Geomorphology and Hydrology of an Alluvial Fan Flood on Tiger Wash, Maricopa and La Paz Counties, West-Central Arizona

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Introduction

Management of flood hazards on alluvial piedmonts in the southwestern United States is increasingly important because urban development is rapidly expanding into these areas. Flows are very infrequent in most desert fluvial systems, yet these events can be extreme because watersheds generate large amounts of runoff per unit area during intense precipitation events associated with convective thunderstorms or incursions of dissipating tropical storms. Distributary (downstream-branching) fluvial systems that are common on desert piedmonts present special challenges because of uncertainties about flow distribution during floods. Portions of many distributary channel networks are incised into Pleistocene surficial deposits. In these areas, channel positions are relatively stable and inundation in floods is limited in extent. In active alluvial fan areas, however, topographic relief associated with channels is minimal and areas between channels are covered with Holocene deposits indicative of fairly recent fluvial activity (Pearthree, 1989; Baker and others, 1990; Pearthree and others, 1992; Field and Pearthree; 1997). These latter systems are of particular concern for floodplain management because of complex flow patterns, local high velocity flow, widespread sheet flooding and the potential for changes in channel position during large floods (NRC, 1996). Hydrologic and hydraulic models commonly used to delineate floodplain areas are not adequate in the complex distributary environment, and newer, more sophisticated 2-dimensional flow models require validation against real flood flows (Pelletier et al., in review). Flood inundation on active alluvial fans has rarely been documented in detail (Vincent, 2000), however, in part because of the complexity of flow and in part because of the requirement that the flood be recognized soon after its occurrence in order to document the details of flow.

A large flood coursed through the distributary system of Tiger Wash in the Sonoran Desert of western Arizona (Fig. 1) as a result of the passage of a dissipating tropical storm in late September, 1997 (Klawon and Pearthree, 2000). During this flood, broad areas of the piedmont were inundated and changes occurred in the distributary channel network. Because we learned of this flood about a year after its occurrence when evidence of flood inundation was abundant and extremely well-preserved, we were able to document the extent and character of flood inundation in detail through much of the distributary system. Ancillary information was available to reconstruct the nature of the storm and the flood flow and to document changes in the channel network. In this paper, we present a combined geomorphologic and hydrologic analysis of the generation of the 1997 flood and its passage through the complex distributary network of the Tiger Wash alluvial fan. We document the surficial geology of the Tiger Wash distributary system as it existed prior to the flood based on pre-flood aerial photographs. We consider the meteorology of the storm event, model runoff and flood generation in the tributary part of watershed, and evaluate the general distribution of flood flow in various parts of the distributary system. We present a map of 1997 flood inundation throughout the distributary system and use these data to describe the character of flow and to document changes in the channel network. Finally, we consider the implications of flow characteristics, the extent of inundation of piedmont alluvial surfaces of different ages, and channel changes for the behavior of distributary systems and floodplain management of desert piedmonts.

Physical Setting

Tiger Wash is a moderately large drainage in the Gila River watershed in west-central Arizona, approximately 100 km west of Phoenix (Fig. 1). The upper part of Tiger Wash

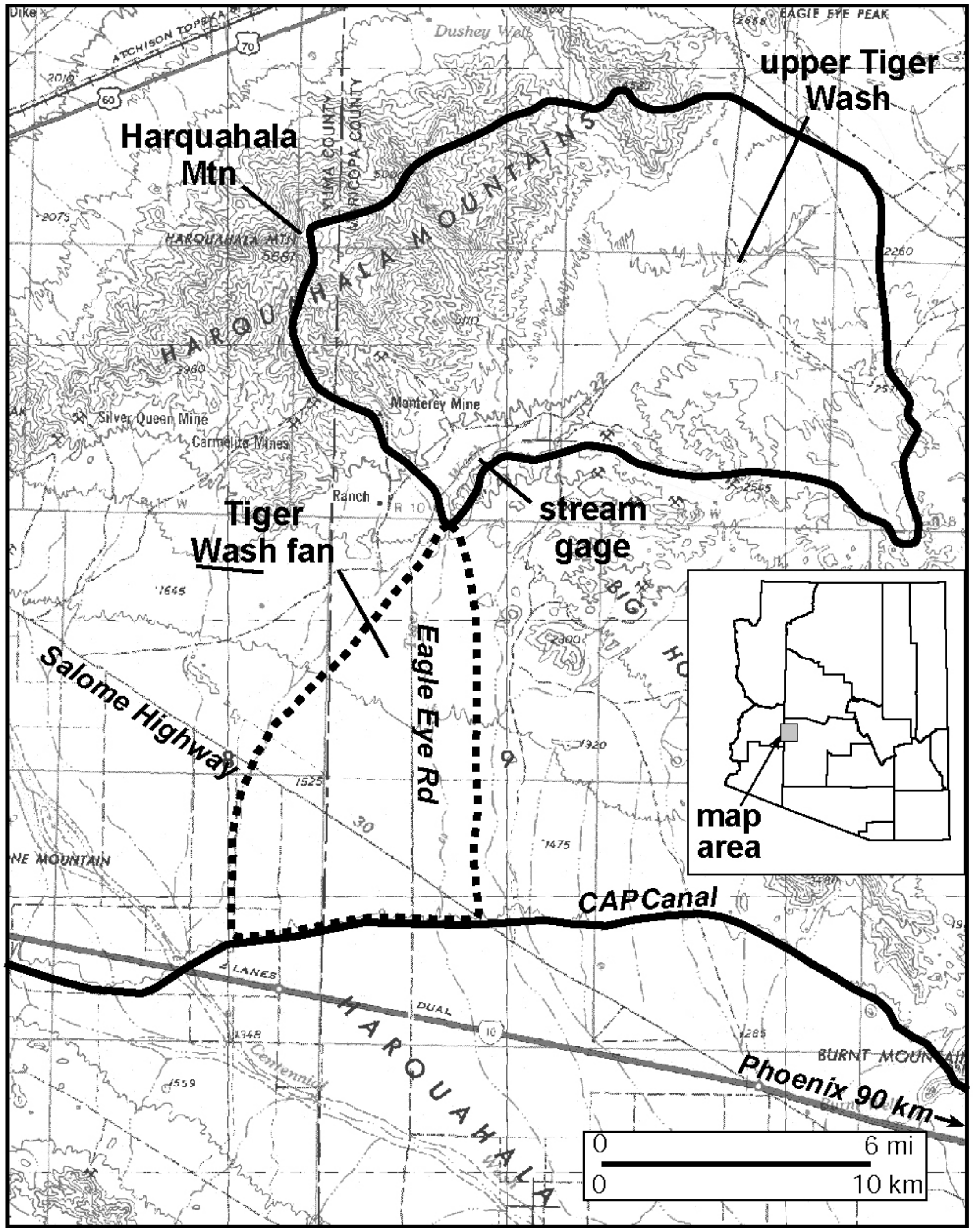

Figure 1. Location of the Tiger Wash watershed in western Arizona. The solid line encompasses the tributary portion of the watershed, and the dotted line bounds the distributary drainage system of Tiger Wash. Locations of the Tiger Wash stream gage and the 3 continuously recording rain gages that were operating in 1997 are identified.

watershed is a ~300 km^2 tributary system that drains parts of the Harquahala and Big Horn mountains and a moderately dissected basin between them. Topographic relief in the roughly circular watershed is typical of this part of Arizona, with maximum altitude difference of 1200 m between the base of the tributary network on Tiger Wash and the top of Harquahala Peak and less than 300 m of topographic relief through most of the basin.

Tiger Wash changes to a large (~120 km^2), downstream-branching distributary drainage system flowing through an alluvial fan complex as it enters the low-relief piedmont of the Harquahala Plain. At the first distributary split (EWS) Tiger Wash divides into two major branches that are primarily east and west of Eagle Eye Road (Fig. 1). Each of these branches splits into multiple channels that decrease in size and increase in number downslope; the linked distributary channel network eventually disappears completely into extensive, young, fine-grained deposits. Channel gradients vary substantially from reach to reach, but average about 0.009 in the distributary network. Local topographic relief across the upper part of the distributary system is a few meters, and much of the area between the distributary channels consists of Pleistocene fan deposits. Farther downslope where Holocene deposits predominate, channels generally are minimally incised and there is very little topographic between adjacent Holocene and Pleistocene alluvial surfaces. Deposits associated with the active distributary system consist of sand and gravel in channels, sheet gravel deposits in channel expansion reaches and at the downstream ends of channels, and very extensive sandy to silty overbank and sheetflood deposits marginal to and downstream from channels. Channel deposits diminish in extent and fine-grained deposits become much more extensive downslope, indicating that sheet flooding between and downstream of channels is a very important component of large floods on Tiger Wash.

Although no significant development has occurred on the Tiger Wash alluvial fan complex, anthropogenic modifications of the landscape have affected the drainage. Several moderate-sized sand and gravel pits have been excavated on the upper part of the east branch of the distributary system, just down slope from the EWS. Channels were diverted around the pits by earthen berms, but some of the berms failed in the 1997 flood and floodwaters spilled into and partially or completely filled the pits. Several low earthen berms were constructed east of Eagle Eye Road to divert flow in the east branch away from the road. The lowermost part of the Tiger Wash system is truncated by large berms constructed upslope from the Central Arizona Project canal; these basins have contained flood flows from Tiger Wash since the construction of the canal in the early 1980's.

The climate of the western Sonoran Desert is warm and arid, but the precipitation regime is subject to dramatic seasonal and inter-annual variations. On average about 35 percent of the annual precipitation falls in the hot season between June and September, when thunderstorms are generated as moist air is drawn northward from the Gulf of California and the Gulf of Mexico. Summer thunderstorms are typically quite localized and affect only part of a large watershed, but because of the intensity of precipitation associated with the strongest of these storms, they have generated most of the floods that have been recorded on Tiger Wash. Occasionally, more widespread precipitation occurs in the late summer to early fall as a result of incursions of moist air derived from dissipating tropical storms in the Pacific Ocean or persistent low pressure troughs, and these storms may also contain pockets of intense precipitation (summarized from Sellers and Hill, 1974). Annual and seasonal precipitation in this region is highly variable. Records from the long-term climate station at Buckeye, Arizona, located about 50 km east of

Tiger Wash, illustrate the annual variability in precipitation in this region. The average annual precipitation over the past century is 195 mm, but it has received as much as 550 mm and as little as 35 mm of precipitation in a year (WRCC, 2003). The largest monthly precipitation during that period (175 mm) records the incursion of a dissipating tropical storm in August, 1951 (Sellers and Hill, 1974), a situation similar to that which occurred at Tiger Wash in 1997.

Previous Work and Data Sources

Previous geomorphologic investigations of the Tiger Wash distributary system help to define the physical framework of the system prior to the 1997 flood. Wells (1977) interpreted the fine-grained alluvial fans on the middle and lower piedmont of the Harquahala Plain as coalescing berm sediments that have spread laterally over shallow interfluves. He also recognized a contact between coarse-grained Pleistocene alluvial fans on the upper piedmont that are being eroded and young, predominantly fine-grained depositional areas, which he called the "zero edge of alluviation" (Wells, 1977). The Tiger Wash distributary system was investigated in regional studies of piedmont flood hazards in Maricopa County in the early 1990's (Hjalmarson and Kemna, 1991; CH2MHill, 1992; Hjalmarson, 1994; Field, 1994; 2001; Pearthree and others, 2000). As part of these investigations, soils, geomorphic, and geologic data were compiled in an effort to identify portions of the Tiger Wash distributary system that are active alluvial fans. Criteria used to assess fan activity included soil survey maps, generalized surficial geologic maps, hydraulic capacities of channels, and the character of the drainage network. Trench investigations done as part of the CH2MHill study uncovered evidence for several generations of gravelly channel deposits and sandy to silty overbank and sheetflood deposits, which implied that loci of deposition on this part of the Tiger Wash system have shifted over a period of decades to centuries (Pearthree and others, 2000). Field (1994; 2001) interpreted historical aerial photographs to document channel changes on Tiger Wash from 1953 to 1988. He observed no substantial channel changes in the distributary channel network during this period, but he noted that some channels appeared to have been recently abandoned within the drainage network. Of the 6 fans Field (1994) studied in southern and central Arizona, Tiger Wash had been the most stable for the period investigated.

The U.S. Geological Survey and the Flood Control District of Maricopa County (FCDMC) have maintained a stream gage on Tiger Wash just above the head of the distributary system for most of the past 40 years. A crest-stage gage was installed by the USGS in 1963 and operated into 1979, and the gage was reoccupied with support from the FCDMC in 1990. The gage was destroyed in the 1997 flood, but the site was investigated after the flood and an indirect estimate of the flood peak was obtained (Tadayon and others, 1998). Since 1999, streamflow at the gage site has been continually monitored by a pressure-transducer gage operated by the FCDMC. The gage record reveals that at least 11 floods larger than 50 m^3/s (1750 cubic ft per second, cfs)have occurred in the past 40 years (Fig. 2). Six of these floods occurred during the late summer monsoon season (late June to mid-September), and the remainder occurred in the early fall (late September through October). The estimated peak discharge of the 1997 flood (230 m^3/s; 8050 cfs) was nearly twice as large as the next largest flood peak of 130 m^3/s (4550 cfs) recorded in August, 1970. Subsequent to the 1997 flood, there have been four floods larger than 50 m^3/s (1750 cfs), but the largest was less than ½ of the 1997 peak discharge. Based on the flood data collected prior to the 1997 flood, the USGS estimated a 100-yr discharge of 210 m^3/s (7350 cfs; Pope and others, 1998). In the context of the largest floods that have been documented in the lower Colorado River region, however, the peak discharge of the 1997 flood was not

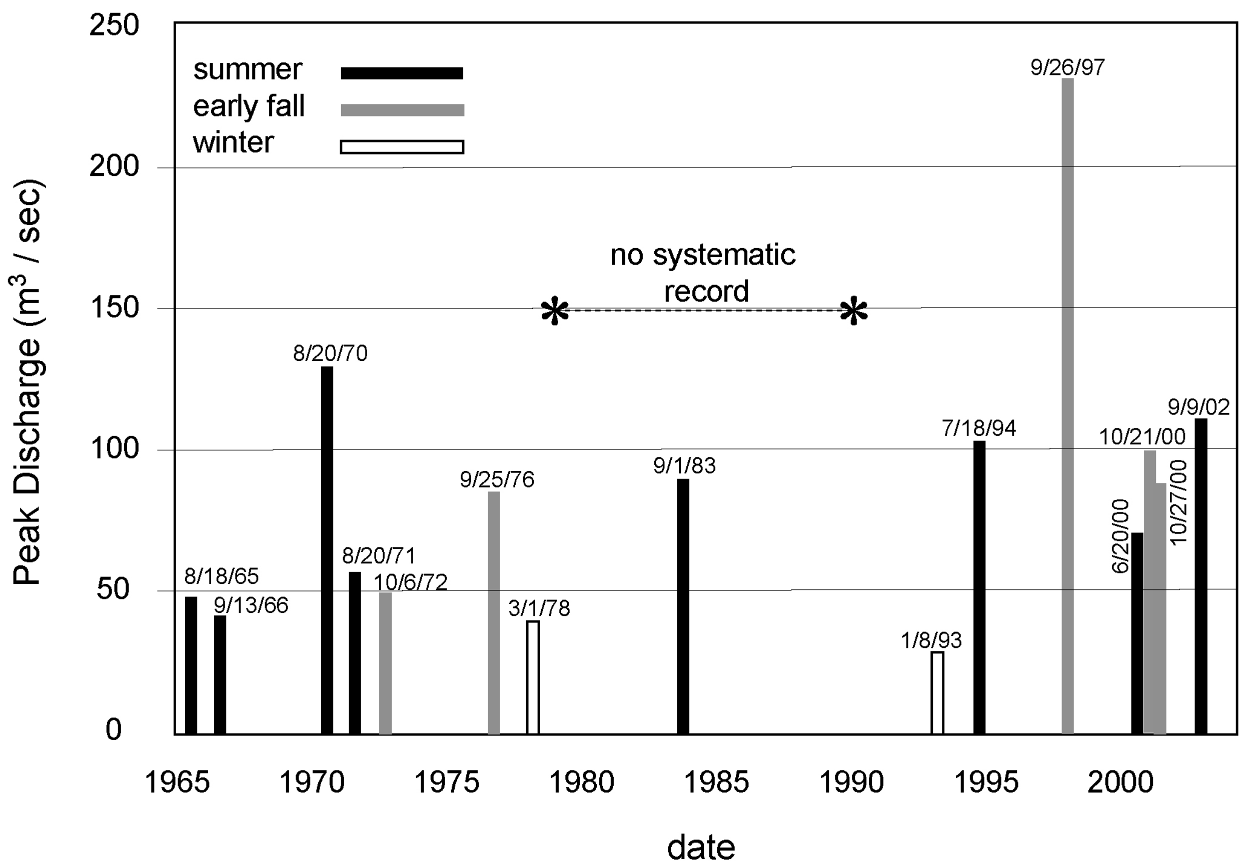

Figure 2. Stream gage record for Tiger Wash. This was a crest-stage gage only from 1965 to 1978 and from 1990 to 1999, and the gage was not checked regularly between 1979 and 1990. Since 1999, the FCDMC has operated a continuously recording pressure-transducer gage at the site. Floods are subdivided into summer (June to Sept. 15), early fall (Sept. 15 through Oct.), and winter (Nov. through March).

extraordinarily large. In fact, peak discharges 2 to 3 times larger have been documented for drainage basins of this size in the region (Enzel and others, 1993; House and Baker, 2001). Paleoflood data collected at the gage site (CH2MHill, 1992) indicate that floods somewhat greater than the 1997 flood have occurred during the Holocene. These investigations documented physical evidence of several floods with peak discharges exceeding 285 m^3/s (10,000 cfs). Based on inferred non-inundation of Pleistocene surfaces above the channel, these workers proposed an upper bound of 370 m^3/s (13,000 cfs) for Holocene floods at the gage site (CH2MHill, 1992).

Surficial Geology of the Tiger Wash Distributary System

Surficial geologic mapping documents the geologically recent history of piedmont erosion and sedimentation and can be used to assess the extent of the active fluvial systems on piedmonts (Baker and others, 1990; Pearthree and others, 1992; 2000). Geomorphic characteristics of alluvial surfaces and geologic characteristics of surficial deposits record the character and extent of fluvial activity on piedmonts over decades to tens or hundreds of thousands of years. Surface color, rock varnish, development of desert pavement, local surface topography, drainage network character and amount of incision, relief between channels and adjacent alluvial surfaces, and soil development can be used to differentiate alluvial surfaces by age. The extent of the active fluvial system is outlined by the mapped extent of young deposits on the piedmont. Surface ages in the Tiger Wash system are roughly estimated by correlation with a chronosequence of soils and surfaces from the lower Colorado River Valley (Bull, 1991).

We mapped the surficial geology of the Tiger Wash distributary system primarily using color 1:24,000-scale aerial photographs taken in 1979 (Fig. 3; Plate 1 on CD). We also conducted field investigations to document surface characteristics and soil development associated with the various alluvial surfaces and to check contacts between map units. The youngest deposits on the piedmont are in modern channels (unit Qyc; Fig. 3; see Table 1 for unit characteristics) and overbank and sheetflood areas (Qy2). Except in areas of gravel bar deposition and local channel incision, topographic relief across these young surfaces generally is less than 0.5 m. Older Holocene deposits (Qy1) cover areas that have recently been part of the active depositional system but have not been subject to substantial flood inundation for hundreds to thousands of years. These surfaces typically are slightly dissected and surface relief is quite variable, depending on particle size and post-depositional entrenchment by local drainages. Qy1 surfaces typically are drained by tributary channel networks, although relict distributary channels are evident in some places. Pleistocene surficial geologic units (Ql, Qm) are also extensive within and along the margins of the Tiger Wash distributary system. These surfaces are weakly to moderately dissected with well-developed tributary channel networks and are several meters above active channels on the upper piedmont, but in middle and lower piedmont areas topographic relief between surfaces of different ages is typically 1 m or less.

The mapped distribution of surficial deposits of different ages points to areas that have been subject to alluvial fan flooding in the recent past (Fig. 3). Young deposits are quite limited in extent in the tributary part of Tiger Wash, where flood flows evidently are confined by bedrock hills and Pleistocene alluvial fan deposits. Along this reach, the Tiger Wash channel pattern is braided and very young terraces (unit Qy2) are fairly wide, but the limits of the flood-prone corridor are well defined by topography and geology. Extensive Holocene deposits exist along both branches of Tiger Wash at the EWS and downstream from that area, but very young deposits (units Qy2 and Qyc) are restricted to fairly narrow strips along the main channel systems indicating that flood flows are topographically confined for the most part. In this area, older alluvial surfaces (Qm, Ql, and Qy1) are up to 3 m above adjacent channels. Because of the limited extent of very young deposits and the topographic relief associated with existing channels, this part of the distributary channel system is reasonably stable and major shifts in channel position in floods are unlikely. Active alluvial fan areas are found in the middle piedmont, where topographic relief across the piedmont is minimal and young, primarily fine-grained deposits are extensive. The extent of very young deposits continues to increase in the southern part of the map area, where channels are small and discontinuous. We infer that these areas are subject to very broad, relatively shallow sheetflooding during large flow events. Some limited areas in the middle and lower piedmont are dominated by Pleistocene deposits that typically stand slightly higher than adjacent young deposits.

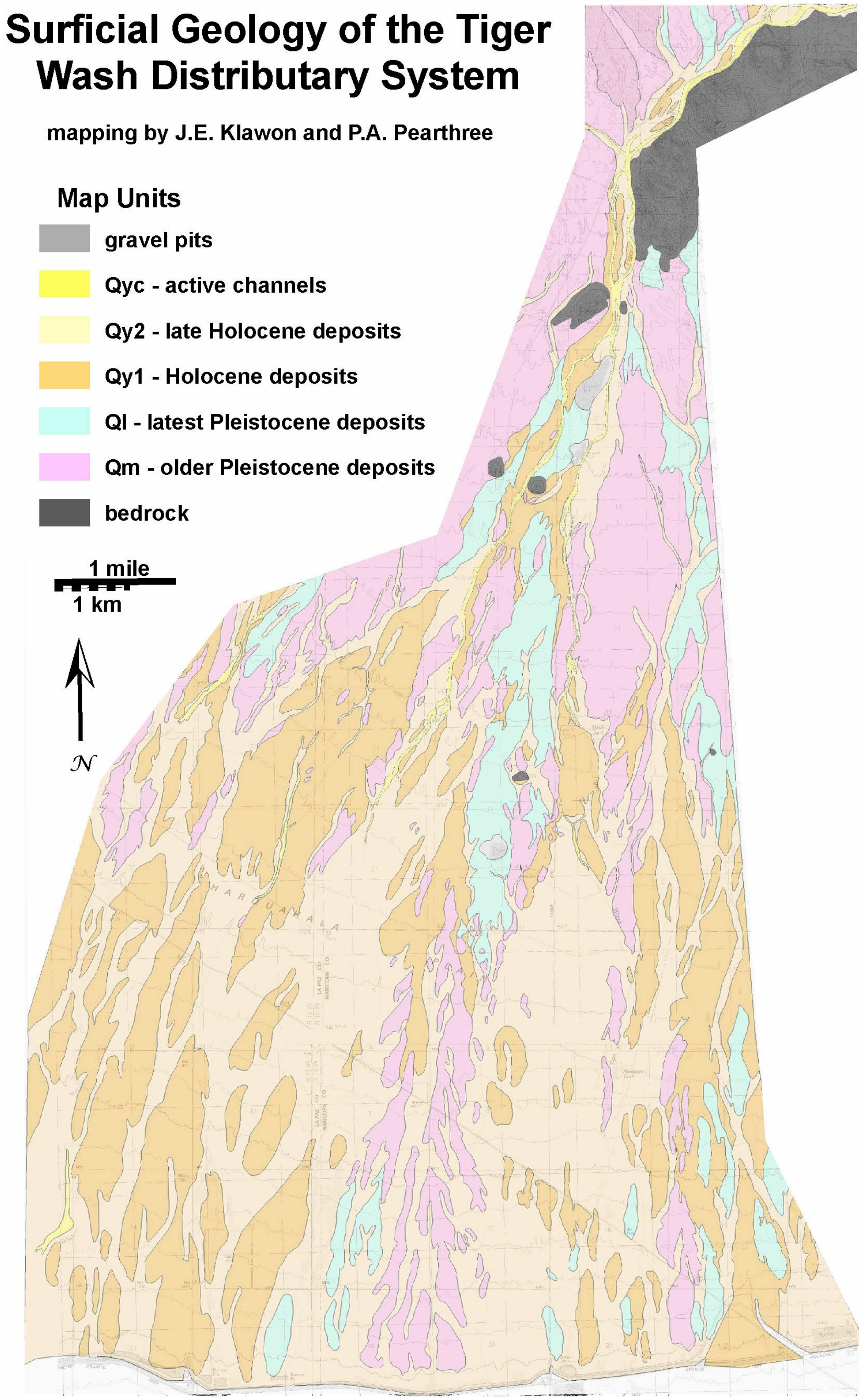

Figure 3. Surficial geologic map of the Tiger Wash piedmont based on 1979 aerial photographs. The active distributary system is outlined by the channels and young sheetflood areas (yellow and tan). Areas of slightly older deposition are shown in butterscotch. Areas that have not been subject to significant Holocene deposition are shown in aqua and pink. See also Plate 1.

Map Unit ***Landform***	**Estimated Age** ***Percent map area***	**Soils**	**Surface Characteristics**	**Drainage characteristics**	**Sedimentology**	**Surface topography**
Qyc *modern channels*	modern ***1.1***	depositional layering, no soil development	light-colored sand and gravel	single, braided, distributary	very poorly sorted sand and gravel	flat-bottomed sandy channels, sand and gravel bars
Qy2 *sheetflood areas and terraces*	modern ***40***	depositional layering, carbonate filaments, weak structure	brown fine sand and silt, local fine gravel	discontinuous small channels and gullies	sand and silt, with some gravel sheet and channel deposits	fairly planar with small gullies and mounds around vegetation
Qy1 *young inactive alluvial fans and terraces*	middle to late Holocene ***25***	weak soil structure and thin, discontinuous carbonate coatings on gravel clasts	gravel lag but no interlocking pavement, minimal rock varnish	entrenched distributary and tributary channels; smaller local swales and channels	poorly sorted sand, pebbles, and cobbles, with small boulders and silt	undulating, with coarse gravel bars and finer-grained swales; smooth where fine-grained
Ql *moderately old relict alluvial fans*	late to latest Pleistocene ***8***	slight reddening, weak soil structure, and thin, discontinuous carbonate coatings	weakly to moderately packed desert pavements; rock varnish fairly dark	local tributary channels, with a few distributary channels	very poorly sorted cobbles, pebbles, sand, small boulders, and silt	broadly rounded and minimally dissected, bars and swales well preserved
Qm *old relict alluvial fan deposits*	middle to late Pleistocene ***22***	reddened zones of clay accumulation, variable carbonate cementation and bottom pendants on gravel clasts	strongly developed, smooth desert pavements with interlocking clasts; dark rock varnish	well-developed, entrenched tributary drainage networks	poorly sorted cobbles, pebbles, sand, small boulders, and silt	smooth to broadly rounded near channels; minimal relief on relict gravel bars

Table 1. Surface, soil, and drainage characteristics of the various surficial geologic map units in the Tiger Wash distributary system.

Meteorology of the 1997 Flood

The 1997 flood on Tiger Wash was generated by heavy rainfall derived from dissipating Hurricane Nora on September 25 and 26, 1997. Incursions of very wet regional storm systems associated with dissipating tropical systems occur infrequently in Arizona and eastern California, but when they do occur they have the potential to generate heavy rainfall and large floods, usually in small portions of the region (Hansen and Schwartz, 1981). Hurricane Nora was one of a number of powerful hurricanes that developed in the eastern Pacific Ocean during the strong El Nino conditions of 1997-98. Nora originated in the eastern Pacific Ocean off the west coast of Mexico, eventually developing wind gusts up to 200 km per hour as it moved northward through the week of September 21-27. It crossed the southern Baja California peninsula on the 22nd through the 24th and into the northern Gulf of California (Fig. 4), where it weakened to a tropical storm as it moved to the head of the Gulf. The storm was still moisture laden, however, delivering 100 mm of rainfall at Yuma, Arizona, on Sept. 24. Nora continued to diminish as it moved to the north and northeast across western Arizona, but in the process it imported a tremendous amount of moisture to the northeast quadrant of the storm system in west-central Arizona (Waters, 1997).

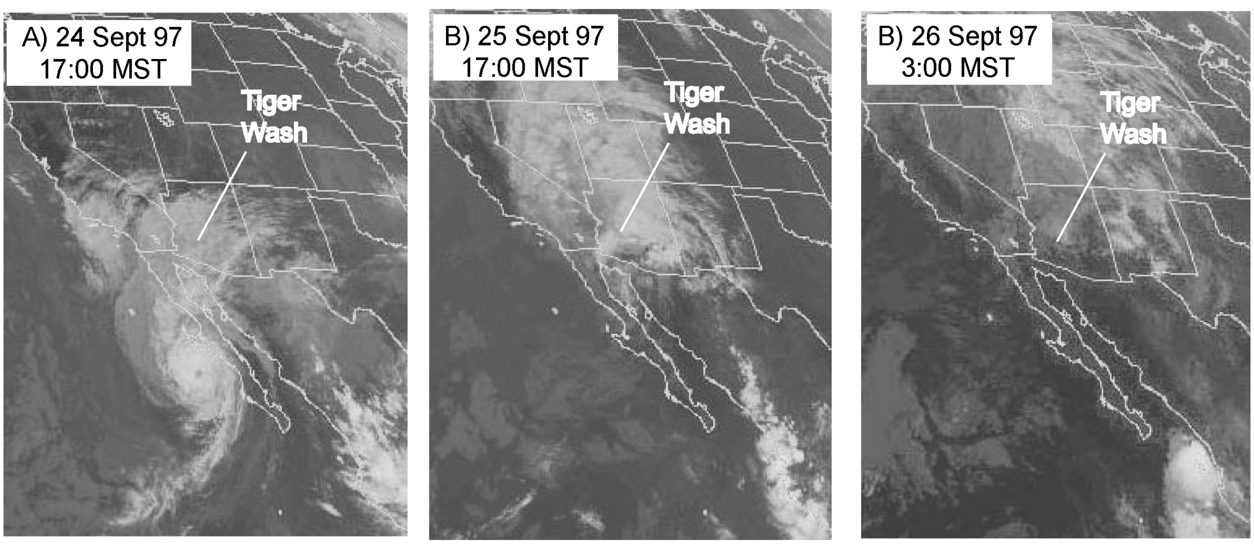

Figure 4. Satellite images showing the northward progression and eventual dissipation of Hurricane Nora over the southwestern United States (satellite images from the National Climate Data Center; http://lwf.ncdc.noaa.gov/servlets/GoesBrowser). Rainfall occurred on the Tiger Wash watershed from 13:00 on 25 September through 7:00 on 26 September, as Nora dissipated.

The amount and duration of rainfall recorded in the Tiger Wash watershed are consistent with the 1997 flood being a fairly extreme event. Precipitation related to dissipating Tropical Storm Nora began about midday on September 25 and by the early evening hours rainfall was moderately intense (Fig. 5). Rainfall persisted through the early morning hours of September 26, when a second period of intense rainfall occurred. Rain had ceased completely in the watershed by 7 AM on September 26. In the uppermost part of the Tiger Wash watershed at the top of the

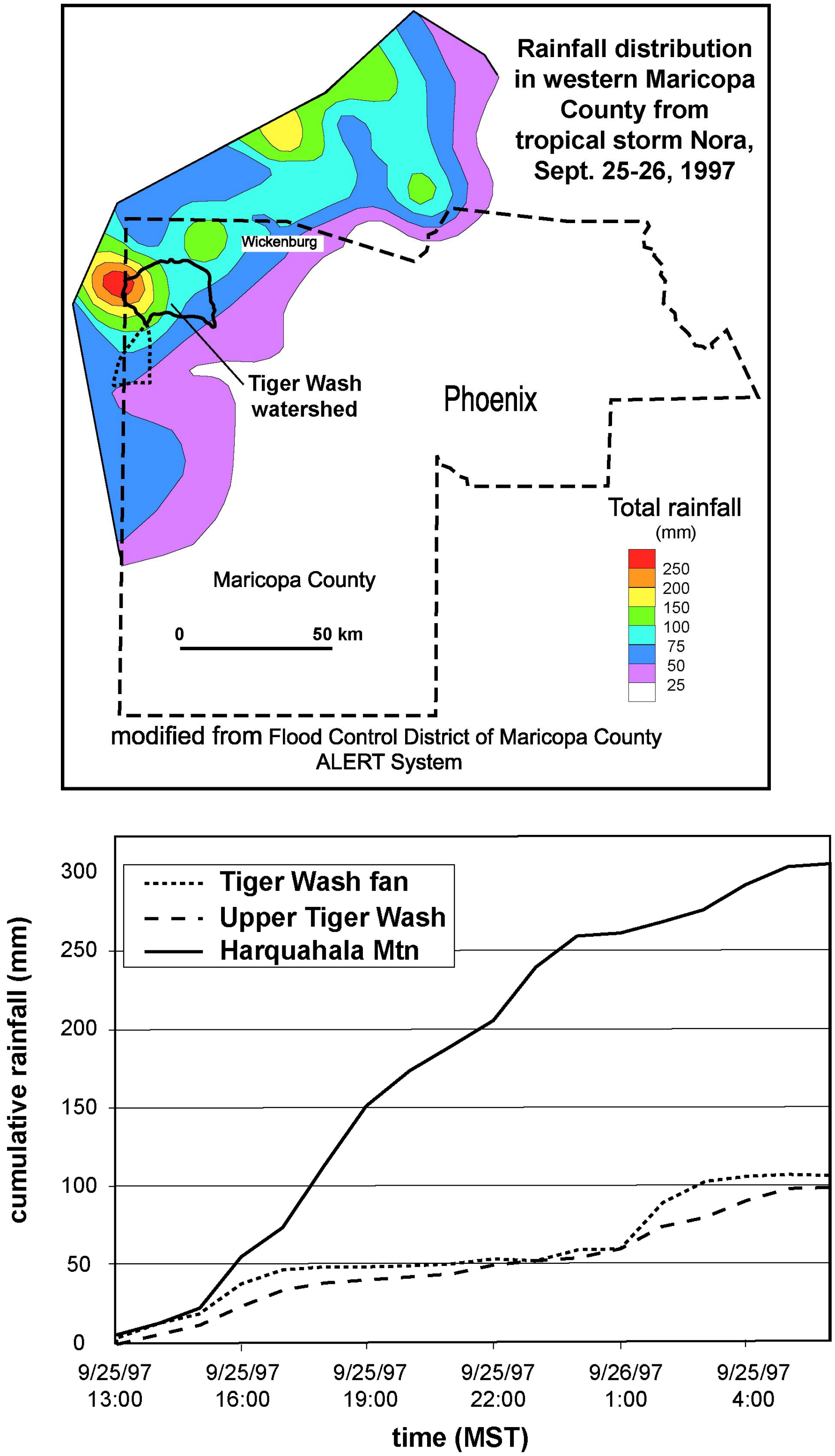

Figure 5. Cumulative rainfall data from Tiger Wash watershed; A) isohyetal map; B) cumulative rainfall at gages in Tiger Wash watershed. Data are from the FCDMC ALERT flood-warning network (http://fcd.maricopa.gov/alert).

Harquahala Mountains, the 304 mm of rain recorded is the highest 24-hour rainfall ever officially measured in Arizona (NCDC, 2003). The maximum hourly rainfall intensity in the uppermost watershed was 41 mm/hr in the evening hours of September 25. Numerous small debris flows occurred in the highest parts of the Harquahala Mountains, attesting to the intensity of precipitation in that area. About 100 mm of rain fell on the lower-altitude rain gages in the Tiger Wash watershed in 18 hours. The most intense precipitation at the lower watershed rain gages occurred in the very early morning hours of September 26, with intensities as high as 26 mm/hr.

Hydrology and Hydraulics of the 1997 Flood

The 1997 flood was the by far the largest flood of the past 40 years on Tiger Wash, and it almost certainly had a relatively long duration of flow compared to any other historical flood on Tiger Wash. Using the rainfall data discussed above, we reconstructed the flood hydrograph by modeling runoff and flow concentration in the watershed and by comparison with more recent floods whose hydrographs were recorded in real time by the FCDMC Alert Network stream gage on Tiger Wash. In addition, we estimated peak discharges at several key locations in the Tiger Wash distributary system to evaluate the apportionment of flow in the system during the 1997 event. Finally, we made a rough estimate of the volume of water that traversed the Tiger Wash distributary system and ponded along the CAP canal.

A rainfall-runoff model developed by the FCDMC for the Tiger Wash watershed (Waters, 1991) was used to develop a model hydrograph for the 1997 flood at the stream gage site. The model included 6 contributing subwatersheds above the head of the distributary network. Runoff was modeled using the HEC-1 model (USACE, 1990). Rainfall excess was computed using the Green-Ampt method with parameters taken from data in the soil survey map of this region (Camp, 1986) as interpreted by Waters (1991). Unit hydrographs were computed from the Phoenix Mountain and Phoenix Valley S-graphs (FCDMC, 1985). Subbasin lag times were based on Manning's *n* values interpreted from field. Routing of flow down the tributary channel network was performed using the Muskingum method with K factors computed from Manning's equation and a flood-wave velocity (wave celerity) factor based on channel shape. Rainfall timing and intensity over the subwatersheds was estimated from the 3 recording rain gages of the FCDMC ALERT network discussed earlier, although the extremely high precipitation recorded on Harquahala Mountain was not given full weight. The resulting model flood hydrograph (Fig. 6A) slightly underestimates the peak discharge as estimated by indirect methods at the stream gage site (210 m^3/s vs. 230 m^3/s; 7350 vs. 8050 cfs), which suggests that somewhat higher amounts of precipitation in the uppermost watershed could have been used in the model. The hydrograph displays 2 peaks, an earlier one associated with precipitation in the late evening of 25 September and a larger peak associated with the intense precipitation in the very early morning hours of 26 September.

Stream gage data recorded by the FCDMC ALERT Network for several post-1997 floods on Tiger Wash also provide insights into the 1997 flood hydrograph. The FCDMC stream gages recorded three moderately large floods in 2000 and another in 2002 (Fig. 6). The floods of June, 2000, and September, 2002 were generated by local thunderstorms. The flood hydrographs rise very rapidly and fall only a little less rapidly, and total flow volumes are relatively small (Table 2). The two floods of October, 2000 were generated by a persistent low pressure trough that produced longer duration, more widespread precipitation with intense intervals imbedded in it

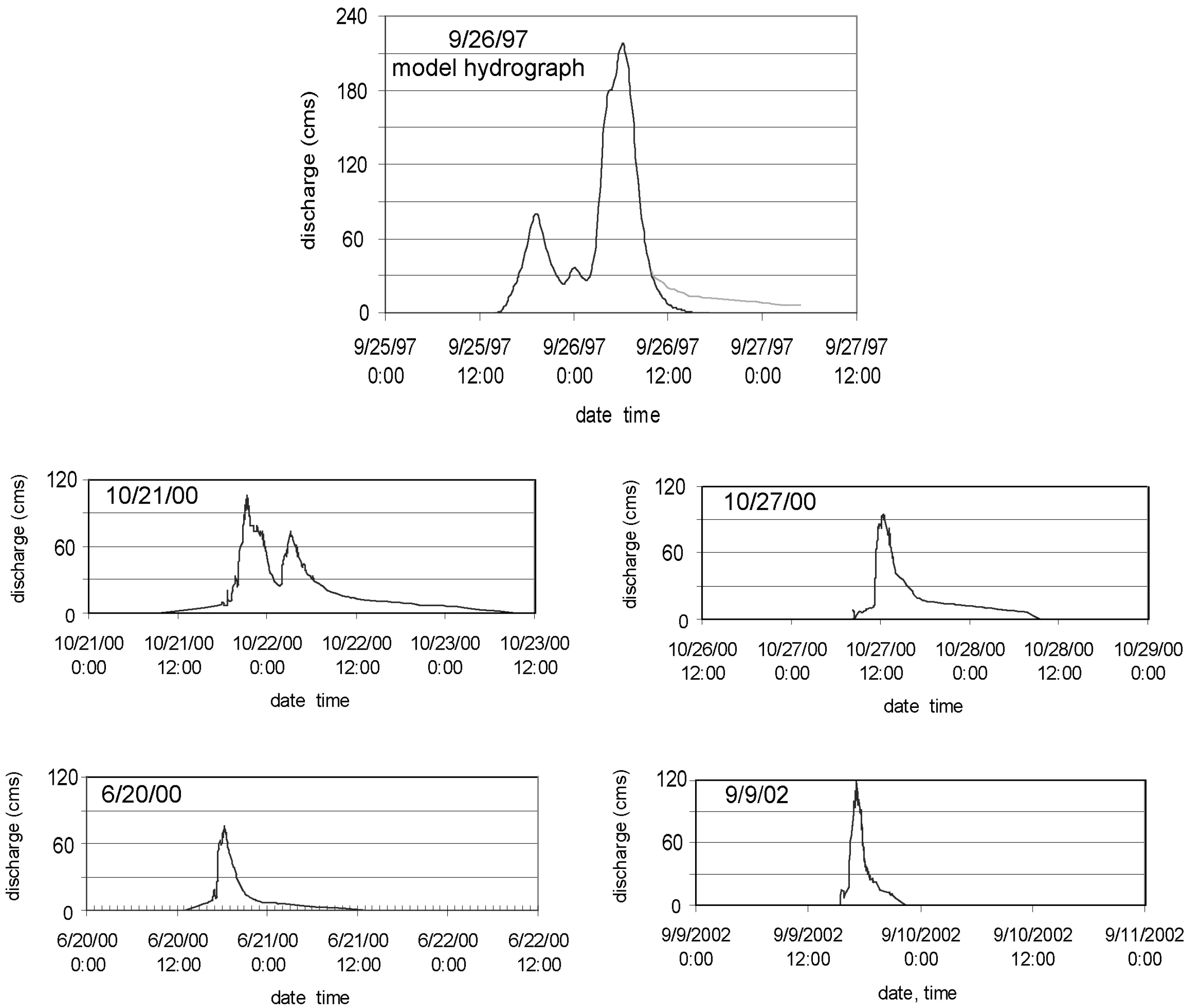

Figure 6. Flood hydrographs for the 1997 flood and subsequent floods above the apex of Tiger Wash fan. The 1997 hydrograph is based on rainfall-runoff modeling of the tributary drainage system. The 2000 and 2002 flood hydrographs were developed using data from the continuously recording pressure transducer stream gage installed in 1999 by the FCDMC. The higher alternative flood tail for the 1997 flood was constructed by appending the tail of the 21 Oct 2000 flood onto the model hydrograph.

(Kellogg and Lehman, 2002), and are certainly more similar to the 1997 flood. The hydrographs for these floods rise quite rapidly but have longer tails, and total flow durations and flow volumes are much greater than from the summer thunderstorm floods. These flood hydrographs provide substantiating evidence for the general form of the modeled 1997 flood hydrograph, and suggest that the actual 1997 flood hydrograph likely had a longer tail than is shown in the model hydrograph. Appending a tail from the 10/21/00 flood to the 1997 hydrograph adds somewhat to the total discharge estimate for the 1997 flood, but even without this manipulation we estimate that the that total 1997 discharge is about twice the total discharge for the 10/21/00 flood and 7 or 8 times larger than the total discharges from recent summer thunderstorm-derived floods. Based on the model 1997 flood hydrograph, the flood was at a stage higher than any of the more recent floods for at least 4 ½ hours (Table 2), and this is consistent with the amount work that was done in the Tiger Wash system during the 1997 flood.

Flood	Peak discharge m^3/s	Flow duration (hours)	Flow volume (m^3)	Time above discharge (hours)				
				30 m^3/s	**60 m^3/s**	**90 m^3/s**	**120 m^3/s**	**180 m^3/s**
9/26/97*	**210**	**25**	**5,140,500**	**13:40**	**7:40**	**5:10**	**4:20**	**1:50**
9/26/97**	**210**	**42**	**5,870,389**	**13:58**	**7:40**	**5:10**	**4:20**	**1:50**
6/21/00	**70**	**9**	**729,372**	**2:35**	**0:57**	**0:00**	**0:00**	**0:00**
10/21/00	**100**	**31**	**2,783,297**	**9:30**	**4:16**	**0:34**	**0:00**	**0:00**
10/27/00	**90**	**25**	**1,672,743**	**4:26**	**1:56**	**0:27**	**0:00**	**0:00**
9/9/02	**110**	**6**	**717,562**	**1:58**	**1:19**	**0:34**	**0:00**	**0:00**

*modeled hydrograph
**modeled hydrograph with tail appended from 10/21/00 flood

Table 2. Measured and estimated flood volumes for recent floods at the stream gage site on Tiger Wash. All of the post-1997 floods were measured in real time by the pressure-transducer stream gage on Tiger Wash operated by the FCDMC. The 1997 flood characteristics are derived from rainfall-runoff modeling.

We estimated peak discharge values during the 1997 flood at several locations in the Tiger Wash system based using slope-area and slope-conveyance methods to evaluate the distribution of flow through the system (Fig. 7). Slope-area analyses rely on multiple channel cross sections, the maximum water surface reconstructed from high-water indicators, channel slopes, and an estimate of bed roughness (Manning's *n*) to estimate peak discharge (Dalrymple and Benson, 1967). Slope-conveyance analyses rely on a single cross section, channel slope through the area of the cross section, and roughness to estimate the peak discharge (JE Fuller Hydrology and Geomorphology, 2000). Based on the peak discharge estimate of 230 m^3/s (8050 cfs) at the Tiger

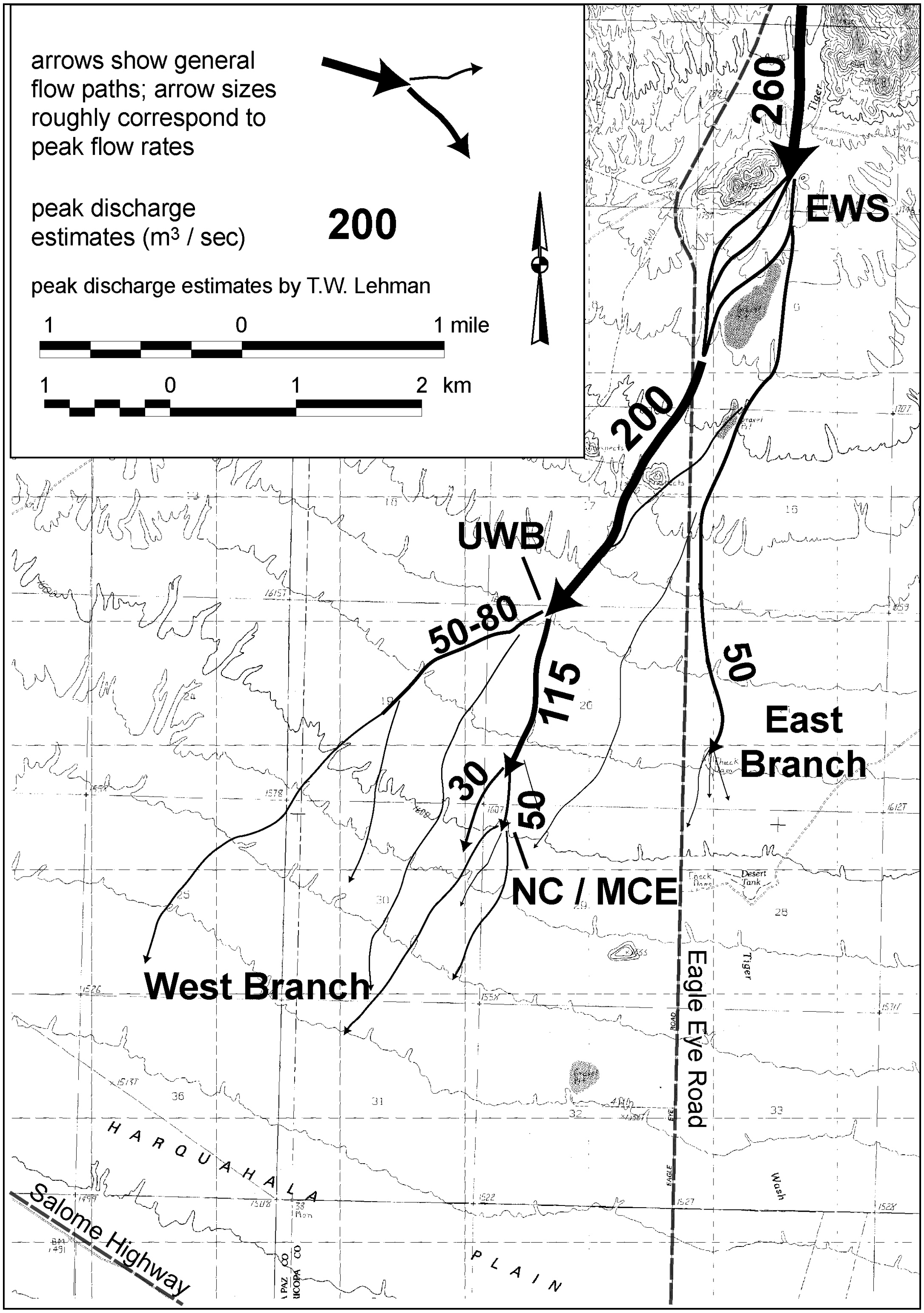

Figure 7. Peak discharge estimates for various locations in the Tiger Wash distributary system. All estimates are in m^3/s. Abbreviations are as follows: EWS, primary east-west distributary split; UWB, upper western breakout; NC/MCE, new channel – main pre-97 channel expansion.

Wash gage site (Tadayon et al, 1998) and the additional contribution of about 30 m^3/s (1050 cfs) from Blue Tank Canyon, we estimate a peak discharge of about 260 m^3/s (9100 cfs) at the head of the distributary system. Below the EWS, the peak discharge in the western branch was about 200 m^3/s (7000 cfs) and the peak on the east branch was about 50 m^3/s (1750 cfs). Peak discharge estimates were made at several key locations down slope in the western distributary system, but some undetermined amount of water was conveyed as unconfined overbank flow and is not accounted for in the discharge estimates. In the area of the upper western breakout (UWB) on the west branch where a new major channel expansion formed, the peak discharge in the new western breakout was at least 50 m^3/s and could have been as much as 80 m^3/s (1750-2800 cfs) based and the peak discharge in the pre-1997 channel below the UWB. This flow continued downslope and eventually entered several discrete pre-existing channels. Just below the UWB, however, most of the west branch flow followed the main channel that existed prior to the 1997 flood; on this reach the flood peak was about 115 m^3/s (4025 cfs). At the new channel breakout (NCB) and main channel expansion (MCE) farther downstream on this flow path, we estimated peak discharges of 30 m^3/s (1050 cfs) in the new channel and 50 m^3/s (1750 cfs)in the main channel pre-flood channel. Downstream of that point the flow continued through multiple channels and broad overbank areas. It should be noted that both the UWB and the NCB, the channel geometry was certainly evolving during the flood and our peak discharge estimates based on post-flood channel geometry are very approximate.

The approximate volume of water that passed through the Tiger Wash system can be estimated because it ponded along the large berms upslope of the CAP canal. We mapped the extent of ponded water based on limited field reconnaissance and the distinctive appearance of the area of ponding on satellite-change imagery (Mayer and Pearthree, 2002; discussed in the next section) and on post-flood aerial photography. The area of ponding was about 3.3 km^2, and the maximum water depth was between 1.5 and 3 m (½ to one 10-ft contour interval). Assuming a triangular cross-sectional geometry with the greatest depth adjacent to the CAP berm, we estimate that the average depth of ponding was ½ the maximum depth. Using a range of average depth estimates of 0.75 and 1.5 m, we estimate that between 2.5 and 5 million m^3 of water passed through the distributary system, which is slightly less or substantially less than the input discharge volume estimated from the model flood hydrograph (5.1 to 5.9 million m^3). Flow may have been augmented by rainfall on the fan during the flood, although the flood peak probably occurred after most rainfall had ceased on the fan (see Fig. 5; Fig. 6) infer that flow would have been diminished substantially by infiltration as floodwater spread through the complex distributary system, which was dry prior to this storm. It is not surprising, therefore, that the ponded volume is less than the input volume, but even if we assume that the smaller ponded volume estimate is correct much of the floodwater made it all the way through the system. This may be explained by several factors: (1) the relatively long duration of flow, such that during the latter part of the flood much of the substrate was saturated; (2) the double-peaked nature of the flood hydrograph, such that the second and larger flood peak flowed through a system that was at least partially saturated by previous flow; and (3) the regional nature of the precipitation event, such that the whole system was moistened by heavy rainfall prior to the flood.

Inundation Mapping

The 1997 flood obviously was a large flood that inundated much of the Tiger Wash distributary system. It was apparent during a preliminary reconnaissance visit to Tiger Wash in November, 1998 that there was abundant evidence of widespread inundation and that some channel change had occurred in the west branch. The evidence of inundation was still very well preserved when we began mapping in earnest in the spring of 1999. We utilized the evidence left by the flood to (1) map in the field the extent of inundated areas in much of the Tiger Wash distributary system; (2) differentiate flow categories based on sedimentologic and high water indicators; and (3) document channel changes from the 1997 flood. More recently, we used satellite-based information to extrapolate our inundation mapping through the whole distributary system above the CAP canal.

Mapping methods

Limits of inundation were initially mapped in the field using a 1:15,000-scale mosaic of black-and-white aerial photos from February, 1998 provided by the FCDMC. Fresh sediment deposited by the flood showed up much better on 1:9,600-scale color aerial photographs covering the west branch that were acquired for this project in March, 1999, so much of the final mapping was done on the color photos (Fig. 8). In addition, processing of multi-spectral satellite data to detect landscape changes associated with inundation correlated extremely well with the independent field inundation mapping (Mayer and Pearthree, 2002). This satellite change information was utilized to map the extent of inundation at lower resolution down slope to the CAP canal. In the area of detailed field mapping, inundation was subdivided into several categories based on spot field observations of flow depth and detailed topographic transects that were surveyed across various parts of the Tiger Wash system. Inundation mapping was compiled, rectified and georeferenced, so that map patterns of inundation may be quantified and compared with the distribution of surficial geologic units of various ages.

Several kinds of field evidence were used to map the extent of inundation. The most ubiquitous evidence left by the flood was freshly transported sediment. In areas of deeper inundation, fresh sediment typically is light-colored sand and gravel. This sediment partially buried vegetation of various sizes, and in many places sandbars were deposited on the lee sides of bushes or trees. In areas of shallower flow, fresh sediment typically consisted of thin sheets of fine sand, silt and clay. The color of this fine-grained sediment was commonly slightly redder than deposits that pre-dated the flood, and this was evident both on the ground and on the color aerial photographs (Fig. 8). This relatively delicate evidence of inundation has degraded quite rapidly and generally was no longer apparent in 2003. In areas of slackwater deposition, typically in the mouths of small tributary channels, the fine sediment deposited by the flood commonly developed moderately large cracks as it dried. Flotsam (floated organic debris) was also a very common indicator of flow. Fine flotsam was found around the margins of inundation and on partially inundated mounds around bushes. In and along channels, flotsam ranged in size up to moderately large uprooted trees. Flotsam was observed in living trees and bushes in areas of deeper flow. Evidence of fresh scour and formation or modification of gullies of various sizes was also common. In these areas, it was evident that the surface had recently been swept clean or substantially altered by erosion. Scour commonly was focused between bushes or in animal burrows in areas of sheet flooding. In a number of places, reddened and moderately indurated Pleistocene deposits were freshly exposed in gullies and stream channels.

Flow categories

We were able to draw some conclusions about the character of flow based on indicators of flow depth and the nature of sedimentation by field-checking parts of the distributary system and surveying several long, detailed topographic cross sections perpendicular to drainage. Because

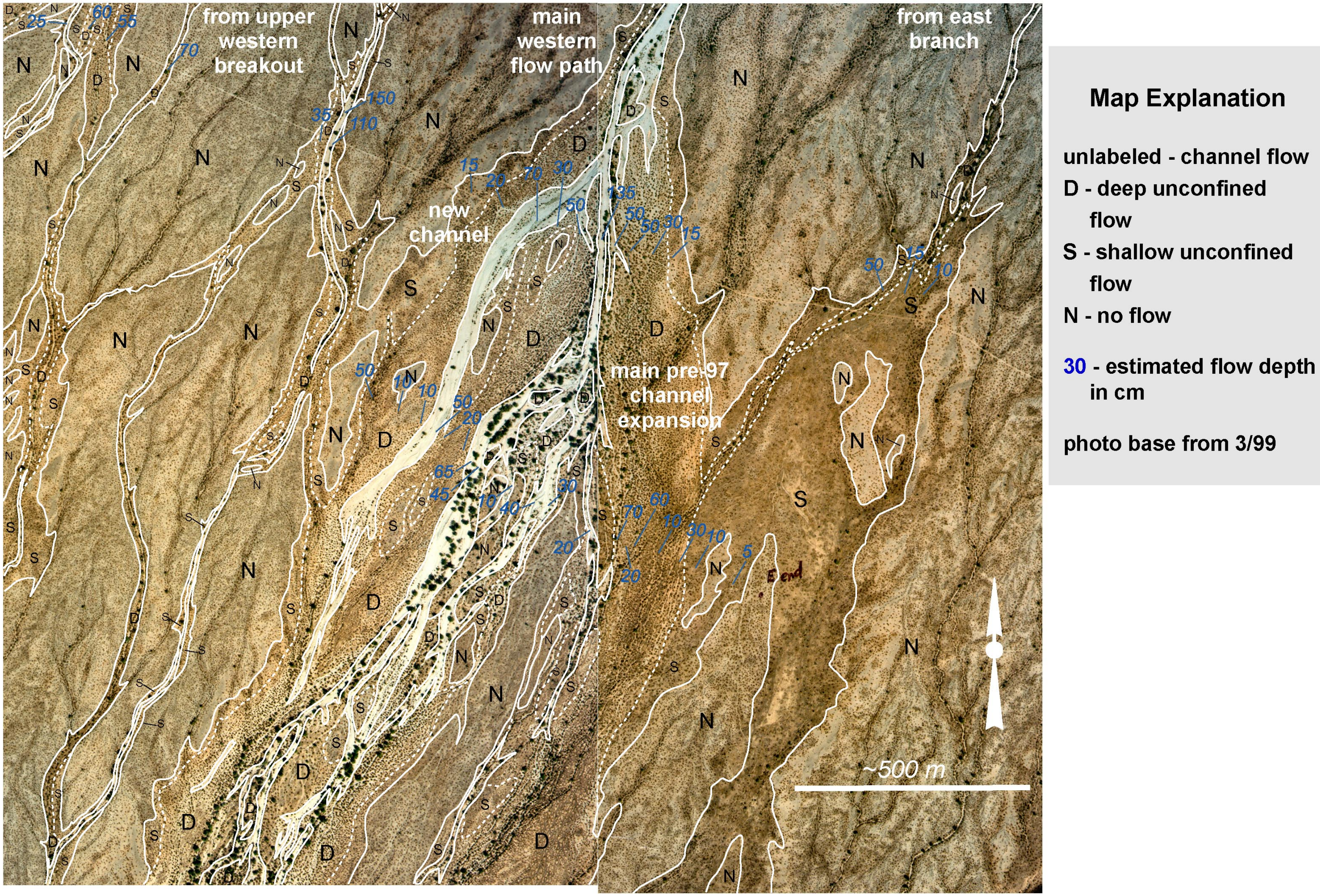

Figure 8. Annotated aerial photograph showing flood inundation mapping in part of the west branch of Tiger Wash.

the following inundation categories have distinctive patterns on the post-flood color aerial photographs, we used the photos to delineate areas of different flow character (Fig. 8).

1) Channel flow – moderately deep to deep flow in areas that are recognizable as channels on the post-flood aerial photos. These areas were mapped based on the light color imparted by extensive fresh sand and gravel and lack of vegetation (Fig. 9). This unit does not include many small channels that cannot be mapped at 1:9,600 scale or larger channels that did not convey significant flow during the 1997 flood. Based on our transect data and spot depth estimates, channel flow depths varied from about 20 to 200 cm.

2) Deep unconfined flow – most of the area included in this category consists of broad swaths of moderately deep flow that was not confined in channels. This flow typically occurred adjacent to channels and down slope from them (Fig. 10). The topography of areas where deep unconfined flow occurred typically consists of alternating small swales or gullies and sand bars oriented parallel to the flow direction, resulting in a corrugated surface. Swales typically had little or no vegetation after the flood, and bars commonly formed on the lee sides of bushes. Flow depths varied substantially over short distances, but flow was at least 20 cm deep in most of the small swales or gullies in these areas. Relatively deep flow in small confined drainageways is also included in this category.

3) Shallow unconfined flow – broad areas of very shallow unconfined flow. In the upper part of the distributary system this flow typically occurred along the margins of overbank areas or on terraces. Shallow sheetflooding was very extensive down slope, so that it comprised nearly all of the inundated area in the lower part of the map area (Fig. 10). Flow was very wide and sheet-like, and less than 20 cm deep except in a few small gullies. Local topographic relief in these areas is generally minimal, and higher areas around bushes commonly were not inundated.

4) Undifferentiated unconfined flow – broad areas of predominantly shallow sheetflooding on the east branch system and down slope from the detailed mapping area. Unconfined flow was not subdivided in these areas because we did not have post-flood color aerial photographs (east branch) or did not field check these areas.

Limitations and Uncertainties

There are several sources of uncertainty in the detailed flood inundation map. It was difficult to identify precise locations in the field in areas with low relief and few trees, especially on the black-and-white aerial photos. Use of the new color aerial photos greatly reduced position uncertainty. For example, limits of inundation in areas where the flood lapped onto fine-grained, young deposits were reasonably obvious in the field but were not obvious on the black and white aerial photomosaic used in most of the field mapping. Contrast between inundated and non-inundated areas is much greater on the large-scale color aerial photos from 1999, so many inundation boundaries were revised from the preliminary inundation map using the color photos with limited field checking. There is more uncertainty in the locations of inundation boundaries on the east branch system, where color photos were not available. The lower half of the inundation map is based on interpretation of satellite change imagery and aerial photographs with minimal field checking, and thus unit boundaries are much more approximate in this area. All boundaries between areas of deep unconfined flow and shallow sheet flooding are gradational. Detailed inundation mapping was done on overlays of aerial photos. Individual aerial photos were rectified and registered in a GIS framework using geographic features in an effort to minimize distortion. There are some variations in scale through the photos and some distortion persists even after rectification.

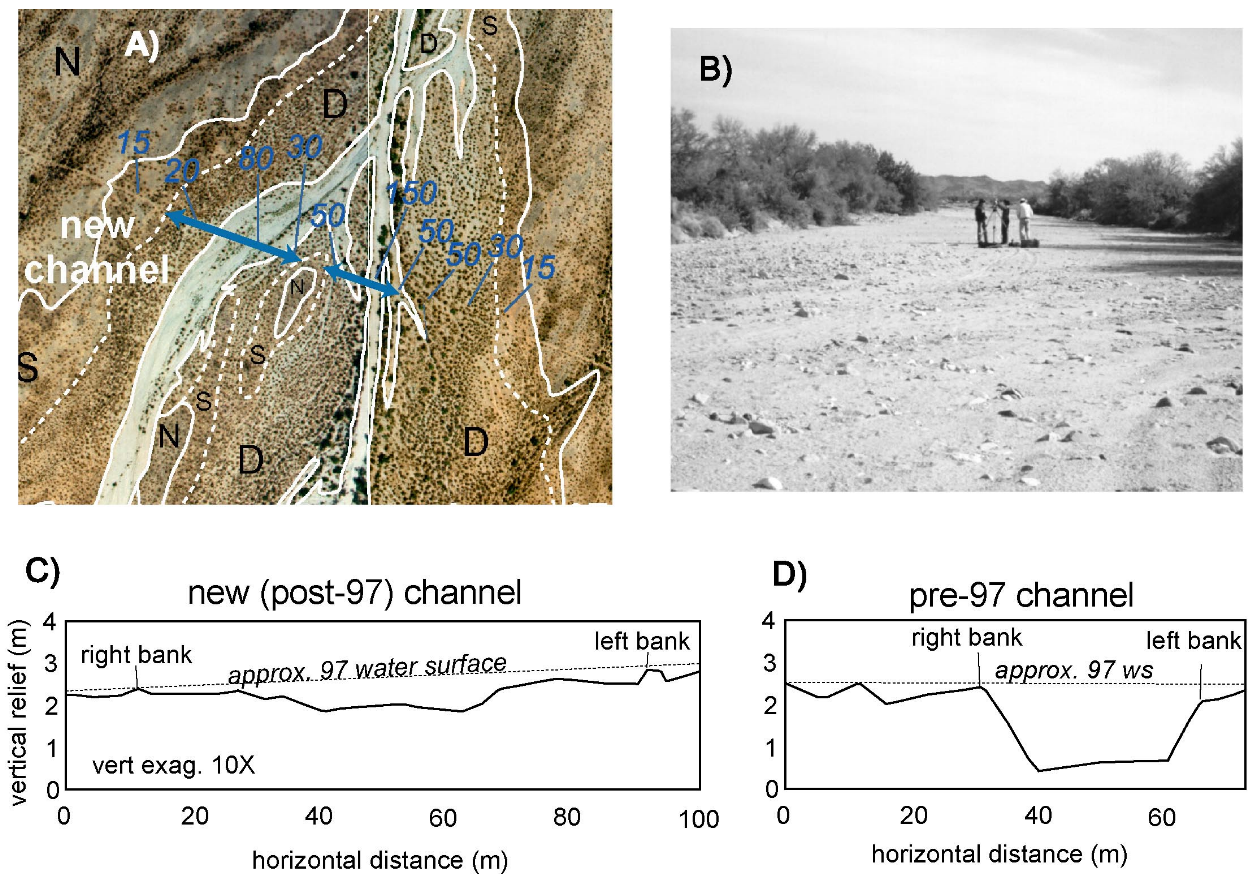

Figure 9. Various characteristics of channel flow. (A) Annotated aerial photo shows part of the main pre-1997 channel (right) and the new channel that formed in 1997 (left). (B) Ground photograph of the main channel above the new channel breakout. (C) Topographic section across the wide, shallow new channel along the dirt track that can be seen in (A); note transect is oblique to the channel, and that is responsible for at least some of the apparent inclination of the water surface. (D) Topographic section across the much narrower and deeper pre-1997 main channel.

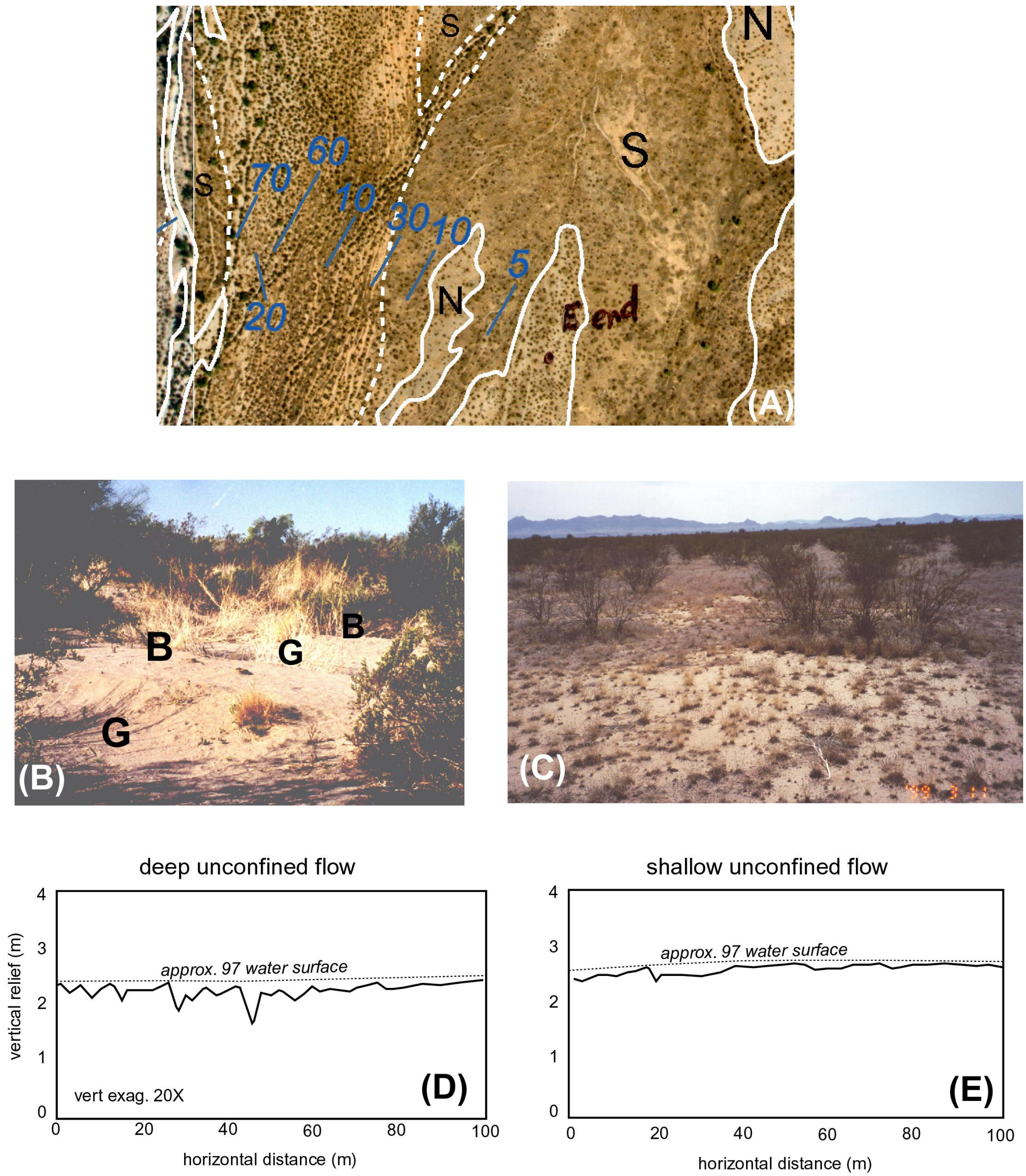

Figure 10. Various characteristics of unconfined flow. (A) Annotated aerial photograph of the area of unconfined flow east of the main channel expansion. (B) Ground photo of the bars (labeled B) and gullies (G) typical of the topography of areas that experienced deep unconfined flow. (C) Ground photo of an area of very shallow flow. Fresh fine-grained sediment from the 1997 flood gives the light tan color to the surface in the foreground. (D, E) Topographic sections typical of areas of deep and shallow unconfined flow.

The Character and Extent of Flood Inundation

The inundation map for the 1997 flood records the transition from narrow, confined flow at the head of the distributary system to multiple flow paths and eventually to very extensive and shallow sheetflooding in the lower piedmont (Fig. 11; Plate 2 on CD). Floodwaters followed the general outlines of the network of distributary channels and young deposits that existed prior to the flood, but because the flood was an extreme event on the western branch inundation was very extensive and flow went into some surprising areas in that part of the system. In this section, we review the general patterns of inundation through the distributary system, including areas that were mapped in detail and those lower in the system that were mapped on a reconnaissance basis only. We discuss in more detail a few particularly interesting areas. In addition, we consider the extent of the different types of inundation and the inundation of alluvial surfaces of various ages as they existed prior to the flood.

General Distribution of Flow

Just above the head of the distributary system, flow filled braided channels and inundated most of the Holocene floodplain, including islands between channels and marginal overbank areas. Flow patterns became much more complex beginning at the EWS, where flow divided into multiple distributary channels. Although there were local areas of widespread flooding at the EWS and in the area of the gravel pits, for the most part flow in the upper piedmont was conveyed in well-defined channels and inundation was very limited (Fig. 12).

Consistent with the indirect discharge estimates discussed earlier, the flood appears to have been a moderately large event in the east branch system. In the upper and middle piedmont, most flow was contained in a channel just east of Eagle Eye Road. Several smaller distributary channels conveyed minor flow to the west of the road and a small amount of flow followed a distributary channel to the east at the top of the EWS, was augmented by flow from smaller washes draining the south side of the Big Horn Mountains, and eventually rejoined the east branch flow above Salome Highway (Fig. 11). Along the primary eastern flow path, flow became much more laterally extensive and shallow in the middle piedmont as topographic confinement of channels diminished abruptly. Downstream from that point, very shallow sheetflooding dominated due to the minimal topographic relief and flow in channels was a minor component of the flooding. Broad, low relief areas covered with late Holocene deposits east and west of Eagle Eye Road were not inundated; it appears that the road and low earthen berms associated with it diverted the shallow sheetflooding to the east and south.

Inundation was more widespread on the west branch of the system, where nearly all of the late Holocene deposits (units Qyc and Qy2) were inundated, inundation of older deposits was fairly extensive, and several new channels developed. In the upper piedmont, nearly all flow in the west branch was confined in a relatively large and deep (2-3 m) channel between Pleistocene and Holocene alluvial fan deposits, although flow nearly spilled out onto these fan surfaces in several places. A minor amount of flow from the east branch joined the west branch system along several confined distributary channels. Down slope, inundation was extensive at a new large channel expansion that developed on the outside of a channel bend (the UWB; Fig. 12). Down slope from this expansion a substantial amount of flow spilled into several pre-existing tributary channels west of the pre-1997 main channel, resulting in their incorporation into the

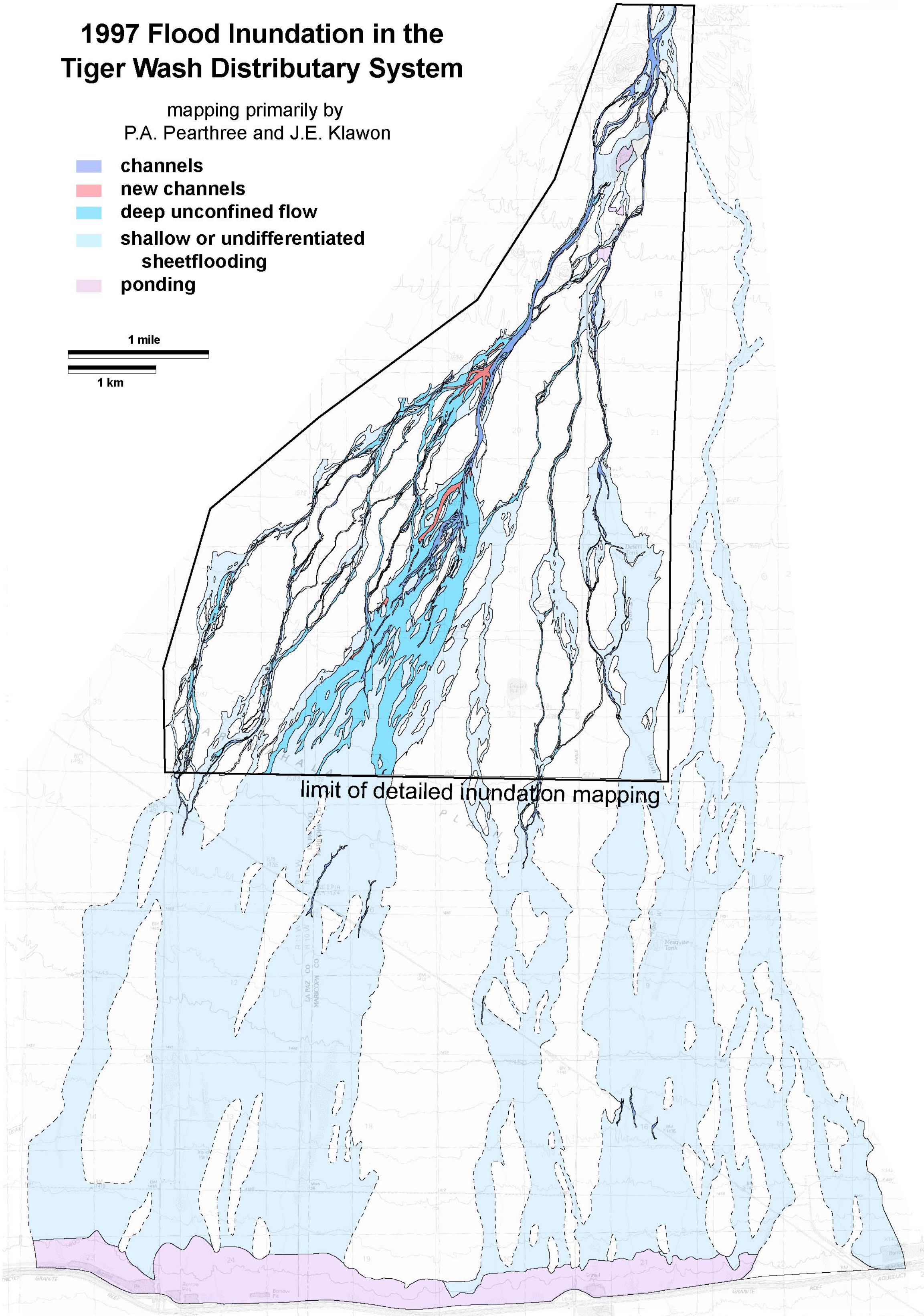

Figure 11. Inundation map for the entire Tiger Wash distributary system. See also Plate 2.

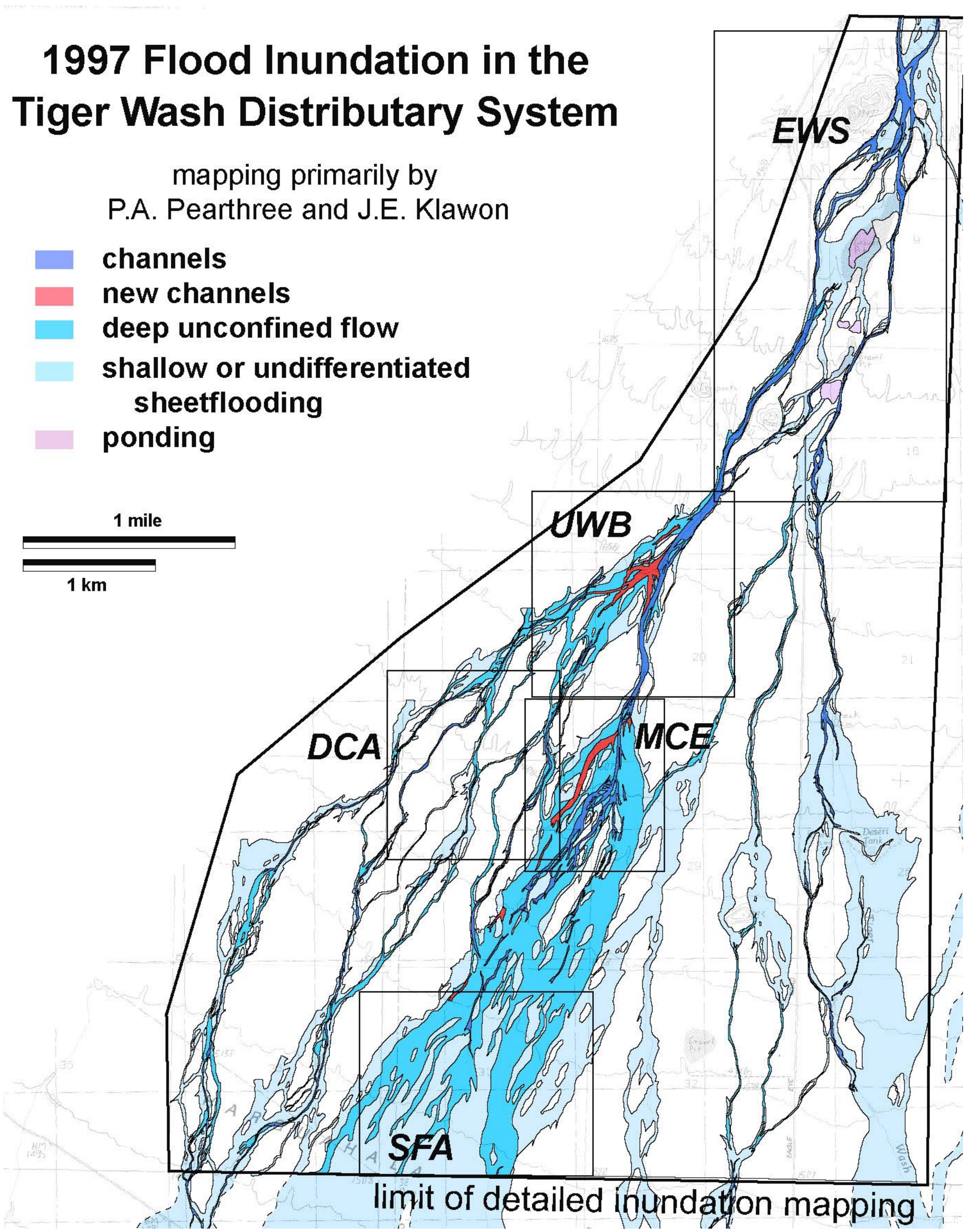

Figure 12. Detailed field-based inundation map of the upper parts of the west and east branches. Limits of inundation were identified and mapped in the field. Division of inundation into various categories was based on field observations and interpretation of post-flood aerial photographs. Specific areas discussed in the text are identified as follows: EWS, primary split between east and west branches; UWB, upper western breakout; DCA, separate distributary channels area; MCE, main pre-1997 channel expansion and new channel area; and SFA, broad sheetflood area.

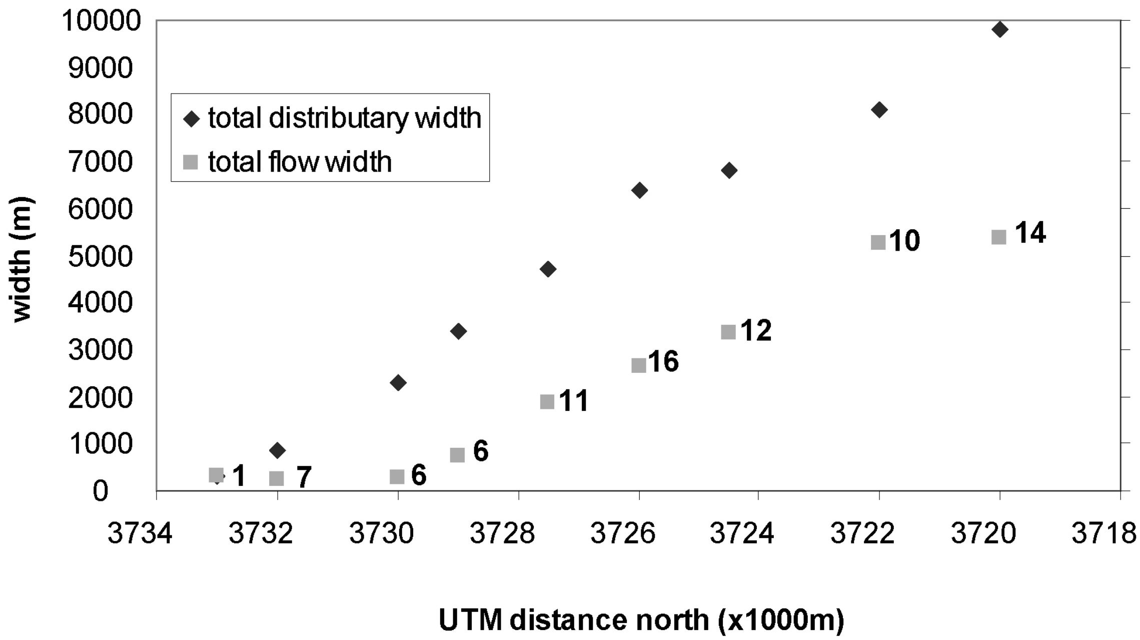

Figure 13. Width of the distributary system and cumulative flow width measured on west-east transects across the entire distributary system. The northernmost transect is located just upstream of the EWS, and the southernmost transect is located about 1 km upslope from the CAP canal. Numbers next to flow width points indicate the number of separate flow paths on each transect.

distributary channel network (DCA, Fig. 12). Flow in the westernmost of these channels was augmented by a few tributary washes that drain the southern piedmont of the Harquahala Mountains. Flow was confined and limited in areal extent long most of these distributary channels, but in areas where topographic confinement diminished flow broke out and joined other channels resulting in a fairly complex pattern of splitting and joining flow paths. Along the primary west branch flow path, inundation became laterally extensive in both overbank areas above the MCE. Deep unconfined flow was extensive and a large new channel developed within the sheetflood area on the west overbank (MCE, Fig. 12). Channel flow gradually diminished in importance down slope from the MCE, but there were broad areas of deep unconfined flow marginal to and downstream from the primary channel network. Very shallow sheetflooding predominated in the lower 10 km of the distributary system (Fig. 11; SFA, Fig. 12), with a few small areas of channel flow just upstream and downstream from Salome Highway.

Inundation unit	Area (m^2)	Percent of Inundated Area	Percent of Mapped Area
channels	805,444	1.8	1.0
new channels	110,235	0.3	0.1
deep unconfined flow	2,625,341	6.0	3.1
shallow sheetflood	4,102,489	9.4	4.9
undifferentiated flow (predominantly shallow sheetflood)	32,672,833	74.7	38.7
ponded areas	3,394,818	7.8	4.0
all inundation	43,711,159		51.7
no flow	40,803,641		48.3

Table 3. Extents of different types of inundation in the whole mapped inundation area. The northern limit is just above the head of the distributary network, the eastern and western limits are extent of any inundation associated with Tiger Wash, and the southern limit is the CAP canal.

The general characteristics of the inundation map outline the types of flow that were dominant in different parts of the system. In the whole map area (including both field mapping and remote-sensing based mapping), about 50 percent of the area within the outer limits of the distributary system was inundated in the 1997 flood (Table 3). Relatively deep channel flow and unconfined flow was quite restricted, comprising only about 8 percent of the detailed map area and a smaller percentage of the whole map area, so by far the most extensive type of flooding was shallow sheetflooding. At the head of the distributary system, the extent of inundation was essentially the same as the width of the system (Fig. 13). Beginning at the EWS, however, the width of the distributary channel network increased dramatically while the width of inundation increased very little, reflecting the allocation of floodwater into a few narrow flow paths in the upper piedmont. The total width of the distributary network increased rapidly in the upper and middle piedmont, and the total number of separate flow paths increased to a maximum of 16. The width of the distributary network reached a maximum of about 10 km just upslope from the CAP canal. Total width of inundated area began to increase substantially in the middle piedmont beginning at the UWB and including the main expansion reaches on both the east and west branches, reflecting the increasing importance of unconfined flow. On the middle and lower piedmont where shallow sheetflooding dominated, individual flow paths were broad and the total width of inundation was 40 to 60 percent of the total width of the distributary network.

Flood Inundation vs. Surface Age

Inundation during the 1997 flood was concentrated on the youngest surficial geologic units, which indicates that surficial geologic mapping is a good predictor of the distribution of flood-prone areas on piedmonts. Mapped channels (unit Qyc) were nearly entirely inundated, and about 70 percent of the young, fine-grained deposits (Qy2) were inundated (Table 4). The percentage of inundation decreased with increasing surface age, clearly indicating that most areas covered with Pleistocene surficial deposits are not prone to flooding in the modern environment. Nonetheless, there were many relatively small areas where Pleistocene surfaces were inundated in 1997 (Fig. 14). Most of the inundation of older alluvial surfaces occurred in thin strips along their margins, and in these situations inundation of adjacent younger surfaces was much more extensive (Figs. 14A, 14B, and 14C). In a few areas, however, inundation of Pleistocene surfaces was deep and serious surface scour occurred. This was especially true along the main western flow path from the area of the MCE down slope, where a relatively large amount of floodwater passed through an area with little topographic relief (Fig. 14D, 14E). This inundation and local erosion of older piedmont deposits illustrates the concept that the margins of active alluvial fan areas are evolving over time, and the contacts between young and older surficial deposits along the active fan margins are modified during large floods.

	Inundation Category						
surficial geologic unit	channel	new channel	deep flow	shallow flow	undivided sheetflow mostly shallow	all inundation	no flow
Qyc	58.5	0.0	12.3	8.5	15.8	96.4	3.6
Qy2	0.8	0.2	4.9	7.0	57.3	70.1	29.8
Qy1	0.6	0.1	2.1	4.1	36.3	43.1	56.9
Ql	0.1	0.0	0.9	2.7	19.6	24.8	75.2
Qm	0	0.1	1.2	2.0	7.3	10.6	89.4

Table 4. Inundation of surficial geologic units as a percentage of the total extent of the unit for whole inundation map area. The presence of minor amounts of "channel" flow in units Qy2, Qy1, Ql, and Qm reflects the greater level of detail in the inundation vs. surficial geologic mapping, as those channels existed prior to the 1997 flood.

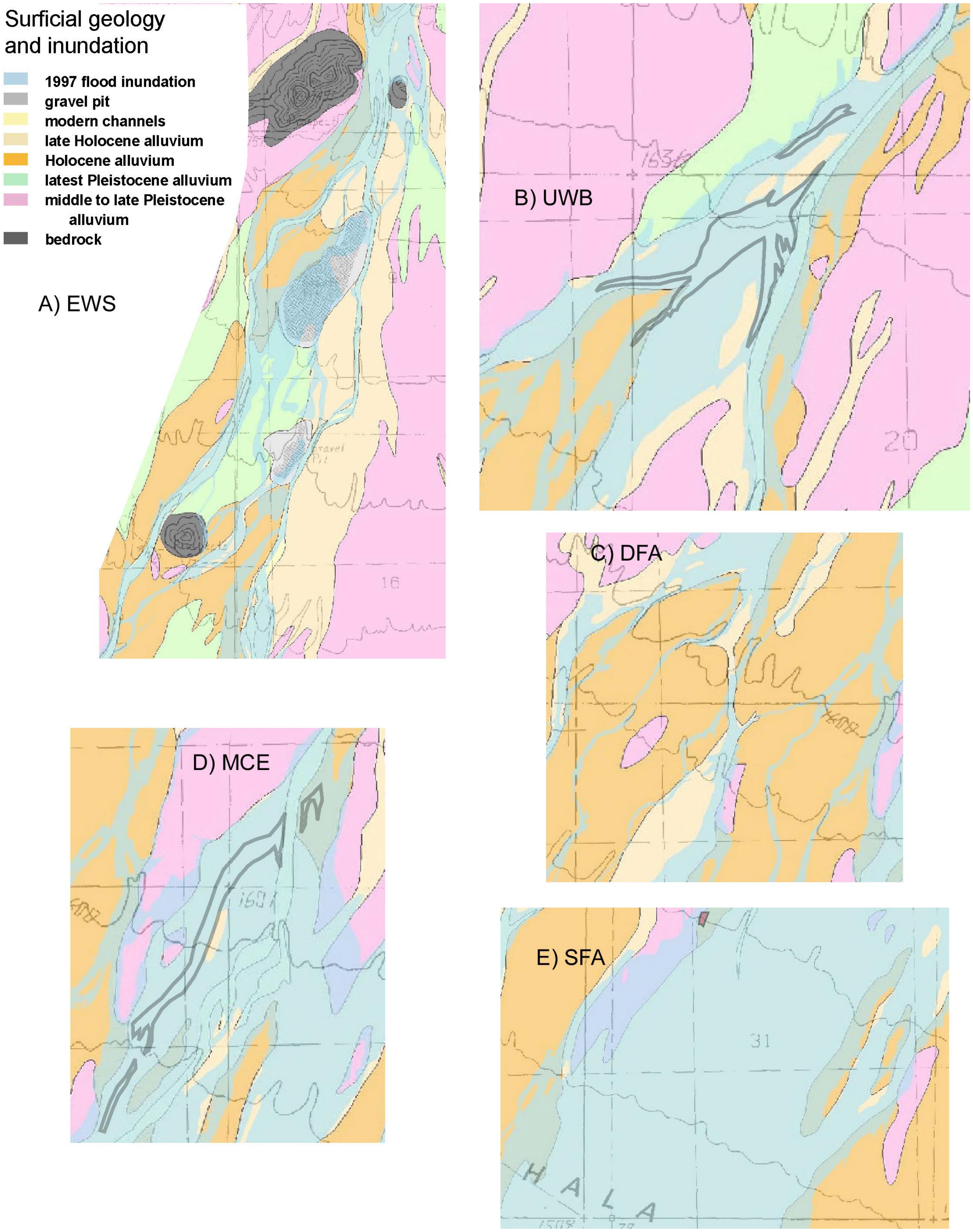

Figure 14. The extent of inundation during the 1997 flood overlain on the surficial geologic mapping. Approximate locations of these areas are shown on Figure 12.

Channel Changes and Development of New Channels

The most dramatic changes that occurred during the 1997 flood resulted from the drastic modification of existing channels or the development of new channels. Development of new channels is also the most frightening flood hazard associated with alluvial fan flooding, as the allocation of flow in the distributary system may be substantially altered and deep, high-velocity flow may occur in areas that did not appear to be particularly dangerous before the flood. As was noted in the previous section, the total area of new channel development in the Tiger Wash distributary system was minor. Nonetheless, increases in channel widths inferred from the aerial photographs were pervasive in the west branch system, and profound channel changes in a few areas likely will have significant impacts on future flood flows. In this section, we examine several areas where channels were substantially altered or new channels developed during the 1997 flood.

Primary East-West Distributary Split

The EWS is obviously the critical area for partitioning of flow between the east and west branches during floods on Tiger Wash. As was discussed earlier, roughly 75 percent of the peak discharge was apportioned to the west branch in 1997, resulting in the flood being an extreme event on the west branch and a modest event on the east branch. Comparison of channel patterns just before and after the 1997 flood does not reveal any dramatic changes (Fig. 15), but it is difficult to confidently assess the impact of the gravel pits that were excavated between the two branches in this area. Prior to the 1997 flood, the main west branch channel looked slightly brighter and wider than the east branch channel, but the differences are rather subtle. During the 1997 flood, a substantial increase in channel size occurred in the western part of the braided channel system at the very top of the EWS (Fig 15, site E), which may have shunted more flow into the western branches of the EWS downstream. There is some increase in apparent channel area on the westernmost distributary channel (site W), but there are few obvious changes on the principal western channel (site C). Flow that was headed down the main eastern channel breached an earthen berm on the right bank (site P), spilled into a series of small gravel pits and rejoined the main western channel (site H). The peak discharge and volume of the flow that took this route is not certain, but the pits were filled with water and flow from both branches mingled over a north-south distance of at least 500 m. Fresh headcuts that developed in the southwestern part of this area imply that significant flow was leaving the gravel pits and entering the western channel, so it is likely that the gravel pits did contribute substantially to diversion of flow into the west branch system.

Upper Western Breakout

The most dramatic changes in the entire Tiger Wash system occurred at the UWB in the west branch system. A major channel expansion developed in an area that had formerly been the right overbank on the outside of a moderate left bend in the main western channel (Fig. 16A). Outside bends are prime locations for channel widening through bank erosion in floods, and it is evident from the bulge in the right bank of the channel in the pre-flood photo that erosion of this bank had occurred prior to the 1997 flood (Fig 16A, site B). Faint lineaments evident on the pre-flood photo (site O) suggest that during floods some flow in the right overbank area was conveyed to the southwest in small swales.

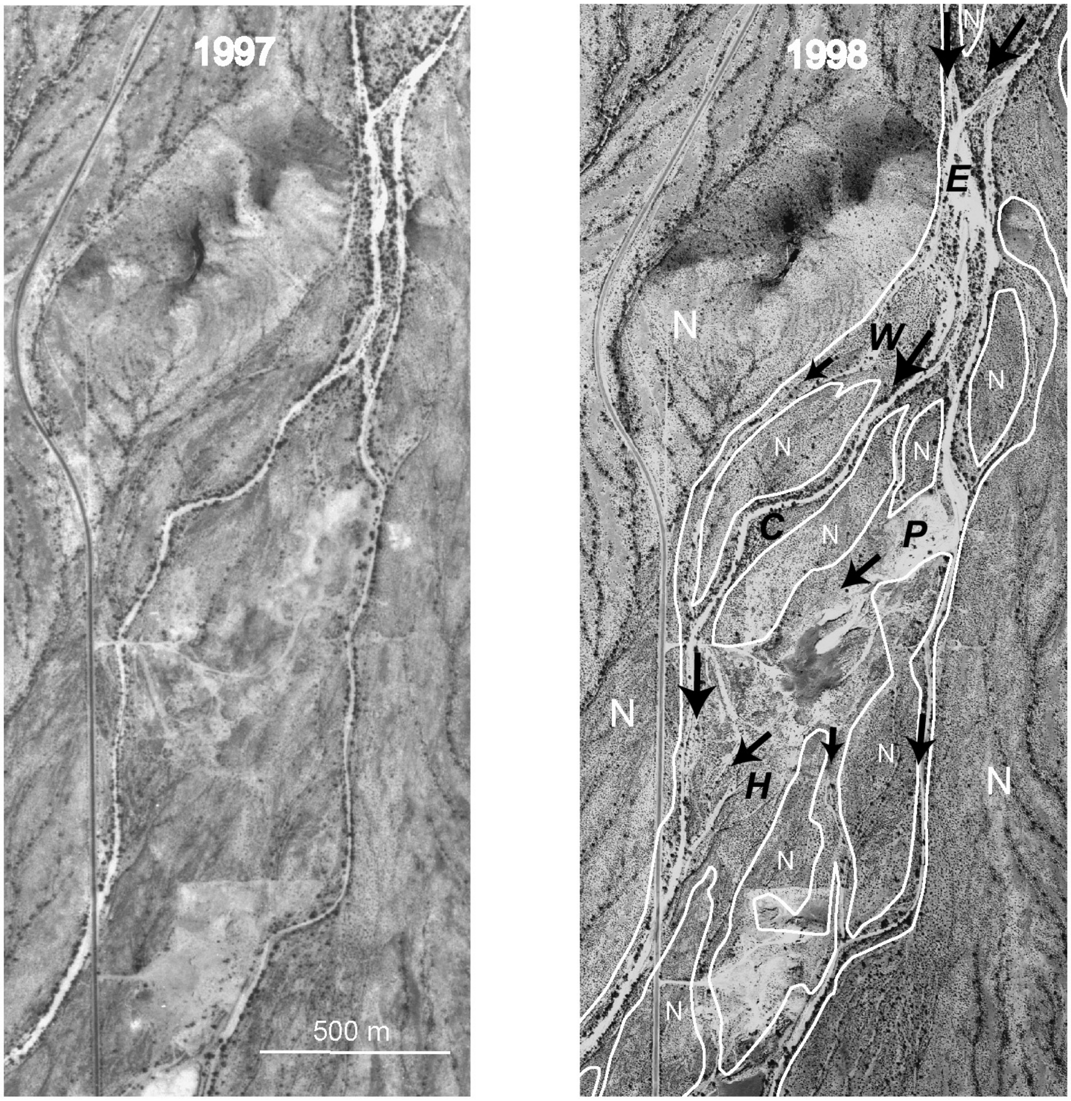

Figure 15. Aerial photographs of the EWS from immediately before and after the 1997 flood. Areas that were not inundated in 1997 are labeled “N”. Specific sites labeled with various letters are discussed in the text. Black arrows on the post-flood photo indicate flow directions.

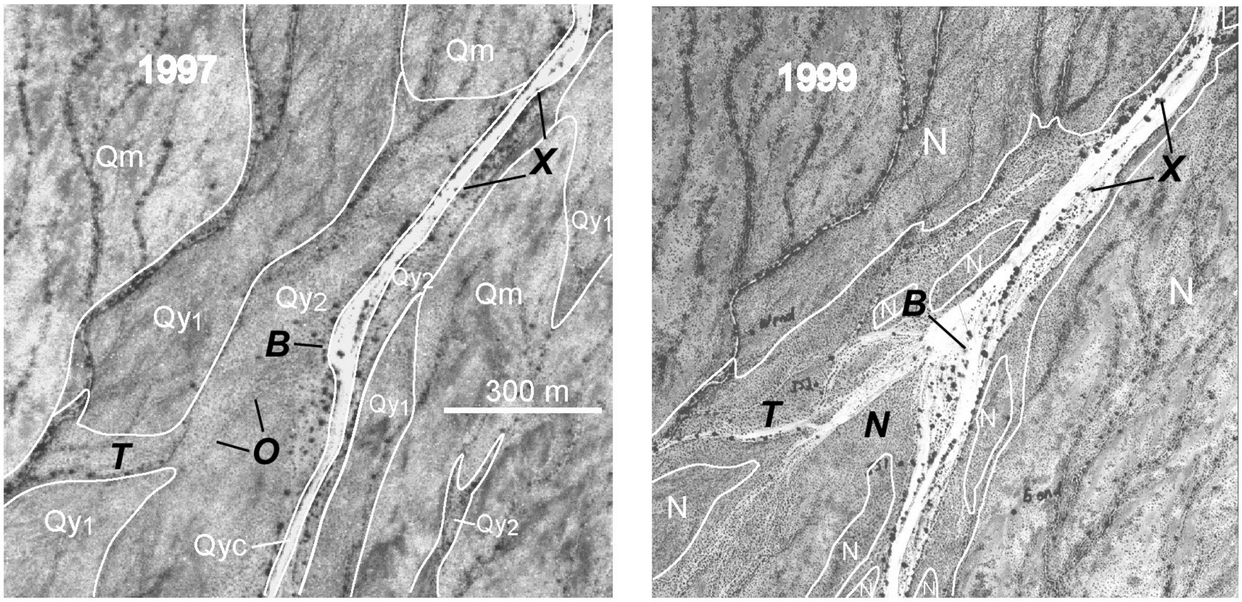

Figure 16A. Before and after aerial photographs illustrate the dramatic channel change that occurred at the UWB in 1997. Black letters identify sites discussed in the text.

Figure 16B. Ground photo looking downstream at the UWB in 1999. The pre-1997 channel slopes more steeply than the breakout channel, but the breakout channel is directly in line with the main channel upstream.

During the 1997 flood the right channel bank that existed prior to the flood was completely obliterated due to some combination of bank erosion and massive sediment deposition, leaving a very broad channel expansion at grade with the channel bed upstream (Fig. 16B). The channel at and just upstream of the pre-1997 channel bend quadrupled in width during the flood and is now more than 200 m wide. A likely source for much of the sediment deposited at the UWB is the main channel upstream. Along that reach, the channel width approximately doubled through incorporation of the left overbank area into the active channel (site X). Trees that formerly lined the left bank of a relatively narrow channel are now in the middle of a much larger channel. The development of a major channel expansion allowed a substantial amount of flow to diverge from the main pre-flood flow path in new channels and a very broad area of sheetflow. One branch channel from the UWB extended to the southwest (site N), linked up directly with pre-existing tributary channel and integrated it with the distributary system (site T). Although they are not directly linked by channels to the distributary network, other tributary channels west of the pre-1997 channel received significant flow as sheetflow became concentrated down slope into existing drainages (Fig. 12). This resulted in a major expansion of the active distributary system to the west during the 1997 flood.

Although the scope of change at the UWB was striking, it developed in a reasonably predictable location and almost entirely in very young deposits (unit Qy2; Fig 16A; Fig 14B). The UWB developed near the outside of a channel bend where banks may have been fairly low. As was noted above, pre-1997 aerial photographs strongly suggest that overbank flow occurred in this area during previous smaller floods of the past few decades. In addition, major channel expansions similar to the current one existed previously during the Holocene because very extensive, moderately coarse older Holocene alluvial-fan deposits (unit Qy1) mantle much of the area down slope of the UWB and west of the pre-1997 flood distributary network (Fig. 3; Fig 14B, 14C). In its current configuration, the western breakout is directly in line with the main channel upstream, which would tend to direct more flow and sediment into the breakout and the western distributary network during future floods. This tendency is counterbalanced by the fact that the gradient down the pre-1997 channel at the UWB is much steeper, so the pre-1997 channel captured most of the flow in the moderate floods of 2000 and 2002. Nonetheless, some of the former tributary drainages southwest of the UWB are now directly linked to the main channel and received flow in all of the post-1997 floods. This is obviously a dynamic part of the Tiger Wash system where continued changes are likely to occur in future floods.

Main West Channel Expansion / New Channel Breakout

Development of a large new channel (NC) above the main pre-1997 channel expansion (MCE) during the 1997 flood was another substantial and surprising change in the system. The MCE was identified as an active alluvial fan area prior to the flood based on a distributary channel network within extensive late Holocene sheetflood deposits and evidence of shifts in channel position over decades to centuries obtained from a trench excavation across much of the MCE (CH2MHill, 1992; Pearthree and others, 2000). Broad areas of late Holocene fine-grained deposits with minor channels existed in both overbank areas for more than 500 m above the apex of the MCE, implying that overbank flow occurred during previous floods (Figure 14D; 17A). During the 1997 flood, however, so much floodwater came through this part of the system that unconfined flow on both sides of the channel was quite deep. In the left overbank, 2 tongues of coarse gravel were deposited near the upper end of the overbank area (Fig. 17A, site G) and a ~150-m-wide swath of deep unconfined flow resulted in the development of many small,

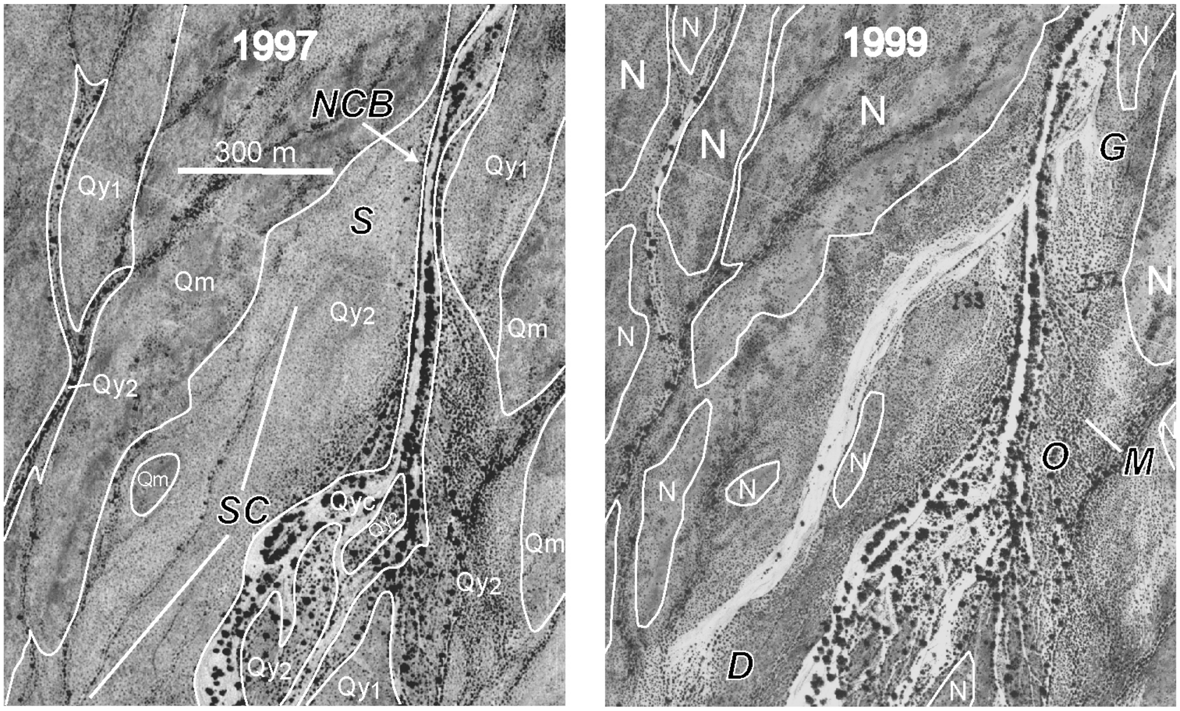

Figure 17A. Before and after aerial photos of the main channel expansion / new channel area. Sites identified with letters are discussed in the text.

Figure 17B. Ground photo taken in 1999 looking downstream at the new channel breakout and the pre-97 main channel.

unmapped channels and the extension and enlargement of several pre-existing channels (site O). Near the margins of the deep unconfined flow, the toes of Pleistocene alluvial surfaces (Qm) were scoured (site M).

In the right overbank, deep unconfined flow was very extensive and the NC developed along the course of a small pre-existing channel (labeled SC in the pre-flood photo) that was not directly linked with the main channel prior to the flood. After the 1997 flood, the NC was about 900 m long, varied in width from about 25 to 75 m, and was less than 1 m deep. Mature trees that existed along the small pre-flood channel were left in the middle of a broad, shallow channel. Pleistocene alluvium was exposed in the NC bed at several locations, and primarily Holocene alluvium was exposed in the channel banks. The relatively cohesive Pleistocene alluvium apparently limited channel downcutting and fostered lateral erosion of the thin blanket of less cohesive Holocene alluvium. After the flood, the levels of the pre-1997 channel and the NC were essentially the same at the new channel breakout (NCB; Fig. 17B). Sediment excavated as the NC developed was deposited in a broad channel expansion reach at the lower end of the channel (site D). Thus, the lower end of the NC did not directly link with the existing channel network, but flow from the new channel rejoined the main channel network within a few hundred meters down slope.

The morphology of the NC suggests a substantially different origin from the UWB and its configuration implies that the potential ramifications from its development are far less than for the UWB. Because there was a channel bank at the site of the NCB at the start of the flood, we think it likely that the initial overbank flow was not transporting much or any bedload from the main channel (see Hooke and Rohrer, 1979; Field, 1994). This probably enhanced the potential for erosion associated with deep unconfined flow in the overbank area. Flow was focused in the area of the small pre-flood tributary channel, which set up a self-enhancing situation wherein lateral erosion of channel banks and headward extension of the NC captured more flow. The NC continued to propagate upslope through a broad swale above the dirt track (site S), and was eventually able to link directly with the main pre-1997 channel because flood flow remained at a high level for a number of hours. In this scenario, the NC developed from downstream to upstream, so the location where the new channel linked with the main channel was governed by relatively subtle local topography and the fact that a lot of water went into the right overbank in this general area. Roughly similar amounts of flow have gone down the new and pre-1997 channels in all of the post-1997 floods, so the NC is now an integral part of the distributary network. The effects of the development of the new channel on the whole distributary system are likely to be quite limited, however, as the flow that leaves the main channel system returns to it less than 1.5 km down slope.

Development of Smaller New Channels Downfan

A number of relatively small, short new channels formed in the main western flow path down slope from the MCE. Several of these new channels formed along the western margin of the main flow path (Fig. 18A). The largest of these channels (Fig. 18A, site L) is about 200 m long, about 15 m wide, and less than 1 m deep. It formed in an area of older Holocene deposits (Qy1) not far from the previous margin of the active distributary system. Three smaller channels formed farther upslope. Most notably, one of the channels developed through a Pleistocene Qm surface (site M) and another developed along the margin of a Qm surface (site N). In both of

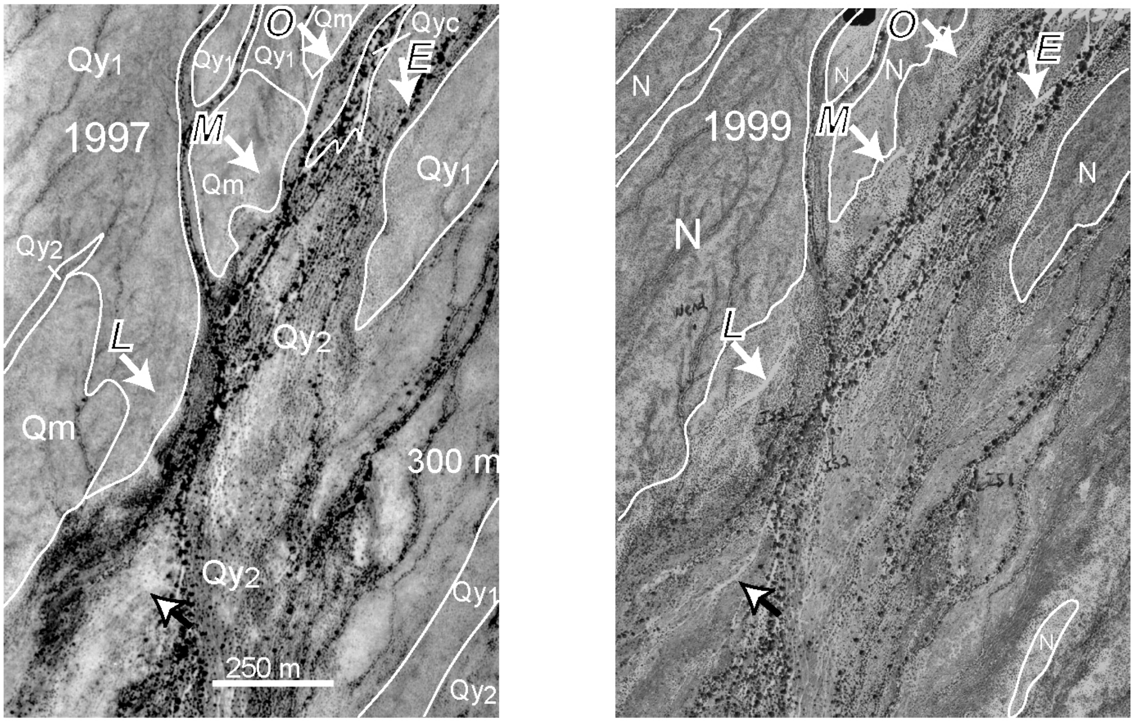

Figure 18A. Before and after aerial photographs of the western part of the main western flow path below the MCE. Several small new channels formed near the margin of flow in this area. The outlined arrow points to a channel splay that existed prior to the flood and did not change detectably during the flood.

Figure 18B. Ground photo taken in 2001 looking downstream in one of the small new channels. Cobbles covering the channel bed were derived from local erosion of Qy1 and Qm deposits.

those areas there was fairly extensive inundation of the margins of the Pleistocene alluvial surfaces. The beds of each of these channels are mostly covered with cobbles derived from erosion of adjacent coarse-grained Qm and Qy1 deposits (see Fig. 18B). Relatively minor expansions of existing channels occurred at many other places in the distributary channel network down slope from the MCE. An example of such changes is shown at site E (Fig. 17A), where an existing channel bank was eroded and the channel extended down slope.

Several small tributary drainage networks existed within a broad area of Qy2 deposits upstream from Salome Highway prior to the 1997 flood (Fig. 19). We surmise that these drainage networks developed at least in part because of the construction of dip crossings along the highway. Changes along most of these drainages as a result of the 1997 flood were subtle, involving only slight increases in apparent channel area (site A for example). Change was dramatic along the incised drainage at the Maricopa County – La Paz County boundary, however. This wash evidently captured a significant amount of flow from the sheetflood area upslope because it widened and lengthened considerably. The upper end of this system currently is a complex set of steep headcuts that developed and migrated about 200 m upslope during the 1997 flood (Fig. 19). Some shallow sheetflow has spilled over these headcuts in the moderate floods that have followed the 1997 flood, but their position has changed very little. We infer that the total volume and duration of flow in the 1997 flood was the major factor leading to the upslope propagation of these headcuts.

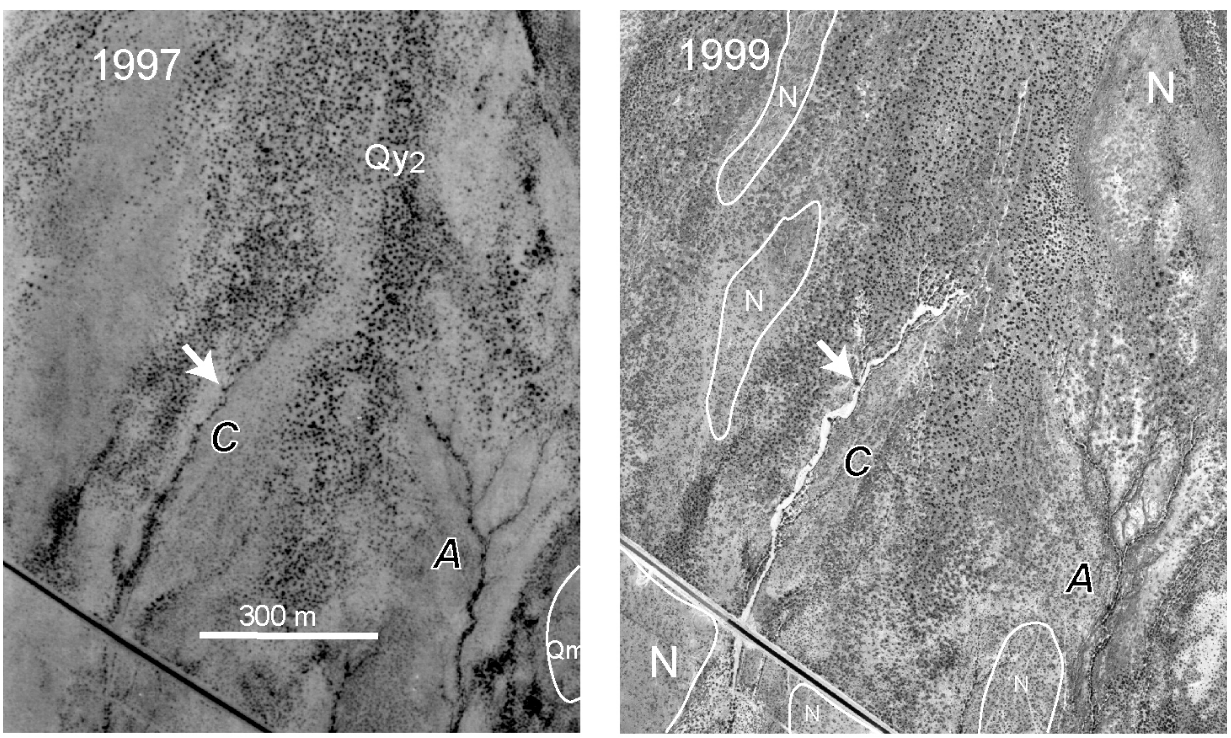

Figure 19. Before and after aerial photographs of part of the main western flow path above Salome Highway. Most flow here was very shallow, but some flow was concentrated in defined drainages upslope from the highway and a significant arroyo developed along drainage “C”.

None of the small channels that developed during the 1997 flood are of great consequence for the whole Tiger Wash system, as they involved very little area and did not result in the redirection of substantial amounts of flow. Rather, their development illustrates the erosive power of floodwater in local areas of concentrated flow within broad areas of shallow inundation. Any human alterations of the landscape that would serve to concentrate flow in these areas of relatively shallow sheetflooding should be done with care to avoiding initiating new channel formation or extension during floods.

Discussion – Implications for system instability and piedmont flood hazard assessment

The extent and character of inundation during the 1997 flood on Tiger Wash and the nature of changes that occurred in the distributary channel network illustrate a number of important facets of desert fluvial systems. Analysis of this flood illustrates the complex patterns of flow through a distributary system, the potential for channel change during floods in distributary systems, the importance of floods in shaping the form of channel networks in desert fluvial systems, and the value surficial geologic mapping in defining piedmont flood hazards.

In desert distributary systems like Tiger Wash, large floods shape the primary morphology of channels and the channel network (Vincent, 2000), and lesser flows along with the growth of riparian vegetation between large floods fine-tune channel morphology. Desert fluvial systems flow infrequently but are subject extreme floods which are the primary geomorphic agents in these systems (see Wolman and Miller, 1960; Wolman and Gerson, 1978; Kochel, 1988). This is especially evident in distributary systems where local areas of minimal topographic confinement of flow provide opportunities for channel change. The recent hydrologic and geomorphic history of Tiger Wash documents this concept very nicely. Many moderate floods occurred on Tiger Wash between 1953 and September 1997, but changes that occurred in the distributary channel network were incremental and minor (Field, 2001; supplemented by this study). In addition, only a few minor channel alterations have occurred in the 4 moderate floods since 1997. The high-magnitude peak discharge and long duration of the September 1997 flood caused more extensive and deeper inundation than anything that had occurred during at least the past 50 years and probably much longer in the Tiger Wash distributary system. Dramatic erosion and sediment deposition during the one day of the 1997 flood resulted in far more substantial channel change than has occurred in the other approximately 18,000 days since 1953.

Given the extreme variability of flow in desert distributary systems, their evolution over centuries to millennia might be best characterized as punctuated change. Substantial system reorganization occurs during at least some large floods, strongly affecting flow in subsequent moderate and large floods. Modest channel alterations occur during smaller floods of the succeeding decades or perhaps even centuries. Very few changes occur in the system during the vast majority of the time when there is little or no flow; what change does occur between floods probably involves the establishment and growth of desert riparian vegetation within and along channels.

The 1997 flood also provides insights into the long-term evolution of desert distributary systems. Pleistocene piedmont alluvial surfaces are relicts of alluvial fans that were active at least 10,000 years ago, and thus define the limits within which the Holocene distributary system has operated. At a shorter time scale, areas covered by Holocene deposits that are not part of the active system are evidence of shifts in loci of erosion and deposition during the Holocene (Pearthree and others, 2000). The boundaries between inactive fan surfaces and areas of active erosion and deposition are not static; rather they change during large floods as fluvial processes shape the system. For example, during the September 1997 flood boundaries between alluvial surfaces of different ages were modified in many places. Generally, the margins of older deposits that were inundated by moderately deep flow were eroded, whereas thin sheets of fine-grained sediment were deposited in areas of shallower flow. In some areas, thin, non-cohesive fine-grained Holocene deposits were eroded, exposing underlying, more cohesive Pleistocene deposits. Almost all of the geomorphic changes observed after the 1997 flood involved relatively minor, incremental erosion or shallow burial of Pleistocene or older Holocene deposits. Dramatic changes in channel configuration like the UWB indicate the potential for substantial change in the distribution of water and sediment over time, however. Future large floods may send a greater proportion of water and sediment to the southwest at the UWB, which would almost certainly increase the extent of very young deposits at the expense of older Holocene and Pleistocene deposits down slope from the UWB.

The 1997 flood also provided an opportunity to evaluate the depth of inundation necessary to substantially alter an older alluvial surface and thus preserve evidence that it had indeed been inundated. On smooth Qm surfaces with well-developed desert pavements formed of varnished rocks, very shallow inundation had a minor impact on the surface that almost certainly will not be evident for long. Flow depths of about 10 cm or more typically scattered the desert pavement, revealing patches of the underlying soil horizon. In local areas of deeper unconfined flow or where channels of various sizes developed (flow depths typically greater than 20 cm), desert pavement was completely removed and underlying soil horizons were scoured. There is substantially more local topographic relief on intermediate-age inactive fan and terrace surfaces (Ql and Qy1). Where these surfaces were inundated, flow typically occurred in the low areas or followed existing drainages. If flow in existing drainages was relatively deep, scour and fresh deposition was evident, but because these drainages also convey local runoff from precipitation that falls on the fan, the chance for long-term preservation of evidence from distributary floods is poor. In areas of shallow inundation of Ql and Qy1 surfaces, it was difficult to detect evidence of inundation a few years after the flood.

A critical issue for assessing flood hazards on alluvial fans is the relative predictability of channel changes during floods. The possibility that channel positions on alluvial fans might not be stable during floods caused the Federal Emergency Management Agency to adopt a flood model that assumed that channels could move anywhere on an active fan during a flood (the FAN model; Dawdy, 1979; FEMA, 1990). Many aspects of the Tiger Wash distributary channel network are inconsistent with this model. For example, the photographic record demonstrates that the modern channel network has been in place for at least the past 50 years, and mature desert riparian trees along many channels suggest that this general channel configuration has existed for a much longer period. Nonetheless, we can use the significant channel changes that did occur in the 1997 flood to evaluate whether their locations may have been predictable (with perfect hindsight). As was noted earlier, the new channels at the UWB and the NC developed in areas of very young deposits that would have been considered potentially flood-prone from a geomorphic perspective. Several clues suggested that the UWB was a candidate for channel change, including a moderate channel bend, extensive very young sheetflood deposits in the right overbank area, and extensive Holocene deposits down slope from the UWB indicating that floods on Tiger Wash had previously inundated the area west of the pre-1997 channel system.

Although the NC developed several hundred meters above the obvious pre-1997 channel expansion (the MCE), it occurred in an area that had been subject to overbank flooding prior to the 1997 flood and it developed along the course of a pre-existing small tributary drainage. We suspect that hydraulic modeling of possible flood discharges would have revealed that the capacity of the channels at the future UWB and the NC was much less than potential flood discharges. Although several factors indicated that the UWB and the NC were fairly high flood hazard areas, the amount of sediment deposition that occurred at the UWB and extent of erosion associated with the development of the NC would have been rather difficult to anticipate in detail.

Finally, our investigations of the 1997 flood on Tiger Wash reaffirm the usefulness of surficial geologic mapping as a predictive tool in piedmont flood hazard assessment. On piedmonts we expect that even during large, expansive floods inundation will be confined primarily to the youngest surficial geologic units (Pearthree and others, 1992; 2000). This expectation is based on the fact that the existing distribution of young deposits records recent fluvial activity on the piedmont and the premise that flood waters will tend to follow existing flow paths. Based on that logic, we would predict that Pleistocene alluvial surfaces (Qm, Ql) in the Tiger Wash distributary system would be unlikely to experience flooding, and very young surfaces (Qyc and Qy2) would likely be inundated in a large flood. Our inundation mapping shows that this was the case in the 1997 flood, as the vast majority of inundation occurred on late Holocene alluvial surfaces. There are many locations, however, where older Holocene and Pleistocene surfaces adjacent to younger surfaces were partially inundated in 1997. This occurred primarily in the lower piedmont where topographic relief is minimal and in the middle piedmont along the margins of the main western flow path. Thus, it is clear that a robust assessment of piedmont flood hazards ought to include surficial geologic mapping, detailed topographic information, and hydrologic / hydraulic modeling of flows (Pelletier and others, in review).

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