Sediment Diversions on the Lower Mississippi River: Insight from Simple Analytical Models

Author(s): Robert G. Dean, John T. Wells, H.J. Fernando, and Peter Goodwin

Source: Journal of Coastal Research, 30(1):13-29.
Published By: Coastal Education and Research Foundation
DOI: http://dx.doi.org/10.2112/JCOASTRES-D-12-00252.1
URL: http://www.bioone.org/doi/full/10.2112/JCOASTRES-D-12-00252.1

Journal of Coastal Research | 30 | 1 | 13–29 | Coconut Creek, Florida | January 2014

Sediment Diversions on the Lower Mississippi River: Insight from Simple Analytical Models

Robert G. Dean[†], **John T. Wells**[‡], **H.J. Fernando**[§], **and Peter Goodwin**[††]

[†]Department of Civil and Coastal Engineering
University of Florida
Gainesville, FL 32611, U.S.A.
dean@coastal.uf.edu

[‡]Virginia Institute of Marine Science
P.O. Box 1346
Gloucester Point, VA 23062, U.S.A.

[§]Department of Civil Engineering and Geological Sciences
University of Notre Dame
South Bend, IN 46556, U.S.A.

[††]University of Idaho
Department of Civil Engineering
Boise, ID 83702, U.S.A.

www.cerf-jcr.org

ABSTRACT

www.JCRonline.org

Dean, R.G.; Wells, J.T.; Fernando, H.J., and Goodwin, P., 2014. Sediment diversions on the lower Mississippi River: insight from simple analytical models. *Journal of Coastal Research,* 30(1), 13–29. Coconut Creek (Florida), ISSN 0749-0208.

River diversions offer a mechanism by which sediment-laden waters can be introduced into interdistributary basins and bays to build new land that provides a substrate for wetland growth. Two geometric models were developed to allow calculation of future performance of river diversions with emphasis on the Mississippi River. These geometries, a truncated cone and a uniform width geometry, assume a constant discharge of sediment into the receiving basin and thus avoid many of the complexities of the evolutionary processes. Model results from both geometries show a clear life cycle of growth and deterioration in a diversion that experiences relative sea level rise and, under certain combinations of relative sea level rise, depth of receiving waters and sediment discharge rate, situations in which a subaerial platform will never form. A comparison of subaerial deposits in larger *versus* smaller diversions, assuming the same total sediment discharge in both cases, reveals that the total subaerial land area for the larger diversions is substantially greater than the sum of the two volumes of the smaller diversions. Model results have been used to illustrate, through examples, the effect of bottom slope and sea level rise on diversion performance. Recommendations have been made for the selection (quantification) of diversion parameters to be used in the models. These include annual sediment input, proportion of sediment retained in the diversion deposit, sediment bulking factor, foreset slope, and subsidence rate. Other required input parameters are considered to be known, namely, average diversion water discharge, initial depth of receiving waters, bottom slope, deposit angle or width, and future sea level rise. We also include general recommendations for selection and utilization of diversion sites.

ADDITIONAL INDEX WORDS: *Coastal restoration, deltaic deposits, geometric models.*

INTRODUCTION

River diversions are one of the fundamental tools available for coastal restoration in Louisiana (CPRA, 2012). Under certain scenarios, they offer an efficient and effective means of building new land, provide a substrate for wetland growth, and provide an opportunity for enhancement of ecological diversity. Although much has been written on river diversions, and indeed much is known from the myriad of studies over the past 30 years, some significant gaps in our understanding remain, perhaps most notably the overarching uncertainty in forcing landscape perturbations of the scale of large river diversions. Basic principles and processes of how diversions function are discussed in this paper, including the role of sea level rise and subsidence, sediment composition and quantity, effects of receiving basin characteristics, and effects of river flow. Challenges and opportunities for using diversions as a tool in the restoration of coastal Louisiana are also presented, and we end by providing a set of recommendations that focus on applicability and limitations of our findings and the importance of sensitivity studies.

At first, diversions may seem an obvious and relatively straightforward approach to restoration in Louisiana: they reconnect the Mississippi River to the surrounding wetlands, removing the hydrologic disconnection that began more than a century ago, thereby allowing nature, largely unaided, to use its own "raw materials" to create new land (Figure 1). However, a closer look reveals that there are many complex issues associated with large river diversions: (1) *Lack of "textbook" design criteria* given that, with the exception of the West Bay project in the birdsfoot delta in 2003 (Kolker, Miner, and Weathers, 2012), previous diversions have been focused primarily on introduction of freshwater rather than sediment; (2) *Unintended effects on the main stem of the river,* primarily as a result of shoaling that may affect navigation and escalate project costs (Allison *et al.,* 2013; Letter *et al.*, 2008); (3) *Uncertainty in subsidence and eustatic sea level rise* leading to considerable controversy in rates of relative sea level rise, their

---

DOI: 10.2112/JCOASTRES-D-12-00252.1 received 3 December 2012; accepted in revision 4 February 2013; corrected proofs received 24 July 2013.

Figure 1. Regional map showing hierarchal and overlapping deltaic landforms, many of which were created by natural diversions, which form the SE coast of Louisiana. Area outlined in red shows location of Figure 2.

temporal and spatial variations, and their relevant driving forces; (4) *Uncertainty in hurricane effects* on coastal wetlands from lack of quantitative analyses that can differentiate storms from other delta-plain processes (Barras, 2007; Morton and Barras, 2011); (5) *Limited predictive capability for land growth* because of the general lack of understanding of the very factors that are discussed in this paper; (6) *Unintended and potentially negative effects from the freshwater introductions* that co-occur with the introduction of sediments; (7) *Societal and economic issues* associated with competing stakeholder interests, project costs and tradeoffs, and effectively communicating expectations; and, (8) *Inaction because of the above issues,* leading to the likelihood that actual addition of significant new land from diversions is still several decades away.

Virtually all of the above questions and concerns must, and almost certainly will, be addressed through application of numerical models or, in some cases, laboratory models. Many currently exist, including simulation of delta formation on geologic time scales (Seybold, Andrade, and Herrmann, 2007); simulation of birdsfoot deltas on 100 to 1000-year time scales (Kim *et al*., 2009; Seybold *et al*., 2009); simulation of individual landform features such as channel networks and river mouth bar formation on time scales of years to decades (Edmonds and Slingerland, 2007; Wolinsky *et al.,* 2010); and simulations that relate delta form to variations in sediment texture (Edmonds and Slingerland, 2010). In contrast, the primary goal in this paper is a modeling approach that uses simple analytical models (herein referred to as geometric models) specifically for the purpose of guiding design and preliminary evaluation by examining interrelationships among key variables.

The work presented herein is based on (1) the results of two simple geometric models that were developed to provide a framework and rational basis for the preliminary design of river diversions and the selection of key design parameters that will affect their performance, (2) the considerable body of published and unpublished literature that draws from the knowledge and experience of others, and (3) our own knowledge, insight, and application of best professional judgment (see Dean *et al*., 2012). We approach the topic of river diversions from the standpoint of voicing considerable urgency and the need for action in the very near future, yet at the same time recognizing that it would be presumptuous to suggest that this paper furnishes definitive answers to complex questions that will require additional analysis and incorporation of flow dynamics.

BACKGROUND: EVOLUTION OF LARGE DIVERSION DEPOSITS

River diversions, if successful, will create new land that mimics scaled-down versions of natural delta lobes, referred to in the literature as subdeltas or bay-fill deposits. Within a major delta lobe, subdeltas and smaller crevasse-splay deposits fill the innumerable shallow bays that flank the deltaic distributaries with sedimentary sequences that are typically less than 10 m thick but with subaerial expressions at maximum development that may reach 300 km^2 or more (Figure 2). The evolution of these deposits on the lower Mississippi Delta, first illustrated by Welder (1959) and Coleman and Gagliano (1964), is now relatively well understood (Coleman, 1988; Coleman, Roberts, and Stone, 1998; Roberts, 1997; Wells, 1996; Wells and Coleman, 1987) and can serve as a geomorphic and sedimentologic model for creating new wetlands from river diversions (Allison and Meselhe, 2010; Davis, 2000).

A subdelta or bay-fill deposit is a sequence that forms initially from a break or crevasse in a major distributary natural levee during flood stage, enlarges as flow increases through successive floods, reaches a peak of maximum discharge and deposition, then wanes and becomes inactive (Coleman, Gagliano, and Morgan, 1969). As a result of high subsidence rates by compactional dewatering, an abandoned subdelta is gradually inundated by brackish water and reverts to an open-bay environment, thus completing one sedimentary cycle of infilling and abandonment that may last 150–200 years (Wells, 1996). Smaller crevasse-splay deposits associated with overbank flooding during very high discharge years also create new land that rarely lasts more than 10–15 years and, during that time, will deposit sedimentary sequences on the order of 3 m thick covering areas of 12–15 km^2 (Coleman, 1988).

Since the middle to late 1800s, four subdeltas have together formed the sedimentary framework for essentially all of the wetlands in the modern birdsfoot delta, and, prior to that, similar features undoubtedly provided the surface expression of this and other major delta lobes that were active during the Holocene. Analysis of the subdeltas from maps, charts, and aerial photographs (Wells and Coleman, 1987) revealed an orderly, almost predictable life cycle, with average and maximum rates of subaerial growth ranging from 0.8 to 2.7 km^2/y and from 1.1 to 7.0 km^2/y, respectively (Figure 3). Average and maximum rates of deterioration were on the same order as the rates of growth, typically several square kilometers *per* year, even though the sediment volumes in the subdeltas continued to increase. At the time of the analysis (ending in 1980), the volumes of sediment deposited in the subdeltas had averaged $(4–26) \times 10^6$ m^3/y, and the Mississippi Delta had acquired a total of $\sim 7000 \times 10^6$ m^3 of new sediment.

During the progradational phase, subdelta growth begins after crevasse development, but not at a constant rate. This is because of the uneven distribution of coarse sediment, which is deposited initially only in the vicinity of the natural break in the levee. Fine-grained sediments are transported farther into the bay and build a platform for future progradation and channel development. At some point in the subaqueous infilling process, usually after 10–15 years, major channels become established, and a well-organized pattern of bifurcations becomes evident. It is only after the development of a well-defined channel pattern, and hence sediment delivery network, that subaerial growth begins to increase rapidly. As the progradation and areal extent of the subdeltas increases rapidly, so does the growth of wetlands, which form a cap on the underlying sedimentary deposits. Patterns of delta growth in the relatively new Atchafalaya and Wax Lake deltas to the west indicate that, after an initial period of channel extension and bifurcation around the river mouth bar deposits, increases in delta area occur primarily from fusion of sand-rich lobes by channel filling and upstream lobe growth (Roberts, 1997).

Ultimately, however, as a subdelta extends farther into the bay and the gradient is diminished, it becomes less efficient and is unable to deliver and disperse sediments at a rate sufficient to offset subsidence over the larger subdelta footprint. Additionally, some diversions may simply become so hydraulically inefficient that they close. Recent laboratory studies, summarized by Paola *et al*. (2011), show that as relative sea level rise causes progradation to cease, the delta surface does not simply drown. Instead, the surface morphology appears able to adjust and thus accommodate more sediments, leading to the conclusion that experimental studies can help test the limits to which delta restoration can withstand subsidence without losing an unacceptable amount of subaerial land. It is noteworthy that during the deterioration phase, as subaerial land was being lost in the Mississippi River subdeltas, the total volume of sediment in each subdelta continued to increase. Sediments were still accumulating, but simply not at a rate sufficient to keep pace with relative sea level rise (sediment cores have revealed that subdeltas may be stacked upon each other, forming thick sequences in the geological record). Sediment supply thus becomes crucial as a suite of processes that, acting in concert, create a system that may be intrinsically capable of maintaining itself (Paola *et al.,* 2011).

VARIABLES THAT AFFECT DIVERSION PERFORMANCE

The performance of river diversions is controlled by numerous factors that can be broadly categorized as (1) basin geometry, (2) sediment characteristics, (3) biological and chemical factors, (4) water motion, and (5) design and operational strategies. Basin geometry includes size, degree of enclosure, and the water depth and is influenced through time by sea level rise and subsidence. Small, shallow basins develop subaerial land more quickly (other factors being equal), and enclosed or partially enclosed basins retain sediments more effectively. Sea level rise and subsidence, which together can increase water level by 2 cm/y or more, are also significant

Figure 2. Existing and planned diversions along the lower course of the Mississippi River. Land-building in the birdsfoot delta (SE of Venice) is shown in the four subdeltas in Figure 3. See CPRA (2012) for summary of planned diversions.

factors in modifying the size and thus geometry of receiving basins over periods as short as one to two decades. Recommendations for planning and executing small crevasse-splay diversions, based in part on research and past experience with basin geometry, are given by Turner and Streever (2002), but these would not necessarily be applicable to the siting of large land-building diversions in the upper reaches of the Mississippi River delta system.

The quantity of new sediment that enters and is retained in a receiving basin must be sufficient to offset the effects of sea level rise and subsidence in order to build new land. Sediments that enter a receiving basin through a river diversion will be a mix of sand, silt, and clay. The size distribution is of paramount importance in that sand is a key ingredient in building new land from diversions (Nittrouer *et al.,* 2012). Bed load may be hard to capture and, even though sand often becomes a suspended-load component, sediment concentration profiles will affect the delivery of sediments given that shallow diversion cuts may not capture the higher concentration of sand that occurs in the lower part of the water column. Further, there may be an optimal coarse sediment time window, and interannual variability in sediment load is a common occurrence in the Mississippi River. Multiple “competing” diversions could certainly create complex relationships between flow and sediment. Finally, it is well established that suspended sediment loads in the lower Mississippi River have declined significantly during the latter half of the 20th century (Allison and Meselhe, 2010).

Even if there is a generally predictable relationship between the volume and speed of water and mass of sediment that enters a receiving basin, the infilling process is controlled by the volume of deposited sediment and the bulk density *of the deposit*. Biological factors are therefore notably important. Bulk density, defined here as dry mass *per* unit volume of the *in situ* deposit, is a measure that reflects the relative amount of organic *versus* inorganic sediment and

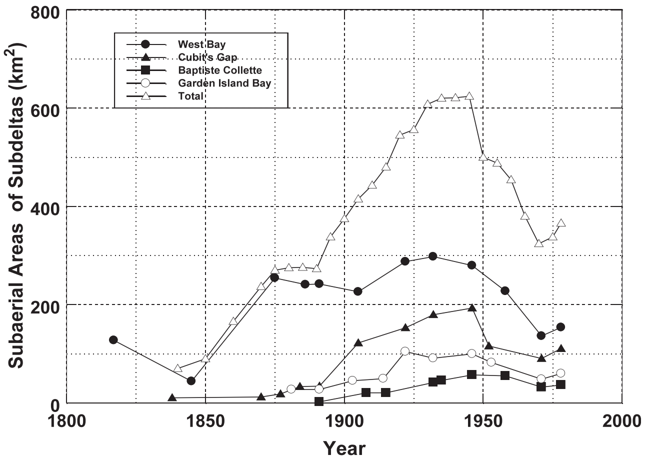

Figure 3. Life cycle of subdeltas of the Mississippi River Delta (from Wells and Coleman, 1987).

water content. Organic sediment, which may contribute more than 50% of the sediment volume, is thus an important factor in diversion performance and is accounted for through "bulking factors" once a diversion deposit becomes subaerial. Moreover, wetland vegetation that is established at or about the time of land emergence helps bind the sediment through its root mass and trap particles from its above-ground biomass.

Most large receiving basins, especially those that are open or partially enclosed, have tidal and wind-driven currents and can accommodate the generation of waves. Most basins are "leaky" in that the land is very low and can be overtopped during flood stage. Critical shear velocities for initiation of motion for fine-grained sediments are low, and these sediments could be resuspended and transported out of the basins. Major floods, while potential sources of high incoming sediment loads, can also cause scour within a receiving basin. Hurricanes can do the same, but there is continuing controversy as to whether significant amounts of new sediment enter the delta from offshore sources during hurricanes (Tornqvist *et al.*, 2007; Turner *et al.,* 2006). Countering this would be turbulence in the column that may resuspend fine sediment and allow advection out of the area. With their higher settling speeds, sands would have shorter distances to reach the point of deposition and are able to withstand water motion under a wider range of conditions than would be expected to occur throughout a hydrologic cycle.

Finally, while not addressed in this paper, diversion performance is dependent on design and operation, including, for example, the degree of control over flow volume that may be addressed by engineered features or augmented by operational strategies. Pulsed introductions have been shown to affect sediment delivery because water diverted during rising and peak flows delivers more sediment *per* unit water volume than during falling river stages (Day *et al.*, 2009). Other strategies, including allowing sediments to be stored in diversion access channels, pumping sediment from the bottom to ensure high sand loads, creating artificial marsh, and employing pulsing introductions at key times during the hydrological cycle (Allison and Meselhe, 2010), are thought to be effective. In the following, we discuss only gravity-driven diversions, and those that are not regulated by gates or other means.

SIMPLE MODELS FOR SCOPING AND SENSITIVITY STUDIES

Two simple geometric models of the evolution of diversion deposits have been developed. The models presented herein were developed with the dual goals of simplicity of application and capturing the underlying processes that would allow the interrelationships of various design parameters to be evaluated and the merits of candidate designs to be compared. Although features such as nonuniformity of depositional processes, spatial distribution of grain sizes, and channelization within the deposits were not included, their omission on candidate designs should not compromise comparison of their relative merits.

Our models avoid many of the complexities of the evolutionary processes but allow the overall character of the diversion over time to be examined. The models include effects of the effective sediment discharge rate into the diversion, relative sea level rise, foreset slope, and slope of the bottom in the receiving area. The advantages of these simple models are that analytical solutions can be obtained and they allow, for the first time, the long-term evolutionary characteristics to be examined. Further, they allow comparison of the performance characteristics of large *vs.* small diversions, allow rational comparisons of the efficacies at different diversion sites, and provide insight into the most relevant factors that govern performance.

The two geometries that were examined include a truncated cone and a uniform width geometry. The former is characteristic of the Wax Lake "Diversion" Delta (Figure 1), a landform to the west of the birdsfoot delta (Roberts, 1997), and the second is similar to that of the planned White Ditch Diversion on the main stem of the river upstream of the birdsfoot delta (Figure 2). Following is a brief description of the two models, interpretation of model results, and limited examples of the applications of these models. Other, more computationally intense models are available, including those of Twilley *et al.* (2008) and Kim *et al.* (2009), building on earlier work by Kostic and Parker (2003), Parker *et al.* (1998, 2008), and the Corps of Engineers models ERDC-SAND and ERDC-SAND2. The unique attribute of the models presented here is their analytical character, allowing features of diversions with different characteristics to be illustrated rapidly and the interrelationships between variables to be shown. The predictive capabilities of these models, including their evolutionary behaviors, are limited by the geometries considered, namely, that the forms of the deposits over time are consistent with these geometries.

Truncated Cone Model

The geometry of the truncated cone depositional model is presented in Figure 4. The volume of a truncated cone, V, is

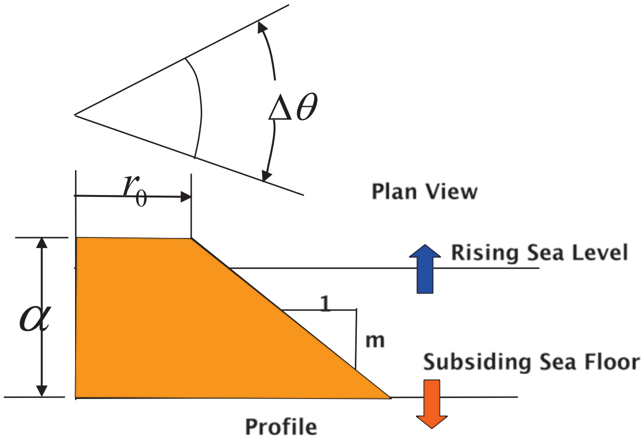

Figure 4. Definition sketch of a truncated cone in water of uniform depth.

$$V = \frac{\Delta\theta}{2}\left[r_0^2\alpha + r_0\frac{\alpha^2}{m} + \frac{\alpha^3}{3m^2}\right], \tag{1}$$

where $V = Qt$, Q is the discharge rate of the retained sediments including "bulking" effects, and t is time. We note from the above that the volume of the cone increases with the cube of the total depth, α. This is critical to the interpretation of the long-term evolution of diversion projects, since the volume supplied is considered to be constant, whereas the depth increases linearly (due to subsidence and sea level rise) such that the volume required to maintain the deposit in a subaerial form increases with the cube of time as shown in Figure 5.

The radius, r_0, of the horizontal portion of this truncated cone is

$$r_0 = -\frac{\alpha}{2m} + \sqrt{\frac{2V}{\alpha\Delta\theta} - \frac{\alpha^2}{12m^2}}. \tag{2}$$

From this equation, it can be seen that if there were no relative sea level rise (α = constant), the radius would increase monotonically (as the square root) with time. However, with a relative sea level rise, the radius will reach a maximum, then decrease, and finally become zero. With this particular geometry and a relative sea level rise, this is an inescapable consequence in the evolution of the diversion deposit.

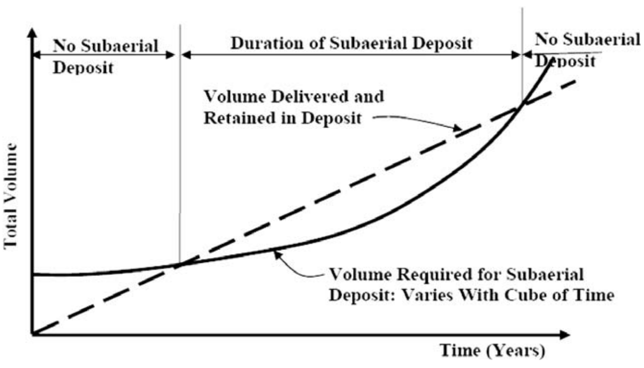

Figure 5. Interpretation of three stages of evolution for truncated cone.

Time to Emergence of a Subaerial Platform for a Truncated Cone

In the presence of relative sea level rise (RSLR), the combination of depth of the receiving waters, sediment discharge rate, and the magnitude of the RSLR can be such that a subaerial platform will never form. This is because the RSLR outpaces the vertical growth of the deposit. It is fortunate that this problem can be solved in a nondimensional form such that it is necessary to consider only one case for all combinations of parameters. The results are presented here in graphical form.

Defining a nondimensional time, $t' = (t/\alpha_0)(\partial\alpha/\partial t)$, and a nondimensional discharge, $Q' = 8Qm^2/(\Delta\theta\alpha_0^2(\partial\alpha/\partial t))$, it can be shown that the nondimensional solution is

$$1 - 3t'(Q'-1) + 3(t')^2 + (t')^3 = 0. \tag{3}$$

There is no solution to this equation for $Q' < 2.25$, meaning that for this range the deposit elevation does not reach the height at which the deposit could commence forming a subaerial platform. Figure 6 presents the relationship between the two nondimensional variables, t' and Q'. Note that the definition of the nondimensional variables establishes the interrelationships among all variables. For example, in the nondimensional discharge, Q' , the sediment discharge, Q, has the same effect on emergence time as the square of the initial depth, α_0, or the inverse of the square of the foreset slope, m, *etc*. Examples will be presented later to illustrate application of the results.

Uniform Width Model

The geometry for this model is shown in Figure 7. The volume of the uniform width model with a horizontal bottom, $m_b = 0$, is given by

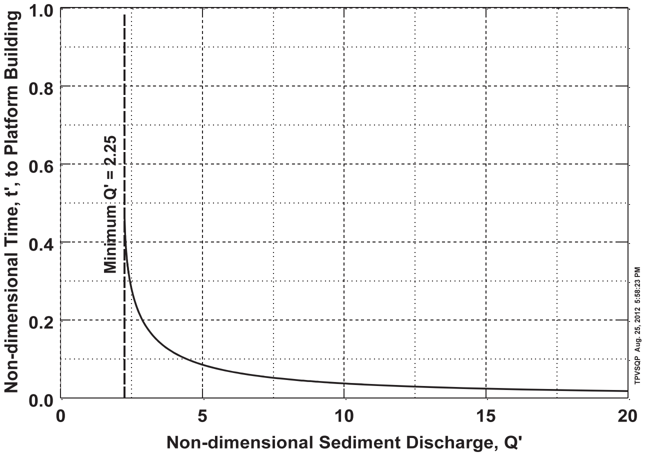

Figure 6. Nondimensional time, t', *vs*. nondimensional discharge, Q', for truncated cone.

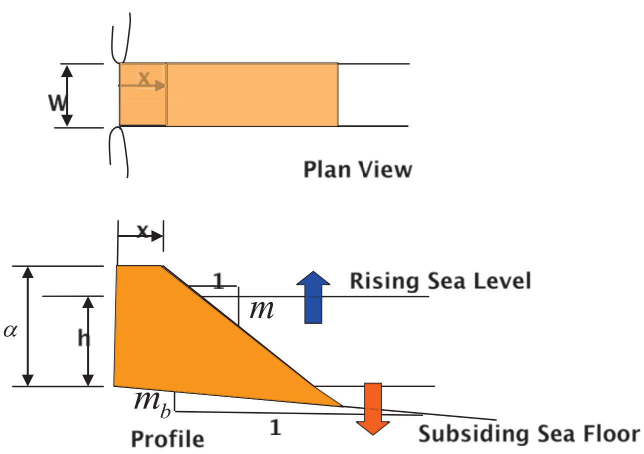

Figure 7. Uniform width model. Sloping sea floor.

$$V = Qt = W\left(\alpha x + \frac{\alpha^2}{2m}\right), \tag{4}$$

and for the case of an emergent deposit, the value of x is expressed by

$$x = \frac{1}{W}\left[\frac{Qt - \frac{W}{2m}\alpha^2}{\alpha}\right]. \tag{5}$$

After some algebra, the solution for the case of a finite bottom slope, m_b, can be written as

$$x^2\left(\frac{m_b}{2} + \frac{m_b^2}{2(m - m_b)}\right) + x\left(\alpha + \frac{2m_b}{m - m_b}\right) + \frac{\alpha^2}{2(m - m_b)} - \frac{Qt}{W} = 0. \tag{6}$$

Time to Emergence of a Subaerial Platform of Uniform Width

For this case, the nondimensional variables are $t' = (t/W\alpha_0)(\partial\alpha/\partial t)$, the same as for the truncated cone; however, the definition of the nondimensional discharge, Q', differs and is $Q' = Qm/(\alpha_0(\partial\alpha/\partial t))$. The governing equation expressed in the nondimensional quantities is

$$1 - 2t'(Q' - 1) + (t')^2 = 0, \tag{7}$$

which can be solved directly for t' as

$$t' = (Q' - 1) + \sqrt{(Q')^2 - 2Q'}. \tag{8}$$

It can be shown that the minimum Q' for subaerial platform development is $Q' = 2.0$, compared with 2.25 for the truncated cone case considered previously. Figure 8 presents the solution for t' as a function of Q'.

As for the case of a truncated cone, the form of the nondimensional variables establishes the interrelationships among all variables. For example, in the nondimensional discharge, the sediment discharge, Q, has the same effect on emergence time as the initial depth or the inverse of the foreset slope, *etc*.

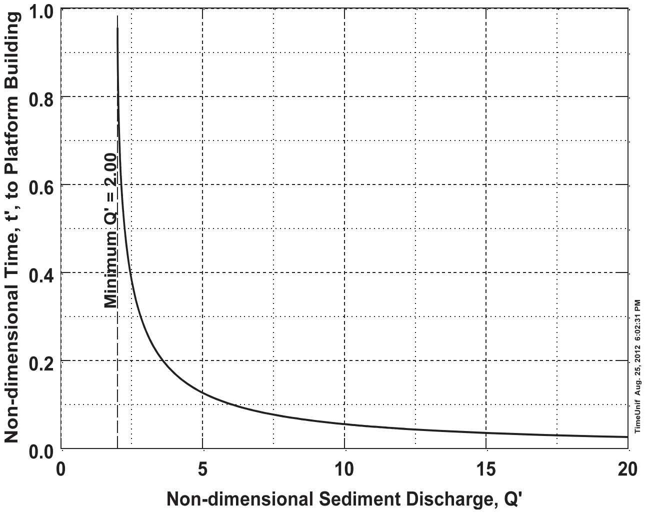

Figure 8. Nondimensional time, t', *vs.* nondimensional discharge, Q', for uniform width and uniform depth model.

Model Application: Examples

In the following, we present examples to illustrate concepts and evolutionary features of diversion deposits. To provide perspective, estimates of the total annual delivery of sediments by the main stem of the Mississippi River range between approximately 35×10^6 m^3 and 50×10^6 m^3, and the annual delivery of suspended sediments in the sand size range is estimated to be between 0.6×10^6 m^3 and 10×10^6 m^3. Based on the relationships developed and recommended here for

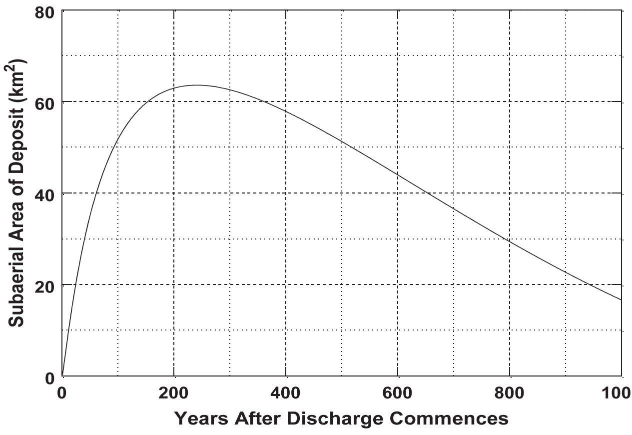

Figure 9. Annual discharge of retained sediment = 3×10^6 m^3/y, initial depth of receiving waters = 2.0 m, elevation of horizontal portion of deposit above mean water level = 0.25 m, rate of relative sea level rise = 2.0 cm/y, foreset slope = 0.002, and the delta opening angle = 180°.

guidance, the ratio of sand to total sediment in suspension is 0.018 (1.8%).

Example of Large-Scale Diversion, Truncated Cone Geometry

This example illustrates the evolutionary phases and time scales of a large diversion. Results are presented in Figure 9. A sediment diversion of this magnitude (3×10^6 m^3/y) would represent approximately 6% to 8% of the total inorganic sediment load of the Mississippi River or, if all of the diversion discharge were sand, up to 30% of the sand discharge. Other characteristics of this example are shown in the figure caption.

The model shows that the subaerial deposit first grows with time, followed by a maximum, and then declines. As noted, the reason that the deposit evolves in this manner is tied to the requirement for additional sediment over time compared with the rate at which it is delivered, as shown in Figure 5. For conditions considered here, the increasing sediment requirement is ultimately greater than the supply.

As shown in the preceding section, for the case of a truncated cone, the volume required to maintain a diversion platform relative to sea level varies with the cube of time (Equation 1); however, for the case of a diversion of uniform width, the required sediment varies with the square of time (Equation 4).

Example of Large vs. Small Diversions, Truncated Cone Geometry

This second example examines the efficacies of larger *versus* smaller diversions. Results are presented in Figure 10. In this example, the total sediment retained in the deposits is the same except that in one case the total sediment is distributed equally through two diversions, and in the second the total sediment is discharged through a single diversion. The two plots in the figure thus represent the *same* total amount of sediment retained in the two diversions as in the single diversion. It is noteworthy that the total subaerial area for the large diversion is substantially greater than the sum of the two volumes of the smaller diversions. Also, the time to emergence is shorter for the larger deposit than for the case of two smaller deposits. The reasons for this evolutionary behavior will become more evident later.

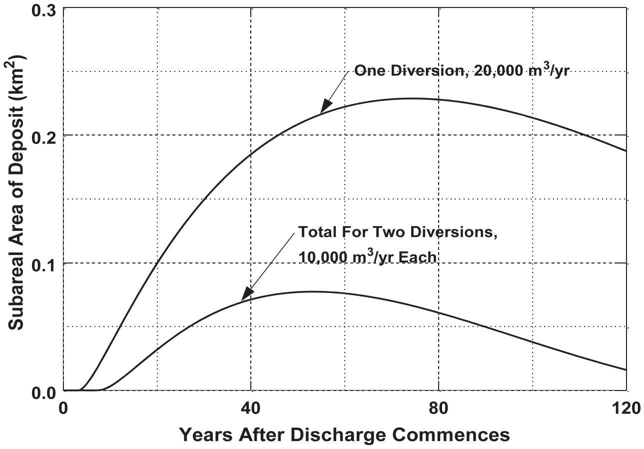

Figure 10. Example 2. Comparison of subaerial areas over time for one large diversion *vs*. two diversions with the *same* total sediment retention. Initial depth of receiving waters = 0.75 m, elevation of horizontal portion of deposit above mean water level = 0.25 m, rate of relative sea level rise = 1.0 cm/y, foreset slope = 0.002, and delta opening angle = 180°.

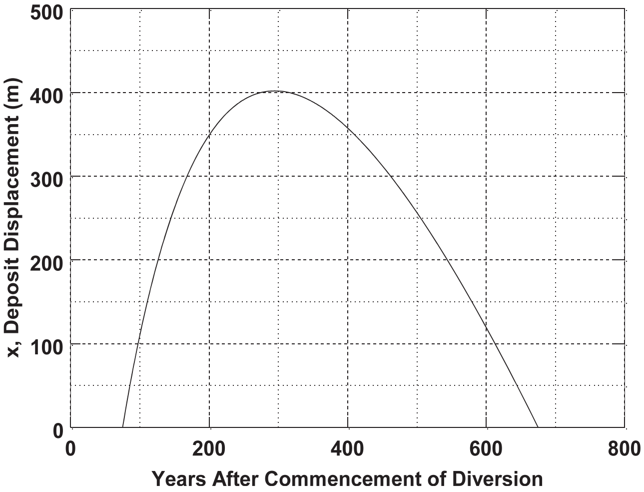

Figure 11. Example 3. Berm length, x, of deposit (see Figure 7) for diversion deposit of uniform width and into receiving waters of uniform depth. Annual volume of sediments retained = 60,000 m^3/y, width of deposit = 2000 m, initial depth = 1.5 m, elevation of deposit platform above water level = 0.25 m, relative sea level rise = 1 cm/y.

Example of General Evolutionary Characteristics, Uniform Width and Depth Geometry

This example portrays the evolutionary behavior for the case of a receiving area of uniform width and depth and the characteristics shown in Figure 11. The same evolutionary phases are present for the uniform width model as have been shown for the truncated cone model, and the same general interpretation of the causes applies. For this case, the receiving water depth, α_0, of 2.0 m and a width, W, of 2000 m results in a time to emergence of approximately 75 years. The extent, x, of the subaerial deposit peaks at approximately 290 years, and becomes submerged at approximately 665 years after commencement of discharge. The sediment retention rate associated with this example represents from 0.12% to 0.17% of the total sediment discharge rate of the main stem of the Mississippi River, or 6% to 10% of the total sand discharge.

Example of Bottom Slope Effects, Uniform Width Geometry

This example illustrates the effect of bottom slope for the uniform width model. With an increasing depth with distance from the diversion location, the sediment discharged must fill an increasing depth, and thus the diversion is not as effective as it is for the case of a horizontal bottom. Figure 12 shows that for the conditions indicated in the figure caption, an increase in bottom slope from 0.0 to 0.001, the long-term effectiveness of a diversion over a sloping bottom is reduced considerably.

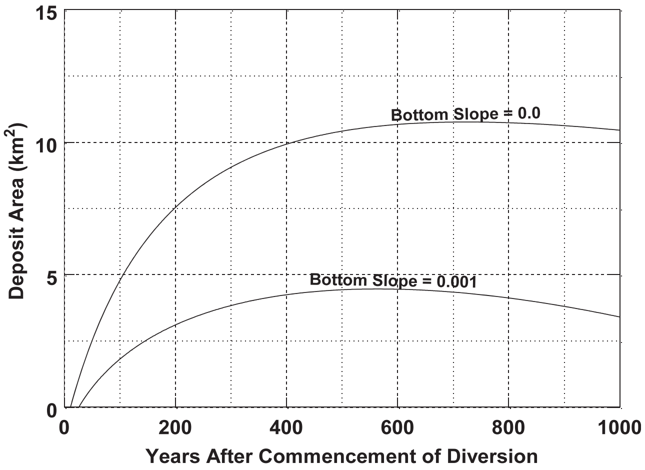

Figure 12. Example 4. Comparison of subaerial areas over time for two bottom slopes. Uniform width, annual retention of sediment = 200,000 m^3/y, relative sea level rise rate = 1.0 cm/y. Initial depth of receiving waters = 0.75 m, Elevation of horizontal portion of deposit above mean water level = 0.25 m, foreset slope = 0.002.

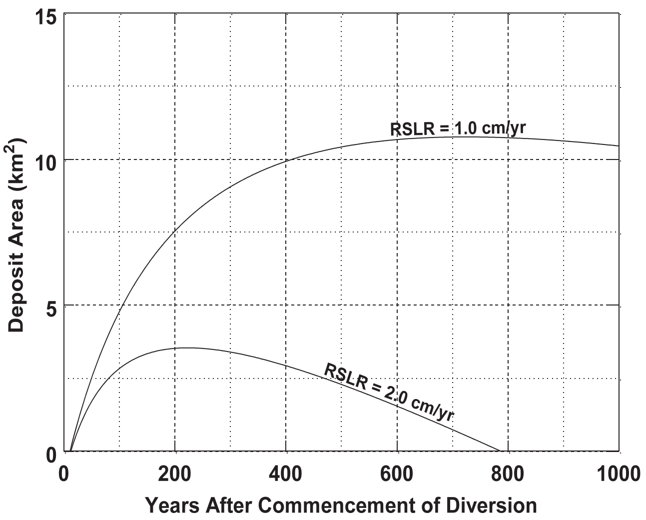

Figure 13. Example 5. Comparison of subaerial areas over time for relative sea level rise rates, uniform width = 2000 m, annual retention of sediment = 200,000 m^3/y. Initial depth of receiving waters = 2.0 m, Elevation of horizontal portion of deposit above mean water level = 0.25 m, foreset slope = 0.002, bottom slope = 0.

Example of Relative Sea Level Rise Effects, Uniform Width Geometry

This example illustrates the effect of RSLR, which is a consideration when evaluating diversion sites at locations where the subsidence differs considerably. For conditions considered, Figure 13 shows that the greater RSLR markedly reduces the diversion land-building performance.

MODEL APPLICATION: PARAMETER SELECTION

General

The validity of the models in providing insight and predictive capability for future diversions depends on the accuracy of parameter selection. Several of the key input variables (subsidence, sediment delivery and retention, volume "bulking" resulting from vegetation growth and water content) are poorly known, and we are thus forced to use approximate values based on our best understanding at this time. The selection of parameters simply offers a framework against which monitoring results can be compared and, on the basis of an adequate number of such comparisons, improvements made in the key parameters and/or methods. The methods and details, then, can be upgraded as more information and experience become available.

The parameters to be quantified for input into the models include annual sediment delivery, proportion of sediment retained in the diversion deposit, sediment bulking factors, foreset slope, and subsidence rate. We assume that the diversion hydraulics have been quantified in terms of their average annual flows. Other required input parameters are considered known and include initial depth of discharge, receiving basin bottom slope, deposit angle or width, and future sea level rise. Because the models are designed to be screening tools that can offer a rational basis for preliminary design of river diversions and provide insight and predictive capabilities, no attempt was made to calibrate the models against actual performance. Indeed the only diversion designed specifically for introduction of sediment into an interdistributary bay was the West Bay diversion, which, at less than a decade old, is considered too young to use for meaningful calibration efforts.

Annual Inorganic Sediment Input

Annual inorganic sediment input is based largely on Allison and Meselhe (2010) during the 2008 flood at Empire, Louisiana, and requires that annual average water diversion discharge, $\bar{Q}_{\text{water}}$, be known with the consideration that there should be some similarity of normal and flood characteristics at various locations along the river. Thus, the recommendations below represent diversions that are free flowing, unlike the Bonnet Carré spillway that is only opened during periods of high river flow (Nittrouer *et al.*, 2012).

It is recommended that sand be delivered annually according to

$$Q_{\text{sand}} = 36\bar{Q}_{\text{water}}, \tag{9}$$

and that fines be delivered annually according to

$$Q_{\text{fines}} = 2000\bar{Q}_{\text{water}}, \tag{10}$$

for the following total

$$Q_{\text{sed total}} = 2036\bar{Q}_{\text{water}}. \tag{11}$$

In the above equations, the sediment discharges are in cubic meters *per* year, and the average diversion discharge is in cubic meters *per* second. These recommendations are compared with more detailed estimates and measurements for the total Mississippi River and West Bay Diversion and White Ditch

Table 1. *Comparison of sediment transport by river diversions on the basis of equations herein along with other estimates.*

River of Diversion	$\bar{Q}$ (m^3/s) Average Annual	Q_{sed} (m^3/y) Estimated by Other Means (Source) Total	Sand	Fines	Silt	Clay	Source	Method Suggested Here Total	Sand	Fines
Mississippi River at Belle Chase	17,000	56.4×10^6	11.6×10^6	44.8×10^6			(Allison, Personal communication)	34.6×10^6	0.61×10^6	34.0×10^6
White Ditch Diversion	111	0.20×10^6	0.002×10^6		0.128×10^6	0.073×10^6	(Wamsley, 2011)	0.23×10^6	0.004×10^6	0.226×10^6
West Bay Diversion	1130	2.63×10^6	0.28×10^6	2.35×10^6			(Allison, Personal communication)	2.31×10^6	0.04×10^6	2.27×10^6

Diversion in Table 1. It is noted that the sand transport estimates above differ substantially for the Mississippi River at Belle Chase and the West Bay Diversion (120 km and 8 km above Head of Passes, respectively). The reason is not clear, since the equations for the column titled "Method Suggested Here" were based on measurements at Empire as reported by Allison and Meselhe (2010).

A more recent study by Allison *et al*. (2012) became available subsequent to the modeling reported herein. Average annual water, total sediment, and sand component transports are presented in that study for flood years 2008, 2009, and 2010 for 11 diversions, the three main outlets to the Gulf of Mexico, and 11 locations along the main stem of the Mississippi River. Comparison of these new results with our recommendations for the West Bay Diversion shows, based on the average annual water and sediment flows for the 3 years, that the total sediment delivery based on the more recent results is 1.43 greater than predicted by the method here; however, the sand delivery is a factor of 7.13 times greater. The reason for this difference is unknown. The ratios of sand to total sediment component transports in the 11 diversions ranges from 10% to 35% with an average of 17.6%, compared with the 1.8% ratio recommended here. Regardless, the wide range of sand proportion serves as a fitting reminder of the spatial (and possibly temporal) variability of the system. In applying the results that we present, it is recommended that sensitivity studies be conducted with full recognition of the uncertainties in the sand component magnitude and the results provided in Allison *et al*. (2012).

Foreset Slope

All depositional slopes on the lower course of the Mississippi River are very gentle, and here we rely on recommendations of Kim *et al*. (2009) and Twilley *et al*. (2008), building on earlier work by Kostic and Parker (2003) and Parker *et al*. (1998, 2008), in which their range of foreset slopes for the final deposit are between 0.002 and 0.005. The smaller slopes would be associated with the smaller grain sizes and the greater tidal currents and wave action. Initial recommendations are presented in Figure 14, which also presents (in parentheses) recommended slopes for the early phases of the diversion in which only sand contributes to the deposit. In application of these figures, the values to be applied are to be interpolated from those shown at various locations along the main stem of the Mississippi River.

Retention of Diverted Sediment

The proportion of diverted sediment retained at a diversion site (<1.0) would depend primarily on the sediment size and the wave and tide energy in the receiving area. The distance to the point of deposition, assuming the velocity decreases with distance from the diversion source, will be controlled by threshold shear stress for scour and the settling time of the sediments. If the fine sediments aggregate, as would be expected when riverine freshwater is discharged into a brackish environment, the fall velocity will increase, thus decreasing the fall distance; however, consideration of a radial velocity spreading results in velocities that would decrease too rapidly from the origin (the spreading would be more "jet-like" and thus spread more slowly) such that the two effects would

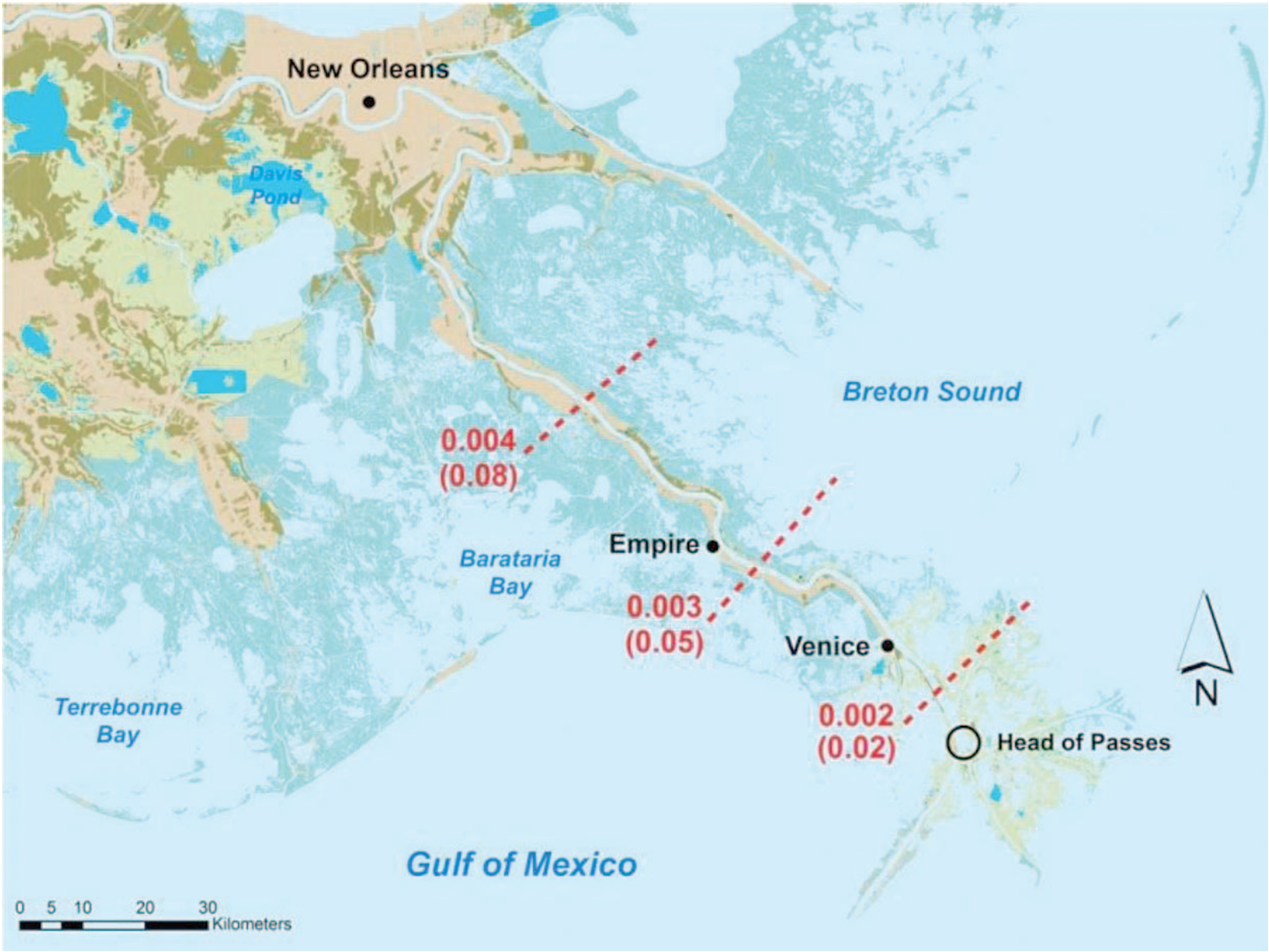

Figure 14. Recommended values for foreset slopes. Values in parentheses apply to sand-sized sediment.

tend to offset each other. Figure 15 presents preliminary recommendations for this proportion at various locations along the lower course of the river.

Subsidence

Subsidence is particularly significant because the ability of river diversions to become subaerial features is tied explicitly to the balance between sediment, primarily sand, that is delivered and remains in the receiving basin, and relative sea level rise, which is likely, but not necessarily, dominated by subsidence. Moreover, there is considerable controversy over actual subsidence rates, the relative contributions from deep *versus* shallow processes, effects of human activities, the effects of measurement techniques on determination of rates, the potential for significant effects from growth faults, and the changes in subsidence rates over time (Dokka, Sella, and Dixon, 2006; Gonzalez and Tornqvist, 2006; Kolker, Allison, and Hameed, 2011; Meckel, 2008; Morton and Bernier, 2010; Tornqvist *et al*., 2008). Figure 16 presents preliminary recommendations for subsidence rates based on the literature. While there is also uncertainty in rates of eustatic sea level rise, any assumed rate for application of the models will not vary over spatial scales of the various planned projects.

Bulking Factors

The bulking factor (>1) is defined as the ratio of the volume of the final matrix of water, organic material, and inorganic material to the in-place (voids included) inorganic sediment. This will increase the sediment volume once the deposit reaches the water surface, allowing the organic constituents to contribute to the total volume. However, in applications here with the geometric models, it is assumed that the bulking factor is constant. As for other factors, a low energy diversion environment will contribute to greater bulking factors. It is reasonable to assume that only the sand fraction should be considered effective in the construction of the deposit until it becomes emergent, after which vegetation can commence to develop and act to trap finer sediments. Figure 17 presents a

Figure 15. Preliminary recommendations for proportion of diverted material retained, F_R.

preliminary estimate of bulking factors at different regions of the lower course of the river.

DISCUSSION

The sedimentary processes associated with diversions are complex and interconnected, and there are no systematic studies dealing with them. With the exception of the West Bay Diversion (Kolker, Miner, and Weathers, 2012) and the planned White Ditch Diversion, the diversions shown in Figure 2 were designed for enhancing flood protection, reducing saltwater intrusion or preserving wetlands, rather than explicitly for sediment delivery and land-building efforts. Our modest level of understanding and resulting limitations on design guidance allow critical questions about diversions to remain, including diversion placement, growth expectations, operational strategies, and economic considerations. These uncertainties slow application of what is clearly an effective approach to restoration of coastal Louisiana.

There is little doubt that geometric models can offer considerable insight into the performance of diversions. By definition, diversions provide a conduit for delivery of sediments into a receiving basin, either open or partially filled with wetlands, and thus lend themselves to geometric considerations with regard to infilling and performance. Despite their simplicity, geometric models capture the important elements of diversions by allowing, for example, RSLR and bottom slope to be evaluated with respect to impact. One of the surprising aspects of model application is the degree to which small changes in parameter selection can have quite large effects on outcomes of various diversion scenarios.

Figures 9–13 show the importance of parameter selection. Virtually every possibility of parameter input to match local conditions can be assessed to determine whether new land will form; if so, how fast subaerial growth will occur; and the degree to which a specific parameter controls the characteristics of any particular diversion deposit. Effects can then be evaluated through sensitivity analysis. One of the challenges is in

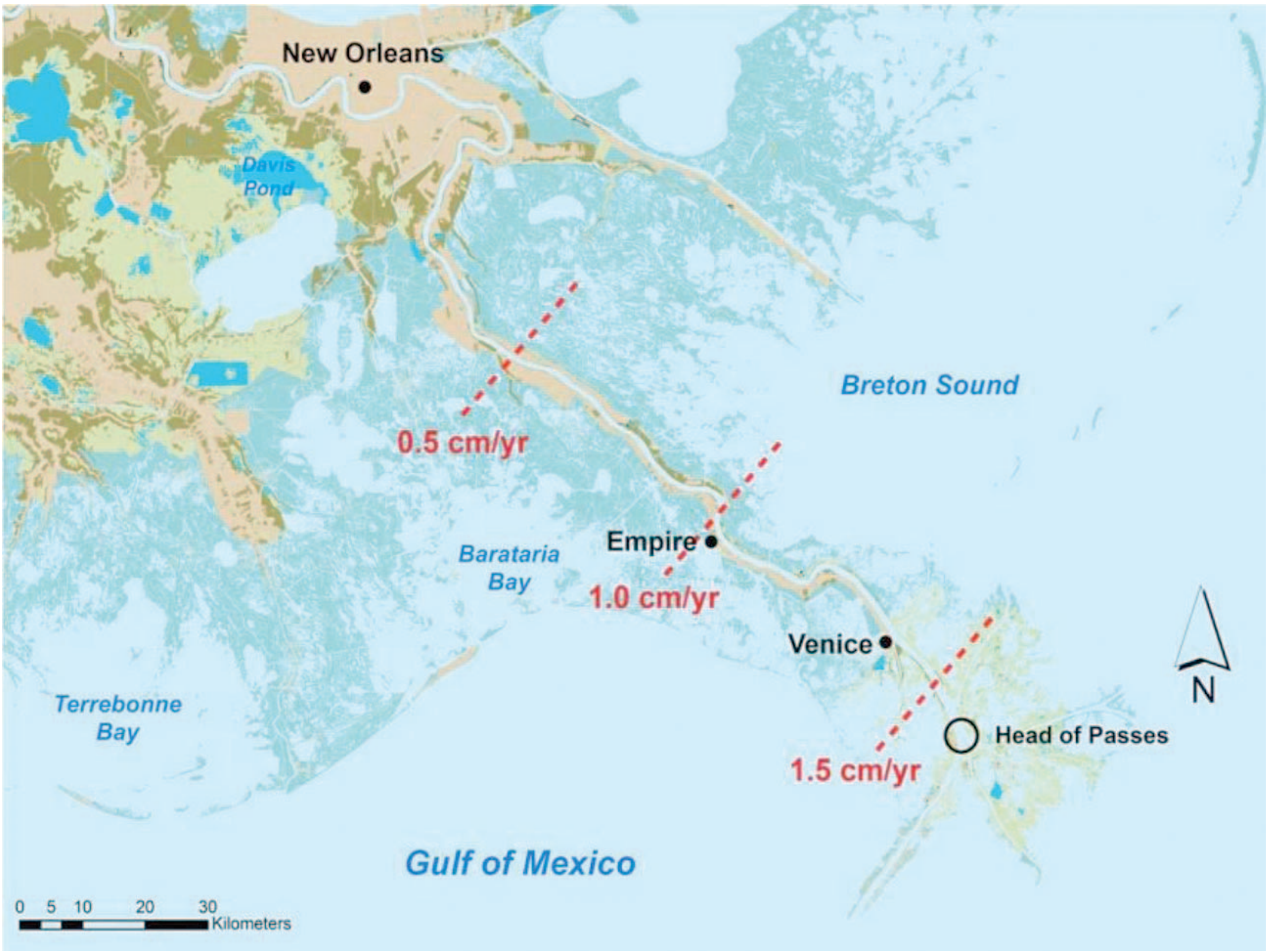

Figure 16. Preliminary recommendations for subsidence rates, F_s.

establishing reasonable values of input parameters, as was attempted in Figures 14–17. As noted previously, subsidence (which is responsible for driving RSLR on much of the lower course of the river) is a particularly troubling variable, but not just because of the disagreement in the scientific literature: it is also an issue because it can have such large effects on diversion performance. As new and more detailed information becomes available, so too will the ability to use more realistic inputs and, likewise, to expect better output from the models.

One unexpected outcome was that, using the truncated cone model, a single large diversion with the same total sediment retention as two small diversions results in more subaerial land in the large diversion and a shorter time period for subaerial emergence. In terms of overall land-building capability, the implication is that, other factors being equal, large diversions are more effective than small diversions. A significant modeling result for long-term evolution is that, in the presence of RSLR, three evolutionary phases occur: an emergence and growth phase, followed by a maximum in subaerial land, and finally a decrease and submergence of the subaerial platform. Within the limitations of the two models, this evolutionary behavior is an inescapable result of the effect of RSLR and is due to the fact that the required sediment delivery rate to maintain the deposit above water increases with time while the rate of sediment delivery by the river is considered to remain constant. This eventual submergence is consistent with the studies of Wells and Coleman (1987) in their examination of the evolution of four historic subdeltas in the lower Mississippi River system (Figure 3) and is also consistent with the formation of floating marshes.

These evolutionary aspects of subdeltas and smaller diversion deposits carry several important implications to land restoration that have immediate and fundamental relevance to Louisiana's plans for coastal restoration as presented in CPRA (2012). The first is that river diversions, which can be expected to have life cycles of decades to perhaps a century or more, like all coastal lands globally, are not permanent features. Rather, they are part of a highly dynamic landscape. The second is that

Figure 17. Preliminary recommendations for bulking factors, F_B.

river diversions may be most effective if staggered in time and alternated between basins. Because there is a natural life cycle, subaerial land and ecological diversity could be maximized with multiple large diversions, each of a different "age." Finally, predictions for subaerial growth using the subdeltas as a model, as shown in Figure 3, would be unrealistic. Because the sediment load, specifically sand, in the Mississippi River has decreased on the order of 50% over the past 60 years or so (Allison and Meselhe, 2010), future diversions will have less sediment for land-building processes than before and, at the same time, will very likely face a higher rate of relative sea level rise. On the other hand, it is important to recognize that diversions built higher in the system (upstream of the modern birdsfoot delta) would almost certainly have greater longevity because of lower subsidence rates and higher bulking factors and sediment retention rates.

The role of sand in building the initial platform for a diversion deposit cannot be underestimated, and expectations will be high for an early return on the diversion investment, *i.e.* appearance of new land on as short a time scale as possible. While the models consider discharge of only one composite sediment type throughout the evolution of a diversion, only the sand fraction should be considered effective in the construction of the deposit until it becomes emergent, after which vegetation can begin to develop and act to trap the finer sediments. Once an emergent platform has developed, the total sediment retained (including "bulking" by vegetation) can then be considered in the long-term evolution of the diversion deposit. This requires a simple adjustment to the two models presented earlier such that the effective sediment discharge is increased by a factor following the emergence of the deposit.

This is accomplished by applying the model with only sand discharge and the steeper foreset slope (Figure 14) associated with sand to determine the time to emergence. It is noted that the time to emergence depends on the nondimensional discharge (Q') definitions and that the smaller sand discharges and larger foreset slopes in the emerging phase and larger discharges and milder slopes in the following phases tend to compensate. For the truncated cone, $Q' \propto Qm^2$, and for the uniform width case, $Q' \propto Qm$. An additional factor that can reduce or increase the effects on the emerging and later phases is the magnitude of the Q' values in the Q' *versus* t' plots (Figures 6 and 8). If the Q' values are large and on the nearly horizontal portions of the relationships, the differences will be small. If the Q' values are small (<2.25 and <2.00 for the truncated cone and uniform widths models, respectively), subaerial land will never form. As noted, first the sand discharge and steeper foreset slope will be applied to determine the time to emergence. Second, the evolution will be calculated with the total sediment and milder foreset slope. The times from the latter calculation will then be offset such that the time to emergence is the same as determined in the first calculation.

The lack of documentation of performance of diversions specifically constructed for building land limits the basis for evaluation of the methodology. However, a companion report by Dean *et al*. (2012) applies and compares the methodology discussed here to the West Bay Diversion (constructed in 2003) and the White Ditch Diversion (designed using a more complicated methodology but not yet constructed). The methodology presented here predicts that land emergence will occur at West Bay in a range from 6.5 to 12.6 years after initiation. The emergence of small islands following the 2011 flood season (8 years after construction) indicates at this point reasonably good agreement if these islands continue to build (additional details in Dean *et al*. 2012).

The range of retained diversion discharges considered in the examples presented above is large, with annual averages of 10,000 m^3/y to 3,000,000 m^3/y. This range was selected to illustrate performance characteristics and the effects on evolutionary time scales. The 2012 State of Louisiana's Master Plan for a Sustainable Coast (CPRA, 2012) identifies 10 planned diversions, including two on the Atchafalaya River. The maximum (flood) discharges of the eight diversions on the Mississippi River range from 20 m^3/s to 7100 m^3/s. To provide an approximate comparison with our work, Equation 11 can be used to determine the associated range of water discharges in our examples; they range from 5 m^3/s to 1470 m^3/s. Thus, recognizing that the ranges of water discharge herein are in terms of average annual values and the range for the eight diversions on the Mississippi River are maximum values, the ranges are reasonably comparable.

In order to use the models to their full potential, it is essential that a rigorous and well-thought-out monitoring plan be undertaken for all future diversion projects to ensure that objectives are achieved, that unwanted consequences are detected early (*e.g.* Allison *et al*., 2013), and that adaptive management is facilitated. Regarding adaptive management, the chief purposes for monitoring large-scale restoration projects include the need (1) to ensure that science is used to deal with uncertainties, (2) to aid in decision support, and (3) to define new directions and methodologies that may be required. Clearly, there must be a commitment to adjust direction as new information becomes available, a willingness to identify new information needs, and a willingness to develop and use new monitoring tools. Site-scale learning will be of immense value in evaluating and implementing future projects.

The basic elements of a monitoring plan must include the following: (1) *Commitment to a long-term approach*: Project success cannot be adequately gauged and adaptive management cannot be implemented unless monitoring is conducted for the duration of the project, scaled at the appropriate level for the size and importance of the project. (2) *Acquisition of accurate bathymetric and subaerial surveys*: Field equipment and remote sensing techniques are widely available and not cost prohibitive for conducting rapid surveys with a high degree of accuracy. These tools should be routinely used. (3) *Implementation of a monitoring frequency that ensures capturing the relevant details of change:* At a minimum, observational data should be acquired annually with additional monitoring to take place when high impact events such as major floods or hurricanes occur. (4) *Acquisition of bottom samples and cores*: Data on sediment size and accumulation history are critical in evaluating the success of any diversion project and for predicting patterns and rates of future land growth. Radiometric tracers (^{7}Be, ^{137}Cs, ^{210}Pb) can provide depositional history on timescales of weeks to centuries. (5) *Acquisition of water and sediment discharge characteristics through the diversion into the receiving basin and at selected monitoring stations*: Accurate data on sediments passing through a diversion are essential for interpreting performance. (6) *Acquisition of data on flow field and sediment concentrations within the receiving basin*: Likewise, accurate data on material that moves through the receiving basin are essential for understanding sediment retention and for interpreting success. (7) *Monitor river channel for additional shoaling tendency*: River cross-sections should be measured over adequate distances upstream and downstream of the diversion. (8) *Commitment to a data management plan*: Data must be made available and disseminated to the scientific community and other stakeholders in a timely fashion.

Although the predictive capabilities of these simple geometric models are limited by the geometries considered, they offer valuable insight into the factors governing the evolution of diversion deposits, the key factors governing success, and, through sensitivity studies, the merits of competing designs (see Dean *et al*. 2012 for further details).

CONCLUSIONS AND RECOMMENDATIONS

River diversions, if successful, will create new land, similar to miniature versions of natural delta lobes. Simple geometric models provide a framework and rational basis for the preliminary design of river diversions and the selection of key design parameters that will affect their performance. The two geometric models that were developed for this study, a truncated cone and a uniform width geometry, avoid many of the complexities of the evolutionary processes. Model results from both geometries show a clear life cycle of growth and deterioration in a diversion that experiences relative sea level rise and, under certain combinations of relative sea level rise, depth of receiving waters and sediment discharge rate, situations in which a subaerial platform will never form. A comparison of subaerial deposits in larger *versus* smaller diversions, assuming the same total sediment discharge rates in both cases, reveals that the total subaerial land area for the larger diversions is substantially greater than the sum of the two volumes of the smaller diversions. Model results have been used to illustrate, through examples, the effect of bottom slope and sea level rise on diversion performance.

General recommendations for selection and use of diversion sites are as follows: (1) *Select sites that, based on all available evidence, are in areas of low subsidence*. Diversions above Myrtle Grove would be favorable and below Venice would be highly unfavorable (Figure 2). (2) *Select sites that have relatively thin Holocene sequences*. There is general agreement that compaction and other shallow processes will be lower in sediment sequences that are thin and contain less organic material. (3) *Select sites that are likely to have very high trapping efficiency*. Given the uncertainty in subsidence, retention of sediments should become a first-order consideration and be maximized. This also argues strongly for diversions that are in the upper part of the distributary system. Rapidly subsiding open bays on the lowermost delta are unlikely to offer the physical characteristics necessary for success. Sediment retention devices can contribute to sediment retention and should be evaluated.

As the pipeline for supply, the diversion cut must be located and oriented to maximize the opportunity for self regulation of water and sediments into a channel network once reaching the receiving basin, while at the same time reaching deep enough vertically to capture and deliver sand into the basin. The basin itself must be sufficiently shallow to create the best opportunity for land growth. We offer the following additional guidance: (4) *Select sites that do not exceed 2 m in depth*. The shallower the depth, the sooner new land will appear (other factors being equal) and the faster new land will accumulate. The highly successful Wax Lake Delta in Atchafalaya Bay has been building in a receiving basin that is only 2 m deep and, as a result, has added 100 km^2 of new land in only 30 years. (5) *Use numerical simulation to determine ideal opening angles and depth of cut*. The effects of meander bends and thus the angle of a diversion opening could be important in sediment delivery through the diversion. (6) *Select sites that have very low bottom gradients*. Atchafalaya Bay constitutes an ideal receiving basin because it is relatively flat such that progradation requires less sediment volume *per* unit of new land than a sloping bottom.

ACKNOWLEDGMENTS

This study was supported by, and undertaken for, the U.S. Army Corps of Engineers in conjunction with the U.S. Geological Survey, and the Louisiana Office of Coastal Protection and Restoration. We thank Barbara Kleiss (USACOE), James Stefanov (USGS), and James Pahl (LAOCPR) for their review and comments. Marcia Berman and Sharon Killeen at the Virginia Institute of Marine Science assisted in preparation of the figures.

LITERATURE CITED

Allison, M.A.; Demas, C.R.; Ebersole, B.A.; Kleiss, B.A.; Little, C.D.; Meselhe, E.A.; Powell, N.J.; Pratt, T.C., and Vosburg, B.M., 2012. A water and sediment budget for the lower Mississippi–Atchafalaya River in flood years 2008–2010: implications for sediment discharge to the oceans and coastal restoration in Louisiana. *Journal of Hydrology*, 432, 84–97.

Allison, M.A. and Meselhe, E.A., 2010. The use of large water and sediment diversions in the Lower Mississippi River (Louisiana) for coastal restoration. *Journal of Hydrology*, 387, 346–360.

Allison, M.A.; Vosburg, B.M.; Ramirez, M. T., and Meselhe, E.A., 2013. Mississippi River channel response to the Bonnet Carré Spillway opening in the 2011 flood and its implications for the design and operation of river diversions. *Journal of Hydrology*, 477, 104–118.

Barras, J.A., 2007. Land area changes in coastal Louisiana after Hurricanes Katrina and Rita. *In*: Farris, G.S.; Smith, G.J.; Crane, M.P.; Demas, C.R.; Robbins, L.L., and Lavoie, D.L. (eds.), *Science and the Storms: The USGS Response to the Hurricanes of 2005. USGS Circular 1306*. Reston, Virginia: U.S. Geological Survey, pp. 98–113. http://pubs.usgs.gov/circ/1306/.

Coleman, J.M., 1988. Dynamic changes and processes in the Mississippi River Delta. *Geological Society of America Bulletin*, 100(7), 999–1015.

Coleman, J.M. and Gagliano, S.M., 1964. Cyclic sedimentation in the Mississippi River deltaic plain. *Gulf Coast Association of Geological Societies Transactions*, 14, 67–80.

Coleman, J.M.; Gagliano, S.M., and Morgan., J.P., 1969. Mississippi River subdeltas, natural models of deltaic sedimentation. *Coastal Studies Institute Bulletin 3*. Baton Rouge, Louisiana: Louisiana State University, pp. 23–27.

Coleman, J.M.; Roberts, H.R., and Stone, G.W., 1998. Mississippi River Delta: an overview. *Journal of Coastal Research*, 14(3), 698–716.

CPRA (Coastal Protection and Restoration Authority), 2012. *Louisiana's Comprehensive Master Plan for a Sustainable Coast*. Baton Rouge: State of Louisiana, 190p. http:// www.coastalmasterplan.louisiana.gov.

Davis, D.W., 2000. Historical perspective on crevasses, levees, and the Mississippi River. *In*: Colten, C.E. (ed.), *Transforming New Orleans and Its Environs*. Pittsburgh, Pennsylvania: University of Pittsburgh Press, pp. 84–106.

Day, J.W.; Cable, J.E.; Cowan, J.H., Jr.; DeLaune, R.; de Mutsert, K.; Fry, B.; Mashriqui, H.; Justic, D.; Kemp, P.; Lane, R.R.; Rick, J.; Rick, S.; Rozas, P.; Snedden, G.; Swenson, E.; Twilley, R.R., and Wissel, B., 2009. The impacts of pulsed reintroduction of river water on a Mississippi Delta coastal basin. *In:* FitzGerald, D. and Reed, D.J. (eds.), *Geologic and Environmental Dynamics of the Pontchartrain Basin*. Journal of Coastal Research, Special Issue No. 54, pp. 225–243.

Dean, R.G.; Wells, J.T.; Fernando, J., and Goodwin, P., 2012. River diversions: principles, processes, challenges and opportunities—a guidance document. *Final Report to the LCA Science & Technology Program Office,* Vicksburg, Mississippi. 57p.

Dokka, R.K.; Sella, G.F., and Dixon, T.H.. 2006. Tectonic control of subsidence and southward displacement of southeast Louisiana with respect to stable North America. *Geophysical Research Letters*, 33, L23308. doi:10.1029/2006GL027250.

Edmonds, D.A. and Slingerland, R.L., 2007. Mechanics of river mouth bar formation: implications for the morphodynamics of delta distributary networks. *Journal of Geophysical Research*, 112, F02034. doi:10:1029/2006FJ000574.

Edmonds, D.A. and Slingerland, R.L., 2010. Significant effect of sediment cohesion on delta morphology. *Nature Geoscience*, 3(2), 105–109.

Gonzalez, J.L. and Tornqvist, T.E., 2006. Coastal Louisiana in crisis: subsidence or sea level rise? *EOS, Transactions, American Geophysical Union*, 87(45), 493–508.

Kim, W.; Mohrig, D.; Twilley, R.; Paola, C., and Parker, G., 2009. Is it feasible to build new land in the Mississippi River Delta? *EOS, Transactions, American Geophysical Union*, 90(42), 373–384.

Kolker, A.S.; Allison, M.A., and Hameed, S., 2011. An evaluation of subsidence rates and sea-level variability in the northern Gulf of Mexico. *Geophysical Research Letters*, 38, L21404. doi:10.1029/2011GL049458.

Kolker, A.S.; Miner, M.D., and Weathers, H.D., 2012. Depositional dynamics in a river diversion receiving basin: the case of the West Bay Mississippi River Diversion. *Estuarine, Coastal and Shelf Science,* 106, 1–12.

Kostic, S. and Parker, G., 2003. Physical and numerical modeling of deltaic sedimentation in lakes and reservoirs. *In: Proceedings of the 30th International Association of Hydraulic Research Congress* (Thessaloniki, Greece), 8p.

Letter, J.V.; Pinkard, C.F.; Fred, C., and Raphelt, N.K., 2008. *River Diversions and Shoaling. Coastal and Hydraulics Engineering Technical Note VII-9*. Vicksburg: Mississippi: Engineering Research and Development Center, Coastal and Hydraulics Laboratory, 21p.

Meckel, T.A. 2008. An attempt to reconcile subsidence rates determined from various techniques in southern Louisiana. *Quaternary Science Reviews*, 27(15–16), 1517–1522.

Morton, R.A. and Barras, J.A., 2011. Hurricane impacts on coastal wetlands: a half-century record of storm-generated features from southeast Louisiana. *Journal of Coastal Research*, 27(6A), 27–43.

Morton, R.A. and Bernier, J.C., 2010. Recent subsidence-rate reductions in the Mississippi Delta and their geological implications. *Journal of Coastal Research*, 26(3), 555–561.

Nittrouer, J.A.; Best, J.L.; Brantly, C.; Cash, R.W.; Czapiga, M.; Kumar, P., and Parker, G., 2012. Mitigating land loss in coastal Louisiana by controlled diversion of Mississippi River sand. *Nature Geoscience*. doi: 10.1038/NGEO1525.

Paola, C.; Twilley, R.R.; Edmonds, D.A.; Kim, W.; Mohrig, D.; Parker, G.; Viparelli, E., and Voller, V.R., 2011. Natural processes in delta restoration: application to the Mississippi Delta. *Annual Review of Marine Science*, 3, 67–91.

Parker, G.; Muto, T.; Akamatsu, Y.; Dietrich, W.E., and Lauer, J.W., 2008. Unraveling the conundrum of river response to rising sea-level from laboratory to field: Part 1. Laboratory experiments. *Sedimentology*, 55(6), 1643–1655.

Parker, G.; Paola, C.; Whipple, K., and Mohrig, D., 1998. Alluvial fans formed by channelized fluvial and sheet flow: I. Theory. *Journal of Hydraulic Engineering*, 124(10), 985–995.

Roberts, H.H. 1997. Dynamic changes of the Holocene Mississippi River Delta plain: the delta cycle. *Journal of Coastal Research*, 13(3), 605–627.

Seybold, H.; Andrade, J.S., Jr., and Herrmann, H.J., 2007. Modeling river delta formation. *Proceedings, National Academy of Sciences*, 104(43), 16804–16809.

Seybold, H.J.; Molnar, P.; Singer, H.M.; Andrade, J.S., Jr.; Herrmann, H.J., and Kinzelbach, W., 2009. Simulation of birdfoot delta formation with application to the Mississippi Delta. *Journal of Geophysical Research*, 114, F03012. doi:10.1029/2009JF001H48.

Tornqvist, T.E.; Paola, C.; Parker, G.; Liu, K-B.; Mohrig, D.; Holbrook, J.M., and Twilley, R.R., 2007. Comment on "Wetland sedimentation from Hurricanes Katrina and Rita." *Science*, 316(5822), 20l. doi:10.1126/science.1136780.

Tornqvist, T.E.; Wallace, D.J.; Storms, J.E.A.; Wallinga, J.; van Dam, R.L.; Blaauw, M.; Derksen, M.S.; Klerks, C.J.W.; Meijneken, C., and Snijders, E.M.A., 2008. Mississippi Delta subsidence primarily caused by compaction of Holocene strata. *Nature Geoscience*, 1(3), 173–176.

Twilley, R.R.; Couvillin, B.R.; Hossain, I.; Kaiser, C.; Owens, A.B.; Steyer, G.R., and Visser, J.V., 2008. Coastal Louisiana ecosystem assessment and restoration (CLEAR) program: the role of ecosystem forecasting in evaluating restoration planning in the Mississippi River deltaic plain. *In:* McLaughlin, K.D. (ed.), *Mitigating Impacts of Natural Hazards on Fishery Ecosystems*, Vol. 64. Bethesda, Maryland: American Fisheries Society, pp. 29–46.

Turner, R.E.; Baustian, J.J.; Swenson, E.M., and Spicer, J.S., 2006. Wetland sedimentation from Hurricanes Katrina and Rita. *Science*, 314(5798), 449–452.

Turner, R.E. and Streever, B., 2002. *Approaches to Coastal Wetland Restoration: Northern Gulf of Mexico*. The Hague, the Netherlands: SPB Academic, 147p.

Wamsley, T.V. 2011., *Land Building Modules: Uncertainty in and Sensitivity to Key Input Parameters*. Vicksburg, Mississippi: Engineering Research and Development Center, U.S. Army Corps of Engineers, 32p.

Welder, F.A., 1959. Processes of deltaic sedimentation in the lower Mississippi River, *Coastal Studies Institute Technical Report No. 12*. Baton Rouge, Louisiana: Louisiana State University, 90p.

Wells, J.T., 1996. Subsidence, sea-level rise, and wetland loss in the lower Mississippi River delta. *In:* Milliman, J.D. and Haq, B.U. (eds.), *Sea-Level Rise and Coastal Subsidence*. The Netherlands: Kluwer, pp. 282–311.

Wells, J.T. and Coleman, J.M., 1987. Wetland loss and the subdelta life cycle. *Estuarine, Coastal and Shelf Science*, 25, 111–125.

Wolinsky, M.A.; Edmonds, D.A.; Martin, J., and Paola, C., 2010. Delta allometry: growth laws for river deltas. *Geophysical Research Letters*, 37, L21403. doi:10.1029/2010GL044592.