Large Scale River Morphodynamics: Application to the Mississippi Delta

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ABSTRACT: The delta of the Mississippi River is in jeopardy. It is rapidly subsiding into the Gulf of Mexico. Delta marshland is being drowned and the shoreline is moving northward toward New Orleans. The cause of these problems is the levee system along the Mississippi River, which prevents the replenishment of sediment to the delta. One way to restore the delta is through the use of one or more controlled partial avulsions of the Mississippi River. The design of such diversions represents a monumental task. A natural example of an avulsion in the Mississippi Delta, however, offers an excellent opportunity to test the concept of land building via river diversions. The Atchafalaya River is a distributary of the Mississippi River. During the flood of 1973, part of the Atchafalaya River avulsed into a man-made channel. The Wax Lake Delta at the mouth of the channel has been building seaward since then. Here a morphodynamic model of the Wax Lake Delta is presented and tested against field data. While the model is preliminary, the fact that it captures the process of land building at the Wax Lake Delta suggests that it can be adapted to the design of a major controlled partial avulsion of the Mississippi River into, for example, Barataria Bay.

1 INTRODUCTION

The extensive levees on lower Mississippi River serve an essential role in a) protecting human lives and infrastructure in New Orleans and the Mississippi Delta and b) preventing an avulsion of the river that would render New Orleans useless as a port. These same levees, however, prevent sediment delivery to the Mississippi Delta itself.

Under natural conditions, the delta was maintained by two counteracting processes; sediment deposition and avulsion which cause the delta to build up and prograde seaward, and compaction of fine-grained delta sediment under its own weight, which causes the delta to subside into the Gulf of Mexico. Under present conditions the delta is subsiding without any sediment replenishment. As a result delta marshland is sinking into the sea and the shoreline is rapidly advancing northward (Hallowell, 2001).

Land loss in the Mississippi Delta has resulted in the disappearance of or damage to large tracts of marshland habitat of unique ecological value. It has forced many Delta inhabitants to move elsewhere, and has damaged the livelihood of many more. In addition the northward movement of the shoreline has reduced the land buffer needed to damp hurricane storm surge, and thus placed New Orleans at risk to powerful hurricanes.

This vulnerability is highlighted by the Hurricane Katrina disaster of August, 2005, which caused a public emergency of major proportions, and rendered the city uninhabitable for months. Figure 1 shows satellite images of the Mississippi Delta just before and after the disaster. The damage to the Delta and the increased risk to New Orleans is clear from the images.

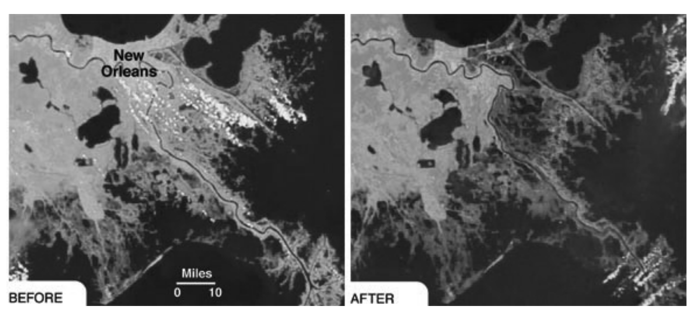

Figure 1. Satellite images of the Mississippi Delta near New Orleans before and after Hurricane Katrina. The image is from the New York Times.

Various proposals have been offered in order to restore the Delta. Among the most attractive of these consists of one or more partial, controlled avulsions of the river either upstream or downstream of New Orleans. These avulsions would be accomplished by means of massive diversion structures of the general type that are already in place at the junction of the Mississippi River and the Old River in northern Louisiana, shown in Figure 2 and located in Figure 3. The Old River Control Structures allow a controlled amount of Mississippi River floodwater to flow into the Old River, and thence into the Atchafalaya River, while preventing a complete capture of the Mississippi River by the Atchafalaya River. Part of the structure nearly failed in the historic flood of 1973; the severe consequences of such a failure are outlined in Kazmann and Johnson (1980). This near failure highlights the importance of careful design of any diversion structures designed to restore sediment to the Delta.

The flood of 1973 also had a consequence that has provided an invaluable case history for restoring the Delta. During that flood, part of the Atchafalaya River near its own delta partially avulsed into a man-made channel known as the Wax Lake Outlet. Ever since that avulsion a new delta at its outlet, the Wax Lake Delta has been building into the Gulf of Mexico. The subsequent growth of the Wax Lake Delta has been monitored by Louisiana researchers (Roberts and Coleman, 1996; Roberts et al, 1997). The locations of New Orleans, the Mississippi and Atchafalaya Rivers, the main mouth of the Mississippi River and the Wax Lake and Atchafalaya Deltas are shown in Figure 3. The Wax Lake Delta itself is shown in Figure 4.

Figure 2. Aerial view of the Old River Control Structures on the Mississippi River, Louisiana. The Mississippi River is to the right; flow in it is from top to bottom.

The well-documented growth of the Wax Lake Delta allows an opportunity for “proof of concept” of land building by river diversions. If a morphodynamic model of river-delta evolution can predict the observed evolution of the Wax Lake Delta with a) reasonable accuracy and b) a minimum of “tuning”, such a model can be adapted into a powerful tool to aid delta restoration. The tool could be used to study a variety of options for one or more much larger controlled avulsions upstream or downstream of New Orleans, so serving as part of the design of an optimal scheme for land building and delta reconstruction, with minimum negative influence on the economy and habitability of the Delta as a whole and New Orleans in particular.

Here a morphodynamic model of the Wax Lake Delta and the fluvial reach immediately upstream is outlined and compared against available data. The results, while preliminary, are encouraging in terms of the use of controlled diversions to build land.

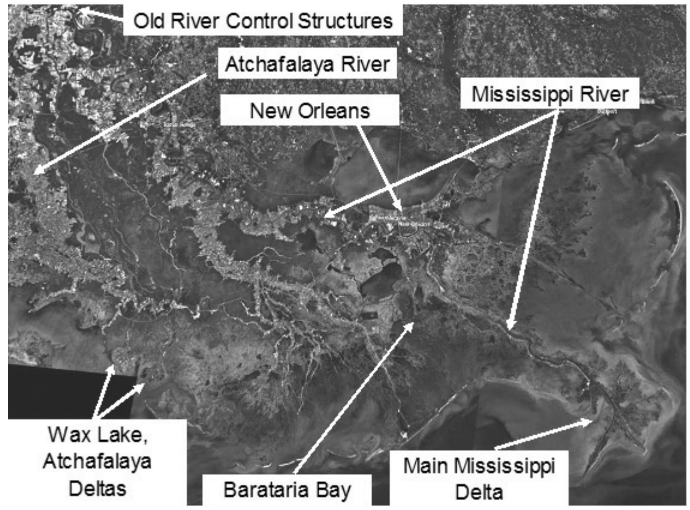

Figure 3. The NASA WorldWind satellite image serves as a locator map for New Orleans, the Mississippi and Atchafalaya Rivers, the Old River Control Structures, the Main Mississippi Delta, the Wax Lake and Atchafalaya Deltas and Barataria Bay circa 2006.

Figure 4. NASA WorldWind satellite image of the Wax Lake Delta, Louisiana as of 2006.

2 THE WAX LAKE DELTA

The Wax Lake Delta is a fan-delta located at the mouth of the Wax Lake Outlet (Figure 5). The Wax Lake Outlet is a man-made channel that was excavated in 1941. It connects the southeastern corner of Six Mile Lake with Atchafalaya Bay of the

Gulf of Mexico. Six Mile Lake is in turn connected to the lower Atchafalaya River (Figure 5; DuMars, 2002).

The Wax Lake Outlet was designed to divert part of the flood flow of the Atchafalaya River. As recently as 1972 the shoreline along Atchafalaya Bay was eroding. The epic flood of the Mississipppi River of 1973 reversed this process (Roberts *et al.*, 1997). A partial avulsion of the Atchafalaya River to the Wax Lake Outlet significantly increased the flow to the Wax Lake Delta.

Subsequent to the flood of 1973 the Old River Control Structures have been used to divert both water and sediment from the Mississippi River to the Atchafalaya River in a prescribed manner. While the design diversion is 30% of the flow of the Mississippi River, as much as 50% of the Mississippi's discharge and over 60% of its suspended load has been flowing into the Atchafalaya River (Roberts *et al.*, 2003a). This delivery of sediment has caused both the Atchafalaya Delta itself and the subsidiary Wax Lake Delta to prograde significantly since 1973. As progressively more flow was captured by the Wax Lake Outlet, a control structure was placed on it in 1988. The structure limited the flow down the Wax Lake Outlet during normal flow, but was less effective at high flows. The structure was finally removed in 1994 (Roberts *et al.*, 2003a).

As of 2006 the Wax Lake Delta continues to prograde into Atchafalaya Bay (Figure 4). While not specifically intended to do so, it serves to illustrate how the sediment-laden water of the Mississippi River can be used to build land.

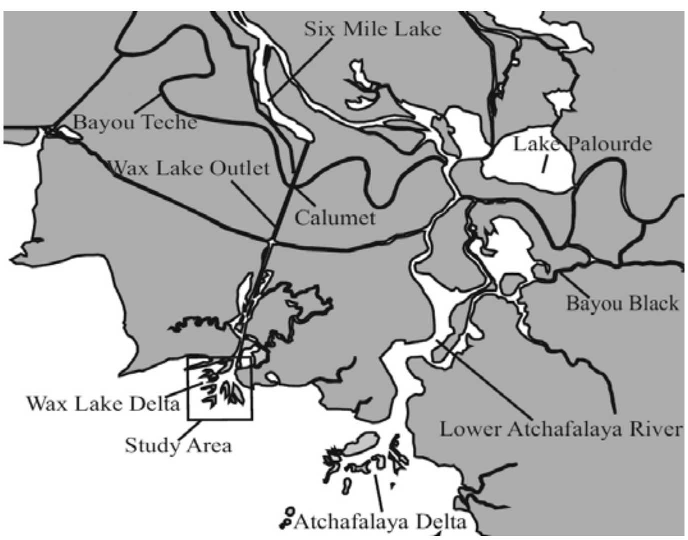

Figure 5. Map showing the Atchafalaya River, Six Mile Lake, the Wax Lake Outlet and the Wax Lake Delta. From DuMars (2002).

3 ELEMENTS THAT MUST BE CAPTURED BY THE MORPHODYNAMIC MODEL

A predictive morphodynamic model of the evolution of the Wax Lake Delta must include at least the following elements:

- account for the flood hydrology of the Atchafalaya River and the Wax Lake Outlet (WLO);
- partition water and sediment in the Atchafalaya River between the WLO and the Atchafalaya River below the outlet;
- discriminate between sand and mud delivered to the WLO;
- account for the Wax Lake Delta as well as a reach of the WLO upstream;
- specify the efficiency of deposition of sand and mud in the WLO, its adjacent "floodplain" and the delta itself; and
- account for the effects of both delta subsidence and sea level rise.

4 MODEL GEOMETRY

The model geometry is illustrated in Figures 6 and 7. A fluvial reach of specified down-valley length L_f and "floodplain" width B_f corresponding to part of the WLO is connected to a fan-delta reach corresponding to the Wax Lake Delta. The downvalley coordinate on the fluvial reach is denoted as x; channel width on the fluvial reach is a variable denoted as B_{fc}.

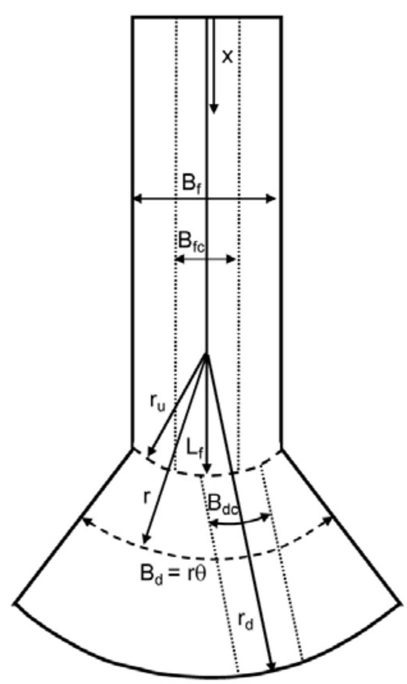

Figure 6. Definition diagram for planform of the fluvial and fan-delta reaches.

The fan-delta has specified fan angle θ. The radial coordinate from the fan-delta apex is denoted as r, such that r_u denotes a specified distance to the upstream end of the fan-delta and r_d denotes the distance from the vertex to the topset-foreset break (shoreline). In so far as the delta is prograding, r_d must be allowed to be a function of time t. Under conditions of any given flood flow there may be more than one active channel on the fan-delta; their amalgamated width is a variable denoted as B_{dc}. That part of the fan-delta that is not channelized at any given time is referred to as "floodplain" below. The width of the fan-delta is given as

$$B_d = \theta r \tag{1}$$

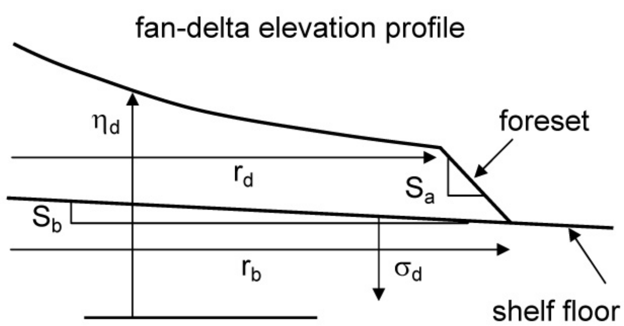

Figure 7. Definition diagram cross-section of the fan-delta reach.

River bed elevation on the fluvial reach is denoted as η_f; the corresponding elevation on the fan-delta reach is denotes as η_d (Figure 7). The distance from the fan vertex to the junction between the base of the foreset and the shelf floor is denoted as r_b. The shelf floor below the fan-delta reach is taken to have constant slope S_b and to be subsiding at rate σ_d, and the basement below the fluvial reach is subsiding at rate σ_f. Both subsidence rates are taken to be specified parameters. The fan-delta is assumed to prograde with a specified foreset angle S_a (Figure 7).

5 EXNER EQUATION OF SEDIMENT CONTINUITY

Rivers are morphologically active during floods. To capture this in a simple way, the river is assumed to be at bankfull flow Q_{bf} for fraction of time I_f, when it is morphologically active; otherwise the river is assumed to be morphologically inactive. The value of I_f is determined by the constraint that the river transports its mean annual bed material load at bankfull flow sustained for fraction I_f of a year (Wright and Parker, 2005).

Sand-bed rivers such as the Mississippi River and its distributaries carry far more mud than sand. For example, Allison *et al.* (2005) estimate that the Lower Mississippi carries annual loads of 124 Mt/year of mud but only about 6 Mt/year of sand. Here the sand is allowed to exchange with the bed, so constituting bed material load, but the mud is allowed to exchange only with the floodplain.

As the channel progrades, the deposit is spread across the entire floodplain (fluvial reach). Here the following parameters are defined for the fluvial and fan-delta reaches, denoted respectively by the final subscripts "*f*" and "*d*"; total bed material (sand) volume transport rates at bankfull flow Q_{tbff} and Q_{tbfd}, channel sinuosity Ω_f and Ω_d and deposit porosity λ_{pf} and λ_{pd}. It is assumed that for each volume unit of sand deposited in the channel-floodplain complex Λ_f units of mud are deposited in the channel-floodplain complex of the fluvial reach and Λ_d units are deposited in the corresponding complex of the fan-delta reach.

The time-averaged Exner equation of sediment continuity thus takes the following respective forms on the fluvial and fan-delta reaches;

$$(1-\lambda_{pf})\left(\frac{\partial \eta_f}{\partial t}+\sigma_f\right) = -\Omega_f \frac{I_f(1+\Lambda_f)}{B_f}\frac{\partial Q_{tbff}}{\partial x} \tag{2a}$$

$$(1-\lambda_{pd})\left(\frac{\partial \eta_d}{\partial t}+\sigma_d\right) = -\Omega_d \frac{I_f(1+\Lambda_d)}{B_d}\frac{\partial Q_{tbfd}}{\partial r} \tag{2b}$$

6 FLOW AND SEDIMENT TRANSPORT

Channel hydraulics at bankfull flow is described in terms of a quasi-steady backwater formulation. Thus where U = bankfull flow velocity, H = bankfull flow depth, S = bed slope, C_f = a dimensionless bed friction coefficient and g denotes the acceleration of gravity, the shallow-water equation of momentum balance takes the following respective forms on the fluvial and fan-delta reaches;

$$U_f \frac{dU_f}{dx} = -g\frac{dH_f}{dx} + gS_f - C_{ff}\frac{U_f^2}{H_f} \tag{3a}$$

$$U_d \frac{dU_d}{dr} = -g\frac{dH_d}{dr} + gS_d - C_{fd}\frac{U_d^2}{H_d} \tag{3b}$$

where the final subscript "*f*" denotes the fluvial reach and the final subscript "*d*" denotes the fan-delta reach. Here the bed slopes S are given by the respective forms

$$S_f = -\frac{\partial \eta_f}{\partial x} \quad , \quad S_d = -\frac{\partial \eta_d}{\partial r} \tag{3c,d}$$

In (3a) and (3b) the friction coefficients are treated as constants specified in terms of the corresponding dimensionless Chezy resistance coefficient Cz, such that

$$C_{ff} = Cz_f^{-1/2} \quad , \quad C_{fd} = Cz_d^{-1/2} \qquad (4a,b)$$

The boundary condition on (3b) is one of specified elevation of standing water (base level) $\xi_d(t)$ in Atchafalaya Bay. Thus at the delta shoreline $r = r_d(t)$ is the position of the topset-foreset break (shoreline),

$$\left(\eta_d + H_d\right)\Big|_{r=r_d} = \xi_d(t) \qquad (5a)$$

Here tides, which are in any case rather low in the Gulf of Mexico, are neglected for simplicity. The corresponding boundary condition on (3a) is continuity in water surface elevation;

$$\left(\eta_f + H_f\right)\Big|_{x=L_f} = \left(\eta_d + H_d\right)\Big|_{r=r_u} \qquad (5b)$$

The mobility of bed material load (sand) can be quantified in terms of the Shields number τ_{bf}^* at bankfull flow, here defined as

$$\tau_{bf}^* = \frac{C_f U^2}{RgD} \qquad (6)$$

where R denotes the submerged specific gravity of the sand (taken here to equal 1.65 for quartz) and D denotes the characteristic size of the sand in the river bed, here assumed to be a specified constant that is identical in the fluvial and fan-delta reaches. Sand transport is described in terms of the total bed material relation of Engelund and Hansen (1967); where B_c denotes the bankfull width of the channel (taking the values B_{fc} on the fluvial reach and B_{dc} on the fan-delta reach),

$$Q_{tbf} = B_c \sqrt{RgD}\, D \frac{0.05}{C_f} (\tau_{bf}^*)^{5/2} \qquad (7)$$

7 DOWNSTREAM VARYING BANKFULL CHANNEL GEOMETRY

A simple way to describe the bankfull characteristics of a channel is in terms of a specified channel-forming bankfull Shields number τ_{bf}^*. Parker *et al.* (1998) and Parker (2004) have found that the following approximate closure is appropriate for sand-bed streams:

$$\tau_{bf}^* = 1.86 \qquad (8)$$

Equation (6) can then be rearranged to yield the following relation for bankfull flow velocity U;

$$\frac{U}{\sqrt{RgD}} = \left(\frac{\tau_{bf}^*}{C_f}\right)^{1/2} \qquad (9)$$

Thus for constant values of τ_{bf}^*, C_f, grain size D and sediment submerged specific gravity R, (9) specifies a bankfull flow velocity U that remains constant in the downstream direction. Substituting (9) into (3a) and (3b) and reducing, the following forms are found for the fluvial and fan-delta reaches;

$$\frac{dH_f}{dx} = S_f - R\tau_{bf}^* \frac{D}{H_f} \qquad (10a)$$

$$\frac{dH_d}{dr} = S_d - R\tau_{bf}^* \frac{D}{H_d} \qquad (10b)$$

For a given river profile on the fan-delta $\eta_d(r, t)$ at any time t, (10b) can be solved subject to (5a) to determine the streamwise variation in bankfull depth H_d on the fan-delta. Then (10a) can be solved subject to (5b) to determine the streamwise variation in bankfull depth on the fluvial reach. It is here assumed that the river has no tributaries over the reach of interest, so that bankfull water discharge Q_{bf} is constant in the streamwise direction, taking the same values on the fluvial and fan-delta reaches. Water continuity requires that

$$Q_{bf} = B_c U H \qquad (11)$$

in which case the streamwise varying bankfull width is given from (7) and (11) as

$$B_c = \left(\frac{C_f}{\tau_{bf}^*}\right)^{1/2} \frac{Q_{bf}}{\sqrt{RgD}\, H} \qquad (12)$$

Once the streamwise variation of H_d and B_{dc} (fan-delta reach) and H_f and B_{fc} (fluvial reach) are computed for a given bed profile, the streamwise variation in total bed material loads Q_{tbfd} (fan-delta reach) and Q_{tbff} (fluvial reach) are computed from (7).

8 SHOCK AND CONTINUITY CONDITIONS

The morphodynamic model has two moving boundaries: the position $r = r_d(t)$ denoting the distance from the fan vertex to the topset-foreset break (shoreline) and the position $r = r_b(t)$ denoting the distance form the fan vertex to the foreset-bottomset break (Figures 6 and 7).

Shoreline migration can be specified in terms of a shock condition (Swenson *et al.*, 2000; Kostic and Parker, 2003). The shoreline is located at $r = r_d(t)$, and bed elevation there is $\eta_d[r_d(t), t]$. It is assumed that the delta progrades with constant foreset slope S_a. The foreset elevation profile is thus given as

$$\eta(r,t) = \eta_d[r_d(t),t] - S_a[r - r_d(t)] \qquad (13)$$

The shock condition is obtained by integrating (2b) from $r = r_d$ to $r = r_b$ subject to (1) and (13). This results in the relation

$$\frac{1}{2}(r_b^2 - r_d^2)\theta_f \left[\left. \frac{\partial \eta_d}{\partial t} \right|_{r_d} + \sigma_d + (S_a - S_{dd})\dot{r}_d \right] = \Omega_d \frac{(1+\Lambda_d)}{(1-\lambda_{pd})} Q_{tbfdd} \qquad (14)$$

where

$$\dot{r}_d = \frac{dr_d}{dt} \qquad (15)$$

denotes the speed of progradation of the shoreline and

$$S_{dd} = -\left.\frac{\partial \eta_d}{\partial x}\right|_{r_d} \quad , \quad Q_{tbfdd} = Q_{tbfd}\Big|_{r_d} \qquad (16a,b)$$

A relation for the migration speed of the position of the foreset-shelf floor break can be obtained by imposing elevation continuity there. This condition is seen from (13) and Figure 7 to take the form

$$\eta_b(x,t) = \eta_d[r_d(t),t] - S_a[r_b(t) - r_d(t)] \qquad (17)$$

Noting that by definition

$$\sigma_d = -\frac{\partial \eta_b}{\partial t} \quad , \quad S_b = -\frac{\partial \eta_b}{\partial x} \qquad (18a,b)$$

and taking the derivative of (17) with respect to time, it is found that

$$(S_a - S_b)\dot{r}_b = (S_a - S_{dd})\dot{r}_d + \left.\frac{\partial \eta_d}{\partial t}\right|_{r_d} + \sigma_d \qquad (19)$$

where

$$\dot{r}_b = \frac{dr_b}{dt} \qquad (20)$$

9 SOLUTION AND TRANSFORMATION TO MOVING BOUNDARY COORDINATES

The specification of the problem is completed by one upstream boundary condition and one more continuity condition. The input volume bed material transport rate Q_{tbfu} must be specified at the upstream end of the fluvial reach;

$$Q_{tbff}\Big|_{x=0} = Q_{tbfu} \qquad (21)$$

In addition, the bed material transport rate should be continuous at the junction between the fluvial and fan-delta reaches;

$$Q_{btff}\Big|_{x=L_d} = Q_{tbfd}\Big|_{r=r_u} \qquad (22)$$

The solution method can now be described as follows. Time and space must be appropriately discretized to allow a numerical solution, using spatial nodes separated by appropriate spatial steps Δx and Δr and an appropriate time step Δt. At any given time it is assumed that the bed profiles $\eta_d(x, t)$ and $\eta_f(x, t)$ are known. First (11b) is solved numerically by stepping upstream subject to (5a) to determine the bankfull depth profile H_d over the fan-delta reach. Then (11a) is solved by stepping upstream subject to (5b) to determine the bank depth profile H_f over the fluvial reach. Bankfull channel widths B_{fc} and B_{dc} are then solved algebraically from (12). The volume transport rates of bed material load at bankfull flow are computed algebraically from (7)

Equations (2a) and (2b) are then solved numerically to determine the bed elevation profiles η_d and η_f at one time step later. In the fan-delta reach, the volume bed material transport rates are given from (7) at all internal nodes. At the upstream node of this reach the continuity condition (22) is applied. At the downstream node of this reach the shock condition (14) is applied to determine the new position of the delta shoreline. Equation (17) is applied to determine the new position of the foreset-shelf floor break.

The initial conditions for the problem are specified initial bed profiles and shoreline position;

$$\eta_f\Big|_{t=0} = \eta_{fI}(x) \qquad (23)$$

$$\eta_d\Big|_{t=0} = \eta_{dI}(x) \qquad (24)$$

$$r_d\Big|_{t=o} = r_{dI} \qquad (25)$$

Here (23) and (24) are implemented in terms a) specified constant initial bed slopes S_{dI} and S_{fI} on the fan-delta and fluvial reaches, respectively, b) a specified initial delta height $\Delta\eta_I$, where

$$\Delta\eta_I = \left\{\eta_d[r_d(t),t] - \eta_b[r_b(t),t]\right\}\Big|_{t=0} \qquad (26)$$

and c) an initial depth of submergence of the topset-foreset break below sea level;

$$H_d[r_d(t),t]\Big|_{t=0} = \xi_d(0) - \eta_d[r_d(t),t]\Big|_{t=0} = H_{ddI} \qquad (27)$$

The initial elevation of standing water must be specified as well;

$$\xi_d(0) = \xi_{dI} \qquad (28)$$

In the present analysis base level is assumed to rise at a specified constant rate $\dot{\xi}_d$

The fact that the fan-delta reach includes two moving boundaries suggests the utility of solving the problem within this domain in moving-boundary coordinates. These are introduced as follows;

$$\bar{r} = \frac{r - r_u}{r_d(t) - r_u} \quad , \quad \bar{t} = t \qquad (29)$$

Equation (2b), (10b), (14) and (19) thus transform to the respective forms

$$(1-\lambda_{pd})\theta\bar{r}r_d\left[\frac{\partial\eta_d}{\partial\bar{t}}+\sigma_d-\left(\frac{\bar{r}\dot{r}_d}{r_d-r_u}\right)\frac{\partial\eta_d}{\partial\bar{r}}\right]= \\ -\Omega_d\frac{I_f(1+\Lambda_d)}{(r_d-r_u)}\frac{\partial Q_{tbff}}{\partial\bar{r}} \tag{30}$$

$$\frac{1}{r_d-r_u}\frac{dH_d}{d\bar{r}}=-\frac{1}{r_d-r_u}\frac{\partial\eta_d}{\partial\bar{r}}-R\tau_{bf}^{*}\frac{D}{H_d} \tag{31}$$

$$\frac{1}{2}(r_b^2-r_d^2)\theta_f\left[\left.\frac{\partial\eta_d}{\partial\bar{t}}\right|_{\bar{r}=1}+\sigma_d+S_a\dot{r}_d\right]= \\ \Omega_d\frac{(1+\Lambda_d)}{(1-\lambda_{pd})}Q_{tbfdd} \tag{32}$$

$$(S_a-S_b)\dot{r}_b=S_a\dot{r}_d+\left.\frac{\partial\eta_d}{\partial\bar{t}}\right|_{\bar{r}=1}+\sigma_d \tag{33}$$

10 MODEL INPUT

Input data were gleaned from a) sediment data on the web site of the US Geological Survey, b) information provided by the US Army Corps of Engineers and c) published papers and reports including Roberts and Coleman (1996), Roberts *et al.* (1997), Majersky *et al.* (1997), DuMars (2002), Roberts *et al.* (2003a,b) and Wellner *et al.* (2006). Some poorly-constrained parameters were refined in the course of performing numerical runs, but arbitrary adjustments of the input parameters were kept to a minimum.

The following parameters were used for the results reported here: D = 0.10 mm, R = 1.65, Q_{bf} = 4100 m^3/s. I_f = 0.27, Q_{tbfu} = 0.292 m^3/s (corresponding to 6.58 Mt/year of sand), τ_{bf}^{*} = 1.86, L_f = 25,000 m, B_f = 800 m, θ = 120°, S_a = 0.002, S_b = 0.00018, $Cz_f = Cz_d$ = 20, $\lambda_{pf} = \lambda_{pd}$ = 0.6, $\Omega_f = \Omega_d$ = 1, $\Lambda_f = \Lambda_d$ = 0.49, σ_f = 0, σ_d = 5.8 mm/year, $\dot{\xi}_d$ = 1.2 mm/year, $\Delta\eta_I$ = 2.0 m, H_{dI} = 5.1 m, $(r_{dI} - r_u)$ = 4,300 m, $r_u = B_f/\theta$ = 382 m, S_{fI} = 0.000062 and S_{dI} = 0.00014. The modelling was commenced starting in year 1981 rather than 1973, because Majersky *et al.* (1997) suggest that it was in this year that upstream deposition became sufficient to allow the Wax Lake Delta to start prograding in its present rapid mode.

11 PRELIMINARY MODEL RESULTS

Figure 8 shows a plot of the position of the delta front r_d as a function of years since 1980. Both the model predictions and four data points extracted from three sources are shown. Figure 9 shows a plot of delta surface area of time as a function of years since 1980. Both the model predictions and five data points from two sources are shown.

The results of these figures are highly preliminary, but they indicate that morphodynamic modeling of land building in the Mississippi Delta is feasible, and can yield reasonable predictions. Figure 10 shows a satellite photograph in which the projected delta front of Wax Lake is estimated out to year 2081. The Wax Lake Delta cannot in fact grow as large as indicated by year 2081, because before then it would partially merge with the Atchafalaya Delta.

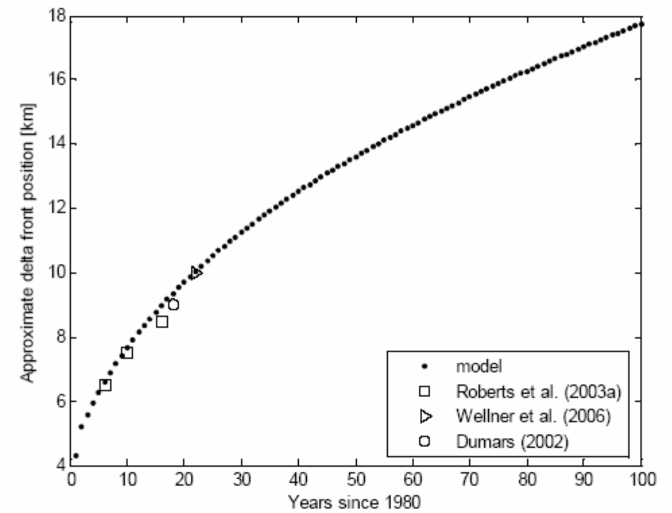

Figure 8. Plot of delta front (shoreline) position as a function of time since 1980.

12 NOTES OF CAUTION

The morphodynamic model of Wax Lake presented here is preliminary and incomplete in many ways. The following revisions and additions need to be made to the model before practical application:

- modification from a single sand grain size to a sand grain size distribution;
- quantitative description of the role of vegetation in increasing the trapping rate of mud in the delta;
- incorporation of removal of delta sediment offshore due to the effect of e.g. cold fronts and hurricanes (Roberts *et al.*, 2003);
- a more detailed description of subsidence, if possible with a link to sediment loading; and
- clarification of the role, if any, of tides on delta dynamics.

It hardly needs pointing out that the morphodynamic model could not have been developed to the present point without the years of patient field campaigns carried out by H. Roberts and colleagues in Louisiana. There are nevertheless important gaps in the data base which need filling by means of further field campaigns.

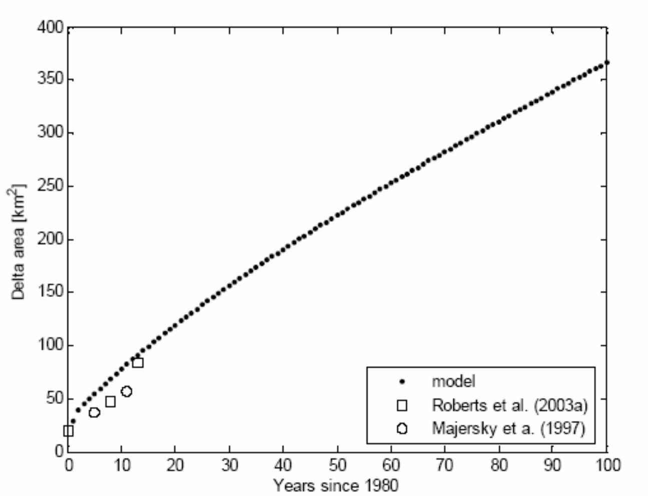

Figure 9. Plot of delta surface area as a function of time since 1980.

13 IMPLICATIONS FOR RESTORATION OF THE MISSISSIPPI DELTA

The results of this study, though preliminary, lend support to the concept of building land in the Mississippi Delta by means of one of more controlled partial avulsions. Each such avulsion would involve a) a rigorously-designed diversion structure that would play a role similar to the Old River Control Structures, b) less rigorously designed levees that confine the flow within the diversion channel until the intended depositional zone is reached, and c) the absence of any and all levees and control structures within this depositional zone, to allow the river to do what it does best, in a delta, i.e. build new land.

A primary candidate for such a depositional zone is Barataria Bay (Figure 3). Barataria Bay has been a zone of significant marshland loss in recent years. It is strategically located just south of New Orleans. In addition, it constitutes an area that is relatively sheltered, and thus less subject to the offshore removal of sediment by cold fronts and hurricanes (Roberts *et al.*,2003b).

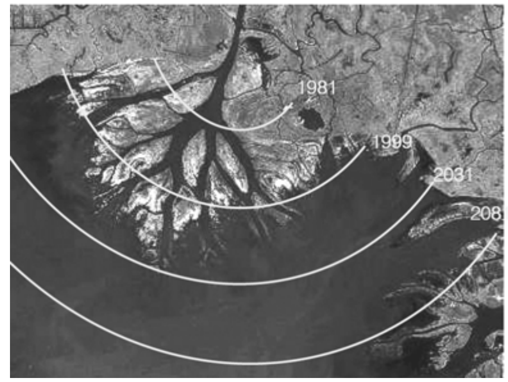

Figure 10. Predictions of the model for the shoreline of Wax Lake Delta overlain onto a satellite image from January 1999.

Two possible sites for diversions are shown in Figure 11. One would divert part of the river into Barataria Bay upstream of New Orleans, and the other would divert part of the river downstream of New Orleans. An extended and refined version of the morphodynamic model presented here combined with extensive field data could be used as part of the design process in selecting a diversion.

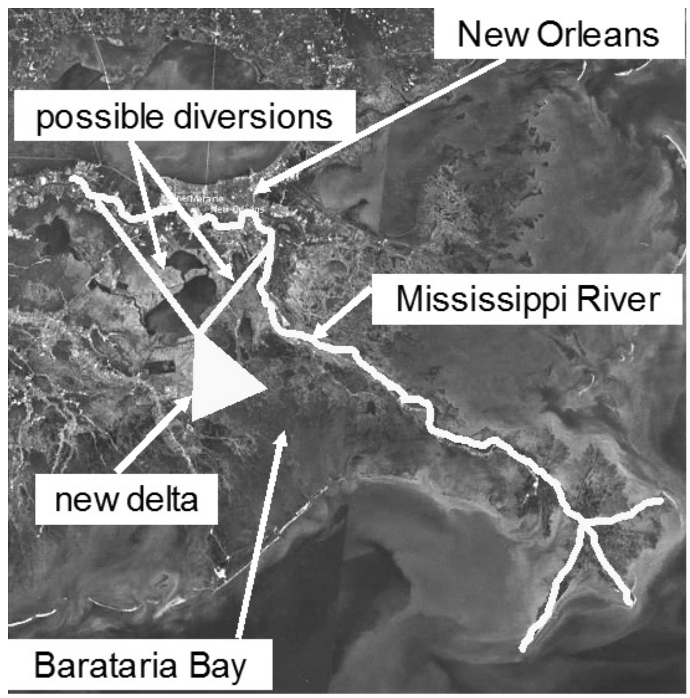

Figure 11. Possible locations for controlled partial avulsions of the Mississippi River into Barataria Bay.

There are many issues in regard to such controlled avulsions which need to be considered carefully, but which are beyond the scope of the present model. For example, a partial diversion downstream of New Orleans could cause a wave of degradation to sweep upstream, with potential damage to bridges, pipeline crossings etc. A partial diversion upstream of New Orleans could cause excessive siltation in the Port of New Orleans. If the diversion were sustained during low flow it could allow a salt wedge to move so far upstream as to contaminate the drinking water of New Orleans. In order to address these issues, the morphodynamic model presented here must be linked to purely channel-based models that can predict channel degradation and aggradation such as that of Meselhe *et al.* (2005).

Issues which need to be considered go beyond those involving the channel of the Mississippi River itself. Any scheme for controlled partial avulsions will require large expenditures of funds. The beneficial results may take decades to realize. In addition, any controlled partial avulsion is likely to have at least some negative consequences. These could, for example include siltation in the Intracoastal Waterway.

In point of fact, Hurricane Katrina was not needed to convince river and delta specialists that the negative consequences of doing nothing in the Mississippi Delta are likely to be far greater, in financial, social and ecological terms (Fischetti, 2001). The time has come to move forward with plans to use the sediment of the Mississippi River to restore the delta. Morphodynamic models of land building have an important role to play in this planning.

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