Contrasting channel response to floods on the middle Gila River, Arizona

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ABSTRACT

Floods of January and February 1993 in Arizona resulted in the most dramatic channel widening on the middle Gila River since 1905. An earlier flood in October 1983 had a larger instantaneous discharge but resulted in little channel change. The 1993 flood was of greater volume and duration, factors important in destabilizing flood-plain vegetation and eroding bank material. The 1983 flood was produced by a dissipating eastern Pacific tropical storm, whereas the 1993 flood was produced by a series of cold fronts from the northern Pacific Ocean supplied with subtropical moisture from a split jet stream. Meridional global circulation patterns enhance the frequency of winter storms that produce sustained flooding in Arizona and are more likely to result in channel widening and flood-plain instability on main trunk streams like the Gila River.

INTRODUCTION

Channel morphology and plan-view form in arid and semiarid stream systems is highly dependent on the frequency and magnitude of large floods (Baker, 1977; Wolman and Gerson, 1978; Graf, 1988). Consequently, such systems seldom maintain a stable form at decadal to century time scales (Stevens et al., 1975). The Gila River in Arizona is an arid-region stream in which this complex relation between floods and channel changes occurs (Burkham, 1972; Graf, 1981; Huckleberry, 1993b). Specific hydroclimatic conditions favor the production of catastrophic floods in the Gila River watershed (Hirschboeck, 1985; Ely et al., 1993), but not all large floods result in the same channel response. Contrasting channel responses to large floods were demonstrated in 1983 and 1993 by the middle reach of the Gila River in south-central Arizona. The 1983 flood had a larger peak discharge than the 1993 flood, but the channel remained relatively stable in 1983. In contrast, the 1993 flood had a larger sustained discharge and the channel underwent its greatest widening since 1905 (Fig. 1). The contrasting flow characteristics of these two floods and the corresponding channel responses are related to duration of the floods which is in turn related to different storm types. This has implications regarding our ability to interpret geomorphic events in the past based on peak discharge data and reaffirms the link between global circulation patterns and local hydrology and fluvial geomorphology.

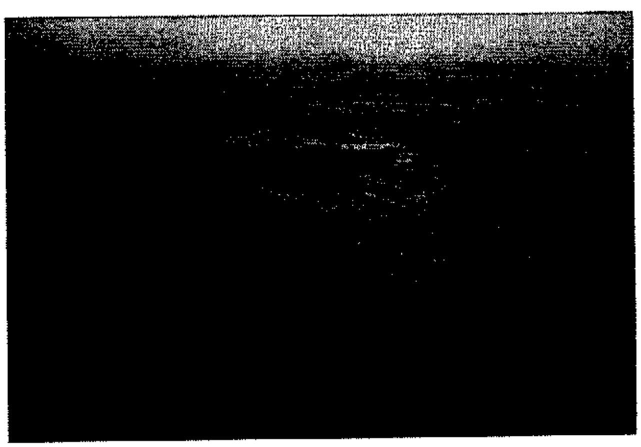

Figure 1. Aerial view of middle Gila River at Interstate 10 bridge, March 22, 1993, following January and February floods. View is to northwest (Gary Huckleberry photograph #4191).

PHYSICAL SETTING AND CLIMATE

This study focuses on the upper 40 km of the middle Gila River near Florence (Fig. 2), an alluvial reach bounded by downstream-converging Pleistocene terraces (Péwé, 1978; Huckleberry, 1993a). Flood-plain altitudes range from 420 to 480 m above mean sea level, and the climate is arid and thermic. The middle Gila River is a mixed-load stream containing both high-energy channel and low-energy overbank sediments (Brakenridge, 1988). Modern channel deposits consist of cobbles, pebbles, gravels, and coarse sands; overbank sediments are characterized by sand, silt, and clay-sized materials. Since completion of the Coolidge Dam in 1928, the middle Gila River has been mostly dry.

Three primary storm types generate floods in Arizona. During the winter and early spring, frontal cyclonic systems from the Pacific often result in statewide rain in the lowlands and snow in the uplands. Summer floods are associated with the monsoon season when moist air steered northward from the gulfs of Mexico and California by the Bermuda High is convectively heated at the surface, generating more intense but isolated rainfall (Sellers and Hill, 1974). The third storm type is the occasional late summer or early fall, eastern Pacific tropical storm (Smith, 1986). Most eastern Pacific tropical storms drift northwestward to colder northern waters, but their moisture is periodically steered over the southwestern United States by stationary or cut-off lows in the upper atmosphere situated off the coast of California (Webb and Betancourt, 1992). Historically, the largest floods on the middle Gila River have been generated by winter frontal storms and autumn dissipating tropical storms (Huckleberry, 1993b).

The frequency of large floods varies through time due to variations in global circulation patterns (Knox, 1984; Ely et al., 1993). Ocean-atmospheric circulation patterns affect the occurrence of split jet streams and cut-off lows that affect Arizona weather. Thus, global-scale climatic phenomena linked to ocean-atmospheric circulation, such as El Niño southern oscillation (ENSO) events (Rasmusson, 1985), influence the frequency of floods in Arizona (Webb and Betancourt, 1992). Negative southern oscillation index conditions result in increased moisture in the spring and autumn (Andrade and Sellers, 1988) and increase the potential for flooding.

HISTORICAL CHANNEL CHANGES

Historical records of floods and channel changes on the middle Gila River indicate that the river has not responded similarly to all large floods. Between 1696 and 1891, both anecdotal evidence and survey plats indicate that the study reach was characterized by a single, narrow channel (Table 1) lined by tall trees (Rea, 1983). This form was maintained despite catastrophic floods in 1833 and 1868 (Dobyns, 1981). The first obvious bank erosion and channel widening occurred in 1891 (Huckleberry, 1993b), but it was not until the floods of 1905 that the middle Gila River changed from a single, slightly sinuous, narrow channel to a wide, straight, braided channel. A similar metamorphosis occurred in the upper reach of the Gila

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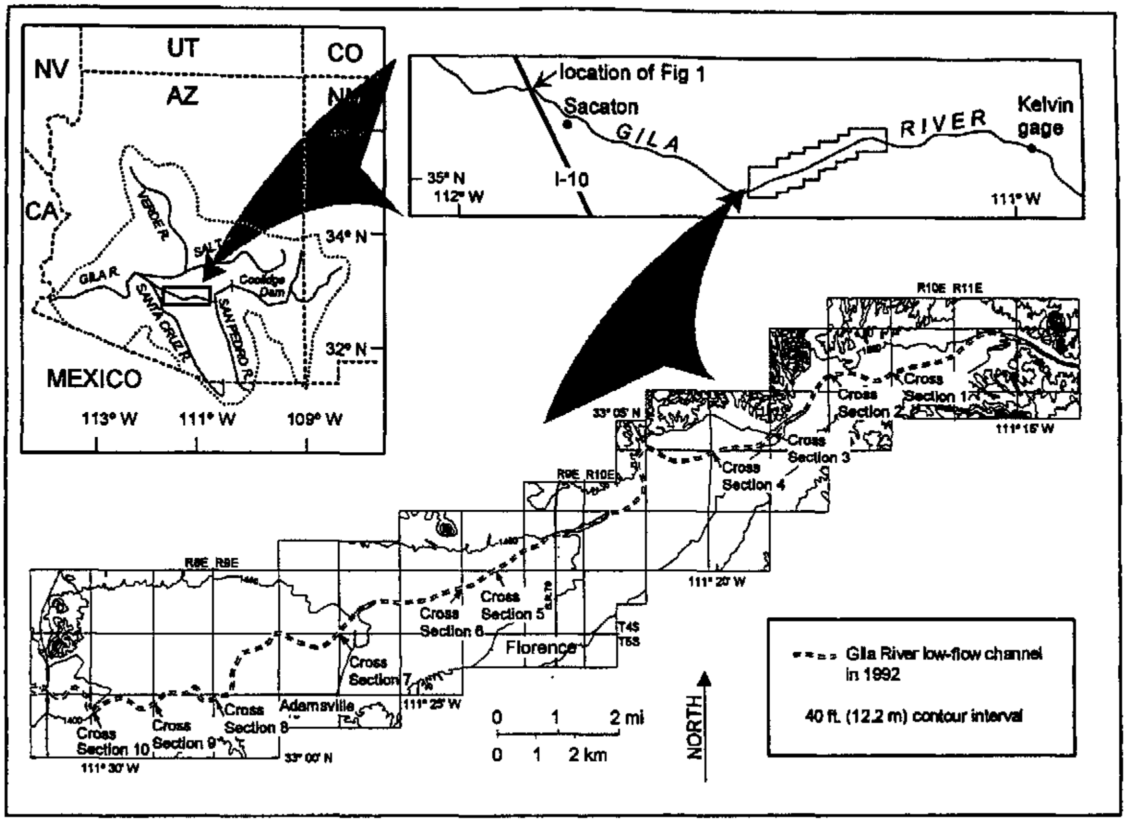

Figure 2. Gila River watershed and study reach of middle Gila River.

River in the Safford Valley, Arizona (Burkham, 1972). Tree-ring evidence indicates that the decade of 1905–1915 was probably the wettest in 500 yr in central Arizona (D. M. Meko and D. A. Graybill, report for Bureau of Land Management, Safford, Arizona). Large floods in 1905, 1914, and 1916 resulted in repeated bank cutting and maintenance of wide, braided channel plan forms. In 1928 the channel was still wide (General Land Office survey notes; Table 1), but thereafter drier conditions and the Coolidge Dam effectively decreased the frequency of large floods passing through the study reach. The normally dry channel was subject to episodic, relatively small stream-flow events that helped to create and maintain a small, relatively narrow and sinuous, low-flow channel within a wider flood channel; i.e., a compound plan form (Graf, 1988). It was not until 1983 that the middle Gila River underwent another large flood.

TABLE 1. CHANNEL WIDTHS (METRES) MEASURED FROM SELECTED CROSS SECTIONS

Cross section	1868	1928	1936	1966	1991-1992	1993
1	70	-	102	61	70	347
2	57	220	43	45	30	353
3	43	339	58	41	80	376
4	82	424	65	15	60	490
5	81	172	58	41	25	656
6	70	517	72	36	37	510
7	-	247	36	40	56	465
8	-	-	28	40	35	645
9	-	-	69	38	29	848
10	-	-	57	34	41	251

Note: 1868 and 1928 measurements derived from General Land Office survey notes. 1936 measurements from aerial photography. 1966 measurements from 7.5-minute quadrangle maps. 1991-1993 measurements from field surveys by the author. See Figure 3 for locations.

1983 FLOOD

A relatively stationary upper atmosphere low-pressure system developed off the coast of California in late September 1983. This cut-off low steered moisture from Hurricane Octave northward off the coast of Baja California and over the southwestern United States (Smith, 1986). Warm waters off Baja associated with El Niño helped to maintain storm strength as it traveled northward. Passing over land, Hurricane Octave degraded into a tropical storm. On October 1, heavy rain fell in southern Arizona and northern Sonora. Antecedent moisture conditions were relatively high because of a strong monsoon season during the previous months, resulting in considerable runoff and flooding. Most of the flooding along the middle Gila River was generated from runoff in the San Pedro watershed (Fig. 2). On October 2 at the Kelvin gage located 40 km upstream from Florence, the discharge increased from 238 m^3/s (8400 ft^3/s) to 2830 m^3/s (100 000 ft^3/s) in 10 h (Fig. 3). Because the flood destroyed the gage, the hydrograph was constructed on the basis of high-water marks and subsequent discharge measurements (Roeske et al., 1989). The peak discharge attenuated downstream to 1726 m^3/s (61 000 ft^3/s) at Florence (also estimated from high-water marks). Downstream from the junction of the San Pedro and Gila rivers, this flood is believed to have a recurrence interval of 50 to 100 yr, based on the log-Pearson Type III method (Garrett et al., 1986). Although this flood inundated large parts of adjacent Holocene terraces, there was little change to the compound plan form of the channel.

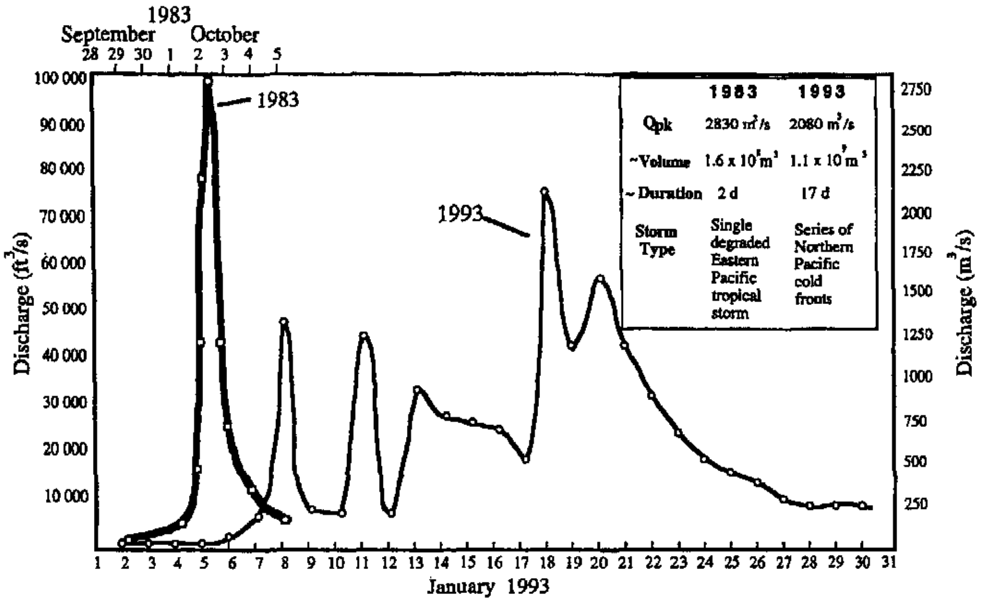

Figure 3. Instantaneous discharge hydrographs at Kelvin for 1983 and 1993 floods.

1993 FLOOD

During the early winter of 1992–1993, a persistent split jet stream steered ~16 cold fronts from the northern Pacific over the southwestern United States, resulting in the largest regional flooding in ~100 yr (House, 1993). Key to the flooding was a sequence of relatively cold storms resulting in above-average snowpack in the upper watershed, followed by relatively warmer storms resulting in rain on old snow. The January storms were warmer and wetter than usual because the split jet stream dipped into lower latitudes, allowing entrainment of subtropical moisture. The result was heavy runoff throughout the upper Gila watershed. Unlike the 1983 flood, most of the middle Gila River streamflow was generated upstream from the Coolidge Dam, and, for the first time since the dam was constructed, large volumes of water flowed through the spillways. Peak discharge at Kelvin was 2120 m^3/s (74 900 ft^3/s) on January 19 (Fig. 3). The 1993 flood hydrograph at Kelvin differs from that of the 1983 flood in terms of duration and volume of flow. During January, there was prolonged high discharge with several peaks associated with individual fronts; average daily discharges exceeded ~ 280 m^3/s (10 000 ft^3/s) over a period of two weeks. Moreover, the volume of flow during the 1993 flood was almost a magnitude greater than that during the 1983 flood (Fig. 3).

The greater duration and volume of flow associated with the 1993 flood had a much greater impact on channel geometry. The channel underwent its greatest widening in 87 yr, and width/depth ratios increased by as much as 800% along some reaches (Table 1, Fig. 4). The single low-flow channel inset within a larger, partly vegetated flood channel was transformed into a single, wide, sandy, braided system (Fig. 1) reminiscent of the 1905 channel.

DISCUSSION

If the amount of geomorphic work accomplished by flooding is defined in terms of channel and flood-plain modification (Wolman and Gerson, 1978), then little geomorphic work was accomplished along the study reach during the 1983 flood. In contrast, considerable geomorphic work was accomplished by the flood of 1993, which had a smaller peak discharge but greater volume and duration of flow. It is common for peak discharge to be used as a proxy for flood size and as a critical hydraulic parameter in assessing channel instability (e.g., Graf, 1983). However, several factors control channel sensitivity, e.g., drainage-basin characteristics, river-channel factors, previous flood history, climate, and human disturbances (Graf, 1988; Kochel, 1988; Rhoads, 1991). Burkham (1972) hypothesized that flood-plain destruction on the upper Gila River was the result of large floods with low sediment loads, such as are generated by rapidly melting snowpack. Ostensibly, relatively low sediment yields contributed to the erosivity of the 1993 flood because it was largely derived from snowmelt, but the greater volume and duration of the 1993 flood were also important in channel transformations. In 1993, sustained flood flow after the peak discharge was most effective in breaking down tamarisk-dominant flood-plain vegetation and eroding sandy bank material. Although the 1983 flood probably generated greater instantaneous shear stress on bank materials, the event was too short-lived to destabilize most of the vegetation and mobilize much sediment.

The duration of flooding along the middle Gila River in 1993 was partly increased by the Coolidge Dam, but the greater than two-week period of sustained flooding was generated primarily by specific storm types within the Gila watershed. Winter-type storms that occur at synoptic scales are more likely to produce prolonged streamflow, especially when meridional global circulation patterns are persistent and result in repeated frontal encroachments enhanced by subtropical moisture (Webb and Betancourt, 1992). Both the 1983 and 1993 floods occurred during El Niño years, supporting the hypothesis that ENSO conditions result in increased moisture in the spring and autumn in Arizona (Andrade and Sellers, 1988).

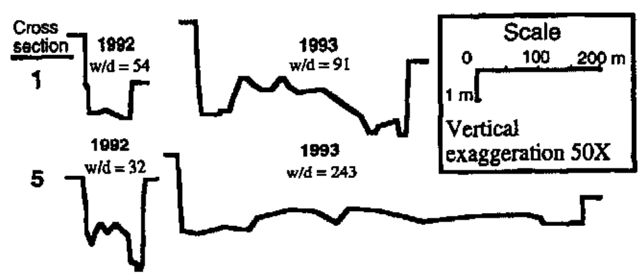

Figure 4. Selected surveyed cross sections of study reach near Florence before and after 1993 floods (see Fig. 2 for locations).

Although there is no evidence of increased generation of eastern Pacific tropical storms during El Niño conditions, the frequency of such storms reaching Arizona does increase (Webb and Betancourt, 1992), probably because of warmer sea-surface temperatures off the coast of Baja California which help maintain storm strength. Such storms, however, generate more large, short-lived flow that have a greater impact on smaller drainage basins and lower order tributaries (Hereford, 1993; Parker, 1993). Whereas a teleconnection between winter precipitation and El Niño has yet to be demonstrated, meridional circulation commonly associated with El Niño increases the potential for winter storms to interact with subtropical moisture, and these types of storms are most likely to produce sustained floods that cause channel changes on main trunk streams like the middle Gila River.

CONCLUSIONS

Large floods vary in magnitude and duration depending on watershed characteristics and the type of meteorological system supplying the moisture. Large floods are responsible for much of the geomorphic work accomplished in arid-region rivers (Graf, 1988), but channel and flood-plain responses to large floods will vary depending on several hydrological variables. The floods of 1983 and 1993 on the middle Gila River demonstrate that flow duration and volume can be more important than peak discharge in flood-plain instability. This is an important notion because only peak discharge can be reconstructed from the stratigraphic record in paleohydrological studies (e.g., Baker, 1987). Consequently interpretations of prehistoric channel changes based on the paleoflood record are limited by our inability to reconstruct flood volume.

The Gila River floods of 1983 and 1993 also suggest that channel changes on arid-region streams with large drainage basins are most favored by large-scale storms that generate prolonged runoff. In the southwestern United States, such storms tend to occur in the winter and are derived from cold fronts from the Pacific Ocean. Moreover, the potential for flooding is enhanced by global meridional circulation whereby the winter storm track dips south and pulls in subtropical moisture. ENSO conditions tend to enhance meridional circulation and thus increase the frequency for large floods in Arizona (Webb and Betancourt, 1992) and channel instability on main-trunk streams like the Gila River. It is thus important to consider the likelihood of global climate change inducing changes in storm types and how this might affect channel geometry and flood hazards along large southwestern U.S. streams.

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