Geomorphic and Sedimentological Controls on the Effectiveness of an Extreme Flood[1]

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ABSTRACT

The 1993 flood on the Upper Mississippi River was a rare, large-magnitude hydrological event. Field and aerial survey analyses and Landsat 5 Thematic Mapper data were used to appraise the thickness of overbank deposits on leveed and unleveed reaches. Results indicate that minimal (<5 mm) overbank sedimentation occurred, except in the immediate vicinity of a levee break. Unleveed sections also lacked overbank sedimentation. Little geomorphological or sedimentological evidence of this extreme event is likely to be preserved. This raises questions about the completeness of the stratigraphic record: in situations where wide floodplains with cohesive soils provide effective resistance and dissipate energy so that erosion is minimized, and/or sediment supply is limited by event timing or sequencing, a large flood may leave little or no substantive evidence of its occurrence.

Introduction

Considerable geomorphic research over the past several decades has addressed the geomorphic impacts, relationships, and importance of both large and small floods. Most of this work has focused on the response and recovery of channels and drainage basins to large floods, and the extent to which such impacts are to be preserved in the landscape (Wolman and Miller 1960; Costa 1974*a*; Stevens et al. 1975; Wolman and Gerson 1978; Gupta 1983; Osterkamp and Costa 1987; Lewin 1989). Although this attention to magnitude-frequency relationships has demonstrated the generally strong relationship between moderate magnitude events and sediment transport and both channel shape and form (Wolman and Miller 1960; Andrews 1980), less consensus exists on the relationship between more extreme floods and geomorphic characteristics. This conundrum results in part because sometimes large floods produce devastating impacts (Baker 1977; Gupta 1983; Nanson 1986; Baker and Pickup 1987; Osterkamp and Costa 1987; Lewin 1989; Pickup 1991), while other times only minor geomorphic changes occur (Dury 1973; Wolman and Eiler 1958; Kochel 1988; Costa and O'Connor 1995). Furthermore, within a single drainage basin, the effects of a single flood can be quite variable, ranging from extensive erosion, to extensive deposition or to negligible change (Costa 1974*a*; Nanson 1986; Miller 1990; Magilligan 1992; Butler and Malanson 1993).

Several explanations have been proposed to explain the poor relationship between flood magnitude and geomorphic impact. Baker and Costa (1987) suggest that the geomorphic effectiveness of floods is linked not to the magnitude of discharge or frequency of occurrence, but instead to shear stress and stream power per unit boundary area relative to the available resistance. The latter is applicable to flood erosion, where large-scale channel modification or floodplain stripping can occur in distinct zones where high shear stress occur—even during the same flood where minimal geomorphic impacts occurred elsewhere (Nanson 1986; Miller 1990; Magilligan 1992). Furthermore, the impact of an extreme flood may not be related to the flow hydraulics. In an overview of the flood geomorphology literature, Carling and Beven (1989) noted that the availability of sediment and the sequence of events may be as important as flood magnitude in determining the effects of flooding. Recently, how-

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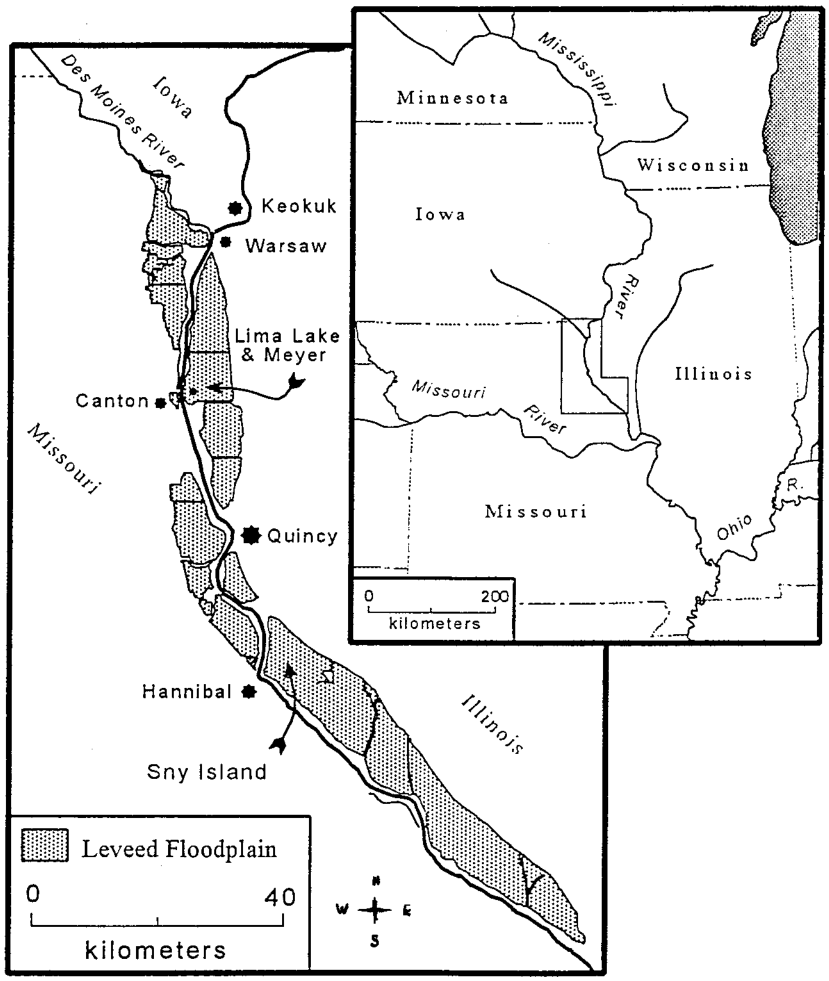

Figure 1. Location map of sites. Shaded area indicates area inundated by levee breaks.

ever, Costa and O'Connor (1995) suggest that the geomorphic impact of a large flood needs to be evaluated relative to the duration of the event as well as to its hydraulic characteristics: a high flood power may not be associated with major modification if the flood was of short duration. Conversely, a long-duration large flood may not leave lasting geomorphic impact if the maximum flood power is below some response threshold (Costa and O'Connor 1995).

In this paper we examine the geomorphological impact of the summer (June through August) 1993 flood on the floodplain of the upper Mississippi River basin within a 70 km long reach located between Keokuk, Iowa, and Hannibal, Missouri (figure 1). To accommodate the spatial scale of flooding within the study reach, we collected and analyzed information derived from post-flood field surveys and combined it with Landsat 5 Thematic Mapper data (Gomez et al. 1995) to ascertain the thickness of the overbank deposits associated with the flood. The objectives of this study are broadly twofold: first, to document the geomorphic and sedimentologic effects of the 1993 Mississippi River flood; second, to embed our results on the magnitude-frequency relationships of floods within the broader rubric of sedimentological and stratigraphic interpretations of both gaged and ungaged large floods. Furthermore, the geomorphic effects were investigated at both unleveed and leveed sections, including levee break sites, to capture the role of structural influences in controlling the depositional and erosional pattern. Although geomorphic channel change is a critical response to extreme floods, little evidence existed on this reach; therefore, this topic was not pursued.

Methods

The study reach (figure 1) was selected on the basis of the extreme stage and discharge that occurred during the flood, and the extensive levee break deposits revealed during the course of aerial reconnaissance undertaken after leaf-fall, in mid-November 1993. The peak discharge at Keokuk, Iowa was 12,320 m^3/s, and the frequency of the flood in the Upper Mississippi River Valley ranged from the 100-yr flood to greater than the 500-yr flood—depending on which flood frequency curve-fitting method is employed (Pitlick 1997). Floodplains along this reach of the Mississippi River typically consist of cohesive fine-grained alluvium, although in-channel deposits possess sandier units in places. Fieldwork commenced during a period of low flow, in early December 1993, and continued through March 1994. The overall purpose of the field survey was to map erosional and depositional features and to determine the thickness of the sediment deposits in the immediate vicinity of break sites. To ascertain the impact of structural controls on sedimentation patterns we determined the extent and thickness of fine sediment deposits on leveed and unleveed portions of the floodplain and evaluated the extent of sediment deposition outside levees, on the bankside, and on mid-channel islands.

Three break sites (The Union Township, Lima Lake, and Sny Island levee breaks) were selected for detailed study on the basis of their setting, accessibility and relatively undisturbed character at the time we conducted the fieldwork. We ran a 1.5 km long transect across the floodplain from two of the break sites and surveyed the floodplain from bankside to bluff in the vicinity of the Lima Lake break site. Water marks on trees and buildings provided an indication of the depth of water on the floodplain. The stratigraphy of the overbank deposits was determined at regular intervals along survey and transect lines by trenching. We also dug soil pits on the floodplain at over 200 locations far removed from the break sites, and generally noted the extent to which the roots of arable crops (principally corn) in a given location were either exposed or buried. The thickness of the sand deposits in the rings and lobes at the levee break sites was determined by auger traverses across each feature.

On unleveed portions of the floodplain, in the vicinity of Canton, Missouri, at bankside locations outside levees and on mid-channel islands, a general survey was conducted. These observations were supplemented by a second aerial survey, undertaken in late March 1994. The thickness of the overbank deposits in these areas was determined using one or more of the following criteria: (i) depth to the base of cultural features; (ii) depth to the basal flare or root crown of riparian vegetation; and (iii) depth to the pre-sedimentation litter layer, discounting the surface layer of largely undecomposed organic litter that represented the autumn 1993 leaf fall.

The thickness of fine-grained overbank deposits was also estimated from sediment concentrations derived from Landsat 5 Thematic Mapper data acquired on the morning of July 25th, prior to the failure of the Sny Island levee (Gomez et al. 1995). Sediment concentrations were determined using the methodology outlined by Mertes et al. (1993) and Mertes (1994). In the absence of the continuous exchange of water and sediment between the channel and the floodplain the concentration estimates convert directly to a sediment depth. Sediment discharge and concentration data were also acquired from nearby U.S. Geological Survey (USGS) gaging stations at Keokuk, Iowa, and Grafton, Illinois.

These different data sources (field surveys, Landsat TM, and USGS sediment data) provided information on different spatial and temporal scales. In essence, the field component of measuring cross-sections and thicknesses of overbank deposits provides information on the at-a-site cumulative effects of the flood; the analysis of the USGS sediment data from gages provides the time series of sediment transport during the event; and the Landsat TM data indicates the transport capacity at a single time but captures the reach scale spatial variability.

Patterns of Overbank Sedimentation

The bulk of floodplain sand deposition was concentrated in an area proportional to the length of the break. The configuration of the sand deposits at the levee breaks was determined by the way the breach widened, but the overall morphology consisted of a horseshoe-shaped sand rim (figure 2). The depth and extent of coarse sediment deposition was influenced by the hydraulics of flow in the vicinity of the break site at the time of levee failure, and by the extent to which scour was able to link the break with the main channel. The former controlled sand dispersal across the floodplain while the latter determined whether or not significant quantities of sand-sized bed material passed through the breach. Sand thicknesses of 0.15 to 1.3 m were typically recorded at the lobe crest with a mm thick splay-like sand sheet that extends out across the floodplain from the leading edge of the horseshoe-shaped lobe crest. The particle size distribution and volume of the sand in the rims we surveyed are consistent with the size and amount of material removed from the levees. At the Union Township and Lima Lake break sites (figure 1), the height and steepness of the banks prevented the transfer of appreciable quantities of bed material on to the floodplain. Only at the Sny Island break site, where scour

Figure 2. Oblique aerial photo of the Sny Island levee break. Note horseshoe-shaped levee break splay

linked the floodplain directly with the channel, did appreciable quantities of sand-sized bed material load encroach through the breach. This sediment accumulated in and plugged the proximal end of the principal elongate scour hole, which was a few tens of meters wide and less than a hundred meters long. The maximum depth of scour at all three break sites was of the order of 2 to 3 m. In areas where plow furrows were oriented perpendicular to the levee and the scour was less localized, a spur and furrow topography developed that extended to the inner edge of the sand rim. The extent and magnitude of the scour was minor compared to that documented by Jacobson et al. (1993) and Bhowmik (1994) in reaches downriver from the confluence with the Missouri River, where the influx of sand reduces the cohesivity of the banks and floodplain.

The TM imagery showed that the pattern of fine-sediment dispersion was dominated by sediment plumes originating at a break site and large-scale eddy circulation across the floodplain. It was generally uncomplicated by longitudinal dispersion because the tops of levees projected above the floodwater, so that after failure the floodplain remained isolated from the channel. Suspended sediment concentrations in the immediate vicinity of a break site were enhanced by scour, but the sediment load of the main channel provided the primary source of suspended sediment in the floodwater. On July 25 concentrations in the main channel were estimated to be between 80–160 mg/l. Suspended sediment concentrations at break sites were of the order of 20 to 160 mg/l, while concentrations across the majority of the floodplain ranged between 10 and 50 mg/l (Gomez et al. 1995). High water marks indicated average water depths of 3 m and 5 m in the Union Township and Lima Lake levee and drainage districts, respectively. The concentration estimates imply that <5 mm of sediment was deposited over most interior portions of the floodplain, if one assumes that all of the suspended sediment settled out from the stagnant water.

Field evidence corroborates the low sediment concentrations revealed by the TM image analysis. We observed barely detectable 3 mm to 4 mm and <2 mm to 3 mm thick veneers of silt over much of the floodplain in the Union Township and Lima Lake levee and drainage districts, respectively. In the Union Township levee and drainage district, multiple overtopping elevated suspended sediment concentrations and generated thicker overbank deposits. The depth of overbank sediment in the interior of the floodplain in the Sny Island levee and drainage district was typically <2 mm. Although the relief of the predominately agricultural terrain of the floodplain behind the levees was very subdued, the pattern of fine sediment deposition was far from uniform due to the influence of the local floodplain topography. In the Lima Lake levee district, for example, over areas <5 km^2 sediment depths of 50 mm to 200 mm were recorded in shallow (<1 m deep) depressions, which concentrated floodwater and functioned as settling basins as the flood waned.

The unleveed sections also recorded minimal deposition. Within the 12 km long (<1 km wide) reach of unleveed floodplain between Canton and La Grange, Missouri, overbank deposition was also very localized. Sections with high (2 to 3 m), steep banks experienced little or no sedimentation. In wooded portions of the floodplain adjacent to the river channel, root crowns were fully exposed and there was no buried litter layer. The root crowns of corn stalks were similarly uncovered in fields in interior portions of the floodplain. At many wooded and unwooded locations where the bank gradually graded to the floodplain surface a continuous but highly variable, <100 mm thick sandy-silt deposit was in evidence. We suspect that this sediment was deposited on the waning limb of the flood hydrograph and represents in-channel rather than overbank deposits. Other extensive in-channel deposits were observed at Warsaw, Illinois, where flow separation in a local eddy recirculation zone encouraged deposition of 500–600 mm of unstratified silt within a <0.5 km^2 area between the channel and the bluff line. Small (<100 m^2) sand splays were sometimes observed at the upstream ends of mid-channel islands and former islands coupled to the banks, in locations where sand bedload was ramped up on to adjacent low-lying, riparian surfaces. In most instances the sand splays were stratified, and some exhibited coarsening-upward sequences. There was no appreciable fine sediment deposition on mid-channel islands.

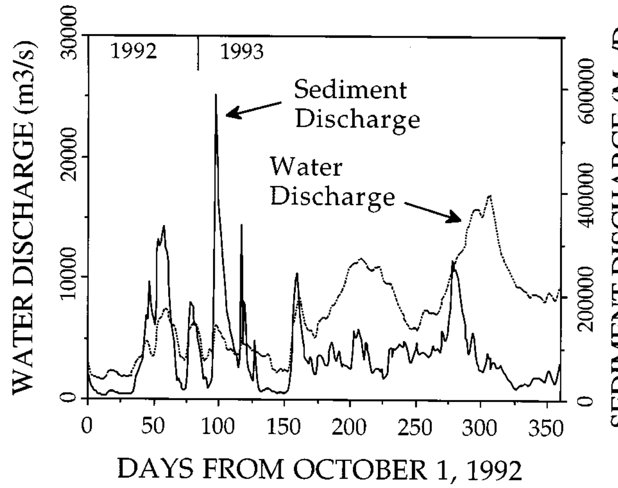

Figure 3. Sediment and water discharge time series for Grafton, Illinois from October 1, 1992. Solid line is sediment discharge (Mg/day), and the dotted line is water discharge (m^3/s).

Event Timing and Effectiveness

Our field and aerial survey indicates that little sedimentation occurred during the 1993 flood on both leveed and unleveed portions of the upper Mississippi River floodplain outside the channel proper. One explanation for this may be that the study reach is non-aggrading, but we reject this interpretation because there is abundant field evidence to the contrary. In many areas, for example, the basal crowns and root flares of saplings and mature trees were buried by pre-1993 sediment. We also infer that the levees failed to inhibit fine-grained overbank sedimentation because there is little evidence of deposition on unleveed portions of the floodplain, or in riparian zones inside levees. The summer 1993 flood was not associated with a sequence of abnormally wet or dry run of years, but we argue that the dominant control is the timing of the event and its occurrence following an unusually wet spring. The suspended sediment record at Grafton (figure 3), 234 km downriver from the study reach, suggests that higher suspended sediment loads were transported in smaller, winter 1992 and spring 1993 floods than during the summer 1993 extreme flood. The wet spring exacerbated the sediment deficiency in part because saturated soils limited spring plowing, thereby reducing soil loss from cropland. Following the spring runoff, which flushed most of the available sediment through the system, the remaining sediment was mobilized several weeks prior to the summer flood peak. Furthermore, in a regional context, suspended sediment concentrations typically peak during spring runoff (Bhowmik 1986), and late summer is not normally associated with significant sediment production, as hillslopes and channel banks are well-vegetated (figure 4). At Keokuk during the spring 1973 flood (the previous maximum flood), suspended sediment concentrations were consistently in the 250 to 500 mg/l range (Chin et al. 1975): whereas, concentrations ranged between 20 and

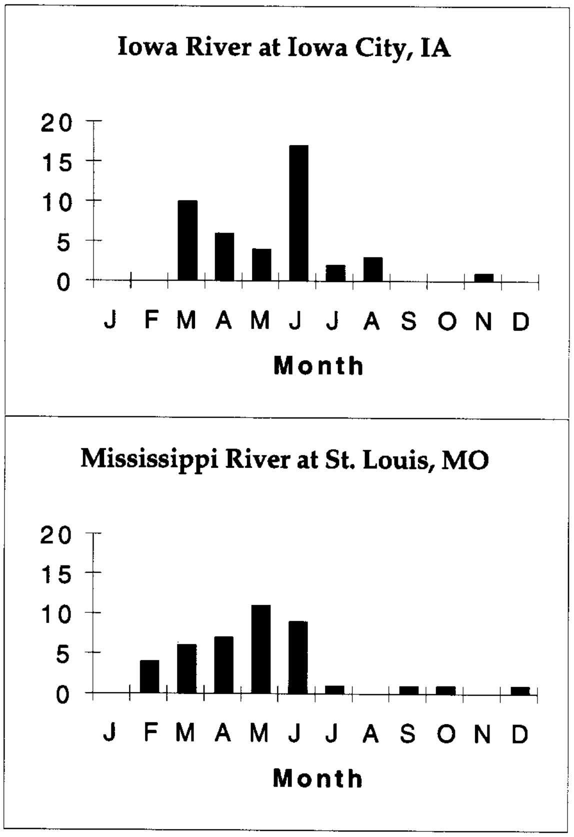

Figure 4. Histogram of the occurrence (by month) of the annual maximum daily sediment discharge for the Iowa River at Iowa City and for the Mississippi River at St. Louis. Both sediment gages represent approximately 40 yrs of daily records.

160 mg/l (mainly <100 mg/l) during the summer 1993 flood; thus sediment loads are generally higher for spring floods (figure 5). The inescapable conclusion is that little sediment was available for transport during the summer 1993 flood.

Considerable effort has been devoted to unraveling the role of frequent or infrequent events in landform and landscape formation (Wolman and Miller 1960; Wolman and Gerson 1978; Nanson 1986; Kochel 1988; Pickup 1991). However, there is no strong, general functional relation between flood magnitude and overbank deposition, and extreme events may or may not correspond with massive deposition (Dury 1973; Costa 1974*a*; Nanson 1986; Nash 1994). Despite the high discharge and widespread economic and cultural damage, the 1993 event had a minimal geomorphological impact on the upper Mississippi River between Keokuk and Hannibal and, except for scour and deposition in the vicinity of a levee break (an artificial event), we observed no evidence that explicitly intimated the magnitude of the 1993 flood. Riparian erosion was minimal, and there was no massive fine-grained overbank sedimentation. In some cases sand splays on islands exhibited the textural discontinuities that Knox (1987) presents as stratigraphic evidence of large floods in the upper Mississippi River valley. However, given the limited and isolated occurrence of these splays and the fact that textural reversals were not present in all cases, it is unlikely that these features would provide convincing stratigraphic evidence of a large flood. Where significant slackwater deposits were preserved their location, several meters below the high water mark, is not a reliable indicator of flood stage.

Paleohydrologic reconstructions based on stratigraphic evidence often provide useful information about the occurrence of ungaged floods (Costa 1974*b*; Costa 1978), and it is tempting to dismiss our observations, inasmuch as they apply to a river strongly affected by human agency. However, experience of the summer 1993 upper Mississippi River flood raises questions about the completeness of the stratigraphic record in specific circumstances. We contend that a large flood might be expected to leave little lasting geomorphological evidence of its passage in situations where: (i) wide floodplains with cohesive soils provide effective resistance and dissipate energy so that erosion is minimized (similar to a Type A stream power graph of Costa and O'Connor 1995); (ii) the sediment supply is limited as a consequence of event timing or sequencing; and (iii) no strong link exists between hillslopes and the channel. Although sedimentologists and stratigraphers have generally acknowledged that the stratigraphic record may be incomplete (Sadler 1981; van Adel 1981; Dott 1983), the incompleteness has been argued to result from either erosion or bioturbation, which are strongly a function of event intensity and age (Dott 1983). However, in the situation of the summer 1993 Mississippi River flood, the lack of evidence is not due to the small intensity of the event or the lack of preservation, but instead results from the minimal deposition caused by the timing of the event (i.e., seasonality), the lack of connection between the hillslopes and the channel, and the occurrence of previous events.

Conclusions

Consideration of the 1993 Upper Mississippi River flood suggests that the relation between the magnitude and effectiveness of floods in large basins is as complex, and is affected by sediment availability and event sequencing in the same manner, as it is in small watersheds (Beven 1981); thus magnitude-frequency relations between water and sediment discharge are often out-of-phase (Nash 1994). The small amount of fine sediment deposition associ-

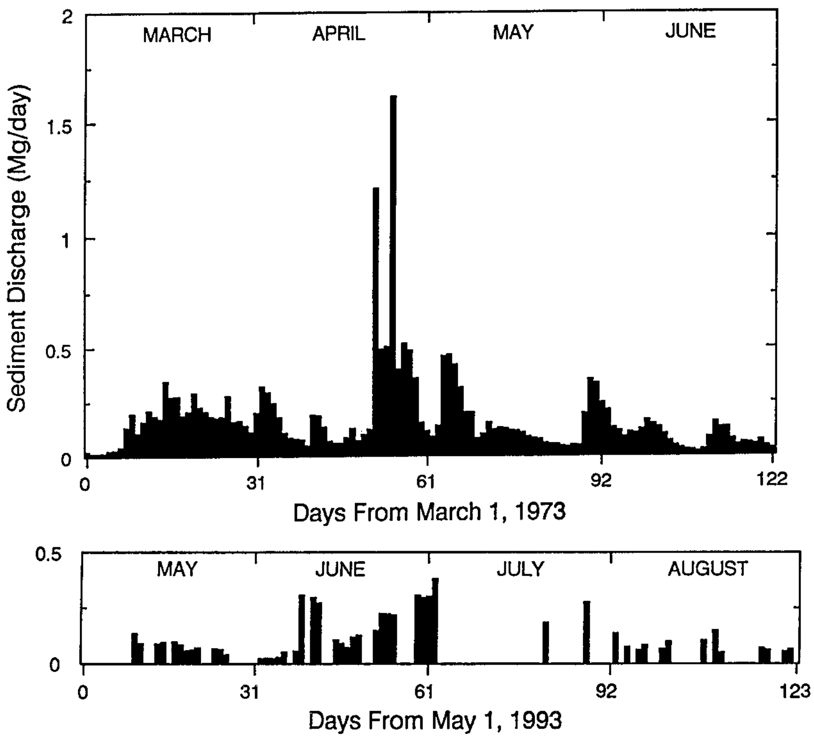

Figure 5. Sediment discharge (units are Mg/day $\times 10^6$) for Keokuk, Iowa for the spring flood in 1973 (upper diagram), and for the 1993 summer flood (lower diagram). The gaps in the 1993 data occur because the U.S. Army Corps of Engineers could not maintain daily sampling during this large event.

ated with the 1993 flood is likely related to the timing of the event. Isolation of much of the floodplain from the channel by artificial levees does not appear to have been the most prominent effect but, all other factors being equal, more overbank deposition was observed where multiple overtopping occurred and variations in floodplain topography modified the pattern of fine sediment deposition.

Post-flood hydrogeomorphological reconstructions, based on either erosional or depositional evidence, would be unlikely to accurately reflect the magnitude of this event. The most compelling post-flood evidence we observed was the location of high water marks on trees and buildings on the floodplain. It is possible that large river systems in well-vegetated humid regions have high thresholds of adjustment. Viewed within the broader rubric of magnitude-frequency relations, our perspective on the 1993 flood indicates that rare floods may not be associated with major landscape change (Wolman and Eiler 1958; Dury 1973). It provides support for the view that flood probabilities and the frequency of geomorphological adjustments are in poor agreement (Baker and Costa 1987; Parker and Troutman 1989; Magilligan 1992; Nash 1994).

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