Are riverine sediment discharges sufficient to offset the sinking coast of Louisiana?

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Abstract The Mississippi River and four other major rivers along Louisiana's coast (USA) discharge a combined total of 620 km^3 of water annually into the Gulf of Mexico. In addition to the vast quantity of freshwater, these river systems carry substantial sediments that affect physical, biological and human domains in the northern Gulf of Mexico. In the past century, river engineering and land use practices in the river basins have changed dramatically. A large number of locks and dams were built along the major tributary rivers including the Upper Mississippi River, Illinois River, Missouri River, Ohio River, Tennessee River, Arkansas River, and Red River, which has greatly contributed to the reduction in sediment yield to the continental shelf of the northern Gulf of Mexico. Concurrently, Louisiana's coast has experienced the highest rate of relative sea-level rise of any region in the USA. In the past 50 years land loss rates along Louisiana's coast have exceeded over 60 km^2 $year^{-1}$, and in the 1990s the rate has been estimated to be between 40 and 56 km^2 $year^{-1}$. This change represents 80% of the coastal wetland loss annually in the entire continental USA. The highest relative sea-level rise is 17.7 mm $year^{-1}$ at Calumet, Louisiana, compared to 6.3 mm $year^{-1}$ at Galveston, Texas, 1.5 mm $year^{-1}$ at Biloxi, Mississippi, and 2.3 mm $year^{-1}$ at Pensacola, Florida. Riverine sediments are precious resources to coastal Louisiana, and their effective management is of long-term strategic importance. This paper reports combined sediment yields from two major distributaries of the Mississippi River and four major coastal rivers in Louisiana for the most recent three decades, and discusses the actual availability of sediment and a new diversion approach – controlled overbank flow – that mimics the natural process of sediment replenishment over large areas.

Key words riverine sediment; TSS yield; Mississippi-Atchafalaya River; coastal Louisiana, USA

INTRODUCTION

The global average sea level has risen from 1961 to the present time at an average rate of 1.8 mm per year, ranging from 1.3 to 2.3 mm (IPCC, 2007). The rise rate was found to be faster for the recent decade, averaging about 3.1 mm per year with a range between 2.4 and 3.8 mm. The Louisiana coast of the northern Gulf of Mexico has experienced one of the highest sea-level rises over the past century (Dixon *et al*., 2006; Ivins *et al*., 2007). Within the last 50 years land loss rates have exceeded 60 km^2 per year, and in the 1990s the rate has been estimated as between 40 and 56 km^2 each year. This loss represents 80% of the coastal wetland loss annually in the entire continental United States. The highest relative sea-level rise (RSLR) is 17.7 mm per year at Calumet station in St. Mary's Parish of Louisiana, according to the US Army Corps of Engineers tide gauge stations (Penland & Ramsey, 1990) compared to 10.4 mm per year at Grand Isle, Louisiana, 6.3 mm per year at Galveston, Texas, 2.3 mm per year at Pensacola, Florida, 2.2 mm per year at Key West, Florida, 1.7 mm per year at Cedar Key, Florida, 1.5 mm per year at Biloxi, Mississippi, and 3.1 mm per year eustatic sea-level rise.

Based on their assessment using long-term historical aerial photos and satellite images, Morton *et al.* (2010) found that much of the land loss in coastal Louisiana is caused by land subsidence, rather than erosion. While the land has been sinking and the sea level has been rising, sediment yields from the Mississippi River and four other major coastal rivers in southern Louisiana have been declining (Horowitz, 2010; Rosen & Xu, 2011). River engineering has confined sediment distribution to only the continental shelf of the northern Gulf of Mexico. Consequently, the Louisiana Gulf coast has been subject to the highest rate of relative sea-level rise of any region in the USA. Couvillion *et al*. (2011) found that approximately 4900 km^2 of low-lying coastal land on Louisiana's delta plain have become submerged since 1932. Previous studies (Britsch & Dunbar, 1993; Barras *et al*., 2003) reported peak delta-plain land losses of 60–75 km^2 each year from the 1960s to the 1980s.

Although much of Louisiana's coastline is eroding and sinking, the mouth of the Atchafalaya River has been gaining land since the early 1970s. The river is the largest distributary of the Mississippi River and currently carries about 25% of the Mississippi's waters into the Gulf of Mexico. Several researchers (Shlemon, 1975; Rouse *et al*., 1978) reported their observations of the early subaerial delta development in the shallow Atchafalaya Bay after the 1973 flood. In the past two decades, a number of studies were conducted to investigate sedimentary processes in the Atchafalaya Bay area (e.g. Wells *et al*., 1984; Roberts *et al*., 1987; Huh *et al*., 1991; Draut *et al*., 2005). These studies mainly focused on nearshore sedimentation rates, stratification, and sediment composition. They often quantified sediment input from the river system with early records of river discharge and sediment concentrations, which may not accurately represent the current condition of sediment transport in the Atchafalaya River. Furthermore, most of these studies used flow and sediment data collected at Simmesport, which is located near to the beginning of the 187-km-long Atchafalaya River basin. Hupp *et al*. (2008) used clay pads at several transects within the basin and found a sedimentation rate ranging from about 2 to 42 mm/year. In a spatial sedimentation analysis with the river's sediment inflow–outflow, Xu (2010) recently reported average sediment retention of 6 MT (or 9%) annually in the basin. The results of these studies imply that a large quantity of the riverine suspended sediment will not reach the continental shelf.

Riverine sediment is a precious resource to coastal Louisiana and its effective management is of long-term strategic importance. This paper synthesizes recent work and newly-derived estimates of sediment delivery from six major rivers along Louisiana's coast. The purpose is to address the question of whether the quantity of the riverine sediment is sufficient to offset the sinking coast.

COASTAL LOUISIANA AND MAJOR RIVER SYSTEMS

Coastal Louisiana is divided into two distinctive physiographic regions: the Chenier Plain in the west and the Mississippi-Atchafalaya River Delta in the east (Fig. 1). The Chenier Plain comprises an area of approximately 5000 km^2 and a west–east coastline of about 200 km. There are four rivers that flow north to south through the Chenier Plain into the Gulf of Mexico. These rivers are the Sabine, Calcasieu, Mermentau and Vermilion rivers. The river mouths are a combination of wave-dominated and tide-dominated, and the landscape is interspaced by chenier ridges composed of river mud-flat deposits and coarse marine and littoral sediments. The Sabine River has a drainage area of 25 267 km^2 with a total length of 893 km bordering Texas and Louisiana and draining into Sabine Lake before the Gulf of Mexico. The Calcasieu River drainage basin is 9780 km^2 and the river is 322 km long and discharges into Calcasieu Lake before the Gulf. The Mermentau River basin is 16 997 km^2 with a length of 115 km discharging into Grand Lake before reaching the Gulf. The Vermilion River is 116 km long with a basin area of 4470 km^2 draining into Vermilion Bay. The Mermentau River and Vermilion River basins are dominated by agriculture and the Calcasieu River and Sabine River basins are dominated by forest.

The Mississippi River Delta has a land area of about 12 000 km^2 and a coast line of about 250 km. At the present time, the delta boundary is commonly considered to include approximately the triangular area east of the Atchafalaya and west of the Mississippi River (Fig. 1). However, the geological extension of the delta is beyond this boundary, as the Mississippi River has changed its course from the west to east several times during the past 8000 years influencing the geomorphic development of the entire southern Louisiana. One of the most engineered rivers in the world, the Mississippi River is currently regulated to flow mainly through two outlets into the Gulf of Mexico – the main stem channel and the Atchafalaya River. The main stem channel is 439 km long, confined by levees, and carries about 75% of the river's water through the currently active delta complex in southeast Louisiana, also known as the bird's foot delta (Fig. 1). The Atchafalaya River is formed where the total flow from the Red River is combined with part of the Mississippi River's water that is diverted through the Old River Control Structure (ORCS) that was built by the US Army Corps of Engineers during the 1960s. In the 1930s the Mississippi River discharged about 20% of its total flow into the Atchafalaya River. By the early 1950s it was

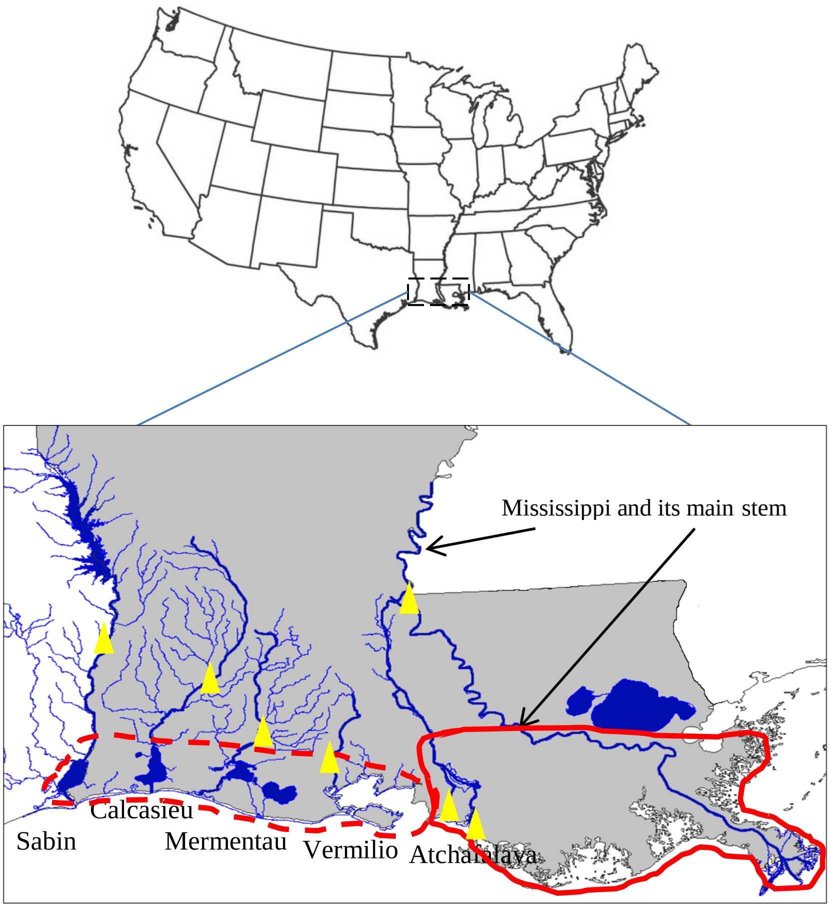

Fig. 1 Major river systems in southern Louisiana, USA, along the northern Gulf of Mexico – The Chenier Plain in the west (dashed line) and the Mississippi River Deltaic Plain in the east (solid line); The triangles indicate gauge stations from which discharge and sediment data were collected.

observed that without intervention, the majority of the Mississippi River flow would be captured by the Atchafalaya River. To prevent total capture of the Mississippi River by the Atchafalaya River, ORCS was built to maintain 25% of the Mississippi discharge flowing into the Atchafalaya River (Horowitz, 2010). Beginning from the control structure, the Atchafalaya River flows southward, first in a well-confined channel for about 87 river kilometres, and then in several braided channels through a low-land swamp area for another 100 river kilometres, discharging its water and sediment into the northern Gulf of Mexico through two outlets, the natural Atchafalaya River channel at Morgan City and the man-made Wax Lake Outlet. The river is confined by levees that surround it to the east and west at about 20–35 km in width. While the Mississippi-Atchafalaya is a typical river-dominated system, the flow of the Atchafalaya is slower and the bay water is much shallower than the main channel.

SEDIMENT DELIVERY TO LOUISIANA'S COAST

Daily river discharge from the US Geological Survey (USGS) and monthly total suspended solids (TSS) data from Louisiana Department of Environmental Quality (LDEQ) were obtained to estimate total suspended sediment yield (TSSY) for the Sabine, Calcasieu, Mermentau and Vermilion rivers for the period 1990–2009. Daily river discharge from US Army Corps of Engineers (USACE) and USGS, as well as weekly/monthly suspended sediment concentration (SSC) data from USGS were obtained to estimate TSSY for the Mississippi River at Tarbert

Landing and the Atchafalaya River at Morgan City and Wax Lake Outlet. The results showed that, on average, the rivers transported a combined total of 181 Mega tonnes of TSSY each year to Louisiana's coast (Table 1), and that much of the sediment yield was produced by the Mississippi River (70.1%) and the Atchafalaya River (29.6%). While all the six rivers showed a clear, similar seasonal trend with greatest TSSY during the winter and spring months, and lowest during the summer and fall months, corresponding to their seasonal flow conditions, interannual variability in TSSY is very high with the four Chenier Plain rivers varying by up to 2600%. Over the past two decades, the Chenier Plain rivers, except for Vermilion, showed a slightly declining trend of TSSY, which is due mainly to the declining discharge corresponding to the decreasing trend in precipitation in the river basins. Vermilion received flow regularly from the Atchafalaya River and therefore, its long-term TSSY was not affected by the regional precipitation.

A number of studies have reported a declining trend in the Mississippi River sediment discharge over the past half century following the 1950s–1960s dam construction and river channelization (e.g. Kesel, 1988, 2003). It is, however, debatable, how the TSSY of the Mississippi River should be interpreted. Our calculation shows that there was a downward trend through the early 1990s followed by a slight upward trend (Fig. 2). Horowitz (2010) suggested that

Table 1 Annual average of total suspended sediment yield from major rivers to Louisiana's coast.

River	TSSY (× 1000 metric tonnes) Mean	Min–Max
Sabine[1]	213	16–417
Calcasieu[1]	47	12–118
Mermentau[1]	40	14–93
Vermilion[1]	43	13–71
Atchafalaya[2]	53 590	22 540–76 960
Mississippi[3]	126 750	73 640–189 040

[1] Estimated yields for Sabine near Bon Wier, TX, Calcasieu River near Kinder, LA, Mermentau River at Mermentau, LA, and Vermilion River at Perry, LA (Rosen & Xu, 2011).

[2] Estimated yield combined from Morgan City and Wax Lake Outlet (Xu, 2010; Rosen & Xu, 2012).

[3] Estimated yield for Tarbert Landing (Rosen & Xu, 2012).

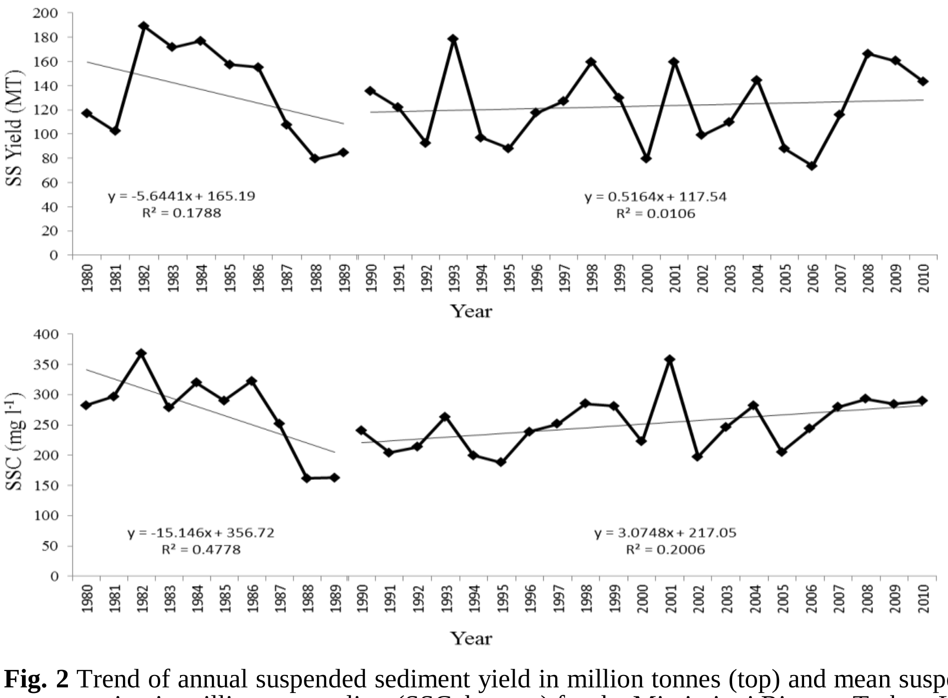

Fig. 2 Trend of annual suspended sediment yield in million tonnes (top) and mean suspended sediment concentration in milligrams per litre (SSC, bottom) for the Mississippi River at Tarbert Landing, MS.

the change started in 1993, while we believe the long-term decline of Mississippi River TSSY may have ended in 1989. This trend was not caused by changes in discharge, but by changes in SSC. From 1980 to 1986 SSCs were elevated compared to the rest of the time period. Following 1986, the Mississippi River at Tarbert Landing went through dramatic suspended sediment concentration reduction from an average of 323 mg L^{-1} in 1986 to a low of 162 mg L^{-1} in 1988. This reduction of SSC and discharge could have been related to a severe drought that affected the Midwestern United States and did not officially break until 1990 (Trenberth & Guillemot, 1995). Another possibility is that the opening of the Auxiliary Structure at ORCS in December 1986 could have affected sediment concentrations by diverting a greater portion of the sand load (Copeland & Thomas, 1992). Since 1989, there has been great fluctuation but an overall general increase in average suspended sediment concentration from 163 mg L^{-1} in 1989 to 289 mg L^{-1} in 2010. The years 2008, 2009 and 2010 are notable because SSCs are all in the top ten for the time period (1980–2010). The increase may reflect suspended sediment slowly reaching equilibrium following the severe drought of 1988–1990, opening of the Auxiliary Structure in 1986, and large flood of 1993. The trend suggests that without any further major alterations to Mississippi River engineering, current sediment load of the Mississippi River would likely remain stable for the foreseeable future.

SPATIAL PATTERN OF LAND LOSS AND GAIN

The Mississippi River main stem delivered nearly 127×10^6 tonnes of suspended sediment each year to the southeast coast of Louisiana. Assuming an average fresh sediment bulk density of 1200 kg/m^3, this annual sediment yield would create a volume of 106×10^6 m^3 of sediment, or a sedimentation of about 4 cm over an area of 2500 km^2, i.e. an approximately 10-km-wide area across the 250-km long Mississippi River Delta Plain (Fig. 1). Instead of gaining land, however, the region lost about 1089 km^2 land from 1978 to 2000, according to a land change assessment with satellite imagery and historical aerial photography by Barras *et al*. (2003). The land loss occurred overwhelmingly along the coastal shoreline, while the vast quantity of sediment from the river was lost to the deep waters as the river discharge dominates the system.

The four Chenier Rivers delivered a total of 343 000 tonnes of suspended sediment each year, which could create a sedimentation volume of 285 833 m^3, assuming a bulk density of 1200 kg/m^3. According to Barras *et al*. (2003), however, the Chenier Plain lost 361 km^2 of land cumulatively from 1978 to 2000. Much of the land loss occurred in the interior area. There was no significant change in the coastal shoreline.

The Atchafalaya River delivered approximately 54×10^6 tonnes of suspended sediment annually to the Atchafalaya Bay. The sediment yield could create a volume of about 45 million m^3 of sediment (assuming a bulk density of 1200 kg m^{-3}). From satellite imagery assessments, Xu (2010) reported a total of 18.4 km^2 of newly created land in the bay in 1984; by 2004 the land area extended to 80.6 km^2, an increase of 3.1 km^2 $year^{-1}$. A recent study (Rosen & Xu, 2012) found a reduced rate of land growth (2.1 km^2 $year^{-1}$) from 2004 to 2010 due mainly to storm surge disturbance by Hurricanes Katrina and Rita in 2005, and Hurricane Gustav in 2008.

RIVER DIVERSION EXPERIENCE

Over the past decade much of the coastal restoration efforts have focused on river diversion to introduce freshwater and sediment. Up to now there have been three major river diversions constructed in southeast Louisiana: Caernarvon, Davis Pond and West Bay at river kilometres 132, 190 and 5 of the Mississippi River, respectively. Although careful work has been done, none of the diversion projects have been successful in terms of creating new land or maintaining current wetlands. For instance:

1. The Caernarvon Diversion was opened in 1991. Despite careful planning and many years of operation, a recent study (Kearney *et al*., 2011) found no significant changes in either relative

vegetation or overall marsh area from 1984 to 2005 in zones closest to the diversion inlets. After Hurricanes Katrina and Rita in 2005, these areas sustained even larger losses in vegetation and overall marsh area, when compared to similar marshes of the adjacent reference sites (Howes *et al.*, 2010; Kearney *et al.*, 2011).

2 The West Bay was opened in 2003 to capture sediment, but it has been reported that the diversion could be impacting navigational interests in the area while not producing the desired land growth (Barras *et al.*, 2009; Brown *et al.*, 2009). This has prompted USACE to close the diversion.

New sediment diversions further up river are under study (Myrtle Grove) or proposed for future investigation (CPRA, 2012), but uncertainty exists about how much and when the most sediment is actually available. It is also questionable whether channelized diversion is the best approach to effectively address various interests, such as capturing sediment while still maintaining navigation, and managing fisheries and wetlands. In general, despite our knowledge of long-term annual suspended sediment yield from the Mississippi River, there is a knowledge gap concerning the actual divertible quantity and variability of the riverine sediment. This was highlighted by Allison & Meselhe (2010) questioning the length and interannual variation of flow periods during which riverine coarse material can be obtained.

FUTURE STRATEGIES FOR SEDIMENT MANAGEMENT IN COASTAL LOUISIANA

Based on the past river diversion experience discussed above, the channelized sediment diversion is ineffective for utilizing riverine sediment. It is likely that the coastal area in Louisiana would be worse or the same in the future if the current situation continues. A completely new approach must be employed to offset the widespread land loss in the region. An alternative approach could be taken whereby levees are periodically dropped to a certain river stage allowing overbank flow to mimic the natural process of sediment replenishment over large areas. High sedimentation rates of coarse particles have been found during floods on floodplain areas bordering the river channel (Walling & He, 1998; Hupp, 2000). Natural overbank flow has been documented to benefit river–floodplain systems, marshland, and fisheries (Baumann *et al.*, 1984; Bayley, 1991; Nyman *et al.*, 2006). This approach could be especially useful for the Chenier Plain, where interior land loss has been occurring and the area is sparsely populated. Most buildings in the coastal area of Louisiana are elevated above the ground (Fig. 3) to prevent damage from river floods and tropical storm surges, making the area suitable for sediment diversion via controlled overbank flow (COF), while incurring minimal damage. To implement COF, the following two aspects need to be considered.

Fig. 3 Elevated residential (left) and public (right) buildings in coastal Louisiana to prevent flooding from rivers and tropical storm surges (photos taken in south Cameron, Louisiana, USA).

Sediment availability under different flow conditions

The knowledge about annual total suspended sediment yield from the Mississippi-Atchafalaya River is well established. It is also clear that not all riverine sediment can be diverted for land creation. Few studies have looked at actual sediment availability under different river flow conditions; e.g. the amount of sediment during high winter and spring flows. In general, there is a knowledge gap concerning the quantity and variability of suspended sediment from the Mississippi-Atchafalaya during its flood pulse, which is critical for developing management strategies to maximize sediment capture. We have recently quantified suspended sediment load of the lower Mississippi River at Tarbert Landing during three river flow conditions: Moderate Flood Stage (16.8 m), Flood Stage (14.6 m), and Action Stage (12.1 m). The assessment provided two relevant findings: (1) high sediment load occurred at Action Stage and Flood Stage, providing approximately 50% of the total annual suspended sediment yield over a period of only 120 days; this implies that sediment diversion outside of this period would be impractical highlighting the need to manage diversions to follow the natural flood regime; and (2) the river showed significantly higher suspended sediment concentration and suspended sediment load during the rising than the receding limb, indicating that the most effective sediment diversions will have to rely on discharge during the rising limb of flood pulses.

Optimization of COF for sediment diversion

Controlled overbank flow can be implemented by lowering a stretch of river levee, as illustrated in Fig. 4. The flow will act similar to a rectangular weir, whose flow rate can be approximated as a function of hydraulic head. Assuming that overbank flow spills over the land in a sectorial shape (Fig. 4), the flooded area and time needed for the flood depend on a number of factors including hydraulic head, width of the lowered levee, topography, soil physical characteristics, and vegetation of the land.

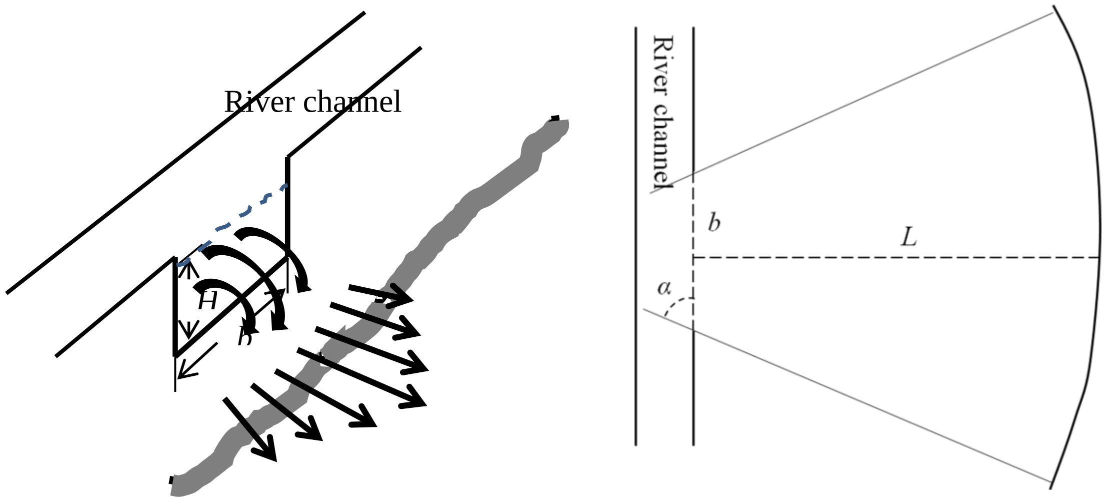

Fig. 4 Diagram of overbank flows via a lowered levee and the geometry of hypothetic sectorial flooding area.

To illustrate the influence of hydraulic head and overbank flow width on the time that is needed for creating a certain depth of sediment, we computed flows for three different hydraulic heads and widths, making the following assumptions: (1) flooding area is a sector-shape flat plane with no shear stress, infiltration, and vegetation effects; (2) hydraulic head and flow velocity remain constant. Based on the geometry, the formula below can be used to determine the sectorial flooding area (A):

$$A = \frac{\beta}{2}\{b/[2\times\tan\left(\frac{\beta}{2}\right)] + L\}^2 - b^2/[4\times\tan\left(\frac{\beta}{2}\right)] \tag{1}$$

where $\beta = 180 - 2\alpha$ in radians, b = overbank flow width, and L = distance from the bank to the flood front edge (see Fig. 4).

To determine the time for flooding the area, overbank flow rate is needed, which may be estimated as follows:

$$Q = k\frac{2}{3}\sqrt{2g}\ bH^{2/3} \tag{2}$$

where k = discharge coefficient, g = gravitational acceleration, b and H are the width and hydraulic head (Fig. 4).

With the information on A and Q (equations (1) and (2)), flow volume and time can be estimated for a certain flooding depth. Table 2 summarizes computational results on the time that would be needed for creating 1 mm depth of sediment for the flooding area under different hydraulic heads and flow widths. In the calculation, k is assumed 0.7 (k is normally obtained through experiments and has been reported to vary from 0.5 to 0.9), riverine sediment concentration 313 mg L^{-1}, and sediment bulk density 1200 kg m^{-3}.

The calculation for hypothetical overbank flow shown here is a simplification of highly complex hydraulic and fluvial processes. The assumptions of zero shear stress, zero infiltration, and a sectorial progression of flooding are not exactly representative of the reality. Nonetheless, the results do indicate a plausible relation between overbank flow width, hydraulic head, and flow rate, as well as their effects on the time needed for flooding. When compared with flow width, hydraulic head shows a stronger effect on the time for flooding. On the other hand, flow width affects flooding area because of a geometric change. Hydraulic head can be regulated based on river stages, while flow width can be either structurally or operationally regulated. Optimization of the two can help maximize sediment capture using COF.

Table 2 Effects of hydraulic head (H) and overbank flow width (b) on flow rate (Q), flooding area (A) and the time (T) that would be needed to create 1 mm depth of sediment over a sectorial area with a distance of 20 km (L) and an outflow angle of 120° (i.e. α = 60°, Fig. 4).

H & b (m)		Q ($m^3\ s^{-1}$)	A (km^2)	T (day)
When H = 0.5	b = 1000	730	228	13.8
	b = 1500	1096	237	9.6
	b = 2000	1461	246	7.5
When b=1000	H = 0.3	339	228	29.8
	H = 0.8	1478	228	6.8
	H = 1.0	2066	228	4.9

CONCLUDING REMARKS

Extending from the Chenier Plain at the Texas border to the Mississippi River Bird Foot Delta, coastal Louisiana is a maze of deltaic plains, bayous, fresh and salt marshes, and barrier islands. These coastal areas are home to over 2 million people, and they support a quarter of the US energy supply and provide vital habitat for wildlife and fisheries. However, this region has experienced one of the highest rates of land loss globally, and so its restoration is a top priority in Louisiana.

Until recently, one of the largest underused resources for coastal restoration was sediment from rivers that drain into the northern Gulf of Mexico. Although there has been much research on the quantity and trend of sediment discharge from the Mississippi River and three major river diversion projects in the past 20 years, neither has been successful in creating new land or maintaining disappearing wetlands. Most of the vast riverine sediment resource has been lost and will continue to be lost to deep water through the channelized rivers. To offset the current land loss in coastal Louisiana, we believe that a completely new approach for utilizing riverine sediment must be developed. The approach should mimic natural processes of sediment replenishment over the broad coastal areas rather than through channelized river diversions to a few small bay areas.

As a first step for developing the approach, we assessed the total amount of sediment input to Louisiana's coast and the quantity of potentially divertible sediment under different river stages. We found the Mississippi-Atchafalaya River system produces 99.8% of the total annual sediment (180×10^6 metric tonnes) to Louisiana's coast, and that suspended sediment concentration and load can be maximized during Flood and Action Stages, accounting for approximately 50% of the total annual sediment yield even though duration of these stages accounted for only one-third of a year. The annual sediment yield estimated by a hydrograph-based approach can produce a sediment volume of approximately 75×10^6 m^3 (assuming a density of 1200 kg m^{-3}). The current river diversion is incapable of using the sediment resource, and here we have presented an alternative approach, COF (controlled overbank flow), that can be periodically used to replenish sediment over large land areas. More studies are needed to examine technical details and the socio-economic feasibility of the approach.

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