Sediment characteristics of an extreme flood: 1993 upper Mississippi River valley

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ABSTRACT

The 1993 Mississippi River flood was notable for its high magnitude, long duration, summer occurrence, and low sediment discharge. A field survey of a 70-km-long reach in the vicinity of Quincy, Illinois, revealed that the event was characterized by <4 mm of vertical accretion on leveed and unleveed parts of the flood plain. Regional patterns of overbank suspended sediment transport and deposition were discerned from Landsat Thematic Mapper imagery. This >100 yr flood had remarkably little sedimentological or geomorphological impact on the flood plain within the study reach because the transport effectiveness of floods in large drainage basins is influenced by event sequencing in the same manner as floods in small watersheds, and the cohesive flood-plain soils were not susceptible to erosion.

INTRODUCTION

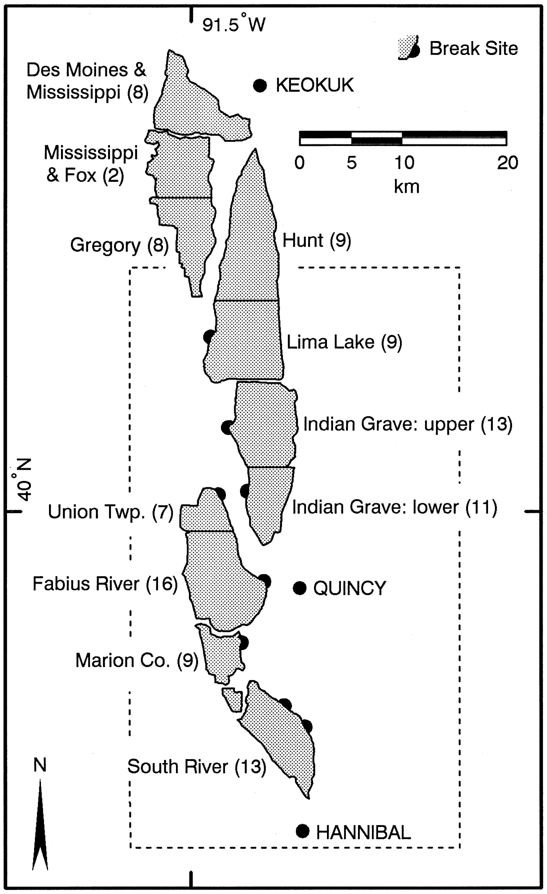
Geomorphological effectiveness is a measure of the ability of an event to form or shape the landscape (Wolman and Gerson, 1978). The effectiveness of a flood may be gauged by the magnitude of erosion and deposition, or by the sediment load transported during an event. High-magnitude, low-frequency floods potentially have the greatest capacity for mobilizing sediment because they exert the largest force against the landscape (Wolman and Miller, 1960; Brunsden and Thornes, 1979). In small basins, however, large floods do not always elicit a consistent hydrogeomorphological response because sediment availability is influenced by the size and order of prior events (Beven, 1981; Nash, 1994). During a flood event, hysteresis between sediment concentration and water discharge controls the rate of fine-sediment transport in the channel and influences the supply of sediment to the overbank environment at times when the flood plain is inundated (Wolman and Leopold, 1957). Remote sensing technology has facilitated the study of overbank sediment transport at reach-length scales on low-energy, cohesive flood plains (Mertes, 1994). However, little is known about the magnitude and spatial variability of overbank deposition, because low rates of fine-sediment deposition make it difficult to distinguish the contribution of individual events to flood-plain stratigraphy (Pizzuto, 1987; Walling et al., 1992). The summer 1993 upper Mississippi River flood afforded a unique opportunity to assess the effectiveness of a high-magnitude event in a large drainage basin, and to examine patterns of overbank deposition at the reach scale. Following the point failure of artificial levees within a 70-km-long reach between Keokuk, Iowa, and Hannibal, Missouri, we used information derived from postflood field surveys and a Landsat 5 Thematic Mapper (TM) image, calibrated to show near-surface suspended sediment concentrations in the floodwater (Fig. 1), to provide the first synoptic perspective on fine-grained sediment transport and resultant deposition across the flood plain of a large, mid-latitude river. The point failure of an artificial levee mimics flood-basin inundation following the formation of crevasses in a natural levee (cf. Popov and Gavrin, 1970; Farrell, 1987). It permits the investigation of sediment transport and the resulting pattern of flood-plain deposition in an overbank environment where water and sediment are delivered from a discrete source.

STUDY REACH AND IMAGE ANALYSIS

During the summer of 1993 numerous gaging stations in the upper Mississippi River basin recorded record peak discharges, and throughout the 300-km-long reach between Keokuk, Iowa, and St. Louis, Missouri, the recurrence interval of the event was >100 yr (Parrett et al., 1993). The flood was generated by a pattern of wetter than average weather that persisted over the upper midwestern United States for at least the first half of 1993, combined with several intense rainstorms in late June and July (Wahl et al., 1993). At Keokuk, the Mississippi River drains an area of 308 000 km^2, and the peak discharge of 12 320 m^3/s was about 20% larger than previous record discharges in 1973 and 1851. The river was in flood for 101 days at Quincy, Illinois. It crested 4.6 m above flood stage on July 13, but the flow did not begin to wane appreciably until July 25.

The flood peak passed through the study reach between July 10 and 16. Within this reach the main channel is ~1 km wide, and the flood plain ranges from 8 to 12 km wide between the bluff lines. Lock and dam construction and flood protection works have effected major changes to the upper Mississippi River channel–flood-plain system and enhanced historic flood stages (Belt, 1975; Chin et al., 1975; Chen and Simons, 1986). The crown elevation of many levees corresponds to a 50 yr flood design with 0.61 m freeboard. Between July 2 and 25, some 450 km^2 of protected flood plain were inundated following the failure of 11 main-channel levees (Fig. 1). Levee failures within the study reach occurred primarily as a consequence of overtopping due to wave action and/or saturation-induced mass failure. After a levee fails water is released through the breach in the form of a jet and the accelerating flow promotes scour in the vicinity of the break. The depth of water gradually increases and the flow velocity decreases as the flow spreads across the flood plain, but the breach remains active until the pressure gradient across the channel–flood-plain boundary nears zero. Depending on the area of flood plain involved, breaches within the study reach were deactivated within a period of 7 to 15 h.

Following an aerial survey in November 1993, we selected three sections of leveed flood plain and a 15-km-long section of unleveed flood plain in the vicinity of Canton, Missouri, for detailed field survey. Two of the sections, the 20.2 km^2 Union Township and the 113.3 km^2 Hunt–Lima Lake levee and drainage districts, were flooded at the time the TM image was acquired on the morning of July 25, 1993. (The third section, a 178.9 km^2 area of flood plain in the Sny Island levee and drainage district, was inundated during the afternoon of July 25, and consequently is not considered in this paper.) We measured or noted the thickness of fine overbank sediment resulting from the 1993 flood at numerous (>1000) random locations on the flood plain and at ~100 m



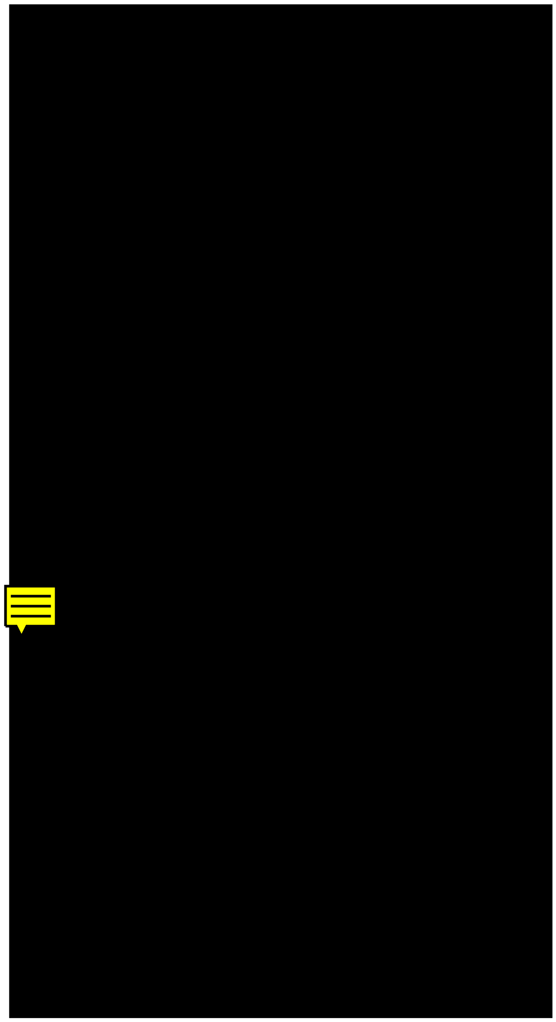


Figure 1. Levee and drainage districts on Mississippi River flood plain in vicinity of Quincy, Illinois, inundated prior to July 25, 1993, and Landsat 5 Thematic Mapper (TM) image calibrated to show near-surface suspended sediment concentration in floodwater. Numbers in parentheses on location map indicate dates in July on which main-channel levees failed. Dashed line delimits area covered by cloud-free part of TM image (path 25, row 32; July 25, 1993). Areas unaffected by flooding and wooded flood plain and mid-channel islands where vegetation screened water surface are masked, for clarity.

intervals along kilometre-long transects originating at a break site. High-water marks on trees and buildings on the flood plain were also surveyed. We derived estimates of the near-surface suspended sediment concentration in the floodwater from the Landsat image (Fig. 1), and we used these estimates to assess the regional pattern of vertical accretion on leveed parts of the flood plain.

The sensitivity of reflectance to scattering of radiation by fine-grained sediment particles in the visible and near-infrared wavelengths permits near-surface suspended sediment concentrations to be determined from TM data (Ritchie and Cooper, 1988). In shallow (<10 m deep) water, near-surface suspended sediment concentrations approximate depth-averaged concentrations (Ongley et al., 1990; Mertes et al., 1993). After nominal calibration to water-surface reflectance based on radiometric coefficients (Markham and Barker, 1986), concentrations were estimated for each 30 m^2 pixel using linear spectral mixture analysis (Mertes et al., 1993). Reference spectral end members were based on reflectance data for sediment-water mixtures that included resuspended Mississippi River sediment (Witte et al., 1981). Reflectance end-member fractions were related to absolute sediment concentrations by a nonlinear calibration curve (Mertes et al., 1993; Mertes, 1994). The estimated error is ±20 mg/L. A depth-integrated suspended sediment sample obtained on July 20, 1993, from the Mississippi River at Keokuk yielded a concentration of 183 mg/L (C. Beckert, 1994, personal commun.). The exact relation between surface and depth-integrated concentrations depends on local boundary shear stress, water depth, and sediment size (McLean, 1992), but our estimated range of near-surface concentrations (60 to 120 mg/L) in the channel on July 25 is within the range expected from the depth-integrated measurement.

LEVEE BREAK COMPLEXES

Breaches within the study reach ranged from 100 m to 1 km wide. Levee break complexes associated with a breach consisted of a localized zone of concentrated scour, an extensive zone of superficial stripping, and a circumjacent zone of coarse sand deposition (cf. Jacobson and Oberg, 1995). Upriver from the confluence with the Missouri River, the sediment load of the Mississippi River consists predominately of silt- and clay-sized material, and the bank and flood-plain sediments are very cohesive. In consequence, scour zones were very localized, rarely extending for a distance of >250 m beyond a break site, and the maximum depth of scour was 2 to 3 m. The most prominent erosional feature was the 0.1–0.5-m-deep, spur and furrow topography of the stripped zone. Post-flood aerial reconnaissance also revealed little evidence of substantive channel change within the study reach. This suggests that at levee breaks, and elsewhere within the study reach, the resistance of the channel and flood plain to erosion generally exceeded the erosive power of the 1993 flood.

A minimal amount of sand-sized bed-load material encroached onto the flood plain, because the scour zone rarely linked a break site directly to the channel bed, and steep, 1–2-m-high banks otherwise inhibited the transfer of sand from the channel to the flood plain. Thus, the circumjacent deposits consisted of coarse sand derived exclusively from the break site. They typically took the form of a 0.15–1.5-m-thick, horseshoe-shaped sand rim with a gently ramped backslope, tens to hundreds of metres long, terminating in a well-defined slip face. The transition to rapidly decelerating, divergent flow on the flood plain in the period immediately following failure was marked by a splaylike sand sheet, a few millimetres thick, that extended 25 to 250 m beyond the leading edge of the sand rim. However, the extent and magnitude of scour and deposition in the vicinity of break sites within the study reach bear no comparison to the catastrophic disruption of the flood plain following levee failures in 1993, downriver from the confluence with the Missouri River (e.g., failure of the Len Small levee at Miller City, Illinois; Bhowmik, 1994; Jacobson and Oberg, 1995). For comparison, the depth of scour in the vicinity of the ~600-m-wide breach in the Len Small levee was >20 m over a distance of 2.2 km across the floodplain. Downriver from St. Louis, the 1993 flood had a recurrence interval of 10 to 50 yr (Parrett et al., 1993), but the flood-plain alluvium is far less cohesive because, despite a similar clay mineralogy, it contains a higher proportion of sand (Parks and Fehrenbacher, 1968; Potter et al., 1975; Bushue, 1979).

FINE-SEDIMENT DEPOSITION

Beyond the sand sheet, fine overbank deposition ($D_{50} < 25$ μm) was controlled by the degree to which water passing through the break site facilitated the transfer of suspended sediment from the channel onto the flood plain and the dispersal of soil eroded from the scoured and stripped zones. Our field surveys revealed that there was a barely detectable <2–3-mm-thick veneer of silt over much of the flood plain in the Hunt–Lima Lake levee and drainage district. In the Union Township levee and drainage district, multiple overtopping generated slightly thicker (3–4 mm) overbank deposits. Although the relief of the predominantly agricultural terrain of the flood plain behind the levees was very subdued, the pattern of fine-sediment deposition was to some extent influenced by local flood-plain topography. In the Hunt–Lima Lake levee district, for example, 50 to 200 mm of sediment was observed in shallow (<1 m deep, <5 km^2) depressions, which concentrated floodwater and functioned as settling basins as the flood waned.

The TM data provide an exceptionally clear perspective on the pattern of fine-sediment transport associated with the levee breaks. The suspended sediment concentration in the floodwater is, in general, similar to the sediment concentration in the main channel, confirming that it is largely decanted from the surface waters of the Mississippi River. Higher sediment concentrations (80 to 140 mg/L in the core of plumes) largely reflect sediment mobilization in response to local scour at the break site and across the stripped zone. Although the TM data were acquired 1 to 2 weeks after most breaks occurred, silt and clay particles remained in suspension in the near-stagnant floodwater, by virtue of their low sedimentation velocity.

In the Fabius River and Hunt–Lima Lake levee and drainage districts, transverse transport across the flood plain is dominated by sediment plumes emanating from levee breaks and/or large-scale eddy circulation. The pattern of transverse transport is generally uncomplicated by longitudinal dispersion because the crowns of most levees projected above the floodwater, isolating the flood plain from the channel after inundation. It is obscured by the enhanced suspended-sediment concentrations that result from multiple overtopping of the Union Township and Marion County levees. Even when a levee failure occurred on the outside of a bend, in the region where flow in the channel was directed toward the bank, the continual transfer of sediment onto the flood plain was inhibited by the relatively restricted breach width and ponding, because flow across the flood plain was curtailed by the lack of a downstream outlet once the break was deactivated.

In the absence of the continuous transfer of water and sediment onto the flood-plain surface and with no appreciable near-bed sand transport, the surface concentrations shown in Figure 1 convert directly to an estimate of sedimentation thickness, if the depth of the water column is known and surface suspended-sediment concentrations approximate depth-averaged values (Mertes, 1994). Assuming all of the sediment in the water column settles out, a sediment concentration of 100 mg/L in water 3 m deep implies ~3 mm of deposition. Behind the Union Township and Hunt–Lima Lake levees, high-water marks indicated average water depths of 3 and 5 m, respectively, and the <2 to 5 mm of overbank sedimentation implied by the concentration estimates accords well with the measured depths.

DISCUSSION AND CONCLUSION

Our field surveys and the TM data indicate that the veneer of sediment on the flood plain throughout the study reach is at the low end of the range of thicknesses (<5 to 840 mm) of overbank deposits associated with other large floods in the Mississippi River basin (Grover, 1938; Kesel et al., 1974). The river is strongly affected by human activity and it is tempting to attribute the minimal overbank deposition to isolation of the flood plain from the channel by the levees. However, we observed equally insignificant amounts of deposition on most unleveed parts of the flood plain within the study reach. Even though most levee failures occurred in the weeks preceding the flood peak, when suspended sediment concentrations for the event were likely at a maximum, suspended sediment records indicate that the summer 1993 flood was characterized by relatively low suspended-sediment concentrations. Sediment discharge in the upper Mississippi River basin typically peaks during spring runoff (Bhowmik et al., 1986), and higher suspended-sediment concentrations

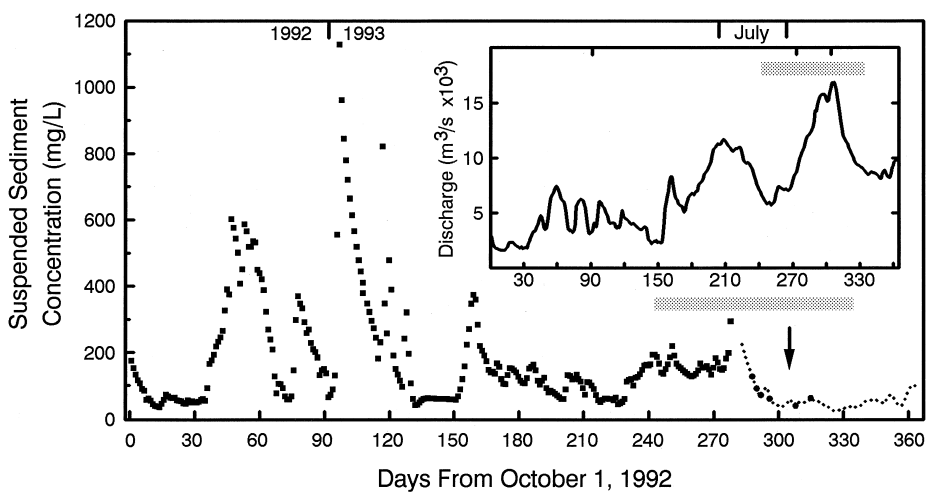


Figure 2. Daily suspended sediment concentration record for Mississippi River 1992–1993 water year, U.S. Geological Survey gauge at Grafton, Illinois, and discharge record (inset). Stippled bars indicate duration of 1993 flood, and arrow indicates timing of flood peak. Solid squares and circles are measured values; dotted line shows concentration estimates made by Holmes (1995) for period when gauging station was inoperative.

were recorded 150 km downriver from the study reach at Grafton, Illinois, in winter and spring 1992–1993 than during the summer 1993 flood (Fig. 2). Thus, from January 4 through January 13, 1993, suspended sediment concentrations >500 mg/L were associated with average daily discharges of between 4673 and 6032 m^3/s. At Grafton, the peak flow on August 3 was 16 879 m^3/s. On August 4 the suspended sediment concentration was 42 mg/L. Prior to the flood peak, the measured concentrations on July 19 and July 23 were 74 and 63 mg/L, respectively (Holmes, 1995).

Comparison of the total suspended-sediment discharge at Keokuk during the summer 1993 and spring 1973 floods affords a similar perspective on the 1993 event. The average annual suspended-sediment load of the Mississippi River at Keokuk is about 11×10^6 t (metric tons) (Keown et al., 1986). For the period March 1 to June 30, 1973, the sediment load was 22×10^6 t (Chin et al., 1975). On the basis of the available concentration and discharge records (we are unaware of any bed-load records), we estimate the sediment load for the period June 1 to August 31, 1993, was about 15×10^6 t. The discharge-weighted, average suspended-sediment concentrations for the 1973 and 1993 floods were 342 and 246 mg/L, respectively.

On the basis of our survey of overbank deposits associated with the summer 1993 upper Mississippi River flood and corroborating evidence provided by suspended sediment records, the transport effectiveness of floods in large drainage basins appears to be influenced by event sequencing in the same manner as in small watersheds (Beven, 1981). The summer 1993 event left little or no substantive sedimentological evidence of its passage through the study reach primarily for this reason. Cohesive flood-plain soils also minimized its erosional impact, but the contrasting geomorphological response of different reaches of the upper Mississippi River flood plain to levee failure graphically emphasizes the necessity of accounting for the threshold imposed by erosional resistance, in addition to flood hydrology (cf. Nanson, 1986; Huckleberry, 1994), when evaluating the sensitivity of flood plains to rare, high-magnitude events.

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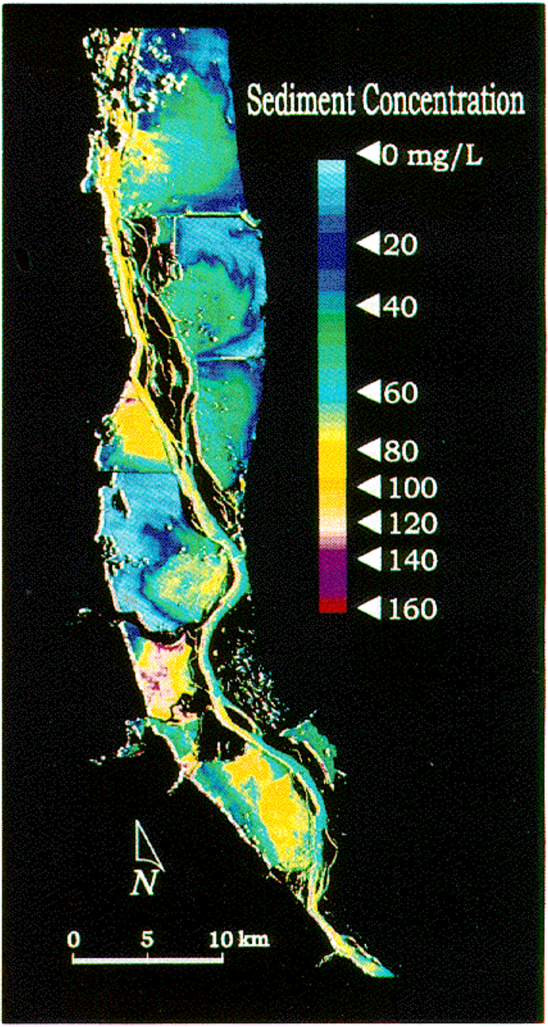
Sediment Concentration
0 mg/L
20
40
60
80
100
120
140
160
N
0
5
10 km