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A Quarter Century of Declining Suspended Sediment Fluxes in the Mississippi River and the Effect of the 1993 Flood

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Abstract

Annual fluxes, flow-weighted concentrations, and linear least squares trendline calculations for a number of long-term Mississippi River Basin (MRB) sampling sites covering 1981 through 2007, whilst somewhat ''noisy,'' display long-term patterns of decline. Annual flow-weighted concentration plots display the same long-term patterns of decline, but are less noisy because they reduce/eliminate variations due to inter-annual discharge differences. The declines appear greatest in the middle MRB, but also are evident elsewhere. The pattern for the lower Ohio River differs, and may reflect ongoing construction at the Olmsted lock and dam that began in 1993.

The ''Great Flood of 1993'' appears to have super-imposed a step function (a sharp drop) on the long-term rate of decline in suspended sediment concentrations (SSC), annual fluxes, and flow-weighted concentrations in the middle MRB at St. Louis and Thebes, Missouri, and Vicksburg, Mississippi, and in the lower MRB at St. Francisville, Louisiana. Evidence for a step function at other sites is less substantial, but may have occurred. The step function appears to have resulted from losses in available (erodible) sediment, rather than to a reduction in discharge; hence, the MRB appears to be sup-ply limited rather than discharge limited. These evaluations support the need for daily discharge and SSC data collections in the MRB to better address questions regarding long-term trends in sediment-related issues. This is apparent when the results for the Mississippi River at Thebes and St. Louis sites are compared with those from other MRB sites where inten-sive (daily) data collections are lacking.

Introduction

Over the past 100 years, based on a combination of actual measurements as well as modeling exercises, there have been marked changes in the annual suspended sediment fluxes of many of the Earth's major river systems (e.g., Meade, *et al.*, 1990; Milliman, *et al.*, 1995; Syvitski, *et al.*, 2005; Syvitski and Kettner, 2008; Walling, 2008). In many cases, these changes have resulted from diverse anthropogenic activities that have either directly or indirectly affected the hydrologic cycle (resulting in changes in discharge and/ or sediment availability) through such diverse factors as: 1) urbanization, 2) population growth, 3) deforestation, 4) mineral extraction, 5) water exploitation, 6) changing agricultural practices, and 7) dam and reservoir construction (e.g., Syvitski, *et al.*, 2005; Walling, 2006, 2008). Global climate change, whether the result of natural weather cycles or through the increasing emission of anthropogenically generated greenhouse gases, also can lead to altered patterns of weathering and erosion, with concomitant changes in the annual fluxes of suspended sediment (e.g., Syvitski and Kettner, 2008; Walling, 2008). Altered trends in annual sediment fluxes can generate numerous downstream effects that involve hydrologic, ecologic, economic, and engineering issues.

Changing patterns of annual suspended sediment fluxes (annual loads, yields) in the Mississippi River Basin (MRB) certainly encompass the majority of the effects cited above (e.g., Meade, 1995; Mossa, 1996; Stone *et al.*, 1997; van Heerden and DeRouen, Jr., 1997). Erosion along the Louisiana coast has been and continues to be extensive; since the 1950s,

wetland losses have been estimated in excess of 90 km² y⁻¹, and landward erosion rates of as much as 20 m y⁻¹ have been noted (e.g., van Heerden and DeRouen, Jr., 1997). The impacts of the storm/tidal surges associated with the relatively recent (August–September, 2005) landfalls of Hurricanes Katrina and Rita and the subsequent flooding of New Orleans have been ascribed to land subsidence, in conjunction with the major loss of coastal wetlands and barrier islands that help reduce storm surges (e.g., Waltham 2005). Further, a number of Louisiana coastal and wetland restoration plans/projects are predicated on the assumption that the Mississippi River could be "mined" for material for that purpose (Davis, Jr., 1997; Thorne, *et al.*, 2008). Finally, the growing spatial and temporal extent of the Gulf of Mexico hypoxic zone has been ascribed, at least in part, to nutrient enrichment from U.S. Midwestern agricultural sources (e.g., Walker and Srinivasan, 1995; Goolsby *et al.*, 1999; Turner *et al.*, 2007). Because it has been estimated that MRB suspended sediments deliver about 85%, 30%, and 50%, respectively, of the annual fluxes of P, N, and organic carbon to the northern Gulf of Mexico, changing suspended sediment fluxes also may affect the spatial and/or temporal extent of the hypoxic zone (e.g., Walker and Srinivasan, 1995; Horowitz *et al.*, 2001; USGS, 2004; Turner *et al.*, 2007).

The Mississippi River is the seventh largest in the world, based on discharge (16,200 m³ s⁻¹; 580 km³ y⁻¹); whereas, the MRB is the third largest in the world based on area (3,225,000 km²), and drains about 41% of the conterminous United States as well as portions of two Canadian provinces (van der Leeden *et al.*, 1990; Meade, 1995; Johnson et al, 2004). The river flows some 3,770 km downstream from Lake Itasca, Minnesota, through ten states, and eventually discharges to the Gulf of Mexico (fig. 1). Approximately 75% of the river's discharge enters the northern Gulf of Mexico through the "bird's-foot" delta; the remaining volume, is diverted by the Old River Control Structure (ORCS) downstream from Vicksburg, Mississippi, where it joins the Red River to form the Atchafalaya River, about 40 km upstream from Melville, Louisiana (e.g., Meade, 1995; Mossa, 1996). The combined volume of diverted Mississippi and Red River water represents 30% of the latitudinal flow of the Mississippi River (Brown, pers. comm., 2009). The Atchafalaya River also discharges to the northern Gulf of Mexico, but further west through two distributaries located at Wax Lake Outlet near Calumet, and Morgan City, Louisiana (fig. 1; Walker and Rouse, 1994; Meade, 1995).

Estimates of average annual sediment fluxes from the Mississippi River cover a range, but appear to have declined by as much as 50–70% (variously estimated initially to have been between 400–500 Mt y⁻¹) since the 1800s, and the onset of major European settlement and subsequent anthropogenic activities (Keown *et al.*, 1986; Kesel, 1988; Kesel *et al.*, 1992; Meade, 1995). Meade and Parker (1985) estimated that the combined annual sediment flux from the Mississippi and Atchafalaya Rivers was between 290 and 310 Mt y⁻¹. In 1986, Keown *et al.* estimated the average annual load at 255 Mt y⁻¹.

In 1996, based on a variety of sources, Mossa cites a value of 230 Mt y⁻¹. In 2001, based on a short-term period of record, Horowitz *et al.* estimated the average annual load at about 255 Mt y⁻¹, and most recently, Thorne *et al.* (2008) and Meade and Moody (2008) have generated average annual estimates of about 145–150 Mt y⁻¹. The combined Mississippi and Atchafalaya Rivers account for about 70% of the mean annual sediment discharge from the conterminous United States and average annual fluxes of even 145–150 Mt y⁻¹ rank the MRB sixth in the world (Milliman *et al.*, 1995; Milliman, pers. comm., 2007; Syvitski and Kettner, 2009).

The Mississippi River and its tributaries (fig. 1) constitute one of the most heavily engineered systems in the United States, if not the world, and much has been written about the effects of these modifications on the annual suspended sediment fluxes in the basin (e.g., Keown *et al.*, 1986; Kesel *et al.*, 1992; Meade, 1995; Kesel, 2003; Meade and Moody, 2008; Thorne, *et al.*, 2008; Jacobson *et al.*, 2009). There are nine dams and two lock and dam structures between Lake Itasca (the headwaters of the Mississippi River) and Lock and Dam #1 near Minneapolis, Minnesota (Wikipedia, 2009a). There are an additional 26 lock and dam structures between Minneapolis and St. Louis, Missouri, which were constructed between 1917 and 1953, which facilitate commercial navigation through a 122 m drop in elevation (Wikipedia, 2009a). Downstream from St. Louis, the river is leveed, and revetments have been installed; both have substantially altered the sediment load in the mainstem by limiting/eliminating contact with the floodplain and subsequent bank erosion or calving (e.g., Mossa, 1996). The next major engineering features are formally known as the Old River Low Sill and Overbank Structures (commonly called the ORCS) downstream from Vicksburg, Mississippi (fig. 1). These structures were designed to prevent the majority of Mississippi River water from being captured by the Atchafalaya River and for flood control and were completed in 1963 (e.g., Meade, 1995). Additional modifications were made in 1987 and 1991, each with separate inflow channels (Mossa, 1996). Between the ORCS and the Mississippi River mouth there are no major tributaries/distributaries, but both the Bonnet Carré (to Lake Ponchartrain; completed in 1937) and the Morganza (to the Atchafalaya River; completed in 1954) Spillways were designed and built for flood control (e.g., Mossa, 1996).

The Missouri River drains about 16% of and is the longest river (4,090 km) in the conterminous United States (van der Leeden *et al.*, 1990; Wikipedia, 2009b). The river begins northwest of Bozeman, Montana (fig. 1), and is formed from the confluence of the Madison, Jefferson, and Gallatin Rivers; the Missouri River nearly doubles the volume of the Mississippi River when it joins it just north of St. Louis, Missouri (Wikipedia, 2009b). Beginning in 1933 and ending in 1964, seven major dams [in order of completion Fort Peck (1940), Canyon Ferry (1954), Garrison (1954), Fort Randall (1956), Gavins Point (1956), Oahe (1963), and Big Bend (1964)] were constructed on the Missouri River
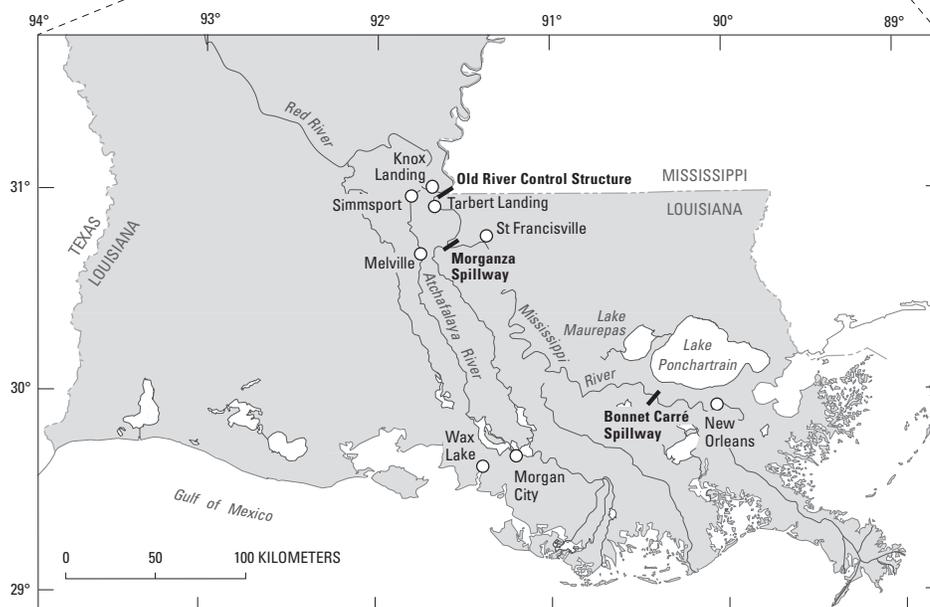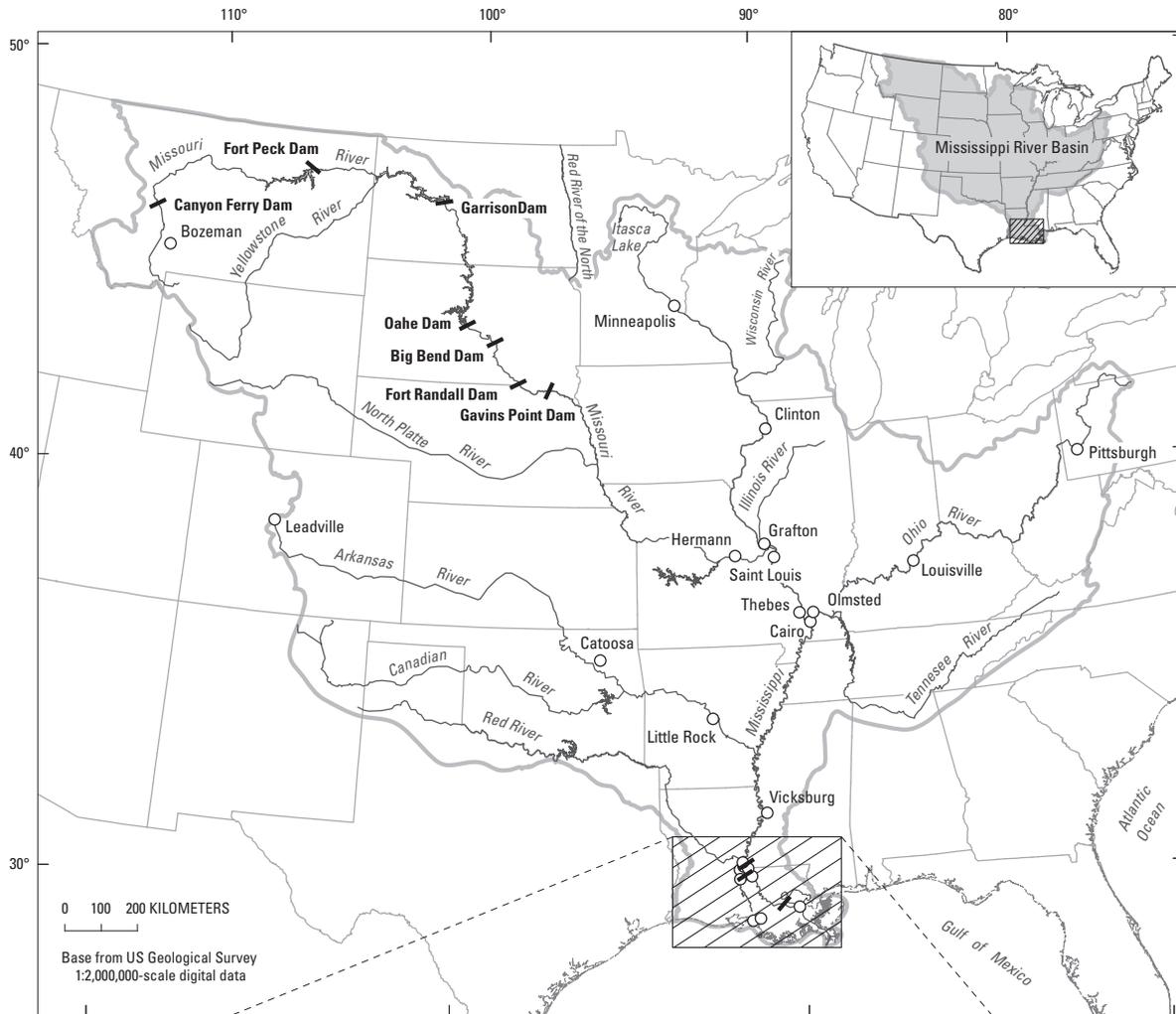
Figure 1.   General location map for the Mississippi River Basin and the sampling sites used in this study. Olmsted and Grand Chain, on the Ohio River overlap at this scale.

for flood control, irrigation, and hydropower generation (Wikipedia, 2009b). The dams lack locks; hence, commercial navigation is restricted above Gavins Point on the South Dakota–Nebraska border (fig. 1). Downstream from the Gavins Point Dam, a series of dikes, revetments, and levees have been constructed to more readily maintain the navigation channel and with the further aim of limiting the need for dredging. The construction of the Missouri River dams, and the sediment trapped behind them, often is cited as the most significant cause of reduced annual suspended sediment loads in the Mississippi River (Keown *et al.*, 1986; Kesel *et al.*, 1992; Meade, 1995; Kesel, 2003; Harmer *et al.*, 2005; Meade and Moody, 2008).

The Ohio River forms at the confluence of the Allegheny and Monongahela Rivers near Pittsburgh, Pennsylvania, is 1,580 km long and drains about 490,000 km². The Ohio joins the Mississippi River near Cairo, Illinois, and by volume, is its largest tributary (fig. 1; van der Leeden *et al.*, 1990; Wikipedia, 2009c). Engineering modifications began as early as 1825 to circumnavigate the Falls of the Ohio and to facilitate navigation beyond Louisville, Kentucky. By 1929, 51 wooden wicket locks and dams had been constructed on the Ohio River; however, by the 1940s, the existing locks proved too small for the level of barge traffic, and a modernization program began in the 1950s (Wikipedia, 2009d). Currently, there are 21 lock and dam structures on the Ohio River that facilitate commercial navigation through a 122 m drop in elevation between Pittsburgh and Olmsted, Illinois. The final lock and dam at Olmsted currently is under construction; it will replace older structures at Brookport and Grand Chain, Illinois, and is scheduled for completion in 2014 (Bibelhauser, oral comm., 2009).

The Arkansas River, the sixth longest (2,364 km) in the United States, is the third largest tributary in the MRB, and drains about 505,000 km², (van der Leeden *et al.*, 1990; Wikipedia, 2009e). The river has its headwaters near Leadville, Colorado (fig. 1), but only is commercially navigable downstream from Tulsa, Oklahoma, due to the McClellan-Kerr Navigation System. Construction of the navigation system began in 1963; it was partially opened in 1968, and completed in 1971. There are 18 lock and dam structures between Catoosa, Oklahoma, and the mouth of the Arkansas where it joins the Mississippi River. According to Meade (1995), the structures on both the Missouri and Arkansas Rivers combined to decrease total annual suspended sediment fluxes in the Mississippi River by about 50% since the first European settlers arrived in the MRB.

Even in the 1930s, before the inception of almost all the major engineering projects described previously, reductions in annual suspended sediment loads in the MRB were noted, and ascribed to the introduction of better land/agricultural management practices such as contour plowing, conservation tillage, bank stabilization, reforestation, etc. (Trimble, 1981; Wittwer, 1982; Keown *et al.*, 1986; Knox, 1987; Kesel. 1988; Meade and Moody, 2008; Thorne, *et al.*, 2008). Finally, major storm events such as the so-called ''Great Mississippi River Flood

of 1993'' also may have led to significant reductions in annual suspended sediment loads by removing substantial amounts of stored, in-channel, bed sediments (Horowitz *et al.*, 2001; Horowitz, 2006).

A recent request regarding estimates for the current levels of annual suspended sediment fluxes in the lower Mississippi River, in conjunction with doubts about the impacts of major flood events on those annual fluxes, triggered an examination/ evaluation of long-term U.S. Geological Survey (USGS) and U.S. Army Corps of Engineers (USCOE) discharge and suspended sediment records throughout the MRB (Allison, pers. comm., 2008; Meade and Moody, 2008). Hence, the evaluation had two objectives: (1) to determine the ''long-term'' (27 years) trends, if any, in annual suspended sediment fluxes and flow-weighted concentrations for the MRB and (2) to evaluate the effect of the 1993 flood, if any, on those long-term trends.

Methodology

The USGS and the USCOE have maintained long-term gaging stations throughout the MRB for measuring/recording daily discharge, some for more than 100 years (e.g., Mississippi River at St. Louis). Unfortunately, at least in the case of the USGS, records of suspended sediment concentration (SSC) are nowhere near as long, complete, nor accurate (e.g., Horowitz *et al.*, 1989; Meade, 1995; Mossa, 1996; Meade and Moody, 2008). The widespread collection of much of the representative USGS suspended sediment data for the Mississippi River, using depth-and-width-integrated isokinetic sampling techniques, coincided with the inception of the National Stream Quality Accounting Network (NASQAN) Program that began in the early to mid-1970s (Ficke and Hawkinson, 1975; Hawkinson et al, 1977; Edwards and Glysson, 1999). For purposes of the current evaluation, discharge and SSC data from a number of these long-term MRB mainstem and tributary sites were used (table 1). Data from the Mississippi River at St. Louis and Thebes are of particular interest because these are two of the few sites in the basin where long-term daily SSC data are collected (e.g., Horowitz, 2003). The record for the Mississippi River at Grafton also consists of discharge and daily SSC values; however, daily SSC data were not collected before 1990, only three data points exist prior to that year, and substantial portions of the records during the 1993 flood were lost when the gaging station was inundated. Hence, a major part of the storm-discharge record was lost. This precluded using data from this site for this evaluation.

Long-term trends in suspended sediment fluxes were evaluated using a combination of calculated/estimated annual fluxes in conjunction with flow-weighted concentrations (annual flux/annual discharge). For trend identification, mean/median flow-weighted concentrations appear more useful than annual fluxes because they tend to ''damp out'' the interannual variations caused by significant differences (high volume versus low volume years) in annual discharge and/or those created when there are missing data.

Table 1. List of sites, locations, and upstream drainage areas used in this evaluation.

[N/A, not applicable]

Site name	Latitude	Longitude	Drainage area (km²)
Mississippi River, Clinton, IA	41°46'50"	90°15'07"	221,702
Missouri River, Hermann, MO	38°42'35.3"	91°26'18.6"	1,353,269
Mississippi River, St. Louis, MO	38°37'44.4"	90°10'47.2"	1,805,222
Mississippi River, Thebes, IL	37°12'59.3"	89°28'03.3"	1,847,179
Ohio River, Lock and Dam 53, near Grand Chain, IL	37°12'11"	89°02'03"	526,026
Arkansas River, David Terry Dam below Little Rock, AK	34°40'02"	92°09'26"	409,964
Mississippi River, Vicksburg, MS	32°18'54"	90°54'21"	2,964,241
Old River Outfall Channel nr Knox Landing, LA	31°03'54"	91°41'08"	N/A
Mississippi River, Tarbert landing. LA	31°00'30"	91°7'25"	2,913,478
Mississippi River, St. Francisville, LA	30°45'30"	91°23'45"	2,914,514

Annual sediment fluxes for each of the sites evaluated were calculated using:

$$\text{Daily suspended sediment flux (t d}^{-1}) = [Q \text{ (ft}^3 \text{ s}^{-1})]$$
$$[\text{SSC (mg l}^{-1})][0.00245] \qquad (1)$$

where

  Q is daily mean discharge
  SSC is daily mean measured/estimated suspended sediment concentration

The unit of discharge is non-metric because that is the U.S. standard; however, fluxes are converted to metric units (tonnes) using an appropriate constant (0.00245; Porterfield, 1977). To calculate a daily flux, values for daily mean discharge and SSC are required. Annual fluxes are then determined by summing the appropriate number of daily flux values. Also note that the U.S. water year (WY) is not the same as a calendar year; a U.S. water year begins on October 1 of the previous year, and ends on September 30 of the year in question (e.g., the 2001 WY runs from October 1, 2000, through September 30, 2001). Annual flow-weighted concentrations require the determination of an annual volume of water; this is determined using:

$$\text{Daily volume (m}^3) = [Q \text{ (ft}^3 \text{ s}^{-1})]$$
$$[86,400 \text{ (s d}^{-1})][0.028317] \qquad (2)$$

where

  Q is daily mean discharge
  $86,400$ is seconds per day
  0.028317 is constant converting ft³ to m³

As with the flux values, annual discharge (water volume) is calculated by summing the appropriate number of daily values. Flow weighted concentrations are calculated using:

$$\text{Flow weighted concentration (mg l}^{-1})$$
$$= [\text{Annual flux (t)}]/[\text{Annual volume (m}^3)][10^6] \qquad (3)$$

Annual fluxes and flow-weighted concentrations for those sites where daily data are available were calculated using formulas (1), (2), and (3). The procedures employed to estimate daily mean SSC values, when daily data are not available, are detailed elsewhere (Horowitz *et al.*, 2001; Horowitz, 2003; 2006). Briefly, there are two potential estimation methods, both using sediment-rating curves ("lumped" or annual). The first entails combining all the available log-transformed paired discharge and SSC data for the period of interest to generate a single, site-specific sediment-rating curve, whereas the other entails generating individual annual rating curves using log-transformed paired discharge and SSC data for a particular year. Both approaches rely on regression equations (e.g., linear, polynomial) that are calculated and subsequently evaluated. Predicted/estimated daily SSCs are then 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 (1) above]. As can occur with these calculations, the conversion from log space to arithmetic space may 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 mean SSC from each curve and a measured daily mean discharge, are then summed to produce a measure of total flux. This approach can generate 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 sets of results (for either lumped or annual) are then compared with the total flux for the calibration set. The uncorrected or corrected rating curve that produces a total flux estimate closest to that of the calibration set is then used to predict daily mean SSCs for the period of record. In turn, these SSC values are used to generate daily fluxes and the appropriate daily fluxes are summed to produce annual fluxes.

Previous work (Horowitz, 2003), some with data sets from the same Mississippi River sites used in this evaluation, demonstrated that the lumped approach, whilst able to generate relatively accurate total fluxes for the entire period of record, also can generate fairly inaccurate interannual

estimates (e.g., ± >50%). However, most of the interannual inaccuracies associated with the lumped approach can be eliminated by substituting individual annual rating curves for the period of record (Horowitz, 2003; 2008). Hence, as the purpose of this evaluation is to examine interannual variability, and long-term annual flux trends, annual rather than lumped rating curves were generated for each site. The annual rating curve approach does have a drawback; typically, there only are limited amounts of actual intraannual sample data (usually 10–12 paired discharge/SSC sets) available for calibration purposes. However, 10–12 paired data sets, if they adequately cover the annual range of discharge, can generate reasonably accurate (±10 to 15%) annual flux estimates (Horowitz, 2003; 2008; Thorne, *et al.*, 2008). All the regression equations used in this evaluation were statistically significant at the 95% confidence limit or higher. Unfortunately, in several instances, the data sets used in this evaluation had periods with fewer than 10 measurements per year that could be used for rating curve generation/calibration. When that occurred, data from the previous and following years were combined with that from the actual year to generate more statistically robust sediment-rating curves (see table 2). The effect of the blended approach was tested at several sites where there were sufficient data to make it unnecessary. The net result of blending was to make the graphs covering the period of record less jagged (e.g., the highs and lows were more muted so the graphs appear somewhat smoother) but did not significantly alter the trends.

Results and Discussion

Long term trends in total suspended sediment fluxes and flow-weighted concentrations

Plots of annual suspended sediment fluxes and flow-weighted concentrations covering the period from 1981 through 2007, whilst somewhat "noisy," clearly display long-term patterns of decline (fig. 2). This conclusion is supported by the consistent negative slopes for calculated least squares linear trendlines for each of the plots (fig. 2, table 3). The annual suspended sediment flow-weighted concentration plots are less noisy than the annual suspended sediment flux plots because they tend to "damp" out variations that can be super-imposed by marked interannual differences in total discharge. Probably as a result, the slopes of the trendlines for the flow-weighted plots tend to be steeper (more negative, indicating greater rates of decline) than those for the annual fluxes and likely provide a more consistent picture of long-term trends (fig. 2; table 3). It should be noted that the declines appear greater (more negative) near the beginning of the evaluation period than toward the end (fig. 2); this is consistent with prior observations (e.g., Meade and Moody, 2008; Thorne, *et al.*, 2008). Furthermore, as flow-weighted suspended sediment concentrations are essentially independent of discharge, the long-term declines in annual suspended sediment fluxes probably reflect concomitant long-term declines in sediment supply

Table 2. Summary of errors associated with the determination of annual fluxes using annual rating curves.

[N/A, not applicable because the fluxes for these sites were calculated from daily data, not from rating curves]

Percent	Mississippi, Clinton[1]	Missouri, Hermann	Mississippi, St. Louis	Mississippi, Thebes	Ohio, Grand Chain	Arkansas, David Terry Dam[2]	Mississippi, Vicksburg[3]	Old River Outfall, Knox Landing	Mississippi, Tarbert Landing	Mississippi, St. Francisville
Maximum over-estimate	17	66	N/A	N/A	8	13	2	12	1.3	2
Maximum under-estimate	–4	–40	N/A	N/A	–7	–30	–6	–2.4	–3	–3
Absolute mean	4.5	9.0	N/A	N/A	2.5	9.7	1.8	1.8	<1	<1
Absolute median	3.2	3.5	N/A	N/A	2.0	6.0	1.5	1.0	<1	<1

[1] Multi-year rating curves were used for portions of the period of record (1983–1986; 1988–1990; 1993–1995).

[2] Multi-year rating curves were used for portions of the period of record (1982–1995; 2005–2006).

[3] Multi-year rating curves were used for portions of the period of record (1982–1983; 1991; 1998–2001; 2007).
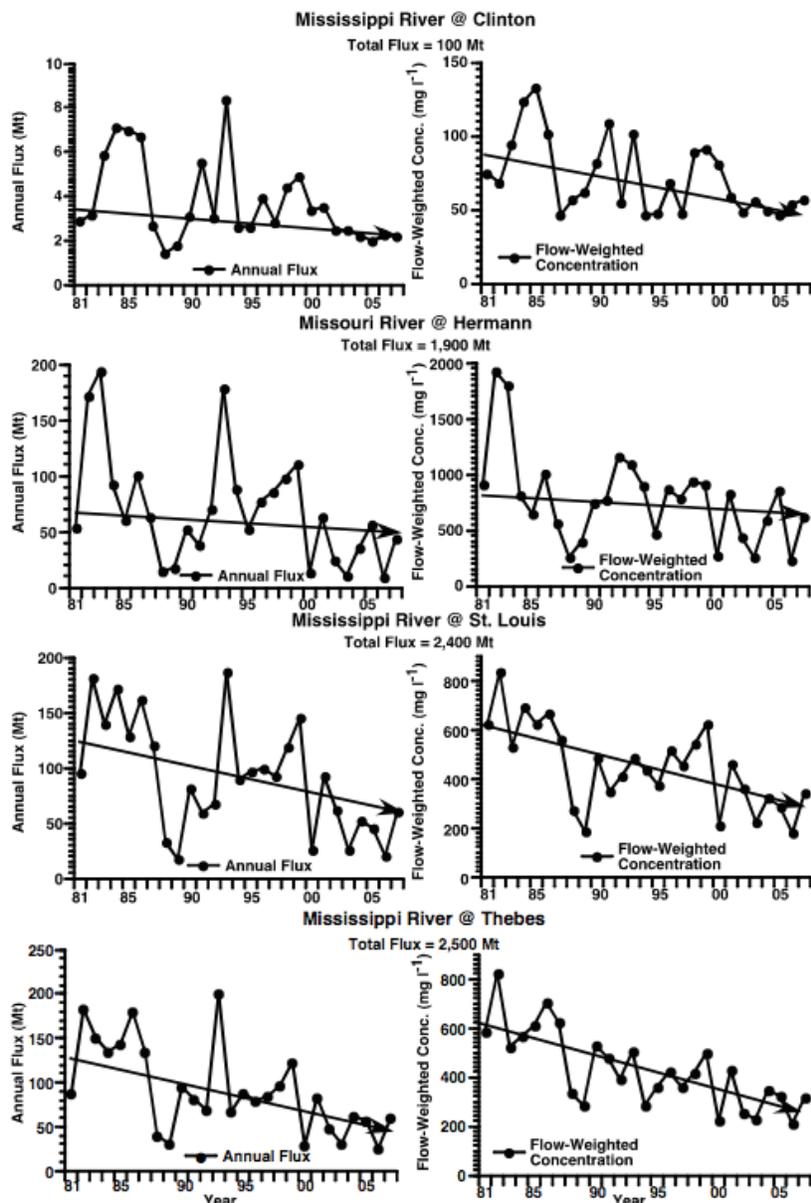
Figure 2. Plots of annual flux and flow-weighted concentrations, plus trendlines, covering 1981 through 2007 for all the sites used in this study.

rather than discharge; hence, suspended sediment fluxes in the MRB are supply limited rather than discharge limited. This too is consistent with prior observations and almost certainly results from a combination of factors including the insertion of numerous engineered structures (e.g., dams, lock and dams, revetments, levees) in conjunction with the introduction/application of better land management practices (e.g., contour plowing, conservation tillage, bank stabilization, reforestation) to limit erosion (e.g., Keown *et al.*, 1986; Kessel 1988; Meade, 1995; Mossa, 1996; Horowitz, 2006; Meade and Moody, 2008; Thorne, *et al.*, 2008).

The mainstem Mississippi River sites at St. Louis, Thebes, and Vicksburg represent the middle section of the MRB. The St. Louis and Thebes sites are separated by about 250 km (fig. 1). Both sites display markedly similar results for total flux, and annual mean/median fluxes and flow-weighted concentrations (table 3). In addition, both sites display similar negative (declining) trendline slopes for annual fluxes and flow-weighted concentrations (table 3). The Vicksburg site is substantially downstream from the confluence of both the Ohio and Arkansas Rivers and is about 890 km from the Thebes site (fig. 1). Despite the fact that the

Figure 2.   Plots of annual flux and flow-weighted concentrations, plus trendlines, covering 1981 through 2007 for all the sites used in this study.—Continued
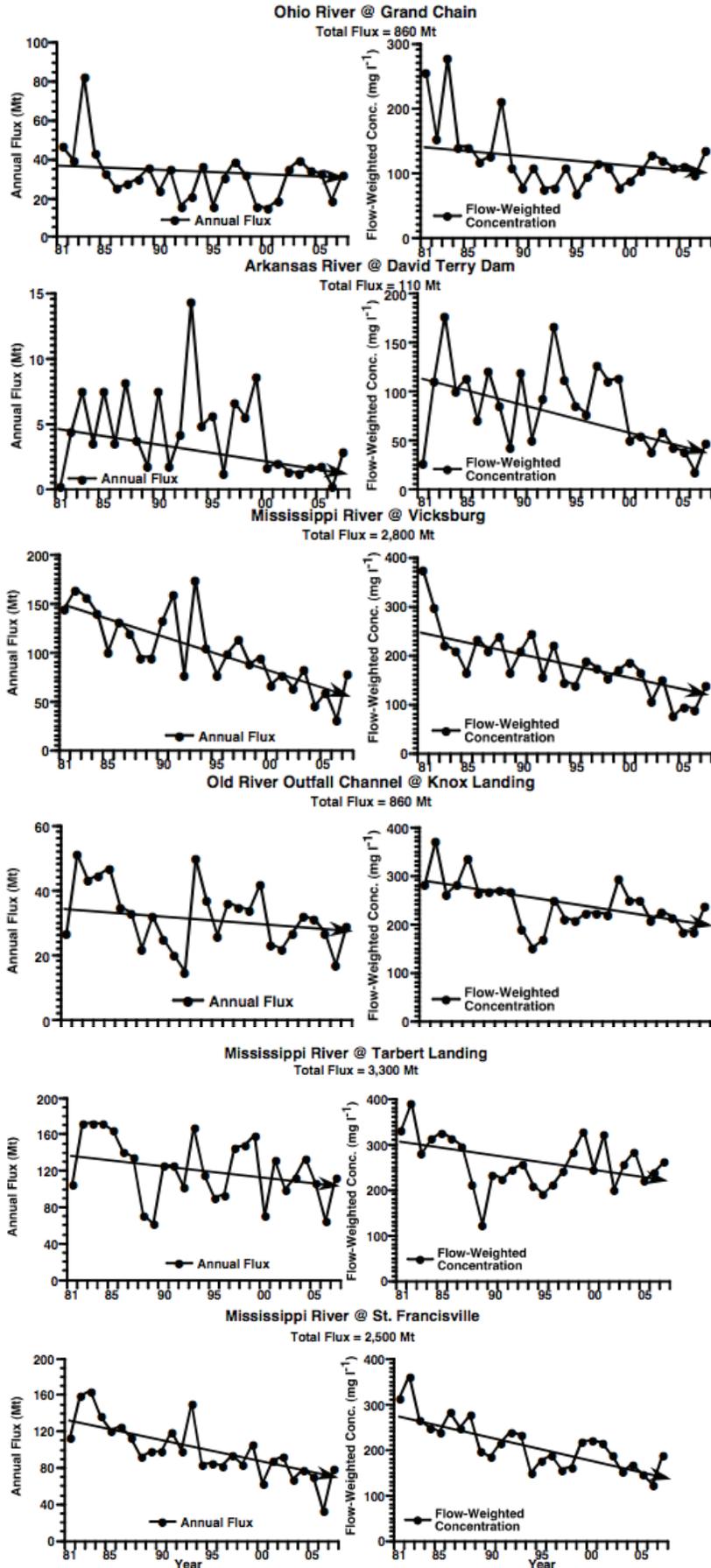
Table 3.   A summary of fluxes, flow-weighted concentrations, and trendline slopes for the Mississippi River Basin sites.

[N/A, not applicable; Mt, megatonnes]

Site	Parameter	Total[1]	Annual mean	Annual median	Trendline slope
Mississippi River, Clinton	Flux (Mt)	100	3.7	3.0	–0.1
	Flow-weighted concentration (mg l^{-1})	N/A	72	62	–1.6
Missouri, Hermann	Flux (Mt)	1,900	70	61	–2.8
	Flow-weighted concentration (mg l^{-1})	N/A	790	780	–25.8
Mississippi River, St. Louis	Flux (Mt)	2,400	90	89	–3.6
	Flow-weighted concentration (mg l^{-1})	N/A	440	440	–14.3
Mississippi River, Thebes	Flux (Mt)	2,500	91	79	–3.8
	Flow-weighted concentration (mg l^{-1})	N/A	430	410	–15.0
Ohio River, Grand Chain	Flux (Mt)	860	32	32	–0.7
	Flow-weighted concentration (mg l^{-1})	N/A	120	110	–3.3
Arkansas River, David Terry Dam below Little Rock	Flux (Mt)	110	4.2	3.5	–0.1
	Flow-weighted concentration (mg l^{-1})	N/A	83	85	–2.4
Mississippi River, Vicksburg	Flux (Mt)	2,800	100	96	–3.7
	Flow-weighted concentration (mg l^{-1})	N/A	180	170	–6.4
Old River Outfall, Knox Landing	Flux (Mt)	860	32	32	–0.5
	Flow-weighted concentration (mg l^{-1})	N/A	240	240	–3.4
Mississippi River, Tarbert Landing	Flux (Mt)	3,300	130	130	–1.6
	Flow-weighted concentration (mg l^{-1})	N/A	260	260	–2.2
Mississippi River, St. Francisville	Flux (Mt)	2,700	100	94	–3.0
	Flow-weighted concentration (mg l^{-1})	N/A	210	220	–5.5

[1]Total flux for the period of record (October 1, 1980, to September 30, 2007).

Ohio and Arkansas Rivers discharged an estimated 1,000 Mt of suspended sediment to the Mississippi River mainstem from 1981 through 2007, the total flux at Vicksburg only is about 15% higher; whereas the annual mean and median fluxes and flow-weighted concentrations are not markedly different from those determined for St. Louis and Thebes (table 3). It is interesting to note that whilst the declining trendline slope for annual flux at Vicksburg is similar to those for Thebes and St. Louis, the trendline slope for annual flow-weighted concentration is significantly shallower (table 3). These comparisons may indicate that there are substantial depositional zones between the upper and lower parts of the middle MRB.

The paired Mississippi River sites at Tarbert Landing and St. Francisville represent the lower MRB, and are separated by only 76 km (fig. 1). Unlike the middle section sites, these display significant differences in total flux and annual mean/median fluxes and flow-weighted concentrations even though the discharge for both sites is the "same"; discharge for both sites is measured at the gage located at Tarbert Landing (table 3). The trendline slope for St. Francisville is nearly double that for Tarbert Landing, indicating a markedly greater rate of decline in annual suspended sediment fluxes and flow-weighted concentrations at the former relative to the latter (table 3). The marked differences between the two sites may, at least in part, reflect substantial grain-size differences in the local source material. Bottom sediment at Tarbert Landing is coarser than at St. Francisville (e.g., Horowitz, unpublished data; Demas and Curwick, 1987); hence, it requires greater energy to resuspend and move it. Further, it appears that at least a portion of the coarser Tarbert Landing material may be depositing just a few kilometers downstream on Miles and Shreves Bars (at low water these features can fill as much as

70% of the channel); hence, this coarser sediment may never reach St. Francisville (Demas, pers. comm., 2009). The bed sediment grain-size differences between the two sites also might be responsible for some of the observed differences in annual fluxes because bedload is not determined at either site; hence, greater amounts of unmeasured coarser sediment may be moving downstream from Tarbert Landing than from St. Francisville. Finally, although the discharge at both sites is the "same" (measured/recorded at the Tarbert Landing gage), instantaneous measurements during high flows indicate that up to 10% of the volume transiting Tarbert Landing can remain in temporary storage upstream of St. Francisville (Demas, pers. comm., 2009); hence the flow reduction between the two sites also may contribute to some of the observed differences in annual fluxes and flow-weighted concentrations.

Hermann is the most downstream site on the Missouri River (fig. 1). The total suspended sediment flux of 1,900 Mt for the evaluation period (27 years) is, by far, the largest for all the Mississippi River tributaries (table 3). Also note that the mean/median flow-weighted concentrations for this site are markedly higher than any of the others determined during this evaluation (table 3). The trendline for flow-weighted concentrations also shows the largest negative slope of all the MRB sites, probably indicating the greatest level of decline (table 3). As the Missouri River represents the single most important source of suspended sediment for the Mississippi River (e.g., Meade, 1995; Meade and Moody, 2008), the decline in annual suspended sediment fluxes at Hermann may represent the most significant cause for the overall decline in sediment fluxes and flow-weighted concentrations throughout the middle and lower MRB (downstream from the confluence of the Missouri and Mississippi Rivers) from 1981 through 2007.

The suspended sediment contributions for the Mississippi River at Clinton (representing the upper MRB) and the Arkansas River at David Terry Dam are equivalent, at about 100 Mt each. Both sites display similar results for annual mean and median fluxes and flow-weighted concentrations; also, their negative trendline slopes are similar (table 3). The total suspended sediment flux for the Arkansas seems particularly low as that river is the third largest tributary in the MRB. The total suspended sediment flux contributions for both the Clinton and Arkansas River sites appear almost insignificant in terms of the total fluxes at the next most downstream sites (Mississippi River at St. Louis and Mississippi River at Vicksburg). In part, the low total and annual suspended sediment fluxes from these sites probably result from the extensive upstream/downstream engineering structures that surround them, and which tend to limit the movement and downstream dispersion of suspended sediment. The Arkansas River site is located at the 12th lock and dam out of 18 in the McClellan-Kerr Navigation System (Wikipedia, 2009e); as such, the annual fluxes for this site may represent an overestimate of Arkansas River contributions to the Mississippi River. The Clinton site is located at the 16th lock and dam out of 26 in the upper MRB (Wikipedia, 2009a)

and for the same reason proposed for the Arkansas site, also may represent an overestimate of the contributions from the upper MRB to the middle MRB.

The long-term patterns for annual fluxes and flow-weighted concentrations for the Ohio River at Grand Chain (Olmsted in fig. 1) are markedly different from the others in this evaluation. The patterns show a sharp decline between 1981 through 1990, appear to level off from 1993 through about 2003, and then display a slight increase from 2003 through 2007 (fig. 2). These pattern variations may reflect several interconnected natural and anthropogenic effects/factors. During the 1993 flood, the site was in backwater for 2–3 months, leading to atypical localized deposition (Darnell, pers. comm., 2009). Further, the site is about 15 km upstream from the ongoing Olmsted lock and dam construction. In 1993 a cofferdam was placed in the river to facilitate that construction, and remained in place until 2003 (Bibelhauser, pers. comm., 2009). The cofferdam affected water flow in the lower Ohio River as long as it was in place, and created a depositional zone within its downstream "shadow" (Darnell, pers. comm., 2009).

The data on annual discharge and annual suspended sediment fluxes from the Mississippi River at Vicksburg, in conjunction with that from the Old River Outfall Channel at Knox Landing, provide a means of evaluating the effectiveness of the past 27 year operation of the ORCS in terms of the diversion of both total water volume and suspended sediment (table 4). The oft-cited figure for the diversion of Mississippi River water to the Atchafalaya River is 30% of the latitudinal flow (literally the flow at the same geographic latitude), and stems from the Flood Control Act of 1954 that authorized the construction and operation of the structure (e.g., Mossa, 1996; Brown, pers. comm., 2009). Pragmatically, this is accomplished by daily adjustments of the outflow from the ORCS based on the previous day's discharge measurements at Tarbert Landing (just downstream from the structure) and at Simmsport (on the Atchafalaya River just downstream from the confluence of the Old and Red Rivers). The formula employed is (Brown, written comm., 2009):

$$\text{Simmsport } Q/(\text{Simmsport } Q + \text{Tarbert Landing } Q)(100) = 30\% \qquad (4)$$

where

Q is daily mean discharge

The data indicate that discharge control has been relatively precise (24 ± 3%) and fairly close to the optimum 30% when contributions from the Red River are included (table 4); however, suspended sediment control has been markedly less precise (34 ± 12%). There do not appear to be any statutory limits nor specific guidelines for the diversion of suspended sediment.

Table 4. A summary of annual discharge and suspended sediment fluxes diverted from the Mississippi River (Vicksburg) through the Old River control structure (Knox Landing).

Year	Parameter	Vicksburg	Knox Landing	Percent diverted
1981	Flux (Mt)	150	27	18
	Discharge (m^3 x 10^9)	390	96	25
1982	Flux (Mt)	160	51	32
	Discharge (m^3 x 10^9)	550	140	25
1983	Flux (Mt)	160	43	27
	Discharge (m^3 x 10^9)	710	160	23
1984	Flux (Mt)	140	45	32
	Discharge (m^3 x 10^9)	670	160	24
1985	Flux (Mt)	100	47	47
	Discharge (m^3 x 10^9)	610	140	23
1986	Flux (Mt)	130	35	27
	Discharge (m^3 x 10^9)	560	130	23
1987	Flux (Mt)	120	33	28
	Discharge (m^3 x 10^9)	580	120	21
1988	Flux (Mt)	96	22	23
	Discharge (m^3 x 10^9)	390	82	21
1989	Flux (Mt)	96	32	33
	Discharge (m^3 x 10^9)	580	120	21
1990	Flux (Mt)	130	25	19
	Discharge (m^3 x 10^9)	630	130	21
1991	Flux (Mt)	160	20	13
	Discharge (m^3 x 10^9)	640	130	20
1992	Flux (Mt)	77	15	19
	Discharge (m^3 x 10^9)	490	92	19
1993	Flux (Mt)	170	50	29
	Discharge (m^3 x 10^9)	790	200	25
1994	Flux (Mt)	110	37	34
	Discharge (m^3 x 10^9)	720	170	24
1995	Flux (Mt)	77	26	34
	Discharge (m^3 x 10^9)	550	130	24
1996	Flux (Mt)	100	36	36
	Discharge (m^3 x 10^9)	530	160	30
1997	Flux (Mt)	110	35	32
	Discharge (m^3 x 10^9)	650	160	25
1998	Flux (Mt)	88	34	39
	Discharge (m^3 x 10^9)	580	160	28
1999	Flux (Mt)	96	42	44
	Discharge (m^3 x 10^9)	560	140	25
2000	Flux (Mt)	68	23	34
	Discharge (m^3 x 10^9)	360	94	26
2001	Flux (Mt)	77	22	29
	Discharge (m^3 x 10^9)	460	90	20
2002	Flux (Mt)	63	27	43
	Discharge (m^3 x 10^9)	600	130	22
2003	Flux (Mt)	83	32	39
	Discharge (m^3 x 10^9)	550	140	25
2004	Flux (Mt)	45	31	69
	Discharge (m^3 x 10^9)	580	150	26
2005	Flux (Mt)	59	27	46
	Discharge (m^3 x 10^9)	610	150	25
2006	Flux (Mt)	32	17	53
	Discharge (m^3 x 10^9)	350	93	27
2007	Flux (Mt)	79	29	37
	Discharge (m^3 x 10^9)	560	120	21

The Impact of the 1993 Flood on Long-Term Trends in Annual Fluxes and Flow-Weighted Concentrations in the Mississippi River Basin

During the past 100 years, major widespread flooding in the MRB has occurred at least three (1927; 1973; 1993) and possibly four (2008) times (Walker and Rouse, 1994; Meade, 1995; Holmes, Jr., 1996; Larson, 1997; Barry, 1998; Johnson *et al.*, 2004; NOAA, 2008; Dirmeyer and Kinter III, 2009). The 1927 flood provided one of the major justifications for the construction of the Bonnet Carré Spillway; the 1973 flood almost destroyed the ORCS by undercutting the support piers and led to the construction of additional structures to relieve some of the pressure on the original one (e.g., Mossa, 1996). Data for the 2008 flood are still incomplete, but there have been some claims that it was on a par with the 1993 flood (NOAA, 2008; Dirmeyer and Kinter III, 2009).

The 1993 flood occurred just about in the middle of the current evaluation period and affected the upper, middle, and lower parts of the Mississippi River as well as the lower Missouri River. The Ohio and Arkansas Rivers were not heavily affected, if at all; albeit, the lower Ohio was in backwater for up to 3 months. Due to unusual weather conditions during the spring/summer of 1993 (April–August), the upper Midwestern United States. experienced above-normal rainfall in April and May that saturated the soils and filled many streams to capacity (Walker and Rouse, 1994; Johnson *et al.*, 2004). In late June, additional precipitation led to flooding in Minnesota and Wisconsin; those floodwaters reached the mainstem of the Mississippi River, and some of its major tributaries, in July (fig. 1, Johnson *et al.*, 2004). At its apex, between 500 and 600 river gages were above flood stage, and throughout the basin, nearly 150 major rivers and tributaries were flooded (Larson, 1997; Johnson *et al.*, 2004). The lower part of the Mississippi River never reached flood stage in 1993 because the Ohio River was not substantially affected by excessive precipitation. However, the annual mean discharge at Tarbert Landing (20,600 m^3 s^{-1}) was one of the highest on record for the 77-year period between 1931 and 2007 (Demas, pers. comm., 2009). This was one of the costliest floods in U.S. history, and came to be known as "The Great Flood of 1993" (Holmes Jr., 1996). Despite this characterization, subse-quent evaluations indicated that the recurrence interval for the flood was on the order of 50–100 years (Holmes Jr., 1996).

Examples of the impacts of the 1993 flood were numerous and diverse (Walker and Rouse, 1994; Larson, 1997; Johnson *et al.*, 2004). The gage on the Mississippi River at St. Louis was above flood stage for 144 days. About 3,000 km^3 of water overflowed onto the floodplains downstream from

St. Louis through breached levees. More than 44,000 km[2] of land were flooded and 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 United States, was halted for up to 2 months. More than 1,000 levees were topped or failed, and more than 3.2 million ha of farmland were inundated.

The first indication of the long-term effect of the 1993 flood on Mississippi River SSC and annual suspended sediment fluxes came from comparisons between the actual and predicted annual fluxes generated from daily data for the Mississippi River at Thebes covering the period from 1981 to 2004 (Horowitz *et al.*, 2001; Horowitz, 2003; 2006). Extending the comparison through 2007 did not substantially alter the pattern. The actual 27-year cumulative suspended sediment flux for the Thebes site, from 1981 through 2007, was 2,500 Mt. A lumped sediment-rating curve (a smearing corrected second-order polynomial) using the entire 27-year data set 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 (2,500 versus 2,300 Mt) for the 27-year period using the lumped rating-curve approach, the differences (+42 to –76%, with an absolute mean of 23%) between actual and estimated fluxes for specific years (e.g. 1981, 1982, 1994, and 2002), can be substantial (fig. 3).

An examination of a plot of actual versus estimated annual fluxes for the 27-year period covering 1981 through 2007 indicates a marked pattern change pre- and post-1993; an examination of the residuals (the differences between actual and predicted annual fluxes) is even more revealing (fig. 3). 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 interrelation occurred. This view is supported by the marked decline in both actual and flow-weighted SSCs for the site, pre- and post-1993 (table 5). 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 ranged from 46 to 64% (fig. 4; table 5). Also note that this decline occurred even though median discharges for the pre- and post-1993 period were similar, indicating that the change almost certainly resulted from a reduction in sediment supply (table 5).
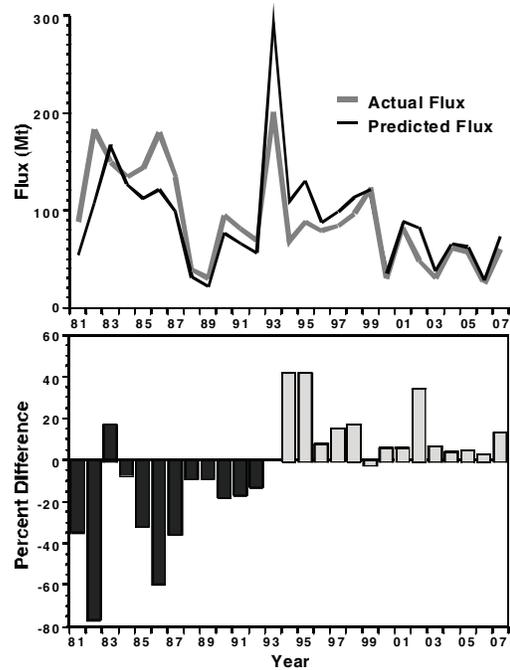

Figure 3.   The upper graph displays a comparison of actual and estimated annual fluxes (1981–2007) for the Mississippi River at Thebes; the estimated fluxes are based on a single "lumped" rating curve generated from daily mean discharge and daily suspended sediment concentration data. The lower graph displays the percent difference between predicted and actual fluxes for the same site; a negative difference indicates an under prediction whereas a positive difference indicates an over prediction.
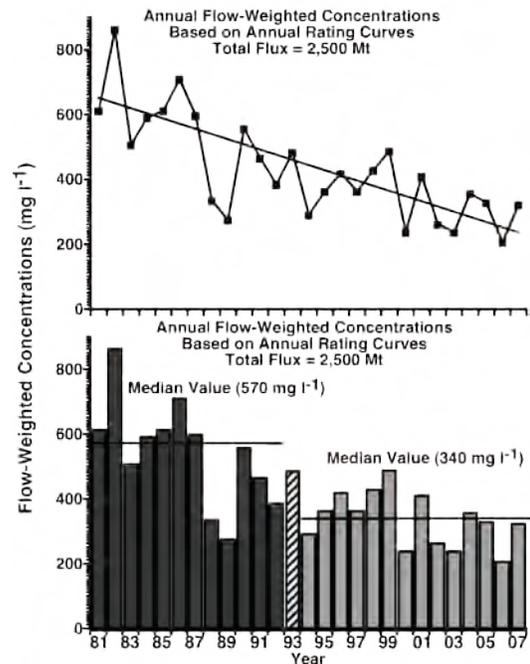

Figure 4.   Linear and bar plots of changes in annual flow-weighted concentration for the Mississippi River at Thebes site; note the sharp change in median flow-weighted concentration pre- and post 1993 in the bar plot.

Table 5. Pre- and post-1993 summary of discharge, suspended sediment concentration, annual flux, and annual flow-weighted concentrations for selected sites in the Mississippi River Basin.

[SSC, suspended sediment concentration; conc., concentration]

Site	Time period	Mean discharge (m³ s⁻¹)	Mean discharge difference (%)	Median discharge (m³ s⁻¹)	Median discharge difference (%)	Mean SSC (mg l⁻¹)	Mean SSC difference (%)	Median SSC (mg l⁻¹)	Median SSC difference (%)	Mean flux (Mt)	Mean flux difference (%)	Median flux (Mt)	Median flux difference (%)	Mean flow-weighted conc. (mg l⁻¹)	Mean flow-weighted conc. diff. (%)	Median flow-weighted conc. (mg l⁻¹)	Median flow-weighted conc. diff. (%)
Mississippi River, Clinton	Pre-1993	1,500	N/A	1,300	N/A	60	N/A	54	N/A	4.2	N/A	3.2	N/A	84	N/A	79	N/A
	Post-1993	1,600	6	1,300	<1	43	-40	35	-54	3.0	-40	2.6	-23	60	-40	55	-44
Missouri River, Hermann	Pre-1993	2,600	N/A	2,000	N/A	500	N/A	300	N/A	79	N/A	62	N/A	940	N/A	790	N/A
	Post-1993	2,500	<1	2,000	<1	420	-19	280	-7	55	-44	54	-15	640	-47	700	-13
Mississippi River, St. Louis	Pre-1993	6,000	N/A	4,900	N/A	500	N/A	250	N/A	110	N/A	110	N/A	520	N/A	550	N/A
	Post-1993	5,700	-5	4,600	-7	420	-19	170	-47	74	-49	76	-45	380	-37	370	-49
Mississippi River, Thebes	Pre-1993	6,500	N/A	5,300	N/A	400	N/A	280	N/A	110	N/A	110	N/A	540	N/A	550	N/A
	Post-1993	6,200	-5	5,000	-6	250	-60	180	-56	66	-67	64	-72	330	-64	340	-62
Ohio River, Grand Chain	Pre-1993	8,000	N/A	5,700	N/A	83	N/A	48	N/A	37	N/A	34	N/A	150	N/A	130	N/A
	Post-1993	8,500	6	6,200	8	65	-28	46	-4	28	-32	32	-6	110	-36	110	-18
Arkansas River, David Terry Dam	Pre-1993	1,400	N/A	910	N/A	44	N/A	27	N/A	4.5	N/A	4.0	N/A	93	N/A	97	N/A
	Post-1993	1,300	-8	780	-17	41	-7	30	10	3.2	-41	1.9	-111	70	-33	57	-70
Mississippi River, Vicksburg	Pre-1993	18,000	N/A	16,000	N/A	180	150	170	N/A	120	N/A	120	N/A	200	N/A	210	N/A
	Post-1993	18,000	<1	15,000	-7	110	-64	99	-72	78	-54	78	-54	140	-43	150	-40
Old River Outflow Channel, Knox Landing	Pre-1993	4,000	N/A	3,400	N/A	230	N/A	220	N/A	37	N/A	33	N/A	280	N/A	270	N/A
	Post-1993	4,300	7	3,700	8	200	-15	200	-10	30	-23	30	-10	220	-27	220	-23
Mississippi River, Tarbert Landing	Pre-1993	15,000	N/A	13,000	N/A	240	N/A	240	N/A	130	N/A	130	N/A	270	N/A	290	N/A
	Post-1993	14,000	-7	12,000	-8	220	-9	220	-9	110	-18	110	-18	250	-8	240	-21
Mississippi River, St. Francisville	Pre-1993	15,000	N/A	13,000	N/A	220	N/A	210	N/A	120	N/A	120	N/A	260	N/A	250	N/A
	Post-1993	14,000	-7	12,000	-8	150	-47	160	-31	79	-52	84	-43	180	-44	170	-47

An examination of the sediment-rating curve for the Mississippi River at Thebes site for 1993, as well as the changing interrelation between discharge and SSC during the course of the flood itself, provides additional insights into the cause of the post-1993 decline in SSC (fig. 5). The 1993 rating curve for Thebes is sharply convex, indicating that the site probably was severely "sediment-starved" during the course of the flood. Actual measurements in the general a rea 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" (in-channel) bed sediment and/or readily erodible deposits, thus eliminating a substantial local source of suspended sediment. It is likely that this "local" problem was further exacerbated by concomitant reductions in SSC/annual suspended sediment fluxes from the upstream Mississippi River site at St. Louis and from the nearby Missouri River site at Hermann (fig. 1).

Additional support for the contention that there was a severe loss in local, stored in-channel bed sediment, comes from an examination of a plot of discharge versus SSC for the Thebes site during the course of the 1993 flood (fig. 5). The pattern 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 concomitant 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 over the actual course of the flood (fig. 5). This pattern indicates that the riverbed probably was scoured, and then subsequently sediment-starved, at this location.

The data and plots for the Thebes site appear to indicate that the 1993 flood superimposed a "step function" (a sudden sharp decrease) on the long-term pattern of declining suspended sediment concentrations and annual suspended sediment fluxes that were noted previously. According to Meade and Moody (2008), the long-term average annual rate of decline, at least in the lower MRB, for the evaluation period is about 2%; the observed differences between pre- and post-1993 median SSC, annual fluxes, and flow-weighted concentrations are well in excess of the 25–30% cumulative decline that would have occurred in the absence of a step function (table 5). Based on the rating curve evaluation, it also appears that the flood changed the discharge-suspended sediment interrelation (e.g., Horowitz, 2003; 2006). One potential explanation is that locally stored, in-channel bed sediment was suspended and redeposited on nearby floodplains through overtopping and/or levee breaches. Once the levees were repaired, the deposited material was no longer available for subsequent downstream transport. Another explanation is that the high flows flushed substantial amounts of stored, in-channel bed sediments downstream; thus removing a major local source of supply. In either case, the local supply of available suspendable sediment would decline and lead to concomitant reductions in SSC, annual fluxes, and annual flow-weighted concentrations. The question then arises as to whether the Thebes step function was localized, or whether there were similar occurrences elsewhere in the MRB.
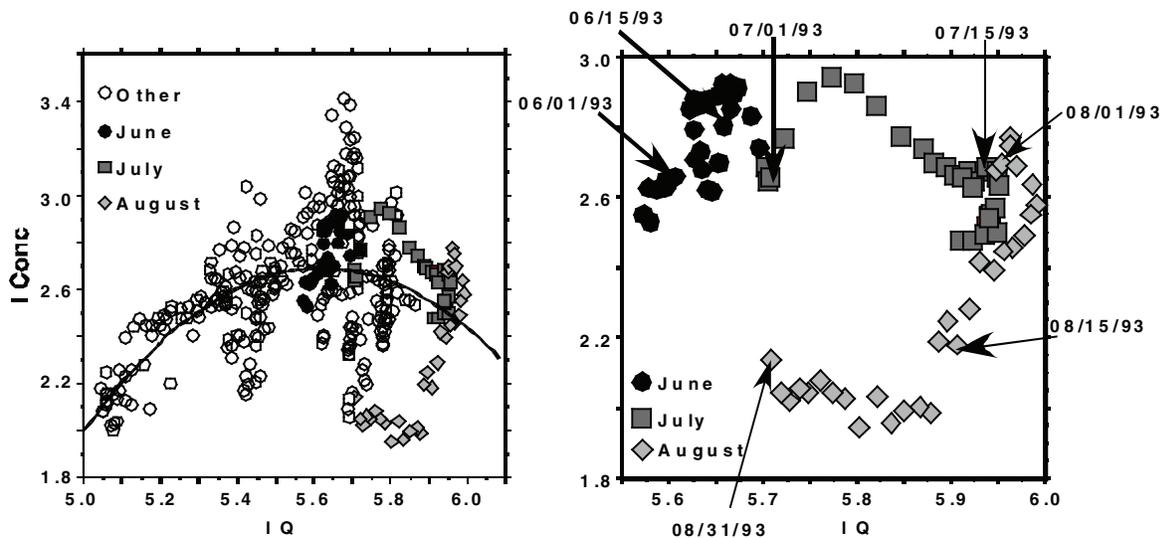

Figure 5.   The graph on the left side is the 1993 sediment-rating curve for the Mississippi River at Thebes site; whereas the graph on the right displays the clockwise hysteresis loop for the 1993 flood. The symbols used in both graphs are the same. The horizontal axes (IQ) are the log of discharge and the vertical axes (I Conc) are the log of suspended sediment concentration.

The Mississippi River at St. Louis site represents an ideal starting point to evaluate whether additional locations in the MRB also experienced a step function of the type noted for Thebes. This accrues because daily data also were collected at this site from 1981 through 2007. An examination of a plot of actual versus estimated annual fluxes and residuals for the 27-year period covering 1981 through 2007 indicates a similar, albeit not as pronounced pre- and post-1993 pattern as that observed at Thebes (fig. 6). Before 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 view is supported by the marked decline in both actual and flow-weighted SSCs for the St. Louis site, pre- and post-1993 (table 5; fig. 7). Like the Thebes site, the marked change in fluxes and concentrations occurred with little change in discharge (table 4). 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 ranged from 37 to 49%; similar to, but not as great as for Thebes (table 5). Again, as with the Thebes site, this is well in excess (>25 to 30%) of what would have occurred if the change were solely the result of just a long-term decline. Additionally, the 1993 rating curve for St. Louis, like that for Thebes, is sharply convex, indicating that the site probably was severely "sediment-starved" during the course of the flood (fig. 8). Finally, a plot of discharge versus SSC for

the St. Louis site during the course of the 1993 flood, like the Thebes site, displays a clockwise hysteresis loop starting in June and ending in late August 1993 (fig. 8). As noted previously, clockwise hysteresis loops are indicative of channel-bed scour (e.g. Walling, 1977; Wood, 1977; Meade *et al.*, 1990).

Unfortunately, the detailed evaluations for the Thebes and St. Louis sites cannot be replicated for other MRB sites because daily data are lacking. However, with some exceptions, there are marked similarities for the Mississippi River sites at Clinton, Vicksburg, and St. Francisville, and some similarities for the Missouri River at Hermann and the Old River Outfall Channel at Knox Landing (table 5; Figs. 9–11). Despite relatively similar pre- and post-1993 median discharges, all the sites display declines in median SSC, annual fluxes, and flow-weighted concentrations (table 5). The 1993 rating curves for all these sites, except Clinton, are sharply convex, indicating that they probably were severely "sediment-starved" during the course of the flood and also may indicate that substantial local erosion/channel bed scour occurred (fig. 9). Finally, all the sites display marked reductions in trendline slope pre- and post-1993, indicating a possible slowing in the declining rate of change in annual suspended sediment fluxes (fig. 10). In fact, Tarbert Landing actually displays a small post-1993 positive trendline, indicating at least a possible temporary reversal of the long-term pattern of decline in annual fluxes (fig. 10).
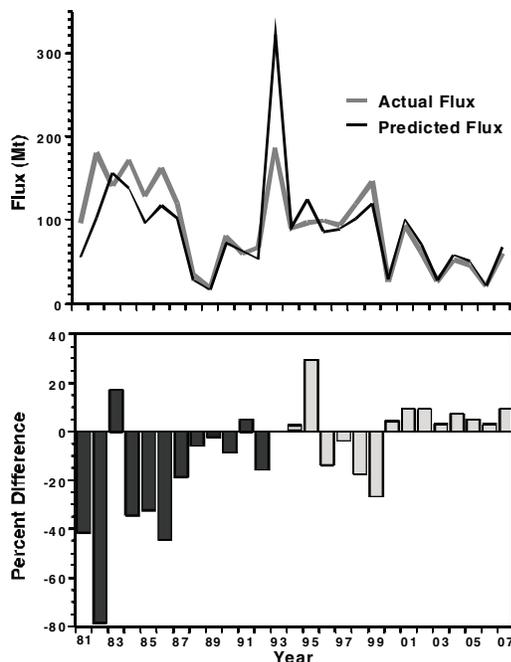

Figure 6. The upper graph displays a comparison of actual and estimated annual fluxes (1981–2007) for the Mississippi River at St. Louis; the estimated fluxes are based on a single "lumped" rating curve generated from daily mean discharge and daily suspended sediment concentration data. The lower graph displays the percent difference between predicted and actual fluxes for the same site; a negative difference indicates an under prediction whereas a positive difference indicates an over prediction.
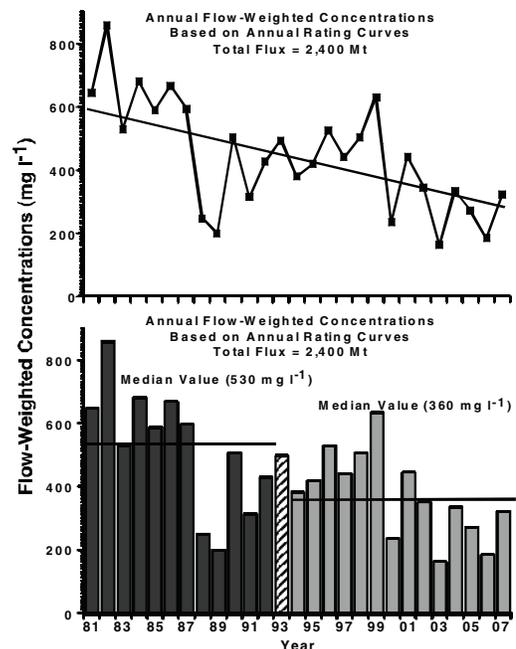

Figure 7. Linear and bar plots of changes in annual flow-weighted concentration for the Mississippi River at St. Louis site; note the sharp change in median flow-weighted concentration pre- and post 1993 in the bar plot.
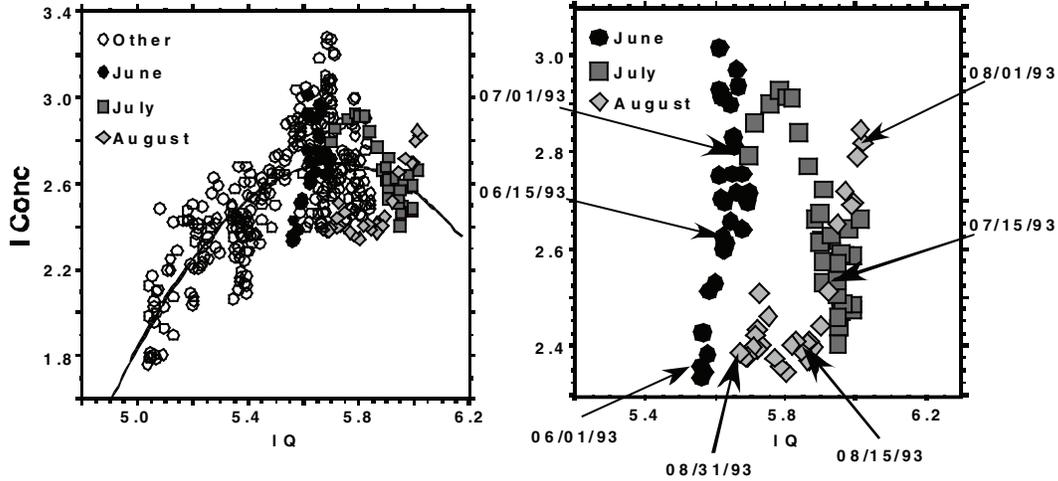
Figure 8. The graph on the left side is the 1993 sediment-rating curve for the Mississippi River at St. Louis site; whereas the graph on the right displays the clockwise hysteresis loop for the 1993 flood. The symbols used in both graphs are the same. The horizontal axes (IQ) are the log of discharge and the vertical axes (I Conc) are the log of suspended sediment concentration.
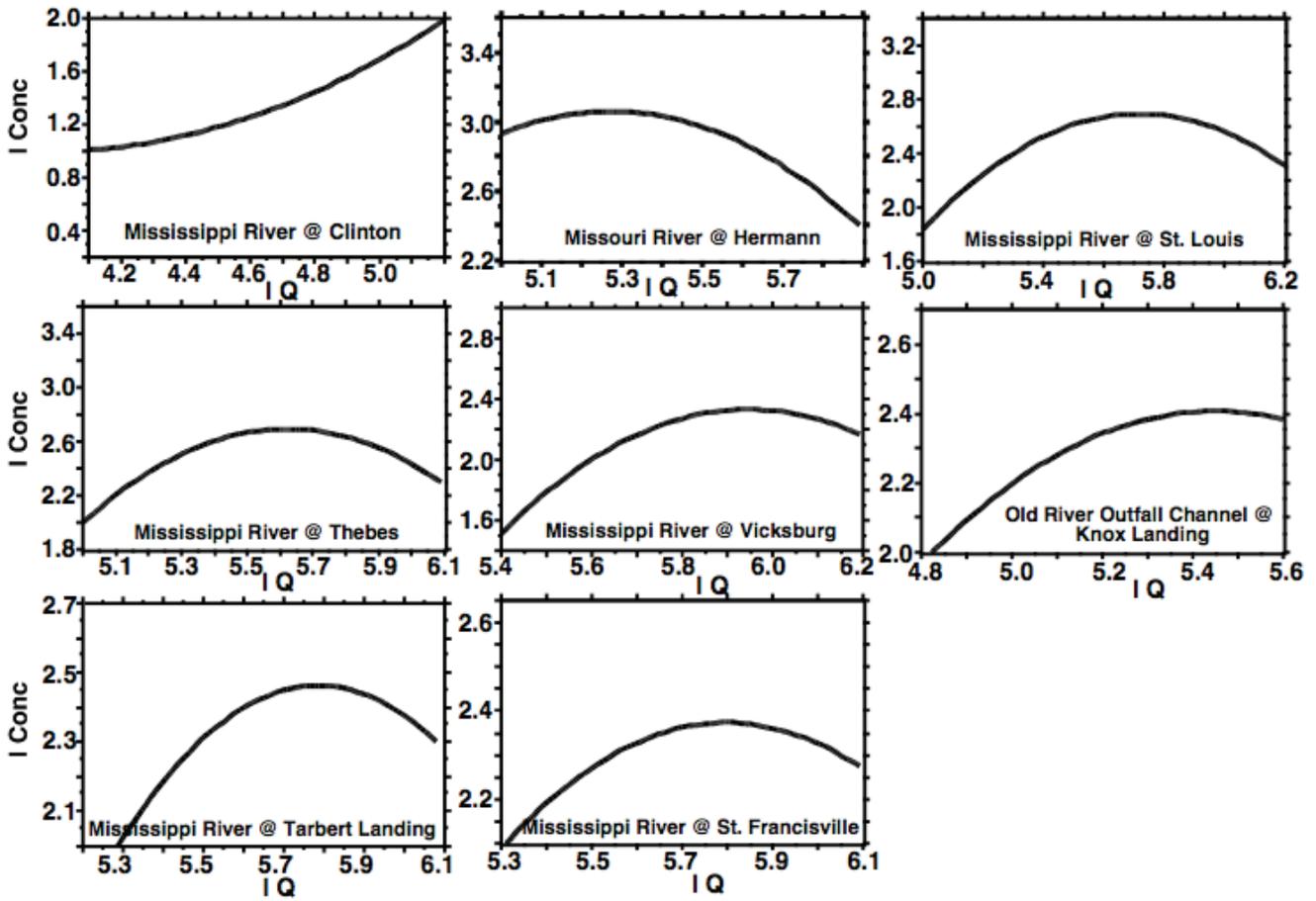

Figure 9. Annual sediment-rating curves for 1993 for selected sites in the Mississippi River Basin; the sample data points have been removed for clarity.

The most marked declines in pre- and post-1993 concentration and fluxes occurred at Clinton, Vicksburg, and St. Francisville, whereas the declines at Hermann, Knox Landing, and Tarbert Landing appear relatively minor, and might well be encompassed in the overall general long-term decline noted previously (table 5; fig. 11). The decline at Clinton is somewhat surprising because the site is located in the upper MRB in the middle of a series of lock and dam structures that almost certainly would have limited downstream dispersion of eroded bed sediments and which also may have been responsible for the 1993 concave rating curve for the site (fig. 9). The contrast between the marked change in trendline slope (from –59 to –26) for the Missouri River at Hermann seems at odds with the relatively minor pre- and post-1993 changes in median SSC, annual flux, and flow-weighted concentrations for the site (table 5; Figs. 10–11). Contrariwise, the trendline slope change for Clinton appears relatively small (–1.9 to –0.6; fig. 10), yet the pre- and post-1993 changes in median SSC (–54%) and median flow-weighted concentration (–44%) are substantial (table 5; fig. 11). Both cases may indicate that trendline slope might not be as sensitive to change as some of the other measured/estimated parameters.

As noted during the initial discussion of long-term trends, the paired Tarbert Landing and St. Francisville sites, separated by only 76 km, appear to display markedly different patterns of decline in annual flux and flow-weighted concentration. That dichotomy has carried over into the evaluation of a storm-related step function as well. Both sites had convex 1993 rating curves (fig. 9) and appear to display substantial differences in pre- and post-1993 trendline slope (fig. 10). However, only St. Francisville displays marked declines in median SSC, annual flux, and flow-weighted concentrations (table 5). The same arguments used to explain the differences in long-term annual flux and flow-weighted concentration trends also apply to the presence of a storm-related step function at St. Francisville but not at Tarbert Landing, and are based on a combination of local bed sediment grain-size differences between the two sites, in conjunction with the flow regime in the lower MRB during the 1993 flood. The bed sediments at Tarbert Landing are markedly coarser than at St. Francisville, and although discharge during the storm event was substantially elevated, it did not reach flood stage. As a result, local erosion and downstream dispersion from the St. Francisville site may have been more substantial than at Tarbert Landing. As a consequence, the post-1993 changes in median SSC, annual flux, and flow-weighted concentration at St. Francisville would likely be more marked than at Tarbert Landing (table 5).
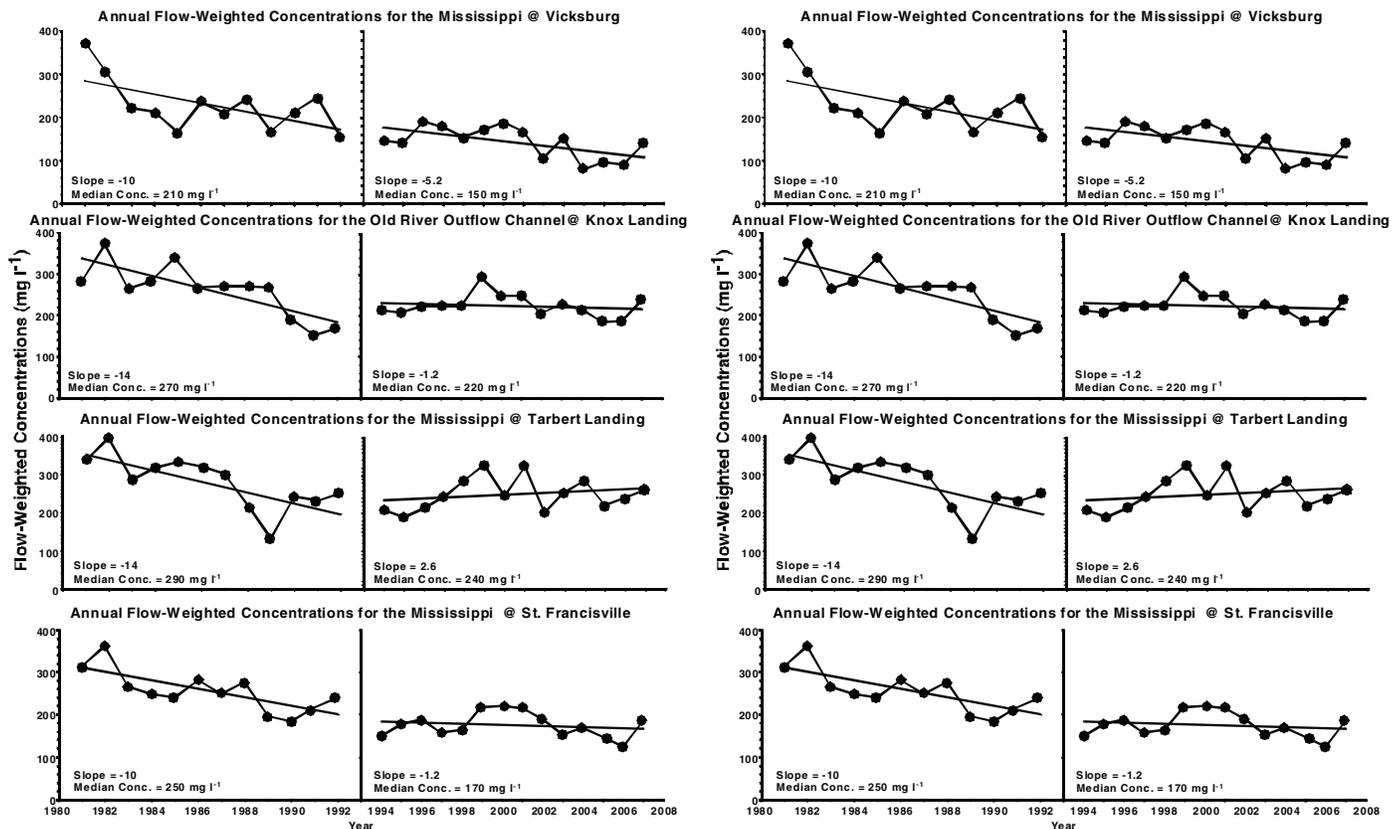

Figure 10.   Plots of pre- and post 1993 changes in annual flow-weighted concentrations, with calculated linear least squares trendlines for selected sites in the Mississippi River Basin. The slope of each trendline and the median flow-weighted concentration for each plot also are provided.
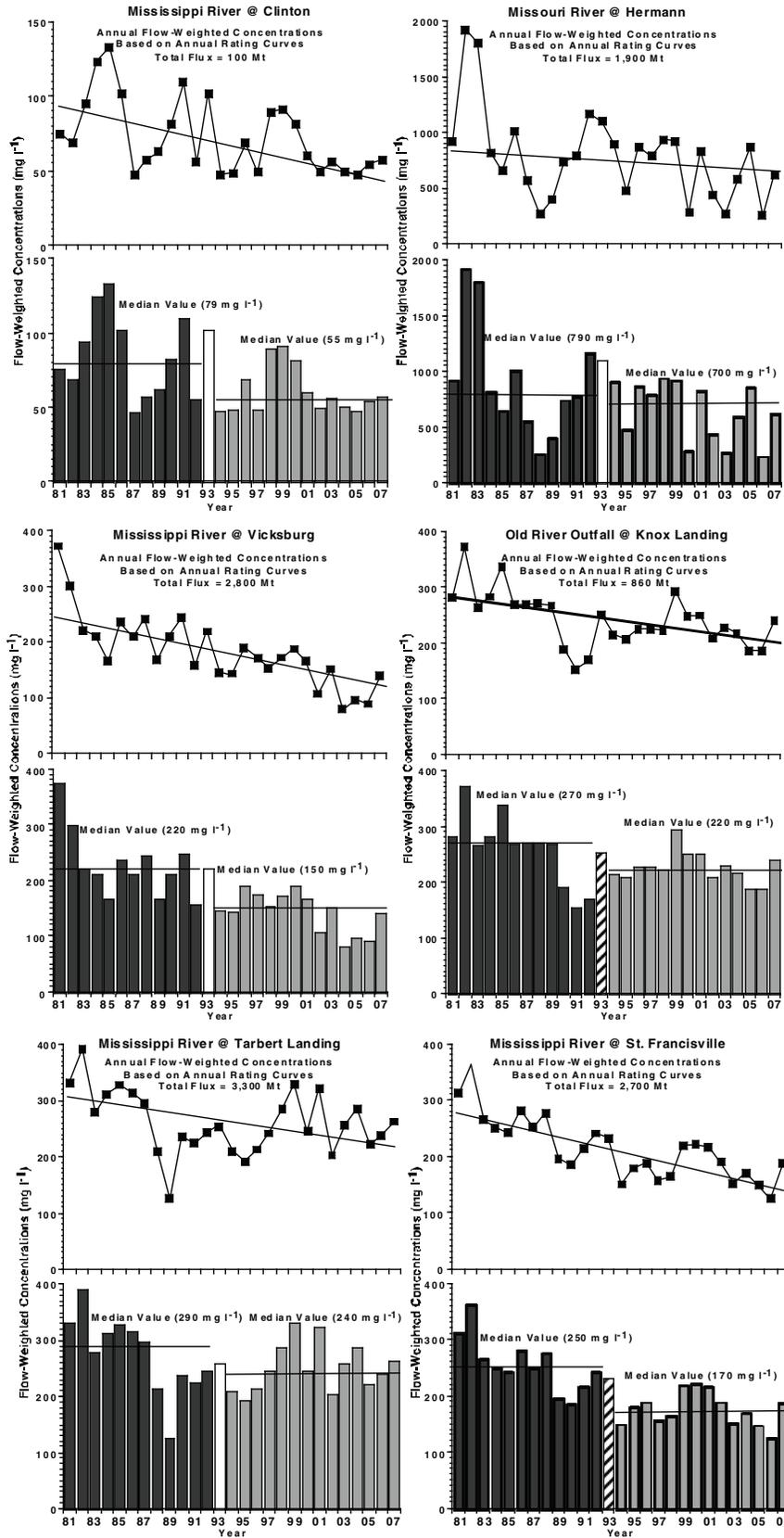
Figure 11.   Linear and bar plots of changes in annual flow-weighted concentration for the selected sites in the Mississippi River Basin; note the changes in median flow-weighted concentration pre- and post 1993 in the bar plots.

Conclusions

1. Plots of annual suspended sediment fluxes and flow-weighted concentrations for a number of MRB long-term sampling sites between 1981 through 2007, whilst somewhat "noisy," clearly display long-term patterns of decline.

2. As expected, the median suspended sediment annual flow-weighted concentration plots are less noisy than the median suspended sediment annual flux plots because they tend to "damp" out variations that can be superimposed by marked differences in interannual discharge.

3. The long-term pattern for the Ohio River at Grand Chain is different from all the others in this evaluation and may reflect ongoing construction at the Olmsted lock and dam structure that began in 1993.

4. The pattern of declining annual fluxes and flow-weighted concentrations appears less substantial in those parts of the MRB where there are numerous engineering structures, particularly locks and dams, which almost certainly limit local erosion and impede the downstream dispersion of suspended sediment (e.g., Ohio River, upper Mississippi River, Arkansas River).

5. There is substantial evidence that the so-called "Great Flood of 1993" caused a step function (a sharp decrease) in the long-term rate of decline in median SSC, annual flux, and flow-weighted concentrations for the middle MRB as evidenced at the Mississippi River sites at St. Louis, Thebes, and Vicksburg, and in the lower MRB at St. Francisville.

6. The evidence for a step function at other MRB sites is less substantial, but probably occurred in the upper MRB at Clinton and might have occurred in the lower Missouri River at Hermann, and in the Old River Outfall Channel at Knox Landing.

7. The long-term declines in flow-weighted concentrations, as well as the similar annual median discharges pre- and post-1993, indicate that the changes noted in MRB annual suspended sediment fluxes, as well as the step function itself, almost certainly result from reductions in sediment supply rather than discharge.

8. The reduction in sediment supply throughout the MRB almost certainly accrued as a result of the insertion of numerous engineered structures in conjunction with the introduction of better land management practices to limit erosion. The 1993 flood contributed to/compounded this effect by "flushing" substantial quantities of stored, readily erodible, in-channel bed sediments from the basin.

9. Once the data for the 2008 WY are finalized, and subsequent data for ongoing years become available, it will be interesting to see if the long-term pattern of decline continues, and/or whether a similar step function can be identified for the 2008 flood. It also would be interesting to examine similar large-scale, heavily engineered river systems where substantial floods have occurred, to see if a similar step function can be detected elsewhere.

10. The value of daily discharge and SSC data, in addressing questions regarding the processes affecting annual fluxes and other sediment-related trends is evident when the results for the Mississippi River at Thebes and St. Louis sites are compared with those from the other MRB sites where such intensive data collections are lacking.

Acknowledgements

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