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With discussion of human induced changes to the natural and ordinary base flow along , sediment contribution to and the morphology along the natural channel of the San Pedro River .

Transportation Research Record 1201

Contents

Flood-Hazard Zonation in Arid Lands

H. W. HJALMARSON

Potential flood hazards in arid southern and western Arizona stem from different geomorphic and hydrologic characteristics and can be grouped into zones. The zonation is based on the physical features of the terrain, the sources of flooding, the expected frequency of flooding, and the expected erosion and sediment deposition. Various combinations of these factors create differing degrees of hazard. Distributary flow areas have stream channels that convey only a small fraction of the 100-year peak discharge and channels that can completely fill with sediments during a single flood. A basic understanding of the common and different flood hazards of areas in southwestern Arizona can lead to effective flood-plain management and design of hydraulic structures.

Desert floods in the southwestern United States result from large amounts of intense rainfall in the steep headwater areas. When this happens, the normally dry channels can suddenly host dangerous, debris-laden torrents (*1*). Typical floods are characterized by a rapid rise and cessation of discharge that are dramatically referred to as flash floods. Discharge generally is decreased by infiltration as the flood wave moves downstream over sandy alluvial channels (*2*). Large amounts of debris are carried down the channels, and the shapes of the channels generally change during flooding. Channels scour and fill during flooding, and channel banks wetted by floodwater often collapse after flooding.

Bridges on base-level streams often fail because of scour. Culverts located in aggrading alluvial areas fill with alluvial debris, and bank protection is ineffective. Many lives have been lost because of bridge failure, and damage to public and private property has been considerable.

This paper presents some generalizations about the nature of flooding in the deserts of southern Arizona that are based largely on the relationship between flood hazards and desert landforms. Flood hazards unique to the desert areas are described, and zones of potential hazard are characterized. Limitations of Federal Emergency Management Agency guidelines (*3*) are identified.

GENERAL CHARACTERISTICS

Degrees and types of potential flood hazard in the desert are related to geomorphic characteristics. Figure 1 illustrates the relationship between geomorphology and flood hazard and lists some general characteristics of the flood-hazard zones. Zone 1 is defined as the area inundated by the 100-year flood on base-level streams, which conforms to the present regulatory flood used by the Federal Emergency Management Agency (FEMA) (*3*). Zone 2 includes land adjacent to zone 1 that is subject to erosion by floods but not subject to inundation by the 100-year flood. Zone 3 includes relatively flat undissected areas where floodflow is shallow and unconfined; it includes former flood plains of base-level streams. Zone 4 includes areas of distributary flow, such as alluvial fans, where the amount of floodflow at a particular location is impossible to predict. Zones 5 and 6 include a variety of landforms where the 100-year flood is confined to rigid channels that generally drain areas less than 100 mi^2.

The mountainous areas (zone 6) are the source of weathered rock debris, and the stream channels usually have very little fine-grained material. A sharp break is often present in the gradient at the junction of the mountain front and the piedmont plain (zone 5) (fig. 2). Pediment areas are sparsely covered by a thin veneer of detritus, and stream channels have a mixture of fine- and coarse-grained material, including boulders. The alluvial fan and the base-level plain (fig. 1) have a wide variety of forms caused by natural and human-induced erosion and deposition that have occurred along the entire desert profile including base-level streams (*4*).

The channels of several alluvial streams have become entrenched because a balance was not maintained between factors such as flow, sediment discharge, slope, meander pattern, channel cross-section, and roughness. For example, minor fluctuations in meteorological conditions over a few years can alter the movement, transport, and production of sediment in a basin. During drier years, sediment can accumulate in stream channels, and subsequent wetter years may cause the sediment to be flushed from the basin. Reaches of channel with conditions of both uniform flow and nonuniform flow may appear to be aggrading or degrading. Thus, a reach of channel on an alluvial stream will not necessarily remain stable over a period of a few years.

ZONE 1

Zone 1 includes the channel and parts of the flood plain that would be inundated by the 100-year flood on playas, base-level streams, and larger tributaries. This zone has a high potential for flooding because floodflow normally is concentrated in defined channels and land adjacent to the channels. The velocity of flow in the channels is high, and the adjacent land is susceptible to erosion.

Historic information indicates that the current defined channels for base-level streams were not present until late in the nineteenth century and early in the twentieth century when some channels became entrenched (*3, 5*). The cause of entrenchment is the subject of considerable debate among hydrologists, but a strong argument can be made for change

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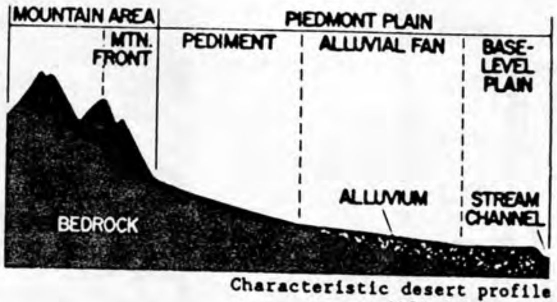
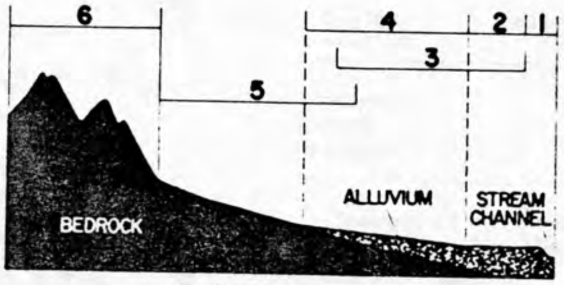
U.S. Geological Survey, 300 West Congress Street, Tucson, Arizona 85701-1393.



Characteristic desert profile modified from (3)

A. Geomorphic components



B. Flood-hazard zones

Zone	Description
1	Extent of the 100-year flood on base-level stream.
2	Part of flood plain that may be inundated by rare large floods and (or) eroded by frequent small floods.
3	Flooding from sheetflow, standing water, and water that collects in depressions.
4	Flooding in channels and sheetflow on slightly dissected alluvial plains. Flow can be distributary and there is a greater than average chance of sediment deposition.
5	Flooding confined to defined channels of small tributary streams.
6	Sheetflow and flooding in defined clean-scoured channels.

FIGURE 1 Geomorphic features and flood-hazard zones of typical mountain-plain desert profile.

FIGURE 2 View looking north at the western slopes of the Tortolita Mountains. The sharp break in land slope at the junction of the mountain front and piedmont plain is typical of mountain-plain deserts.

of climate. Floodflow in entrenched channels is more confined and the channel beds are less rough. Flood-wave celerity is greater and wave dispersion is less than for pre-entrenchment conditions. The entrenchment has had a significant effect on the flood characteristics of several base-level streams. Channel beds and banks can scour greatly in short periods during floodflow.

Zone 1 includes a variety of trenched and untrenched channels. Floodwater that is confined within a vertical walled arroyo only a few hundred feet wide can spread over an unchanneled valley for several miles downstream (figs. 3 and 4). Runoff that enters the desert-plain areas crosses progressively more alluvium where there is a great potential for infiltration (fig. 5). Burkham (*2*) found that the amount of loss along channels in the Santa Cruz River basin is related to the length of reach and the infiltration capacity of the channel.

Bridges on base-level streams become vulnerable to failure when the stream channel that supports the bridge is scoured. The abutments of many bridges in southern Arizona failed

FIGURE 3 View looking downstream at the entrenched channel of the Santa Cruz River at Tucson, Arizona. Floodwater of the 100-year flood is confined within the channel of the reach. Lateral erosion of the channel banks is restricted by massive soil-cement banks. Interstate 10 is located to the left of the 200-foot-wide by 20-foot-deep river channel. Since 1914, the channel has widened about 100 feet and deepened about 15 feet.

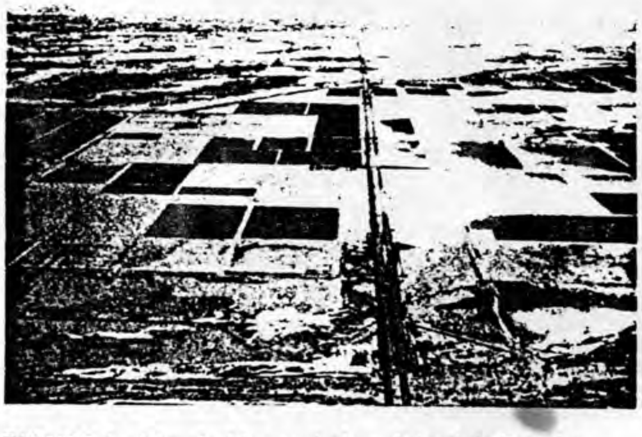
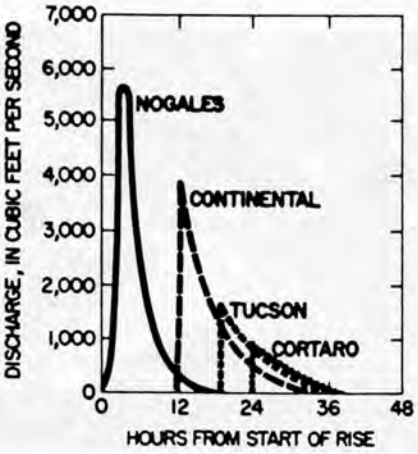


FIGURE 4 View looking east along Interstate 8 at the Santa Cruz River downstream from Tucson near Casa Grande, Arizona. The width of the flooding in zones 1 and 2 on October 4, 1983, was about 8 miles. Some water is on the road.



Gaging station	Miles from Nogales	Average annual runoff, in percent[1]
Continental	50	29
Tucson	79	19
Cortaro	88	14

[1] Amount of the average runoff at the Nogales gage that reached the indicated gage (1940-46, 1952-68).

FIGURE 5 Typical flow event showing transmission losses and attenuation of peaks for the Santa Cruz River, a base-level stream in southern Arizona (*7*).

during the flooding of October 1983 (figs. 6 and 7). Local scour around abutments and piers is a major cause of bridge failure on base-level streams in Arizona and throughout the United States (*8*).

Playa surfaces are rather flat, generally smooth, and composed of silt and clay. Many small, poorly defined channels are distributary or serve as distributary channels during floodflow as water crosses low divides. For example, during the large storm of early October 1983, runoff from Ash Creek, which is an unentrenched stream draining an area of about 500 square miles, spread laterally for more than 3 miles as floodflow entered the Willcox Playa. Nearly 2 miles of Interstate 10 near the town of Willcox was inundated with shallow floodwater, which resulted in highway closure for a few hours.

ZONE 2

Zone 2 includes areas adjacent to Zone 1 that could potentially be inundated by rare floods larger than the 100-year flood if the conveyance of the main channel changed or the hydraulic gradient changed or was eroded by floodflow. The potential hazard resulting from inundation is less than for areas in zone 1. For areas subject to erosion, the potential hazard is variable and can be greater than that for zone 1. Land adjacent to banks on the outside of bends or at constrictions or obstructions can erode quickly and extensively during frequent small flows of long duration (fig. 8).

Hazards in zone 2 are related more to lateral bank erosion than to inundation, and, at present, FEMA does not include

FIGURE 6 View looking south at one of many abutment failures resulting from floodwaters of October 1983 in southeastern Arizona. The scene is Interstate 10 at the Gila River on October 4, 1983. Flow is to the right.

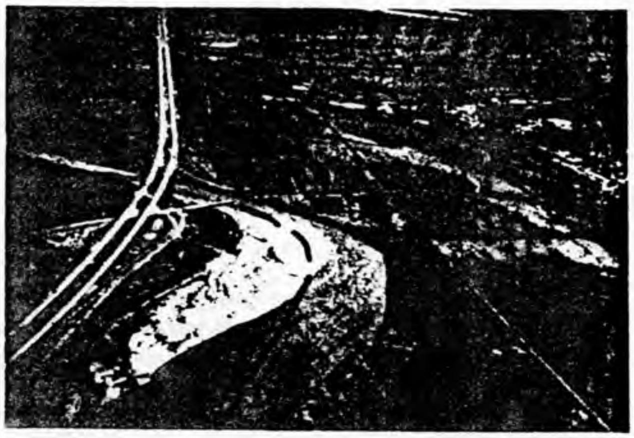


FIGURE 8 View looking south and upstream at the Santa Cruz River at Interstate 19 on October 3, 1983. The right bank abutment of the northbound lane failed and the left bank abutment of the bridge to the right of Interstate 19 was destroyed during flooding on October 1 and 2. The dashed line approximately represents the location of the left bank of the entrenched channel before the flood.

expected bank movement in the definition of hazard degree. In fact, FEMA does not accept water-surface computations reflecting channel scour even where scour during floodflow is a common occurrence. Many models that predict channel scour, such as HEC-6, are in use, but the models do not consistently produce reliable results for all channels. Thus, improved models are needed to reliably define bank erosion for non-arbitrary flood-plain management of zone 2.

Many zone 2 floods originate in the surrounding mountains, where there is little soil and much exposed rock. Floodflow from these areas may carry sediment that is greater than the load. When floods confined in the channels reach the base-level streams (zone 1), the water picks up sediment from the channel banks. Floodflow in the steep, smooth channels can carry much sediment; thus, the banks in zone 2 areas can erode laterally tens of feet and even 100 feet or more during a single flood.

ZONE 3

Zone 3 is former flood plain of base-level streams and other relatively flat undissected areas. Areas are subject to sheetflow of a few inches to about 2 feet deep from floodflow originating in higher zones (figs. 9 and 10). Sheetflow a few inches deep can result from direct rainfall. Runoff generally is unconfined, and flow velocities generally are less than 2 or 3 square feet. The erosion hazard is low except along the few short incised channels.

Floodwater entering zone 3 spreads laterally and coalesces with floodwater entering the zone at other locations. Decreasing depth and velocity of flow as the width increases results in a reduced sediment-carrying capacity. Large amounts of sediment are deposited because of this spreading. Another

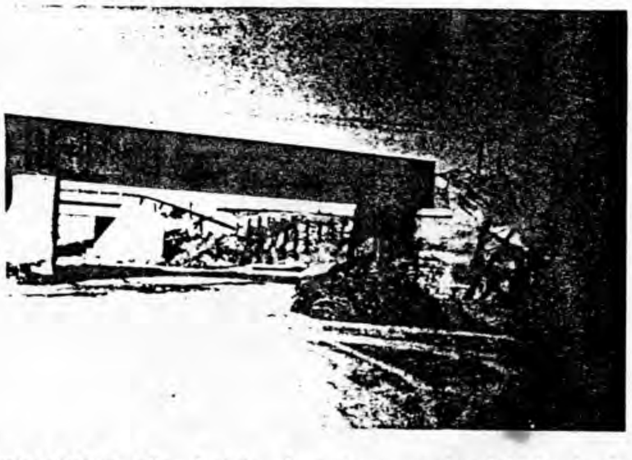


FIGURE 7 View looking downstream at the right bank of Rillito Creek at the Southern Pacific and Interstate 10 bridges at Tucson, Arizona. The failure of the wire-rock revetment at the abutments is typical for base-level streams in the area.

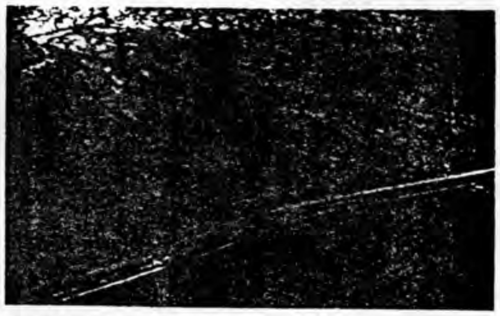
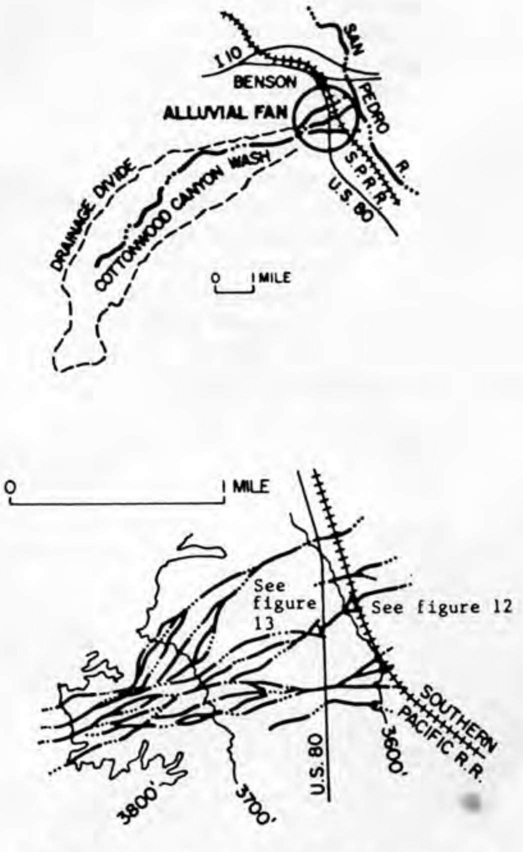


FIGURE 9 View looking northeast at floodwater from a small confined wash debouching onto land in zone 3. Floodflow spread to a width of more than 1 mile about half a mile downstream from the confinement. Flooding was on June 22, 1972, upstream from the Arizona canal east of Scottsdale, Arizona.

FIGURE 10 View looking south and downstream at sheetflow in zone 3 on June 22, 1972. The scene is in northeast Phoenix at 44th Street between Bell and Greenway Roads.

factor contributing to sediment deposition is loss of flow due to infiltration.

Culverts and bridges in zone 3 are usually not subject to serious erosion hazards unless the structure causes excessive backwater. Where excessive backwater does occur, the high head and corresponding high velocities through the structure opening can result in hazardous erosion of material supporting the structure. Sediment deposition resulting in the filling of structure openings, such as culverts, with debris is an occasional problem.



◄ Location and view angle of photograph.

FIGURE 11 Alluvial fan showing contours and distributary channels on Cottonwood Canyon Wash at Benson, Arizona.

ZONE 4

Floodwater entering zone 4 from confined channels in zones 5 and 6 spreads into distributary channels (fig. 11) with a corresponding decrease of velocity and depth. The amount of flow also is decreased by infiltration into the sandy beds. There is less water and less energy to transport sediment, and thus sediment is deposited in and along the channels to form a mound of alluvial material. Channels completely fill during flash flows, and culvert and bridge openings become ineffective (figs. 12 and 13). Frequent cleaning of culvert and bridge openings is needed at many stream channels in zone 4.

Zone 4 includes the slightly dissected alluvial slopes that commonly exhibit a distributary drainage system. The flood potential of zone 4 has often been overlooked (*9*). Bajadas and single alluvial fans (fig. 14) are typical landforms in the aggrading area. The rate of sediment deposition, one aspect of the dynamic behavior of the fans, is complex and variable (*3, 5*). Some fans seem to aggrade at a rapid rate, and the active channels change frequently. Many of the fans in southern Arizona appear to be less dynamic than fans in areas of southern California (*10*) and Nevada (*11*), where tectonic activity is greater. Also, on the basis of soil characteristics such as the age of the bajada soils (*12*), the alluvial slopes in some areas are relatively stable; apparently, little aggradation or degradation occurred during the Holocene epoch (about the past 10,000 years). Many alluvial fans are present in southern Arizona (*13*), and they may occupy about 30 to 40 percent of the area.

FEMA has presented methods for evaluating flood hazards on alluvial fans that assume channels downstream from the fan apex are equally likely to occur any place on the fan

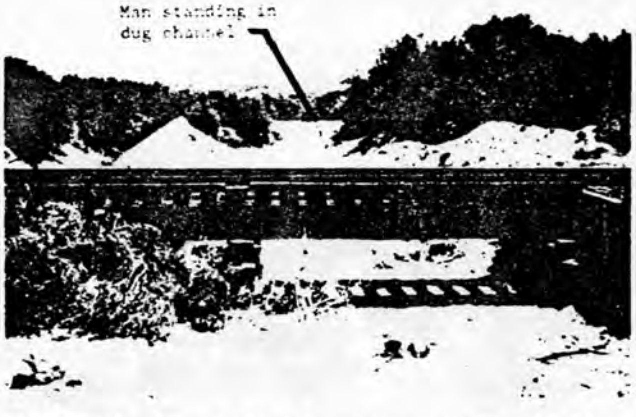


FIGURE 12 View looking downstream at railroad bridge in south Benson, Arizona. The opening was completely filled during a 1-hour flash flood on July 6, 1981. Note the depth of the channel where the filled material has been removed about 100 yards downstream from the bridge. See figure 11 for location of photograph.

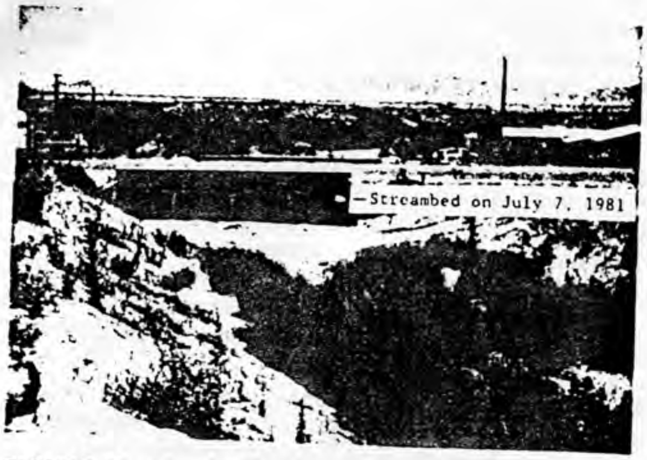


FIGURE 13 View looking downstream at culvert on U.S. Highway 80 in south Benson, Arizona. The opening was nearly filled during the flash flood of July 6, 1981. Floodflow velocities in the main channel downstream from the culvert were very high and a local resident observed two standing waves about 20 feet apart at the flood peak. See figure 11 for location of photograph.

surface (*4*). Although this assumption may be valid for estimating the flood hazard of highly active fans, it may not be applicable for the many fan surfaces in southern Arizona that are relatively inactive. The more stable fans have a defined network of distributary channels with some abandoned channels that presently head on the fan surface. Floodflow is more likely in the defined channels that head in mountains, less likely in the abandoned channels, and unlikely on much of the high ground between the channels. Although the amount of discharge in a particular branch of a divided channel is difficult to determine, the likelihood of floodflow at any location on the fan surface is not equal.

The topographic relief across single alluvial fans and bajadas is variable and is an index of the age of the landform. The local relief between channels in zone 4 is commonly less than 5 feet but occasionally more than 20 feet. Alluvial fans with small local relief tend to be more active than alluvial slopes with large relief.

The filling of the stream channel shown in figures 12 and 13 may be offsetting the potentially hazardous headcutting of the channel. The stream is tributary to the San Pedro River, which is entrenched. Tributaries to the San Pedro River also have become entrenched near the river (fig. 15). The hazardous conditions shown in figures 14 and 15 are representative of the variable and dynamic behavior of streams in southern Arizona.

Floodwater on inactive fans generally is in entrenched channels that anastomose, divide, and combine. Much of the land clearly is above the 100-year flood, but flood hazards on fans are unpredictable. Possible consequences of floods in the low-lying land and channels include:

1. Channel erosion and lateral bank movement.
2. Channel filling with deposited sediment and the associated increased flooding of adjacent flood plain.
3. Lateral shifting (avulsion) among distributary channels.

The FEMA type of flood hazard assessment (random distribution of flood depth and velocity) may not be applicable. Flood hazard assessment for bridge or culvert design is difficult because flood response at any given location on channels in zone 4 is unpredictable.

ZONE 5

Zone 5 is defined as the pediment and upper alluvial plain areas with defined channels that commonly form a tributary system. The surface of the pediment areas is a complex mixture of rock, alluvium, and thin soils of various ages. Stream channels commonly have slopes from 0.02 to 0.04 with an upper limit of about 0.2 (*3*). Channel beds in the pediment or upper area of the zone are often composed of scattered boulders with cobbles, gravel, and some sand. Channel beds in the upper alluvial areas tend to have fewer boulders and more sand. The potential for significant scour of the channel

FIGURE 14 View looking east at distributary channels of zone 4 on the western slopes of the Tortolita Mountains north of Tucson, Arizona. The land in about the top quarter of the photograph is in zone 5.

FIGURE 15 View looking downstream from U.S. Highway 80 at small scoured channel of a tributary to the San Pedro River located 0.6 mile south of the filled channel shown in figures 12 and 13.

bed and banks in the pediment area is low. Marked scour along some channels in the upper alluvial plain area can occur, but the general potential for scour is not great. Debris flows, defined here as slurries of sediment and water with a sediment weight-percentage above 80 percent, that are potentially hazardous can occur in zone 5.

The boundary between zones 4 and 5 generally coincides with the boundary between Quaternary and Tertiary valley-fill deposits. In some places, the tributary-defined channels characteristic of zone 5 extend into the Quaternary deposits. The small distributary channels of zone 4 rarely extend upslope in the Tertiary deposits. In some places, the boundary that separates zones 4 and 5 is a transition area several hundred feet wide.

The greatest potential hazard in zone 5 is from flooding in the channels and narrow flood plains that occupy the lowlands between the defined ridges. Marked scouring occurs along some of the channels and flood plains, and floods carry large amounts of sediment. In many channels, the depth of flooding depends on the amount of erosion and deposition that takes place during the flood. The depth of flooding generally does not exceed 10 ft except where channels are obstructed, on the outside of sharp bends, and on the few channels that drain areas of more than about 100 mi^2. The depth of floodwater also increases behind debris jams and manmade obstructions. The degree of potential flood hazard of the larger washes in zone 5 is similar to that in zone 1 but with less potential for scour. The main channel of some washes is deceptively small, and large amounts of floodwater will spread over wide areas adjacent to the channel.

ZONE 6

Mountain areas that include steep, well-drained slopes composed mostly of rock are characteristic of zone 6. Interspersed among the rock surface are scattered thin debris mantles and thin soils. Stream channels are steep, scoured, and rocky. Channels of streams draining basins of a few tenths of a square mile are well defined.

The dominant hazard is along the defined channels where flood velocities are high; velocities in the large channels may be as much as 15 feet per second. Sheetflow accompanied by debris flow may occur along some steep slopes. Peak-discharge rates of as much as 500 cubic feet per second from a 0.1-square-mile area can be expected an average of once every 100 years. A large part of the flood-hazard potential in this zone can be attributed to sudden flooding from summer thunderstorms and the high velocity of flow.

If the potential for debris flows exists, then the hazard associated with a debris flow may be the greatest in this zone. The potential for debris flows is directly related to the amount and size of unconsolidated material on steep, nonvegetated slopes.

TABLE 1 TYPE AND DEGREE OF FLOOD HAZARD FOR ZONES

Type of hazard	Flood-hazard zone					
	[1]1	2	3	4	5	6
Inundation of land along channels	high[2]	moderate	moderate	high[2]	moderate	low
Velocity of floodflow	high	moderate	low	high[2]	high	high
Scour of channel bed	high	moderate	low	moderate	low[3]	low
Lateral bank erosion	high	high[2]	low	high[2]	low	low
Sediment deposition	low[4]	low	high[5]	high[5]	low	low
Debris flows	low	low	low	low	moderate	high

[1] High incidence of bridge failure because of scour of piers, abutments, and roadway approaches.

[2] The assumption on which FEMA guidelines is based may not be applicable for fan surfaces that are relatively inactive.

[3] Moderate in upper alluvial plain areas and in large channels.

[4] Moderate to high in unchanneled reaches.

[5] Conveyance of many culverts and bridges reduced because of sediment deposition.

DISCUSSION AND SUMMARY

Geomorphology plays an important role in determining flood hazard. Although this fact is common knowledge, structures continue to fail or become less effective, at least in part because of flood-plain management regulations that may not be applicable for some zones. The hazards that commonly plague engineering works are the lateral bank erosion in zone 2, the scour of channel beds in zone 1, and the sediment deposition and unpredictable flow paths in zone 4.

The relative degree and type of hazard for the six zones are summarized in table 1.

The zonation is based on distinct geomorphic and hydrologic differences between the zones, but there is some overlap (see fig. 1). Zones 2 and 3, for example, can define the hazard of the same land where there is a potential for lateral movement of the banks of channels in zone 1 and also for sheetflow from local rainfall or from runoff from zones 4 or 5. Alluvial fans have a wide variety of flood characteristics, and thus specific areas can be best described by zones 3, 4, or 5. In general, large areas of fans will exhibit characteristics of a single zone.

This general zonation is not intended to replace the detailed engineering definition of hydrologic and geologic characteristics of a particular site of interest. Rather, the zonation of flood hazards can be useful to practicing engineers for the general identification of the type and degree of flood hazard.

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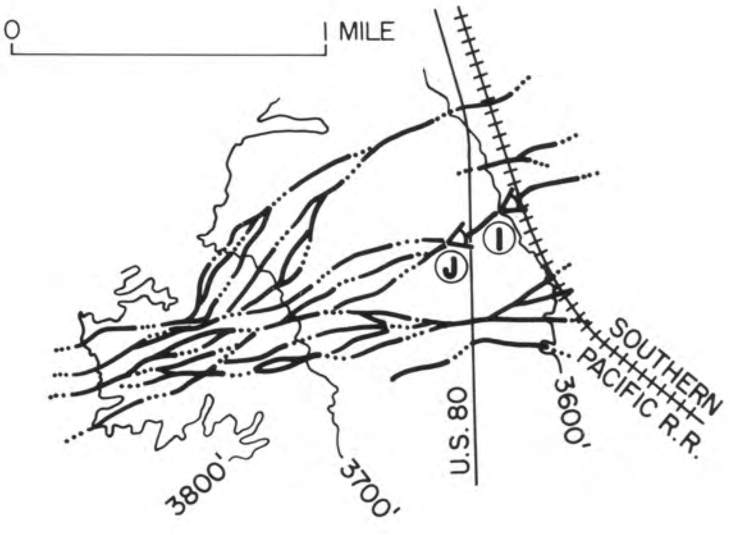
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View looking downstream from U. S. Hwy 80 at small channel located 0.6 mile south of Cottonwood Canyon Wash. San Pedro River is about 1 mile beyond this site. There is several feel of head cutting at the exit of this culvert.

Schumm, S. A., 1968. RIVER ADJUSTMENT TO ALTERED HYDROLOGIC REGIMEN-MURRUMBIDGEE RIVER AND PALEOCHANNELS, AUSTRALIA, USGS Professional Paper 598, 65 pp.

Schumm discusses the affects of altering vegetation cover in watersheds and thereby changing tributary runoff and sediment contribution. "For example, the control of tributary runoff and sediment contribution to an alluvial channel will-if both runoff and ·the type of sediment load are significantly altered - induce a long-term adjustment of the river system. The induced changes may be difficult to recognize in a short span of time, but they will, nevertheless, be significant over very long reaches of alluvial rivers, especially in arid, semiarid, and subhumid climatic regions. Depending on the type of sediment load transported by the river, quite different types of adjustment can occur." These photos of channels in south Benson clearly show the variable nature of tributary channel adjustment.

Early accounts of the base flow along the San Pedro River and also the variable channel morphology in the Tres Alamos area also suggest major changes in dimensions, pattern, and shape of the San Pedro River channel in response to man-induced alterations of hydrologic regimen occurred as a result of diversion for irrigation and over grazing of cattle. For example, Parke stated "At the Tres Alamos the stream is about fifteen inches deep and twelve feet wide, and flows with a rapid current over a light, sandy bed, about fifteen feet below its banks, which are nearly vertical. The water here is turbid, and not a stick of timber is seen to mark the meanderings of its bed. In the gorge below, and in some of the meadows, the stream approaches more nearly the surface, and often spreads itself on a wide area, producing a dense growth of cotton-wood, willows and underbrush, which forced us to ascend and cross the terraces. The flow of water, however, is not continuous. One or two localities were observed where it had entirely disappeared, but to rise again a few miles distant, clear and limpid." Tres Alamos is a ghost town. Settled 1874. In 1768 Spanish soldiers from the Presidio de Tucson farmed the Tres Alamos area along the San Pedro River to supply food for the Presidio. Later, in 1830, Mexican farmers settled in the area, establishing more permanent farming operations and transporting their produce through the Redington Pass to Tucson with the protection of soldiers from the Presidio.

Parke, J.G., 1857. Report of Exploration of Railroad Routes. 33rd Congress, 2nd Session, Senate Exhibit Document 78, vol. 7.