LETTERS
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Drowning of the Mississippi Delta due to insufficient sediment supply and global sea-level rise

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Over the past few centuries, 25% of the deltaic wetlands associated with the Mississippi Delta have been lost to the ocean[1]. Plans to protect and restore the coast call for diversions of the Mississippi River, and its associated sediment, to sustain and build new land[2,3]. However, the sediment load of the Mississippi River has been reduced by 50% through dam construction in the Mississippi Basin, which could affect the effectiveness of diversion plans[4–6]. Here we calculate the amount of sediment stored on the delta plain for the past 12,000 years, and find that mean storage rates necessary to construct the flood plain and delta over this period exceed modern Mississippi River sediment loads. We estimate that, in the absence of sediment input, an additional 10,000–13,500 km² will be submerged by the year 2100 owing to subsidence and sea-level rise. Sustaining existing delta surface area would require 18–24 billion tons of sediment, which is significantly more than can be drawn from the Mississippi River in its current state. We conclude that significant drowning is inevitable, even if sediment loads are restored, because sea level is now rising at least three times faster than during delta-plain construction.

During the last glacial period sea-level lowstand, the lower Mississippi Valley was incised, and the Mississippi River discharged directly to a submarine canyon at the shelf margin. Global sea-level rise of 115–135 m accompanied deglaciation from about 19–7 kyr BP, with little eustatic rise since[7]. For the Gulf of Mexico, rates of sea-level rise exceeded 3–5 mm yr^{-1} until about 7 kyr, then decelerated: although details are debated, all data indicate that regional sea level was rising at rates of <1 mm yr^{-1}, or mostly stable, for the past 7 kyr (refs 8, 9). The Mississippi Valley began to fill with sediment in response to sea-level rise by about 12 kyr BP (ref. 10). However, most large deltas, including the Mississippi, did not begin to form until sea-level rise decelerated[11]: the Mississippi Delta plain (Fig. 1) represents a succession of river courses and five delta complexes (hereafter deltas) that were built during the middle to late Holocene epoch[12,13] (see Supplementary Information).

Before artificial levee construction, the river avulsed and a new delta was constructed every 1,000–1,500 yr: the active Plaquemines–Balize Delta began to form about 1,000 yr ago, and was for some time contemporaneous with the older Lafourche Delta, whereas diversion to the Atchafalaya River course began about 500 yr ago, but is now managed by the US Army Corps of Engineers. In each case, after river diversion, the abandoned delta was subject to subsidence, reworking of mouth-bar sands into transgressive barrier-island chains, and submergence[12,14]. The extent to which this cycle has gone to completion for the older Teche, St Bernard and Lafourche deltas reflects time elapsed since abandonment. However, except for the Plaquemines–Balize and Atchafalaya–Wax Lake deltas, the Holocene delta plain as a whole is in this transgressive phase. Before levee construction, sediment was dispersed to older deltas during floods through crevasse and distributary channels, but continuous levees now render the delta plain transport limited.

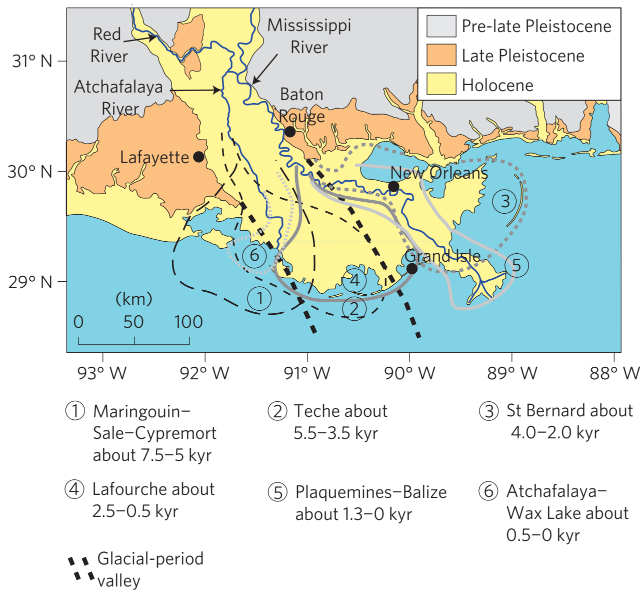

Figure 1 | Geologic map of the Mississippi River delta plain. The map illustrates the extent of the present Holocene delta plain, as well as the mapped extent of individual deltas (numbered 1 to 6) that were constructed at various times in the past 7,000–8,000 yr. Modified from refs 9, 12. Age estimates represent the range of published ages from the literature[12,13], and are given in calendar years BP.

Post-glacial alluvial and deltaic sediments cover an estimated 60,500 km², and range in thickness from <10 m in far upstream reaches near Memphis, Tennessee, to ~60 m under the present-day Lafourche Delta and ~100 m in far-downstream reaches of the Plaquemines–Balize Delta[9,15]. We estimate that 2,790–3,450 billion tons (BT) of sediment has been stored during the post-glacial period, which would have required a mean rate of ~230–290 million tons (MT) yr^{-1} over the past about 12 kyr. At the latitude of Baton Rouge, the incised valley was mostly full by about 4 kyr BP (ref. 10), after which time most sediment storage took place within the Teche, St Bernard and Lafourche deltas, in the shelf-margin Plaquemines–Balize Delta, and now within the Atchafalaya–Wax Lake delta. Approximately 80% of stored sediment lies within the delta plain and inner shelf (see Supplementary Information).

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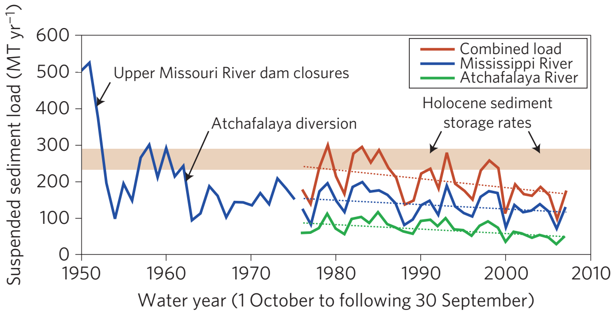

Figure 2 | Suspended sediment loads for the lower Mississippi River at Tarbert Landing, Mississippi, the Atchafalaya River at Simmesport, Louisiana, and for the combined Mississippi and Atchafalaya, obtained by summing the two data sets. Pre-1976 data are from refs 5, 6. For the 30 yr period 1977–2006, we use data for the Mississippi River at Tarbert Landing, MS (station 07295100), and the Atchafalaya River at Simmesport, LA (station 07381490). All post-1976 data are from refs 18, 19. The light brown bar represents estimated mean time-averaged post-glacial rates of sediment storage in the alluvial valley and delta plain.

Post-glacial rates of sediment storage provide context for modern land loss. Sediment budgets are poorly constrained for most rivers, but ~30–70% of the total load can be trapped on the alluvial–deltaic plain, with remaining amounts transferred to the delta front or farther basinward and/or alongshore[16,17]. For the lower Mississippi River, pre-dam suspended load is estimated to have been ~400–500 MT yr^{-1} (refs 5, 6), so our time-averaged rates of storage of ~230–290 MT yr^{-1} fall within trapping efficiencies for other systems. However, for the period 1976–2006, the mean suspended sediment load is ~136 MT yr^{-1} for the Mississippi below the Atchafalaya diversion and ~69 MT yr^{-1} for the Atchafalaya River, which sums to ~205 MT yr^{-1} for the combined Mississippi and Atchafalaya[18,19] (see Supplementary Information). Modern loads are therefore less than the time-averaged rates for sediment storage that were necessary to construct the late Holocene delta plain in the first place; hence, the modern delta plain is supply limited (Fig. 2).

The success of land-building and land-sustaining diversions will depend on the balance between sediment supply and accommodation created by subsidence and sea-level rise. Land-surface subsidence is the cumulative result of a variety of processes that operate over different spatial and temporal scales. To estimate the subsidence component, we use conservative rates that are supported by the geologic record, and which are more likely to be representative of century or longer timescales[20] (see Supplementary Information). The long tide-gauge record at Grand Isle, Louisiana, located on the Lafourche Delta (Fig. 1), is an important benchmark, and indicates that subsidence rates are 6–8 mm yr^{-1} (ref. 21). Higher rates apply to the Plaquemines–Balize Delta owing to sediment loading, compaction and faulting, whereas rates probably decrease to ~1–3 mm yr^{-1} farther inland at the latitude of Baton Rouge.

The Intergovernmental Panel on Climate Change (IPCC) concludes that rates of global sea-level rise are accelerating: tide-gauge records from tectonically stable sites show a mean of 1.7 mm yr^{-1} for the twentieth century, whereas tide gauges and satellite observations indicate rates of about 3 mm yr^{-1} since 1993 (ref. 22). IPCC models predict extra global sea-level rise of 0.2–0.6 m by the year 2100 (ref. 23), although there is uncertainty about the potential loss of land ice, as well as the steric expansion of ocean waters, and IPCC estimates are more conservative than other recent studies[24]. Nevertheless, rates of rise during the last half of the twentieth century were twice as high as maximum rates for the past 7 kyr, and year 2100 rates may be four times greater or more. Accelerated rates of global sea-level rise add to delta subsidence to significantly increase rates of relative sea-level rise (Fig. 3a).

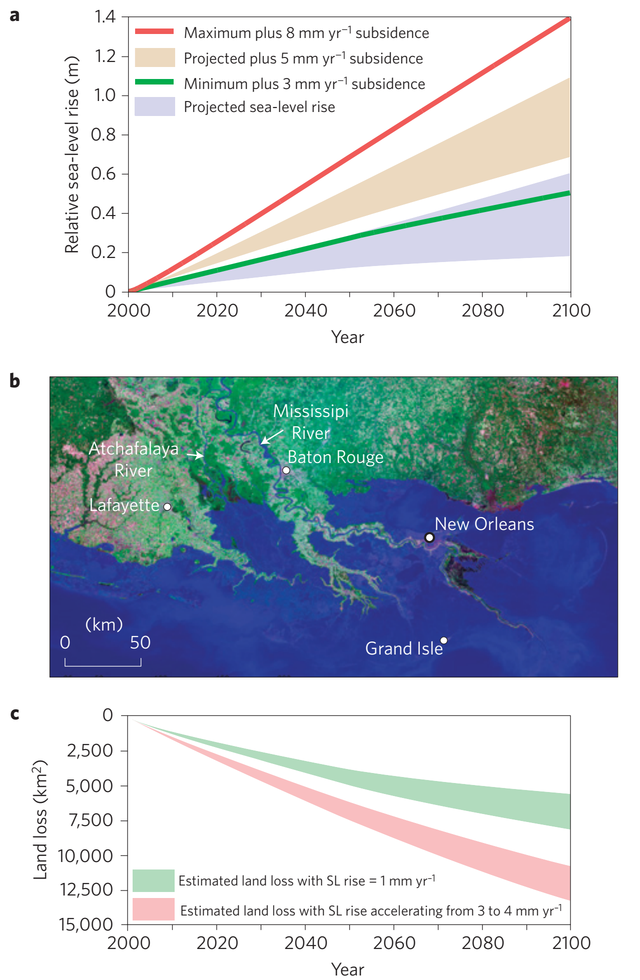

Figure 3 | Predictions of relative sea-level change, submergence and land loss. a, Predictions of global sea-level change and subsidence to the year 2100. The upper and lower limits on the projected sea-level rise reflect the minima and maxima in IPCC 2007 models[22,23]. Minimum plus 3 mm yr^{-1} subsidence and maximum plus 8 mm yr^{-1} subsidence illustrate the minima and maxima in IPCC 2007 models, plus low versus high rates of subsidence. **b**, GIS rendering of a static submergence model, defined as delta-plain surface area that can be submerged or converted to brackish marsh owing to 1 m relative sea-level rise, no mineral sediment input and no catastrophic events. **c**, Predicted land loss for the delta region to the year 2100 from the submergence model in **b**, compared with predicted land loss with sea-level change = 1 mm yr^{-1}. The lower limit (higher rates of land loss) to each field is defined by a hinge-like subsidence model that varies linearly from 3 mm yr^{-1} at the latitude of Baton Rouge to 8 mm yr^{-1} at the latitude of Grand Isle. The upper limit (lower rates of loss) represents subsidence that varies linearly from 1 to 6 mm yr^{-1} over the same distance.

Previous projections of twentieth-century land-loss trends suggest submergence of 5,700 km^2 of the delta plain between 1950 and 2050, mostly on the Teche, St Bernard and Lafourche deltas, with 400 km^2 gained through deposition in the Plaquemines–Balize and Atchafalaya–Wax Lake deltas[25] (see Supplementary Information). We project submergence to the year 2100 using conservative subsidence rates, and sea-level rise that accelerates linearly from 3 mmyr^{-1} in the year 2000 to 4 mm yr^{-1} in 2100: in the absence of sediment input, land surfaces that are now below 1 m in elevation will be converted to open water or marsh (Fig. 3b). Landward of the barrier-island chains of the St Bernard and Lafourche deltas, ~7000 km^2 of the delta plain already lies below sea level, with estimated submergence of an

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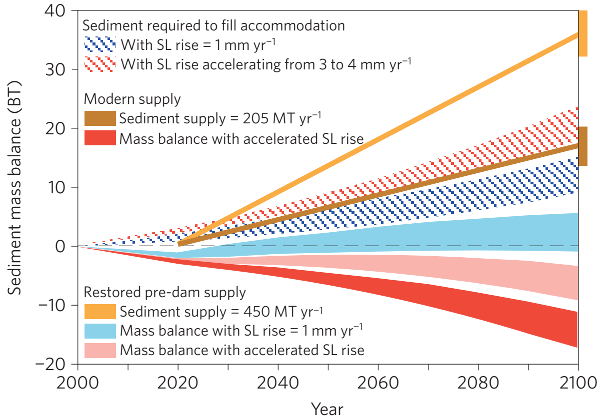

Figure 4 | Sediment mass balance for the delta region with modern sediment loads, and with hypothetical restored sediment loads. Supplies are held to 0 until the year 2020, then projected to the year 2100: the blocks at the right illustrate the standard deviation for modern loads, and ±10 for restored loads. The sediment required to fill accommodation is estimated for steady sea-level rise of 1 mm yr^{-1}, and sea-level rise that accelerates linearly from 3 to 4 mm yr^{-1} between the years 2000 and 2100. Each mass balance estimate uses subsidence models from Fig. 3c to define the upper and lower boundaries, and a 40% trapping efficiency.

extra 10,500–13,500 km^2 by the year 2100 (Fig. 3c). In this scenario, the new accommodation created will be ∼12–16 km^3, which will require ∼18–24 BT of sediment to fill.

We predict sediment mass balance to the year 2100 using four scenarios for sediment supply and sea-level change (see Supplementary Information). (1) With modern sediment loads for the combined Mississippi and Atchafalaya rivers, a trapping efficiency of 40% and sea-level rise of 1 mm yr^{-1}, the creation of accommodation outpaces sediment supply and results in a mass deficit of ∼1–5 BT by the year 2100: even with typical late Holocene rates of sea-level rise, further land loss would be inevitable unless the trapping efficiency approaches 100%. (2) With modern loads and sea-level rise that accelerates from 3 mm yr^{-1} in the year 2000 to 4 mm yr^{-1} in 2100, accommodation increases ∼3–4 times as fast as sediment can be supplied. The sediment mass balance deficit will be ∼11–17 BT by the year 2100, and even a trapping efficiency of 100% results in significant submergence. (3) With sediment loads restored to pre-dam values of 400–500 MT yr^{-1}, supplies would be sufficient to sustain the deltaic landscape with rates of sea-level rise of ∼1 mm yr^{-1}. (4) With restored loads and sea-level rise that accelerates from 3 mm yr^{-1} in the year 2000 to 4 mm yr^{-1} in 2100, there would be a mass balance deficit of 3–9 BT by the year 2100: significant drowning would be inevitable even with restored sediment loads unless the trapping efficiency is 100% (Fig. 4).

These results need to be viewed in the appropriate geologic context. Subsidence is intrinsic to large deltas, but most deltas did not form in their present positions until global sea-level rise decelerated[11]. In the Mississippi case, the alluvial valley filled with sediment in response to rapid early to middle Holocene sea-level rise, but the delta stepped landward. In contrast, during the late Holocene, after sea-level rise decelerated to <1 mm yr^{-1}, the Teche, St Bernard and Lafourche deltas were constructed on the inner shelf, and the shelf-margin Plaquemines–Balize Delta began to form. At no time in the late Holocene was the entire delta plain maintained in some steady state, and land loss and land gain occurred simultaneously to produce an evolving wetland matrix. However, modern total sediment loads are significantly less than the rates of sediment storage that were necessary to construct the delta plain in the first place, and modern loads are not sufficient to sustain a significant portion of the remaining delta surface area even with late Holocene rates of sea-level rise. Moreover, sea level is now rising at rates not experienced over the previous 7 kyr, and much of the delta region will drown in a manner similar to the backstepping and submergence events of the early Holocene even if natural loads and pathways for sediment dispersal are restored.

Mass balance considerations ensure that the future deltaic landscape cannot resemble the recent past, and even the most prudent selection of diversion sites can only slow the overall rate of submergence. A recent state-of-the-art model provides quantitative estimates for two diversions located to the south of New Orleans, which would have access to 45% of the lower Mississippi sediment load, or about 25% of the total Mississippi and Atchafalaya loads. With a trapping efficiency of 40%, and values for subsidence and sea-level rise similar to those above, 700–900 km^2 of new land can be built by the year 2110 (ref. 26). These modelling efforts highlight the mass balance problem, because the new land to be built is <10% of the extra submerged area that we predict for the year 2100. Building and/or sustaining significant land-surface area in far-downstream locations will therefore require bypass of most of the lower Mississippi sediment load through upstream reaches, which will be drowning at the same time. In contrast, diversions that disperse sediment into partially submerged or still emergent areas farther upstream will build or sustain more land-surface area with the available sediment supply: upstream diversions can leverage organic contributions to marsh accretion[27] (see Supplementary Information), as well as maximize the trapping efficiency because most sediment would be deposited on marsh and swamp surfaces, in tidal channels or in shallow lakes or bays where storm-generated sediment resuspension and landward transport is common[28,29]. Upstream diversions also have the virtue of mirroring geological processes that build deltas from the top down, from upstream to downstream.

Our calculations of sediment mass balance represent a conservative first-order assessment because we use modest subsidence rates, conservative sea-level rise estimates, optimistic sediment supplies and an optimistic timeline for implementation of large-scale diversions. More precise results are desirable, but will not change the fundamental nature and scale of the problem, and uncertainty should not be used to defer action to restore the delta region to a desired level of sustainability, or plan an inevitable retreat. Every decade of delay will increase the mass balance deficiency by more than a billion tons of sediment.

Methods

The estimated volume of post-glacial sediment in the Mississippi Valley and Delta is based on geographic information system (GIS) calculations of Holocene flood-plain and delta-plain area, integrated with the thickness of post-glacial deposits[9,15]: the estimated volume is 1,860–2,300 km^3. Mass estimates are based on a density of 1.5 g cm^{-3} for mixed sand and mud with 45% water-filled porosity. This results in 1.5 BT km^{-3}, and 2,790–3,450 BT of sediment. Over the 12 kyr period of valley filling and delta-plain construction, this requires a mean time-averaged storage rate of ∼230–290 MT yr^{-1}. The fraction stored in the delta plain is based on post-glacial sediments downstream from the latitude of Baton Rouge.

Estimates of relative sea-level rise integrate subsidence with predictions of global sea-level rise. We use subsidence rates supported by the geologic record[20], and assume that land-surface subsidence over century and longer timescales reflects <1 mm yr^{-1} for the pre-Holocene delta depocentre from isostatic adjustments to Holocene loading[9], and 1–8 mm yr^{-1} from compaction of the overlying Holocene section[30]. Compaction is the most important factor: compaction rates depend on the thickness of the Holocene section, and increase basinward. We assume the higher rates measured by geodetic techniques are transient and unrepresentative of century-scale and longer periods.

The tide gauge at Pensacola, Florida, located along a relatively stable part of the Gulf of Mexico shoreline, closely tracks global sea-level rise[21]: we therefore assume IPCC projections of global sea-level rise apply to the Gulf of Mexico. We estimate sea-level rise by increasing rates linearly from measured values for the year 2000 of 3 to 4 mm yr^{-1} in the year 2100, which is consistent with the IPCC SRES scenario A1B prediction of 4 mm yr^{-1} rates of sea-level rise for the year 2099 (ref. 23). Our values for relative sea-level rise are conservative, and would increase if we used higher values for subsidence and/or estimates for sea-level rise from other recent studies that explicitly consider ice-sheet dynamics[24].

Accommodation is calculated using GIS measurements of surface area that will be submerged, and a hinge-like model for subsidence. We define the area of submergence as land area now below 1 m elevation, calculated from the US National Geophysical Data Center Coastal Relief Model[31]. The area of submergence is defined statically, assuming no sediment input and no catastrophic high-energy tropical storm and hurricane events. We vary subsidence linearly from the latitude of Baton Rouge (30.5° N) to the latitude of Grand Isle (29° N). Lower and upper limits for estimated accommodation correspond to subsidence rates that vary from 1–6 mm $\mathrm{yr^{-1}}$ and 3–8 mm $\mathrm{yr^{-1}}$, respectively, over that distance. We exclude the Plaquemines–Balize Delta from our calculations, because its fate will be determined by whatever sediment passes through the system downstream from any diversions. We also exclude the Chenier Plain to the west, with an estimated 3,500 $\mathrm{km^2}$ of land surface area below 1 m in elevation[27], because existing diversion plans would not directly replenish that part of the coastline. Hence, our estimated accommodation would increase if we used higher values for subsidence and/or global sea-level rise, assumed step-wise change due to high-energy events or included the Plaquemines–Balize Delta and the Chenier Plain. We estimate the mass of sediment needed to fill this accommodation assuming 1.5 BT of sediment to fill 1 $\mathrm{km^3}$ of accommodation.

The mineral sediment available for dispersal to the delta plain is estimated using the mean suspended load of 205 MT $\mathrm{yr^{-1}}$ for the combined Mississippi and Atchafalaya rivers over the period 1976–2006 (refs 18, 19). We hold sediment supply = 0 until 2020, assuming no significant diversions will be implemented until then. This sums to 16.4 BT by the year 2100, which may be optimistic because of the downward trend in loads during the period of the record (Fig. 2), and because implementation of diversions may take longer.

Sediment mass balance is estimated using modern suspended sediment loads, or sediment loads restored to presumed pre-dam values of 400–500 MT $\mathrm{yr^{-1}}$. We calculate mass balance changes as the difference between accommodation and sediment supply for each scenario for 10-year increments between 2000 and 2100. A mass balance = 0 indicates rates of accommodation and sediment supply balance with a trapping efficiency of 40%, whereas negative numbers indicate supply deficiencies relative to accommodation. Our calculations do not consider organic contributions to increases in elevation of the land surface, which may be considerable[27], but are poorly known over spatial scales that correspond to the delta region as a whole, and over century timescales. In general, however, organic contributions will be minimized for diversions located in downstream reaches, where the land surface must first be built up to the intertidal zone before organic contributions can have a significant role, and maximized for diversions that are farther upstream where sediment can be dispersed onto land that is now intertidal or emergent.

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Author contributions

Modelling of submergence and sediment mass balance was conducted by M.D.B. Previous work on the lower Mississippi Valley, the Mississippi Delta and the Gulf of Mexico shoreline by H.H.R. and M.D.B. provided data and context for this study.

Additional information

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