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Drowning of the Mississippi Delta due to Insufficient Sediment Supply and Global Sea-Level Rise

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SUPPLEMENTAL INFORMATION

Research in the lower Mississippi valley and delta has a long and distinguished history, however there are uncertainties associated with nearly every aspect of valley and delta evolution, as well as rates of modern processes. The following outlines some of these issues, as well as provides key references to literature on the Mississippi system.

Post-Glacial Sediment Stored in Mississippi Valley and Delta

During the last glacial period, the lower Mississippi valley was incised below its previous highstand surface, and significantly deeper than the valley is now. Incision likely began during isotope stage 4 when global sea level fell significantly, but the majority of incision occurred after ca. 30 ka (late isotope stage 3), continuing through the last glacial maximum (isotope stage 2), then into the period of deglaciation. Incision was not a continuous process, but rather occurred stepwise, punctuated by periods of braided stream deposition. Incision followed by braided stream deposition began prior to ca. 65 ka, and continued until ca. 12 ka, with 3 high-frequency events between 20-12 ka in response to fluctuations in meltwater discharge from the ice margin in the upper Mississippi drainage. The youngest extensive braided stream deposits in the northern half of the valley have been dated with optically-stimulated luminescence (OSL) techniques to the period 12.4-11.3 ka, with transformation to a meandering regime by ca. 11-10 ka (Rittenour et al., 2005; 2007).

Post-glacial sediment in the Lower Mississippi alluvial valley consists of flood basin and lacustrine organic-rich mud interbedded with sandy meander-belt deposits (including crevasse-splay and levee sands and silts; Saucier, 1994). The post-glacial succession occurs as a wedge that tapers upstream, and flood-basin organic-rich muds onlap glacial period braided stream deposits. Kesel (2008) provides a radiocarbon-based chronology for the post-glacial sediment fill at the latitude of Baton Rouge, showing that the fine-grained part of the succession began to accumulate by ca. 11.5 ka, roughly the same time that OSL dating shows braided stream deposition ended in the northern half of the valley (Rittenour et al., 2005; 2007). According to Kesel (2008), channel belts continued to form through the late Holocene, but the valley as a whole was essentially full by ca. 4 ka.

Delta evolution is reasonably well-known, although chronological details remain the subject of ongoing research. The delta plain is a composite landscape that represents a succession of coupled channel courses and 5 constructional delta complexes (hereafter deltas) that were built over a period of ~7000-8000 yrs (see Fig. 1 in the paper; Törnqvist et al. 1996; Roberts and Coleman, 1996; Roberts et al., 1997; Stapor and Stone, 2004), with each delta consisting of a series of subdeltas. For example, the Maringouin delta formed on the mid-shelf by ca. 7.5 ka, when sea level was still rising rapidly, and was followed by formation of the Teche delta on the inner shelf by ca. 4.0-3.5 ka. Avulsion then relocated the river to the eastern margins of the alluvial valley, where the St. Bernard delta formed to the east of present-day New Orleans from ca. 4.0-2.0 ka, followed by avulsion and formation of the Lafourche delta to the west of New Orleans from 2.5-0.5 ka. The modern channel course flows between the St. Bernard and Lafourche courses, and has constructed the shelf-margin Plaquemine-Balize delta in the last millennium. Diversion to the Atchafalaya River course began around 500 yr ago, and represents the most recent attempt to avulse and construct a new delta, although it is now effectively limited by the USACE to ~30% of the Mississippi discharge. After the Atchafalaya Basin was filled with sediment, the Atchafalaya and Wax Lake deltas began to prograde into Atchafalaya Bay in the mid 20th century, and are actively growing today. LaFourche subdelta, and more than 180 m in far downstream reaches of the shelf-margin Plaquemine-Balize subdelta.

Blum (2007), Rittenour et al. (2007) and Blum et al. (2008) trace OSL-dated braided stream surfaces to the lowermost part of the valley using Corps of Engineer borehole data, at the latitude of New Orleans, and defined the overall thickness and extent of the post-glacial tapering wedge of sediments. Kulp (2000) among others (May et al., 1984; Dunbar et al., 1994) compiled borehole data from the delta region, and constructed detailed maps of post-glacial sediment thickness. Blum et al. (2008) merged these two sets of data to construct the wedge of post-glacial sediments from the upper valley to the shelf margin (Supplementary Fig. 1).

Calculation of net sediment stored in the Lower Mississippi Valley and delta is based on the thickness of flood basin facies that onlap glacial-period braided stream sands and gravels, and on the thickness of the post-glacial delta succession. In the upper half of the alluvial valley, Holocene channel belts partially cut out braided stream facies, but these effects were not included in sediment stored, because there is no net change in sediment mass balance, one set of deposits is merely replacing another. The upstream limits of onlap, as defined in Blum (2007) and Rittenour et al. (2007), lies just to the north of Memphis, at 35.5°N, some 600 km upstream from New Orleans.

Key references include:

Aslan, A. et al. Late Holocene Avulsion History of the Lower Mississippi River, South Louisiana. *J. Sed. Res.* **75**, 648-662 (2005).

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Saucier, R.T. *Geomorphology and Quaternary geologic history of the Lower Mississippi Valley*. Vicksburg, Mississippi River Commission, 364 p (1994).

Stapor, F.W. and Stone, G.W. A new depositional model for the buried 4000 yr BP New Orleans barrier: implications for sea-level fuctuations and onshore transport from a nearshore shelf source. Marine Geology **204**, 215-234 (2004).

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Sediment Supply

There are ~40,000 dams and reservoirs of some kind within the Mississippi drainage basin (Graf, 1999). Like most large river systems (see Syvitski et al., 2005), the Mississippi drainage has seen increases in rates of erosion due to agriculture and other activities, increased trapping of sediments within reservoirs and behind dams, with net reductions in delivery of sediment to lower reaches and the coastal oceans. Early 20th century suspended sediment load is estimated to have been ~400-500 MT/yr, but an estimated 70% of the Mississippi's natural sediment load has been trapped in dams and reservoirs constructed since 1950, with the largest reduction of load resulting from closure of 3 reservoirs on the upper Missouri River (Kesel, 1992). An additional ~30% decrease for the lower river resulted from construction of the Old River Control Structure, and permanent diversion of floodwaters down the Atchafalaya River, starting in 1963 (Roberts and Coleman, 1996).

For sediment supply estimates, we use sediment load data that was ultimately collected and/or published by the USGS and/or US Army Corps of Engineers. For sediment loads of the Lower Mississippi below the Atchafalaya diversion, we use data from USGS station 07295100, the Mississippi River at Tarbert Landing, Mississippi. For sediment loads of the Atchafalaya River, we use data from USGS station 07381490, the Atchafalaya River at Simmesport, Louisiana. For the time period prior to 1976, we use data compiled and published in Meade et al. (1990), Kesel et al. (1992), Mossa (1996) and Knox (2007). Within this longer time series, it is important to note that there are just a few years of data to actually base estimates of pre-dam (pre-1953) sediment loads upon, but the dramatic reduction due to dam closure is clear, with values of ~500 MT/yr recorded in the earliest 1950's. However, this short period of record follows widespread agricultural clearance in the Mississippi drainage, so the pre-dam estimates may be high relative to longer-term late Holocene averages.

For the more recent post-dam and post Atchafalaya diversion record, the 30-yr time period from 1977-2006, we use data directly from the USGS online database, at:

http://waterdata.usgs.gov/la/nwis/annual/?format=sites_selection_links&search_site_no=07295100&referred_module=sw

http://waterdata.usgs.gov/la/nwis/annual/?search_site_no=07381490&agency_cd=USGS&referred_module=sw&format=sites_selection_links

The sediment load values we use are not significantly different than values published by others in older publications, but tend to be slightly higher than the most recent papers suggest. For example, we use the mean for the period of record, but, as shown in our text Fig. 2, there is a general downward trend in sediment loads through the period of record, which has been discussed by Horowitz (2006) among others, and is attributed to effects of the 1993 flood. Moreover, there is some evidence that sediment storage between the Tarbert Landing station and New Orleans has reduced the loads farther downstream. These insights emerge from a examination of modern bedload transported in migrating dunes (Nittrouer et al. (2008) and processes for fine-grained sediment storage (Galler and Allison, 2008) in the reach below New Orleans.

Key studies of sediment load include:

Galler, J.J., Allison, M.A. Estuarine controls on fine-grained sediment storage in the lower Mississippi and Atchafalaya rivers. *GSA Bulletin* **120,** 386-398 (2008).

Graf, WL. Dam nation: a geographic census of American dams and their large-scale hydrologic impacts. *Water Resources Research,* **35**, 1305-1311 (1999).

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Kesel, R.H. et al. An approximation of the sediment budget of the lower Mississippi River prior to major human modification. *Earth Surf. Proc. Landforms* **17**, 711 (1992).

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Roberts, H.H. and Coleman, J.M. Holocene evolution of the deltaic plain: a perspective – from Fisk to present. *Engineering Geology* **45**, 113-138 (1996).

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Subsidence Rates

Land-surface subsidence in the delta region is the cumulative result of a variety of processes that vary spatially, and through time (Kulp, 2000). Subsidence rates are controversial, in part because of the disparity between rates measured by modern geodetic and space-born instruments, which measures rates over the period of instrument data collection, and rates that can be supported by the geologic record, which reflect time-averaging over the period of record. For example, rates of 3-25 mm/yr have been reported from various parts of the delta region based on releveling of benchmarks (Shinkle and Dokka, 2004), high-resolution GPS (Dokka, 2006; Dokka et al., 2006), or synthetic-aperture radar measurements (Dixon et al., 2006). By contrast, stratigraphic data do not support rates significantly higher than 3-8 mm/yr over Holocene time scales, or >0.3 mm/yr over longer time periods (Meckel, 2008).

Much of the controversy around subsidence rates also concerns the relative influence of deep-seated processes (primarily growth faulting and isostatic compensation), vs. compaction of the Holocene sediment load, and human activities. For this paper, we assume the high short-term rates measured by geodetic and space-borne techniques are dominated by transient processes, and are not representative of the delta plain over century-scale and longer periods. For example, high rates of subsidence have been attributed to inferred growth faults in the New Orleans area (Dokka, 2006 and Dokka et al., 2006; Supplementary Fig. 2), yet in areas where faults have been inferred, there is no subsurface evidence for significant deformation of late Pleistocene through Miocene strata (Edrington et al., 2008; Supplementary Fig. 3). If motion on the Michoud Fault averaged 0.1 mm/yr, there should be more than 10 m of offset on the Pleistocene-Holocene stratal contact, and hundreds of meters within Miocene strata. We therefore conclude there is no evidence for sustained or repeat activity on these faults, and measured rates should not be extrapolated to different or longer periods of time (see also Meckel, 2008).

High rates of isostatic compensation to Holocene loading have also been inferred. For example, Ivins et al. (2007) modeled isostatic response to Holocene loading, and inferred rates of isostatic subsidence of 4 mm/yr for the New Orleans area. They conditioned their model to GPS stations within the delta region. However, as noted by Törnqvist et al. (2008), the three GPS stations used are all located on Holocene successions that are at least twice as thick as the depth of their monuments, and the actual record of land-surface subsidence at those locations must include a significant Holocene compaction component, in addition to any isostatic compensation from the load itself. Blum et al. (2008) model isostatic adjustments of the Pleistocene-Holocene contact in response to Holocene loading to be < 1 mm/yr through most of the delta at the latitude of New Orleans, dissipating over distances of 15 km from the Mississippi valley margin, whereas modeling by Syvitski (2008; also Hutton and Syvitski, 2008) suggests isostatic rates varied spatially and temporally through the late Holocene, from < 1 to ~4 mm/yr.

Rates of isostatic and other deep-seated mechanisms can be constrained by geologic data. Törnqvist et al. (2004, 2006) provide a detailed set of age versus present depth relations for brackish-marsh basal peats that onlap the Pleistocene-Holocene contact along the eastern and western margins of the lower Mississippi Valley, roughly at the latitude of New Orleans, at the updip margins of the delta plain. Basal peats form as the local water table rises in response to local sea-level rise, and therefore provide a record of motion of the Pleistocene-Holocene contact, the top of the pre-Holocene depocenter, relative to Gulf of Mexico sea level change itself (Blum et al., 2008). For example, if the surface has been stable, relative to sea-level change, the Törnqvist et al. (2004; 2006) data would indicate time-averaged rates of sea-level rise = 0.8 mm/yr. Or, conversely, if sea-level change = 0, the Törnqvist et al. (2004; 2006) data would provide a precise record of time-averaged rates of subsidence for the top of the deltaic depocenter, and would constrain those rates to 0.8 mm/yr at the locations studied. However, subsidence of the Pleistocene-Holocene contact at rates > 1.3 mm/yr would require significant sea-level fall over the basal-peat period of record, at mean time-averaged rates of 50 cm/1000 yrs (see Supplementary Fig. 4), and a cumulative fall of 3 m over the last 6 kyrs. As discussed more fully below, we know of no significant body of evidence, either globally or locally, that suggests rates of sea-level fall have been this high or higher through the entire late Holocene period.

Transient high rates are also known to result from subsurface fluid withdrawals and loading due to construction activities, which have been, or will be mitigated (Morton et al., 2006). We do not consider these factors because of the time scales involved, and assume they will be mitigated within the next decade or so. The effects of such anthropogenic effects are therefore part of the higher rates inferred from the mid-late 20th century, and will not be a key feature for the 21st century.

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Our estimates of accommodation therefore use subsidence rates that can be supported by the geologic record, following similar arguments in Meckel (2008). We assume that land-surface subsidence over century and longer time scales is dominated by compaction of the Holocene section, and minor isostatic adjustments to Holocene loading (see discussion of relative sea-level change below). We assume values of 0-7 mm/yr from compaction of the overlying Holocene section (Roberts and Coleman, 1996; Meckel et al., 2006; Törnqvist et al., 2008), and a mean value of 1 mm/yr for deep-seated subsidence, which includes growth faulting and isostatic adjustments to Holocene loading. Compaction rates and isostatic adjustments depend on thickness of the Holocene section, and increase basinward, with rates of isostatic adjustment decreasing alongshore with distance from the Holocene load center. However, major rate increases occur downdip from our area of interest within the Plaquemines-Balize delta, and seaward from the barrier-island arcs of the Lafourche delta.

Key references include:

Blum, M.D. et al., Ups and downs of the Mississippi delta. *Geology* **36**, 675-678 (2008).

Dixon, T.H. et al., Subsidence and flooding in New Orleans. *Nature* **441**, 587-588 (2006);

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Sea-Level Change

The record of Holocene sea-level change in the Gulf of Mexico is controversial (Blum et al., 2001; 2003; 2008; Otvos, 2004; Törnqvist et al., 2004; 2006; Gonzalez and Törnqvist, 2006; Milliken et al., 2008; Donnelly and Giosan, 2008). We think of this record in terms of end-member interpretations that are conditioned by data location and type, the suite of processes that compile to produce the signal of relative sea-level change, and an inherent spatial variability of sea-level records that reflects the influence of the Mississippi delta depocenter and perhaps a range of other poorly understood processes.

One end-member view interprets continual submergence, with late Holocene rates of rise for the Gulf as a whole equal to 0.55-1 mm/yr. As noted above, these rates are derived from radiocarbon-dated basal peat in the delta region, which onlap the Pleistocene-Holocene contact in the delta region as the local water table rises in response to local sea-level rise (Törnqvist et al., 2004, 2006). Basal-peat data have the virtue of eliminating the effects of compaction of Holocene sediments from sea-level calculations, which otherwise dominates the signal of relative sea-level change in the delta region: Törnqvist et al. (2004, 2006) interpret the Pleistocene-Holocene contact on which basal peats accumulated to be stable, and interpret basal peat data to represent a regional signal of relative sea-level change that is representative of the northern Gulf of Mexico as a whole, with continual submergence due to ongoing glacio-isostatic adjustments. An alternative end-member view, based on optical and radiocarbon dating of coastal landforms from parts of the Gulf Coast that are far removed from the delta region (Blum et al., 2001; 2002; 2003; 2008), suggests that sea-level change for the Gulf of Mexico as a whole may be negligible, or sea level may have actually fallen slightly (< 1 m) in the late Holocene prior to the historic period. Blum et al. (2008) suggest that basal peat data from the delta region can only document rates of motion of the Pleistocene-Holocene surface, relative to sea-level change in the Gulf of Mexico as a whole, and the signal of continual relative sea-level rise from the delta region must also include isostatic adjustments to Holocene sediment loading. These two contrasting views of Holocene sea-level change are illustrated in Supplementary Fig. 4a. For a discussion of this controversy see Donnelly and Giosan (2008).

The primary significance of these two contrasting models lies in assumptions about the relationship between Mississippi delta aggradation and progradation on the one hand, and relative sea-level change on the other: it is commonly assumed that, prior to human interference, deltaic deposition kept pace with relative sea-level rise by dispersing sediments through the network of distributary channels. In theory, the delta should respond to relative sea-level change, which we define as the motion of the land surface relative to the sea surface. Differentiating relative sea-level change into its components, this would include (a) relative sea-level change for the Gulf of Mexico as a whole (changes in water surface elevation, as well as ongoing glacio- and hydroisostatic adjustments of the land surface), (b) isostatic deformation of the Pleistocene-Holocene surface within the delta depocenter, from where the Törnqvist et al. (2004, 2006) data is derived, and (c) syndepositional and early post-depositional compaction of the Holocene sediment load.

Under the continual-submergence model, aggradation and progradation of the St. Bernard, Lafourche, and Plaquemines-Balize deltas took place when relative sea-level rise for the Gulf of Mexico as a whole was < 1 mm/yr. Under the alternative model, major deltaic aggradation and progradation would have taken place under stable or slightly falling sea level for the Gulf of Mexico as a whole, and much of the recent submergence results from a change in the direction of sea-level change following the Little Ice Age, such that sea-level rise began at that time (~200 yrs ago). Submergence then accelerated as a result of human activities that included levee construction, reductions of sediment load, and subsurface fluid withdrawals, but also 20th century accelerated sea-level rise.

For the mass balance calculations presented here, we assume that rates of sea-level change can be bracketed by these alternative end-member views (Supplementary Fig. 4b), and these end-member views in turn bracket rates of deep-seated subsidence. These assumptions are based on the following: (a) the regional signal of sea-level change is best represented by data far from the delta region, is very small (<< ±0.5 mm/yr) over late Holocene time scales, and includes changes in water surface elevation, as well as ongoing glacio- and hydroisostatic adjustments, (b) basal-peat data from the delta region must include some isostatic component from the Holocene load, and perhaps other deep-seated effects as well, and (c) when considered in the context of available data on global and regional sea-level change, basal-peat data from the delta region define a maximum deep-seated subsidence rate of < 1.3 mm/yr (if Gulf of Mexico sea-level fall has been 0.5 mm/yr), and a maximum rate of sea-level rise of < 1 mm/yr (if deep-seated subsidence = 0). We assume that, over late Holocene time scales, sediment supply and rates of deposition were sufficient to aggrade and prograde the St. Bernard, Lafourche, and Plaquemines-Balize deltas, with the aggradational component filling space created by compaction of Holocene sediments themselves, plus a regional sea-level rise and deep-seated subsidence component that was ≤ 1.3 mm/yr for the latitude of New Orleans.

Estimates of future sea-level change are uncertain as well, however, there is every reason to assume that Gulf of Mexico sea level is closely tied to the globally-coherent eustatic component. Based on close correspondence between the tide gauge at Pensacola, Florida, and a generally-agreed eustatic rate (Gonzalez et al., 2006), we assume the Gulf as a whole has a strongly eustatic component, so we use IPCC 2007 estimates (Bindoff et al., 2007; Meehl et al., 2007) to predict future sea-level rise for the Gulf of Mexico as a whole, independent from projections of subsidence rates. However, IPCC estimates are considered to be conservative by many workers, with recent publications suggesting future rates that are 2-3 (Pfeffer et al., 2008) and even 5 times as high (Rahmstorf, 2007) by the year 2100.

Key references on sea-level change are as follows:

Bindoff, N. et al. Observations: Oceanic Climate Change and Sea Level (*Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change:* Cambridge University Press, 2007);

Blum, M.D. et al. Middle Holocene sea-level rise and highstand at +2 m, central Texas Coast: *Journal of Sedimentary Research*, **71**, 581-588 (2001).

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Donnelly, J.P, Giosan, L., Tempestuous highs and lows in the Gulf of Mexico. *Geology* **36**, 751-752 (2008);

Gonzalez, J.L., Törnqvist, T.E., Coastal Louisiana in crisis: Subsidence or sea level rise? *Eos* **87**, 493–498 (2006);

Meehl, G.A. et al. Global Climate Projections (*Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change:* Cambridge University Press, 2007);

Milliken, K.T. et al. A new composite Holocene sea-level curve for the northern Gulf of Mexico (*Response of Upper Gulf Coast Estuaries to Holocene Climate Change and Sea-Level Rise*: Geological Society of America Special Paper **443**, 1-11; 2008).

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Törnqvist, T.E. et al., How stable is the Mississippi Delta? *Geology* **34**, 697-700 (2006).

Estimated Land Loss and Accommodation

USGS estimates for additional submergence and land loss by the year 2050 are lower than ours, primarily due to different methods (Barras et al., 2004). USGS estimates are based on extrapolation of 20th century trends, whereas ours are based on integration of present land-surface elevation with a subsidence model, and a model for accelerating sea-level rise. Recent land loss and submergence rates are known to be lower than 20th century maximum values, which is attributed to reductions in withdrawal of subsurface oil and gas (Morton et al., 2006). However, USGS estimates are based on extrapolation of trends from a time period dominated by lower rates of sea-level rise. Even with subsidence = 0, more than half of our estimated accommodation would be created simply due to an acceleration of sea-level rise from current rates of 3 mm/yr to 4 mm/yr by the year 2100.

We use the NOAA Coastal Relief model to generate the area of submergence, however results do not change substantially when higher-resolution LIDAR data is used. Our area of submergence corresponds to the 1 m contour interval, but there is little difference in projected area of submergence if we used the 50 cm contour.

Assumptions about subsidence rates play a key role in calculation of accommodation. There would be no disagreement about the overall hinge-like subsidence profile, which is typical of all passive margins. However, rates are controversial, as noted above. We use 2 subsidence models to calculate accommodation. The more conservative model varies subsidence from 1 mm/yr at the latitude of Baton Rouge to 6 mm/yr at the latitude of Grand Isle, located on the barrier island arc of the Lafourche delta. The less conservative model varies subsidence from 3-8 mm/yr over that same distance.

Key references on land loss estimates include:

Barras, J.A. et al. *Historic and predicted coastal Louisiana land changes: 1978-2050* (U.S. Geological Survey Open File Report 03-334. U.S. Geological Survey, National Wetlands Research Center, Lafayette, LA. 2003);

Barras, J.A. et al. *Land Area Change in Coastal Louisiana: A Multidecadal Perspective (from 1956 to 2006)* (Pamphlet to accompany U.S. Geological Survey Scientific Investigations Map 3019. U.S. Geological Survey, National Wetlands Research Center, Lafayette, LA. 2008);

Divins, D.L., Metzger, D. NGDC Coastal Relief Model, 88.5-92.5°W and 28.5-32°N. http://www.ngdc.noaa.gov/mgg/coastal/coastal.html.

Morton, R. A., Bernier, J. C. & Barras, J. A. Evidence of regional subsidence and associated interior wetland loss induced by hydrocarbon production, Gulf Coast region, USA. *Environmental Geology* **50**, 261–274 (2006).

Sediment Required to Sustain Delta Surface Area

Our estimates for sediment required to fill accommodation are based on mineral sediment supply only. We assume a trapping efficiency of 40%, but also note that trapping efficiencies of 100% may not be sufficient. Supplementary Table 1 shows our predicted mass balance calculations.

A considerable body of literature shows that organic contributions can play a key role in vertical accretion of marsh surfaces in the delta region (e.g. DeLaune et al., 1983; Baumann et al., 1984; Nyman et al., 1990; Reed, 2002; Lane et al., 2006), but the net contributions are spatially non-uniform and depend on a variety of factors, and there are significant differences between fresh (high rates or organic contribution) and brackish marsh (lower rates) environments. However, in a commentary on plans for coastal restoration, Dean (2006) suggests that organic contributions can be 4-10 times that of mineral sediment, and concludes there is more than enough sediment available to rebuild the delta region through land-building and land-sustaining diversions. We think it likely that organic contributions can contribute a significant component to vertical accretion, but only after the land surface has been raised to the intertidal zone or higher by mineral sediment deposition. Hence, organic contributions will be most significant for any diversion plans that are implemented upstream from New Orleans, where much of the delta plain remains emergent or minimally submerged. In far downstream reaches, where submergence has already occurred, the sediment-water interface must be raised to the intertidal zone by mineral sediment deposition before organic contributions can be leveraged.

Organic contributions to vertical accretion of marsh surfaces should not be ignored, but organic contributions at a scale comparable to the area of predicted submergence are not known, nor are the sustained contribution of organic material over time, since it will be affected by shallow compaction, decomposition, and other processes. In fact, the delta as a whole contains widespread peats and organic-rich sediments that accumulated in mostly freshwater environments, but most of the volume is comprised of mineral sediment (Kosters and Suter, 1993; Kosters et al., 1987). Moreover, as shown by Törnqvist et al. (2008), mineral sediment deposition on top of organic-rich substrates will result in high rates of compaction of the organic-rich component.

We suggest it is possible that, like many Earth surface processes (see Sadler, 1981), the net rates of organic contributions measured over century time scales will be significantly less than rates measured over a period of years. As shown by Kosters et al. (1987), rates of vertical accretion of peats measured from shallow subsurface data are an order of magnitude lower than modern measurements of surface accretion, which illustrates the effects of shallow compaction, and the potentially transient nature of net elevation gain by organic contributions.

Key references on the role of organic contributions include:

Baumann, R.H. et al. Mississippi deltaic wetland survival: sedimentation versus coastal submergence. *Science* **224**, 1093-1095 (1984).

Dean, R.G., New Orleans and the wetlands of southern Louisiana. *The Bridge* **36**, 35-42 (2006).

DeLaune, R.D. et al. Relationships among vertical accretion, coastal submergence, and erosion in a Louisiana Gulf Coast marsh. *Journal of Sedimentary Research* **53**, 147-157 (1983).

Kosters, E.C. et al. Sedimentary and botanical factors influencing peat accumulation in the Mississippi delta. *Journal of the Geological Society* **144**, 423-434 (1987).

Kosters, E.C. and Suter, J.R. Facies relationships and systems tracts in the late Holocene Mississippi delta plain. *Journal of Sedimentary Petrology* **63**, 727-733 (1993).

Lane, R.R. et al. Wetland surface elevation, vertical accretion, and subsidence at three Louisiana estuaries receiving diverted Mississippi River water. *Wetlands* **26**, 1130-1142 (2006).

Nyman, J.A. et al. Wetland soil formation in the rapidly subsiding Mississippi River deltaic plain: mineral and organic matter relationships. *Estuarine, Coastal and Shelf Science* **31**, 57-69 (1990).

Reed, D.J. Sea-level rise and coastal marsh sustainability: geological and ecological factors in the Mississippi delta plain. *Geomorphology* **48**, 233 (2002).

Sadler, P.M. Sediment accumulation rates and the completeness of stratigraphic sections. *Journal of Geology* **89**, 569–584 (1981).

Törnqvist, T.E. et al., Mississippi Delta subsidence primarily caused by compaction of Holocene strata. *Nature Geoscience* 1, 173-176 (2008).

DOI: 10.1038/NGEO553

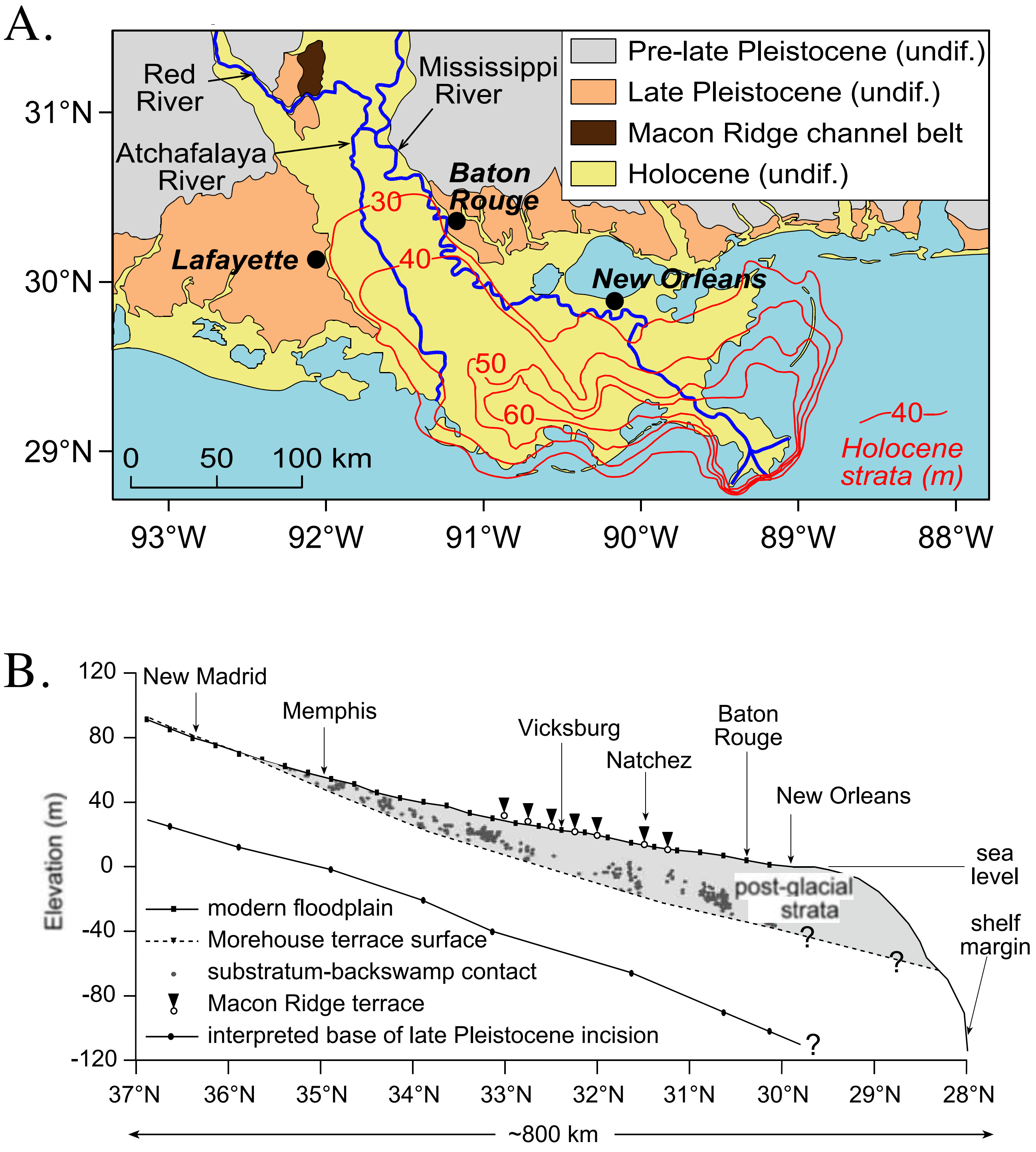

Fig. 1 - (a) Geologic map of the delta region, illustrating the extent of the Holocene delta plain, and thickness of post-glacial sediments. (b) Longitudinal profile of the lower Mississippi valley, illustrating thickness of post-glacial sediments for the valley as a whole (after Kulp, 2000; Blum et al., 2008).

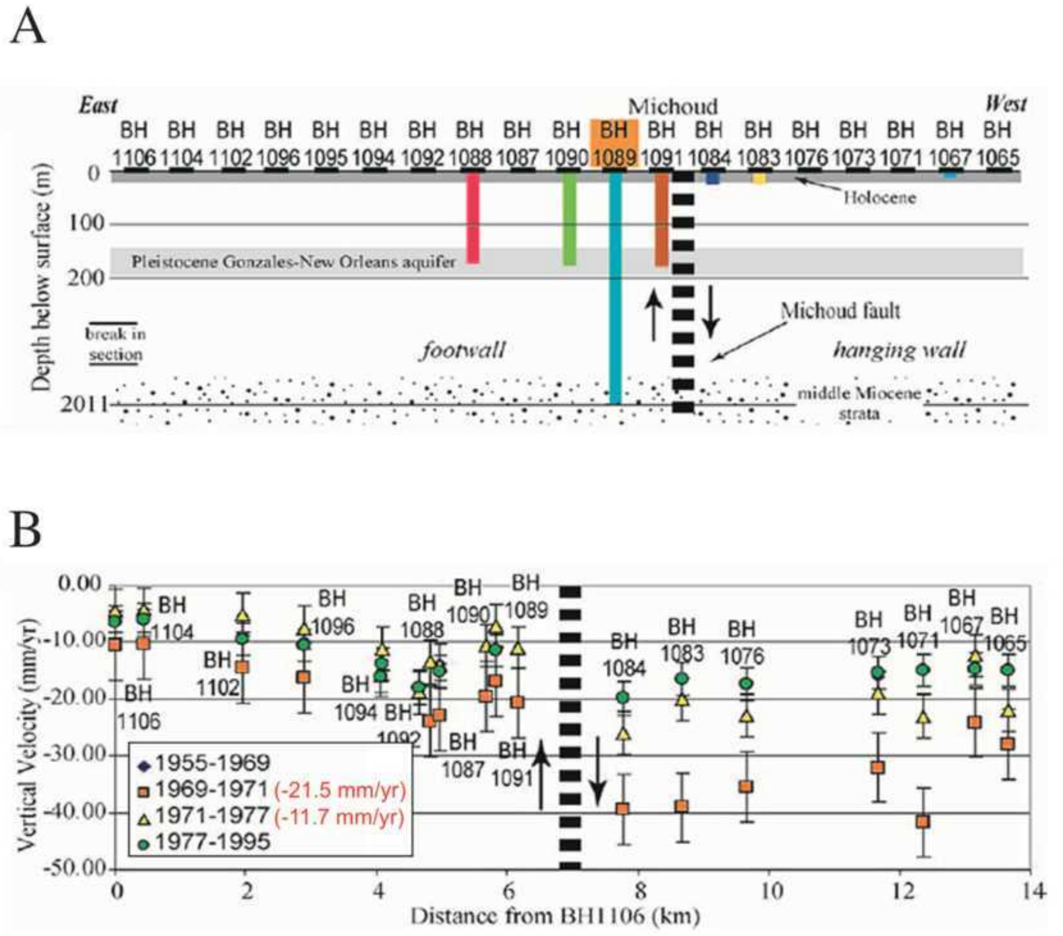

Fig. 2 - (a) Location of benchmarks used to compute vertical velocities of land-surface motion for New Orleans East, and the location of the inferred Michoud Fault. (b) Rates of vertical motion based on releveling of benchmarks for the period 1955-1995. Abnormally high rates for the period 1969-1977 are interpreted to represent motion on the inferred Michoud Fault, which is, in turn inferred to contribute to high rates of subsidence from tectonic processes, rather than from compaction of Holocene strata (after Dokka, 2006).

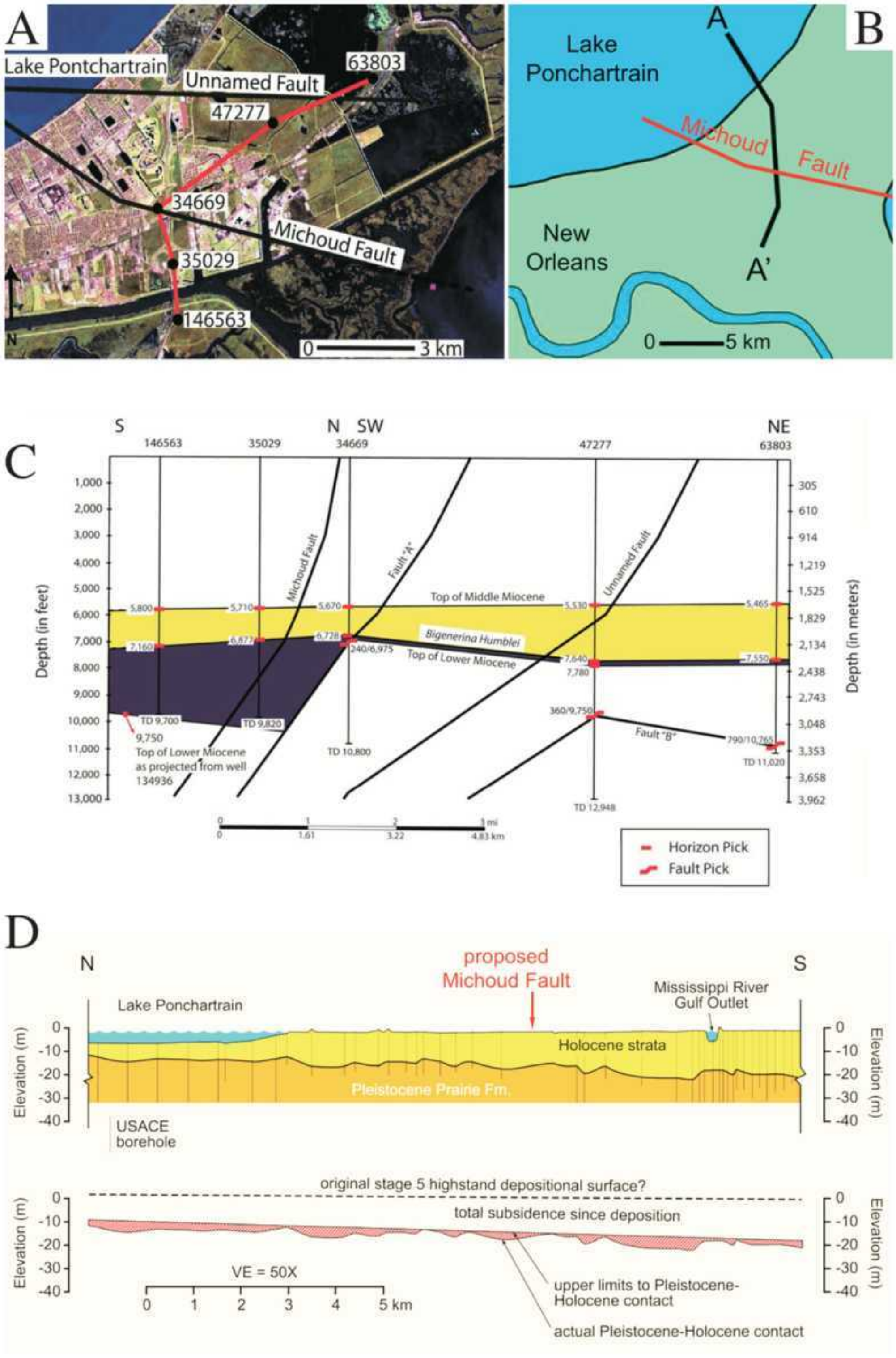

Fig. 3 - Geologic constraints on subsidence rates for the New Orleans area. (a) Landsat image of New Orleans East, showing the location of the inferred Michoud Fault, and the location of cross-section in Fig. 3c. (b) Map showing location of cross-section in Fig. 3d, relative to the inferred Michoud Fault. (c) Stratigraphic and structural cross-section from well logs, illustrating lack of deformation of middle Miocene strata (from Edrington et al., 2008). (d) Stratigraphic cross-section from US Army Corps of Engineers boreholes, showing lack of deformation of Late Pleistocene strata in area of the inferred Michoud Fault (from Edrington et al., 2008).

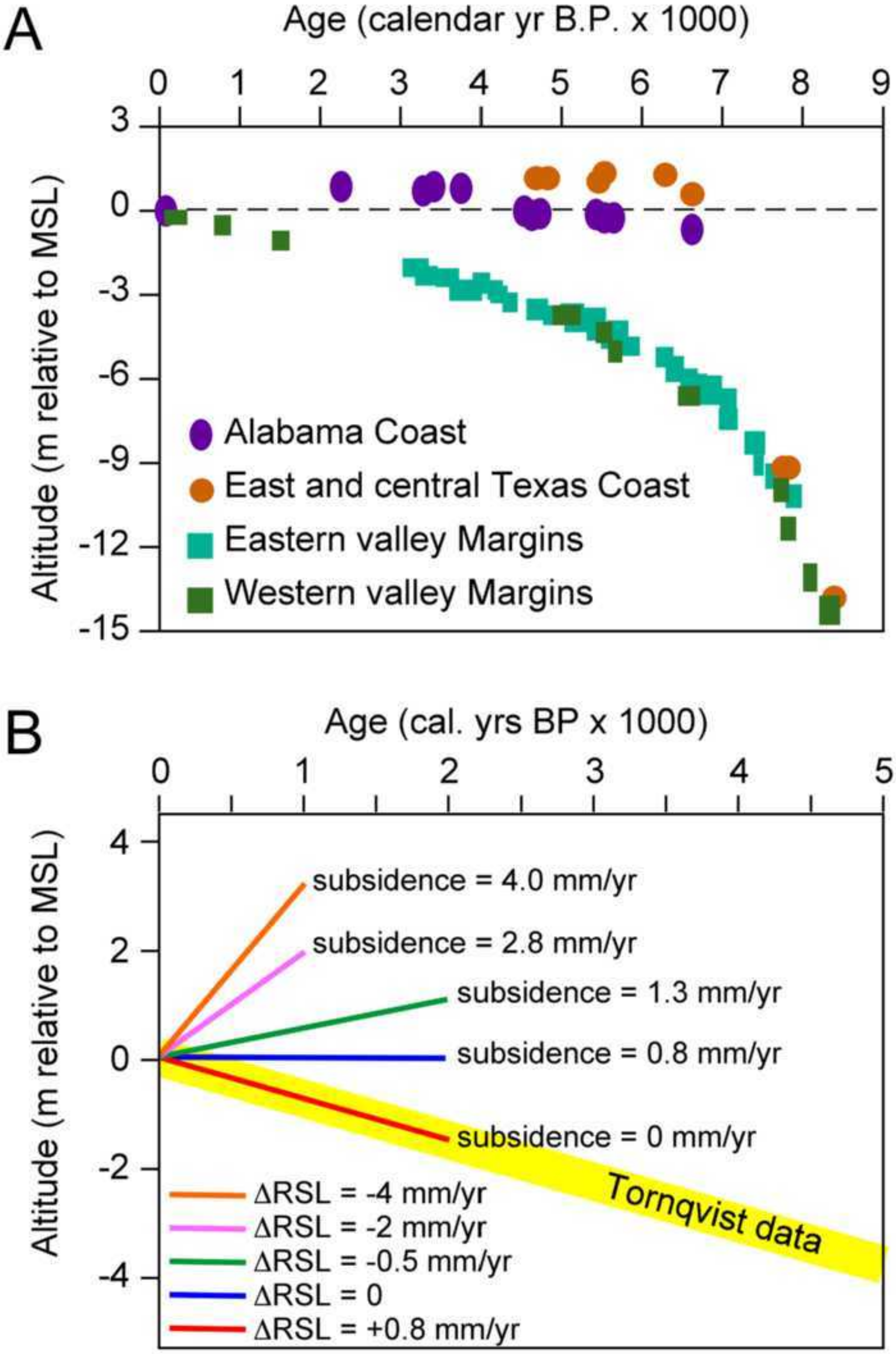

Fig. 4 - (a) Contrasts between sea-level data from the Texas and Alabama coasts, and data from the Mississippi delta region (after Blum et al., 2008). (b) Model to estimate maximum rates of sea-level rise over late Holocene time scales, based on the assumption that the Tornqvist et al. (2004; 2006) basal peat data defines the rate of movement of the Pleistocene-Holocene contact in the delta region with respect to relative sea-level change (ΔRSL) for the Gulf of Mexico as a whole. If the Pleistocene-Holocene contact in the delta region is stable and subsidence = 0, then ΔRSL is defined by the Tornqvist et al. (2004; 2006) data, ~ +0.8 mm/yr. If ΔRSL = 0, then the Tornqvist et al. (2004; 2006) data would indicate rates of deep-seated subsidence = 0.8 mm/yr. Higher rates of deep-seated subsidence would require relative sea-level fall so as to reconcile with the Tornqvist et al (2004; 2006) basal-peat data. Reconciling basal peat data with the rates of deep-seated subsidence modelled by Ivins et al. (2007) for the New Orleans area, ~ 4 mm/yr, would require sea-level fall of ~4 m over the last 1000 yrs.

Table 1. Mass balance calculations.

Mass Balance With Combined Modern Mississippi and Atchafalaya Loads = 205 MT/yr

Year	Modern Mississippi and Atchafalaya Sediment Supply (BT)	Low Subsidence 1 mm/yr SL Rise Accommodation (km3)	Sediment Needed (BT)	Mass Balance with TE=100% (BT)	Mass Balance with TE=40% (BT)	High Subsidence 1 mm/yr SL Rise Accommodation (km3)	Sediment Needed (BT)	Mass Balance with TE=100% (BT)	Mass Balance with TE=40% (BT)	Low Subsidence IPCC SL Change Accommodation (km3)	Sediment Needed (BT)	Mass Balance with TE=100% (BT)	Mass Balance with TE=40% (BT)	High Subsidence IPCC SL Change Accommodation (km3)	Sediment Needed (BT)	Mass Balance with TE=100% (BT)	Mass Balance with TE=40% (BT)
2000	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
2010	0.00	0.46	0.69	0.00	-0.69	0.71	1.07	-1.07	-1.07	0.73	1.10	-1.10	-1.10	0.90	1.35	-1.35	-1.35
2020	0.00	0.93	1.40	-1.40	-1.40	1.49	2.24	-2.24	-2.24	1.54	2.31	-2.31	-2.31	1.94	2.91	-2.91	-2.91
2030	2.05	1.45	2.18	-0.13	-1.36	2.34	3.51	-1.46	-2.69	2.46	3.69	-1.64	-2.87	3.15	4.73	-2.68	-3.91
2040	4.10	1.98	2.97	1.13	-1.33	3.27	4.91	-0.81	-3.27	3.45	5.18	-1.08	-3.54	4.49	6.74	-2.64	-5.10
2050	6.15	2.54	3.81	2.34	-1.35	4.28	6.42	-0.27	-3.96	4.53	6.80	-0.65	-4.34	5.98	8.97	-2.82	-6.51
2060	8.20	3.24	4.86	3.34	-1.58	5.52	8.28	-0.08	-5.00	5.70	8.55	-0.35	-5.27	7.62	11.43	-3.23	-8.15
2070	10.25	3.84	5.76	4.49	-1.66	6.46	9.69	0.56	-5.59	6.94	10.41	-0.16	-6.31	9.39	14.09	-3.84	-9.99
2080	12.30	4.49	6.74	5.57	-1.82	7.62	11.43	0.87	-6.51	8.52	12.78	-0.48	-7.86	11.32	16.98	-4.68	-12.06
2090	14.35	5.15	7.73	6.63	-1.99	8.85	13.28	1.08	-7.54	10.01	15.02	-0.66	-9.28	13.43	20.15	-5.80	-14.41
2100	16.40	5.81	8.72	7.69	-2.16	10.12	15.18	1.22	-8.62	11.80	17.70	-1.30	-11.14	15.69	23.54	-7.14	-16.98

Mass Balance With Hypothetical Restored Pre-Dam Total Lower Mississippi Sediment Load = 450 MT/yr

Year	Natural Sediment Supply (BT)	Low Subsidence 1 mm/yr SL Rise Accommodation (km3)	Sediment Needed (BT)	Mass Balance with TE=100% (BT)	Mass Balance with TE=40% (BT)	High Subsidence 1 mm/yr SL Rise Accommodation (km3)	Sediment Needed (BT)	Mass Balance with TE=100% (BT)	Mass Balance with TE=40% (BT)	Low Subsidence IPCC SL Change Accommodation (km3)	Sediment Needed (BT)	Mass Balance with TE=100% (BT)	Mass Balance with TE=40% (BT)	High Subsidence IPCC SL Change Accommodation (km3)	Sediment Needed (BT)	Mass Balance with TE=100% (BT)	Mass Balance with TE=40% (BT)
2000	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
2010	0.00	0.46	0.69	0.00	-0.69	0.71	1.07	-1.07	-1.07	0.73	1.10	-1.10	-1.10	0.90	1.35	-1.35	-1.35
2020	0.00	0.93	1.40	-1.40	-1.40	1.49	2.24	-2.24	-2.24	1.54	2.31	-2.31	-2.31	1.94	2.91	-2.91	-2.91
2030	4.50	1.45	2.18	2.33	-0.38	2.34	3.51	0.99	-1.71	2.46	3.69	0.81	-1.89	3.15	4.73	-0.23	-2.93
2040	9.00	1.98	2.97	6.03	0.63	3.27	4.91	4.10	-1.31	3.45	5.18	3.83	-1.58	4.49	6.74	2.27	-3.14
2050	13.50	2.54	3.81	9.69	1.59	4.28	6.42	7.08	-1.02	4.53	6.80	6.71	-1.40	5.98	8.97	4.53	-3.57
2060	18.00	3.24	4.86	13.14	2.34	5.52	8.28	9.72	-1.08	5.70	8.55	9.45	-1.35	7.62	11.43	6.57	-4.23
2070	22.50	3.84	5.76	16.74	3.24	6.46	9.69	12.81	-0.69	6.94	10.41	12.09	-1.41	9.39	14.09	8.42	-5.09
2080	27.00	4.49	6.74	20.27	4.07	7.62	11.43	15.57	-0.63	8.52	12.78	14.22	-1.98	11.32	16.98	10.02	-6.18
2090	31.50	5.15	7.73	23.78	4.88	8.85	13.28	18.23	-0.67	10.01	15.02	16.49	-2.42	13.43	20.15	11.36	-7.55
2100	36.00	5.81	8.72	27.29	5.69	10.12	15.18	20.82	-0.78	11.80	17.70	18.30	-3.30	15.69	23.54	12.47	-9.14

1. Calculations assume sediment-water mixture of 1.5 T/m3 = 1.5 BT/km3. This value assumes 45% porosity, which is filled with water, and that the remaining volume must be filled with mineral sediment mass.
2. Calculations assume no significant sediment diversions to the delta plain until after 2020, and either the modern sediment load is not dispersed until that time, or natural sediment load is not returned to the river, and dispersed to the delta plain, until that time.
3. IPCC SL Change is approximated by a linear acceleration of sea-level rise from current rates of 3 mm/yr to 4 mm/yr by the year 2100, the rate estimated by the IPCC 2007 A1B scenario.
4. TE = trapping efficiency, defined as the fraction of sediment available that is deposited on the delta surface. Mass balance is positive if there is more sediment available than required, and negative if sediment supply is insufficient to fill accomodation.