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Geologic Insights into Flood Hazards in Piedmont Areas of Arizona

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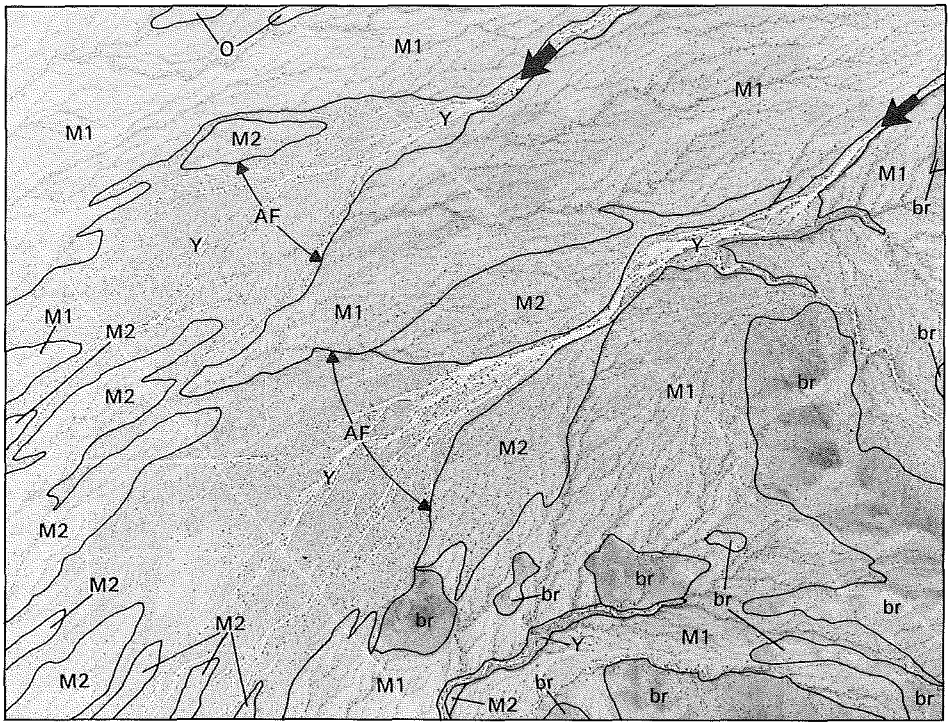

*Figure 1. Aerial photograph of the western piedmont of the White Tank Mountains, which shows alluvial surfaces of different ages. The approximate ages of the deposits in thousands of years (ka) are as follows: Y, younger than 10 ka; M2, 10 to 150 ka; M1, 150 to 800 ka; O, older than 800 ka (br = bedrock). The arrows point to relatively large drainages that head in the mountains and flow from right to left across the piedmont. The areas of recent alluvial-fan activity (labeled AF) along these drainages are identified by extensive young deposits (Y) and **distributary channel patterns**, which consist of streams that branch and flow out of a larger stream. Old, inactive alluvial fans (units M1, M2, and O) are characterized by a lighter color and **tributary drainage patterns**, which consist of streams that flow into a larger stream. These old fans compose much of the piedmont and have been isolated from floods associated with the larger drainages for more than 10,000 years.*

Proper management of flood hazards in piedmont areas of Arizona is becoming increasingly important as the State's population grows and urban areas expand. In the Basin and Range Province of the western United States, **piedmonts** (literally, "the foot of the mountains") are the low-relief, gently sloping plains between the mountain ranges and the streams or playas that occupy the lowest portions of the valleys. Much of southern, central, and western Arizona is composed of piedmonts, and they comprise most of the developable land near the rapidly expanding population centers of the State.

Viewed from above, piedmonts of Arizona are complex mosaics composed of alluvial fans and stream terraces of different ages that record the recent geologic history of an area. **Alluvial fans** are generally cone-shaped depositional landforms that emanate from a discrete source and increase in width downslope; adjacent fan surfaces may merge downslope to form a continuous **alluvial apron**. Alluvial fans represent periods of net aggradation, when large amounts of sediment were removed from mountain areas and deposited on adjacent piedmonts. The Quaternary Period (roughly the past 2 million years) has been characterized by repeated changes in global climate. Periods of alluvial-fan deposition in Arizona were probably due to climate changes that increased the amount of sediment supplied to streams from mountain slopes and possibly decreased the capacity of streams to transport sediment across piedmonts (Bull, 1991). **Stream terraces** are steplike landforms that are typically inset below adjacent fan surfaces. They represent former floors of stream valleys that were abandoned as the streams downcut even further. Terraces thus exist in areas where the long-term trend has been for streams to entrench themselves into older deposits.

Piedmont areas subject to active alluvial-fan flooding are of particular concern from a floodplain-management perspective. Piedmonts in Arizona are typically drained by a few relatively large streams that head in adjacent mountains and many smaller streams that head on the piedmont (Figure 1). Active alluvial fans along the larger streams may be subject to widespread inundation, local high-velocity flow, and drastic changes in channel positions during floods because there is little topographic relief to confine the floodwaters. If development on piedmonts occurs without regard to the distribution of active alluvial fans, lives and

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property may be put at risk. It is preferable and less expensive to mitigate these flood hazards before an area is developed than to deal with them afterwards, when floodwaters are lapping at doorsteps.

The long history of stream behavior and flooding recorded in the geology and geomorphology of piedmonts provides an invaluable perspective on floodplain-management issues. Floods leave physical evidence of their occurrence in the form of alluvial deposits. Characteristics of large floods that have occurred during the past few years may be reconstructed in some detail because evidence of their impact on the landscape is fresh. Over hundreds or thousands of years, the impact of individual floods is more difficult to resolve, but the cumulative effects of many floods are recorded in the geology and geomorphology of a piedmont. Geological studies can address several key issues: (1) How large are the extreme floods on particular drainages?; (2) Which portions of piedmonts are prone to flooding, especially alluvial-fan flooding?; (3) Do the positions of channels on alluvial fans typically change during floods?; and (4) What are the depths and velocities of floodwaters during alluvial-fan floods?

The Arizona Geological Survey (AZGS) is engaged in cooperative efforts with local floodplain-management agencies, the University of Arizona, and the Arizona Department of Water Resources. These studies combine geologic investigations with more traditional hydrologic analyses to delineate flood-prone areas more accurately and to understand better the flooding processes on piedmonts in Arizona.

FLOODPLAIN-MANAGEMENT ISSUES

The principal objective of floodplain-management agencies is to prevent humans and their property from being exposed to undue risks from flooding. These agencies must also maintain credibility with the persons whom they regulate and include in their purview only the areas that are truly at risk of being flooded. Concepts of floodplain management are firmly rooted in the disciplines of hydrology and civil engineering; geologic information typically has not been used in flood-hazard evaluations. Because flooding in piedmont areas may be quite complex, however, standard hydrologic or engineering methods for accurately assessing and managing flood hazards are of questionable value. Critical technical issues, such as determining the extent and character of flooding on piedmonts, cannot be adequately addressed without integrating hydrologic methods and geologic investigations.

Streams that cross piedmont areas in Arizona have several characteristics that make them particularly hazardous to life and property. As is typical in the desert, piedmont streams flow infrequently, lending a false sense of security to persons who live near washes or on active alluvial fans. Large piedmont floods are usually generated by intense precipitation in adjacent mountains. Piedmont dwellings may thus become flooded even if it has rained very little in those areas. During alluvial-fan flooding, floodwaters are free to spread out and inundate wide areas, and drastic changes in channel patterns may occur. If waters take a new path during a flood, a channel that seemed insignificant can grow in size and capacity. Human alterations to natural stream systems on piedmonts may have a profound impact on the course of floodwaters; ill-advised obstruction or diversion of natural channels may cause adjacent areas to receive the brunt of floodwaters. For all of these reasons, local, State, and Federal floodplain-management officials in the United States have come to realize the importance of adequately defining and managing flood hazards in piedmont areas.

Traditional methods of defining regulatory floodplains typically involve four steps: (1) making the assumption that channel beds and banks are fairly stable; (2) estimating the size of the flood that has a 0.01 probability of occurring in any given year on a particular stream (the **100-year flood**); (3) routing the 100-year flood downstream using some preferred hydrologic model; and (4) determining the area that will be flooded and how deep the floodwaters will be at any flooded locality. These procedures, however, are inappropriate for defining areas that are prone to alluvial-fan flooding. As outlined above, channels on alluvial fans may or may not be stable during large floods. In addition, floodwaters may spread so widely that accurate modeling of their extent and depth is difficult. Furthermore, the available data for estimating the sizes of 100-year floods on drainages in Arizona are modest at best; different methods yield dramatically different sizes (e.g., House, 1991).

Hydrologists and engineers have proposed several models to simulate alluvial-fan flooding. The most widely used model is one that is mandated by the Federal Emergency Management Agency (FEMA) to set flood-insurance rates. This FEMA alluvial-fan methodology (AFM) is based on several simplifying assumptions about flow behavior during alluvial-fan floods: (1) floodwaters affect only part of an alluvial fan during any one flood; (2) floodwaters are conveyed in one or more channels of a specific and predictable depth and width; and (3) these channels can form anywhere on the alluvial fan at the beginning of or during a flood (Dawdy, 1979; FEMA, 1985). The AFM uses the width of the channels that are supposed to form during a flood and the total width of the alluvial fan to determine 100-

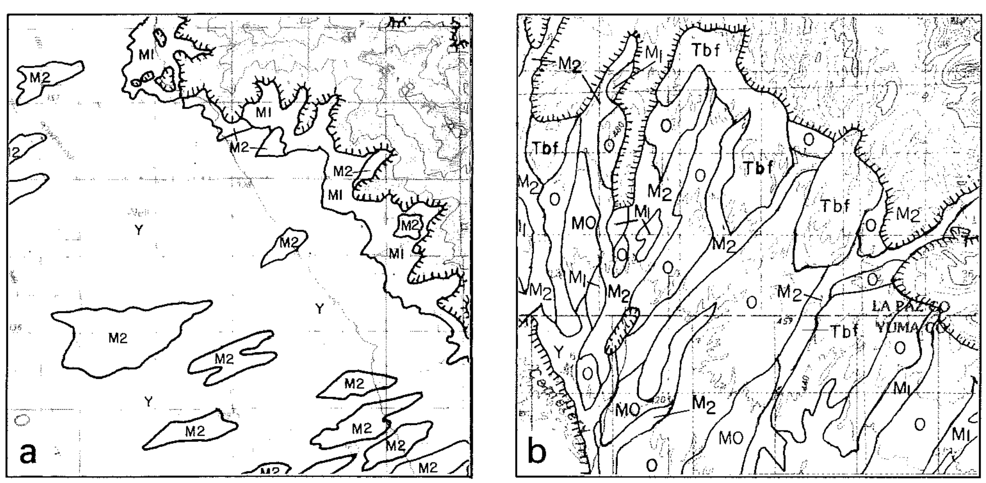
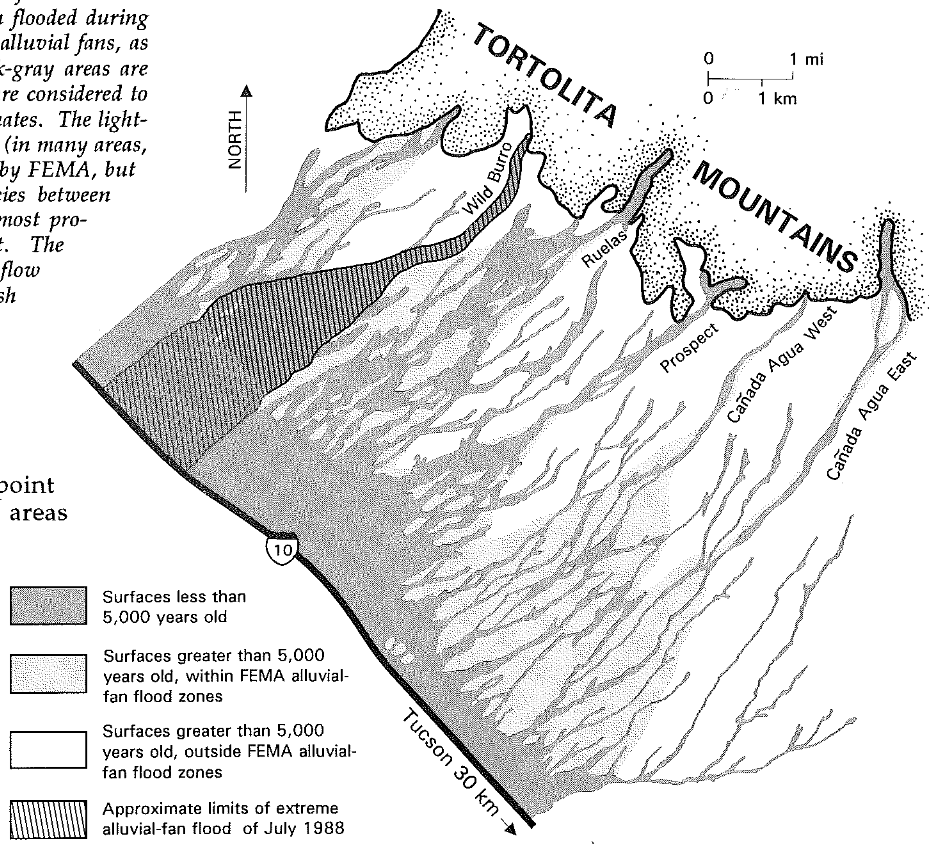


Figure 2. Surficial geologic maps that illustrate differences in the extent of young deposits and alluvial-fan flooding hazards on two piedmonts in Arizona. The map-unit designations are the same as those used in Figure 1; additional map units are as follows: MO, 500 to 1,000 ka alluvial fans; and Tbf, dissected basin-fill deposits older than 1,000 ka. (a) The southwestern piedmont of the Sierra Estrella Mountains in central Arizona is mostly covered with young alluvial deposits less than 10,000 years old (map unit Y), which indicates that alluvial-fan flooding is an important process on this piedmont (from Demsey, 1989). (b) The southwestern piedmont of the Eagle Tail Mountains in southwestern Arizona is almost entirely composed of alluvial fans and terraces more than 10,000 years old (map units M2, M1, O, and Tbf). No active alluvial fans exist on this piedmont (from Demsey, 1990).

Figure 3. Generalized map of the southern piedmont of the Tortolita Mountains. This map contrasts areas that have been flooded during the past few thousand years with the limits of active alluvial fans, as defined by the AFM mandated by FEMA. The dark-gray areas are surfaces that are younger than 5,000 years and that are considered to be flood prone based on geologic data and FEMA estimates. The light-gray areas are surfaces that are older than 5,000 years (in many areas, much older) and that are considered to be flood prone by FEMA, but have not been flooded for a long time. Discrepancies between geologic data and the FEMA alluvial-fan areas are most pronounced in the southeastern portion of the piedmont. The approximate area between the outermost threads of flow during the 1988 alluvial-fan flood on Wild Burro Wash is shown by the hachured pattern. The lighter hachures indicate areas that were probably affected by the flood but were not mapped in detail. The area that was affected by this flood coincides very closely with the flood-prone areas determined from geologic data.



year flood-flow depths and velocities at any point on the fan. FEMA regulations include all areas subject to inundation of 6 inches or more during the 100-year flood in the 100-year floodplain. On piedmonts in Arizona, the extent of the 100-year floodplain has been defined using the assumptions of the AFM and topographic information (Fuller, 1990).

Application of the AFM in Arizona has generated a storm of controversy, however, because it has designated broad portions of piedmonts as potential sites of inundation by the 100-year flood. Three questions highlight the technical aspects of this controversy: (1) Has the AFM been applied to areas that are actually subject to alluvial-fan flooding?; (2) Are the fundamental assumptions of the AFM concerning the behavior of floodwaters on alluvial fans realistic?; and (3) Are the sizes of the 100-year floods used in the AFM realistic? Geologic investigations of piedmont areas can provide an independent assessment of each of these questions.

GEOLOGY AND GEOMORPHOLOGY OF PIEDMONTS IN ARIZONA

The physical characteristics of alluvial surfaces (alluvial fans and stream terraces) on piedmonts may be used to differentiate them by age. Alluvial surfaces are typically deposited by the larger drainages that cross a piedmont; thus, the initial surface features are shaped by large-scale depositional processes. When surfaces are isolated from further deposition or reworking by large streams, they are gradually modified over thousands of years by other processes, which operate very slowly and on a smaller scale. These modifying processes include (1) small-scale erosion and deposition that smooth the original surface topography; (2) **bioturbation**, the churning of sediments by organisms, which obliterates depositional structures; (3) development of soils, primarily through accumulation of silt, clay, and calcium carbonate; (4) development of surficial gravel pavements (desert pavements) above zones of accumulated silt and clay; (5) accumulation of rock varnish on surface gravel; (6) development of tributary **dendritic** (treelike) stream networks on surfaces; and (7) entrenchment of these stream networks below original depositional surfaces and subsequent surface dissection.

Alluvial surfaces of similar age have a characteristic appearance because they have undergone similar postdepositional modifications, and they are distinctly different from both younger and older surfaces. Young (less than a few thousand years old) alluvial-fan surfaces, for example, still retain clear evidence of the original depositional topography, such as **bars** (ridges) of coarse deposits, **swales** (troughlike depressions) where low flows passed between bars, and **distributary channel networks** (networks that branch downstream), which are characteristic of active alluvial fans (Figure 1). Young fan surfaces also show minimal development of soil, desert pavement, and rock varnish and are basically undissected. Very old alluvial-fan surfaces, on the other hand, have not been subject to large-scale flooding for hundreds of thousands of years. These surfaces are characterized by well-developed soils with clay- and calcium-carbonate-rich horizons, well-developed dendritic stream networks that are entrenched several meters below the fan surface, and strongly developed varnish on surface rocks. Old alluvial-fan surfaces may also have smooth, closely packed desert pavements between the entrenched drainages. The ages of alluvial surfaces in the southwestern United States may be roughly estimated based on these surface characteristics, especially soil development (Gile and others, 1981; Bull, 1991).

The distribution, character, and relative abundance of surfaces of different ages clarify the long-term history of stream behavior on piedmonts, which, in turn, illuminates the nature and distribution of potential flood hazards. The broad spectrum of stream behavior on the piedmonts of Arizona is illustrated by variations in the areal extent of young deposits. Some piedmonts have extensive deposits of Holocene age (less than 10,000 years old), which indicates that the alluvial fans have been recently active; other piedmonts have few Holocene deposits (Figure 2). The extent of active alluvial fans depends on the rock types in the adjacent mountains and on the stability of base-level at the lower end of the piedmont. Many piedmonts in Arizona, however, show similar patterns of long-term erosion and deposition. The upper piedmont areas near the mountain ranges are dominated by abandoned alluvial fans of Pleistocene age (greater than 10,000 years old); active stream systems are

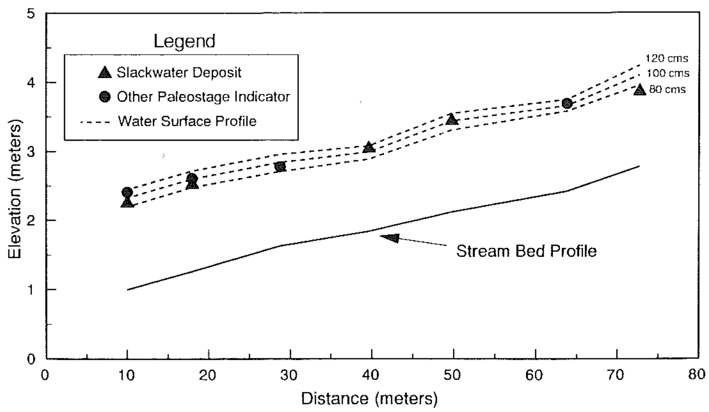


Figure 4. Illustration of the integration of geologic data with the HEC-2 hydrologic model to estimate the size of a paleoflood. Physical evidence of flooding is used to estimate the highest level of the flood. Water-surface profiles generated by the HEC-2 model using different discharge rates (in cubic meters per second, or cms) are compared with the high-water marks to estimate paleoflood discharges (from House, 1991).

entrenched well below these fans, and young deposits are restricted to channels and low terraces. Young deposits are commonly more extensive in the middle and lower portions of the piedmonts, which indicates that these are areas of unconfined distributary flow and alluvial-fan activity. The areas in Arizona that are subject to alluvial-fan flooding, therefore, are typically located in the middle and lower piedmont areas.

GEOLOGIC STUDIES OF PIEDMONT FLOOD HAZARDS IN ARIZONA

Geologic studies of piedmonts in southern and central Arizona have provided a variety of useful information on the character and extent of flood hazards. AZGS geologists have mapped piedmonts in detail to define flood-prone areas. Financial support for these efforts came from the Pima County Flood Control District, Flood Control District of Maricopa County, Arizona Department of Water Resources, and U.S. Geological Survey COGEOMAP program. Other investigations of the size and character of piedmont flooding have been undertaken cooperatively by the AZGS and University of Arizona Department of Geosciences, with financial support from the Pima County Flood Control District and National Science Foundation. The following paragraphs summarize the results of these investigations.

As discussed above, surficial geologic mapping delineates the extent of geologically young deposits, thus revealing the areas that have been subject to alluvial-fan flooding in the recent geologic past (during the past few thousand years). AZGS geologists have mapped in detail the surficial deposits in several areas of southern and central Arizona (McKittrick, 1988; Jackson, 1989, 1990a,b; Field and Pearthree, 1991b). They have also conducted specific mapping projects to evaluate flood hazards on the Tortolita piedmont north of Tucson (Pearthree and others, 1991) and on the piedmonts around the White Tank Mountains west of Phoenix (Field and Pearthree, 1991a).

The geologic assessment of flood-prone areas on the Tortolita piedmont is particularly interesting because this is one of the few areas in Arizona where the AFM has been used to generate flood-insurance-rate maps (FEMA, 1989). The implications of geologic investigations, therefore, may be directly compared with the alluvial-fan boundaries determined through the AFM. The geologic data and the alluvial fans depicted on the flood-insurance-rate maps, however, are substantially different. The flood-insurance-rate maps identify broad areas as being flood prone that have not been flooded for 5,000 years or more (Figure 3). The most serious discrepancies are in the southeastern portion of the piedmont, where young deposits associated with the larger drainages are very limited. The results of the AZGS geologic-mapping effort clearly imply that there are substantive problems with the AFM itself or with the manner in which it was applied to the Tortolita piedmont. Because of these problems, large portions of the piedmont were included in the 100-year floodplain that are not flood prone.

By integrating geologic evidence with hydrologic flow models, geologists can estimate the sizes of the largest floods that have occurred along streams during the past tens, hundreds, or thousands of years. Large floods leave behind evidence that may be used to estimate the height of the water during the flood. This evidence includes fine-grained sediment and floated debris deposited in areas of slow water flow, as well as scour lines where floodwaters eroded older sediments (Baker, 1987). **Paleofloods** are commonly reconstructed in bedrock canyons and upper piedmont areas, where the floods were confined by stable valley sides and the channel beds were relatively unscoured. To reconstruct these floods, researchers use the HEC-2 hydrologic flow model (Hydrologic Engineering Center, 1982) to generate water-surface profiles of different discharges. They then compare these profiles with the geologic evidence of the water-surface elevation above the channel bed (Figure 4). The most reasonable estimates of the maximum paleoflood discharge are those that best fit the geologic evidence.

House (1991) reconstructed paleoflood discharges on the five largest streams that cross the southern portion of the Tortolita piedmont. The purpose of these studies was to evaluate the validity of the 100-year discharges that were used in the AFM to determine flood hazards on the piedmont. The AFM 100-year discharges were determined through the use of a rainfall-runoff model based on idealized, intense rainfall events and estimates of water runoff in stream channels (Zeller, 1979). The results of this model, however, are suspect because of uncertainties in the size, duration, and intensity of rainfall events that generate large floods in these drainages, as well as uncertainties in the parameters used to obtain the runoff estimates. The geologic record of flooding in each of the Tortolita drainages is at least several hundred years long, yet the largest reconstructed paleofloods are substantially smaller than the 100-year-flood estimates obtained from the rainfall-runoff model. This discrepancy suggests that the 100-year discharges used in the flood-hazard assessment of the Tortolita piedmont are unrealistically large.

To realistically assess the hazards of alluvial-fan flooding, researchers must understand the character of water flow during these floods. Flood-hazard assessments must include answers to the following questions: (1) How deep and fast are water flows during floods on alluvial fans?; (2) Do channel patterns commonly change during fan floods or are they relatively stable?; (3) How much of the fan area is affected by relatively deep, high-velocity channelized flow?; and (4) How important is shallower, less hazardous sheet flooding? Researchers have used several hydrologic models of alluvial-fan flooding to assess flood hazards (e.g., the AFM mandated by FEMA). It is difficult to determine how closely these models approximate reality, however, because information on alluvial-fan floods is scant. AZGS geologists made a detailed reconstruction of flow patterns during a very recent, extreme alluvial-fan flood, which affected part of the southern piedmont of the Tortolita Mountains. This study provides a real data set that may be used to test the models' predictions.

AZGS geologists discovered fresh evidence (channel scour and deposition, damaged vegetation, plant flotsam, and fine-

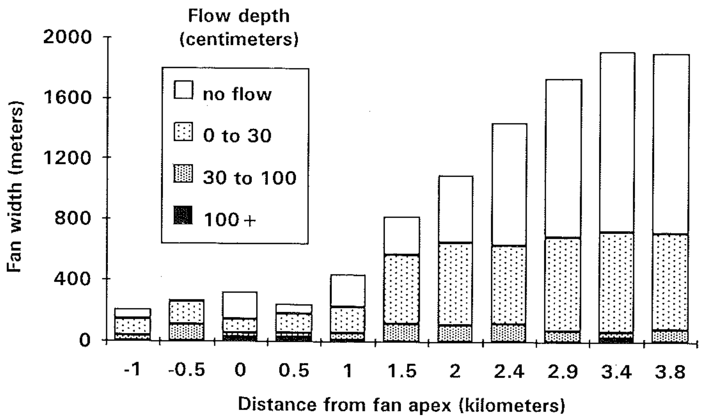


Figure 5. Histogram that shows the distribution of flood-flow depths during the 1988 Wild Burro flood on the southern piedmont of the Tortolita Mountains. The areas that were covered by three depths of flow were determined from 11 transects made across the flood zone, starting above the fan apex. The area of relatively deep flow (greater than 30 centimeters, or 1 foot) remained fairly constant downfan. The flow diverged rapidly below the fan apex, however; the number of distinct flow paths separated by dry areas increased, as did the total flooded area (from Pearthree and others, in prep.).

grained slackwater deposits) of a very large flood that affected much of the active alluvial fan of Wild Burro Wash (Figure 3; Pearthree and others, in prep.). Datable material in the flood deposits, reports of flood damage at the lower end of the piedmont, and weather radar records were used to determine that the flood occurred in July 1988. The maximum discharge at the apex of the alluvial fan, which was estimated through the use of paleoflood techniques (see above), is the largest flood recorded for a drainage of this size in southern Arizona. AZGS geologists mapped flow paths and depths on the alluvial fan in the field, using large-scale aerial photographs with detailed topographic contours that were constructed before the flood. Flow depths and velocities in channels were reconstructed at about 20 locations on the fan.

The results of this study have several ramifications for flood-hazard analysis on alluvial fans. The portion of the piedmont that was flooded closely coincides with deposits that are less than 5,000 years old and associated with Wild Burro Wash. The detailed surficial geologic mapping, therefore, accurately delimited flood-prone areas (Figure 3). Flood flow on the alluvial fan was very complex. From relatively few paths at the fan apex, the flow quickly became more complicated downfan and eventually split into 42 paths separated by dry areas (Figure 5). Although deep channelized flow and shallow sheet flow were both important, flow that was less than 30 centimeters (1 foot) deep was much more widespread. Areas that were not inundated between the outermost flow paths became larger downfan, composing more than half of the fan area at the lowermost limit of mapping. Local flow within channels was much deeper and faster than the AFM predicted. Channels that existed before the flood conveyed most of the floodwaters, and very little change in preflood channel patterns occurred during the flood. This clearly implies that areas in or adjacent to existing channels on alluvial fans have much higher flood potential than areas away from channels.

CONCLUSIONS

Geologic analyses of piedmonts in Arizona can supply unique and invaluable insights into the character and extent of piedmont flooding. A long history of stream behavior and flooding is preserved in the geology and geomorphology of a piedmont. By deciphering this history, geologists can help identify flood-prone areas, estimate the sizes of the largest floods that are likely to occur, and illuminate the nature of flood flow on piedmonts.

By integrating geologic data with hydrologic models, researchers can improve these models and make more accurate, realistic assessments of flood hazards on piedmonts. AZGS geologists have outlined the areas that are potentially subject to alluvial-fan flooding by mapping in detail young sediments deposited by streams on several piedmonts in Arizona. Alluvial-fan areas determined by these geologic studies differ significantly from those determined by the model that FEMA mandates for establishing flood-insurance rates. This suggests that either the model or the manner in which it has been applied in Arizona is incorrect. Geologists can also estimate the sizes of the largest floods during the past few hundred years by integrating physical evidence left by the floods with hydrologic models. These paleoflood investigations may be used to check the validity of hydrologic models that rely solely on idealized rainfall and runoff parameters. AZGS geologists reconstructed in detail the flow during a recent, extreme alluvial-fan flood. The information on flow paths, depths, and velocities should be used to evaluate how closely the models represent conditions during a real flood.

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