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Enhancing mud supply from the Lower Missouri River to the Mississippi River Delta USA: Dam bypassing and coastal restoration

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ABSTRACT

Sand transport to the Mississippi River Delta (MRD) remains sufficient to build wetlands in shallow, sheltered coastal bays fed by engineered diversions on the Mississippi River (MR) and its Atchafalaya River (AR) distributary. But suspended mud (silt & clay) flux to the coast has dropped from a mean of 390 Mt y^{-1} in the early 1950s, to 100 Mt y^{-1} since 1970. This fine-grained sediment travels deeper into receiving estuarine basins and plays a critical role in sustaining existing marshes. Virtually all of the 300 Mt y^{-1} of missing mud once flowed from the Missouri River (MOR) Basin before nearly 100 dams were built as part of the Pick-Sloan water development project. About 100 Mt y^{-1} is now intercepted by main-stem Upper MOR dams closed in 1953. But the remaining 200 Mt y^{-1} is trapped by impoundments built on tributaries to the Lower MOR in the 1950s and 1960s. Sediment flux during the post-dam high MOR discharge years of 1973, 1993 and 2011 approached pre-dam levels when tributaries to the Lower MOR, including the Platte and Kansas Rivers, contributed to flood flows. West bank tributaries drain a vast, arid part of the Great Plains, while those entering from the east bank traverse the lowlands of the MOR floodplain. Both provinces are dominated by highly erodible loess soils. Staunching the continued decline in MR fine-grained sediment flux has assumed greater importance now that engineered diversions are being built to reconnect the Lowermost MR to the MRD. Tributary dam bypassing in the Lower MOR basin could increase mud supply to the MRD by 100–200 Mt y^{-1} within 1–2 decades. Such emergency measures to save the MRD are compatible with objectives of the Missouri River Restoration and Platte River Recovery Programs to restore MOR riparian habitat for endangered species. Rapid mobilization to shunt fine-grained sediments past as many as 50 Lower MOR tributary dams in several U.S. states will undoubtedly require as much regional coordination and funding in the 21st century as the monumental effort it took to build the dams in the last century.

1. Introduction

Syvitski et al. (2009) found that dam and reservoir construction since the 1950s has caused an average 44% decline in sediment supply to 33 of the world's major deltas. Anthropogenic reductions in sediment loads coupled with rising sea level are affecting sustainability of deltaic ecosystems worldwide (Giosan et al., 2014; Syvitski and Kettner, 2011; Syvitski and Milliman, 2007). An ambitious initiative to staunch the loss of deltaic wetlands in the Mississippi River Delta (MRD), 25% since 1932 (4900 km^2), is now underway in Louisiana (Couvillion et al., 2011). The MRD restoration "Master Plan" calls for at least two large (Q_{max}>2100 m^3 s^{-1}), controllable sediment diversions on the Lowermost Mississippi River (MR) downstream of New Orleans (Fig. 1). These will be gated channels passing through the banks and flood control levees to reintroduce water and sediment to adjacent, sinking wetland basins (Coastal Protection and Restoration Authority, 2012).

These projects are being sited and designed to divert suspended sand (>62.5 μm) at a concentration at least equivalent to that in the main stream. This is done to minimize downstream deposition in

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dredged reaches of the deep-draft MR navigation channel (Meselhe et al., 2012). By maximizing sand capture, diversion designers ensure that diverted silt and clay (mud<62.5 μm) will also be proportional.

Sand and mud passed through artificial outlets will serve different restoration purposes. The sand will build new deltaic platforms in shallow, open water near the diversion outlet (Coleman et al., 1998; Roberts et al., 2003), while the mud will travel farther into the receiving basin. There, newly introduced mud can be deposited and resuspended by waves until a portion is retained on vegetated surfaces during high astronomical and wind tides (Perez et al., 2000; Day et al., 2011; Twilley et al., 2016). Relatively minor additions of inorganic sediment neutralize toxic sulfides and stimulate build-up of a largely organic soil that can rapidly aggrade the marsh surface to keep up with relative sea-level rise (RSLR). RSLR is the combined displacement caused by eustatic rise and local subsidence (DeLaune et al., 2016). The effectiveness of diversions to build new land and save existing wetlands from submergence depends on the volume of sand and mud conveyed to the MRD from the interior of the continent (Fig. 1), and on its subsequent distribution throughout the MRD (Allison and Meselhe, 2010).

Allison et al. (2012) constructed an MRD sediment budget for both the mainstem MR and the Atchafalaya River (AR) distributary channel for three high-discharge years (2008–2010). The AR leaves the main MR course upstream of Baton Rouge at Old River at the upstream apex of the MRD (Fig. 1). It receives all of the Red River (RR) discharge, along with 20–25% of the water and sediment load carried by the MR from Natchez. Since 1963, the U.S. Army Corps of Engineers (USACE) has regulated this distribution daily to stop the progressive capture of MR mainstem flow by the shorter AR distributary (Reuss, 2004). The USACE manipulates flow through gated dams constituting the Old River Control Structure (ORCS) complex to maintain a latitudinal 70:30 split between the MR and AR/RR.

Allison et al. (2012) found that 44% of the average suspended sediment load entering the MRD (Mean $Q_{sed} = 228$ million metric tons per year, Mt y^{-1}) from the MR (193 Mt y^{-1}) and RR (35 Mt y^{-1}), was sequestered in overbank storage and channel bed aggradation inside the flood control levees. This sediment, 100 Mt y^{-1}, including 75 Mt y^{-1} of sand, found accommodation space in the interior of the sinking delta rather than on its periphery. So, only 56% of Q_{sed} during these high-discharge years could have been distributed to coastal wetlands outside the flood protection system, had the planned diversions been in operation. It might be inferred that a Q_{sed} of 100 Mt y^{-1} is the volume required just to maintain the alluvial portion of the MRD upstream of Baton Rouge and in the Atchafalaya Basin above Morgan City (Fig. 1).

The AR carried 62% of the 78 Mt y^{-1} of suspended sediment that, on average, reached the mouths of the two MR branches in the 2008–2010 water years (October 1-September 30). This sediment was conveyed by only 31% of the combined MR and RR mean water discharge (Q_{water}) of 745 km^3 y^{-1}. The sediment that reaches Atchafalaya Bay on the western side of the MRD has built two sand-dominant subaerial delta splays since first emergence in 1973. These now cover 200 km^2 of former bay bottom (van Heerden and Roberts, 1980; Roberts et al., 2003). Moreover, introduction of fine-grained sediment by the AR has created a submerged clay pro-delta deposit that extends many kilometers onto the inner continental shelf (Roberts et al., 2003).

Mud input from the AR has also prevented loss of an estimated 1400 km^2 of wetlands around Atchafalaya Bay over the past 80

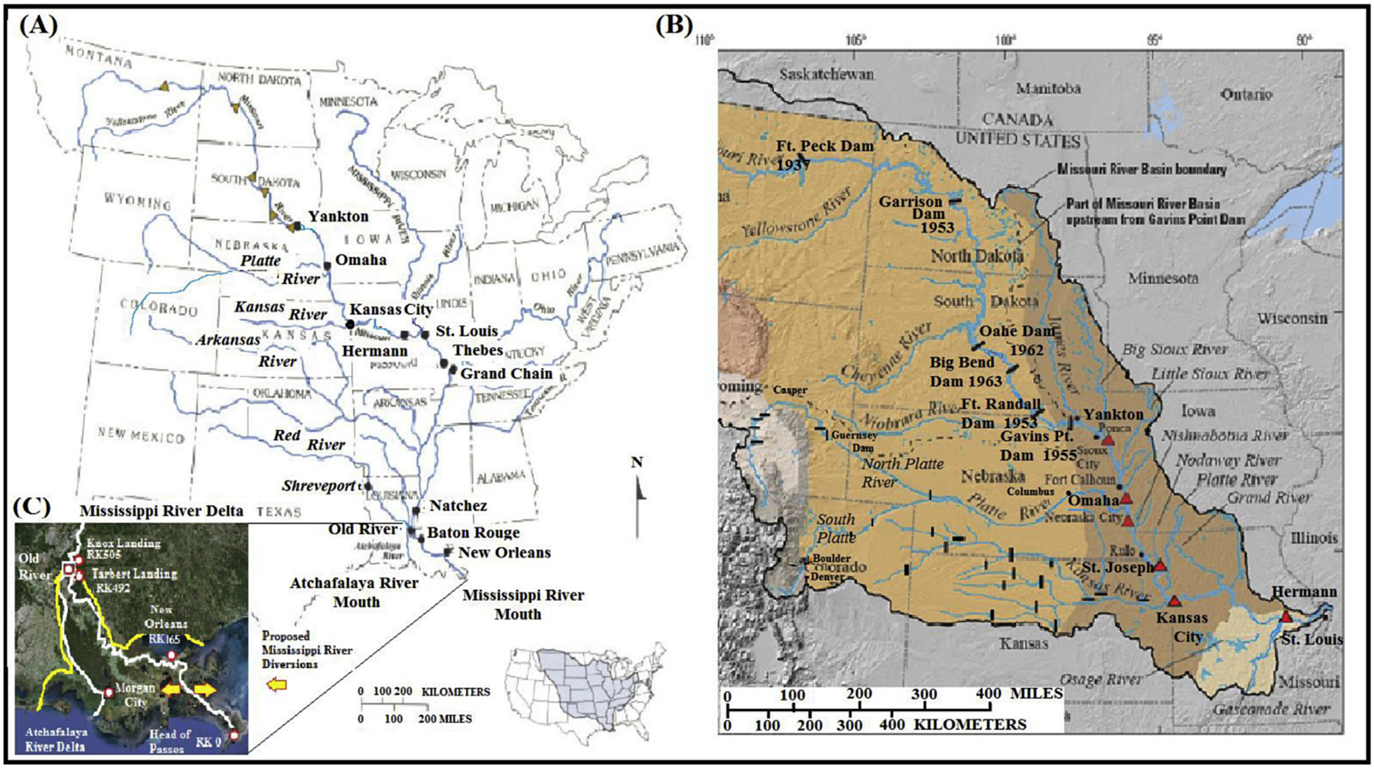

Fig. 1. (A) Mississippi River watershed with suspended sediment sampling stations, modified from Meade and Moody (2010). (B) Missouri River Basin showing some of the larger dams and USGS sediment sampling stations (red triangles), modified from Alexander et al. (2013). (C) MR Delta Plain (yellow line) and proposed large river diversion sites on the Lowermost MR (Coastal Protection and Restoration Authority, 2012). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

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years, despite an RSLR of 7 mm y^{-1} (Perez et al., 2000; Syvitski et al., 2009; Day et al., 2011; DeLaune et al., 2016; Twilley et al., 2016). Swamps and marshes south and east of New Orleans are, however, outside the beneficial influence of the Atchafalaya and are rapidly slipping below sea level, exposing much of the human population and economic infrastructure of the MRD to a greater risk of flooding during hurricanes (Kemp et al., 2014; Twilley et al., 2016).

Blum and Roberts (2009) estimated that 230–290 Mt y^{-1} is required to account for the volume of sediment deposited in the MRD over the past 6000 years. However, they also note that the requisite Q_{sed} rises to 345–435 Mt y^{-1} when a deltaic capture rate of 60% is imposed, similar to what Allison et al. (2012) measured for 2008–2010. This flux to the MRD is 100–200 Mt y^{-1} higher than the 2008–2010 mean (228 Mt y^{-1}), but Q_{sed} values of more than 500 Mt y^{-1} were measured at Tarbert Landing in the MRD (Fig. 2) as recently as the early 1950s (Keown et al., 1986; Kesel et al., 1992; Mossa, 1996; Kesel, 2003; Thorne et al., 2008; Meade and Moody, 2010; Kemp et al., 2014).

It is well established that MR Q_{sed} to the MRD has declined since the middle of the 20th century as flux from the Missouri River (MOR) has diminished, a change also seen to a lesser degree on the Upper Mississippi and other major MR tributaries (Arkansas and Ohio Rivers) (Heimann et al., 2011). Sediment interception has been attributed to 95 federal dams and reservoirs built as part of the Pick-Sloan Plan in the MOR Basin by the USACE and U.S. Bureau of Reclamation (USBOR) between 1950 and 1967 (Ferrell, 1993). Pick-Sloan added 5 large mainstem impoundments on the Upper MOR that virtually eliminated sediment yield from 629,000 km^2, or 53% of the 1.4 million km^2 MOR watershed (Fig. 1).

A National Research Council (2011) expert team explored whether the decline in MOR Q_{sed} could be reversed to bolster supply to MRD wetlands. But this analysis dealt only with the potential to bypass the Gavins Point Dam with sediment now accumulating in Lewis and Clark Lake, the smallest and lowest reservoir of those impounded by mainstem dams on the Upper MOR (Fig. 1). The team concluded that even complete removal of this dam would return only 6 Mt y^{-1} to the MOR/MR system. Recognizing the difficulties associated with bypassing the mainstem dams, we focus here on the opportunity to remobilize sediment stored behind smaller dams on tributaries to the Lower MOR.

2. Decline in Mississippi River sediment flux to the delta

The USACE monitors Q_{sed} 492 km above Head of Passes (RK492) on the MR at Tarbert Landing, just downstream of the AR diversion at Old River. This bifurcation forms the upstream apex of the MRD (RK505, Fig. 1). Q_{sed} and Q_{sand} (with Q_{mud} as the difference) have been calculated since 1950 by the USACE using data from isokinetic water samplers deployed on verticals over 90% of the cross-section as often as every 2-weeks (Meade and Moody, 2010). Little and Biedenharn (2014) found that this data set, with the exception of suspended sand for the 1986 to 1989 interval (excluded from our analysis), was methodologically consistent over the 63-year record (Fig. 2). Annual MR suspended sediment loads at Tarbert Landing have been calculated by a number of researchers for water or calendar years over different intervals using slightly different methods (Keown et al., 1986; Kesel et al., 1992; Mossa, 1996; Thorne et al., 2008; Meade and Moody, 2010; Heimann et al., 2011; Nittrouer and Viparelli, 2014; Rosen and Xu, 2014). For consistency, we have used Tarbert Landing water year sediment flux as it has been calculated by the U.S. Geological Survey (USGS) through 2013 (Heimann et al., 2010, 2011; USGS NWIS, 2015) (Fig. 2).

Mean Q_{water} at Tarbert Landing has experienced a small (50 m^3 s^{-1} y^{-1}), but significant ($p < 0.05$), increase over the 1950–2013 interval, so the decline in Q_{sed} is not explained by a drop in water discharge. Q_{water} supplied to the MRD since 1970 has averaged 20,148 m^3 s^{-1}, the sum of 14,820 at Tarbert Landing and 6060 m^3 s^{-1}, the mean combined annual flow of the AR and RR. Meade and Moody (2010) identified two temporally distinct linear trends in the Q_{sed} record at Tarbert Landing (Fig. 2). The first is a significant 14 Mt y^{-1} drop for 1950–1969 ($r^2 = 0.43$, $p < 0.05$) when the Pick-Sloan Plan was under construction. The second is a more gradual Q_{sed} decline since 1970 of 0.9 Mt y^{-1}. This trend is statistically significant ($p < 0.05$) but explains little of the variability ($r^2 = 0.11$). There was no significant trend in Q_{sand} during either the 1950–1969 or 1970–2013 intervals. Thus, the only significant

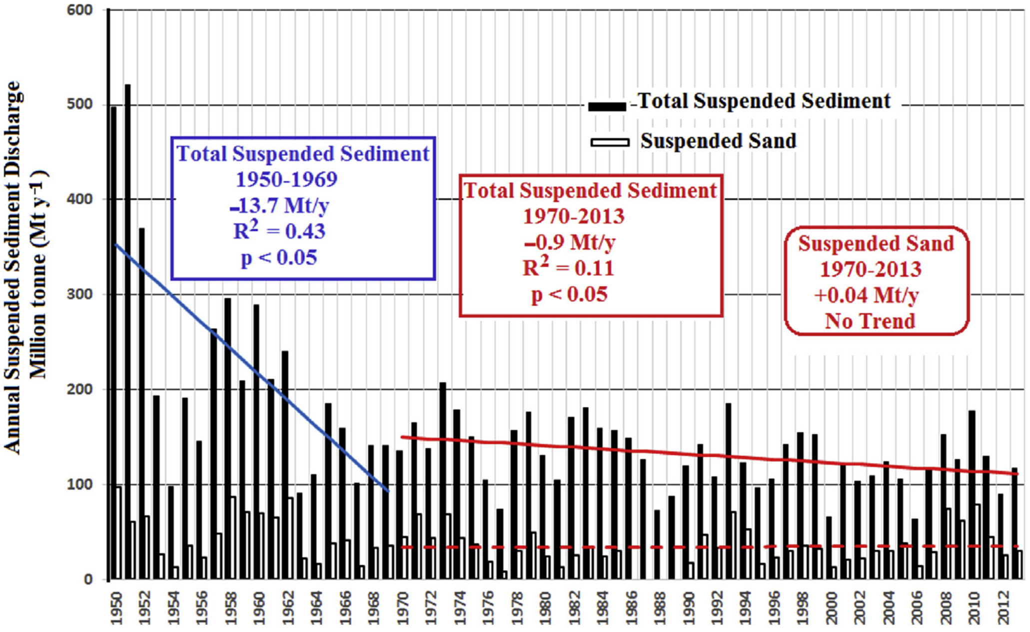

Fig. 2. Annual total suspended sediment and suspended sand loads in the Mississippi River at Tarbert Landing with trends 1950–1969 and 1970–2013, modified from Meade and Moody (2010).

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changes in Q_{sed} at Tarbert Landing for both periods are caused by decreases in Q_{mud}.

Nittrouer and Viparelli (2014) recently added an analysis of MR suspended sediment trends (1970–2012) at Thebes, Illinois (RK1602), just above the Ohio River confluence and 300 km downstream of the MOR entrance at St. Louis (RK1915) (Fig. 1). MR Q_{water} and Q_{sed} at Thebes averaged 29% and 67% of annual water and sediment fluxes at Tarbert Landing, respectively (Nittrouer and Viparelli, 2014). The post-1970 decrease in Q_{sed} at Thebes (1.0 Mt y^{-1}) is similar to that at Tarbert Landing. Nittrouer and Viparelli (2014) used the Thebes and Tarbert Landing data to calibrate a numerical model of river morphodynamics for the 1000 km between these sampling stations. They conclude that Q_{sand} on the MR at these two stations has not changed significantly in 40 years. The model predicted that sand supply through the alluvial valley to the head of the MRD was unlikely to decrease for centuries (200–800 years).

The drop in Q_{sed} on the MOR after 1952 was precipitous, as is apparent in the record from Omaha, Nebraska, more than 300 km downstream of the Gavins Point Dam (Fig. 3). But this shift also affected same year suspended sediment transport 1000 km downstream at Hermann, Missouri, the last sampling station above the Mississippi confluence at St. Louis, as well as 2700 km downstream on the MR at Tarbert Landing (Fig. 1). Q_{sed} at Hermann is significantly ($p < 0.01$) correlated with Q_{sed} at Tarbert Landing for the entire 1950–2013 period of record, explaining 71% of the variability (Fig. 4). Q_{sed} at Hermann and Tarbert Landing have almost a 1:1 correspondence. The high degree of Q_{sed} correlation between Hermann and Tarbert Landing indicates that input or deposition of suspended sediment to the MR other than from the MOR is limited. Kesel (2003) and Meade and Moody (2010) have attributed the diminishment of non-MOR sediment sources to adoption of soil conservation practices by farmers, and by USACE build-out of channel stabilization and training structures (revetments and dikes) on the MR in the 1950s and 1960s. These measures have effectively stopped MR meandering and bank caving.

Q_{sed} additions from the Upper Mississippi (above St. Louis), as well as the Ohio and Arkansas Rivers, averaged 60 Mt-y^{-1} (1976–2009) but must be reduced by the suspended sediment leaving the MR at Old River (34 Mt-y^{-1}) to compare with MR flux at Tarbert Landing (Heimann et al., 2011). The residual (26 Mt y^{-1}) accounts for 38% of the 68 Mt y^{-1} higher mean annual flux at Tarbert Landing compared to Hermann (Fig. 4). Q_{sed} from within channel, rather than tributary sources, then, averages 42 Mt y^{-1}, or 34% of suspended sediment flux to the mainstem MR in the MRD. The drop in total suspended sediment at Hermann 1970–2013, 0.9 Mt y^{-1}, is the same as at Tarbert Landing though it is not statistically significant. A decrease of 0.4 Mt y^{-1} in Q_{sand} at Hermann, however, is significant ($p < 0.01$) for the same interval.

It is likely that most of the sedimentary material deposited over the last 6000 years in deltaic lobes of the MRD is mud and sand that originated in the MOR basin (Blum and Roberts, 2009; Coleman et al., 1998; Tornqvist et al., 1996). Q_{sand} from the MOR to the MR is decreasing, but Nittrouer and Viparelli (2014) have shown that this supply limitation does not yet appear to be affecting sand supply as far downstream as the MRD. If the supply of sand to the MRD from the alluvial valley were dropping, as will happen at some point, reversing this trend would take centuries (Nittrouer and Viparelli, 2014). On the other hand, an increase in suspended mud supply from the MOR would reach the MRD almost immediately, on the same time-scale as the original reduction (Fig. 3).

If mud supply to the Mississippi from the Missouri River (MOR) basin could be augmented, the ongoing decline in suspended sediment flux to the delta might be reversed or stabilized within 1–2 decades. More mud would enhance the effectiveness of all river diversions, but particularly improve sediment transport through simple overbank spillway structures because suspended mud is more uniformly distributed in the fluvial water column than sand (Meselhe et al., 2012). Next, we discuss where the missing

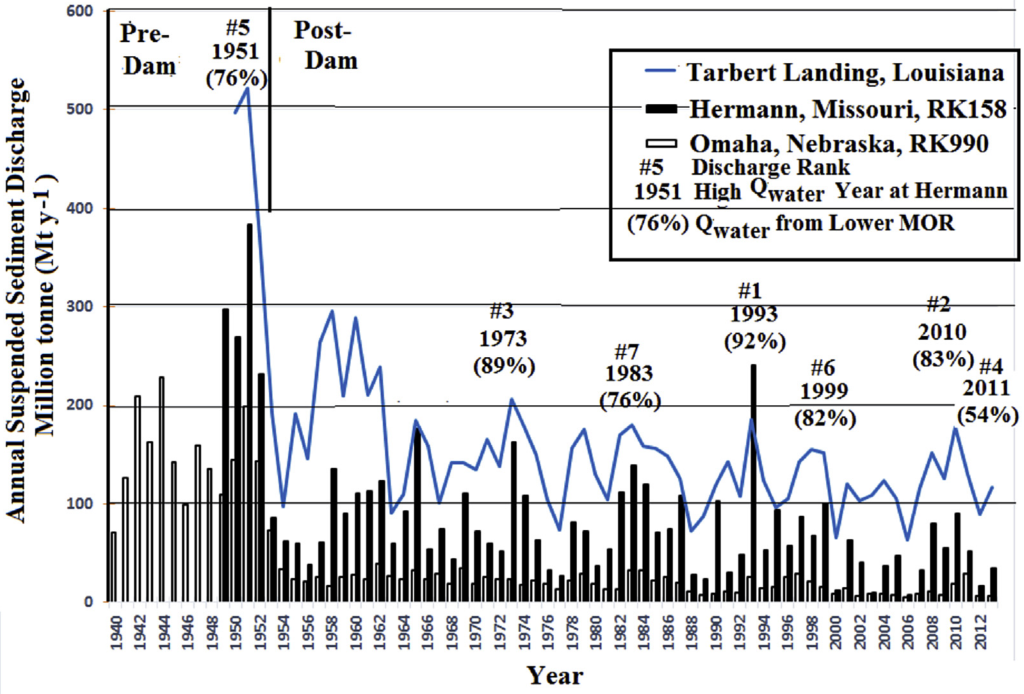

Fig. 3. Total annual Q_{sed} on the MOR at Omaha and Hermann and at Tarbert Landing on the Mississippi River. Rank and year of highest floods on the MOR showing percent of flow at Hermann from Upper MOR.

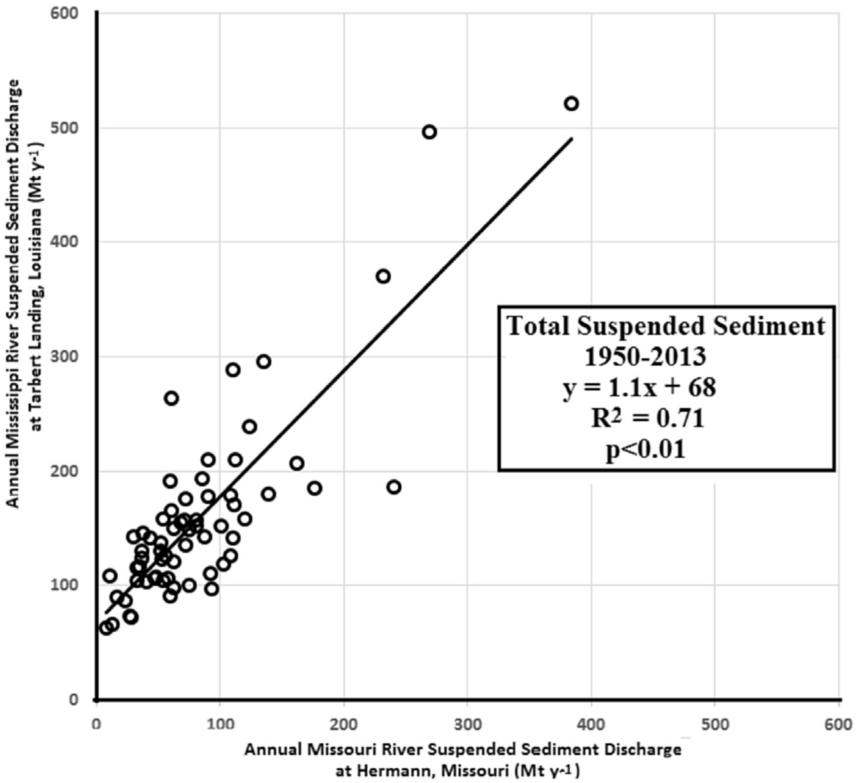

Fig. 4. Significant linear correlation between Mississippi River Q_{sed} at Tarbert Landing, Louisiana, and Missouri River Q_{sed} at Hermann, Missouri 1950–2013.

mud is now, and, more importantly, how much might be returned to the MR soon enough to save the MRD.

3. Potential to restore mud supply

The MOR has historically delivered more sediment to the MRD than any other tributary even though its flow is only 12% of MR mean flow above Old River (Table 1). The mean annual MOR discharge, 2400 $m^3\ s^{-1}$, is not much more than the projected maximum conveyance of either of the two large diversions planned for the Lowermost MR (Fig. 1). After closure of the Gavins Point Dam, mean discharge decreased from the Upper to Lower MOR at Yankton, South Dakota, by 25% (Table 1). Concerted Upper MOR dam operations lowered peak spring discharge from snowmelt while providing additional flow in late summer and fall for a 6–8-month navigation season on the Lower MOR, from St. Louis to Sioux City (Jacobson and Galat, 2008).

Regular measurements to calculate Q_{sed} started in 1940 at Yankton and Omaha (Fig. 3). Otherwise, few pre-1950 estimates of annual sediment flux exist on the MOR or MR systems (Heimann et al., 2011). Given that the post-dam era began in 1953, only 3–4 years of pre-dam data are generally available at long-term stations. These pre-dam years include 1951, the fifth highest MOR flood year since 1950, with a Q_{water} that has since been exceeded only in 1973, 1993, 2010 and 2011.

Since the mainstem and tributary Pick-Sloan dams were installed, Q_{sed} at Hermann has decreased by 80% (Table 1). This decrease was echoed at Tarbert Landing in a 76% drop. Today, water from the Upper MOR only dilutes the suspended sediment load contributed by downstream tributaries. Q_{sed} passing Hermann in 2011 was just 52 Mt compared to 163 Mt in 1973 for a similar Q_{water} because the flow fraction sourced from the Upper MOR was much greater in 2011 (46%) than in 1973 (11%) (Fig. 3).

So, where did the mud go? Some of it, about 122 Mt y^{-1}, is

Table 1
Pre- and Post-Dam Mean and (σ) Q_{water}, Q_{sed} and Q_{sand} on the Lower MOR, and at Tarbert Landing, Louisiana, on the MR showing Suspended Sediment Added by Tributaries between Sampling Stations.

Discharge range	Mean annual discharge 1948–1952	Mean annual discharge 1970–2013	Pre-dam 1948–1952				Post-dam 1970–2013			
			Total suspended load		Sand load	Sand	Total suspended load		Sand load	Sand
Location	($m^3\ s^{-1}$)	($m^3\ s^{-1}$)	(Mt y^{-1})			%	(Mt y^{-1})			%
Yankton	1006 (120)	756 (247)	122 (27)	+122	nd	nd	0.2 (0.0)	+0	0.01	3
Omaha	1164 (145)	1027 (324)	147 (33)	+23	nd	nd	17 (8)	+17	11 (5)	65
St. Joseph	1572 (229)	1401 (427)	234 (47)	+87	60 (13)	26	39 (26)	+22	14 (8)	36
Kansas City	2012 (406)	1671 (529)	297 (102)	+63	44 (7)	15	47 (30)	+8	22 (5)	47
Hermann	3056 (622)	2621 (893)	296 (64)	+/−?	58 (10)	20	67 (44)	+20	20 (13)	30
Tarbert Landing	17,320 (1757)	14,820 (3107)	463 (81)	+167	75 (19)	16	131 (34)	+64	36 (18)	27

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retained behind the main stem Upper MOR dams (Jacobson et al., 2009) constructed under the Pick-Sloan Plan (Table 1). Meade and Moody (2010) note, however, that this loss accounts for only 41% of the reduction from pre-to post-dam suspended sediment flux at Hermann (Table 1). The majority of MOR suspended sediment has always come from the Lower MOR. An additional 173 Mt y^{-1} of the 297 Mt y^{-1} pre-dam flux once came largely from the Platte and Kansas Rivers that enter the MOR downstream of Omaha, Nebraska, and at Kansas City, Missouri, respectively. Today, these and all other Lower MOR tributaries, on average, contribute only 67 Mt y^{-1}. So, in addition to what is being retained in Upper MOR reservoirs, another 100 Mt y^{-1} that once reached the MOR/MR system is now being trapped by dams within the watersheds of Lower MOR tributaries during normal discharge years.

The Platte and Kansas River watersheds occupy 27% of the MOR basin (Alexander et al., 2013). Together, they once contributed more than 800 m^3 s^{-1} to Lower MOR discharge, but today add less than 500 m^3 s^{-1} (Heimann et al., 2011). The Platte River is heavily used for water supply and irrigation in the arid region from Denver, Colorado (South Platte) and Casper, Wyoming (North Platte) east to Columbus, Nebraska, at the downstream end of the Platte's Big Bend (Fig. 1). More than 80% of the water delivered by the Platte to the Lower MOR comes not from the far west, but from dammed eastern tributaries like the Loup and Elkhorn Rivers. The Loup enters the Platte at Columbus (Fig. 1), 160 km above the MOR confluence below Omaha, while the Elkhorn River comes in only 52 km upstream of the confluence (Platte River Recovery Implementation Program, 2015).

An average of 1000 m^3 s^{-1} flows into the Lower MOR downstream of Kansas City (Table 1). The Osage and Gasconade Rivers, west bank tributaries that rise in the sediment poor Ozark Plateau south of Hermann (Fig. 1), contribute about half of this discharge, but little sediment. In contrast, the Grand River, an east bank tributary – and the only one that has not been dammed – has a mean discharge of only 194 m^3 s^{-1} but today contributes an average of 10 Mt y^{-1} of suspended sediment to the Lower MOR, more than either the Platte or Kansas Rivers in an average year (Heimann et al., 2011).

Heimann et al. (2010) reported 2.8 g l^{-1} as the 1975–1991 median streamflow-weighted suspended sediment concentration for the Grand River, which is similar to pre-dam values on most of the Lower MOR tributaries draining loess deposits. Streamflow-weighted suspended sediment concentrations for the Platte River near Omaha still average 1.3 g l^{-1}, but this is less than half the pre-dam concentration (Blevins, 2006).

The highest annual Q_{sed} in the 1970–2013 record at Hermann and Thebes, and second highest at Tarbert Landing (Horowitz, 2006, 2010), occurred in 1993 (Fig. 3). Thebes Q_{sed} for this year was 364 Mt y^{-1}, higher than any suspended sediment flux reported at Tarbert Landing since the 1950s (Nittrouer and Viparelli, 2014). MOR Q_{water} was also highest in 1993, but this discharge was only 30% greater than in the 1951 water year. Annual Q_{water} in 1951 and 1993 were similar as far downstream as Kansas City (RK584). This similarity makes it possible to estimate how much of the 1951 sediment load was trapped by dams on Lower MOR tributaries in 1993 (Table 2). Q_{sed} at Kansas City in 1951 was 300 Mt higher than in 1993, of which only 100 Mt came from the pre-dam Upper MOR. An estimated 100 Mt entered above Omaha in 1951 from now dammed east bank tributaries like the Big and Little Sioux Rivers, compared with 26 Mt in 1993, indicating retention of 74 Mt (Table 2). Yet another 100 Mt was added primarily by the Platte River, but also by now dammed east bank tributaries above St. Joseph (Nishnabotna and Nodaway Rivers) in both 1951 and 1993, with little apparent retention. The Kansas River and the "Missouri Platte," a small east bank tributary, added 150 Mt at Kansas City in 1951, but only 25 Mt in 1993, suggesting retention of 125 Mt in this reach.

Tributaries between Kansas City and Hermann (Grand, Osage and Gasconade Rivers) added an unknown amount of suspended sediment to the MOR in 1951 because some was lost to deposition on the floodplain before reaching Hermann (Table 2). In 1993, these tributaries added almost 100 Mt and possibly more (Holmes, 1996). It is known from suspended sediment measurements on the undammed Grand River tributary that this east bank stream contributed 90 Mt in 1993, about 15 Mt more than the Platte (Heimann et al., 2010). If we assume that a similar amount of sediment was conveyed past Kansas City in both flood years, at least 200 Mt was retained by dams on all tributaries to the Lower MOR in 1993 that would otherwise have reached the MR, in addition to 100 Mt deposited in Upper Missouri reservoirs.

Thus, sediment storage in reservoirs on tributaries to the Lower MOR has ranged from 100 Mt y^{-1} in average years to 200 Mt y^{-1} during major flood years, since construction of the Pick-Sloan dams. Retained sediment is still mobilized during large floods as it was in 1993 despite the reservoir storage infrastructure (Perry, 1994). This raises the possibility that coordinated releases of trapped mud from Lower MOR tributary basins could restore 100 to 200 Mt y^{-1} of suspended silt and clay to the MR and ultimately the MRD.

As mentioned above, the National Research Council (2011) Committee on Missouri River Recovery and Sediment Management examined the potential to flush sediment around the Gavins Point Dam, or remove it altogether. Lewis and Clark Lake, the reservoir created by this dam, receives the entire sediment load of the Niobrara River (Fig. 1), and has already lost more than 25 percent of its water storage capacity (Coker et al., 2009). But because Lewis and Clark Lake is only the last and smallest main-stem sediment trap in a series of reservoirs, the Committee found that regular flushing, or even removal of the dam, would likely yield only 6 Mt y^{-1} in additional sediment. This would do little to improve habitats for the three endangered species that are driving re-naturalization efforts on the Upper and Lower MOR, or reduce wetland loss in the MRD (Jacobson and Galat, 2008).

Sediment flushing around smaller dams is demonstrated routinely at Spencer Dam on the Niobrara River just upstream of Lewis and Clark Lake (National Research Council, 2011). The reservoir of this run-of-the-river hydroelectric power dam is drained each spring and fall to re-establish fluvial processes, which then move sediment below the dam to final deposition in Lewis and Clark Lake (Gutzmer et al., 2002). Similar annual "silt runs" are scheduled in the fall for Guernsey Lake reservoir (Fig. 1) and at other dams on the North and South Platte in Wyoming and Colorado. These structures were built before authorization of the Pick-Sloan Plan and were designed to be flushed in this way (U.S. Bureau of Reclamation, 2011).

Where flushing is infeasible or not pursued for other reasons, alluvial rivers adapt to trapping of sand in impoundments by eroding sediment from the bed downstream of the dam, causing channel incision (Galay, 1983; Williams and Wolman, 1984). One to 4 m of degradation has entrenched the Lower MOR downstream of the Gavins Point dam. This has reduced connectivity between the river and the floodplain for nearly 300 km (Jacobson et al., 2009), but has helped to confine the once wide (up to 2000 m) and shallow Lower MOR to a narrow (300 m) 3 m deep navigation channel (Pinter and Heine, 2005). About 800 of the 1300 km of the Lower Missouri has experienced significant channel degradation. This scour has been an important post-dam source of suspended sand in the Lower MOR (Heimann et al., 2011), and a reason that annual Q_{sand} at Hermann has dropped only 66% since 1953, compared to 80% for Q_{mud} (Table 1).

The general pattern of Lower MOR degradation is reversed,

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Table 2
Suspended sediment discharge on lower MOR between Gavins Point Dam and MR confluence during the 1951 and 1993 flood years showing tributary contributions by MOR reach.

Discharge range	Distance from Mississippi river	Mean annual Q_{water} 1970–2013	Pre-dam 1951 flood				Post-dam 1993 flood			
			Q_{sed}		Q_{sand}	Q_{water}	Q_{sed}		Q_{sand}	Q_{water}
Location	(km)	($m^3 s^{-1}$)	(Mt y^{-1})			($m^3 s^{-1}$)	(Mt y^{-1})			($m^3 s^{-1}$)
Yankton	1299	756	98	+98	nd	937	1	+1	nd	583
Omaha	990	1027	199	+102	nd	1219	26	+25	12	1030
St. Joseph	721	1401	302	+103	52	1712	123	+97	20	1896
Kansas City	584	1671	448	+146	47	2570	148	+25	nd	2887
Hermann	158	2621	384	−64	63	3934	240	+92	58	5150
Tarbert Landing	*From Hermann* 1073	14,820	522	+138	61	17,433	186	−54	71	20,687

however, at the confluence of the Platte River below Omaha, and for 200 km downstream (Fig. 1). The floodplain there is aggrading due to deposition during overbank flooding that occurs in this reach as frequently as every other year, on average, often breaching low levees protecting agricultural lands (Jacobson et al., 2009). After a second degrading reach, another 200 km of aggradation is observed downstream of the Kansas River entrance at Kansas City.

The North and South Platte join to form the lower Platte 526 km upstream of the MOR confluence south of Omaha. Natural flow of the Platte River has been much modified by storage reservoirs, power development, groundwater withdrawals, diversions for irrigation, and return flow from irrigated areas. Although the Pick-Sloan Plan resulted in construction of multiple dams on the North and South Platte and on several tributaries to the Kansas River, the mainstems of these rivers have not been blocked except by relatively low-impact, run-of-the-river dams.

Costigan and Daniels (2012) found that the highest flow continues to occur during April with snow melt, and in June and July associated with convective thunderstorms along frontal boundaries. Because the impoundments on the Kansas and Platte Rivers are confined to the tributaries, the hydrologic regime is competent to convey more sediment to the Lower MOR if this material is allowed past the dams. The Lower MOR, in contrast, has seen a 61 percent reduction in the 7-day maximum discharge as flow from the Upper MOR is distributed more uniformly over the year (Costigan and Daniels, 2012).

4. The Missouri River recovery program

There are federal and state partnerships in place to “restore” habitat on the Missouri, Kansas and Platte Rivers, as well as in the MRD. These fluvial systems are alike in that native plant and animal species of each were adapted to very high pre-dam suspended sediment loads. It is not surprising that populations of some native species have declined in the MOR basin as shallow, muddy streams have been replaced with deep, clear water lakes. The U.S. Fish and Wildlife Service (USFWS) has issued several Biological Opinions (BiOps) since 2000 for the MOR and Kansas Rivers, as well as for the Platte River, as is required under the Endangered Species Act. One BiOp mandated that the USACE initiate a Missouri River Recovery Program (MRRP) to avoid extirpation of the endangered pallid sturgeon (*Scaphirhynchus albus*), while also supporting increases in populations of two sandbar nesting birds, the threatened piping plover (*Charadrius melodus*) and endangered interior least tern (*Sternula antillarum athalassos*).

Despite explicit mention of “operation of the Kansas River reservoir system” in the title of the BiOp establishing the MRRP, changes in reservoir management on the Kansas River have yet to be proposed or adopted. The most recent annual reports of the MRRP prepared by the USACE (2013, 2015) mention no projects in the Kansas River drainage beyond biological monitoring. The Platte River has seen more activity on recovery with the signing of a Final Program agreement by the U.S. Secretary of the Interior and the Governors of the states of Colorado, Wyoming and Nebraska in 2006 (Anderson and Rodney, 2006). This compact led to establishment of the Platte River Recovery Implementation Program (PRRIP) in 2007. An updated Water Action Plan approved in 2010 calls for increasing the availability of water for environmental purposes by putting conservation measures in place, shifting water supply away from the Platte River, and coordinating releases from dams to create bank-full pulses in the spring (Platte River Recovery Implementation Program, 2010).

The Lower Platte River is currently an important refugium for the three species mentioned in the BiOp that led to the MRRP, while the Central Platte provides critical habitat for the endangered Whooping Crane (*Grus americana*). A key objective of the PRRIP is to use controlled floods to enhance critical, unvegetated sandbars that are high enough to allow nesting birds to raise their young before nests are washed away. Management for this purpose will also increase suspended sediment delivery to the Lower Platte and MOR, which is another goal of the PRRIP.

The Master Plan guiding the MRD restoration program acknowledges diminishment of MR suspended sediment supply, but this awareness has not yet led to any official effort to reverse this trend (Coastal Protection and Restoration Authority, 2012). Rather, current MR Q_{mud} is treated as a hard boundary constraint, when it could be regarded as a policy choice that might be altered as national river management priorities change over time (Bentley et al., 2014).

5. Conclusions

The MRD is currently undergoing a rapid shrinking of deltaic wetland area, having lost nearly 5000 km^2 to open water since 1932 (Couvillion et al., 2011). Much of this loss occurred as a consequence of the severing of the MR from its sinking delta by flood control levees, as well as through disruption of estuarine hydrology by dredging of navigation and oil/gas/pipeline channels (Day et al., 2007; Kemp et al., 2014). Reconnecting the MR to its delta with engineered diversions assumed a greater urgency, however, after the flooding of New Orleans during Hurricane Katrina in 2005 (Coastal Protection and Restoration Authority, 2012).

Sand transport to the Mississippi River Delta (MRD) remains sufficient to build wetlands in shallow, sheltered coastal bays fed by engineered diversions on the Mississippi River (MR) and its Atchafalaya River (AR) distributary (Nittrouer and Viparelli, 2014). But suspended mud flux to the coast has dropped from a mean of 390 Mt y^{-1} in the early 1950s, to 100 Mt y^{-1} since 1970. This fine-grained sediment travels deeper into receiving estuarine basins and plays a critical role in sustaining existing marshes. Virtually all of the 300 Mt y^{-1} of missing mud once flowed from the Missouri River (MOR) Basin before nearly 100 dams were built as part of the Pick-

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Sloan water development project after it was authorized by the U.S. Congress in 1944. About 100 Mt y^{-1} is now intercepted by mainstem Upper MOR dams closed in 1953. But the remaining 200 Mt y^{-1} is trapped by impoundments built on tributaries to the Lower MOR in the 1950s and 1960s.

Sediment flux during the post-dam, high MOR discharge years of 1973, 1993 and 2011 approached pre-dam levels when tributaries to the Lower MOR, including the Platte and Kansas Rivers, contributed to flood flows. West bank tributaries drain a vast, arid part of the Great Plains, while east bank tributaries traverse the lowlands of the MOR floodplain. Both provinces are dominated by highly erodible loess soils.

Historically, dam bypassing projects tend to be delayed until reservoir storage is significantly reduced, with less attention paid to ongoing destruction of downstream river ecosystems, delta habitat, and populations of endangered species (Graf, 2005). Any proposal to change dam management is inherently controversial. Downstream advocates of ecosystem restoration may see modification of existing dam infrastructure and operations, up to and including complete removal, as correcting a mismatch between outdated practice and what is needed today. Traditional stakeholders may, in contrast, view efforts to change dams or their operations for environmental reasons as interfering with local control or sacrificing local benefits, on which they depend, for downstream improvements that they never see.

Tributary dam bypassing in the Lower MOR basin could increase mud supply to the MRD by 100–200 Mt y^{-1} within 1–2 decades. Such emergency measures to save the MRD are compatible with objectives of the Missouri River Restoration and Platte River Recovery Programs to restore MOR riparian habitat for endangered species. Rapid mobilization to shunt fine-grained sediments past as many as 50 Lower MOR tributary dams in several U.S. states will undoubtedly require more regional coordination and funding in the 21st century than the monumental effort it took to build the dams in the last century.

Q_{mud} at Tarbert Landing responds in a muted way to occasional spikes of suspended sediment introduction during Lower MOR floods. Meade and Moody (2010) point out, however, that increasing mud transport to the MRD will require a sustained higher flux from the Lower MOR to also replenish short-term sediment storage along the MR. The next steps are to determine how much of the missing sediment is stored within each impoundment, and the feasibility of flushing each without major retrofitting. Adding 100 Mt y^{-1} may be an achievable near-term goal, and would nearly double fine-grained sediment transport in the MR at Tarbert Landing (Fig. 2).

Those engaged in MRD restoration are just beginning to focus on increasing mud delivery to the MRD. The relative “reversibility” of a decline in fine-grained sediment transport to the coast, in contrast to a more lagged response for the sand fraction, is characteristic of most regulated rivers and relevant to delta management initiatives worldwide. Kondolf et al. (2014) draw on experience from 5 continents to show the diversity of techniques now being used to pass sediments through or around reservoirs. If the 20th Century was characterized by dam building, the 21st will witness the rise of dam bypassing, not only to preserve reservoir functionality, but to also improve downstream riparian habitat and save deltas.

The Genissiat Dam on the Rhone River in France provides an instructive example of what is possible. Upstream, Swiss dam operators routinely flush reservoirs in the Alps during large floods to maintain hydroelectric power generation capacity. This can result in downstream flows with sediment concentrations of more than 40 g l^{-1} (Peteuil et al., 2013). French authorities not only have to pass this sediment through the reservoir but also dilute concentrations transmitted downstream. They use high and low dam outlets to simultaneously release clear water from the surface of the reservoir along with the sediment charged flow at depth. The end result is that natural, and still large, suspended sediment loads are conveyed to the Rhone Delta, allowing coastal wetlands there to aggrade with sea level rise, without causing ecologically destructive levels of sedimentation within the river itself (Pont et al., 2002; Peteuil et al., 2013).

Where multiple tributaries enter below large mainstem dams, as is the case on the Lower MOR, an initial focus on systematically enhancing fine-grained sediment flux from smaller tributary dams may be a good start to improving the sustainability of deltas during a time of accelerating sea level rise. Such an approach is not feasible in other systems like the Ebro and Nile Rivers where large mainstem dams have been constructed downstream of all major tributaries (Stanley, 1988; Stanley and Warne, 1993; Ibañez et al., 1996). Kondolf et al. (2014) have shown, however, that it may still be possible to manage fine-grain sediment release by changes in dam operation that maximize throughput and minimize residence time when upstream sensors indicate arrival of sediment-charged water (Lee and Foster, 2013).

A number of deltas, including the Nile and Ebro, have sophisticated water distribution systems developed over many centuries for agricultural purposes that can also serve to spread sediment introduced by more ecosystem-friendly upstream dam management (Ibáñez et al., 2010). Trapping of suspended sediments in the Danube delta through an extensive network of man-made fishing channels, has kept the delta plain rising in sync with sea level (Giosan et al., 2013). In the MRD, however, channels were dredged for navigation and energy extraction without awareness of, or concern for, the underlying delta hydrology. MRD deterioration is so rapid that an engineered system of constructed river diversions, in addition to added mud from the MOR/MR, will be required just to sustain a fraction of the existing deltaic landmass as sea level rises (Coastal Protection and Restoration Authority, 2012). Rapid mobilization to shunt fine-grained sediments past as many as 50 Lower MOR tributary dams in several U.S. states will require as much regional coordination and funding in the 21st century as the monumental effort it took to build the Pick-Sloan Plan in the last century.

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