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Causes for the decline of suspended-sediment discharge in the Mississippi River system, 1940–2007[†]

Robert H. Meade[1]* and John A. Moody[2]

[1] *US Geological Survey, MS 413, Box 25046, Federal Center, Denver, CO 80225-0046, USA*
[2] *US Geological Survey, 3215 Marine Street, Suite E-127, Boulder, CO 80303, USA*

Abstract:

Before 1900, the Missouri–Mississippi River system transported an estimated 400 million metric tons per year of sediment from the interior of the United States to coastal Louisiana. During the last two decades (1987–2006), this transport has averaged 145 million metric tons per year. The cause for this substantial decrease in sediment has been attributed to the trapping characteristics of dams constructed on the muddy part of the Missouri River during the 1950s. However, reexamination of more than 60 years of water- and sediment-discharge data indicates that the dams alone are not the sole cause. These dams trap about 100–150 million metric tons per year, which represent about half the decrease in sediment discharge near the mouth of the Mississippi. Changes in relations between water discharge and suspended-sediment concentration suggest that the Missouri–Mississippi has been transformed from a transport-limited to a supply-limited system. Thus, other engineering activities such as meander cutoffs, river-training structures, and bank revetments as well as soil erosion controls have trapped sediment, eliminated sediment sources, or protected sediment that was once available for transport episodically throughout the year. Removing major engineering structures such as dams probably would not restore sediment discharges to pre-1900 state, mainly because of the numerous smaller engineering structures and other soil-retention works throughout the Missouri–Mississippi system. Published in 2009 by John Wiley & Sons, Ltd.

KEY WORDS suspended-sediment discharge; river engineering; Missouri River; Mississippi River

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INTRODUCTION

The Mississippi River and its longest tributary, the Missouri River, together provide the largest conveyance system on the North American continent for transporting sediment from the interior uplands to the coastal ocean. During the last century, however, the engineering of the Missouri–Mississippi River system has caused profound changes in the ways in which these rivers transport and store their sediment loads. Engineering works have been constructed for flood control, navigation, irrigation, hydropower generation, and soil erosion control, and depending on their magnitudes and locations within the Missouri–Mississippi River basin, have resulted in different effects and consequences (Meade, 2004). Major dams were constructed across the Missouri River, which impounded the especially sediment-rich water in the reach upstream from Yankton, South Dakota (Figure 1). Channel-stabilization works farther downstream in the Missouri and Mississippi rivers have strongly altered the riparian landscapes and the hydraulic processes that transport, store, and remobilize fluvial sediment between the northern Great Plains (Nebraska and the Dakotas) and the Gulf of Mexico (Keown *et al.*, 1986; Kesel, 2003; Harmar *et al.*, 2005) and, finally, soil-erosion control measures since the 1930s along the uplands of tributaries to the Missouri and Mississippi rivers have reduced long-term sediment discharges to the system (Knox, 2007).

Prominent among issues being discussed at present are the restoration of sediment-affected ecosystems along the Lower Missouri River and in the Mississippi delta of Louisiana. Of specific interest is how these ecosystems have been affected by engineering works (Kesel, 2003; Harmar *et al.*, 2005), and also how the engineering works might be altered or operated in the future to better serve or manage these deteriorating ecosystems (National Research Council, 2002, 2006, 2009). Sediment-discharge data from gauging stations operated by the US Army Corps of Engineers and US Geological Survey along the Missouri and Mississippi rivers are available in sufficient quantity to assess some of these issues and to address some of the technical questions that they raise. Data collected at these stations through the early 1980s were presented earlier by Meade and Parker (1985), and reiterated in subsequent articles (Meade *et al.*, 1990; Meade, 1995). Because the collection of water- and sediment-discharge data has continued uninterrupted at some of these stations (some data sets span more than 50 years, doubling the length of record we used earlier), we are encouraged to revisit, update and clarify our earlier analyses, and to add our perspectives to the ongoing discussions (see, e.g. Blum

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* Correspondence to: Robert H. Meade, US Geological Survey, MS 413, Box 25046, Federal Center, Denver, CO 80225-0046, USA.
E-mail: rhmeade@usgs.gov

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Figure 1. Map showing Mississippi River basin and its major tributaries. Locations of cities mentioned in the text are shown as solid black circles, larger dams are shown as triangles and the region of engineering diversion structures at Old River is also shown as a solid black circle. See the map in Figure 9 for locations of Tarbert Landing and other stations in Old River complex

and Roberts 2009; Horowitz, 2009). The main specific objectives of this article are (1) a reexamination of the contribution of the Missouri River dams and (2) an updated assessment of the contribution of other factors, to the reduction in the sediment loads of the Mississippi River.

The data discussed in this article pertain only to the suspended-sediment fraction of the total sediment discharge (suspended-sediment discharge plus bedload discharge) that the rivers are transporting. In addition to the finer particles usually referred to as *washload*, the suspended sediment also includes sand particles in suspension (usually referred to as *bed-material load*, rather than true *bedload*), which are collected by isokinetic-nozzle samplers. It does not include sand particles that roll and slide along the river bed, below the reach of the suspended-sediment sampler. In our article, we presume that this routinely unmeasured bedload accounts for less than 5% of the total sediment discharge (Nittrouer *et al*., 2008), which places it well within the range of the error of measurement of the suspended-sediment discharge. In this overview, we address these data in a historical framework, using only the annual totals of suspended-sediment and water discharges recorded at the gauging stations.

SOURCES OF SEDIMENT DATA

Most of the suspended-sediment samples whose data are represented in this article were collected using isokinetic samplers, i.e. samplers equipped with intake nozzles that point directly upstream into the river flow and in which the internal diameter is slightly flared to compensate for internal friction so as to allow the water and its suspended sediment to flow smoothly into the collection bottle with no change from the ambient flow velocity (Edwards and Glysson, 1999). Given the variability, in both space and time, of the distribution of suspended sediment and water velocity within any given cross-section, the individual measurements of daily suspended-sediment discharge can be considered accurate only within 10–15%. And, assuming that the scatter of sampling error is random rather than systematically biased, the annual totals may be considered accurate within 5–10%. See the discussion of "Accuracy of Suspended-sediment Concentrations and Loads" given by Holmes (1996, p. 11–14).

Mississippi River at Tarbert Landing, Mississippi

This station is operated by the New Orleans District of the US Army Corps of Engineers at a section upstream from Baton Rouge (Figure 1). Isokinetic point samples are collected at five depths, at each of 5–8 verticals across the Tarbert Landing cross-section (see Moody and Meade, 1994, their Figure 2 for an example of the spatial layout). Actual sediment discharge measurements are made once every two weeks, which gives 26 sediment-discharge values annually. All other reported daily values are estimated from the daily water discharges (computed from daily measurements of river stage and the stage-discharge rating curve) and from sediment-transport curves of sediment discharge versus water discharge. Details of the Tarbert Landing sediment-sampling record listed in the appendices by Thorne *et al.* (2000, 2008) show the variations over time in the number of verticals and depths of samples. The scatter of points in diagrams of individual sediment samplings versus daily water discharges at Tarbert Landing (Mossa, 1996; Thorne *et al.*, 2000, 2008) leads us to suspect that the interpolated values for suspended-sediment discharge on the days between actual measurements might sometimes contain individual errors as great as 15–20%. Our working assumption in this article is that these day-to-day errors are largely random and that the annual totals that we portray are accurate within 10%. This assumption, however, may be overly optimistic; see the extensive discussion of errors in sediment-rating-curve methods by Horowitz (2003).

The record of annual discharges of water and suspended sediment in the Mississippi River at and near Baton Rouge spans more than 50 years. The gauge has been located at three different sites during the last six decades–Baton Rouge (Mississippi River Mile 234) from 1949 to 1958, Red River Landing (Mississippi River Mile 302) from 1958 to 1963, and Tarbert Landing (Mississippi River Mile 306) since 1963. All three sites are downstream from the Old River Outflow Channel (Figures 1 and 9), which diverts approximately 25% of the water and sediment from the Mississippi River. These data may be considered a continuous record as they were all collected using compatible sampling methods and no tributaries or distributaries of any consequence intervene between the three sites. Therefore, in this article, we refer to these three sites as 'Tarbert Landing' and treat the data as a continuous record.

Atchafalaya River at Simmesport, Louisiana

Sediment data are also collected by the New Orleans District of the US Army Corps of Engineers from a section located just downstream from the Old River Outflow Channel between the Mississippi and Atchafalaya rivers (Figure 1 and map in Figure 9). Point samples are collected twice monthly (and weekly, at high stages) at five depths at each of three verticals.

Old River Outflow Channel near Knox Landing, Louisiana

This station was established in 1963 by New Orleans District of the US Army Corps of Engineers in the Old River Outflow Channel, which is 130 km upstream from Baton Rouge. The measurement cross-section is about 1·2 km upstream from its confluence with Red River (Figure 1 and map in Figure 9). Point samples are collected twice monthly (and weekly, at high stages) at five depths at each of three verticals. Further details are given by Keown *et al.* (1977, p. A317–A320).

Ohio River near Grand Chain (Olmsted), Illinois

This station is 11 km upriver from the Ohio–Mississippi River confluence and is sampled 6–12 times per year by the US Geological Survey's Kentucky Water Science Center, as part of National Stream Quality Accounting Network (NASQAN). Samples are collected by depth integration at 5–9 verticals spaced across the channel. This is a difficult place to collect discharge-weighted-average samples because the Tennessee, Cumberland, and Wabash rivers enter the lower Ohio upstream from this station and bring in waters that differ markedly in their sediment loads. Clearer waters of the extensively dammed Tennessee and Cumberland rivers enter from the left-bank and mix with muddier waters from right-bank tributaries such as the Wabash River to produce strong cross-channel concentration gradients in sediment and chemical properties that persist in the lower Ohio River as far downstream as its confluence with the Mississippi, and for tens of kilometers below the confluence (Rathbun and Rostad, 2004, their Figures 2–4). Our estimate of 40 million metric tons per year (million T y^{-1}) for the long-term average sediment discharge at this station is based on ten measurements that we made during the years 1987–1992, over a sufficiently wide range of river-discharge conditions to allow us to construct a usable sediment-rating curve. Each of these ten represents a composite measurement of depth-integrated samples collected at 11–15 verticals across the channel (Meade and Stevens, 1990; Moody and Meade, 1992, 1993, 1995). Our estimate agrees, within 15%, with the 46 million metric tons per year that Horowitz *et al.* (2001, p. 1184) computed from NASQAN data (1996–1998) at this station. However, it disagrees substantially with the 80 million T y^{-1} that Keown *et al.* (1986, p. 1559) estimated by assigning to the Ohio River most of the left-over sediment otherwise unaccounted for in their comprehensive budget for the Mississippi River system.

Mississippi River at St Louis, Missouri

Sediment and turbidity data are collected by the US Geological Survey's Missouri Water Science Center from under the Poplar Street Bridge over the Mississippi River. This station is only 27 km downstream from the confluence of the Mississippi and Missouri rivers. Consequently, the suspended-sediment concentrations differ markedly, sometimes by an order of magnitude, from one side of the measurement section to the other. For example, see color Figure 10 in the article by Holmes (1996) and the detailed cross-sectional data presented by Jordan (1965) and Scott and Stephens (1966). Depth-integrated samples are collected at 10 verticals six times per year to calibrate another series of samples collected at 2 verticals ten times per year. This latter series of 2-vertical samplings is used to further calibrate the daily turbidity data measured at the intakes for two water-treatment plants: one at Howard Bend on the Missouri River, 23 km above its confluence with the Mississippi River, and the other on the left bank of the Mississippi River in East St Louis (Upper Mississippi River Mile 178·2). Therefore, all but 10–20 of the daily sediment discharges reported each year at St Louis are calculated from these daily turbidity measurements. Further details of these calculations are given by Keown *et al.* (1977, p. A181–A192).

Missouri River at Hermann, Missouri

The station is operated by the US Geological Survey's Missouri Water Science Center and the section is measured from a bridge crossing the Missouri River. Suspended sediment is collected at least once a week (more frequently during high flows) by depth integration at five verticals. Since the Hermann station began operating in 1948, a mixture of point-sampling and depth-integrated sampling procedures has been employed here, but in ways that probably did not introduce significant sampling errors. For details, see Keown *et al.* (1977, p. A225–A230).

Missouri River at Omaha, Nebraska

This station was first operated from 1939 to 1952 by the Omaha District of the US Army Corps of Engineers. Later, during 1952 it was operated by the US Geological Survey's Iowa Water Science Center at Missouri River Mile 615·9 and since 1953, at Missouri River Mile 613·9. Samples are collected every four days. From 1939 to 1948, point samples were collected at three or more depths at each of five verticals by using the 'Omaha Sampler', which had an intake perpendicular to the streamflow (Dardeau and Causey, 1990, p. B5–B6) and therefore may have under-sampled the sand particles in suspension. The magnitude of the error that this under-sampling of sand might have introduced in the computation of annual suspended-sediment loads awaits a field-calibration study that compares simultaneously the sediment-collection characteristics of the Omaha Sampler and an isokinetic sampler—like the comparative study of the Colorado River Sampler that was made by Topping *et al.* (1996). Meanwhile, we estimate that the under-sampling of suspended sand by the Omaha Sampler gave measurement errors during the years 1939–1948 at Omaha that probably did not exceed 20–25% of the total daily suspended-sediment discharge. From 1948 to 1955, point samples were collected as before, but this time using isokinetic samplers. Between 1955 and 1972, sediment was collected both by point sampling and depth-integrated sampling. Since 1972, the usual procedure has been to collect depth-integrated samples every four days at three verticals along the cross-section at Omaha. Further details of the history of operations at the Omaha station are given by Keown *et al.* (1977, p.A251–A259).

Missouri River at Yankton, South Dakota

The Omaha District of the US Army Corps of Engineers also operated this station 8 km downriver of Gavins Point Dam (Missouri River Mile 806). From 1939 to 1969, suspended sediment was sampled here on an average of once every four days. From 1939 to 1954, point samples were collected, using the Omaha Sampler, at three or more depths at each of five verticals. After 1954, point samples were collected, using isokinetic samplers, once every four days at three verticals; and approximately once monthly samples were collected by depth integration. Further details of the history of sampling at this station are given by Keown *et al.* (1977, p. A269–A274).

MISSOURI–MISSISSIPPI RIVER SEDIMENT-DELIVERY SYSTEM

Spatial patterns of river runoff and sediment yield in the Mississippi River basin (Figure 2) are asymmetrical and incongruent. The western tributaries deliver substantially more than half the sediment, but the eastern tributaries deliver more than half the water. Because the Mississippi River basin lies across a marked southeast–northwest gradient in rainfall–from 1200 mm per year along the southeastern edges to less than 400 mm per year in the northwestern Great Plains (Knox, 2007)–the contrasts in runoff are correspondingly large. From only 16% of the total drainage area, the Ohio River contributes nearly half the total water discharged at the mouth of the Mississippi. By contrast, Missouri River drains 43% of the total area, but contributes only 12% of the total water. Between these two large tributary drainage basins, therefore, the difference in basin-wide unit runoff is a factor of ten.

In the Lower Mississippi River, 130 km upstream from Baton Rouge (Figure 1), a quarter of the discharge of the Mississippi is diverted through the Old River Outflow Channel to become, with additional water from the Red River, the Atchafalaya River. These two distributaries (lower Mississippi and Atchafalaya rivers) discharge a combined average of 580 km^3 per year of fresh water to the Gulf of Mexico.

The Missouri River is by far the major supplier of sediment to the Mississippi River. The left side of Figure 3 shows our estimate of how much more pronounced this might have been in the recent past than it is today. Meriwether Lewis and William Clark, who traveled along the Missouri River in 1804–1806, probably were the first to point out that the northern Great Plains, rather than the Rocky Mountains, are the source areas of the large sediment loads (Moody *et al.*, 2003). The rocks that hold up the Rocky Mountains are less readily erodible than those underlying the plains. Many of the soils of the plains are underlain by massive beds of shale and siltstone, the epitome of which is the late Mesozoic (Upper Cretaceous) Pierre Shale (Tourtelot, 1962) that crops out near the Missouri River along much of its course through North and South Dakota. The association of extensive outcroppings of readily erodible

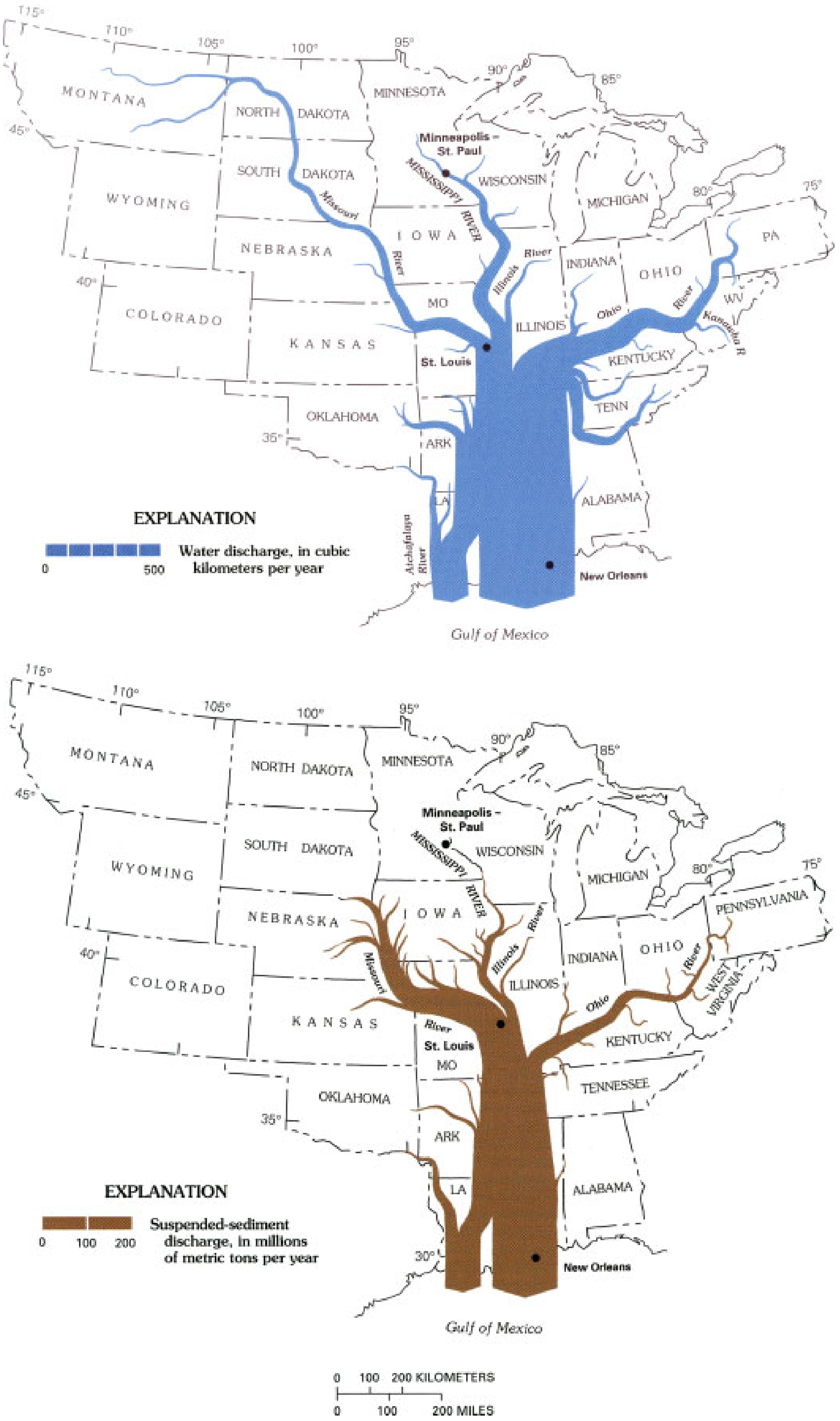

Figure 2. Fluxes of water and suspended sediment in Mississippi River basin *circa* 1980 (from Meade and Leenheer, 1995). *Upper*, Average annual water discharge compiled from gauging-station records of US Geological Survey. *Lower*, Average annual suspended-sediment discharge compiled mostly from data of Keown *et al*. (1981,1986), plus supplemental data on Lower Missouri River from Parker (1988) and data on lower Ohio River from Moody and Meade (1992, 1993, 1995)

shales in the central Missouri basin with areas of small-to-moderate rainfall is the basis for the relation between sediment yield and precipitation devised by Langbein and Schumm (1958). They demonstrated that the maximum sediment yields in this region were associated with only moderate amounts of precipitation, which were sufficient to wash the sediment off the land but were insufficient to support enough vegetation to protect the land from being eroded. Although the "Langbein-Schumm Rule" has fallen out of favor because of its inapplicability to other areas of the world (Walling and Webb, 1983; Meade *et al*., 1990, p. 261–262), it remains a useful generalization in the Great Plains and the Missouri River basin because most of the data on which it was based were originally collected here. The Missouri River sediment plus lesser amounts of sediment from the Upper Mississippi, Ohio and Red rivers gives a total sediment discharge to the Gulf of Mexico that was reckoned by

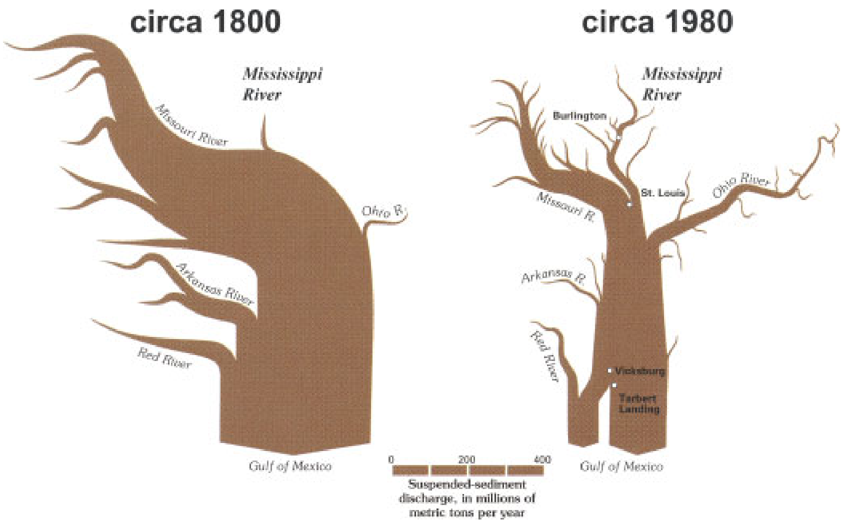

Figure 3. Flow diagrams of average annual suspended-sediment discharges in Missouri–Mississippi River basin. *Left, circa* 1800. *Right, circa* 1980. Diagrams were originally published by Meade (1995). Diagram for 1800 is an impressionistic estimate, based on our readings of the Journals of Lewis and Clark (Moody *et al*., 2003), results of Humphreys and Abbot (1876), observations reported by Mark Twain (1883) and on more recent analyses (Blevins, 2006) that concluded sediment concentrations in the Missouri River have decreased at least 70–80% from predevelopment conditions. Diagram for 1980 is taken from the lower panel of Figure 2

Keown *et al*. (1986) around 1980 to average 255 million T y^{-1}. More recent data, shown later in this article, indicate that this total has declined to about 170 million T y^{-1}.

These estimates of sediment discharge inherently assume sediment transport is continuous over long temporal and spatial scales. This presumption may not always be accurate, especially at time scales shorter than decades, and therefore, the flow diagrams such as those in Figures 2 and 3 must be interpreted with caution. The averaging of hydrologic data, and especially sedimentologic data, over long enough time periods to smooth out year-to-year variations can obscure our understanding of the dynamic processes that move water and sediment downriver. The spatial presumption of hydraulic connectivity from original source to ultimate sink is probably valid for the flow of water (upper panel of Figure 2), in which one may reasonably expect a given molecule or parcel of water to leave the headwaters and arrive at the sea within a single runoff season. However, the presumption does not apply so well to sediment, which moves downriver in episodic or periodic pulses (Meade, 1985, 2007; Moody and Meade, 2008). While most of the finest colloidal particles may well behave like water molecules and be transported long distances during a runoff season, the annual trajectory of a sand grain may be only from one point bar to the next point bar downstream. We can expect the intermediate-sized particles (such as coarse silts and the finest sands) to be transported over varying distances in any given runoff season, to be deposited and stored where they will remain for years, decades or centuries and to be remobilized from storage sites at varying times to be transported varying distances farther downstream. Thus, the presumption of hydraulic connectivity for sediment is valid if viewed as an episodic connectivity over the appropriate time scale.

CAUSES FOR DECLINE IN SUSPENDED-SEDIMENT DISCHARGE

The record of annual suspended-sediment discharge of the Mississippi River at Tarbert Landing (Figure 4, upper panel) shows a marked decline of about 23 million T y^{-1} from 1950 to 1967 and a substantially more gradual decline of about 3·3 million T y^{-1} from 1967 to 2007 (see computed regression lines in Figure 8, below). Note also that annual water discharges (Figure 4, lower panel) decreased markedly (96 km^3 y^{-1}) from 1950 to 1954, since which time they appear to have been more or less steady, or perhaps slightly increasing. The reexamination of the causes for the decrease in suspended-sediment discharge at Tarbert Landing shown in Figure 4 and for the overall substantial reductions in sediment in the Missouri–Mississippi River system between 1800 and 1980 shown in Figure 3 is the main subject of this article.

Effects of the Missouri River dams

The closures of the two farthest downstream dams on the Missouri River–first Fort Randall Dam in 1953 and later Gavins Point Dam farther downstream in 1955 (Figure 5)—were the most important engineered events for decreasing suspended-sediment discharge to the free-flowing Missouri River. Their closures coincided with the precipitous decline in the suspended-sediment discharge past gauging stations on the Lower Missouri and Mississippi rivers. Some authors (ourselves included: Meade and Parker, 1985; Meade *et al*., 1990; Meade, 1995, 2004) have helped to promote the notion that the dams themselves were the principal cause of the precipitous five-fold decline in suspended sediment all the way downriver to the Mississippi delta. This notion has led to the suggestion (by Sparks, 2006, among others) that one of the means of delivering restorative sediment to the eroding wetlands of the Mississippi delta might be

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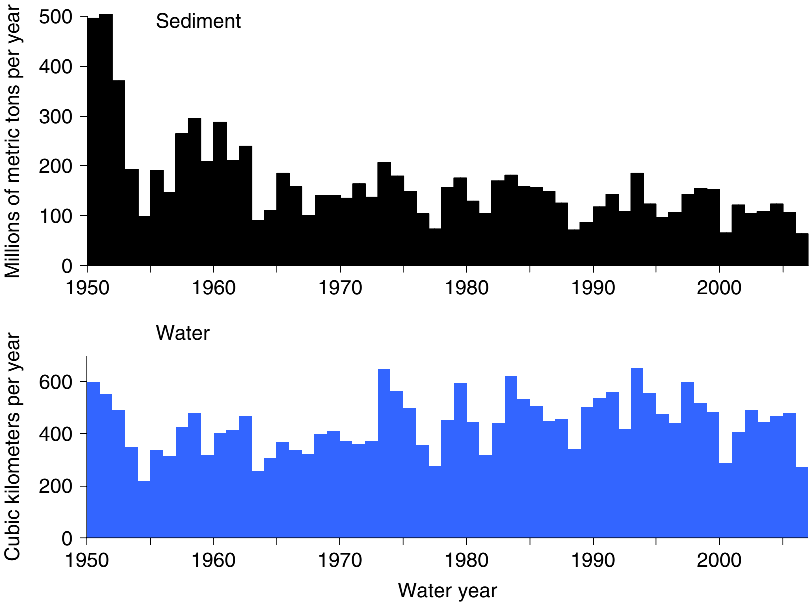

Figure 4. Annual flows in Mississippi River at Tarbert Landing, 1950–2007. *Upper*, Suspended sediment discharge. *Lower*, Water discharge. Tick marks on horizontal scale here indicate the beginning of the water year (1 October of previous year) and in all other similar figures with histograms. The area within the bar is proportional to the flux

the removal of the Missouri dams or the construction of bypassing works to divert the sediment over or around the dams. This notion of the Missouri River dams as the prime cause for the decrease in sediment discharge to the Mississippi delta needs reexamination. Certainly the dams are the causes of much of the decrease of sediment discharge. But *how much* of this decrease is directly due to the dams, and how much is due to other causes?

Four of the relevant suspended-sediment records on the Missouri and Mississippi rivers for the years before, during, and after the closure of the dams at Fort Randall and Gavins Point are shown in Figure 5. The suspended-sediment discharge at Yankton, South Dakota, decreased from 160 million T y^{-1} in 1952 to 50 million T y^{-1} in 1953, immediately following the closure of Fort Randall Dam. This was followed by a smaller decrease in sediment discharge (40 million T y^{-1}) during the 2 years before the closure of Gavins Point Dam in 1955 just upstream from Yankton. This later decrease corresponded in time with an episode of river-bed scouring between Fort Randall and Gavins Point, during which the sands and silts were winnowed out to leave behind a residual layer of gravel that eventually armored the bed against further scour (Livesey, 1965). After 1955, any further material scoured from the channel bed just below Fort Randall would have been trapped, along with sediment inputs from intervening tributaries, behind Gavins Point Dam. Thus, the result of closing the two dams was a decrease in suspended-sediment discharge of about 150 million T y^{-1}.

Looking further at Figure 5 allows us to follow the precipitous decline in sediment discharges during the early 1950s down the Missouri River and then down the Mississippi River. But closer inspection leads us to be wary of making too close a causal connection between the closure of the downstream-most dams in South Dakota and the decrease of sediment discharge at Tarbert Landing. First, the decrease in annual sediment discharge at Yankton of about 150 million T y^{-1} (represents the quantity of sediment trapped in reservoirs behind the dams) is substantially less than the observed decrease of 300–400 million T y^{-1} measured at Tarbert Landing. Second, the water-discharge at Tarbert Landing decreased steadily during the 5-year period, from 600 km^3 y^{-1} in 1950 to 217 km^3 y^{-1} in 1954 (see the record of water discharge for these years in the lower histogram of Figure 4). By coincidence, 1951 was a year of record flooding in the Lower Missouri River and 1954 was the year of smallest water discharge in the Lower Mississippi River during the seven decades between the mid-1930s and 2006. The precipitous rate of the 1950–1954 decline in the annual suspended-sediment discharge, therefore, was largely a consequence of the steep decline in water discharge.

The resumption of greater water and sediment discharges at Tarbert Landing during the years following 1954 (although not so large as the discharges previous to 1953) leads us to speculate that, had the water discharges remained larger during the years 1953–1956, the sediment discharges likely would have shown a more gradual decrease during those same 4 years. The decline in suspended-sediment discharge likely would have been a gradual decrease from 1950 to the mid-1960s. Suspended-sediment concentrations show a similar decline and can be modeled by a hyperbolic function ($R^2 = 0{\cdot}71$). Depletion and degradation of river beds below dams also have been found to follow a gradual hyperbolic decrease (Williams and Wolman, 1984), which has been interpreted as a diminishing availability of sediment. We hypothesize that this gradual decline in sediment discharge and concentration

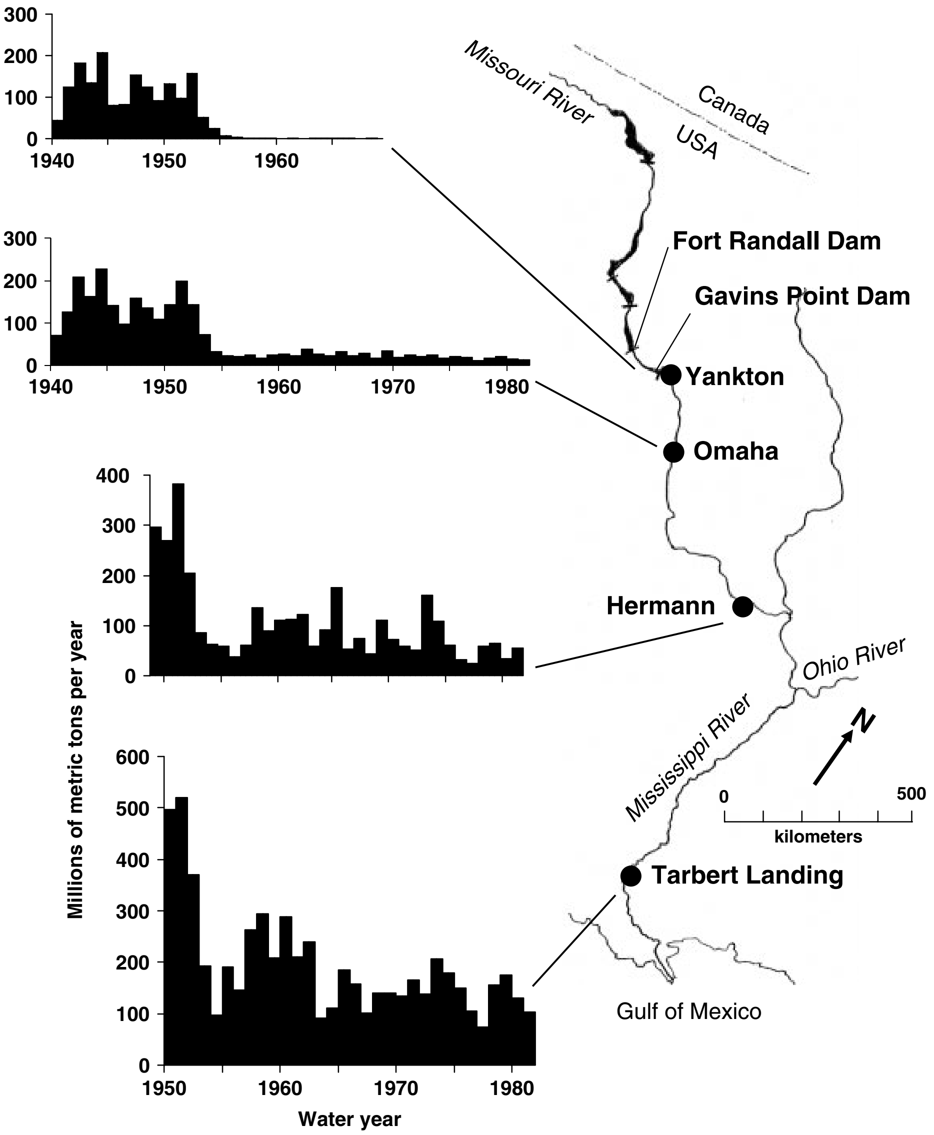

Figure 5. Suspended-sediment discharges at stations on Missouri River at Yankton, South Dakota; Omaha, Nebraska and Hermann, Missouri; and on Mississippi River at Tarbert Landing, Mississippi, during the years 1940–1981. Principal effects on records at Yankton and Omaha, and probably on records at Hermann, were due to the closures of dams at Fort Randall (1953) and Gavins Point (1955). Data from Yankton and Omaha are presented here with the caveat that samples prior to 1950 were collected using equipment that predated the adoption of isokinetic nozzles (see "Sources of Sediment Data")

reflects the progressive remobilization and gradual depletion of previously stored alluvium in the more accessible storage sites in and along the main channel of the Missouri River below Yankton and in and along the mainstem of the Mississippi River below St Louis (Figure 1). That this initial depletion was nearly completed by the mid-1960s is suggested by the abrupt change, around 1966 or 1967, in the relation between annual water discharge and mean annual suspended-sediment concentration at the Tarbert Landing gauge (Figure 6). The discharge-sediment concentration relation for 1950–1966 probably represents an alluvial river in equilibrium such that the suspended-sediment concentration is controlled primarily by the water discharge. However, the 1950s and early 1960s were a period of intense bank stabilization and enlargement of the navigation channel of the Missouri River. This stabilization actually began in the early 1900s when wooden pile dikes and woven-willow and wooden revetments were first used to create a single self-scouring navigation channel (1·8 m deep and 61 m wide). This later period involved the construction of river-training structures such as rock dikes, spur dikes, wing dikes, and trail dikes, which were completed by 1981 (Slizeski *et al.*, 1982; Galat *et al.*, 2005). As the main sources of sediment in the system—namely, the storage sites on floodplains, in the bed and along the banks of the channel—were depleted or protected from erosion by bank revetment, or as the sediment was trapped by such river-training structures (Jacobson *et al.*, 2009), the sediment concentration-discharge relation changed. The discharge-sediment concentration relation for 1967–2007 is indicative of a supply-limited system (Asselman, 1999; Topping *et al.*, 2000). Further inspection of the discharge-sediment concentration relation for 1967–2007 indicated predominantly clockwise hysteresis for 1972–1978,

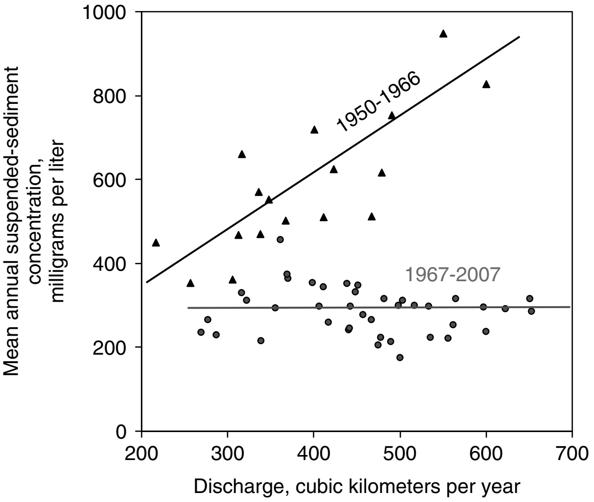

Figure 6. Relations between annual water discharge and mean annual suspended-sediment concentration, Mississippi River at Tarbert Landing, for periods 1950–1966 and 1967–2007. Mean annual suspended-sediment concentration is the quotient of annual suspended-sediment discharge divided by annual water discharge and multiplied by a units-conversion constant

1978–1984 and 1992–1997, which supports the view that the river is sediment-starved on interannual time scale (Asselman, 1999; Horowitz, 2006).

Suspended-sediment discharges of the Missouri River at Hermann have remained consistently greater than those at Omaha, owing to the inputs from tributaries between the two stations (Figure 7, *Upper*). Parker (1988) shows the importance of sediment inputs from these tributaries, especially those draining the agricultural lands of western Iowa and northwestern Missouri that lie on easily erodible loess. These inputs of sediments from the loessland tributaries probably have diminished in recent years as a result of soil-conservation practices (Piest and Spomer, 1968; Piest and Ziemnicki, 1979).

Differences between sediment discharges recorded near the mouth of the Missouri River at Hermann and those recorded at Tarbert Landing (differences shown as solid black in upper histogram of Figure 7) fall into two separate patterns during the years 1950–1981. The larger differences (100–200 million T y^{-1}) recorded for the years 1950–1963 probably reflect the remobilization of older fluvial sediments that had been deposited prior to 1950 in temporary transit-storage sites along the Mississippi between St Louis and Tarbert Landing. These pre-1950 deposits consisted of sediments stored along the meandering channel and in the meander belt that had been forming and evolving along the Mississippi mainstem over the previous decades to centuries - probably since the end of the Pleistocene ice ages (Autin *et al.*, 1991) - and they probably were remobilized progressively during the 1950s and early 1960s, in quantities that varied directly with the discharges of water that were available to move them downriver. In the Lower Mississippi River, Harmar *et al.* (2005) have indirectly measured this remobilization as an average downriver increase in thalweg depth during the period 1949–1989 of 0·09 m per 10 km and a greater decrease between 1949–1951 and 1962–1964. Differences between the sediment discharges at Hermann and Tarbert Landing became smaller (*very* small in 1965, 1969 and 1973) during the late 1960s and the 1970s, which we interpret as showing that the formerly large accumulations of stored sediment along the Middle and Lower Mississippi had been mostly flushed downriver by about 1965.

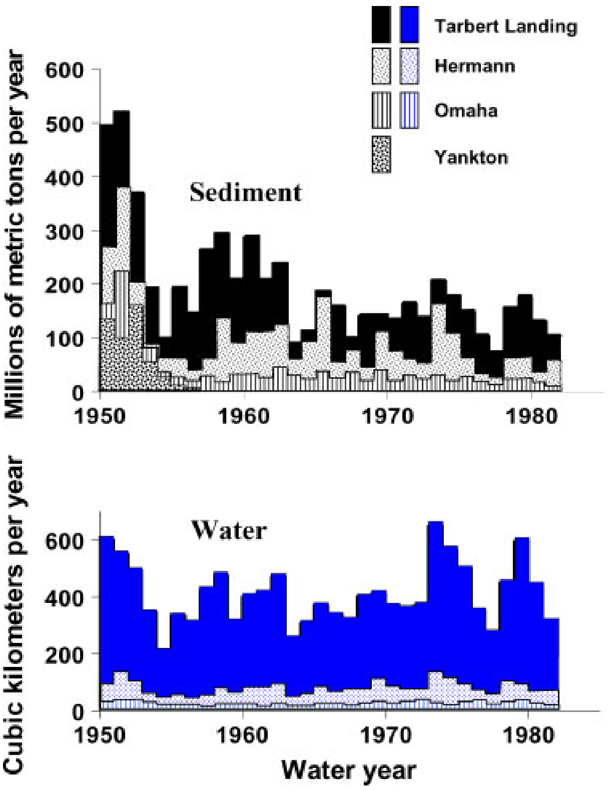

Figure 7. Nested histograms of suspended-sediment and water discharge from 1950–1981. *Upper*, Suspended-sediment discharge at Tarbert Landing, Hermann, Omaha, and Yankton (see also figure 5). L*ower*, Water discharges at Tarbert Landing, Hermann, and Omaha (water discharges at Yankton were not included because they were too similar to those at Omaha to be discernible at this scale.) Note that, while sediment discharges from Missouri River (at Hermann) accounted for at least half the sediment discharges recorded in the Lower Mississippi (at Tarbert Landing), water discharges from Missouri River are proportionately much smaller

For the years 1964–1981, at least half the difference between the sediment discharges at Hermann and Tarbert Landing (solid black in upper histogram, Figure 7) could be accounted for by sediment contributions from the Upper Mississippi (16 million T y^{-1}) and Ohio (40 million T y^{-1}) rivers (Meade, 1995). Thus, sediment sources downstream from the dams on the Missouri River still contribute to the Missouri River and this sediment discharge is hydraulically connected to the Lower Mississippi River. Most of the water that transports this Missouri River sediment from the mouth of the Missouri to the Lower Mississippi comes largely (around 90%) from other sources such as the Upper Mississippi and Ohio rivers.

Effects of other causes

Other engineering activities that might be complicit in the decrease of sediment in the Middle and Lower Mississippi River have been enumerated within recent decades by Kesel *et al.* (1992), Winkley (1994), Mossa (1996), Kesel (2003), Pinter *et al.* (2004), Harmar (2004), Harmar *et al.* (2005), Schumm (2005, p. 82), Hudson *et al.* (2008) and Jemberie *et al.* (2008). Kesel *et al.* (1992, p. 712) present a useful graph showing that the activities most likely to have induced changes in sediment discharge during the post-1950 years represented by the Tarbert Landing record are, in addition to the closure of the dams on Missouri River, meander cutoffs and the construction of river-training structures on the Missouri and Lower Mississippi rivers (Figure 8). These river-training structures serve to trap and store sediment and the revetments prevent river-bank erosion, which, in the preengineered Mississippi and in other nonengineered rivers, has proven to be a major source of suspended sediment (Dunne *et al.*, 1998; Hudson and Kesel, 2000; Meade, 2007). Even where bank-erosion sources of sediment are counterbalanced by deposition elsewhere (point bars, e.g.) in the river system, each episode of bank erosion results in a net transfer of sediment in the downriver direction. It may not be entirely coincidental that the early-to-mid-1960s period of maximum construction of river-training structures and bank revetments in the Lower Mississippi River (Kesel, 2003) corresponds to the period of transition between the two discharge-sediment concentration regimes shown in Figure 6. And, if nothing else, these engineering structures certainly have changed the configuration of the riparian sediment-storage sites along the river and their efficacy in the downriver transfer of sediment.

Although the Old River control structures for the Old River Outflow Channel are upstream from Baton Rouge (Figures 1 and 9) and only a few kilometers upstream from Tarbert Landing, we do not believe them to have been a significant cause of any of the changes in the quantities of sediment discharge that have been observed at Tarbert Landing. The Old River low-sill control structure was completed in 1963 to fulfill a mandate by the US Congress to control the diversion of Mississippi River water into the Atchafalaya River in such a way that the flow down the Atchafalaya was maintained at 30% of the 'Latitude Flow', which was defined as the total combined flow of the Mississippi and Red rivers (Reuss, 2004; see map in our Figure 9). Over the years, this has meant that the proportion of the Mississippi River flow diverted through the Old River Outflow Channel has hovered near 25% of the flow reported at Natchez (Figure 1) upstream from the Old River control structures, while the other 75% of the Mississippi River discharge has continued to flow past Tarbert Landing and into the Gulf of Mexico through the main mouths in the Bird Foot Delta. Figure 10 shows that the quantity of water being diverted from the Mississippi River was already around 25% at the time that the first regulating structure was closed in 1963. These proportions have continued through the periods of construction of the auxiliary control structure (completed 1987) and a low-head hydropower dam (completed 1990). Histograms portraying the suspended-sediment discharges of the Mississippi River at Tarbert Landing and of the Atchafalaya River at Simmesport (Figure 9) show no long-term changes or interruptions that can be attributed to these control structures.

Sediment transport during more recent years

We now turn our attention to the period of record from mid-1960s to the present. We chose to use the water-discharge and sediment-discharge record of the Mississippi River at St Louis for several reasons: (1) it is a complete record for this period, (2) it contains the significant water discharges from the Upper Mississippi as well as those from the Lower Missouri and (3) it avoids

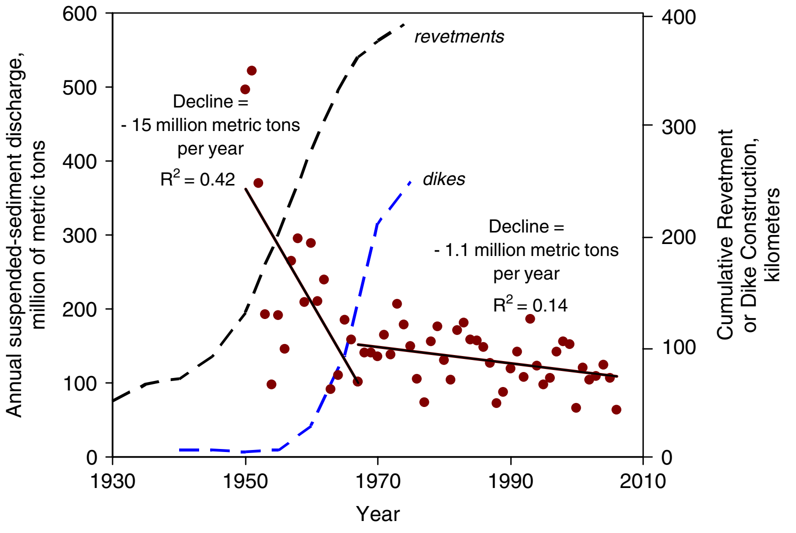

Figure 8. Annual suspended-sediment discharge at Tarbert Landing and construction of engineered dikes and bank revetment along the Lower Mississippi River, 1930–2007. Solid circles correspond to the annual suspended-sediment discharge at Tarbert Landing (Figure 4) and the trend lines have been fit by least-squares regression. Data for dikes and bank revetment were adapted from graphs in the paper published by Westphal *et al.* (1976). The lower dashed line corresponds to dike construction in the Memphis District of the Lower Mississippi River and the upper dashed line corresponds to bank revetment construction in the Vicksburg District of the Lower Mississippi River

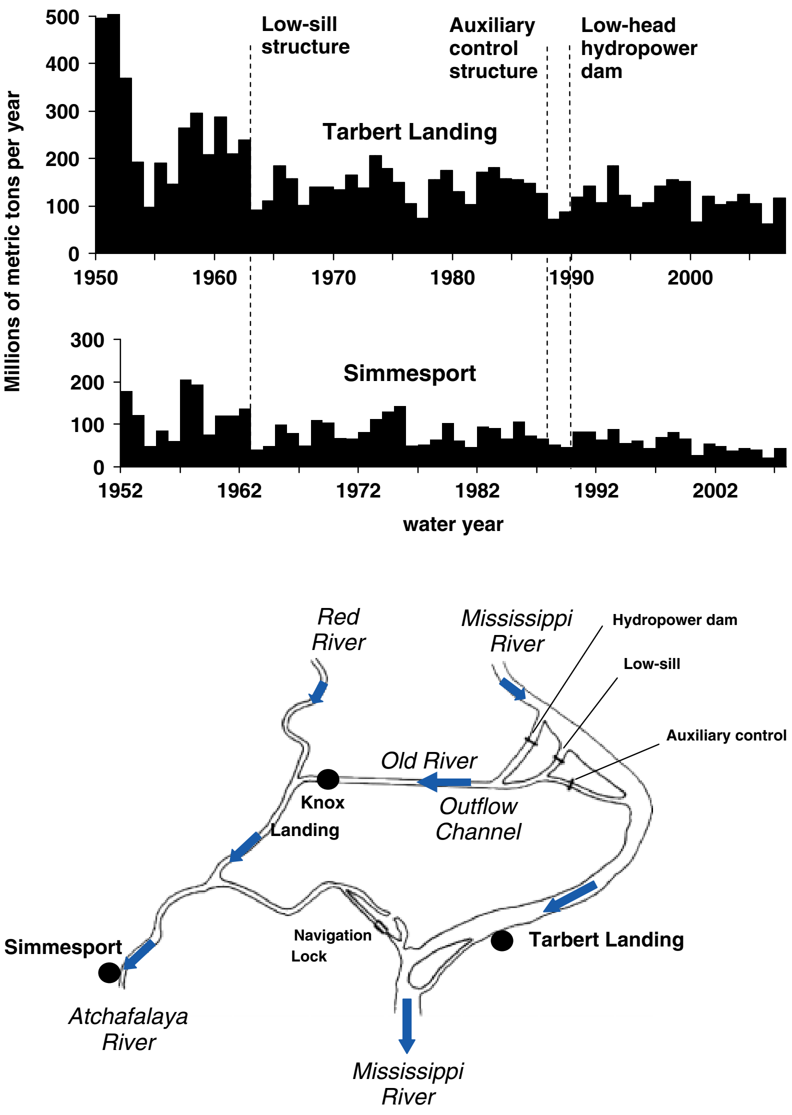

Figure 9. Suspended-sediment discharge, 1950–2007, Mississippi River at Tarbert Landing and Atchafalaya River at Simmesport. The map shows the present configuration of rivers and control structures at Old River, Louisiana. Flow measured at Simmesport is the sum of Red River plus the water and sediment diverted from the Mississippi River. The sum of the measurements made at Simmesport and Tarbert Landing, therefore, is the best available indication of the total amount of sediment being delivered by the combined Red River and mainstem Mississippi River to coastal Louisiana

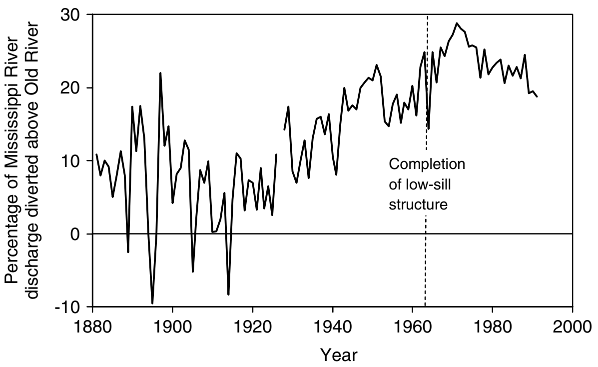

Figure 10. Percentage of the Mississippi River flow diverted first naturally, then artificially, through Old River. From Mossa (1996, p. 461). Negative numbers show years in which the Red River provided flow to the Mississippi River, when Old River was bidirectional

the complicating issues of storage and remobilization of sediment in the lowermost Missouri River [i.e. between Hermann and the mouth–see Holmes, (1996) and Jacobson *et al.*, (2009) for discussions of some of these issues]. These data then provide an opportunity for more direct assessment of what might be happening in the Mississippi River mainstem between St Louis and the Old River diversion. The record just upriver from Old River was constructed by adding together the record for the Mississippi River at Tarbert Landing and the record (begun in 1966) for the Old River Outflow Channel at Knox Landing. The combinations of these two records should provide appropriate facsimiles of the sediment and water discharges that might have been measured in a section of Mississippi River at Natchez or at some other station just above the Old River Outflow Channel.

Sediment discharges in the Mississippi River have declined slowly during the last 40 years at both St Louis and upriver from Old River. Rebich and Demcheck (2007) show a similar slow decline averaging 3% per year at St Francisville, Louisiana, about 60 km downriver from Tarbert Landing. Horowitz (2006) has suggested, based on sediment records following the Flood of 1993 in the Upper Mississippi, that major declines during this time period have followed large floods that flushed older sediments out of riparian storage sites. Horowitz (2009) further suggested that the effect of the Flood of 1993 could be shown in stepwise decreases in decadal sediment loads before and after 1993 in the Lower Mississippi. However, our examination of Figure 11 convinces us that the recent (1981–2007 are the years of data analyzed by Horowitz, 2009) decrease in sediment loads at Tarbert Landing could be interpreted as a simple downward trend rather than an abrupt step-like decrease after 1993. Apparently, large proportions of the sediment discharge, as indicated by the solid black areas in the upper histogram in Figure 11, continue to be supplied during most years from sources downriver from St Louis. The Ohio River and other tributaries, on average, can only account for 40–50 million T y^{-1} of contributed sediment. The remaining added sediment, which averaged about 30 million T y^{-1} during the 40-year period 1966–2005, probably represents the remobilization of previously stored sediment deposits along the Mississippi mainstem.

Certainly a part of the long-term slow decline in sediment discharge is likely due to the reduction of soil erosion in the uplands of the source regions (Glymph, 1951), where large-scale soil-conservation practices have been in effect since the 1930s. Although most of the responses of the landscape to soil-conservation practices appear as adjustments *within* the individual tributary basins (Trimble, 1983, 1999), their eventual outcome must be a decline in the delivery of upland sediment to mainstem rivers. We suspect that a significant proportion of the slow decline in mainstem sediment discharges during the last 40 years (Figure 11) is attributable to basinwide soil-conservation efforts. Because the imprints of these efforts are subtle—and their subtlety increases with increasing basin size—their effects were obscured during the 1950s and early 1960s by the more massive remobilizations and transfers of mainstem sediments.

The sediment budget at the Old River Outflow Channel is critical to understanding sediment availability. The inputs and outputs of river-borne suspended sediment to and from the Old River region are summarized in Table I. These quantities, because they are averages of the last 20 years, are the maximum quantities that can be used in any calculations of river sediment that might be available for the future restoration of coastal wetlands. The sediment input from Red River has decreased rapidly since 2002, presumably in delayed but continuing response to the completion between 1984 and 1995 of five new low-head navigational structures between Shreveport and Old River (Combs *et al.*, 1994). Whether the other sediment inputs are continuing to decline slowly or they have been stabilized at their present levels (Mead Allison, personal communication, 2008) is, to us, uncertain.

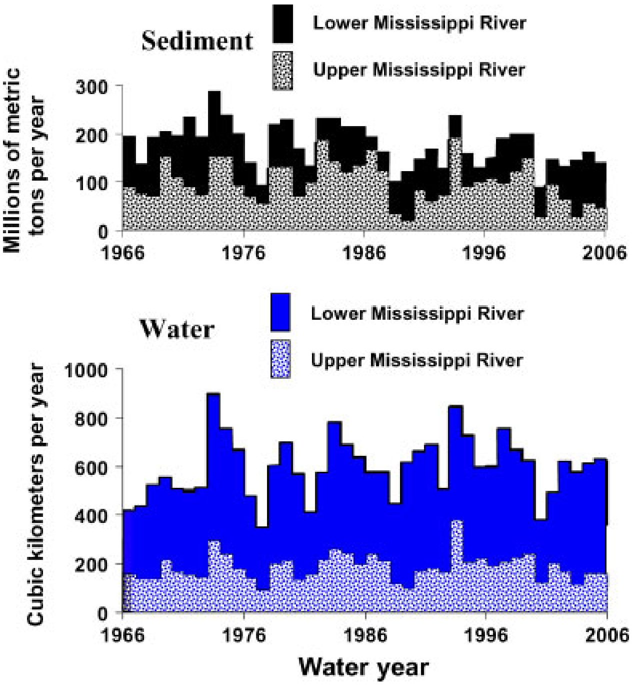

Figure 11. Annual discharges of suspended sediment and water during the years 1966–2006, in Upper Mississippi River at St Louis and in Lower Mississippi River just upriver from the Old River diversions. The Lower Mississippi records are the sums of annual suspended-sediment discharges and annual water discharges recorded at two stations: Mississippi River at Tarbert Landing and Old River Outflow Channel at Knox Landing (see map in Figure 9). The nesting of the histograms is not meant to imply that every individual sediment particle that passed St Louis during a given year was transported into the Lower Mississippi River during the same year. It does imply, however, that any losses of transported sediment to storage sites along the way downriver were compensated by gains from tributaries or from the remobilization of previously stored particles. These sums are the best available indicators of the total quantities of sediment and water that are being delivered to central Louisiana by the mainstem Mississippi River

Table I. Summary of sediment discharges to and from the Old River Outflow Channel (numbers given are 20-year averages from 1987 to 2006)

Station	Suspended-sediment discharge, in millions of metric tons per year
Measured	
Mississippi River at Tarbert Landing	115
Old River Outflow Channel at Knox Landing	30
Atchafalaya River at Simmesport	57
Calculated	
Input from Mississippi River (Tarbert Landing plus Knox Landing)	145
Input from Red River (Simmesport minus Knox Landing)	27
Output to coastal Louisiana and Gulf of Mexico (Tarbert Landing plus Simmesport)	172

Can the pre-1950 discharges of suspended sediment be restored to the Lower Mississippi River? Because of the complexities of the sediment-delivery system and the multiplicity of the engineering works that have influenced it, we can conceive of no single action (not even the complete removal of the dams on the Missouri River) that would restore the large loads of sediment that the Mississippi River formerly carried to its delta. Even in the extremely unlikely event that all engineering works were completely removed and the rivers were allowed to return fully to their pre-1900 transport-limited state, we speculate that many decades would be required to reestablish the episodic hydraulic connectivity of the sediment-delivery system of storage and remobilization that formerly provided large sediment discharges to the Lower Mississippi River and its delta.

SUMMARY AND CONCLUSION

During the first half of the 20th century, before about 1950, the Missouri River and the segment of the Mississippi River below St Louis functioned as a hydraulically connected system for the conveyance of sediment from the northern Great Plains to the Gulf of Mexico. The bulk of the movable sediment was transported episodically, a finite distance each runoff season, from one storage site to another site farther downriver. Some of the sediment would have been deposited for longer time periods (decades to perhaps centuries) in storage sites that made them less susceptible to remobilization. We see this temporary loss as having been compensated during preengineering years by sediment that was remobilized along the way by bank erosion. So the hydraulic connectivity of the sediment transport proceeded downriver simultaneously at many different time scales, at different locations and over many different distances of travel of individual particles.

Following the closure of Fort Randall Dam on the Missouri River in 1953, the sediment discharges of the Missouri and Mississippi rivers went into rapid decline. Although the closure at Fort Randall and the closures of other dams on the Missouri River during the middle and late 1950s were certainly the proximal causes of the river-wide decline in sediment discharges, they do not tell the whole story. That the magnitude of the post-1953 decline in sediment discharge in the Lower Mississippi River at Tarbert Landing was substantially greater than the quantity of sediment that was trapped behind Fort Randall and the other Missouri River dams. This indicates that there are other causes for the river-wide decline in sediment discharges related to other sources of sediment than just those upstream from the Missouri River dams. These other sources are most likely the intervening tributaries, such as those entering the Lower Missouri River below Yankton and the fluvial sediments stored along the mainstem Mississippi River between St Louis and Tarbert Landing.

Sediment discharges declined most rapidly between 1950 and the mid-1960s, after which time the decline became more gradual. We interpret this shift in the rate of decline as a probable indication that, by 1965, the most accessible of the sediments stored in riparian storage sites along the Mississippi River had been flushed downriver, trapped by river training structures, or protected by bank erosion structures, and that soil conservation measures were implemented in the uplands surrounding the Missouri–Mississippi River system. And we further interpret the shift in the rate of decline as a signal of the transition of the Missouri–Mississippi from a transport-limited system to a supply-limited system.

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REFERENCES

Asselman NEM. 1999. Suspended sediment dynamics in a large drainage basin: the River Rhine. *Hydrological Processes* **13**: 1437–1450.

Autin WJ, Burns SF, Miller BJ, Saucier RT, Snead JI. 1991. Quaternary geology of the Lower Mississippi Valley. In *Quaternary Nonglacial Geology: Conterminous U.S*, K-2, Morrison RB. (ed), Geological Society of America, The Geology of North America: Boulder, Colorado; 547–582.

Blevins DW. 2006. *The Response of Suspended Sediment, Turbidity, and Velocity to Historical Alterations of the Missouri River*. US Geological Survey Circular 1301, 8p. http://pubs.usgs.gov/circ/2006/1301.

Blum MD, Roberts HH. 2009. Drowning of the Mississippi Delta due to insufficient sediment supply and global sea-level rise. *Nature Geoscience* **2**: 488–491. DOI: 10.1038/NGEO553.

Combs PG, Pinkard CF Jr, Espey WH Jr, Littlepage B. 1994. Management of sediments on the Red River Waterway Project. In *Hydraulic Engineering '94, Proceedings of 1994 Conference*, vol. 2, Cotroneo GV, Rumer RR (eds). American Society of Civil Engineers, Hydraulics Division; 1125–1130.

Dardeau EA Jr, Causey EM. 1990. *Downward Trend in Mississippi River Suspended-Sediment Loads*. US Army Engineer Waterways Experiment Station Potamology Program (P-1) Report5, 67 p. (plus 2 app: 3 p. & 14 p).

Dunne T, Mertes LAK, Meade RH, Richey JE, Forsberg BR. 1998. Exchanges of sediment between the flood plain and channel of the Amazon River in Brazil. *Geological Society of America Bulletin* **110**: 450–467.

Edwards TK, Glysson GD. 1999. Field methods for measurement of fluvial sediment, *US Geological Survey Techniques of Water-Resources Investigations*, *Book 3, Chapter* 89 p.

Galat DL, Berry CR Jr, Peters EJ, White RG. 2005. Missouri River basin. In *Rivers of North America*, (Benke AC, Cushing CE (eds). Elsevier Science/Academic Press: Boston/San Diego; 426–480.

Glymph LM. 1951. *Relation of Sedimentation to Accelerated Erosion in the Missouri River Basin*. US Soil Conservation Service Report SCS-TP-102, 23 p. (plus 2 figures).

Harmar OP. 2004. *Morphological and process dynamics of the Lower Mississippi river*. PhD dissertation, University of Nottingham, 409 p. http://etheses.nottingham.ac.uk/archive/00000056/01/OPH_PhD_thesis.pdf.

Harmar OP, Clifford NJ, Thorne CR, Biedenharn DS. 2005. Morphological changes of the lower Mississippi River: geomorphological response to engineering intervention. *River Research and Applications* **21**: 1107–1131.DOI:10.1002/rra.887.

Holmes RR Jr. 1996. *Sediment Transport in the Lower Missouri and the Central Mississippi Rivers*, June 26 through September 14, 1993. US Geological Survey Circular 1120-I, 23p. http://pubs.usgs.gov/circ/1993/circ1120-I/.

Horowitz AJ. 2003. An evaluation of sediment rating curves for estimating suspended sediment concentrations for subsequent flux calculations. *Hydrological Processes* **17**: 3387–3409. DOI:10.1002/hyp.1299.

Horowitz AJ. 2006. The effect of the "Great Flood of 1993" on subsequent suspended sediment concentrations and fluxes in the Mississippi River Basin, USA. In *Sediment Dynamics and the Hydromorphology of Fluvial Systems*, Rowan JS, Duck RW, Werrity A (eds.) International Association of Hydrological Sciences Publication306, IAHS: 110–119.

Horowitz AJ. 2009. A quarter century of declining suspended sediment fluxes in the Mississippi River and the effect of the 1993 flood. *Hydrological Processes* **24**: 13–34.

Horowitz AJ, Elrick KA, Smith JJ. 2001. Annual suspended sediment and trace element fluxes in the Mississippi, Columbia, Colorado, and Rio Grande drainage basins. *Hydrological Processes* **15**: 1169–1207. DOI:10.1002/hyp.209.

Hudson PF, Kesel RH. 2000. Channel migration and meander-bend curvature in the lower Mississippi River prior to major human modification. *Geology* **28**: 531–534.

Hudson PF, Middelkoop H, Stouthamer E. 2008. Flood management along the Lower Mississippi and Rhine Rivers (The Netherlands) and the continuum of geomorphic adjustmemt. *Geomorphology* **101**: 209–236. DOI:10.1016/j.geomorph.2008.07.001.

Humphreys AA, Abbot HL. 1876. *Report upon the Physics and Hydraulics of the Mississippi River*. US Army Corps of Engineers Professional Paper 13: 691 p. (25 pl).

Jacobson RB, Blevins DW, Bitner CJ. 2009. Sediment regime constraints on river restoration—an example from the Lower Missouri River. In *Management and Restoration of Fluvial Systems with Broad Historical Changes and Human Impacts*, James LA, Rathburn SL, Whittecar GR (eds). *Geological Society of America Special Paper* 451, 1–22. DOI:10.1130/2008.2451(01).

Jemberie AA, Pinter N, Remo JWF. 2008. Hydrologic history of the Mississippi and Lower Missouri Rivers based upon a refined specific-gauge approach. *Hydrological Processes* **22**: 4436–4447. DOI:10.1002/hyp.7046.

Jordan PR. 1965. *Fluvial Sediment of the Mississippi River at St. Louis, Missouri*. US Geological Survey Water-Supply Paper 1802, 89 p.

Keown MP, Dardeau EA Jr, Causey EM. 1981. Characterization of the suspended-sediment regime and bed-material gradation of the Mississippi River Basin Vicksburg MS. *US Army Engineer Waterways Experiment Station Potamology Program (P-1) Report* vol. 1, 2 vols., 62 p., 7 app.

Keown MP, Dardeau EA Jr, Kennedy JG. 1977. Inventory of sediment sample collection stations in the Mississippi River basin, Vicksburg MS. *US Army Engineer Waterways Experiment Station* Technical Report M-77-1, 49 p. (plus 1 app: 430 p).

Keown MP, Dardeau EA, Jr, Causey EM. 1986. Historic trends in the sediment flow regime of the Mississippi River. *Water Resources Research* **22**: 1555–1564.

Kesel RH. 2003. Human modifications to the sediment regime of the Lower Mississippi River flood plain. *Geomorphology* **56**: 326–334. DOI:10.1016/S0169-555X(03)00159.

Kesel RH, Yodis EG, McCraw DJ. 1992. An approximation of the sediment budget of the Lower Mississippi River prior to major human modification. *Earth Surface Processes and Landforms* **17**: 711–722.

Knox JC. 2007. The Mississippi river system. In *Large Rivers: Geomorphology and Management*, (Gupta A (ed.) John Wiley & Sons: Chichester; 145–182.

Langbein WB, Schumm SA. 1958. Yield of sediment in relation to mean annual precipitation. *American Geophysical Union Transactions* **39**: 1076–1084.

Livesey RH. 1965. Channel armoring below Fort Randall Dam. In *Proceedings of the Federal Inter-Agency Sedimentation Conference 1963*. US Department of Agriculture Miscellaneous Publication970, US Department of Agriculture; 461–470.

Meade RH. 1985. Wavelike movement of bedload sediment, East Fork River, Wyoming. *Environmental Geology and Water Sciences* **7**: 215–225.

Meade RH. 1995. Setting: Geology, hydrology, sediments, and engineering of the Mississippi River. In *Contaminants in the Mississippi River, 1987–92*, Meade RH (ed.) *US Geological Survey Circular* 1133, 12–28. http://pubs.usgs.gov/circ/circ1133.

Meade RH. 2004. Engineering works and their effects on movement and storage of sediment in Mississippi River and its major tributaries. In *Proceedings of the Ninth International Symposium on River Sedimentation, Yichang, China*, vol. 1, Tan Y, (ed.) Tsinghua University Press: Beijing; 154–161.

Meade RH. 2007. Transcontinental moving and storage: the Orinoco and Amazon Rivers transfer the Andes to the Atlantic. In *Large Rivers: Geomorphology and Management*, (Gupta A (ed.) John Wiley & Sons: Chichester; 45–63.

Meade RH, Leenheer JA. 1995. Executive summary. In *Contaminants in the Mississippi River, 1987–92*, Meade RH (ed.) *US Geological Survey Circular* 1133, 1–8. http://pubs.usgs.gov/circ/circ1133.

Meade RH, Moody JA, Stevens HH Jr. 1995. Sampling the big rivers. In *Contaminants in the Mississippi River, 1987–92*, Meade RH (ed.) *US Geological Survey Circular* 1133, 40–51. http://pubs.usgs.gov/circ/circ1133.

Meade RH, Parker RS. 1985. Sediment in rivers of the United States. *National Water Summary 1984*. US Geological Survey Water-Supply Paper 2275, 49–60.

Meade RH, Stevens HH Jr. 1990. Strategies and equipment for sampling suspended sediment and associated toxic chemicals in large rivers—with emphasis on the Mississippi River. *The Science of the Total Environment* **97/98**: 125–135.

Meade RH, Yuzyk TR, Day TJ. 1990. Movement and storage of sediment in rivers of the United States and Canada. In *Surface Water Hydrology*, vol. O-1, Wolman MG, Riggs HC (eds.) Geological Society of America, The Geology of North America: Boulder, Colorado; 255–280.

Moody JA, Meade RH. 1992. *Hydrologic and Sedimentologic Data Collected during Three Cruises at Low Water on the Mississippi River and Some of its Tributaries*, July 1987-June 1988. US Geological Survey Open-File Report 91–485, 143 p.

Moody JA, Meade RH. 1993. *Hydrologic and Sedimentologic Data Collected During Four Cruises at High Water on the Mississippi River and Some of its Tributaries*, March 1989-June 1990. US Geological Survey Open-File Report 92–651, 227 p.

Moody JA, Meade RH. 1994. Evaluation of the method of collecting suspended sediment from large rivers by discharge-weighted pumping and separation by continuous-flow centrifugation. *Hydrological Processes* **8**: 513–530.

Moody JA, Meade RH. 1995. *Hydrologic and Sedimentologic Data Collected During Three Cruises on the Mississippi River and Some of its Tributaries from Minneapolis, Minnesota, to New Orleans, Louisiana*, July 1991-May 1992. US Geological Survey Open-File Report 94–474, 159 p.

Moody JA, Meade RH. 2008. Terrace aggradation during the 1978 flood on Powder River, Montana, USA. *Geomorphology* **99**: 387–403. DOI:10.1016/j.geomorph.2007.12.002.

Moody JA, Meade RH, Jones DR. 2003. *Lewis and Clark's Observations and Measurements of Geomorphology and Hydrology, and Changes with Time*. US Geological Survey Circular 1246, 110 p. http://pubs.usgs.gov/circ/circ1246.

Mossa J. 1996. Sediment dynamics in the lowermost Mississippi River. *Engineering Geology* **45**: 457–479.

National Research Council. 2002. *The Missouri River Ecosystem: Exploring the Prospects for Recovery*. National Academy Press: Washington, DC; 175 p.

National Research Council. 2006. *Drawing Louisiana's New Map: Addressing Land Loss in Coastal Louisiana*. National Academy Press: Washington, DC; 190 p.

National Research Council. 2009. *Final Report from the NRC Committee on the Review of the Louisiana Coastal Protection and Restoration (LACPR) Program*. National Academy Press: Washington, DC: 40 p.

Nittrouer JA, Allison MA, Campanella R. 2008. Bedform transport rates for the lowermost Mississippi River. *Journal of Geophysical Research: Earth Surface* **113**: F03004. DOI:10.1029/2007JF000795.

Parker RS. 1988. Uncertainties in defining the suspended sediment budget for large drainage basins. In *Sediment Budgets*, Bordas MP, Walling DE (eds.) *International Association of Hydrological Sciences* Publication 174, IAHS; 523–532.

Piest RF, Spomer RG. 1968. Sheet and gully erosion in the Missouri Valley loessial region. *American Society of Agricultural Engineers Transactions* **11**: 850–853.

Piest RF, Ziemnicki S. 1979. Comparative erosion rates of loess soils in Poland and Iowa. *American Society of Agricultural Engineers Transactions* **22**: 822–827.

Pinter N, Miller K, Wlosinski JH, van der Ploeg RR. 2004. Recurrent shoaling and channel dredging, Middle and Upper Mississippi River, USA. *Journal of Hydrology* **290**: 275–296. DOI:10.1016/j.jhydrol.2003.12.021.

Rathbun RE, Rostad CE. 2004. Lateral mixing in the Mississippi River below the confluence with the Ohio River. *Water Resources Research* **40**: W05207. DOI:10.1029/2003WR002381.

Rebich RA, Demcheck DK. 2007. *Trends in Nutrient and Sediment Concentrations and Loads in Major River Basins of the South-central United States, 1993-2004*. US Geological Survey Scientific Investigations Report 2007–5090, 112 p.

Reuss M. 2004. *Designing the Bayous: The Control of Water in the Atchafalaya Basin 1800-1995*. Texas A&M University Press: College Station; 474 p.

Schumm SA. 2005. *River Variability and Complexity*. Cambridge University Press: Cambridge, UK; 220 p.

Scott CH, Stephens HD. 1966. *Special Sediment Investigations, Mississippi River at St. Louis, Missouri, 1961–63*. US Geological Survey Water-Supply Paper 1819-J, 35 p., 3 pl.

Slizeski JJ, Andersen JL, Dorough WG. 1982. Hydrologic setting, system operation, present and future stresses. In *The Middle Missouri River—A Collection of Papers on the Biology, with Special Reference to Power Station Effects*, Hesse LW, Hergenrader GL, Lewis HS, Reetz SD, Schlesinger AB (eds.) The Missouri River Study Group: Norfolk, Nebraska; 15–37.

Sparks RE. 2006. Rethinking, then rebuilding New Orleans. *Issues in Science and Technology Online* **22**(2): 1–12. http://www.issues.org/issues/22.2/sparks.html.

Thorne CR, Harmar OP, Wallerstein N. 2000. *Sediment Transport in the Lower Mississippi River*. University of Nottingham School of Geography, Final Report to US Army Research, Development and Standardization Group-U.K., London, under Contract N68171-00-M-EN01, 70 p.

Thorne CR, Harmar OP, Watson C, Clifford N. Biedenharn DS, Measures R. 2008. *Current and Historical Sediment Loads in the Lower Mississippi River*. University of Nottingham School of Geography, Final Report to US Army European Research Office, London, under Contract 1106- EN-01, 145 p.

Topping DJ, Parker RS, Nelson JM, Bennett JP. 1996. The apparent mid-20th century load decreases in the Colorado River basin: an investigation of the Colorado River Sampler. *Geological Society of America Abstracts with Programs* **29**(7): 261.

Topping DJ, Rubin DM, Vierra LE Jr. 2000. Colorado River sediment transport, 1, Natural sediment supply limitation and the influence of Glen Canyon Dam. *Water Resources Research* **36**: 515–542.

Tourtelot HA. 1962. *Preliminary Investigation of the Geologic Setting and Chemical Composition of the Pierre Shale, Great Plains Region*. US Geological Survey Professional Paper 390, 74 p.

Trimble SW. 1983. A sediment budget for Coon Creek basin in the Driftless Area, Wisconsin, 1853–1975. *American Journal of Science* **283**: 454–474.

Trimble SW. 1999. Decreased rates of alluvial sediment storage in the Coon Creek basin, Wisconsin, 1975–1993. *Science* **285**: 1244–1246.

Twain M. 1883. *Life on the Mississippi*. James R Osgood and Company: Boston; 624 p.

Walling DE, Webb BW. 1983. Patterns of sediment yield. In *Background to Palaeohydrology*, Gregory KJ (ed.) John Wiley & Sons: New York; 69–100.

Westphal JA, Munger PR, Muir CD. 1976. Mississippi River dikes and stage-discharge relations. *Rivers '76*. American Society of Civil Engineers Symposia on Inland Waterways for Navigation, Flood Control, and Water Diversion; 1383–1398.

Williams GP, Wolman MG. 1984. *Downstream Effects of Dams on Alluvial Rivers*. US Geological Survey Professional Paper 1286, 83 p.

Winkley BR. 1994. Response of the lower Mississippi River to flood control and navigation improvements. In *The Variability of Large Alluvial Rivers*, Schumm SA, Winkley BR (eds.) American Society of Civil Engineers: New York; 45–74.