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*Guidelines for*  
**Determining Flood  
Hazards on Alluvial  
Fans**



FEDERAL EMERGENCY  
MANAGEMENT AGENCY

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## GUIDELINES FOR DETERMINING FLOOD HAZARDS ON ALLUVIAL FANS

### 1 INTRODUCTION

Alluvial fans, and flooding on alluvial fans, show great diversity because of variations in climate, fan history, rates and styles of tectonism, source area lithology, vegetation, and land use. Acknowledging this diversity, this document provides an approach that considers site-specific conditions in the identification and mapping of flood hazards on alluvial fans. Investigation and analysis of the site-specific conditions may require knowledge in various disciplines such as geomorphology, soil science, hydrology, and hydraulic engineering. Although the scope of study may constrain the degree of site-specific consideration undertaken, it is essential that field inspections of the alluvial fan be conducted.

*As defined in 44 CFR 59.1, the current (1999) definition of "Alluvial Fan Flooding" means flooding that occurs on the surface of an alluvial fan or similar landform, originates at the apex, and is characterized by high-velocity flows; active processes of erosion, sediment transport, and deposition; and unpredictable flowpaths.*

*The current definition under 44 CFR 59.1 will be revised to be consistent with the approach described in this document and specifically to eliminate reference to "similar landforms." The process described in this document is intended for flooding only on alluvial fans as described below.*

*As interim guidance in the determination of "similar landform," unless the landform under investigation meets the three criteria under Stage 1 for composition, morphology, and location, the landform is not considered to be "similar."*

This document provides guidance for the identification and mapping of flood hazards occurring on alluvial fans, irrespective of the level of fan forming activity. The term *alluvial fan flooding* encompasses what will be described as *active alluvial fan flooding* and *inactive alluvial fan flooding*.

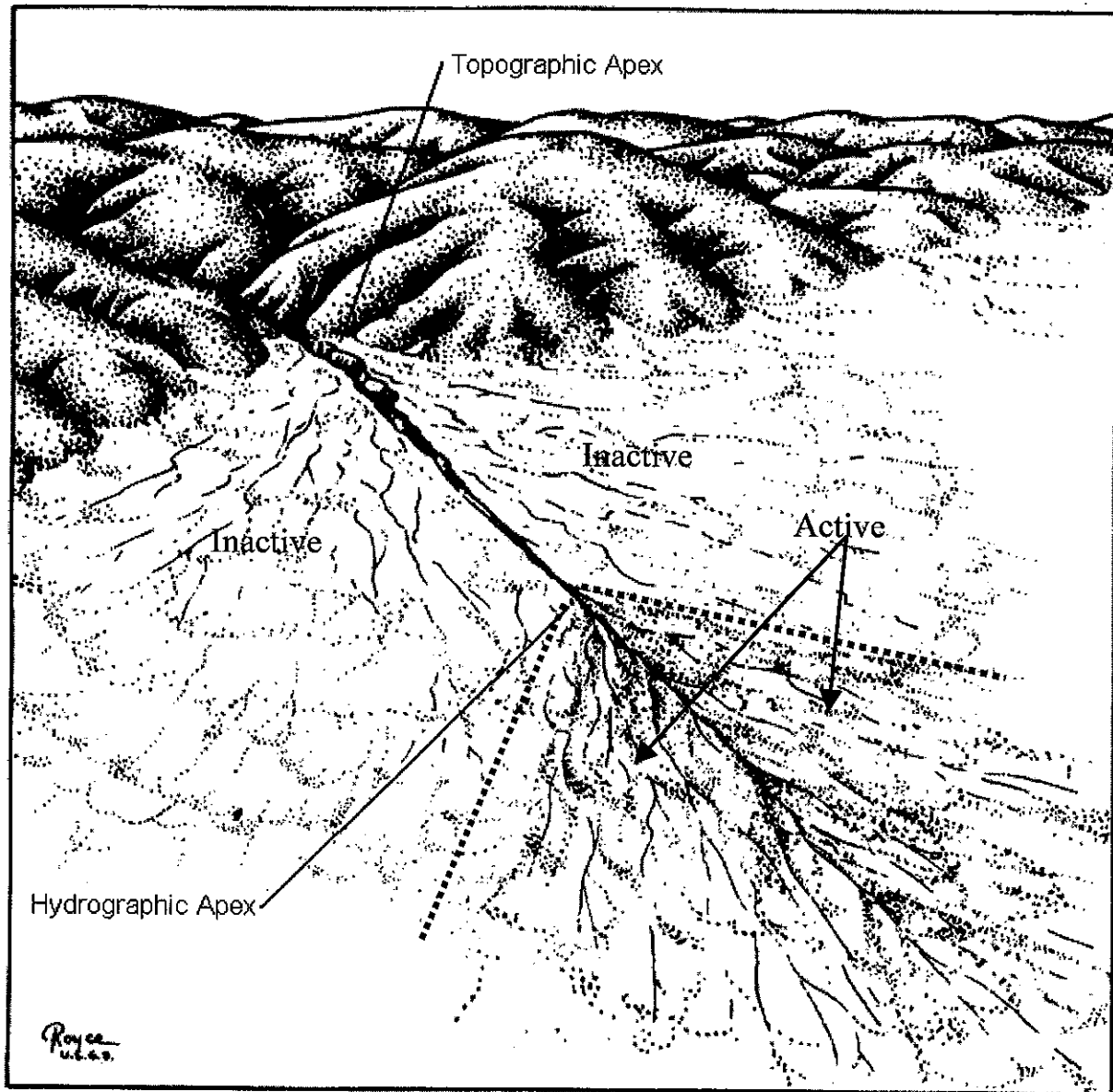
*Active alluvial fan flooding* is a type of flood-hazard that occurs only on alluvial fans. It is characterized by flow path uncertainty so great that this uncertainty cannot be set aside in realistic assessments of flood risk or in the reliable mitigation of the hazard. An *active alluvial fan flooding* hazard is indicated by three related criteria: (a) flow path uncertainty below the hydrographic apex, (b) abrupt deposition and ensuing erosion of sediment as a stream or debris flow loses its competence to carry material eroded from a steeper, upstream source area; and (c) an environment where the combination of sediment availability, slope, and topography creates an ultrahazardous condition for which elevation on fill will not reliably mitigate the risk.

*Inactive alluvial fan flooding* is similar to traditional riverine flood hazards, but occurs only on alluvial fans. It is characterized by flow paths with a higher degree of certainty in realistic

assessments of flood risk or in the reliable mitigation of the hazard. Counter to *active alluvial fan flooding* hazards, an *inactive alluvial fan flooding* hazard is characterized by relatively stable flow paths. However, areas of *inactive alluvial fan flooding*, as with *active alluvial fan flooding*, may be subject to sediment deposition and erosion, but to a degree that does not cause flow path instability and uncertainty.

An alluvial fan may exhibit both *active alluvial fan flooding* and *inactive alluvial fan flooding* hazards. The hazards may vary spatially or vary at the same location, contingent on the level of flow discharge. Spatially, for example, upstream inactive portions of the alluvial fan may distribute flood flow to active areas at the distal part of the alluvial fan. Hazards may vary at the same location, for example, with a flow path that may be stable for lower flows, but become unstable at higher flows.

An example of an alluvial fan that exhibits both active and inactive alluvial fan flooding is depicted in Figure 1. In this example, the area between the topographic apex and the hydrographic apex (apex definitions will be discussed below) would be considered *inactive alluvial fan flooding* because this reach is characterized by a stable, entrenched channel which can convey the 100-year flood discharge without overbank flooding. The area below the hydrographic apex would be considered *active alluvial fan flooding* because this area is characterized by flow path uncertainty, abrupt deposition, and ensuing erosion of sediment as the channel loses its competence to carry material eroded from a steeper, entrenched upstream source area.



**Figure 1**

Alluvial Fan With Entrenched Channel Leading to Active Deposition at Distal Part of the Fan (Reproduced with permission from the National Research Council, Figure 3-2, © 1996, The National Academy Press, Washington, DC; annotations added by FEMA)

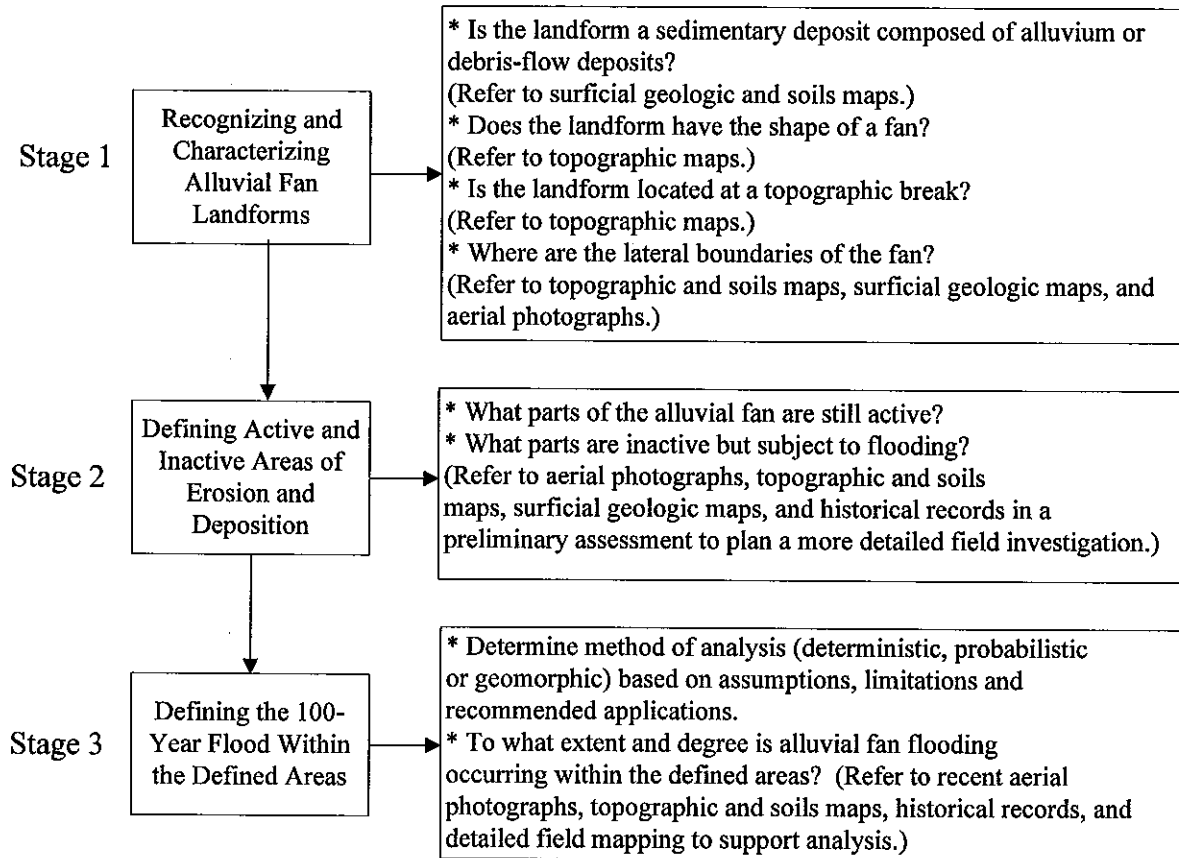
## 2 APPROACH

The approach for *alluvial fan flooding* identification and mapping first seeks to identify whether the area under study is an alluvial fan and second, which portions, if any, of this area are characterized by or subject to *active alluvial fan flooding*. After these steps, various methods unique to different situations can be employed to analyze and define the 100-year flood within the areas of *alluvial fan flooding* identified on the alluvial fan. Thus, the approach for the identification and mapping of *alluvial fan flooding* can be divided into three stages. Each of these stages must be addressed and thoroughly documented during the study process.

1. Recognizing and characterizing alluvial fan landforms
2. Defining the nature of the alluvial fan environment and identifying active and inactive areas of the fan
3. Defining and characterizing the 100-year flood within the defined areas

Each stage is described in detail in later sections. Additional information can also be found in the National Research Council report, *Alluvial Fan Flooding* (1996). Coordination with the Regional Project Officer (PO) and Headquarters is required from the onset of the study, because each stage builds upon the previous stage and because of the complexity of many alluvial fans. Figure 2 shows the progression of the process.

Progression through each of the stages results in a procedure that narrows or divides the problem to smaller and smaller areas. In Stage 1, the landform on which the flooding occurs must be characterized. If the location of study is an alluvial fan, the analyst proceeds to Stage 2, in which the parts of the alluvial fan that are still active or inactive are identified. Finally, in Stage 3 the analyst utilizes various methods to define and analyze the 100-year flood within each identified area of *alluvial fan flooding*. Progression through these stages requires a variety of maps and photographs, as well as a significant amount of fieldwork and analysis to fully understand the flood-hazard.



**Figure 2**

Three Stages of the Process To Identify and Map Alluvial Fan Flooding (Original published in National Research Council, 1996, Figure 3-1; amended by FEMA)



### 3 STAGE 1: RECOGNIZING AND CHARACTERIZING ALLUVIAL FAN LANDFORMS

#### Determining Whether or Not a Landform Is an Alluvial Fan.

As defined in this document, alluvial fan flooding occurs only on alluvial fans. Therefore, the first stage of the process is to determine whether the landform in question is an alluvial fan. If, after following the guidelines in this section, it is concluded that the landform is not an alluvial fan, then the methods described in this document are not intended for, or necessarily applicable to, the landform in question.

*An alluvial fan is a sedimentary deposit located at a topographic break such as the base of a mountain front, escarpment, or valley side, that is composed of streamflow and/or debris flow sediments and has the shape of a fan, either fully or partially extended.* These characteristics can be categorized by composition, morphology, and location as follows.

#### 3A Composition

Alluvial fans are landforms constructed from deposits of alluvial sediments or debris flow materials. These deposits, "alluvium", are an accumulation of loose, unconsolidated to weakly consolidated sediments. Alluvium refers to sediments transported by either streamflow or debris flows. Geologic maps and field reconnaissance can be used to determine whether the landform is composed of alluvium.

#### 3B Morphology

Alluvial fans are landforms that have the shape of a fan, either partly or fully extended. Flow paths may radiate outward to the perimeter of the fan; however, drainage may exhibit a range of patterns such as dendritic, anastomosing, and distributary. Topographic maps and aerial photos can be used to assess this criterion.

#### 3C Location

Alluvial fan landforms are located at a topographic break where long-term channel migration and sediment accumulation become markedly less confined than upstream of the break. This locus of increased channel migration and sedimentation is referred to as the alluvial fan apex. The topographic apex is at the extreme upstream extent of the alluvial fan landform. The hydrographic apex is the highest point on the alluvial fan where there exists physical evidence of channel bifurcation and/or significant flow outside the defined channel; its location may be either coincidental with, or at a point downstream of, the topographic apex as seen in Figure 1. The hydrographic apex may be discharge dependent and may vary with the magnitude of the flooding event.

### 3D Boundaries of an Alluvial Fan

Define the Toe and Lateral Boundaries of the Alluvial Fan.

#### 3D (1) Toe

The distal terminus, or toe, of an alluvial fan commonly is defined by:

- A stream that intersects the fan and transports deposits away from the fan
- A playa lake
- An alluvial plain
- Smoother, gentler slopes of the piedmont plain

Such boundaries can often be identified on topographic maps by changes in contour lines or identified on aerial photographs or by field inspection as changes in vegetation as a result of sediment changes or increased water table depth.

#### 3D (2) Lateral Boundaries

Lateral boundaries of alluvial fans are the edges of deposited and reworked alluvial materials. The lateral boundary of a single alluvial fan typically is a trough, channel, or swale formed at the lateral limits of deposition. The lateral boundary may also be a confining mountainside.

Lateral boundaries of single alluvial fans can often be identified as a contact of distinct differences between light-colored, freshly abraded, alluvial deposits and darker-colored, weathered deposits with well-developed soils on piedmont plains. Care should be taken to ensure that the contact is not simply a divide between older and more recent deposits of the alluvial fan.

The lateral boundaries of alluvial fans that coalesce with adjacent alluvial fans are generally less distinct than those of single alluvial fans. These lateral boundaries may be marked by a topographic trough or ridge. It is sometimes possible to distinguish between surfaces of adjacent alluvial fans based on different source-basin rock types. Defining the lateral boundaries of coalescing fans will likely require additional fieldwork, use of surficial geologic and soils maps, and consultation with a geomorphologist or soil scientist.

## 4 STAGE 2: DEFINING ACTIVE AND INACTIVE AREAS

Stage 1 identified whether the landform in question is an alluvial fan. Stage 2 seeks to delineate areas of the alluvial fan that are active or are inactive in the deposition, erosion, and unstable flow path flooding that builds alluvial fans. Stage 2 attempts to narrow the area of concern for Stage 3, which is the specific identification of the extent of the 100-year flood.

Although active alluvial fan flooding has occurred on all parts of an alluvial fan at some time in the geologic past in order to construct the landform itself, this does not mean that all parts are equally susceptible to active alluvial fan flooding now. Also, flooding may be occurring on inactive areas of the alluvial fan.

In most of the United States, it is possible to identify parts of alluvial fans that were actively constructed during Pleistocene time (about 2 million to 10,000 years ago) and parts that have been active (i.e., flooded) in the Holocene (the past 10,000 years). The reason that this broad distinction generally is possible is that the two time periods were identified and defined on the basis of climatic conditions. The Holocene epoch is a time of interglacial warm conditions, whereas the Pleistocene epoch was marked by repeated full glacial, cool conditions alternating with warm interglacials like that of the Holocene. As a result of these climatic differences, flooding and sedimentation occurred at different rates and magnitudes during the Pleistocene and Holocene epochs. The impacts of these climatic changes on alluvial fan formation can be inferred from geologic, geomorphic, and soil data.

A change in the rate of tectonic uplift along a mountain front can also result in abandonment of parts of alluvial fans. For example, a decrease in the rate of uplift at a mountain front relative to the alluvial fan could result in stream channel downcutting at the mountain front/alluvial fan apex over a period of time. As a consequence, the upper part of the fan would become entrenched, and the active area of deposition would shift downfan.

#### 4A Identification of Active Areas

The term *active* refers to that portion of an alluvial fan where deposition, erosion, and unstable flow paths are possible. If flooding and deposition have occurred on a part of an alluvial fan in the past 100 years, clearly that part of the fan can be considered to be active. This conclusion may be supported by historic records, photographs, time-sequence aerial photography, and engineering and geomorphic information. If flooding and deposition have occurred on a part of an alluvial fan in the past 1,000 years, for example, that part of the fan may be subject to future alluvial fan flooding. This conclusion may only be supported by geomorphic information, however. It becomes more difficult to determine whether or not a part of the fan that has not experienced sedimentation for more than 1,000 years really is active, that is, that there is some likelihood of flooding and sedimentation under the present climate.

Because there is no clear analytical technique for making such projections of the estimates of the spatial extent of inundation, Stage 2 analysis involves systematically applied judgement and the combination of hydraulic computations and qualitative interpretations of geologic evidence concerning the recent history and probable future evolution of channel forms, as well as flooding and sedimentation processes. It must be kept in mind, however, that the intent of Stage 2 is to narrow the area of concern with regard to active deposition, erosion, and unstable flow paths over a period of time generally exceeding 100 years. Therefore, the combination of engineering and geomorphic analyses, both qualitative and quantitative, provide an indication of the approximate spatial extent of possible inundation over a relatively long time period (i.e., several thousand years). Stage 3 will determine the floodplain limits associated with the 100-year flood.

#### 4B Identification of Inactive Areas

For a given area of the alluvial fan, if the situations described in Section 4A do not exist, then the area is considered inactive and not subject to the deposition, erosion, and unstable flow path flooding that builds alluvial fans. Inactive areas may be subject to flooding though, most notably within entrenched channels.

Evidence of inactive areas may include armoring along the margin of the area bordering active areas, older vegetation, and the lack of change in flow paths viewed over the aerial photographic record. This evidence, though, does not preclude the area from possibly being classified as an active area as a result of changes in, or conditions within, adjacent active areas.

Older alluvial fan surfaces are considered active if any of the following are true:

- The recently active sedimentation zone is migrating into the older surface
- The elevation difference between the recently active sedimentation zone and the older surface is small relative to flood, deposition, and debris depths conceivable in the current regime of climate, hydrology, or land use in the source area
- Upstream of the site, there is an opportunity for avulsions that could lead channels or sheetfloods across the older surface

#### 4C Identification Process

Once a relative time period is chosen (e.g., <1,000 years) to help evaluate the active areas of an alluvial fan, the analyst must determine relative ages for the morphologic features on the alluvial fan. Indicators of land surface age for Stage 2 are based on relative age indicators. Absolute (numerical) dating techniques, such as radiocarbon dating, are generally beyond the scope of many studies.

Detailed soils and surficial geological maps, when available, provide useful delineation of soil types and surface ages. An examination of the historical record of flooding and deposition can enhance the information gained from the soils map. Aerial photographs from different years can be used to identify sites of deposition. Field examination of morphologic features on the alluvial fan surface, particularly noting relicts of human activity (recent or archaeological) or weathering characteristics such as desert pavement, rock varnish, B-horizon development in the soil profile, calcic-horizon development, and pitting and rilling of clasts may also provide relative age information.

Density and type of vegetation can provide useful clues to the age of an alluvial fan surface area. Texture and composition of the sediment, in addition to the water-holding capacity, relate to the surface vegetation. Fresh alluvial deposits contain little organic carbon or clay and, as a result, do not promote vegetation growth. Vegetation is limited on older surfaces because they receive only direct rain, are often erosional, and can be less fertile (carbonate soil cropping out at the surface, for example). Intermediate-age surfaces (middle to late Holocene) contain the most dense and diverse vegetation.

Use and interpretation of diagnostic vegetation, like the use and interpretation of desert pavement, varnish, or soil properties, are generally specific to the individual fan in question. Within a geographic region, however, surface characteristics of alluvial fans may be correlated from one fan to another.

Detailed topographic maps (i.e., 2-foot contour interval) are instrumental in identifying potential avulsion areas and in delineating the boundaries of areas subject to different flood, deposition and debris flow depths. Topographic maps also can be used to identify older alluvial surfaces within active zones that are not subject to flooding.

Areas of question noted during the analysis of maps and aerial photographs should be closely examined during the field inspection. All flow paths should be walked to verify the active and inactive areas that have been delineated. Stage 2 is complete when the analyst has defined and delineated all active and inactive areas of deposition, erosion, and unstable flow path flooding, as well as adjacent inactive fan areas. All inactive areas with stable flow path flooding and all active areas may be considered floodprone, but through Stage 2, the degree to which these areas are floodprone is not yet known. **The delineated floodprone areas of Stage 2 should approximate the largest possible extent of the 100-year flood.**

#### 4D Types of Alluvial Fan Flooding

Several types of flooding occur on alluvial fans. The most common ones are described in this section.

##### 4D (1) Flooding Along Stable Channels

A deeply entrenched channel or network of channels often is subject to inactive alluvial fan flooding. This type of flooding usually occurs within distributary flow systems that were formed during climatic or tectonic conditions different from the present. This flooding can occur at the head of the alluvial fan but become unstable downstream. Conversely, unstable channels can become stable in the downstream direction because of headcutting into the toe as a result of changing hydraulic conditions downstream from the toe. Human intervention, directly by channel modification or indirectly by land-use change, can create stable channels.

##### 4D (2) Sheetflow

Some parts of alluvial fans are characterized by sheetflow, which is the flow of water as broad sheets that are completely unconfined by any channel boundaries. Sheetflow might occur where flow departs from a confined channel and no new channel is formed. It might also occur where several shallow, distributary channels join together near the toe of a fan and the gradient of the fan is so low that the flows merge into a broad sheet. Because such sheetflows can carry high concentrations of sediment in shallow water and follow unpredictable flow paths, they are classified as active alluvial fan flooding. Sheetflow generally occurs on downslope parts of fans, where channel depths are low

and the boundaries of channels become indiscernible. They are also more common at distal locations because of the likelihood of fine-grained sediments and shallow groundwater; during prolonged rainfall, the ground can become saturated, resulting in extensive sheetflooding as runoff arrives from upslope. Fine-grained sediments can aggravate the likelihood of sheetflow because some clay minerals swell when wet, forming an impermeable surface at the beginning of a rainstorm.

#### 4D (3) Debris Flow

Some parts of alluvial fans are characterized by debris flows, flows with a very high concentration of sediment in relation to water. Debris flows pose hazards that are very different from those of sheetflows or water flows in channels. Identifying those parts of alluvial fans where debris flow deposition might occur requires the examination of deposits from past flows. Debris flow deposits can be distinguished from fluvial deposits by differences in morphology, depositional relief, stratigraphy, and clast fabric. Exposures in channel banks can be examined and can be supplemented with shallow trenches in different deposits.

#### 4D (4) Unstable Flow Path Flooding

Active areas of an alluvial fan will generally be characterized by unstable and uncertain flow path flooding. This type of flooding usually creates a single channel just below the apex, but splits into multiple channels as it proceeds down the alluvial fan. These channels are subject to deposition and bank or bottom erosion that cause channel migration, avulsion, and the formation of new channels. Areas subject to this type of flooding are characterized by shallow, braided or distributary, sand-to gravel-bed channels. Recently formed channels may have less established vegetation, such as trees, than older channels in the same general area.

### 5 STAGE 3: DEFINING THE 100-YEAR FLOOD WITHIN THE DEFINED AREAS

The National Flood Insurance Program (NFIP) uses the 100-year flood, the flood having a 1-percent chance of being exceeded in any given year, to delineate Special Flood Hazard Areas (SFHA). Stages 1 and 2 describe methods of identifying alluvial fan landforms and areas of active and inactive deposition, erosion, and unstable flow path flooding. Stage 3 determines the severity and delineates the extent of the 100-year flood within any floodprone area identified in Stage 2.

The broad spectrum of alluvial fan landforms and types of flooding illustrates, as previously discussed, the futility of developing a "cookbook" method to apply to all fans in all geographic areas. The analysis of the flood hazards on alluvial fans therefore requires a flexible approach that is based on site-specific evaluations. Several methods for quantifying the 100-year flood are presented in the following sections and are summarized in Table 1. Not all methods are appropriate for all situations. The assumptions and limitations of each should be carefully considered in deciding which methods to apply to particular areas of an alluvial fan. Example maps resulting from the application of some of the available methods are included in Appendix 1.

**Table 1.** Methods for defining the 100-year flood within areas defined in Stage 2.

METHOD	ASSUMPTIONS	LIMITATIONS	RECOMMENDED APPLICATIONS	EXAMPLE MAP No.
Risk-Based Analysis	Refer to <i>Guidelines for Risk and Uncertainty Analysis in Water Resources Planning</i> (U.S. Army Corps of Engineers, 1992).	_____	_____	_____
FAN Program	flooding in rectangular channel; critical depth, erosion of rectangular channel banks until the change in width per the change in depth equals $-200$ ; the probability density function of a discharge occurring at the apex is log-Pearson Type III; the frequency of flood events for various recurrence intervals, i.e., 2-year through 500-year, can be adequately defined; equal probability along contour arcs (random flow paths); (also provides for multiple channels at normal depth, assuming total width is 3.8 times the single-channel width)	fluvial (as opposed to debris flow) formed fan, unstable flow paths	highly active conical fans	1
Sheetflow	broad, unconfined, shallow flooding	not for use in areas of undulating terrain	shallow flooding across uniformly sloping surfaces	9
Hydraulic Analytical Methods	stable flow path, uncertainty is to a degree that may be disregarded	not for use with active alluvial fan flooding	entrenched stable channel networks, constructed channels, urbanized areas	2 and 8
Geomorphic Data, Post-Flood Hazard Verification, and Historical Information	relies primarily on qualitative information, post-flood verification, historical data, and interpretive studies	approximate method	alluvial fans with little or no urbanization	3 and 4
Composite Methods	as identified in the sections referring to the methods being applied	must integrate multiple methods into one result	floodprone areas that contain unique physical features in some locations or have areas varying in levels of erosion and migration activity	5, 6, and 7

## 5A Risk-Based Analysis

The U.S Army Corps of Engineers has provided a framework that may be used to analyze flood hazards on alluvial fans using the principles of risk-based analysis in *Guidelines for Risk and Uncertainty Analysis in Water Resources Planning* (1992). This method uses the total probability equation that will be discussed in detail in Section 5B. The degree of uncertainty associated with a prediction of a given flood scenario is assessed by bringing to bear evidence derived from geomorphologic and other studies. This method tracks the effects of the error associated with a calculation to provide a confidence band in ensuing predictions of flood-hazard severity.

## 5B FAN Program

**Assumptions:** flooding in rectangular channel; critical depth; erosion of rectangular channel banks until the change in width per the change in depth equals  $-200$ ; the probability density function of a discharge occurring at the apex is log-Pearson Type III; the frequency of flood events for various recurrence intervals, i.e., 2-year through 500-year, can be adequately defined, equal probability along contour arcs (random flow paths); (also provides for multiple channels at normal depth, assuming total width is 3.8 times the single channel width)

**Limitations:** fluvial (as opposed to debris flow) formed fan, unstable flow paths

**Recommended Applications:** highly active conical fans

The FAN computer program provides one method of analyzing the flood hazards on alluvial fans. The methodology used by the FAN program defines the risk of inundation at any particular location by applying the definition of the base flood through the theorem of total probability. The methodology itself is broader than the use within the FAN program. Let  $\mathbf{H}$  be a random variable denoting the occurrence of flooding at a particular location. That is:

$$\mathbf{H} = \begin{cases} 1 & \text{if the location is inundated} \\ 0 & \text{if the location is not inundated} \end{cases}$$



Then the probability of the location being inundated by a flood above a given magnitude, say  $q_0$ , is:

$$P[H = 1 \cap Q > q_0] = \int_{q_0}^{\infty} P_{H|Q}(1, q) f_Q(q) dq \quad (1)$$

where  $Q$  is a random variable denoting the magnitude of the flood;  $P_{H|Q}(1, q)$  is the conditional probability that the location will be inundated, given that a flood of magnitude  $q$  is occurring; and  $f_Q(q)$  is the probability density function (PDF) defining the likelihood that a flood of a magnitude between  $q$  and  $q+dq$  will occur in any given year.

Equation (1) only defines whether a location is within an SFHA and does so in terms of the parameter  $q_0$ . For riverine flooding  $q_0$  represents an elevation, and  $P_{H|Q}(1, q)$  is 1 if the elevation of the location is less than  $q_0$  and 0 if it is greater than  $q_0$ . At a given location (point on a cross section), there is a one-to-one relationship between the discharge being conveyed by the stream and the elevation of the surface of the floodwater (i.e., the rating curve for the cross section). For riverine flooding, solving Equation (1) reduces to defining the discharge-frequency relationship for the reach of the stream under consideration (hence the notation  $q_0$  to denote magnitude).

As in riverine analysis, the PDF describing frequency of the magnitude of flooding for alluvial fan flooding is taken to be the discharge-frequency relationship of the contributing drainage basin. Unlike riverine analysis,  $P_{H|Q}(1, q)$  does not simplify to 0 or 1, because there is uncertainty in the flow path. The FAN program provides energy depths and velocities relating to discharge for use in defining the flood-hazard.

The FAN program uses the assumptions outlined below. Where noted with an \* below, these assumptions may be adjusted for observed field conditions; however, the FAN program does not readily accommodate these adjustments.

This method's assumptions are as follows. Floods on alluvial fans are at liberty to expend energy to create the most efficient path to convey the water and sediment load. That path is shallow and approximately rectangular in cross section. Energy is expended through sediment movement until the minimum energy possible is reached. In short, the reasoning is that a flood flows at critical depth and is confined to a rectangular path. The flow path would not widen indefinitely but, instead, would reach a point where it would stabilize. From empirical data, of which there is very little, that point is taken to be where the rate of change of topwidth per change in depth ( $dW/dd$ ) is  $-200$  (\* may be adjusted). The reasoning leads to the one-to-one relationships:

$$d = 0.106 q^{1/5} \quad (2)$$

$$v = 1.506 q^{1/5} \quad (3)$$

where  $d$  is the specific energy in feet,  $v$  is the velocity in feet per second, and  $q$  is the discharge in cubic feet per second (cfs).

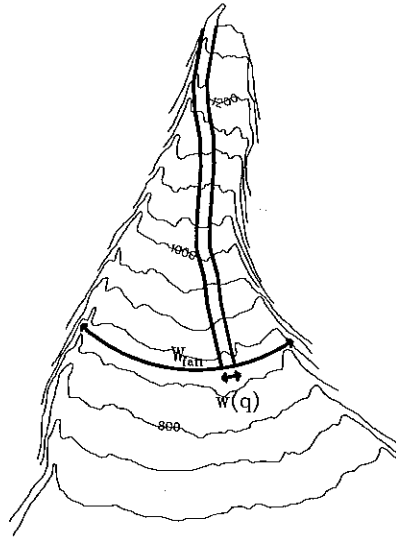
The conditional probability in Equation (1) accounts for the uncertainty in the path of a flood with a given magnitude. Even if the path of the flood can be predicted with reasonable certainty, the magnitude of the flood at a particular location may not be so certain, as deposition or scour in shallow channels may greatly affect the direction of flow at channel splits. Many alluvial fans exhibit a channel network. The capacities of the individual channels as well as the capacities of the networks in aggregate vary from almost negligible to more than the 100-year flood discharge. The treatment of the uncertainty in a given discharge being exceeded at a particular location given the discharge somewhere else [ $P_{H|Q}(1,q)$ ] varies.

The least complex treatment (used in the FAN program) follows from the reasoning that the topography of the area is the result of deposition that occurred during the past. If that process continues, then, over the long term, the probability of every point on a contour being inundated is the same. That is,  $P_{H|Q}(1,q)$  is uniformly distributed and, for a given point, is approximately the width of the flood path divided by the width (the "contour width") of the area subject to flooding at the elevation of that point (\* may be adjusted). This method assumes that all areas of the alluvial fan are subject to flooding and that there is a fixed relationship between flooding depth and discharge. In general, these assumptions apply when there is absolute uncertainty regarding how floods will occur. Thus, for the FAN program, under the simple conditions,

$$P_{H|Q}(1,q) = \frac{w(q)}{W_{fan}} = \frac{9.408 q^{2/5}}{W_{fan}} \quad (4)$$

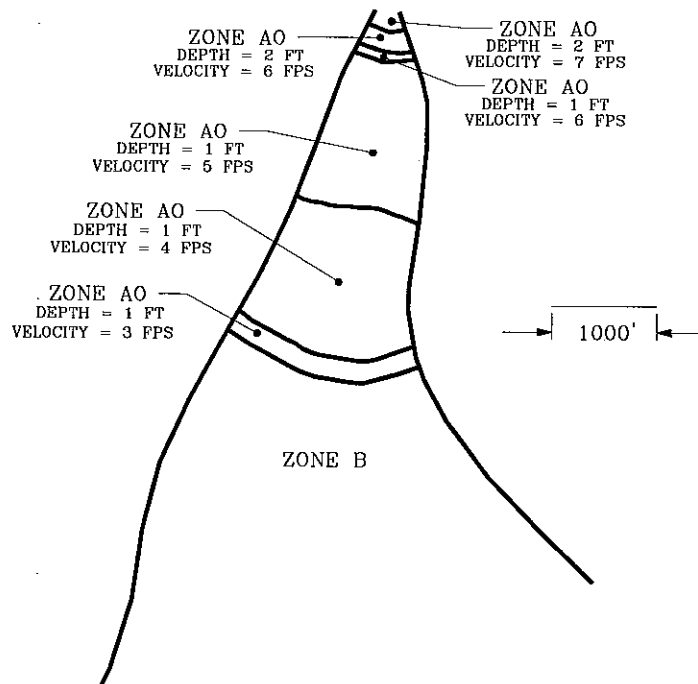
where  $w(q)$  is the width of the path conveying  $q$  cfs and  $W_{fan}$  is the contour width seen in Figure 3. The resulting flood insurance rate zones are depicted in Figure 4 for this example. The functional form of Equation (4) is a consequence of the reasoning leading to Equations (2) and (3) and is presented here for demonstrative purposes, not as the only form possible.

The FAN program provides for the situation where flows are near normal depth in multiple channels. Program output includes results for this situation in addition to the single channel at critical depth. The results are then applied based on observed field conditions. Please refer to *FAN An Alluvial Fan Flooding Computer Program User's Manual and Program Disk* for more information.



**Figure 3**

Fan and Single-Channel Widths



**Figure 4**

Flood Insurance Rate Zones  
Respective to Figure 3

## 5C Sheetflow

Assumptions: broad, unconfined, shallow flooding

Limitations: not for use in areas of undulating terrain

Recommended Applications: shallow flooding across uniformly sloping surfaces

Please refer to Appendix 2 of FEMA 37, *Flood Insurance Study Guidelines and Specifications for Study Contractors*, for guidelines on the analysis and mapping of shallow flooding. Although it is stated in Appendix 2 that the procedures are not to be used for alluvial fan flooding, the approach established by this document enables the use of those methods described in Appendix 2, except for highly active conical fans that are studied using the FAN program.

## 5D Hydraulic Analytical Methods

Assumptions: stable flow path, uncertainty is to a degree that may be disregarded

Limitations: not for use with active alluvial fan flooding

Recommended Applications: entrenched stable channels and channel networks, constructed channels, urbanized areas

Inactive, yet floodprone areas should use “riverine” hydraulic analytical methods. Where flow paths are stable and flow is reasonably confined, standard hydraulic engineering methods such as backwater computations may be used to define the elevation (or depth), velocity and extent of the 100-year flood. Hydraulic methods may also be used for stable channel networks when applicable. For example, relict alluvial fans or inactive fans with stable channels, as determined by a geomorphic analysis, may be subject to flow splits throughout the distributary system that exists. Hydraulic modeling can generally handle split-flow analyses through stream junctions of this type. In general, for stable channels on alluvial fans, physically based methods that consider site processes and hydraulics, such as channel geometry, grade and roughness, and channel bank and bed material are preferred.

Where precise computations of water-surface profiles using energy and momentum based methods may not be feasible based on the scope of the study, the use of normal depth calculations for definition of approximate 100-year flood boundaries may be warranted.

Chapter 5 of FEMA 37 provides guidelines for hydraulic analytical methods. Within Section D of Chapter 5, several methods applicable to conditions found on alluvial fans are described. These methods include two-dimensional water-surface models, modeling techniques of streams with supercritical flow regimes, and split-flow analysis.

Two-dimensional models may be appropriate for determining flood hazards on an alluvial fan. Different two-dimensional models may be particularly useful in the analysis and modeling of some or all of the following situations: flows that contain a high amount of sediment, unconfined flows, splitflows, mud/debris flows, and complex urban flooding. For use in defining flood hazards for the NFIP, all hydraulic models must meet the conditions of Section 65.6 (a) (6) of the Code of Federal Regulations.

One-dimensional sediment transport models or the methods described in Section 6A are also useful for the analysis of conditions on alluvial fans.

#### 5E Geomorphic Data, Post-Flood Hazard Verification, and Historical Information

Assumptions: relies primarily on qualitative information, post-flood verification, historical data, and interpretive studies

Limitations: approximate method

Recommended Applications: alluvial fans with little or no urbanization

The geomorphic approach is for active alluvial fans where deposition, erosion, and unstable flow paths are possible. Traditional engineering methods as described in Section 5D generally are inappropriate for areas with these hydraulic characteristics. Probabilistic methods as described in Section 5B and contained in the FAN computer program, also contain inherent limiting assumptions that may not adequately represent field conditions and may not be applicable to many active alluvial fans.

In some situations the information collected during Stage 2 (identification of active and inactive areas) may be used to delineate an approximate floodplain on an alluvial fan. In situations where geomorphic field investigations, coupled with historical documentation, and documentation of hydrologic and hydraulic characteristics of flood event(s) (post-flood hazard verification) is available, an approximate flood-hazard delineation is possible.

By combining quantitative data on an actual flood event, historical information and photographs of other flood events, time-sequence aerial photography documenting recent activity or inactivity, and field investigation of the morphologic characteristics and relative ages of the fan, an approximate (Zone A) flood-hazard map may be warranted.

For many alluvial fans, the various flood indicators (Stage 2 information) provide limited or partial information. Because the flood assessment of active alluvial fans is more uncertain than more traditional flood assessment, all assumptions and limitations should be well documented and considered in the overall evaluation.

## 5F Composite Methods

Assumptions: as identified in the sections referring to the methods being applied

Limitations: must integrate multiple methods into one result

Recommended Applications: floodprone areas that contain unique physical features in some locations or have areas varying in levels of erosion and migration activity

Site-specific conditions on alluvial fans may lend themselves to the use of multiple or combined methods previously described for the determination of flood hazards. For example, in areas that contain manmade conveyance channels or deeply entrenched stable channels, one can combine the results of traditional hydraulic computer programs with methods for analyzing active areas. Coordination with the Regional PO and Headquarters is required in developing a study plan.

## 6 ADDITIONAL INFORMATION

### 6A Sediment Transport

The following section regarding sediment transport is included as supplemental information for the analysis of alluvial fans. Sediment transport analyses are generally required for alluvial fan studies and revisions.

The boundaries of the stream channel are usually soil material with a given resistance to erosion. Bed material can range from large boulders to very fine clay particles. In general terms, sediment can be cohesive, including clay, silt, and mixtures, or noncohesive, including sand, gravel, and larger particles. Transport of noncohesive materials is strongly dependent on particle size. The entire size distribution of the material is needed to ascertain its erodibility. The bond between particles in cohesive soil dictates its resistance to erosion and is far more important than size distribution. However, size becomes important once the material has been eroded and is transported by the flow.

An important sediment transport process is the development of an armor layer in beds containing gravel and cobbles. Water flowing over the mixture of sand and coarser material lifts the smaller grains and leaves an upper layer or armor of large particles. This armor protects the underlying sediment from further erosion and controls the subsequent behavior of sediment transport. A flood event of large magnitude can disturb the protective layer, and the armoring process will start again.

Sediment transport exerts substantial control over morphology and channel geometric configuration. An indicator of this influence is the sediment transport rate, which is the rate at which material moves in the stream as quantified in units of weight per unit time. The transport rate is closely dependent on the water discharge. There are two classification methods to describe the sediment load in a stream. The first one divides the load into bed load and suspended load. The *bed load* is that portion of the sediment that moves along the bottom by sliding, rolling, or saltation. The

*suspended load* is comprised of all of the material carried in suspension. The second system of classification divides the sediment load into wash load and bed-material load. The *wash load* is made of very fine materials, clay and silt, rarely found in the bed. The wash load does not depend on the carrying capacity of the stream but on the amount supplied by the watershed. The *bed-material load* is comprised of all of the material found in the bed. Some of it will move very close to the bottom, but some may be found in suspension.

Quantification of sediment transport is fraught with uncertainty because of the complexity of the phenomenon and its inherent spatial and temporal variability. Existing mathematical representations have relied heavily on experimental results. The available sediment transport formulas have been grouped according to the approach used to derive them. Three major approaches have been used: shear stress, power, and parametric. Formulas can also be grouped according to the component of the total load they attempt to quantify: bed load, suspended load, or bed-material load. Table 2 summarizes the more commonly used formulas; however, it is not intended to be a complete listing.