Sediment Dynamics and the Hydromorphology of Fluvial Systems (Proceedings of a symposium held in Dundee, UK, July 2006). IAHS Publ. 306, 2006.

The effect of the "Great Flood of 1993" on subsequent suspended sediment concentrations and fluxes in the Mississippi River Basin, USA

ARTHUR J. HOROWITZ
US Geological Survey, Peachtree Business Center, Suite 130, 3039 Amwiler Road, Atlanta, Georgia 30360, USA
horowitz@usgs.gov

Abstract During the spring/summer of 1993, the upper Midwestern USA experienced unusually heavy precipitation (200–350% above normal). More than 500 gauging stations in the region were simultaneously above flood stage, and nearly 150 major rivers and tributaries over-topped their banks. This was one of the costliest floods in the history of the USA, and came to be known as the "Great Flood of 1993". An examination of the long-term daily sediment record for the Mississippi River at Thebes, Illinois (representing the middle, or lower part of the upper basin), indicates that the flood had a severe and long-lasting impact on subsequent suspended sediment concentrations (SSC) and annual suspended sediment fluxes in the basin. At Thebes, pre-1993 (1981–1992) median discharge and SSC were about 5400 $m^3 s^{-1}$ and 304 mg L^{-1}, respectively; whereas, post-1993 (1994–2004) median discharge and SSC were about 5200 $m^3 s^{-1}$ and 189 mg L^{-1}, respectively. Clearly, the 1993 flood removed substantial amounts of "stored" bed sediment and/or readily erodible flood plain deposits, eliminating a major source of SSC for the Thebes site. Examination of additional, but discontinuous sediment records (covering the period from 1981–2004) for other sites in the basin indicates that current post-flood declines in SSC and suspended sediment fluxes range from a low of about 10% to a high of about 36%.

Key words Mississippi River Basin; suspended sediment concentration; suspended sediment fluxes

INTRODUCTION

The Mississippi River is the seventh largest river in the world, based on its discharge (580 km^3 $year^{-1}$), and drains about 40% of the conterminous USA, as well as portions of two Canadian provinces (Walker & Rouse, 1994; Meade, 1995; Johnson *et al.*, 2004). Approximately 70% of the river's drainage enters the northern Gulf of Mexico through the "bird-foot" delta, whereas the remaining 30% is diverted by the Old River Control Structure downstream of Vicksburg. The diverted flow combines with the Red River to form the Atchafalaya River, about 40 km upstream of Melville (Fig. 1). The Atchafalaya River also discharges to the northern Gulf of Mexico, but further west at Wax Lake and Morgan City (Fig. 1; Walker & Rouse, 1994; Meade, 1995). In addition, the Mississippi River is the sixth largest in the world, based on an average annual sediment discharge of about 200 Mt $year^{-1}$. The current average annual sediment discharge is about 50% lower since the Mississippi Valley was first settled by Europeans due to the construction of major reservoirs on the Missouri and Arkansas Rivers (Meade, 1995).

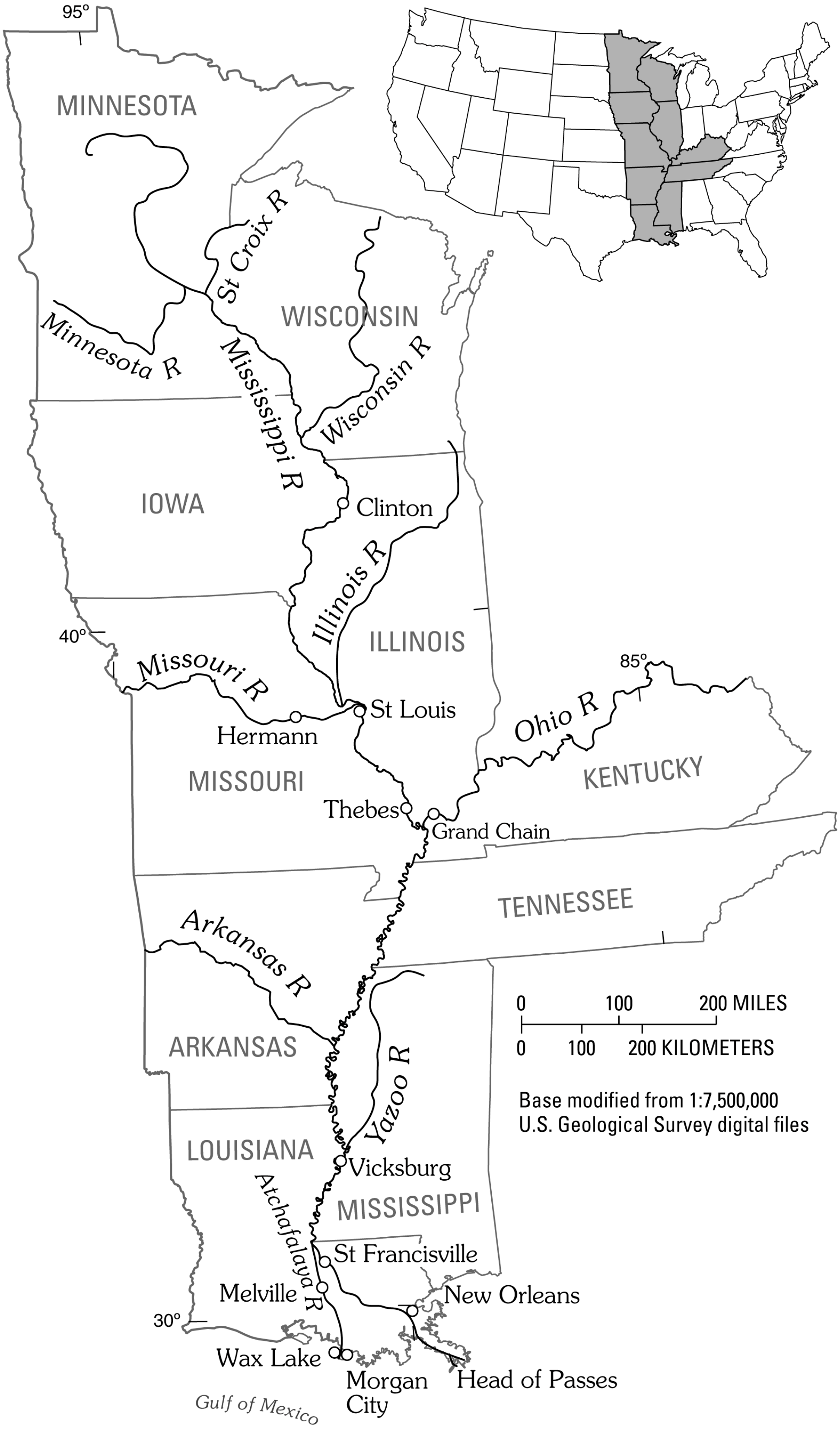

Fig. 1 General location map for the Mississippi River Basin.

As a result of unusual weather conditions during the summer of 1993 (April–August), the upper Midwestern USA experienced 200 to 350% greater than normal precipitation (Johnson *et al*., 2004). Above-normal rainfall in April and May saturated the soils, and filled many streams to capacity (Walker & Rouse, 1994; Johnson *et al*., 2004). Additional precipitation during the ensuing months led to flooding in Minnesota and Wisconsin in late June, and reached the mainstem of the Mississippi River and its major tributaries in July (Fig. 1, Johnson *et al*., 2004). At its apex, between 500 and 600 river gauges were above flood stage, and nearly 150 major rivers and tributaries were flooded throughout the basin (Larson, 1997; Johnson *et al*., 2004). This was one of the costliest floods in the history of the USA, and came to be known as the “Great Flood of 1993” (Holmes Jr, 1996). Surprisingly, despite this characterization, subsequent evaluations indicated that the recurrence interval for this event was on the order of 50–100 years (Holmes Jr, 1996).

The impacts of the Great Flood were numerous and diverse (Walker & Rouse, 1994; Larson, 1997; Johnson *et al.*, 2004). The gauge on the Mississippi River at St Louis, Missouri, was above flood stage for 144 days. About 3000 km^3 of water overflowed onto the flood plains downstream from St. Louis. More than 44 000 km^2 of land were flooded. More than 250 000 people lost potable water for as many as 19 days. Barge traffic along the river, which carries substantial portions of all the annually transported coal, petroleum, and exported grain in the USA, was halted for as long as two months. More than 1000 levees were topped or failed, and more than 3.2×10^6 ha of farmland were inundated.

In 1995–1996, the US Geological Survey’s (USGS) National Stream Quality Accounting Network (NASQAN) was revised from an occurrence-and-distribution-based network to a large-river flux-based water-quality monitoring network covering the Mississippi, Colorado, Rio Grande and Columbia Basins (Horowitz *et al.*, 2001a). Suspended sediment concentration (SSC) and discharge measurements were part of the original, as well as the revised programme; however, only the revised programme entailed annual flux estimates (Horowitz *et al.*, 2001a). During the preparation of a series of papers describing the results for the first three years of the revised programme, as well as during a later evaluation of sediment rating curves for estimating SSC for subsequent flux calculations, it appeared that the 1993 flood had induced a fundamental, long-term change in the concentration and annual transport of suspended sediment in the Mississippi River Basin (Horowitz *et al.*, 2001a,b; Horowitz, 2003). The impacts of the Great Mississippi River Flood of 1993 on subsequent SSC and annual fluxes were still detectable at the end of 2004, and are summarized and discussed herein.

METHODOLOGY

Within the NASQAN network, manual SSC samples are collected at each site between 12 and 14 times a year following standard USGS depth- and width-integrated sampling techniques (Edwards & Glysson, 1988). The Mississippi River at the Thebes site is unique because it constitutes the only long-term, ongoing, daily sediment-measuring site in the network. The manually-collected data from this site are supplemented with daily estimates of SSC based on a single, observer-collected, depth-integrated vertical obtained near the centroid of flow, that is related to a manually-collected cross-sectionally representative sample via a regression equation (Horowitz, 2003). Each NASQAN site is also equipped with a "continuous" (typically, measurements are recorded every 15–60 min) stage recorder; discharge is calculated from site-specific stage–discharge relations. However, for purposes of flux calculations, daily mean discharges, determined from the continuous data were used.

Daily sediment fluxes for NASQAN sites were calculated based on the following:

$$\textit{Suspended sediment flux}\ (\text{tonnes day}^{-1}) = [Q(\text{ft}^3\ \text{s}^{-1})][SSC(\text{mg L}^{-1})][0.00245] \quad (1)$$

where: Q = daily mean discharge, and SSC = daily suspended sediment concentration.

Note that the unit of discharge is non-metric, but fluxes were converted to metric units (tonnes) through the use of an appropriate constant (0.00245) (Porterfield, 1977). Hence, to calculate annual suspended sediment fluxes, daily mean SSC estimates are required, and the daily fluxes calculated from them are summed for the period of interest. At all the NASQAN sites, other than the Mississippi River at Thebes, these values were obtained from site-specific sediment rating (transport) curves. Although there are more than 20 methods for developing sediment rating curves, the most common is a power function (regression) that relates SSC to water discharge, with discharge constituting the independent variable (e.g. de Vries & Klavers, 1994; Phillips *et al*., 1999; Asselman, 2000). Typically, because discharge and SSC are not normally distributed, the data are log-transformed prior to the analysis. Comparisons of actual and predicted SSC, partially as a result of scatter about the regression line, as well as the conversion of results from log-space to arithmetic-space, indicate that sediment rating curves can underestimate actual concentrations (Ferguson, 1986; Walling & Webb, 1988; Asselman, 2000). To compensate, various modifications have been applied; these have included dividing the SSC/discharge data into seasonal or hydrological groupings, developing various correction factors, or using nonlinear regression equations (Duan, 1983; Ferguson, 1986; Walling & Webb, 1988; Phillips *et al*., 1999; Asselman, 2000).

The procedures employed for the NASQAN programme, for estimating daily SSC in the absence of actual sample data, are detailed elsewhere (Horowitz *et al*., 2001a; Horowitz, 2003). Briefly, all the available (current and historic) discharge and SSC data for a specific site are used. The data are combined into a single calibration set and log transformed. A series of regression equations (e.g. linear, polynomial) are calculated and subsequently evaluated. Residual analyses are performed for each regression. If the pattern for the residual analysis is random, then predicted daily SSCs are generated for each of the acceptable curves. In turn, these SSCs are used to calculate daily fluxes for each set of data points from each curve (see equation (1) above). As can occur with these types of calculations, the conversion from log-space to arithmetic-space can produce a bias. When compensation is necessary to reduce/eliminate bias, a "smearing correction" is applied (Duan, 1983). The daily fluxes, based on a daily SSC from each curve, and a measured daily mean discharge, are then summed to produce a measure of total flux. This approach can produce as many as four flux estimates for each calibration set: (1) linear uncorrected; (2) linear "smearing" corrected; (3) polynomial uncorrected; and (4) polynomial "smearing" corrected. The four results are then compared with the total flux for the calibration set. The rating curve, with or without a "smearing" correction that produces a total flux estimate closest to that for the calibration set, is then used to predict SSCs where no manually-collected SSC data are available. Further, the differences between the actual and estimated fluxes (from the rating-curve derived SSCs) for the calibration sets are used to estimate the error associated with the selected method. For the large-river sites in the NASQAN programme, these errors typically have been less than ±15% (Horowitz *et al*., 2001a,b; Horowitz, 2003).

RESULTS AND DISCUSSION

The first indication of the long-term impact of the 1993 Mississippi River flood on SSC and annual suspended sediment fluxes came from comparisons between the actual and predicted concentrations and fluxes developed from the daily data from the Thebes site, covering the period from 1981 to 2000 (Horowitz *et al.*, 2001a; Horowitz, 2003). Extending the comparison through 2004 (the latest available data) did not significantly alter the pattern. The actual 24-year cumulative suspended sediment flux for the Mississippi River at Thebes site for the 1981–2004 water year (WY; 1 October–30 September) period is 2300 Mt. A single sediment rating curve, using the entire 24-year data set (a smearing corrected second-order polynomial, Fig. 2(a)), also yielded an estimate of ~2300 Mt for the same period. This is a standard approach for generating site-specific sediment rating curves where long-term data are available, and is predicated on the assumption that all the data from the site are part of the same statistical population. Note that despite the close agreement between the actual and estimated cumulative suspended sediment fluxes (~2300 Mt) for the 24-year period using the single rating-curve approach, the differences (+64 to –45%, with an absolute mean of 24%) between the actual and estimated fluxes for individual years (e.g. 1981, 1982, 1994, and 2002), can be substantial (Fig. 2(b)).

An examination of a plot of the actual *vs* the estimated annual fluxes for the 24-year period covering the 1981–2004 WY appears to indicate a marked pattern change pre- and post-1993 (Fig. 2(a) and (b)). Prior to 1993, the actual annual fluxes tended to exceed the predicted annual fluxes, whereas after 1993, the predicted annual fluxes tended to exceed the actual annual fluxes. This shift appears to imply that around 1993, a fundamental change in the SSC–discharge relation occurred. This view is supported by an examination of the mean and median SSC values at the Thebes site pre- and post-1993, which show a marked decline from 304 mg L^{-1} to 189 mg L^{-1}, respectively (Table 1). Depending on which measure of central tendency is employed, and whether it is evaluated against the entire period or against the pre- and post-1993 periods, the decline in SSC ranged from 36 to 48% (Table 1).

As noted previously, 1993 was the year of the Great Mississippi River Flood. An examination of the sediment rating curve for the Mississippi River at the Thebes site for 1993, as well as the changing relationship between discharge and SSC during the course of the flood itself, provides additional insights into the cause for the post-1993 decline in SSC (Fig. 3). The 1993 rating curve for the Thebes site is sharply convex, which indicates that the site probably was severely "sediment-starved" during the

Table 1 Differences in mean/median discharge and suspended sediment concentration for the Mississippi River at Thebes Site, pre- and post-1993 for the 1981 to 2004 WY period.

	Mean discharge (m^3 L s^{-1})	Discharge diff. (%)	Median discharge (m^3 L s^{-1})	Discharge diff (%)	Mean SSC (mg L^{-1})	Mean SSC diff. (%)	Median SSC. (mg L^{-1})	Median SSC. diff. (%)
Pre-1993	6500		5400		420		304	
Post-1993	6500	<1	5200	–4	270	–36	189	–38

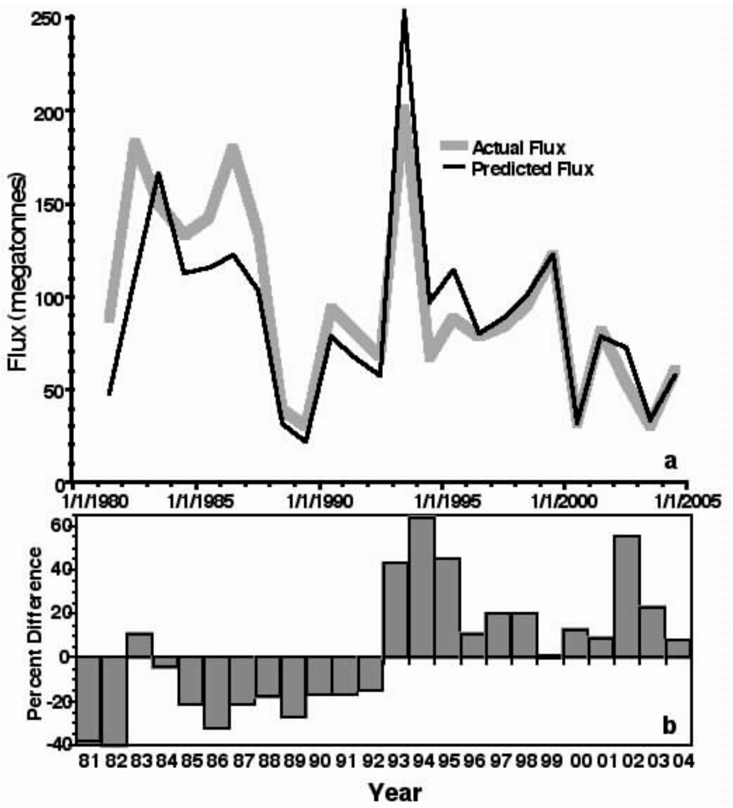

Fig. 2 (a) A comparison of actual and estimated annual fluxes (water years 1981–2004) for the Mississippi River at Thebes; the estimated fluxes are based on a single rating curve generated from daily mean discharge and daily suspended sediment concentration data. (b) The percent difference between predicted and actual fluxes for the Mississippi River at Thebes; a negative difference indicates an under prediction whereas a positive difference indicates an over prediction

course of the flood. Actual measurements in the general area around Thebes indicated as much as 4 m of channel-bed scour during the rise, and although aggradation was noted during the recession, it appears that erosion far exceeded deposition during and just after the 1993 flood (Holmes Jr, 1996). Clearly, the flood removed substantial amounts of "stored" bed sediment and/or readily erodible flood plain deposits, thus eliminating a major local source of suspended sediment. No doubt the problem was further exacerbated by a concomitant reduction in SSC and suspended sediment fluxes from the nearby Missouri River, just upstream of the Thebes site (Fig. 1, also, see later).

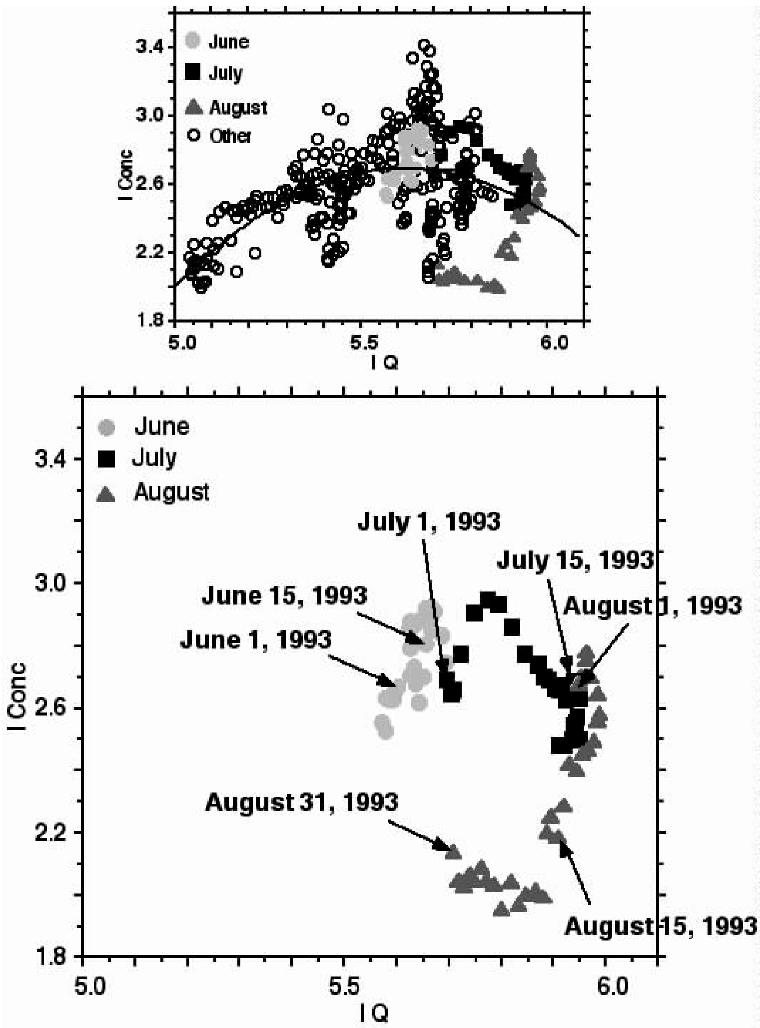

Fig. 3 The upper graph is the 1993 water year sediment rating curve for the Mississippi River at Thebes; whereas the lower graph depicts the clockwise hysteresis loop for the 1993 flood. Note that for purposes of clarity, the symbols used in both graphs are the same. The horizontal axes (l Q) are the log of discharge and the vertical axes (l Conc) are the log of the concentration of suspended sediment.

Additional support for this contention comes from an examination of the plot of discharge *vs* SSC for the Mississippi River at the Thebes site during the course of the 1993 flood (Fig. 3). The relation follows a clockwise hysteresis loop starting in June, and ending in late August 1993. Clockwise hysteresis loops are indicative of channel-bed scour, with the subsequent removal of stored, in-channel bed sediment (e.g. Walling, 1977; Wood, 1977; Meade *et al.*, 1990). SSC clearly peaked in early July on the rising limb of the hydrograph, and continued to decline through the actual course of the flood (Fig. 3). This pattern would appear to support the view that the river was sediment-starved at this location, and the observed channel-bed scour would indicate that the probable cause was the loss of stored bed sediment.

An examination of the pre- and post-1993 sediment rating curves and the associated flux estimates for the other NASQAN Mississippi River mainstem sites, as well as those for the outlets from both the Missouri (Hermann) and Ohio rivers (Grand

Table 2 The effect of using pre- and post-1993 discharge and suspended sediment concentrations on flux estimates for selected sites in the Mississippi River Basin.

Site	Old data *n*	New data *n*	Flux (Mt) for WY 1981–1999 using: All data	Old data	New data	Difference* %
Clinton	128	52	76	80	69	13
Hermann	211	66	2000	2400	1500	36
Thebes	4152	2092	2200	2600	1600	39
Grand Chain	204	62	530	590	470	21
St. Francisville	157	69	2200	2500	1700	30

Site	Old data *n*	New data *n*	Flux (Mt) for WY 1981–2004 using: All data	Old data	New data	Difference* %
Clinton	128	116	95	100	90	10
Hermann	211	130	2100	2600	1800	29
Thebes	4152	3865	2300	3000	1900	36
Grand Chain	204	131	670	720	620	14
St. Francisville	157	138	2600	3000	2100	29

* The percent differences are for the total fluxes calculated using old (pre-1993) and new (post 1993) discharge and suspended sediment data.

Chain) (Fig. 1), indicates that the flood affected almost the entire upper basin (Table 2). Note the substantial differences in suspended sediment flux estimates based on their pre- and post-1993 rating curves. All the site-specific cumulative suspended sediment flux estimates for the 1981 to 2004 WYs, based on pre-1993 data and rating curves are substantially greater than those estimates based on post-1993 data and rating curves (Table 2).

Even though the flood was confined to the upper part of the Mississippi River, the loss of stored sediment upstream almost certainly affected the lower part of the river as well (St Francisville, Table 2). This probably was further exacerbated by the loss of locally stored bed sediment because even though the lower part of the river never reached flood stage in 1993, annual mean discharge (20 600 $m^3 s^{-1}$) at St Francisville was the second highest on record for the 1931 to 2004 WY period (Demas, USGS, oral communication, 2004).

The only potential exception to this pattern of reduced post-1993 SSC and estimated suspended sediment fluxes occurred in the upper part of the Mississippi River (Clinton, Table 2). The relatively unchanged level of annual suspended sediment fluxes occurred even though the upper part of the river clearly exceeded flood stage in 1993, and experienced significant amounts of bed scour (Holmes Jr, 1996). However, substantial downstream dispersion of the scoured material was limited by the extensive lock and dam system in the upper part of the Mississippi River (Meade, USGS, oral communication, 2002). Hence, the majority of the bed sediment in local storage, while somewhat displaced, never really was transported out of the immediate area.

It might be argued that the decline between pre- and post-1993 Mississippi River Basin fluxes was the result of a concomitant long-term decline in discharge. However, the differences between pre- and post-1993 mean/median discharges for all the Mississippi River Basin sites, with the possible exception of Grand Chain, which

Table 3 A summary of average pre- and post-1993 discharge and flow-weighted concentrations for selected sites in the Mississippi River Basin for the 1981 to 2004 WY period.

	Pre-1993			Post-1993			
Site	Average discharge ($m^3 s^{-1}$)	Median discharge ($m^3 s^{-1}$)	Average flow-weighted conc. ($mg L^{-1}$)	Average discharge ($m^3 s^{-1}$)	Median discharge ($m^3 s^{-1}$)	Average flow-weighted conc. ($mg L^{-1}$)	Difference in conc. (%)
Clinton	1 497	1 246	76	1 643	1 365	74	–3
Hermann	2 532	1 988	1150	2 645	2 202	834	–27
Thebes	6 542	5 400	544	6 542	5 200	360	–34
Grand Chain	7 986	5 721	116	8 666	6 259	102	–12
St Francisville	15 038	13 282	267	14 868	13 027	188	–30

increased, were relatively minor (Table 3). To eliminate the possibility that the pre- and post-1993 flux differences could be the result of a bias introduced by extended high- and/or low-flow periods, flow-weighted average SSCs were calculated for each site (Table 3). All the post-1993 flow-weighted average SSCs are lower than the pre-1993 ones; albeit, the difference at Clinton, not surprisingly, is negligible. Therefore, it would appear that the change between pre- and post-1993 fluxes resulted from a reduction in SSC, rather than a change in discharge. As such, it also would appear that suspended sediment fluxes in the Mississippi River Basin are supply- rather than discharge-limited.

A comparison of the pre- and post-1993 flux estimates for the 1981 to 1999 WYs and those for the 1981 to 2004 WYs indicates that annual suspended sediment fluxes in the Mississippi River Basin have increased during the 5-year period since 1999 (Table 2). It should be noted that the "recovery" is occurring more rapidly in the Missouri (Hermann) and Ohio (Grand Chain) rivers than in the Mississippi River itself, and that the lower part of the mainstem (St Francisville) has shown the least amount of change between 1999 and 2004. These results also would appear to indicate that the factors/processes affecting suspended sediment and sediment-associated constituents that occur in the upper part of the Mississippi River Basin, may not be reflected in the lower part of the system for decades.

CONCLUSIONS

1. In 1993, due to exceptionally high levels of precipitation in the upper Midwest, the Mississippi River Basin experienced one of the costliest floods in the history of the USA.
2. The flood made a substantial impact on the post-1993 levels of SSC and their associated annual fluxes, reducing them by as much as 48%.
3. Although the flood was restricted to the upper part of the Mississippi River Basin, the entire system was affected.
4. Despite the fact that there has been some recovery since 1993, as of 2004, SSC and their associated fluxes are still well below pre-1993 levels.

5. Based on flow-weighted SSC averages, the reduced post-1993 fluxes appear to be the result of a substantial decrease in SSC, rather than to a reduction in discharge; hence suspended sediment fluxes throughout the basin appear to be supply-limited.
6. The results also appear to indicate that the factors/processes affecting SSC and SSC-associated constituents that occur in the upper part of the basin may not be reflected in the lower part of the system for decades.

REFERENCES

Asselman, N. E. M. (2000) Fitting and interpretation of sediment rating curves. *J. Hydrol.* **234**, 228–248.

de Vries, A. & Klavers, H. C. (1994) Riverine fluxes of pollutants: monitoring strategy first, calculation methods second. *European J. Water Pollution Control* **4**, 12–17.

Duan, N. (1983) Smearing estimate: a nonparametric retransformation method. *J. American Statist. Soc.* **78**, 605–610.

Edwards, T. K. & Glysson, G. D. (1988) Field methods for measurement of fluvial sediment. *US Geol. Survey Open-File Report 86-531*.

Ferguson, R. I. (1986) River loads underestimated by rating curves. *Water Resour. Res.* **22**, 74–76.

Holmes Jr, R. R. (1996) Sediment transport in the lower Missouri and the central Mississippi Rivers, June 26 through September 14, 1993. *US Geological Survey Circular 1120-I.*

Horowitz, A. J. (2003) An evaluation of sediment rating curves for estimating suspended sediment concentrations for subsequent flux calculations. *Hydrol. Processes* **17**, 3387–3409.

Horowitz, A. J., Elrick, K. A. & Smith J. J. (2001a) Estimating suspended sediment and trace element fluxes in large river basins: methodological considerations as applied to the NASQAN programme. *Hydrol. Processes* **15**, 1107–1132.

Horowitz, A J., Elrick, K. A. & Smith J. J. (2001b) Annual suspended sediment and trace element fluxes in the Mississippi, Columbia, Colorado, and Rio Grande drainage basins. *Hydrol. Processes* **15**, 1169–1207.

Johnson, G. P., Holmes Jr, R. R, & Waite, L. A. (2004) The great flood of 1993 on the upper Mississippi River – 10 years later. *US Geol. Survey Fact Sheet 2004-3024, May 2004*.

Larson, L. W. (1997) The great USA flood of 1993. In: *Destructive Water; Water-Caused Natural Disasters, Their Abatement and Control* (ed. by G. H. Leavesley, H. F. Lins, F. Nobilis, R. S. Parker, V. R. Schneider & F. H. M. van de Ven), 13–20.

Meade, R. H. (1995) Setting: geology, hydrology, sediments, and engineering of the Mississippi River. In: *Contaminants in the Mississippi River 1987–92* (ed by R. H. Meade), 13–30. *US Geological Survey Circular 1133*, US Government Printing Office, Washington, DC, USA.

Meade, R. H., Yuzyk, T. R. & Day, T. J. (1990) Movement and storage of sediment in rivers of the United States and Canada. In: *Surface Water Hydrology: The Geology of North America* (ed by M. G. Wolman & H. C. Riggs), vol. O, 255–280. Geological Society of America.

Phillips, J. M., Webb, B. W., Walling, D. E. & Leeks, G. J. L. (1999) Estimating the suspended sediment loads of rivers in the LOIS study area using infrequent samples. *Hydrol. Processes* **13**, 1035-1050.

Porterfield, G. (1977) Computation of fluvial-sediment discharge. In: *Techniques of Water-Resources Investigations of the US Geological Survey*, Chapter C3, Book 3.

Walker, N. D. & Rouse Jr, L. J. (1994) The great flood of summer 1993: Mississippi River discharge studied. *Earth in Space* **7**, November 1994, 11–14.

Walling, D. E. (1977) Suspended sediment and solute response characteristics of the River Exe, Devon, England. In: *Research in Fluvial Geomorphology* (Proc. Guelph Symp. on Geomorphology), 5, 169–197. Geoabstracts Ltd, Norwich, UK.

Walling, D. E. & Webb B. W. (1988) The reliability of rating curve estimates of suspended sediment yield: some further comments. In: *Sediment Budgets* (ed by M. P. Bordas & D. E. Walling), 337–350. IAHS Publ. 174. IAHS Press, Wallingford, UK.

Wood, P. A. (1977) Controls of variation in suspended sediment concentration in the River Rother, West Sussex, England. *Sedimentology* **24**, 437–445.