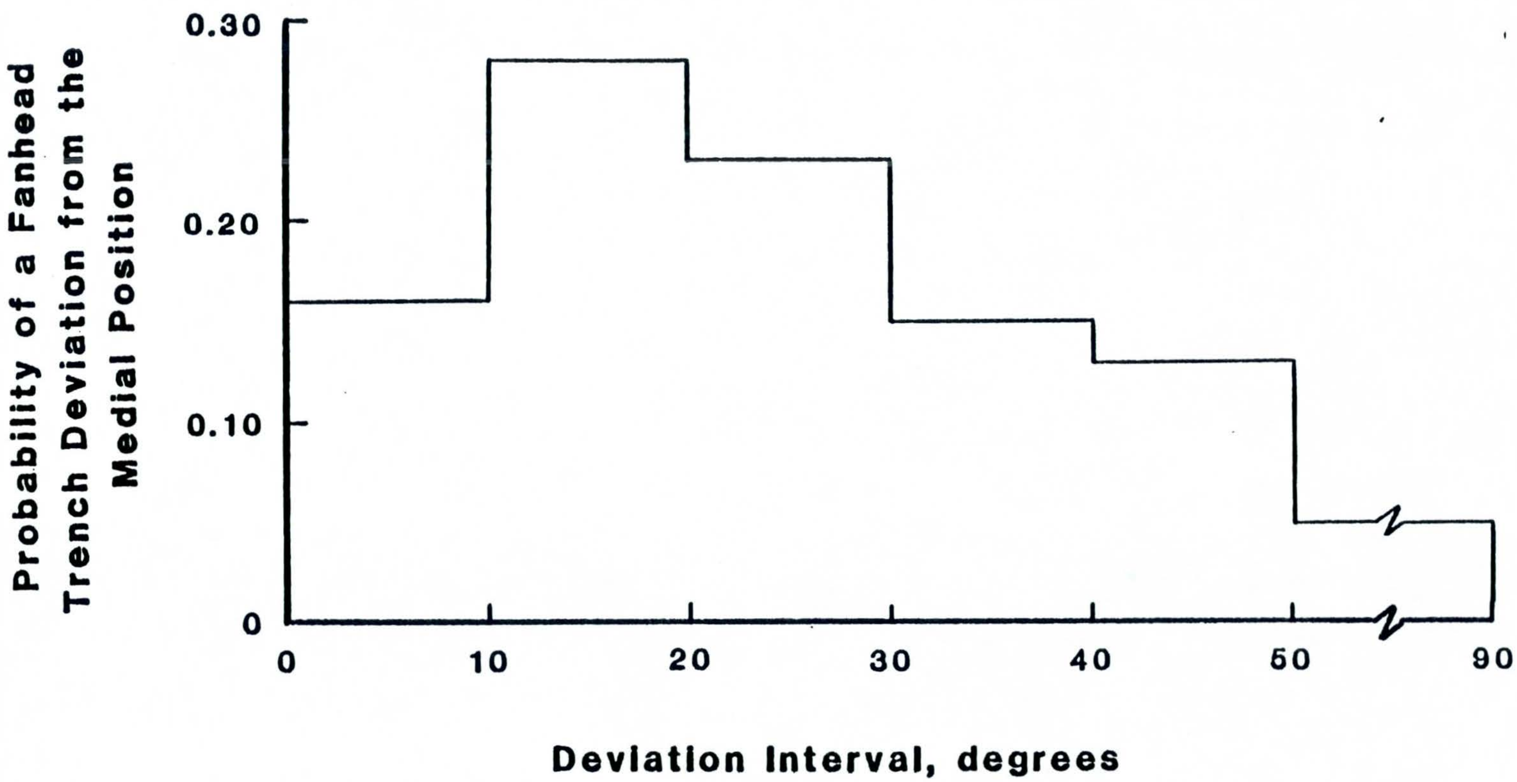


FIGURE 2: Probability of a channel deviation from the medial position.

where u = normal velocity of flow, n = Manning resistance coefficient, R = hydraulic radius, and S = longitudinal slope of the channel. Under critical flow conditions in a rectangular channel

$$u = \sqrt{gy} \qquad (4)$$

and

$$y = \sqrt[3]{\frac{q^2}{g}} \qquad (5)$$

where q = flow per unit width and g = acceleration of gravity. Substitution of Equations (4) and (5) in Equation (3) yields upon rearrangement an equation for the critical slope or

$$S_c = \frac{21.3\ n^2}{q^{2/9}} \qquad (6)$$

where S_c = critical slope. When $S > S_c$, supercritical flow occurs; and when $S < S_c$, subcritical flow occurs. There are a number of semi-empirical methods of estimating a value of n based on an analysis of the size of the materials composing the bed of the channel. In the material which follows, the equation suggested by Lane and Carlson (31) for channels whose beds are paved with cobbles or

$$n = \frac{d_{75}^{1/6}}{39} \qquad (7)$$

and the equation suggested by Meyer-Peter and Muller (38) for channels whose beds are not paved with cobbles or

$$n = \frac{d_{90}^{1/6}}{26} \qquad (8)$$

are used. In Equations (7) and (8), d_{75} = diameter of the bed material in inches such that 75% of the material, by weight, is smaller and d_{90} = diameter of the bed material in meters such that 90% of the material, by weight, is smaller.

In Area 5 of the Nevada Test Site a detailed study of the hazard floods present to a facility, including the estimation of peak flood flows and an intensive soil sampling program, was performed. In Tables 1, 2, and 3, a limited portion of the results of this study are summarized for the watershed and alluvial fan shown in Figure 3. In Figure 4, S_c is plotted as a function of the flow per unit width and the extreme values of $\bar{n}$, Table 3, and S, Table 2. In this figure, the width of channel required to produce a flow per unit width q is noted where the symbolism T_R indicates the top width of a rectangular channel required to produce the peak flood flow in Table 1 with a return period R in years. Figure 4 demonstrates that under most conditions flow on the alluvial fan will be critical or supercritical. Although the state of flow is strongly dependent on the width of the channel in which it occurs, Figure 4 demonstrates that it is reasonable to assume critical or supercritical flow would exist during flood flows across the Scarp Canyon Fan.

The third assumption is perhaps the most difficult to evaluate. The assessment of flood risk by the conditional probabilities given in Equations (1) and (2) require that the width of the flood channel be estimated. On many alluvial fans below the intersection point there are no well-defined, stable channels; and thus, some methodology must be used to estimate the geometry of the channel which will be formed by the flood flow. Dawdy (18) and (19), and Anon. (2) assumed that the width, depth, and velocity of flow can be written in terms of flow rate Q; or

$$u = C_1 Q^m \qquad (9)$$

TABLE 1

SUMMARY OF PEAK FLOOD FLOWS AND OTHER VARIABLES FOR WATERSHED 3, FIGURE 3

Return Period (years) (1)	Peak Flood Flow (ft^3/s) (2)	T (ft) (3)	y (ft) (4)	q ($ft^3/s/ft$) (5)
10	790	110	1.0	7.2
25	2000	200	1.5	10.
50	3600	250	1.8	14.
100	6100	310	2.3	20.
500	16000	450	3.3	36.

TABLE 2

SUMMARY OF AVERAGE SLOPE DATA FOR
ALLUVIAL FAN 3, FIGURE 3

Elevation (ft) (1)	Distance Between Elevations (ft) (2)	Average slope (3)
3800		
	5075	0.0197
3700		
	6950	0.0144
3600		
	4300	0.0233
3500		
	4150	0.0241
3400		
	4500	0.0222
3300		
	5200	0.0192
3200		
	7400	0.0135
3100		
	3300	0.0061
3080		

TABLE 3

SUMMARY OF SOIL SAMPLE AND SIEVE ANALYSIS RESULTS FOR SITES SHOWN IN FIGURE 3

Site (1)	d_{75} (inches) (2)	n by Eq (7) (3)	d_{90} (m) (4)	n by Eq (8) (5)
From current channel areas:				
S-15	0.13	0.018	0.0080	0.017
S-27	0.11	0.018	0.0059	0.016
S-28	0.26	0.020	0.013	0.019
S-29	0.18	0.019	0.012	0.018
S-30	0.13	0.018	0.0095	0.018
S-31	0.45	0.022	0.022	0.020
S-32	0.53	0.023	0.024	0.021
S-33	0.35	0.022	0.014	0.019
S-34	0.20	0.020	0.013	0.019
S-45	>1.2	>0.026	>0.030	>0.021
S-46	0.20	0.020	0.012	0.018
S-47	0.20	0.020	0.011	0.018
S-48	0.11	0.018	0.0051	0.016
S-49	0.09	0.017	0.0039	0.015
S-50	0.31	0.021	0.021	0.020
S-54	0.19	0.019	0.0068	0.017
S-55	0.16	0.019	0.0088	0.017
S-58	0.24	0.020	0.0095	0.018
S-59	0.67	0.024	0.032	0.022
S-63	0.23	0.020	0.010	0.018
S-64	0.43	0.022	0.020	0.020
S-67	0.17	0.019	0.012	0.018
S-68	0.091	0.017	0.0048	0.016
S-69	0.20	0.020	0.017	0.020
S-70	0.055	0.016	0.0060	0.016
S-75	0.10	0.017	0.0080	0.017
S-76	0.039	0.015	0.0042	0.015
	$\bar{d}_{75}$=0.22 in	$\bar{n}$=0.019	$\bar{d}_{90}$=0.012 m	$\bar{n}$=0.018
	σ_{75}=0.15 in	σ_n=0.002	σ_{90}=0.0069	σ_n=0.002

Site (1)	d_{75} (inches) (2)	n by Eq (7) (3)	d_{90} (m) (4)	n by Eq (8) (5)
From non-channel areas:				
S-51	0.04	0.015	0.004	0.015
S-52	0.03	0.014	0.0017	0.013
S-53	0.03	0.014	0.0022	0.014
S-56	0.28	0.021	0.022	0.020
S-57	0.20	0.020	0.021	0.020
S-60	>1.2	>0.026	>0.030	>0.021
S-61	0.047	0.015	0.0042	0.015
S-62	0.032	0.014	0.0032	0.015
S-65	0.098	0.017	0.0085	0.017
S-66	0.051	0.016	0.0070	0.017
S-71	0.79	0.025	>0.030	>0.021
S-72	0.28	0.021	>0.030	>0.021
S-73	0.079	0.017	0.0072	0.017
S-74	0.14	0.018	>0.030	>0.021
S-77	0.071	0.016	0.010	0.018
S-78	0.079	0.017	0.0075	0.017
S-79	0.016	0.013	0.0009	0.012
S-80	0.017	0.013	0.0010	0.012
S-81	0.20	0.020	0.015	0.019
S-82	0.13	0.018	0.0090	0.018
S-83	0.030	0.014	0.0052	0.016
S-84	0.027	0.014	0.0041	0.015
S-85	0.034	0.015	0.011	0.018
S-86	0.13	0.018	0.019	0.020
S-87	0.020	0.013	0.0020	0.014
S-88	0.024	0.014	0.0029	0.014
S-89	0.026	0.014	0.0080	0.017
S-90	0.024	0.014	0.0034	0.015
S-91	0.027	0.014	0.0048	0.016
S-92	0.033	0.014	0.0058	0.016
S-93	0.24	0.020	0.020	0.020
S-94	0.26	0.021	>0.030	>0.021
S-95	0.032	0.014	0.0030	0.015
S-96	0.030	0.014	0.0020	0.014
	$\bar{d}_{75}$=0.11 in	$\bar{n}$=0.016	$\bar{d}_{90}$=0.0074 m	$\bar{n}$=0.016
	σ_{75}=0.15 in	σ_n=0.003	σ_{90}=0.0063 m	σ_n=0.002

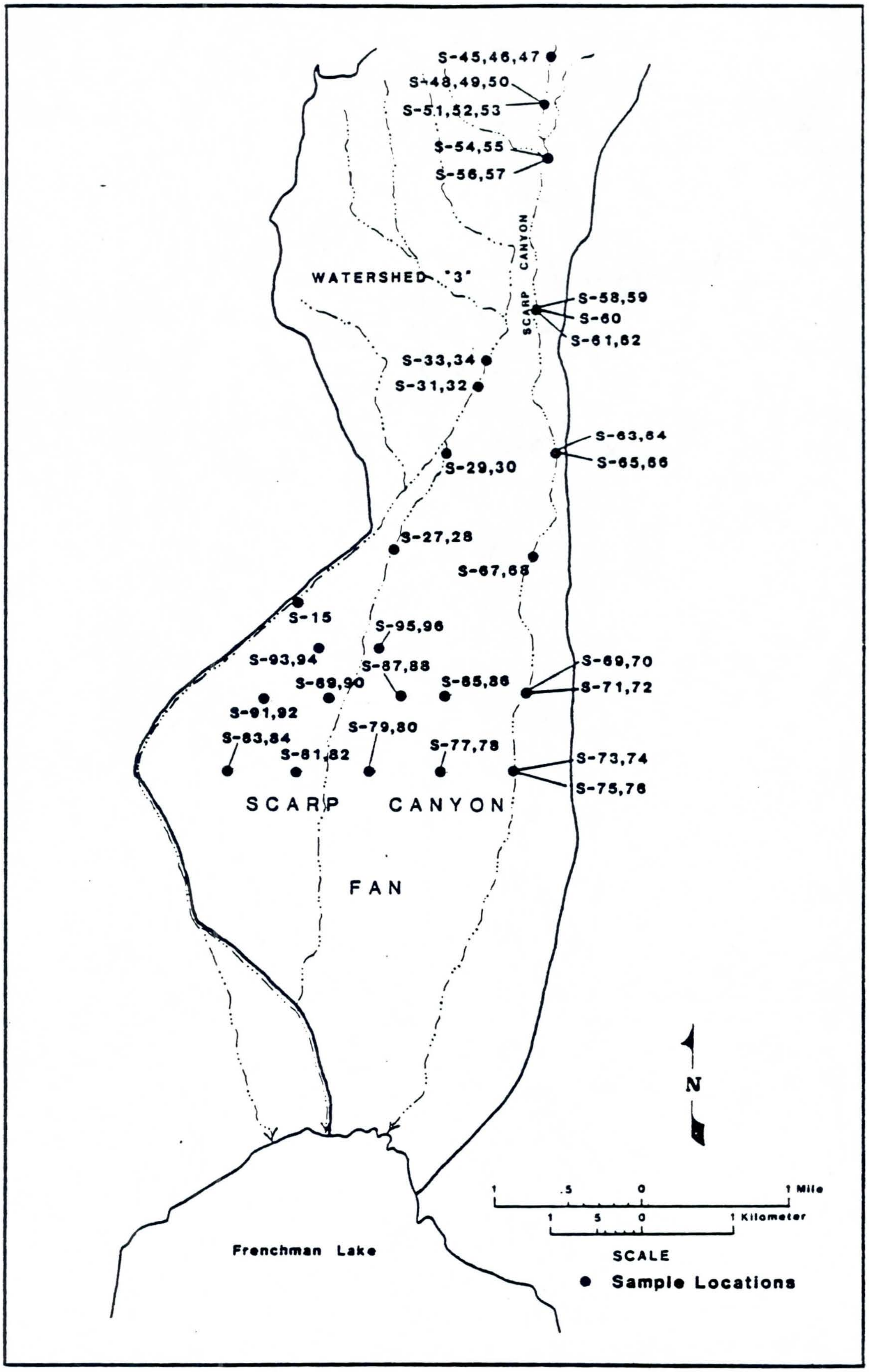
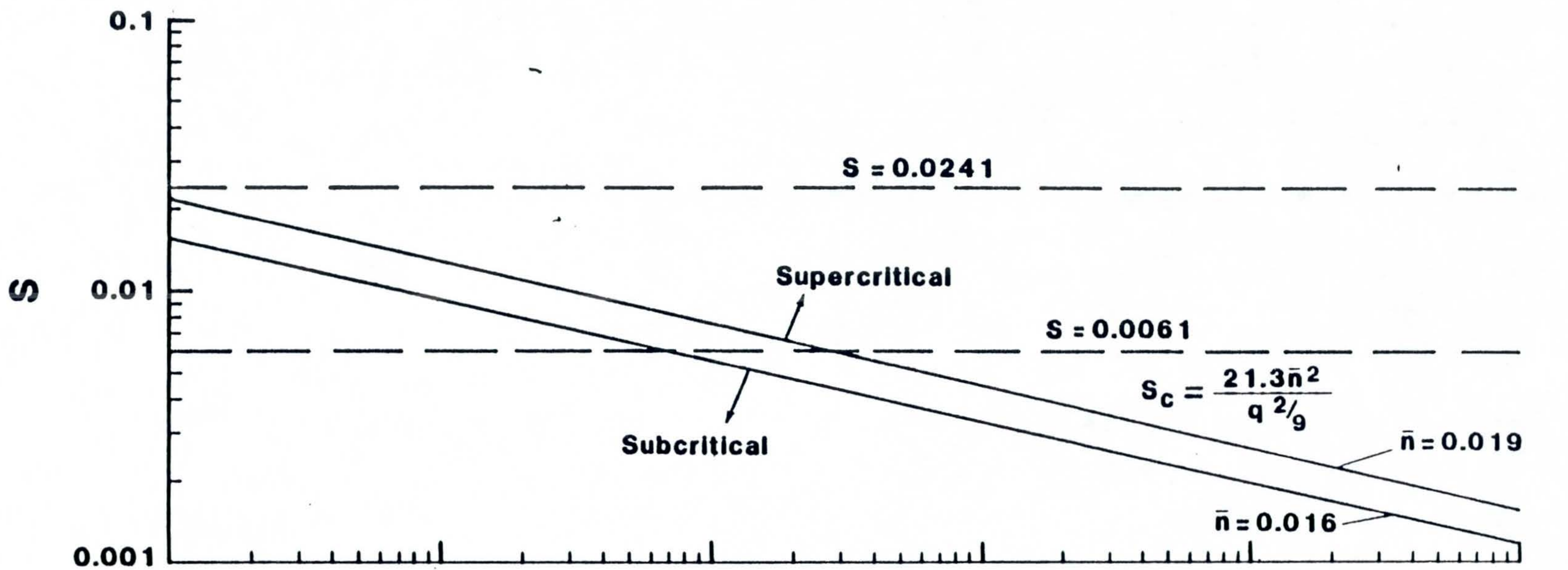


FIGURE 3: Location of soil sampling sites on the Scarp Canyon Fan, Area 5, Nevada Test Site, Nevada.



$q(ft^3/s/ft) \rightarrow$	0.01	0.10	1.0	10	100	1000
Top Width (ft) T_5	79,000	7900	790	79	7.9	0.79
T_{25}	200,000	20,000	2000	200	20	2
T_{50}	360,000	36,000	3600	360	36	3.6
T_{100}	610,000	61,000	6100	610	61	6.1
T_{500}	1,600,000	160,000	16,000	1600	160	16

FIGURE 4: Critical slope as a function of flow per unit for floods of various return periods and extreme values of $\bar{n}$.

$$y = C_2Q^f \quad (10)$$

$$T = C_3Q^b \quad (11)$$

where Q = flow rate, y = depth of flow, and C_1, C_2, C_3, m, f, and b = coefficients. Note, to maintain the validity of the continuity equation, it is usually assumed that both the sum of the exponents; i.e., (m + f + b), and the product of the leading coefficients; i.e., ($C_1 * C_2 * C_3$) equal 1. In the terminology of hydraulic engineering, Equations (9) - (11) have been previously termed the regime theory; see for example Henderson (23). In fact, this is not a theory but an empirical correlation of data from stable canals and rivers. The theory implies that a channel will adjust its slope and channel section so that the rate of sediment transport equals the rate of sediment supply. In the geologic literature, the hypothesis quantified by Equations (9) - (11) is commonly referred to as the hydraulic geometry, a terminology that was apparently first introduced by Leopold and Maddock (35). It is obvious that these equations present an easy and explicit solution to the problem of estimating channel width and depth and the velocity of flow across an alluvial fan; and hence a method of quantifying flood hazard. The crucial question is whether these equations are valid; and if they are valid, then what are the true values of the coefficients?

Numerous investigators in addition to Leopold and Maddock (35) have made detailed studies of alluvial channels in attempts to determine an average set of coefficient values, either for a group of streams in a particular physiographic setting or on a global basis. There have also been a number of attempts to use theoretical methods to determine the hydraulic geometry; see for example, Langbein (32) and (33) with discussions by Blench (5), Kennedy et al (28); Yang et al (57); and Williams (51). Some of the field and theoretical results that are available are summarized in Table 4. Williams (51) presented rather comprehensive data for 165 U.S. rivers in his study; and space does not allow these data to be duplicated here. There have also been a number of investigations which question the basis of this theory. Dawdy (20) described discontinuities in depth-discharge relationships when the flow changes from the plane bed-ripple-dune regime (the lower regime) to the wave-antidune regime (the upper regime). Simons and Richardson (45) noted that the variation of bedforms with discharge also affect the discharge-stage relationship. Richards (43) noted that depth and velocity are functions of roughness and that when the rate of change of roughness is non-uniform the simple power functions for these variables are not valid. Knighton (29) and (30), and Park (39) also examined the power functions and demonstrated that there is a considerable range of exponents in both the at-a-station and downstream cases if the data from the available studies are examined together. Thus, at the present time there are sufficient data to suggest that there is not a tendency towards a unique series of relationships for either the downstream or the at-a-station cases.

However, for the moment, assume that the basic tenets of the hydraulic geometry hypothesis are valid in the general case, we must still consider the validity of this hypothesis in relation to hydraulic processes on alluvial fans. Two points should be noted. First, almost without exception all previous hydraulic geometry studies, both field and theoretical, have examined perennial alluvial streams which according to the hypothesis are stable channels. Further, these previous investigations have considered only steady flow. Thus, if the validity of the hydraulic geometry hypothesis is questioned in perennial alluvial channels with reasonably stable geometry and steady flow, it must certainly

TABLE 4

SUMMARY OF THEORETICAL AND FIELD RESULTS
FOR THE REGIME (HYDRAULIC GEOMETRY) THEORY

Coefficient	Source						
	Theoretical			Field			
(1)	Leopold and Langbein (34) (2)	Langbein (33)	Yang, Song, and Woldenberg (57)	Leopold and Maddock (35) Midwest	Leopold and Maddock (35) Semi-Arid	Dawdy (19)	Williams (51)
f (depth)	0.36	0.37	0.41	0.40	0.30	0.40	0.42
b (width)	0.55	0.53	0.41	0.50	0.50	0.40	0.22
m (velocity)	0.09	0.10	0.18	0.10	0.20	0.20	0.37

be questioned in ephemeral channels composed of non-cohesive materials and under very unsteady conditions. Second, the current hydraulic geometry hypothesis does not explicitly mention the Froude number. In the foregoing material, it was demonstrated that flood flow across one particular alluvial fan can reasonably be assumed to be critical or supercritical flow. Field experience with the regime/hydraulic geometry theory in the India-Pakistan Canals has demonstrated that the stability of canals will be maintained if they are in the lower flow regime but that meandering and bank erosion often develop as the upper flow regime is reached. Canal designers often use a Froude number criterion for regime flow; and Chang (13) noted that the value of the Froude number has usually been kept at about 0.2 and has never been allowed to exceed 0.3.

Again using the data from the Scarp Canyon Fan on the Nevada Test Site, the validity of the regime theory in the case of flood flows across alluvial fans can be examined. In Table 5, the average slopes of the watershed and alluvial fan shown in Figure 3 between elevations 3800 ft. (1160 m) and 3100 ft (945 m) are summarized along with the peak flood flows of both a ten and five hundred year return period (Table 1). Subsequent columns of this table provide the following information; Column (3) is the depth of flow estimated by

$$y = 0.07Q^{0.4} \qquad (12)$$

which is the formulation suggested by Dawdy (19); Column (4) is the shear velocity estimated by

$$u_* = \sqrt{gyS} \qquad (13)$$

TABLE 5

SUMMARY OF DATA REQUIRED TO TEST THE VALIDITY OF THE REGIME (HYDRAULIC GEOMETRY) THEORY FOR THE FAN SHOWN IN FIGURE 3

Slope (1)	Peak Flood Flow ft^3/s (2)	Depth of Flow ft (3)	Shear Velocity ft/s (4)	Average Particle Size ft (5)	F_s (6)	R_* (7)	I.D. Number (8)
0.0197	790	1.0	0.80	0.010	1.2	760	1
				0.0011	11.	83	2
	16000	3.3	1.4	0.010	3.7	1,300	3
				0.0011	3.4	150	4
0.0144	790	1.0	0.68	0.010	0.87	640	5
				0.0031	2.8	200	6
	16000	3.3	1.2	0.010	2.7	1,100	7
				0.0031	8.7	350	8
0.0233	790	1.0	0.87	0.014	1.0	1,100	9
	16000	3.3	2.5	0.014	8.4	3,300	10
0.0241	790	1.0	0.88	0.0079	1.8	660	11
				0.0017	8.6	140	12
	16000	3.3	1.6	0.0079	6.1	1,200	13
				0.0017	28.	260	14
0.0222	790	1.0	0.85	0.0036	3.8	290	15
				0.0046	3.0	370	16
	16000	3.3	1.5	0.0036	12.	510	17
				0.0046	9.2	650	18
0.0192	790	1.0	0.79	0.0014	8.4	100	19
				0.0010	12.	75	20
	16000	3.3	1.4	0.0014	26.	190	21
				0.0010	37.	130	22

where y is obtained from Column (3), S from Column (1), and a wide channel is assumed; Column (5) is the average particle size estimated from soil samples; Column (6) is the parameter F_s (the entrainment function) where

$$F_s = \frac{u_*^2}{(S_s - 1)\, gd} \qquad (14)$$

and S_s = specific gravity of the soil (S_s = 2.65); Column (7) is the parameter R_* (the particle Reynolds number) where

$$R_* = \frac{u_* d}{\nu} \qquad (15)$$

and $\nu = 1.059 \times 10^{-5}$ ft^2/sec (0.984×10^{-6} m^2/s); and Column (7) identifies the point in Figure 5 which represents these data. Figure 5 is a plot of R_* versus F_s demonstrating the dependence of the bed forms identified by Simons and Richardson (45) on these parameters. Thus, on the basis of the assumption made by Dawdy (19), these flows will result in antidunes in the upper regime of flow. Based on these data, it is concluded that the regime/hydraulic geometry theory is not a valid methodology for predicting channel widths and depths for flood flows across the Scarp Canyon Fan on the Nevada Test Site.

If the regime hypothesis is not valid for use in evaluating hydraulic processes on alluvial fans during flood flows, then alternative techniques for estimating channel geometry must be sought. The primary problem of fluvial hydraulics is that there are more unknowns than there are equations. The concepts of minimum unit stream power and minimum stream power are attempts to solve the indicated closure problem. The minimum unit stream power hypothesis asserts that an alluvial channel tends to adjust its velocity, slope, roughness, and channel geometry such that

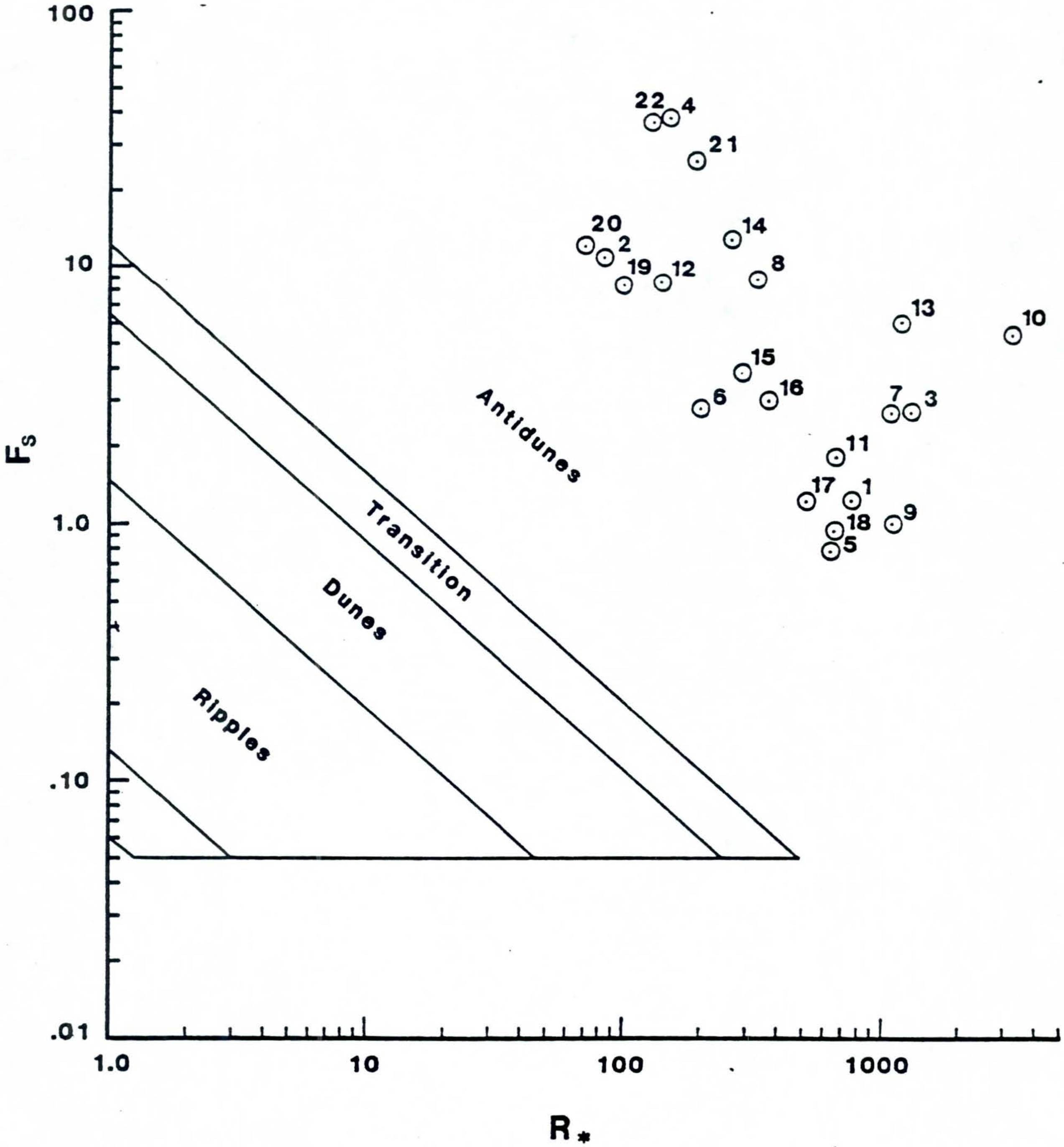


FIGURE 5: F_s versus R_* for sample points on Scarp Canyon Fan.

mimimum unit stream power is used to transport a given sediment concentration and water discharge; see for example, Yang (54, 55, 56), Yang and Stall (58), and Song and Yang (46). The minimum stream power hypothesis asserts that an alluvial stream, in response to changes in the environment, adjusts itself so that the total stream power of the channel reach is minimized; see for example, Chang and Hill (14), and Chang (11 and 12). The minimum unit stream hypothesis, in its current form, is not applicable to flood flows across alluvial fans because this hypothesis was developed for subcritical flows in the lower flow regime, Yang (54). The applicability of the minimum stream power hypothesis to the type of alluvial channel formed on a fan is less clear.

It appears that the minimum stream power hypothesis, as presented by Chang and Hill (14), and Chang (12) could, with some changes, be used to predict alluvial channel formation and modification on alluvial fans under flooding conditions. Among the modifications which might be required are the following. First, provision must be made to take into account the substantial infiltration losses that may be experienced in ephemeral streams; see for example Renard and Laursen (42). Note, in some cases infiltration may be inhibited by naturally occurring deposits of calcium carbonate; see for example, Cooley et al (16). Second, some modification of the minimum stream power hypothesis to account for both the unsteady nature of the water flow and the unsteady supply of sediment is required. Third, the validity of this concept at Froude numbers exceeding one must be considered in relation to either field or laboratory data. Although Chang (11) found the model satisfactory at Froude numbers of approximately one, his data neither incorporated experiments where the Froude number significantly exceeded one nor did he present any data regarding bedforms. In fact, his analogy between deltas and alluvial fans of the type commonly found in the Southwest is rather tenuous. Fourth, the comments made by Thorne and Simmons (50) regarding what they view as as the oversimplification of the criterion used by Chang (12) for bank stability must also be taken into account.

Thus, the conclusion regarding the third primary hypothesis is that it is not valid and must be reconsidered. However, it must be admitted that whatever the inadequacies of the Dawdy (19) theory regarding the estimation of channel width and depth, there is not presently a theory which is superior to it.

At this point, attention must be given to the two assumptions which were not explicitly stated by Dawdy (19) and Anon. (2) but were implied. First, flow rates in many arid areas cannot be estimated by the standard methods recommended in Anon. (1) because there is not a sufficient period of record. French and Lombardo (22) discussed this problem and concluded that for the present in the Southern Nevada area peak flood flow rates should be estimated by either regional regression models; see for example Riggs (44), or envelope curve methods; see for example Crippen (17). It should be noted that in many arid areas both of these methods have a number of severe limitations; see for example, French and Lombardo (22) and Wolman and Costa (52). Second, the validity of the implied assumption that debris flows do not present a significant hazard to facilities on alluvial fans depends to a large extent on the location of the facility on the fan. For facilities located in the vicinity of the intersection point, debris flows must be considered. For facilities located in the vicinity of the toe of the fan, debris flows may not present a severe hazard. The analytic methods for assessing the debris flow hazard can best be described as a developing technology; see for example

Takahashi (48 and 49), DeLeon and Jeppson (21), and Jeppson and Rodriguez (27). For facilities located away from the intersection point, debris flows present less of a hazard. It is clear that more consideration should be given to this implied assumption.

OTHER FLOOD HAZARD ASSESSMENT METHODOLOGIES

At this point, it should be noted that in this report only the assumptions crucial to the Federal Emergency Management Agency flood hazard assessment methodology have been examined. Other flood hazard investigations on alluvial fans have used different assumptions and methodologies, and it is appropriate that these be briefly considered.

Christensen and Spahr (15) and Squires and Young (47) used a technique based on the Manning equation. Inherent in this methodology are the following assumptions:

1. steady, uniform flow
2. minimal sediment transport
3. permanently entrenched channels
4. stable channel geometry.

For a number of reasons, this methodology is not appropriate to the alluvial fan environment. First, by definition, floods are neither steady nor uniform flow events. Therefore, the basic assumptions used to derive the Manning equation are violated; and the equation is rendered invalid. If a traditional hydraulic engineering approach is used, then the partial differential equations describing unsteady flow must be used. Second, flood events on alluvial fans transport significant quantities of sediment; and this is also a factor that must be considered. Third, as noted previously in this report, channels on alluvial fans may either be permanently entrenched or temporarily entrenched. Christensen and Spahr (15) and Squires and Young (47) make no attempt to identify or differentiate between permanently or temporarily entrenched channels. Fourth, stable alluvial channels can only exist when a state of equlibrium exists between the supply and transport of sediment. Under unsteady flow conditions, an alluvial channel cannot be considered stable. Although non-erodible channel sections may exist in the alluvial fan environment, they are not common.

Magura and Wood (36) in their methodology took into account the non-uniform nature of flood flows, the possibility of temporarily and permanently entrenched channels, and the unstable nature of alluvial channels under flood conditions. However, this methodology did not explicitly take into account sediment transport or the unsteady nature of the flow.

CONCLUSION

In conclusion, a number of comments can be made and a number of questions must be raised. First, the assumption that a flow on an alluvial fan has an equal probability of crossing any point on a given contour seems to be a very conservative assumption; however, from the viewpoint of flood hazard analysis this assumption is for the present acceptable. Second, given the data from the Nevada Test Site, it would appear that the assumption that fans have critical to supercritical slopes is acceptable. However, validity of this assumption is dependent on the third assumption regarding channel width and depth. Third, the present methods of estimating channel width and depth on alluvial fans seem to be invalid. However, it must be noted that at the present time there does not seem to be a superior method available. Therefore, for the present, the assumptions of Dawdy (19) and Anon. (2) should be accepted, but the unquantifiable errors present in these assumptions must be recognized. Fourth, the specific flood hazard evaluation procedures described by Dawdy (19) and Anon. (2) are not valid in some cases because they are based on the assumption that sufficient records exist to do a peak flow analysis along the lines recommended by Anon. (1). It is obvious that for much of the Southwest this is not a valid assumption since sufficient data are not available. Fifth, the implied assumption regarding debris flows is only valid once a location on a fan relative to the intersection point has been established. It must also be recognized that the location of the intersection point may change dramatically even on an engineering time scale. Thus, it is concluded that the current methods of flood hazard assessment on alluvial fans are not adequate given the current and projected economic value of structures and development on alluvial fans in the southwestern United States.

Given the above comments, at least three areas of basic and applied research can be identified. First, there is a need to understand how alluvial fans develop on a geologic time scale. The initial laboratory studies of Hooke (24) and the model developed by Price (40) should be carefully studied and a new program incorporating co-ordinated physical and numeric model studies with field verification of the results must be designed.

Second, numeric models capable of estimating the location and size of channels formed by unsteady, high Froude number flows in alluvial fill must be developed. Although it may be possible to modify currently available models to accomplish this goal, field and laboratory verification of the results will be required.

Third, in areas where there are not adequate stream gaging records, techniques which are superior to the regional method of peak flood flow analysis and the envelope curve method must be developed. If this is not possible, then error limits on these methodologies must be developed and the error estimates carried through the subsequent calculations. Further, if the regional or envelope curve methodologies are used, then a technique of estimating a hydrograph shape must be developed for use in routing the flow across the fan and estimating sediment transport.

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