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The mineral sediment loading of the modern Mississippi River Delta: what is the restoration baseline?

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Abstract A restoration baseline for river deltas establishes a framework for achieving goals that can be thwarted by choosing an improper historical background. The problem addressed here is identify the size of the modern Mississippi River delta that restoration should use as that baseline. The sediment loading to the Mississippi River main stem delta fluctuated over the last 160 years with a consequential dependent plasticity in delta size. A visual time series of the delta size is presented, and the area: sediment loading ratio is calculated. This ratio ranged from 1.8 to 3.9 km^2 per Mmt sediment y^{-1} during the pre-European colonization of the watershed in the 1800s, a maximum size in the 1930s, and then lower after soil conservation and dam construction decades later. This land building rate is similar to the 1.3 to 3.7 km^2 per Mmt sediment y^{-1} for the Wax Lake and Atchafalaya subdeltas located to the west, which receives some of the Mississippi River sediment and water from the main channel below St. Francisville, LA. The significance to restoration of delta land lost since the 1930s is that the baseline for the 1930s was conditioned on previous sediment loading that has since declined. Most sediment is trapped in the delta, and so the existing situation is close to a zero-sum land balance. The restoration potential should be based on the delta land area that could be built from the current sediment loading, not from those of the era during peak agricultural expansion and soil erosion in the watershed. Sediment diversions upstream will, therefore, deplete sediment supply downstream where delta land will be lost. The choice of which baseline is used can be seen as a choice between unrealistic perceptions that leads to unachievable goals and agency failures, or, the realism of a delta size limited by current sediment loading.

Keywords River delta · Sediment supply · Landuse · Restoration

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Introduction

The wetland soils along the main stem of the world's coastal deltas are primarily mineral soils. The loss and gain of wetlands there are largely in a well-recognized balance between the availability of these mineral materials and the sediment capture efficiencies which depend on, for example, subsidence rate, tide, sea level rise, vegetation, and soil stability. The supply of these inorganic minerals (sediments) from the watershed is, therefore, an important primary influence on wetland land gain and loss in coastal deltas (Yang et al. 2003; Syvitski et al. 2005), and are important to quantify in order to understand the restoration potential.

The sediment load to the Mississippi River delta (MRD) fluctuated greatly over the last two hundred years creating different delta sizes. The population of the Midwest grew from no more than 106,000 in the early 1600s, to 1 to 10 persons km^{-2} by the 1850s when the population center of the US crossed the Appalachian Mountains and headed into the Mississippi River watershed (Turner and Rabalais 2003). Vegetation cover was grossly reduced in the Mississippi River watershed and the soil structure disturbed as the area and intensity of agricultural land use increased. Erosion became severe throughout the watershed as it did elsewhere (Fig. 1), with

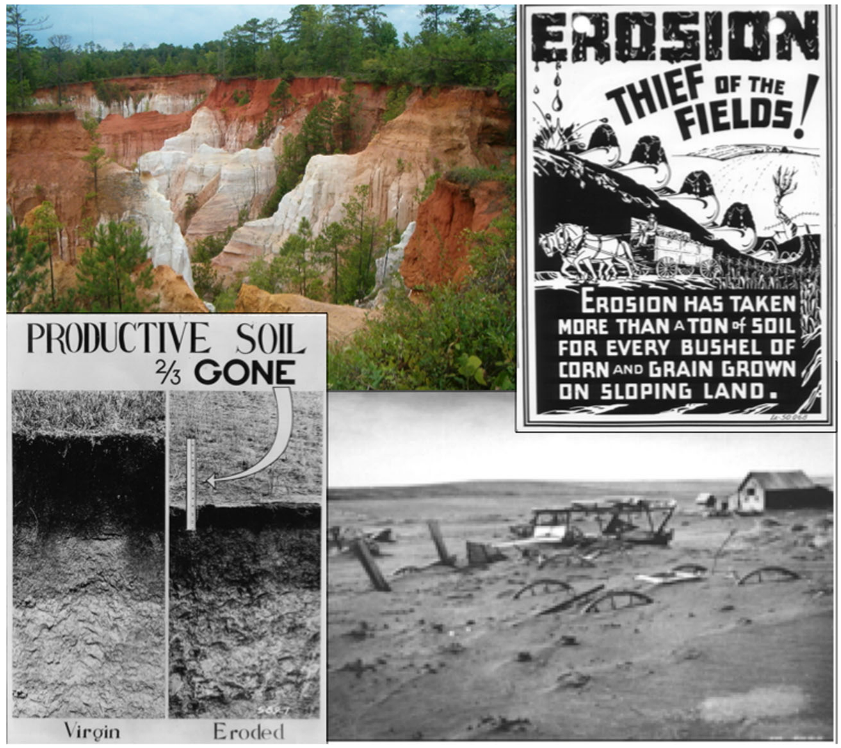

Fig. 1 Soil erosion examples from the last 150 years. Top left: Providence Canyon State Park, Georgia. The gullies are 150 ft. deep and several hundred yards wide in places. These are relics from 'poor farming practices during the 1800s (Sutter 2010). Photo by R. Honerkamp; 6 July 2008; Creative Commons Attribution-Share Alike 3.0 Unported license (https://creativecommons.org/licenses/by-sa/3.0/deed.en). Top Right: National Archives photo 114 SC MO 80.300, cartoon of soil losses in Missouri, 1935–36. Bottom Left: National Archives photo 114 SC Mo3.450, 1935–34. The land was first farmed in 1853; Bottom Right: National Archives photo 114 SC 5089, Soil Conservation Service "Buried machinery in barn lot. Dallas, South Dakota. May 13, 1936"

the symptomatic release of soil nutrients (Broussard and Turner 2009). A visitor in the 1800s noted that:

> "There is no portion of the globe that is being exhausted of its fertility by injudicious cultivation, so rapidly as the Mississippi Valley" (Bateham 1849, cited in Whiteney 1994, pg. 226).

The recognition of the seriousness of soil erosion and attendant soil fertility decline led to the formation of the Soil Erosion Service (re-named the Soil Conservation Service in 1935, and re-named again in 1994 as the Natural Resources Conservation Service). The suspended sediment concentration at New Orleans doubled that estimated for the pre-European colonization era by the 1870s (Tweel and Turner 2012). It then declined after 1910, and especially so in the early 1950s, after extensive dam construction on the relatively sediment-rich Missouri River. Similar changes worldwide have caused an average 10% net loss of sediment loading to the ocean in recent decades (Syvitski et al. 2005; Syvitski and Kettner 2011). Herein the relationship between sediment loading to the lower MRD and its size are quantified, and the area of land per sediment load is compared to those of the Wax Lake and Atchfalaya River deltas to the west. The results are discussed within the context of restoration efforts involving planned river diversions in the MRB whose restoration target is 20% of the land lost since the 1930s (Turner 2009).

Materials and methods

Figure 2 is a location map of the study area with the place names cited herein. The area in the MRD is less than 10% of the total area of the deltaic plain and the area of the MRD in 2016 was estimated to be 45% of that present in 1932 (Couvillion et al. 2017). The registered maps from Tweel and Turner (2012) were digitized to measure the size of the

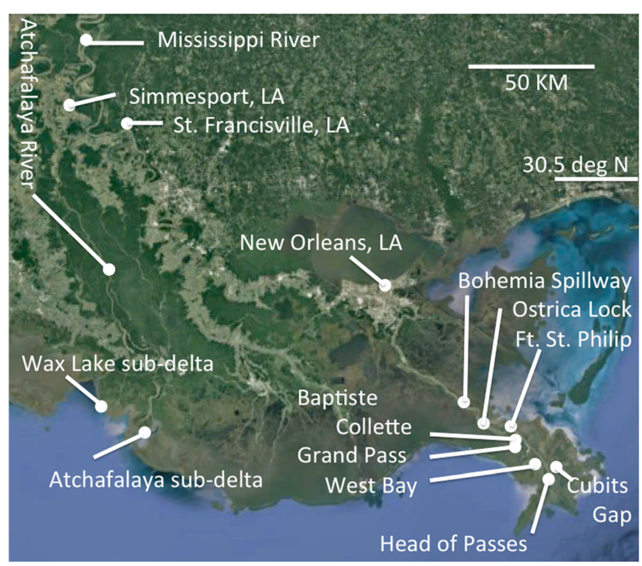

Fig. 2 The location of the various places mentioned in the Mississippi-Atchafalaya River deltas

modern delta from 1838 to 2002. This area is sometimes called the 'birds foot' and contains the modern Balize delta Coleman et al. (1998). Maps were selected to represent responses to the Mississippi River sediment load: 1) before European colonization, 2) the peak response to the maximum loading in the 1890s creating land measured in 1932, and 3) the modern era when the sediment load was reduced following changes in land use and from upstream dams that trapped sediments and reduced the sediment load by about 50%.

The suspended sediment concentration data are for the Mississippi River at New Orleans, Louisiana, that are from 1838; portions of this data set have been discussed previously (Turner and Rabalais 2003; Thorne et al. 2008). Other data from before 1877 are sparse (Humphreys and Abbot 1876; Vogel 1930; Keown et al. 1981a, b), but two years of suspended sediment data were collected at Carrollton, Louisiana, starting in February 1851, and ending February 1853 (Humphreys and Abbot 1876). The New Orleans Water and Sewerage Board determined suspended sediment concentrations beginning in 1910 which are reported in Tweel and Turner (2012). A final estimate assumed that there is would be no delta land without a sediment load. A simple linear regression of the data was forced through the 0,0 intercept.

We compared the land size : sediment load values for the Mississippi River delta to literature values were obtained for the Atchafalaya and Wax Lake sub-deltas, situated to the west; the sediment loading data is from Allison et al. (2012) and the land area is from Roberts et al. (1997), Coleman et al. (1998), Allen et al. (2012), and Carle et al. (2015)

Results

The historical maps of the area examined are shown in chronological order in Fig. 3. The sediment load estimates were 174 × 10^9 Mt. y^{-1} (pre-disturbance), 348 × 10^9 Mt. y^{-1} (1880–1890) and 91 × 10^9 Mt. y^{-1} (1970s). The delta was relatively narrow at the time of the European arrival (total area = 314 km^2), but then thickened as the sediment load increased until it reached its peak around 1932 (total area = 692 km^2). The delta size then decreased as the sediment load decreased, especially after the 1950s with dam construction, and with a shorter response time than that of its growth phase. The total amount of land in the MRD circa 1971–2002 was 358 km^2. The regression slope for the quantified relationship of the MRD area and sediment load for all data is in Fig. 4, and is 2.05 km^2 land per Mt. y^{-1} of sediment load. The relationship does not apply to wetland area in the rest of the deltaic plain whose areal changes do not coincide with those of the modern delta.

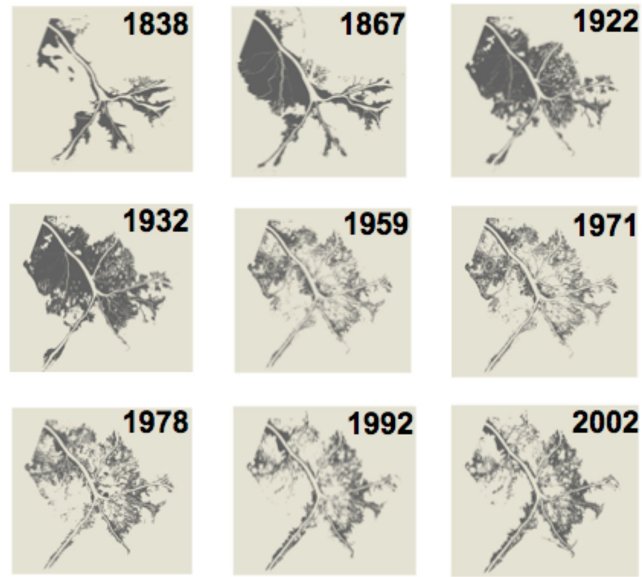

Fig. 3 Nine registered maps of the Mississippi River delta land from 1838 to 2002

The ratio of land per sediment load in the MRD ranges from 1.8 to 3.9 km^2 per Mmt sediment y^{-1} for the interval from pre-European colonization of the watershed to present (Table 1). This rate is similar to the 1.3 to 3.7 km^2 per Mmt sediment y^{-1} for the Wax Lake and Atchafalaya delta located to the west (Table 1), that receives 30% of the Mississippi River main stem sediment and water below St. Francisville, LA.

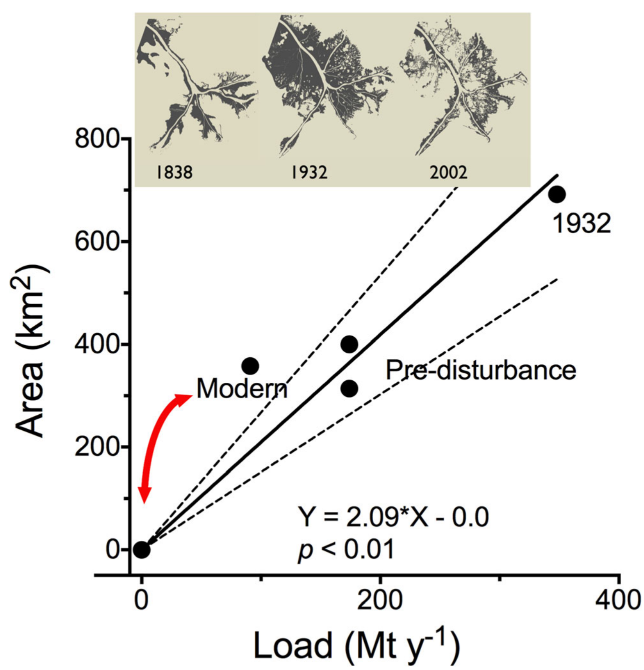

Fig. 4 The size of the modern delta and sediment load of the river at New Orleans. The X, Y intercept of 0, 0 is an assumption. A simple linear regression line with a 95% CI is shown

Table 1 The land area : sediment load (km^2 per Mmt y^{-1}) for coastal deltas in Louisiana

Area	Land Area (km^2)	Sediment Loading (Mmt y^{-1})	km^2 per Mmt y^{-1}	Source: Land Area	Source: Sediment loading
Mississippi River bird foot's delta					
pre-disturbance	314	174	1.80	Tweel and Turner 2012	Tweel and Turner 2012
1932	692	348	1.99	Tweel and Turner 2012	Tweel and Turner 2012
1970s	358	91	3.93	Tweel and Turner 2012	Tweel and Turner 2012
historical average			2.09	this paper; Fig. 3	
Mississippi River bird foot's delta					
pre-disturbance	400	174	2.30	Syvitski et al. 2003	Tweel and Turner 2012
Wax Lake sub-delta					
1997	63	20.5	3.07	Coleman et al. 1998	Allison et al. 2012
1997	51.1	20.5	2.49	Roberts et al. 1997	Allison et al. 2012
2010	33.65	20.5	1.64	Carle et al. 2015; Table 1	Allison et al. 2012
2010	26	20.5	1.27	Allen et al. 2012	Allison et al. 2012
2011	38.54	20.5	1.88	Carle et al. 2015; vegetated area	Allison et al. 2012
Atchafalaya sub-delta					
1997	102	27.9	3.66	Coleman et al. 1998	Allison et al. 2012
Wax Lake and Atchafalaya sub-Deltas combined					
1997	125.8	48.4	2.60	Roberts et al. 1997	Allison et al. 2012

Discussion

The size of the MRD is proportional to the sediment delivery to the coast for the years of measurement over a few decades. This result is consistent with results of Blum and Roberts (2009) who examined the fluctuations in sediment supply over several thousands of years for the entire coast (Blum and Roberts 2009), and by the global analysis of sediment delivery and delta size by Syvitski and Sato (2007). The delta size present in the 1930s was the result of historical conditioning arising from the watershed soil erosion of the 1800s, and not the sediment supply of the 1930s, nor of the last half of the twentieth century. The delta that built up from the 1800s to 1932 was destined to decline further after the sediment loading decreased later in the last century, albeit with a lagged response. Sediment supply to the whole delta must increase to have a net gain in the size of the MRD above the 1930s land mass. This means that the modern wetland restoration goal for the MRD is dependent on an unlikely and substantial increase in sediment load.

It is assumed the delta land area is zero when sediment load is zero (Fig. 4), but it is also possible that the land area will be zero *before* the sediment load is zero (a system collapse). A sediment-supply control of delta size has significance to the restoration of Louisiana's coast, if not other coasts. One future consequence will come from the 0.69% yr^{-1} decline in annual flow-weighted sediment concentration from 1976 to 2009 at Tarbert Landing, MS, near St. Francisville, LA (Table 8, Heimann et al. 2011). The present land area may become even smaller, as a result.

It is important to recognize that the distribution of the majority of sediment supplied to the lower MRD stays in the MRD. Allison et al. (2012), for example, measured the distribution of total sediment loading in the river south of New Orleans, LA, for the flood years of 2008–2011. They found that 30 % of the total sediment load enters the three southern-most passes, and that the remaining 70% of the sediment load enters various channels of the river to sustain the existing (wet)lands in the lower MRD (from north to south below New Orleans: Bohemia, Ostrica, Ft. St. Philip, Baptiste Collette, Grand Pass, Cubit's Gap, West Bay) and the small cuts located to the south that are above the Head of Passes at the river's terminus (Fig. 2). These flows through the river distributaries can be considered a 'diversion' in the sense that the mineral sediments accumulate and sustain the land there or nearby. Sixty-five percent of the sand, however, stays in the channel as bedload, and 9 % of the total sand load leaves through the 3 southern-most passes; sand is the main constituent of land building (Fig. 7 in Allison et al. 2012) and some of this sand (unmeasured) is also retained in the local wetlands. It does not go offshore as a missed restoration opportunity.

The effect of the constructed flood protection levees on changing the sediments over the Mississippi River and into the adjacent wetlands was minimal, amounting to about 2% of the river's load (Kesel 1988). Furthermore, the overflow would be concentrated near the riverbank (hence the formation of the riverbank levee).

A major conclusion, therefore, is that the balance of sediment load distribution to the coast is that of a nearly 'zero-sum' gain for the MRD. This includes in the lower MRD which offers some hurricane protection for New Orleans and is an area of heavy commerce. Reducing the sediment load to any of the channel openings before it reaches the Gulf of Mexico will likely result in land loss downstream.

There are plans intended to restore and sustain wetlands through the use of Mississippi River water diversions (Anon 2017). Some of these occasionally include moving more water from the main channel of the Mississippi River to join with the Red River where it forms a new channel called the Atchafalaya River. The Atchafalaya already receives 30% from the Mississippi River main channel just above St. Francisville, LA. A proposed westward re-allocation of sediments upstream of Baton Rouge and into the Atchafalaya basin increases the sediment loading to the Wax Lake and Atchafalaya sub-deltas (Fig. 2), but also reduces the sediment loading in the main river channel. A further complication is that only 35% of the sediment entering the upstream end of the Atchafalaya Basin at Simmesport, LA, reaches Morgan City just before the river bifurcates to the Wax Lake and Atchafalaya deltas (Allison et al. 2012). Changing sediment delivery from one basin to another, therefore, will result in trade offs. Are the effects of adding sediments to one basin a more efficient use of sediments, in terms of land building, than is caused by the removal of sediments from another basin? This is a major management decision requiring good field data and modeling to address management outcomes. A recommendation, therefore, is to further develop an understanding of how to quantify the trade-offs of moving sediment from one basin to another, and of the effects downstream of diverting sediment upstream, etc. These are tractable field and modeling problems to address that have strong management outcomes, including some for other river basins

The increased sediment loading from a MRD river diversion to a specific area *may* convert open water to land in the immediate area where mineral matter is being added to a mineral platform, but with a net loss to the MRD in the larger area. Ninety percent of the deltaic plain is beyond the mineral depositional footprint of large sediment diversions, but the nutrients in presently planned river diversions will also spread over organic soils in the diversion flow path of the deltaic plain. These organic soils are derived from the emergent vegetation overlying the mineral soil. Wetland losses of these mostly organic soils since the 1930s are directly proportional to dredging activities in a dose-response manner (Turner 2009, 2014). Further, these wetlands are susceptible to damage from nutrient additions of a modern Mississippi River that have five times the concentration of nitrate, for example, than before Europeans began farming in the watershed (Turner and Rabalais 2003). The Wax Lake and Atchafalaya sub-deltas, made of mostly mineral soils, are probably inadequate models to use for diversion of water and sediments into the more organic soils where the proposed main channel MRD diversions would flow. A small land gain within a few kms of the diversion entry location may be relatively insignificant compared to the wetland loss in the organic soils downstream, as it was in the case of the Caernarvon diversion where one-third of the wetlands in the flowpath were lost (142 km^2; Kearney et al. 2011). Those organic soil losses are certainly a plausible cause-and-effect outcome of loading nutrients (N and P) into the organic soil matrix that comprises most of the deltaic plain. Indeed, there is evidence that introducing Mississippi River diversions may result in additional wetland loss. The natural crevasse (100–130 thousand cfs) at Fort St. Philip, for example, was described as a "loss accelerant" because it has not regained the 52% of land lost when it opened in 1973 (Suir et al. 2014). One should be careful, therefore, to avoid minimizing the differences in characteristics between organic and inorganic soils, and to appreciate the differences.

The restoration of the MRD using a baseline whose size is contingent on the 1930s area is inappropriate. The delta's size in the 1930s was made possible by a higher sediment delivery from decades earlier. The sediment loading from the watershed in the last century and is now lower because of many management decisions made upstream, and is now about the amount of before Europeans arrived in the watershed in the early 1800s. In other words, the restoration baseline needs to be based on present conditions, which are quite different from those of the 1930s. McClenachan (2009) provided examples of how trophy fish size and species changed in the last 100 years; she showed how baseline choices could affect the willingness to accept whether coral reefs could support different restoration trajectories – in this case the possibility for restoration of many large sized fish species. Jackson (2001) demonstrated how the choice of baselines affects marine reserve management, and provides different science frameworks for restoration and benefits. He provides an instructive and applicable argument to use an historical context to make intelligent choices about baselines, so that we avoid favoring unrealistic perceptions that lead to unachievable goals and agency failures.

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