River Diversions: Principles, Processes, Challenges and Opportunities

A Guidance Document

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Executive Summary

This *Guidance Document* provides a framework and rational basis for the preliminary design of river diversions and the selection of key design parameters that will impact their performance. The document is based on the assumption that river diversions are, and will continue to be, one of the principal tools for building new land in coastal Louisiana, and that the significant gaps in our understanding of performance must, and almost certainly will, be addressed through application of numerical models. The guidance presented in this document is based on 1) the body of published and unpublished literature that draws from the knowledge and experience of others, 2) the results of simple analytical models that were developed specifically for this document, and 3) our own knowledge, insight and application of best professional judgment.

River diversions, if successful, will create new land that mimics scaled-down versions of natural delta lobes. The evolution of these features as they occur in nature, referred to in the literature as subdeltas or bay-fill deposits, is well documented. It begins with 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, all within a time frame of decades to centuries. The performance of river diversions will be controlled by numerous factors that can be broadly categorized as 1) basin geometry, 2) sediment characteristics, 3) biological factors, 4) water motion including turbulence, and 5) design and operational strategies. Included in these broad categories are important variables including water depth, sea level rise, subsidence, input of sand, impact of storms and major floods, and the role of vegetation in changing bulk density and stabilizing the deposits.

Two geometric models were developed to allow calculation of future performance of river diversions. 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.

Preliminary 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 User-specified, namely average diversion water discharge, initial depth of receiving waters, bottom slope, deposit angle or width, and future sea level rise. Using recommendations in the document that were taken from a synthesis of data in the literature, calculations for time to emergence for various sediment delivery estimates were made for the White Ditch Diversion and the West Bay Diversion. Estimates can vary widely depending on foreset slope and whether sediments include a mix of sand, silt and clay (versus sand only), but values in the range of 5-15 years for White Ditch and 11-13 years for West Bay are considered to be reasonable.

This *Guidance Document* also includes general recommendations for selection and utilization of diversion sites: 1) select sites that, based on all available evidence, are in areas of low subsidence; 2) select sites that are likely to have very high trapping efficiency; 3) select sites that are less than 2 m in depth; 4) select sites that have very low bottom gradients; 5) implement a well-thought-out monitoring plan to be part of each diversion project; 6) apply adaptive management as new information and understanding becomes available from monitoring; 7) recognize that diversions will have a life cycle and are not permanent features; and, 8) recognize and model insofar as possible the effects on navigation that will likely result from large diversions.

Appendix A presents useful conversion factors and estimates of Mississippi River average annual water and sediment discharges.

River Diversions: Principles, Processes, Challenges and Opportunities

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1.0 Introduction

River diversions are one of the fundamental tools available for coastal restoration in Louisiana. Under certain scenarios, they offer an efficient and effective means of building new land, providing a substrate for wetland growth and an opportunity for enhancement of ecological diversity. We have conducted an extensive literature survey of the state of knowledge of diversions with regard to basic principles and processes, and have examined the efficacy of diversion projects at multiple scales on the Louisiana coast. 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 document, including the role of sea level rise and subsidence, sediment composition and quantity, effects of receiving basin characteristics, and impacts 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 guidance, and the importance of sensitivity studies. Figure 1 presents locations of existing and planned diversions along the main stem of the Mississippi River.

Figure 1. Location map showing diversion locations along the main stem of the Mississippi River.

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. 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 2003, previous diversions have been focused primarily on introduction of freshwater rather than sediment. *2) Unintended impacts on the main stem of the river,* primarily as a result of shoaling that may affect navigation and escalate project costs. *3) Uncertainty in subsidence* leading to considerable controversy in subsidence rates, their temporal and spatial variations, and their relevant driving forces. *4) Limited predictive capability for land growth* because of the general lack of understanding of the very factors that are discussed in this guidance document. *5) Unintended and potentially negative impacts from the freshwater introductions* that co-occur with the introduction of sediments. *6) Societal and economic issues* associated with competing stakeholder interests, projects costs and tradeoffs, and effectively communicating expectations. *7) 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 geological time scales (Seybold et al., 2007); simulation of birdsfoot deltas on 100 to 1,000-yr 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, we offer in this document a modeling approach that utilizes simple analytical models specifically for the purpose of guiding design and preliminary evaluation by examining interrelationships among key variables.

The guidance presented herein is based on 1) the considerable body of published and unpublished literature that draws from the knowledge and experience of others, 2) the results of the simple analytical models that were developed specifically for this document, and 3) our own knowledge, insight, and application of best professional judgment. 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 guidance document furnishes definitive answers to complex questions that will require additional analysis.

2.0 Evolution Characteristics 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. 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 (Wells and Coleman, 1987; Coleman, 1988; Wells, 1996; Roberts, 1997; Coleman et al., 1998) and can serve as a geomorphic and sedimentologic model for creating new wetlands from river diversions (Davis, 2000; Allison and Meselhe, 2010).

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 et al., 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 yr (Wells, 1996). Smaller crevasse-splay deposits that are associated with overbank flooding during very high discharge years also create new land but rarely last more than 10-15 yr 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 mid 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 that ranged from 0.8-2.7 km^2/yr and 1.1-7.0 km^2/yr, respectively (Fig. 2). Average and maximum rates of deterioration were on the same order as rates of growth, typically several km^2/yr 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 x 10^6 m^3/yr, and the Mississippi Delta had acquired a total of ~7000 x $10^6/m^3$ of new sediment.

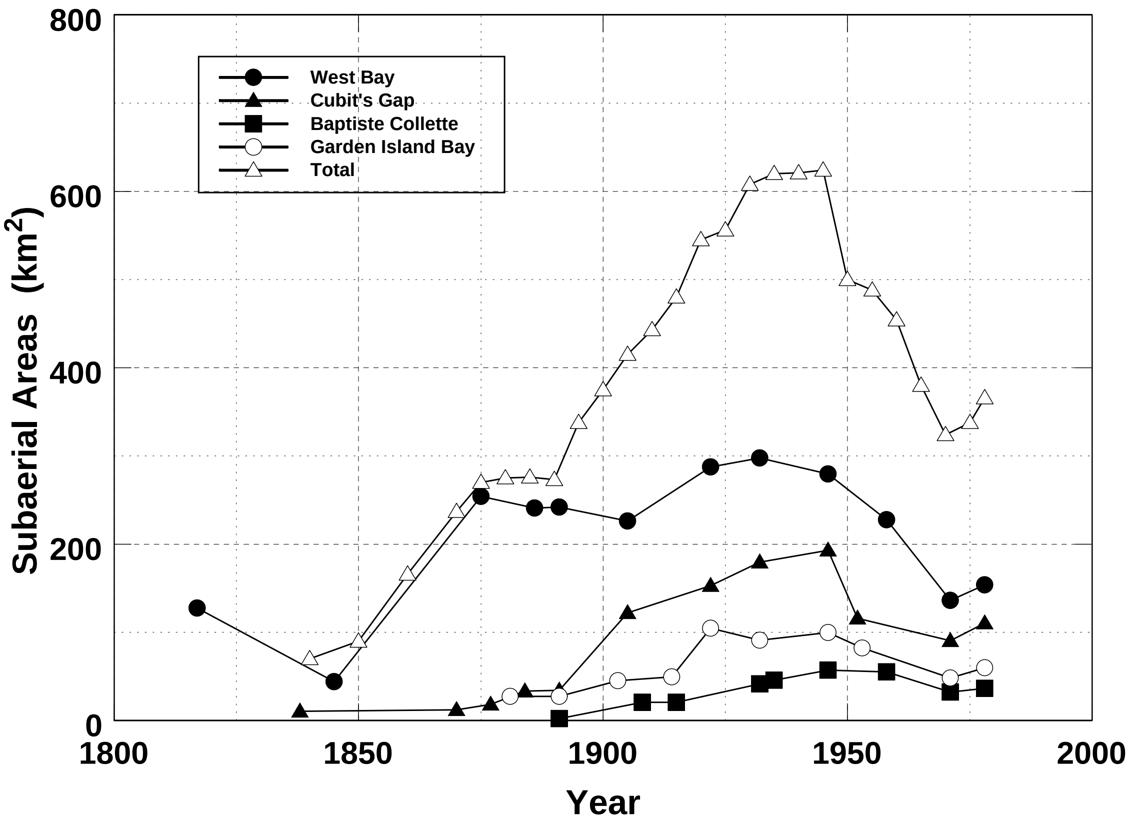

Figure 2. Life cycle of subdeltas of the Mississippi River Delta (from Wells and Coleman, 1987).

During the progradational phase of development, 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 up 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, hence sediment delivery network, that subaerial growth begins to increase rapidly. As 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 new Atchafalaya and Wax Lake deltas 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. 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. Rather, 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).

However, the fact that the four subdelta deposits each underwent a deterioration phase while continuing to receive significant sediment discharge from the Mississippi River (75% of the original land area of the Cubits Gap subdelta had been lost by the late 1980s; Coleman, 1988), carries important implications for restoration, especially if it were to be undertaken in the lower delta. *Implication #1: 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. *Implication #2: 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 diversions, each of a different “age”. *Implication #3: Predictions for subaerial growth using the subdeltas as a model 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, 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 for reasons discussed later in this report.

3.0 Variables that Impact 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 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/yr are also significant 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 inter-annual 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 of water and mass of sediment that enters a receiving basin, the infilling process is controlled by the volume of 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 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 (see next section) 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 (Turner et al., 2006). With their higher settling speeds, sands would have shorter distances to reach the point of deposition (see next section) 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 document, diversion performance is dependent on diversion 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 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 pulsed 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.

4.0 Criteria for Deposition and Stability of Diversion Sediments

4.1 Critical Shear Stress

Consider a case of uniform depth in a receiving basin in which the velocity decreases with distance from the source. The distance to deposition will be controlled by at least two mechanisms. One is the threshold shear stress for scour and the second is the settling time of the sediments. The criterion for critical shear stress can be written as

$$\tau_c = \frac{\rho f}{8} u_c^2 \qquad (1)$$

in which τ_c is the critical shear stress, ρ the mass density of water, f the Weisbach-Darcy friction factor, and u_c the critical velocity associated with the critical shear stress. A reasonable value of τ_c for fine sediments (silt and clay) is 1N/m^2 (recognizing that very compact clays would be considerably less erodible) and for a Weisbach-Darcy coefficient of 0.08, the threshold velocity, u_c, is approximately 0.32 m/s (=1.05 ft/s). For a water discharge Q from a small diversion opening and uniform angular spreading radial flow over an angle $\Delta\theta$ and uniform depth, h, the average velocity varies with distance, r, from the origin as

$$u = \frac{Q}{\Delta\theta r h}. \qquad (2)$$

Thus, the distance to which fine sediments could remain stable, r_c, for uniform angular spreading would be

$$r_c = \frac{Q}{h\Delta\theta u_c} = \frac{Q}{h\Delta\theta}\sqrt{\frac{\rho f}{8\tau_c}}. \qquad (3)$$

As an example, consider a diversion discharge of 40,000 cfs (1,134 m^3/s) which is approximately the average for the West Bay Diversion. For a depth, h , of the receiving waters of 4.6 m, the distance is

$$r_c = \frac{1{,}134}{4.6\pi(0.32)} = 245 \text{ m.} \qquad (4)$$

Of course, during flood conditions the distance would be greater; however, the discharge of a greater proportion of coarser sediments would partially offset this effect.

4.2 Fall Velocity

A second criterion is that the distance must be great enough so that the sediment particles in suspension can fall to the bottom. This depends on the fall velocity of the sediment which is a function of diameter as shown in Figure 3 for the case of quiescent water. Turbulence would decrease the fall velocity.

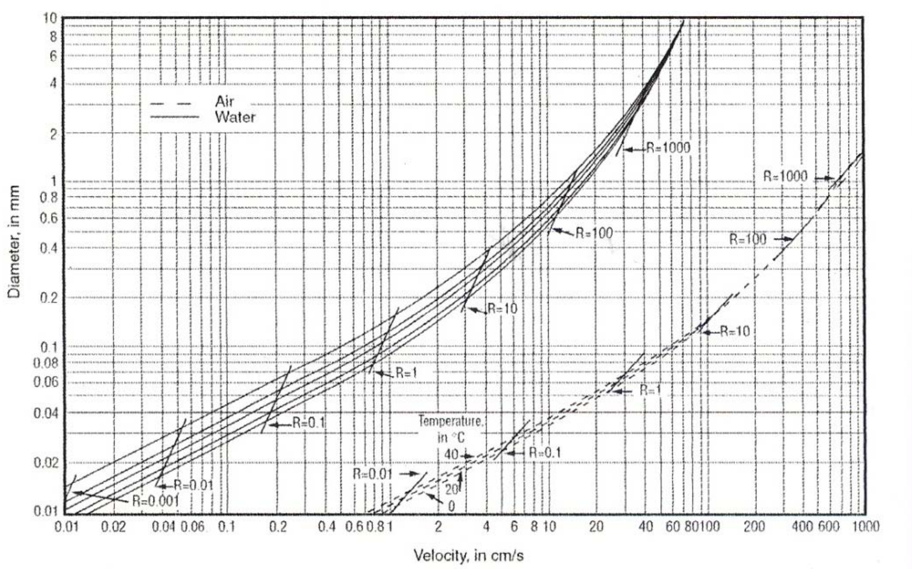

Figure 3. Fall velocity vs. sediment diameter (Rouse, 1937)

It is seen that for a sediment size of 0.01 mm as measured in the West Bay studies for suspended sediment (Brown et al., 2009), w_f is approximately 0.01 cm/s. The time, t_f , required for a particle to fall through one-half the water depth, h (considered as representative), is

$$t_f = \frac{h}{2w_f}. \qquad (5)$$

Considering the same geometry as before, the distance r_f associated with the fall time is

$$r_f = \sqrt{\frac{Q}{\Delta\theta w_f}}\,. \tag{6}$$

For the approximate West Bay Diversion conditions considered earlier, the distance, r_f is

$$r_f = \sqrt{\frac{1{,}130}{\pi 0.0001}} = 1{,}897 \text{ m.} \tag{7}$$

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 model results in velocities that probably decrease too rapidly from the origin (the spreading would be more "jet-like" and thus spread more slowly) such that these two effects would tend to offset each other. In this example, using the two criteria and conditions evaluated, the required fall distance would be the limiting factor governing the deposition of the sediments. The fall velocity for sand (considered 0.2 mm) is 3 cm/s and the corresponding fall distance r_f is 109 m. This finding is relevant to the proportion of retained sediment that should be considered in application of the simple geometric models presented here. Because the effects of turbulence will reduce the fall velocity, the fall distance approach described here will underestimate the fall distances.

5.0 Simple Models For Scoping and Sensitivity Studies

This guidance document presents analytical methods which can be applied to various diversion-related tasks, including comparing different designs at one location, comparing the same design at different locations and conducting sensitivity tests. Several of the key input variables (e.g. subsidence, sediment delivered and retained, volume bulking due to vegetation and water content) are poorly known such that estimates must now suffice for diversions along the main stem of the Mississippi River. The philosophy associated with this method is that it represents 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. In applying the models, we recommend that better estimates of the key parameters be used as they become available. A central feature of the method is that no attempt has been made to calibrate with results from known diversions. For example, the calculations for the West Bay Diversion appear to differ significantly from the actual performance but, because the reason(s) for this are not known and this diversion has been in operation for less than 10 years, calibration efforts could target the wrong parameters/mechanisms. Rather, we consider it best at this stage to leave any difference as a cautionary notice to the User with the recognition that changes based on detailed monitoring are the only appropriate basis on which to develop modifications. In the following, the method is illustrated by application to hypothetical cases to illustrate principles, and to the West Bay Diversion and the planned White Ditch Diversion.

Two simple geometric models of the evolution of diversion deposits have been developed. These 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 geometry of uniform-width. The former is characteristic of the Wax Lake Diversion Delta and the second is similar to that of the planned White Ditch Diversion. It is found that in the presence of relative sea level rise, the subaerial deposit evolution occurs in three phases following the emergence of a subaerial platform: (1) a growth phase, (2) a phase in which the platform growth reaches a maximum and may display a period of stability, and (3) a phase in which the platform dimensions decrease and the platform finally becomes submerged. 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 Parker et al. (1998), Kostic and Parker (2003) and Parker et al. (2008) and the Corps of Engineers models ERDC-SAND and ERDC-SAND2 models. The unique feature 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.

5.1 Geometric Model 1: Truncated Cone, Uniform Depth

5.1.1 General

The geometry of the truncated cone considered is presented in Figure 4.

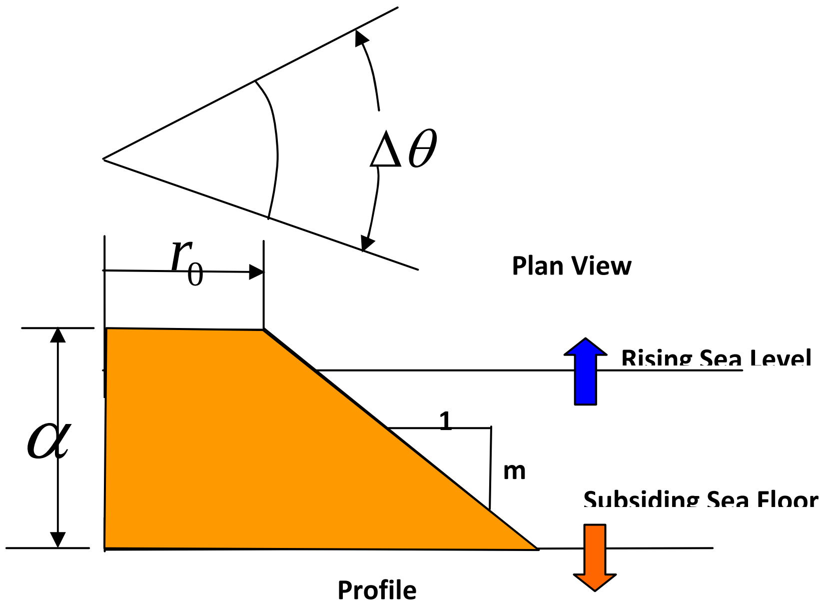

Figure 4. Definition sketch of a truncated cone in water of uniform depth.

The volume of a truncated cone, V , is

$$V = \frac{\Delta\theta}{2}\left[r_0^2\alpha + r_0\frac{\alpha^2}{m} + \frac{\alpha^3}{3m^2} \right] \tag{8}$$

where $V = Qt$ and 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 as the volume supplied is considered to be constant whereas the depth increase (due to subsidence and sea level rise) increases linearly such that the required volume to maintain the deposit subaerial increases with the cube of time as shown in Figure 5.

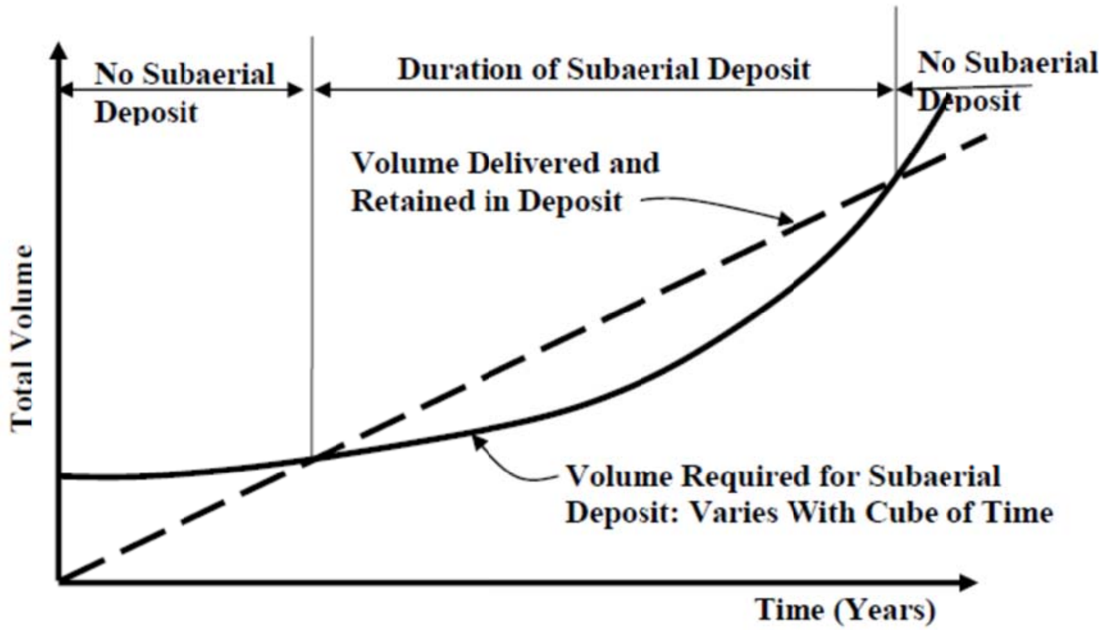

Figure 5. Interpretation of three stages of evolution for truncated cone.

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

$$r_0 = -\frac{\alpha}{2m} + \sqrt{\frac{2V}{\alpha \Delta \theta} - \frac{\alpha^2}{12m^2}} \ . \qquad (9)$$

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 be zero. With this particular geometry and a relative sea level rise, this is an inescapable consequence in the evolution of the diversion deposit.

5.1.2 Time to Emergence of a Subaerial Platform for a Truncated Cone

In the presence of a 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 non-dimensional form such that it is necessary to consider only one case for all combinations of parameters. The results are presented here in graphical form with additional details in Appendix B.

Defining a non-dimensional time, $t' = \frac{t}{\alpha_o} \frac{\partial \alpha}{\partial t}$ and a non-dimensional discharge, $Q' = \frac{8\, Qm^2}{\Delta\theta\alpha_o^2 \frac{\partial \alpha}{\partial t}}$,

it can be shown that the non-dimensional solution is

$$1 - 3t'\left(Q' - 1\right) + 3(t')^2 + (t')^3 = 0\,. \tag{10}$$

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 non-dimensional variables, t' and Q'. Note that the definition of the non-dimensional variables establishes the interrelationships among all variables. For example, in the non-dimensional discharge, Q', the sediment discharge, Q, has the same effect on emergence time as the square of the initial depth, α_o, or the inverse of the square of the foreset slope, m, etc. Examples will be presented later to illustrate application of the results.

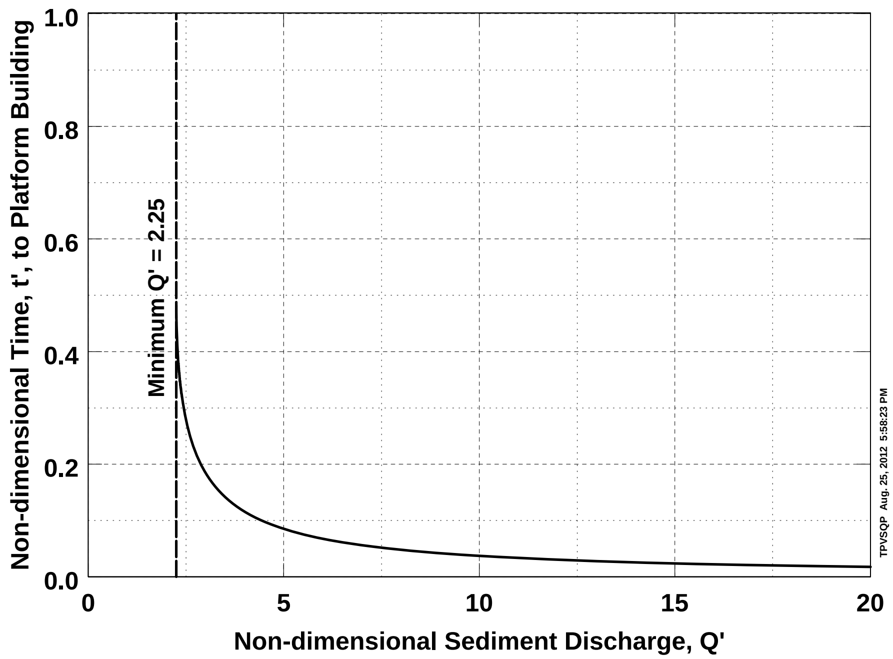

Figure 6. Non-dimensional time, t’, vs non-dimensional discharge, Q’, for truncated cone.

5.2 Geometric Model 2: Uniform Width

5.2.1 General

The geometry for this model is shown in Figure 7.

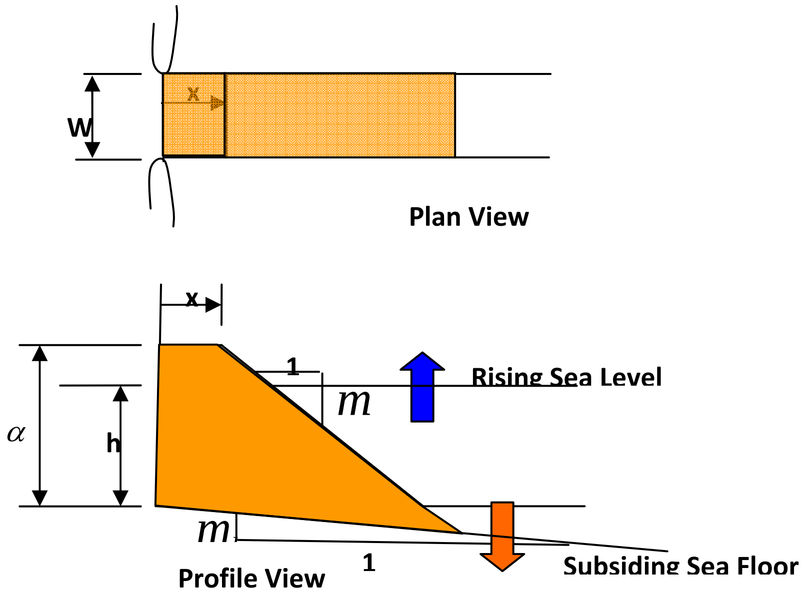

Figure 7. Uniform width model. Sloping sea floor.

The volume of the uniform width model with a horizontal bottom, is given by

$$V = Qt = W\left(\alpha x + \frac{\alpha^2}{2m}\right), \tag{11}$$

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

$$x = \frac{1}{W}\left[\frac{Qt - \frac{W}{2m}\alpha^2}{\alpha}\right]. \tag{12}$$

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

$$x^2\left(\frac{m_b}{2}+\frac{m_b^2}{2(m-m_b)}\right)+x\left(\alpha+\frac{2m_b}{m-m_b}\right)+\frac{\alpha^2}{2\left(m-m_b\right)}-\frac{Qt}{W}=0\,. \tag{13}$$

5.2.2 Time to Emergence of a Subaerial Platform of Uniform Width and Depth

For this case, the non-dimensional variables are

$t'=\frac{t}{W\alpha_o}\frac{\partial\alpha}{\partial t}$, the same as for the truncated cone; however, the definition of the non-dimensional discharge, Q', differs and is $Q'=\dfrac{Qm}{\alpha_o\dfrac{\partial\alpha}{\partial t}}$. The governing equation, expressed in the non-dimensional quantities is

$$1-2t'\left(Q'-1\right)+(t')^2=0 \tag{14}$$

which can be solved directly for t' as

$$t'=(Q'-1)+\sqrt{(Q')^2-2Q'}\,. \tag{15}$$

It can be shown that the minimum Q' for subaerial platform development is $Q'=2.0$ compared to 2.25 for the truncated cone case considered previously. Details are presented in Appendix B. Figure 8 presents the solution for t' as a function of Q'.

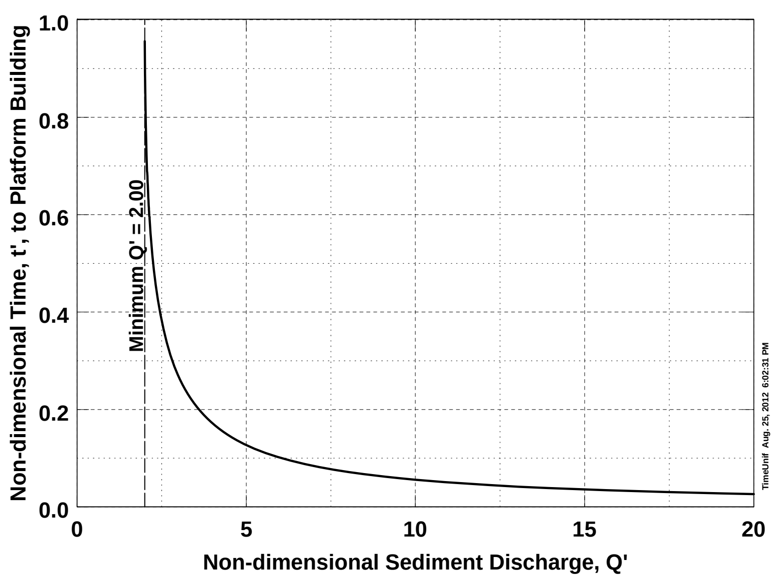

Figure 8. Non-dimensional time, t’, vs non-dimensional discharge, Q’, for uniform width and uniform depth model.

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

5.3 Examples Illustrating Application of the Two Models

In the following, we present several 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 ranges between approximately 35 x 10^6 m^3 and 50 x 10^6 m^3 and the annual delivery of suspended sediments in the sand size range is estimated to be between 0.6 x 10^6 m^3 and 10 x 10^6 m^3 (Appendix A). Based on the relationships developed and recommended here for guidance, the ratio of sand to total sediment in suspension is 0.018 (1.8%).

5.3.1 Example 1. Case 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 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. The characteristics of this example are shown in the figure caption.

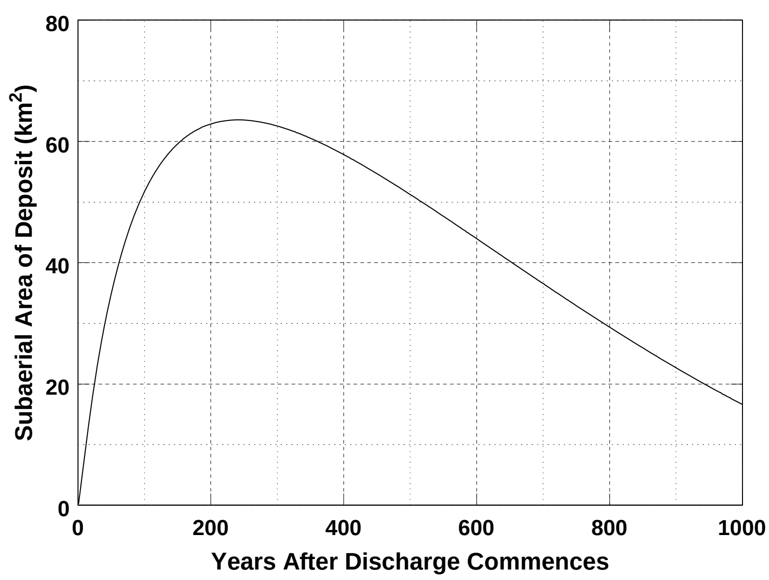

Figure 9. Example 1. Annual discharge of retained sediment = 3 x 10^6 m^3/yr, initial depth of receiving waters = 2.0 m, elevation of horizontal portion of deposit above mean water level = 0.25 m, rate of relative sea level Rise = 2.0 cm/yr, foreset slope = 0.002 and delta opening angle = 180^o.

This model application 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 related to the requirement for additional sediment vs time compared to the rate at which it is delivered as shown in Figure 5. For conditions considered here, the increased 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 (Eq. (8)); however, for the case of a diversion of uniform width, the required sediment varies with the square of time (Eq. (11)).

5.3.2 Example 2. Large vs Small Diversions, Truncated Cone Geometry

This second example examines the efficacies of larger vs. smaller diversions. Results are presented in Figure 10. In this example, the total volume of 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 Figure 10 thus represent the *same* total amount of sediment retained in the two diversions and 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 in this section.

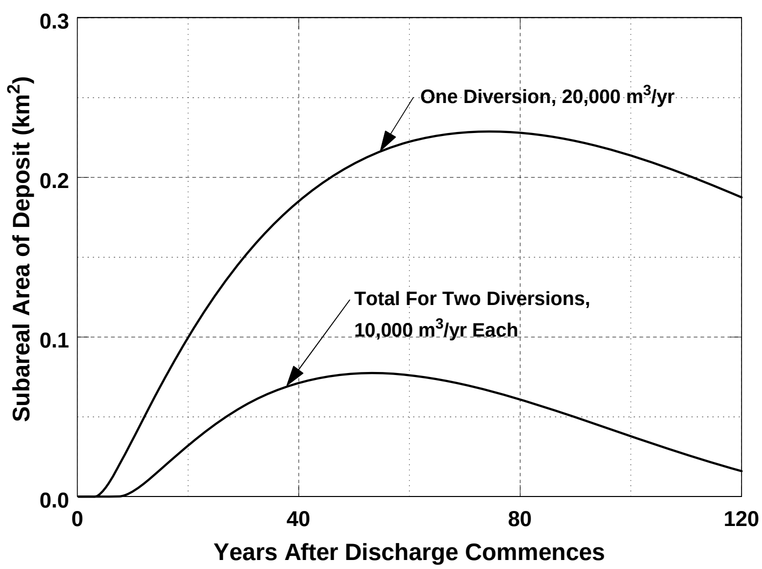

Figure 10. Example 2. Comparison of subaerial areas over time for one large diversion vs two diversions with the *same* total sediment retention. Initial depth of receiving waters = 0.75 m, elevation of horizontal portion of deposit above mean water level = 0.25 m, rate of relative sea level rise = 1.0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

5.3.3 Example 3. Uniform Width and Depth Model, General Evolutionary Characteristics

This example portrays the evolutionary behavior for the case of a receiving area of uniform width and depth model with the characteristics shown in the caption of 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 apply. For this case, the receiving water depth α_o of 2.0 m and a width W = 2,000 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.

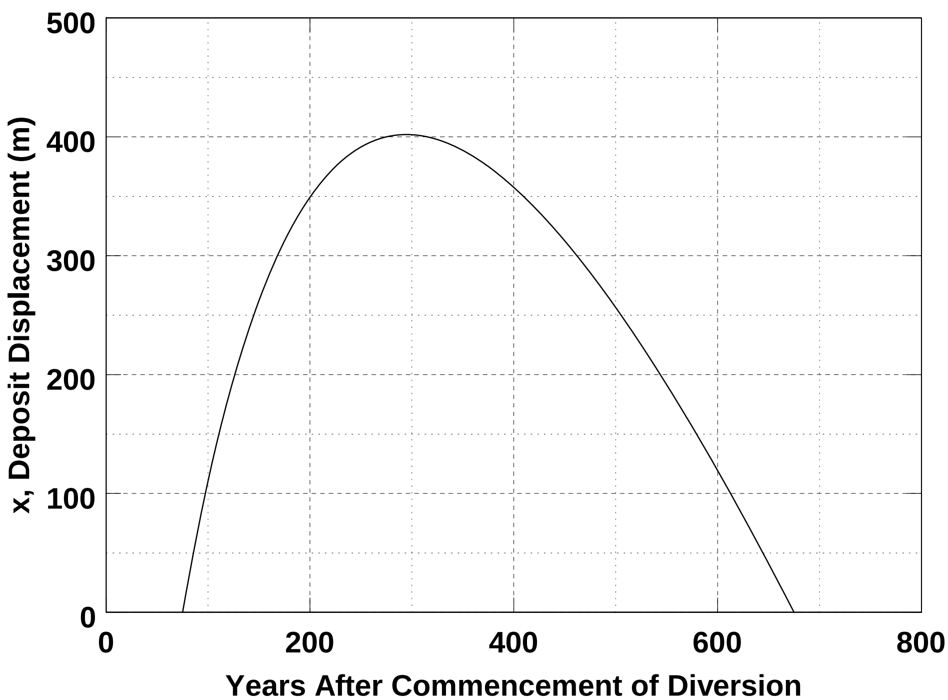

Figure 11. Example 3. Berm length, x, of deposit (see Figure 7) for diversion deposit of uniform width and into receiving waters of uniform depth. Annual volume of sediments retained = 60,000 m^3/year, width of deposit = 2,000 m, initial depth = 1.5 m, elevation of deposit platform above water level = 0.25 m, relative sea level rise = 1 cm/yr.

5.3.4 Example 4. Uniform Width Model, Effect of Bottom Slope

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 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.

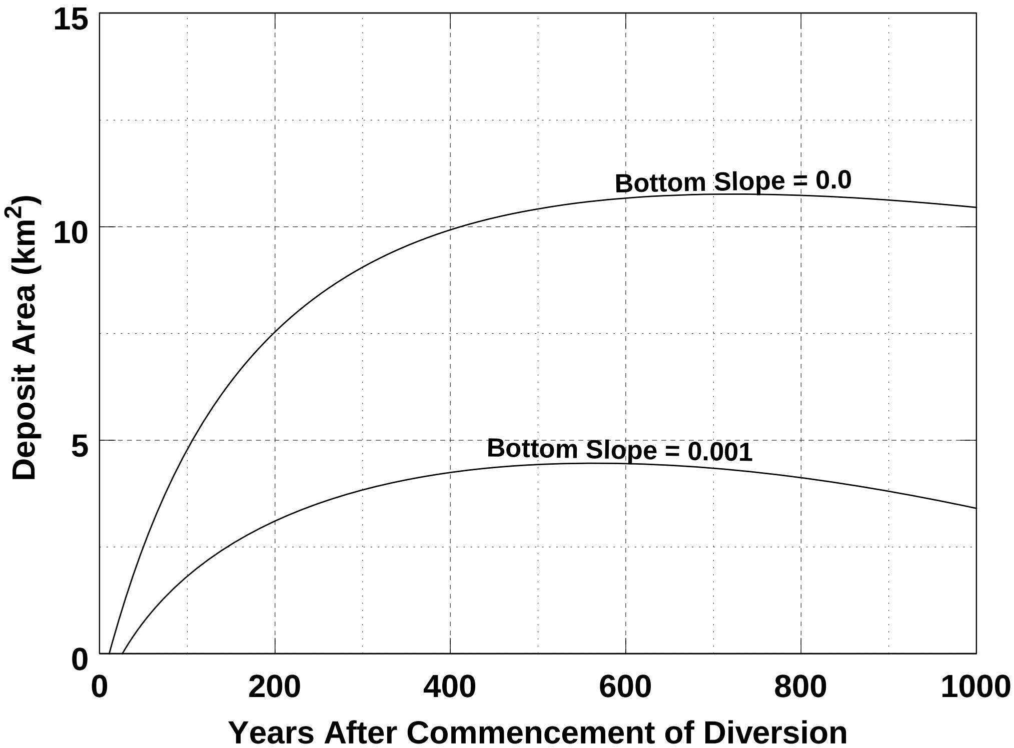

Figure 12. Example 4. Comparison of subaerial areas over time for two bottom slopes. Uniform width, annual retention of sediment = 200,000 m^3/yr, relative sea level rise rate = 1.0 cm/yr. Initial depth of receiving waters = 0.75 m, Elevation of horizontal portion of deposit above mean water level =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

5.3.5 Example 5. Uniform Width and Depth, Effect of Relative Sea Level Rise

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

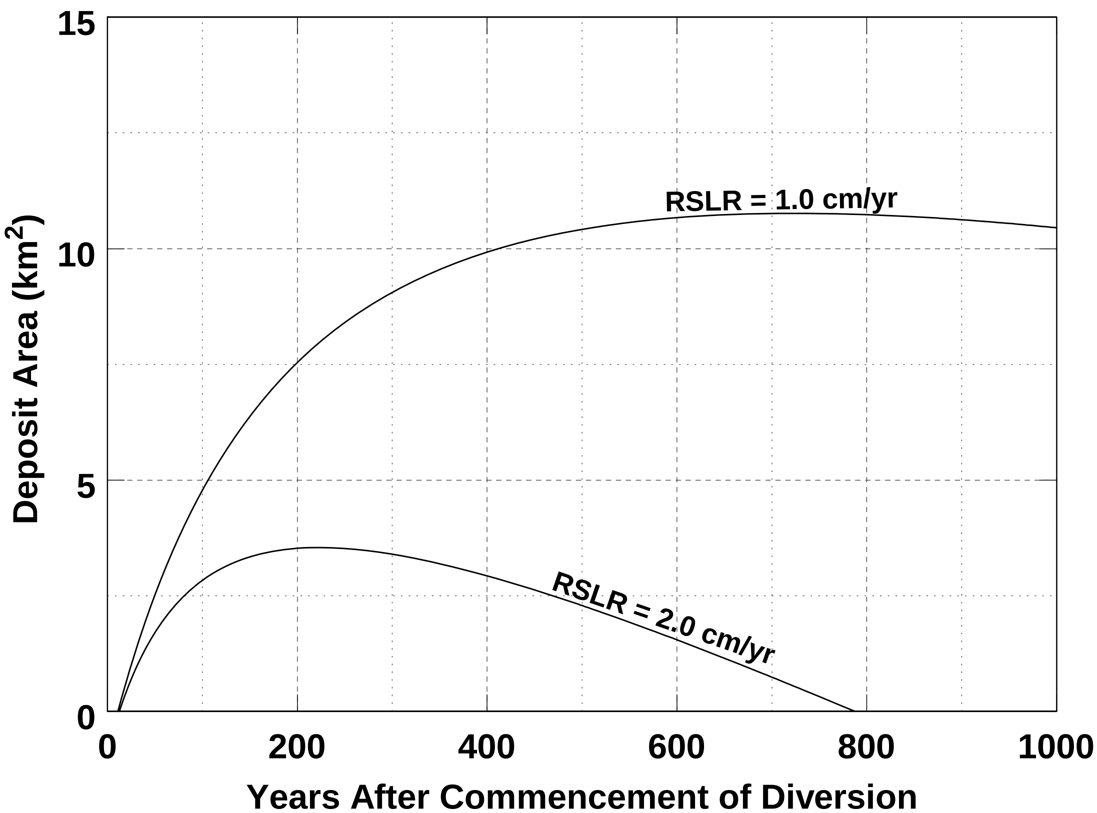

Figure 13. Example 5. Comparison of subaerial areas over time for relative sea level rise rates, uniform width = 2,000 m, annual retention of sediment = 200,000 m^3/yr. Initial depth of receiving waters = 2.0 m, elevation of horizontal portion of deposit above mean water level = 0.25 m, foreset slope = 0.002, bottom slope = 0.

6.0 Guidance for Selection of Diversion Parameters

6.1 General

This section provides recommendations for the quantification of parameters to be applied in the models described. The concept is to recommend methods of quantifying the parameters with the understanding that the values are approximate based on information and best judgment at this time. Thus, this guidance document represents a structure with which to compare monitoring results such that the methods and details will be improved as more information and experience become available.

In the guidance recommendations presented in the following sections, it is assumed that the diversion hydraulics have been quantified in terms of their average annual flows. The parameters to be quantified for input into the models 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 User-specified and include: initial depth of discharge, receiving basin bottom slope, deposit angle or width, and future sea level rise. Prior to presenting our preliminary recommendations for input parameters, it is noted that all available diversions should be examined with special attention directed to those that are close and/or similar to the site of interest and those parameters should be weighed heavily in the parameter selection. Additionally, sensitivity tests are recommended to assess the significance of the choice of input parameters.

6.1.1 Annual Inorganic Sediment Input

The recommended annual inorganic sediment input is based largely on Allison and Mesehle (2010) during the 2008 flood at Empire, LA and requires that annual average water diversion discharge, $\overline{Q}_{Water}$, 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 the annual delivery of sand be according to the following

$$Q_{sand} = 36\overline{Q}_{Water} \tag{16}$$

and the annual delivery of fines

$$Q_{Fines} = 2,000\overline{Q}_{Water} \tag{17}$$

for a total

$$Q_{Sed\ Total} = 2,036\overline{Q}_{Water}\ . \tag{18}$$

In the above equations, <u>the sediment discharges are in cubic meters per year and the average diversion discharge is in cubic meters per second</u>. These recommendations are compared with more detailed estimates and measurements for the total Mississippi River and West Bay Diversion and White Ditch Diversion in Table 1.

Table 1

Comparison of sediment transport by river diversions on the basis of equations herein and other estimates

River of Diversion	$\overline{Q}_{water}$ (m^3/s) Average Annual	Q_{Sed} (m^3/year)	
		Estimated by Other Means (Source)	Method Suggested Here
Mississippi River at Belle Chase	17,000	56.4×10^6 (Total) 11.6×10^6 (Sand) 44.8×10^6 (Fines) (Allison, Personal communication)	34.6×10^6 (Total) 0.61×10^6 (Sand) 34.0×10^6 (Fines)
White Ditch Diversion	111	0.20×10^6 (Total) 0.002×10^6 (Sand) 0.128×10^6 (Silt) 0.073×10^6 (Clay) (Wamsley, 2011)	0.23×10^6 (Total) 0.004×10^6 (Sand) 0.226×10^6 (Fines)
West Bay Diversion	1,130	2.63×10^6 (Total) 0.28×10^6 (Sand) 2.35×10^6 (Fines) (Allison, Personal communication)	2.31×10^6 (Total) 0.04×10^6 (Sand) 2.27×10^6 (Fines)

It is noted that the sand transport estimates above differ substantially for the Mississippi River at Belle Chase and West Bay Diversion. The reason is not clear as the equations for the column titled "Method Suggested Here" were based on measurements at Empire as reported by Allison and Mesehle (2010).

6.1.2 Foreset Slope

All depositional slopes on the lower Mississippi River are very gentle and here we rely on recommendations of Twilley et al. (2008) and Kim et al. (2009), building on earlier work by Parker et al. (1998), Kostic and Parker (2003) and Parker et al. (2008), in which their range of foreset slopes for the final deposit is between 0.002 and 0.005. The smaller slopes would be associated with the smaller grain sizes and the greater tidal current 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.

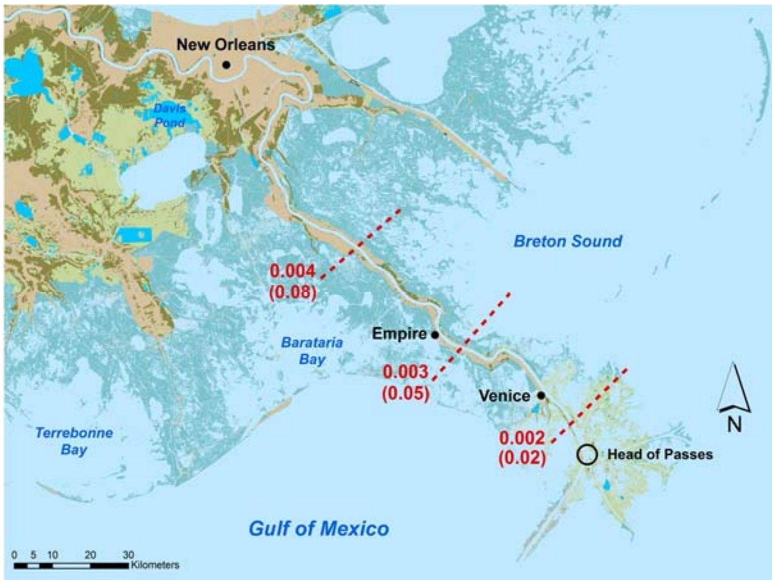

Figure 14. Recommended values for foreset slopes. Values in parentheses apply to sand size sediment.

6.1.3 Proportion of Diverted Material Retained

The proportion of diverted material retained (<1.0) would depend primarily on the sediment size and the wave and tide energy in the receiving area. Figure 15 presents preliminary recommendations for this proportion.

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

6.1.4 Subsidence

Figure 16 presents preliminary recommendations for subsidence rates in the literature (see Section 11.2.1).

Figure 16. Preliminary recommendations for subsidence rates, F_s.

6.1.5 Bulking Factors

The bulking factor (>1) is defined as the ratio of the volume of the final matrix of water, organic 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 simple 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. Figure 17 presents a preliminary estimate of bulking factors with the expectation that this figure will be improved with the availability of more data.

Figure 17. Preliminary recommendations for bulking factors, F_B.

7.0 Examples Illustrating Application of the Recommended Methodology

Two examples are presented that illustrate application of the recommended methodology to designs of particular interest.

7.1 Planned White Ditch Diversion

The parameters applied for the planned White Ditch Diversion are presented in Table 2. This diversion is best represented by the uniform width geometry model. Note that the quantity Q_{Sed_Eff} is the effective annual sediment retention ratee and incorporates effects of bulking and retention according to

$$Q_{Sed\_Eff} = F_R F_B Q_{Sed}\text{, where} \tag{19}$$

$$Q_{Sed\_Eff} \text{ would always be greater than } Q_{Sed}. \tag{20}$$

In this case, we first calculate whether or not, and if so, the time required for the deposit to achieve an emergent subaerial platform for various considerations of the sediment size classes. Table 3 presents the results.

Table 2

Summary of recommended input values for White Ditch and West Bay Diversions

Diversion	$\overline{Q}_{Water}$ (m^3/s)	$Q_{Sed\ Total}$ (m^3/year)	Q_{Sand} (m^3/year)	Prop. Retained, F_R Fig. 13	Bulking Factor, F_B Fig. 15	Q_{Sed_Eff} (m^3/year)	Subsidence Rate, F_S (m/yr) Fig. 14	SLR, (m/yr)	Initial Receiving Depth, α_o (m)	Foreset Slope, m Fig.12
White Ditch (Uniform Width)	111	226,000 (Eq. (18)) 200,000 (by Wamsley, 2011)	4,000 (Eq. (16)) (2,030 by Wamsley, 2011)	0.85	12	2,600,000	0.006	0.003	0.6	0.004
West Bay (Truncated Cone)	1,134	2,310,000 (Eq. (18)) 2,630,000 (Allison, Personal communication)	40,810 (Eq. (16)) 280,000 (Allison, Personal communication)	0.5	4	4,620,000	0.015	0.003	4.6	0.002

Table 3

Calculations to time of emergence for various sediment delivery estimates
for the planned White Ditch Diversion

Q (m^3/y), (Basis)	Foreset Slope, m Fig. 12	Q'	t'	t (years)
4,000 (Sand, Method Here)	0.08	7.8	0.074	13.0
2,030 (Sand, Wamsley, 2011)	0.08	4.0	0.173	30.5
129,940 (Sand and Silt, Wamsley, 2011)	0.08	254.8	0.002	0.4
203,030 (Sands, Silts and Clays, Wamsley, 2011)	0.004	19.9	0.027	2.0
230,000 (Total Sediment, Method Here)	0.004	22.5	0.018	1.4

The sand discharge based on Wamsley (2011) is 2,030 m^3/year and 4,000 m^3/year based on methods suggested here. The width of the deposit area is 8,500 m. The values of Q', t', and t are presented in Table 3 along with other variables considered. When only sand is considered the times to emergence range from 13 to 30.5 years. For the case of sand and silt and the steeper foreset slope, the time to emergence is 0.35 years; however, this is probably too optimistic. The more realistic estimate is probably in the range of 5 to 15 years. This case illustrates the sensitivity of the results to sand discharge and the associated slope.

The uniform width and depth model was applied to determine the long-term evolutionary behavior of the White Ditch Diversion with the results shown in Figure 18 which considers the full sediment discharge and the other parameters listed in Table 3. It is seen that the method indicates that the deposit will become emergent in Year 2 after commencement of the diversion and that after 50 years, the subaerial deposit will be some 99.2 km^2 (24,500 acres) compared to the predictions in Wamsley (2011) on the order of 30,000 acres. The close agreement of these two estimates is considered somewhat fortuitous. However, examining Figure 18, the effect of the difference in times to emergence for the full sediment discharge (1 to 2 years) and that if only sand contributes to the emergence time (13 to 30 years) can be appreciated. This issue will be discussed further later.

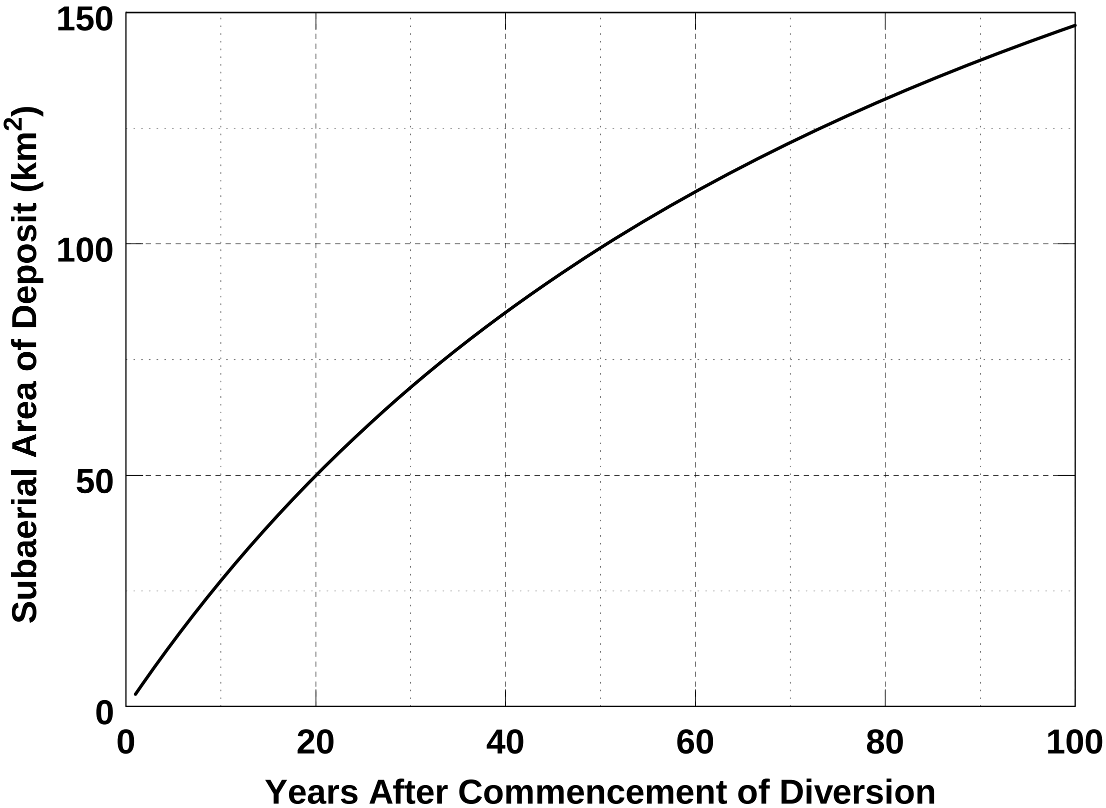

Figure 18. Results from application of method to planned White Ditch Diversion.

7.2 West Bay Diversion

The characteristics of the West Bay Diversion by the method here are presented in Table 2. As for the previous case of White Ditch, it is of interest to calculate the time to subaerial platform emergence for various estimates of sediment size fractions and associated slopes. The two estimates of sand discharge are 280,000 m^3/yr and 40,000 m^3/yr by Allison (personal communication) and method presented here, respectively. Results are presented in Table 4 and indicate a range of time to platform emergence from 0.9 years to 6.5 years. Based on monitoring results (Barras et al., 2009), these estimates may be too optimistic. Other combinations including the complete sediment discharge and associated milder slopes result in a range of 10.8 to 12.6 years which seem more reasonable in view of the small subaerial deposits that formed after the 2011 flood season.

Table 4

Calculations of time of emergence for various sediment delivery estimates for the West Bay Diversion

Q (m^3/y), (and Basis)	Foreset Slope, m Fig. 12	Q'	t'	t (years)
40,810 (Sand, Method Here)	0.02	15.3	0.023	6.5
280,000 (Sand, Allison)	0.02	105.3	0.0032	0.9
2.31×10^6 (All Sediment, Method Here)	0.002	8.7	0.044	12.6
2.63×10^6 (All Sediment, Allison)	0.002	9.9	0.038	10.8

The calculated long-term results for the case of a truncated cone and a deposit angle of 180^o including the effects of bulking and other factors presented in Table 4 are presented in Figure 19. This method predicts that in Year 50, the subaerial deposit will be 21 km^2 (5,200 acres) compared to the first estimate of 9,800 acres http://lacoast.gov/reports/gpfs/MR-03.pdf . Based on earlier monitoring results (Barras et al., 2009), these estimates initially appeared to be too optimistic; however, the record flood of 2011 which led to the growth of new subaerial land in the form of small islands (Kolker et al., 2012) suggests that this may not be the case.

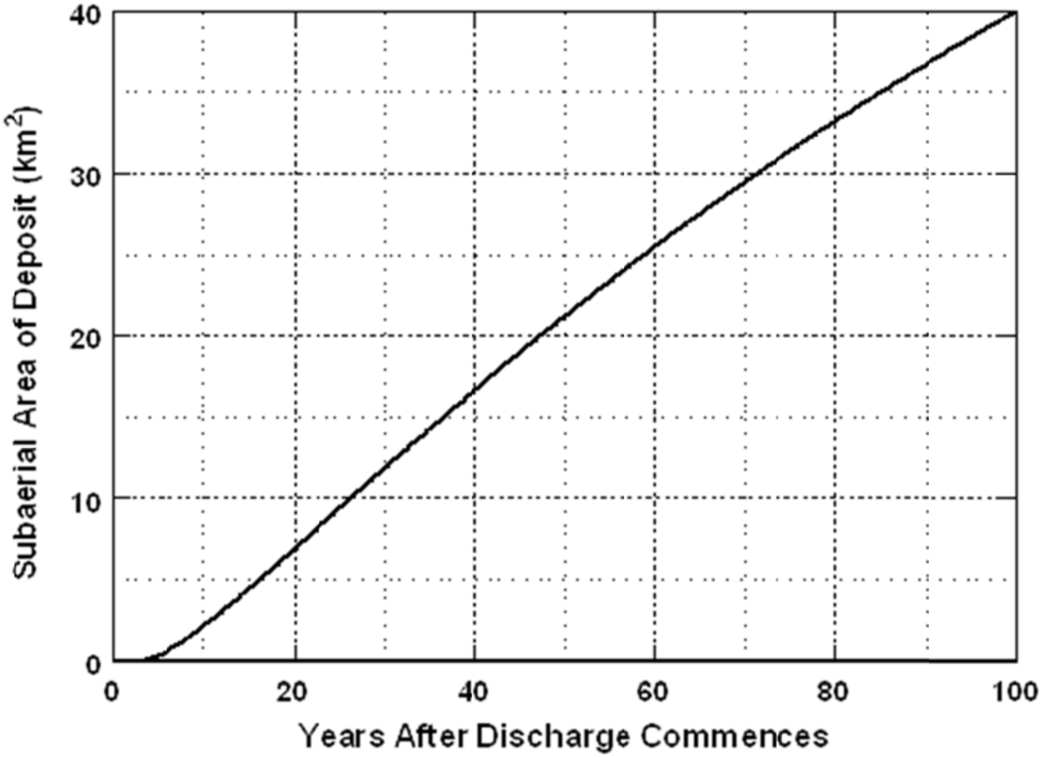

Figure 19. Results from application of method to West Bay Diversion.

8.0 The Role of Monitoring

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, unwanted consequences are detected early and that adaptive management is facilitated. This includes a program of quality assurance/quality control documentation of the monitoring data. The cost of monitoring will be modest when compared to the cost of engineering, constructing and maintaining a diversion. The added incremental cost of high-quality monitoring thus does not provide a valid argument for failure to undertake this important component of a diversion project and aggressive provisions for establishing a funding model need to be put into place prior to project initiation. Inadequate temporal monitoring in the West Bay Diversion project, which was widely deemed to have been unsuccessful prior to the record flood on the Mississippi River in 2011, resulted in a lost opportunity to better understand the only large diversion that was designed specifically to build new land.

As pertains to 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. Following standard guidance, the Corps of Engineers and other Federal and State partners should include an adaptive management plan that is scaled to the scope of the project and involves stakeholder collaboration. Clearly, there must be a commitment to adjust direction as new information becomes available, and a willingness to identify new information needs, and to develop and use new monitoring tools. Site-scale learning will be of immense value in evaluating and implementing future projects. Adaptive management will put what is learned to work.

The basic elements of a monitoring plan must include: *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. Although it has been hypothesized that failure of the West Bay Diversion project was in part a result of Hurricane Katrina, the absence of monitoring before and after this event will prevent that important question from ever being answered. *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 time scales of weeks to centuries. *5) Acquisition of water and sediment discharge characteristics through the diversion into the receiving basin.* Accurate data on material passing through a diversion is 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 is essential for understanding sediment retention and for interpreting success. *7) Commitment to a data management plan.* Data must be made available and disseminated to stakeholders in a timely fashion. It is suggested that monitoring could be improved based on the predictive methods of this guidance document.

9.0 Improved Method for Applying Models

The role of the sand component in building the initial platform for a diversion deposit has been noted throughout this document. However, the methods presented consider only one sediment type discharge throughout the deposit evolution. It is recommended that (1) only the sand fraction be considered as effective in the construction of the deposit until it becomes emergent, after which vegetation can commence to develop and act to trap the finer sediments, and (2) once an emergent platform has developed, the total sediment retained (including “bulking” by vegetation) be considered in the long-term evolution of the long-term 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.

First the model is applied 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 non-dimensional 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' vs t' plots (Figures 5 and 7). If the Q' values are large and on the nearly horizontal portions of the relationships, the differences will be small.

As noted, first the sand discharge and steeper foreset slope will be applied to determine the time to emergence. Secondly, 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.

10.0 Lessons from Previous Diversions

Undoubtedly the sedimentary processes associated with diversions are complex and interconnected, and there are no systematic studies dealing with them. The drivers are the climatic and oceanic conditions, inputs of water and sediments, geometric aspect of the diversion and physicochemical and sedimentary processes. Models dealing with diversions do not take into account these in detail, and model validations will be a requisite in such studies. A few diversions have received detailed scrutiny (West Bay) but some others (eg, Bayou Lamoque) are poorly documented. Table 5 is based on observations reported from a number of diversions, and general trends therein clearly demonstrate the importance of underlying processes; for example, the land gained over a period of years can possibly be eroded significantly by a single hurricane.

Table 5

Background on other diversions

Diversion	Purpose	Capacity	Comments
Bonnet Carré Spillway (since early 1930s)	Flood protection (as needed; when river flow > 35,375 m^3/s). Operated 10 times since construction.	7,075 m^3/s, gated	Not optimized for water/sediment ratio; most sediment falls out within 1-2 km; velocities (< 0.6 m/s) lead to beneficial sediment accretion for land building; temperature difference between river and marshes reduces vertical mixing; opened 42 days during the 2011 flood and resulted in the

			deposition of 3 million m^3 of sand (Nittrouer et al., 2012).
Caernarvon (small, lower Mississippi; since 1991)	Limit salt water intrusions; minimum sediment capture	100 m^3/s, gated (maximum 285 m^3/s)	Expects to reduce marsh loss by 82,700 acres in 50 years. Prior to the diversion, the land loss in the area was 1000 acres annually, but in 1992-4, the land growth rate was 406 acres. A significant increase of wetlands and wild life was observed. Caernarvon area was the epicenter of land loss during Katrina due to winds and waves and velocities.
Davis Pond (operated since 2002)	Limit salt water intrusions with minimum sediment capture	225 m^3/s; Rated – 300 m^3/s, gated	Expected to preserve ~ 33,000 acres in 50 years; so far has been losing land; water quality issues because of insufficient circulation; concerns over freshening bay area (detrimental to oysters).
Bayou Lamoque Diversion (two diversions; built (115 m^3/s, 1955); 225 m^3/s (1978)	Freshwater diversion; intermittent operation, not monitored	Gated, but planned for 365 m^3/s without gates	Relatively small land loss in the area after the diversion, but little operational data exists. New free flowing structures are expected to provide 620 acres of wetlands in the next 20 years. This modification authorized in 2006 but not yet constructed.
West Bay (since 2004)	Land and wetland building	570 m^3/s, with potential to increase 1,415 m^3/s	Predicted to build 9,831 acres of vegetated wetlands in 20 years; West Bay was not successful for land building until the record flood of 2011, but land loss was greatly reduced during 2001-2009 (Barras et al., 2009). Only areas with pumped sediments gained new land initially. May have caused downstream shoaling leading to a 2010 decision to close the diversion;

			however, it remains open in 2012.
Myrtle Grove (authorized in 2001), now de-authorized, engineering and design studies continue.	Land building, coupled with pipeline conveyance; includes reversed flow inflow channels for sediment capture	425 m^3/s, gated	Goal is to maintain 33,880 acres of marsh areas over 50 year period; modeling shows pulsed operation is beneficial; options of placing dredged sediments only (so far ~500 acres has been created) versus the efficacy of a diversion are evaluated; concerns of excessive freshening that harm fisheries.
Cubits Gap (excavated in 1862)	To allow passage of shallow boats (initial width ~ 120 meters, but after floods it expanded to 1 km by early 1900).	10% of the total flow in the river	Naturally evolved after an artificial crevasse. Initial building up of distributory channels, coarse sediments near the breach, shoaling in the bay by underwater deposition of finer sediments. Sediment deprivation in the 1970s caused a large part of crevasse system to be inundated by seawater. Illustrates the cycle of delta lobe building and abandonment, with time scale ~100 years (Wells and Coleman, 1987).

Many questions remain on the effectiveness of diversions in land building: For example, how large should the diversion be; where should be it placed; how much water should be diverted; should it be gated or natural; what optimal geometry and sill height should be used; how do the characteristics of the receiving area respond to sedimentation; when should sediment trapping devices be introduced; should water be diverted in a continuous or pulsating manner; how much land building is expected near/intermediate and long-term; what is the useful life of the diversion; and should each diversion be operated independently or as a group? Related issues also arise with regard to bio-geo-physical interactions such as the adverse effects of high nutrient loads carried by the river in creating dead zones in diversion areas and its effect on fisheries. The impacts on navigation are also important, and simple fluid mechanical arguments suggest that the shoaling is unavoidable for straight reaches. The influence of curvature and secondary circulations need to be understood so the basin scale implications of operating diversions can be established. A vexing question is the economics of diversions: can beneficial use of sediments be an alternative, not a supplement or operating in tandem, to diversions? Monitoring of the recent land building at West Bay during the floods of 2011 will provide valuable information relating to the role of episodic events.

11.0 Summary and Recommendations

11.1 Summary of Methodology and Parameter Selection

River diversions are considered as one of the most effective approaches to restoration and maintenance of wetland areas, in part because they mimic natural processes. Diversions considered here are those in the free surface, freely flowing class, i.e. no gates, siphons or pumped delivery.

This guidance document has presented methodology and recommended parameters for preliminary evaluation of the efficacy of diversions of various sizes and locations. Two simple models for deposit geometry are presented: a radially symmetric truncated cone which is similar to the Wax Lake Diversion, and a deposit of uniform width which is more like the planned White Ditch Diversion.

The advantage of guidance such as presented here is that a fixed methodology is defined against which past and future experience and monitoring results can be compared, thereby providing a basis for objective refinement of the overall method as well as conducting sensitivity studies. It is envisioned that results presented in this document can be applied to provide preliminary screening and comparison of conceptual designs at different sites or different design characteristics at one site. Recommendations are presented for annual sand and total sediment discharge as simple proportions of the annual average water discharged through the diversion. Recommended parameters recommended as functions along the main stem of the Mississippi River include: subsidence rates, foreset slopes, bulking factors, and proportion of material retained.

For each of the two geometric models, methods are presented for calculating time to emergence and the long-term evolutionary behavior. For the time to emergence, it is recommended that only the coarser fraction of sediment be considered along with an appropriate foreset slope. The results suggest that formation of the initial deposit primarily from the sand size fraction may be a critical phase in the success of the diversion. A significant result for the long-term evolution is that, for the geometric models examined in the presence of relative sea level rise, three evolutionary phases are found: an emergence and growth phase followed by a maximum land area and finally a decrease and submergence of the subaerial platform. Within the limitations of the models examined, this evolutionary behavior is an inescapable result of the effect of relative sea level rise 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 2) and is also consistent with the formation of floating marshes.

Although sediment retention devices, such as artificial islands or sills could improve the performance of diversions, they have not been addressed here. Finally, the 2011 floods on the Mississippi River and the associated land building at West Bay Diversion provide an opportunity which, if well monitored, can advance our understanding of these processes significantly.

11.2 General Recommendations for Parameter Selection

11.2.1 Subsidence Rates and Sediment Retention

Subsidence is particularly problematic 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, impact from human activities, the effects of measurement techniques on determination of rates, the potential for significant impacts from growth faults, and the changes in subsidence rates over time (Dokka et al., 2006; Gonzalez and Tornqvist, 2006; Meckel, 2008; Tornqvist et al., 2008; Morton and Bernier, 2010; Kolker et al., 2011)). In short, relative to its importance, we know less about subsidence than any other process that will affect the success of river diversions. However, it is crucial that lack of consensus on the above issues not lead to inaction. We thus offer the following general guidance: *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. *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.

11.2.2 Delta Opening Angle and Diversion Depths and Slopes

Flow from the main stem of the river through a diversion opening into a receiving basin will expand and decelerate, providing the potential for subaqueous deposition of sediments that over time could aggrade to create subaerial land. As the pipeline for supply, the diversion cut must be located and oriented to maximize the opportunity for self organization 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 guidance: *1) 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. *2) Use numerical simulation to determine ideal opening angles.* The effects of meander bends and thus the angle of a diversion opening could be important in sediment delivery through the diversion. *3) 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.

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Appendix A

Useful Conversion Factors (Some are Approximate) and Estimates

A.1 Useful Conversion Factors

1 Megaton (MT) of Sediment = 580,000 m^3 prior to bulking

1 mg/Liter = 10^{-12} MT/m^3

1 cfs = 0.0283 m^3/s

10^3 Liters = 1 m^3

1 Pascal = 1 $Newton/m^2$ = 0.1 $dyne/cm^2$

1 Acre = 0.405 Hectares

1 Hectare = 2.47 Acres

1 km^2 = 247 Acres

A.2 Useful Estimates

Average water discharge of the Mississippi River = 17,000 m^3/s = 600,700 cfs

Average annual sediment discharge of the Mississippi River = 35 x 10^6 m^3/y to 50 x 10^6 m^3/y

Average annual sand discharge of the Mississippi River = 0.6 x 10^6 m^3/y to 12 x 10^6 m^3/y

Appendix B

Time to 'Platform Building"

B.0 General

This appendix addresses the time to "platform building" of a deposit for a truncated cone and a deposit of uniform width.

B.1 Truncated Cone

The elevation, h of a cone prior to platform building to the deposit height is related to the volume as (see Figure 4 for definition of variables)

$$V = Qt = \frac{hR^2}{6\Delta\theta} = \frac{h^3}{6m^2\Delta\theta}. \tag{B.1}$$

The total height α required to commence platform building is $\alpha = \alpha_o + \frac{\partial\alpha}{\partial t}t$. Equating h and α yields

$$\alpha_o^3 + 3t\left(\alpha_o^2\frac{\partial\alpha}{\partial t} - \frac{m^2Q}{\Delta\theta}\right) + 3t^2\alpha_o\left(\frac{\partial\alpha}{\partial t}\right)^2 + \left(\frac{\partial\alpha}{\partial t}\right)^3 t^3 = 0. \tag{B.2}$$

Defining a non-dimensional time, $t' = \frac{t}{\alpha_o}\frac{\partial\alpha}{\partial t}$ and a non-dimensional discharge, $Q' = \frac{8\,Qm^2}{\Delta\theta\alpha_o^2\frac{\partial\alpha}{\partial t}}$, the above equation reduces to

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

which must be solved by iteration. The above form is convenient as there is only one independent variable, Q'. It can be shown that there is no solution for $Q' < 2.25$. For $Q' < 2.25$, the deposit height does not reach the height at which the deposit would commence forming a platform. Figure B-1 presents the relationship between the two non-dimensional variables, t' and Q'.

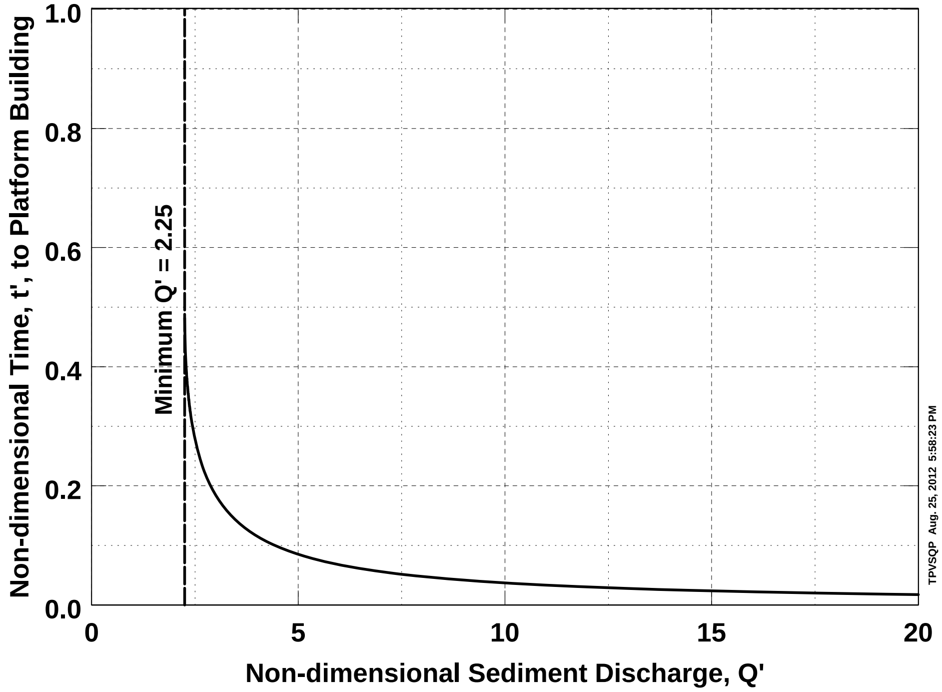

Figure B-1. Non-dimensional Time, t', vs Non-dimensional Discharge, Q' for Truncated Cone.

B.2 Uniform Width and Depth Case

For this case, the equation for the deposit height prior to platform building is (see Figure 7 for definitions of variables)

$$V = Qt = \frac{Whx}{2} = \frac{Wh^2}{2m}. \tag{B.4}$$

Equating h and α yields

$$\alpha_o^2 + 2t\left(\alpha_o \frac{\partial \alpha}{\partial t} - \frac{mQ}{W}\right) + t^2\left(\frac{\partial \alpha}{\partial t}\right)^2 = 0. \tag{B.5}$$

Again defining non-dimensional variables as

$t' = \dfrac{t}{\alpha_o}\dfrac{\partial \alpha}{\partial t}$ and $Q' = \dfrac{Qm}{\alpha_o \dfrac{\partial \alpha}{\partial t}}$ and the above equation, expressed in the non-dimensional quantities is

$$1 - 2t'(Q' - 1) + (t')^2 = 0, \tag{B.6}$$

which can be solved directly for t' as

$$t' = (Q'-1) + \sqrt{(Q')^2 - 2Q'}\ . \qquad \text{(B.7)}$$

It can be shown that the minimum Q' = 2.0. Figure B-2 presents the solution for t' as a function of Q'.

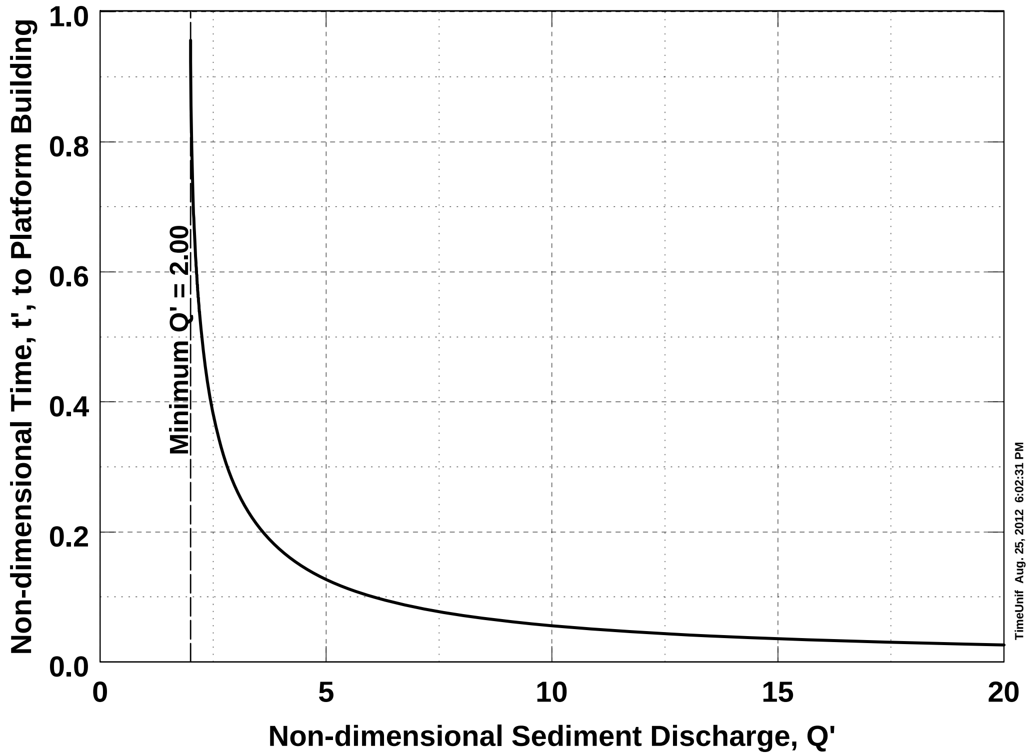

Figure B-2. Non-dimensional Time, t’, vs Non-dimensional Discharge, Q’ for Uniform Width Model.