Landscape Modeling of the Mississippi Delta

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Using a series of landscape models, we examined the survival and creation of Mississippi Delta marshes and the impact of altered riverine inputs, accelerated sea-level rise, and management proposals on these marshes.

Deltas of large rivers are among the most variable environments on Earth (Wright 1985, Day et al. 1997). Active sediment deposition associated with river discharge leads to delta growth into open water, as typified by the delta that is forming at the mouth of the Atchafalaya River, the main distributary of the Mississippi River (Figure 1; Roberts 1997). As a river shifts its locus of deposition, abandoned areas subside and revert to open water (Baumann et al. 1984). Under natural conditions, the interaction of these processes with climatic and marine influences results in the fluctuation of habitat types within a delta and a relatively stable or increasing amount of land coverage across a delta (Roberts 1997).

Today, many of the world’s deltas, including the Barataria Basin of the Mississippi Delta (Figure 1) are experiencing rapid rates of deterioration because of human activities (Milliman et al. 1989, Stanley and Warne 1993, Day et al. 1997, 2000). These actions have isolated deltaic wetlands from riverine inputs that formed and sustained them, threatening the vitality of these systems and the ecological, societal, and economic benefits they produce. Flood control levees (Day et al. 1995, 1997), the closure of distributaries (Day et al. 1997, Roberts 1997), and the construction of impoundments and canals (Cahoone 1994, Turner 1997) have interrupted the natural delta cycle by eliminating the annual flooding of deltaic marshes and limiting the development of new depositional areas. Isolated marshes succumb to subsidence and are rapidly converted to open water at rates greater than 100 square kilometers per year (km² per yr) (Gagliano et al. 1981, Reyes et al. 2000).

Marsh loss has negative ecological and economic consequences, because net primary productivity declines by as much as about 67% in the Mississippi Delta when marsh is converted to open water (Bahr 1982). From 1956 to 1988, marsh loss in the Barataria Basin resulted in a 26% decrease in net primary productivity (Day et al. 1997). Our results predict that marsh loss in this region will continue and that the rate of loss will increase with accelerated sea-level rise. Coastal fishery productivity relies on coastal marshes (Nixon 1988, Deegan 1993, Houde and Rutherford 1993, Rouzas and Reed 1993), thus such loss of wetlands could have drastic economic effects. For example, construction of the Aswan Dam and subsequent reduction of freshwater input and erosion of the Nile Delta led to sharp declines in fish populations in lagoons and seaward of the delta (Stanley and Warne 1993), including a 95% decrease in sardine catches and an economic loss equivalent to US $61 million (year 2000 dollars) (Aleem 1972). Continued land loss across the Mississippi Delta over the next 50 years, by some estimates, will exact a toll of more than $37 billion (Bourne 2000) in lost public resources.

To assess the future of delta landscapes, we need tools that can predict the response of these systems to anticipated environmental changes and to modifications designed to restore these systems and protect human investments. The full effects of such alterations on processes at the delta or basin scale may not be evident in the landscape for 20 or more years (Boesch et al. 1994). At extended decadal temporal scales and landscape
spatial scales, assumptions used to predict ecosystem behavior can oversimplify systems by causing nonlinear relationships to appear linear, disregarding temporal and spatial lags and feedbacks, and isolating systems from their surroundings. When the interaction of multiple factors must be considered across extended temporal and spatial scales, tools that can account for these phenomena—landscape models, for example—are needed (Costanza and Ruth 1998, Martin et al. 2000).

Most spatial models applied to the Mississippi Delta, including those of the US Army Corps of Engineers, focus on short-term hydrodynamics and are more appropriate for project design than for predictive purposes (Moffatt and Nichol Engineers 2000). By contrast, the objective of the three models we review here is to predict changes in land cover across large geographic areas over long time scales as a result of natural alterations and site-specific management alternatives. A report comparing 32 hydrodynamic models of the Mississippi Delta (Moffatt and Nichol Engineers 2000) found that these three models are indispensable planning tools at a basin-wide scale, because they are the only models capable of simulating potential habitat changes and true long-term effects of proposed management alternatives.

**Landscape models of the Mississippi Delta**

To examine future management alternatives, a series of three spatial models have been developed for regions of the Mississippi Delta (Figure 1): (1) the Coastal Ecological Landscape Spatial Simulation (CELS; Sklar et al. 1985, Costanza et al. 1990), (2) the Barataria–Terrebonne Ecological Landscape Spatial Simulation (BTELSS; Martin et al. 2000, Reyes et al. 2000), and (3) the Mississippi Delta Model (MDM; Martin 2000). Although in this article we summarize the characteristics of all of these models, we focus on the most recent one, MDM, and its unique ability to simulate prograding deltaic environments (i.e., environments that are building seaward by deposition and accumulation). By integrating and linking hydrodynamic routines with ecological and soil modules, these models can simulate highly dynamic deltaic landscapes. Our methods allow simulation of feedbacks and spatial interactions of ecosystem dynamics for long periods (30–70 years) and across large areas (more than 2000 km²) of marsh habitat. Although substantial advancements have occurred over the 15-year period in which this series of models was developed, all three models have similar fundamental components.

For each model, we partitioned the landscape into a grid of 1 km² cells that were categorized as a specific habitat type (Table 1) based on US Fish and Wildlife Service (FWS) maps constructed from remote sensing data. Within each 1 km² cell, a unit model simulated processes such as aboveground and belowground productivity, mortality, decomposition, and soil building (Figure 2). After each iteration, each 1 km² cell exchanges materials with its four nearest neighbors as a function of water flow simulated with a hydrodynamic module. Water flow between cells is regulated by habitat-specific Manning coefficients (empirical values quantifying the amount of friction impeding water flow) (Casulli 1990). Habitat change occurs when vegetative production, salinity, and flooding duration within each cell cross preestablished thresholds (Reyes et al. 2000). The BTELSS and MDM simulate ecological processes at 1 km² and daily scales, whereas the CELSS uses a weekly time step. The temporal and spatial scales by which the hydrodynamic module distributes salt, sediment, and water vary among the three models (Table 1).
A higher resolution, variable time-step hydrodynamic module; a mass-balance sediment component; and a marsh colonization routine distinguish the MDM from the BTELSS and CELSS (Table 1). Reducing the spatial scale of the hydrodynamic module from 100 km² to 1 km² allowed the MDM to simulate river channels and jetties and addressed limitations of the BTELSS (Martin et al. 2000); a variable time step ranging from 20 to 1200 seconds allowed the MDM to optimize computation time while completing lengthy simulations at the 1 km² resolution; and the creation of new marshes enabled the MDM to simulate progradation of the Atchafalaya Delta. Because of an abundant seed source and plentiful fresh water, the Atchafalaya Delta will grow when substrate elevation crosses a threshold with regard to mean water level (Rejmanek et al. 1987). When the duration of flooding in each open water grid cell fell below 11 hours per day (Shaffer et al. 1992) because of changes in substrate elevation (Figure 2), the cell was reclassified as the marsh type that corresponds to the average annual salinity. These additions make the MDM the first model to simulate the interaction of physical and ecological processes that result in delta building. All three models are advanced simulation tools that test the relative importance of natural forcing functions and human alterations on the dynamics of deltas.

Simulating future landscape evolution required the designation of future forcing functions. Forcing functions consist of historical data series from 1956 through 1995 (Martin 2000, Reyes et al. 2000) that include climatic variables (precipitation, wind, temperature), river flow and sediment concentration, relative sea-level rise (comprising subsidence and eustatic sea-level rise), tides, and salinity. We did not randomly choose data sets from previous years to drive future simulations, because climatic events and river flows are cyclic and correlated over time (Latif and Barnett 1994, Thomson 1995, Malamud et al. 1996). In the MDM, we used data from 1956 to 1995 to drive the model for all future scenarios. (For further discussion on the sensitivity of model results to the ordering of forcing functions, see Reyes et al. 2000).

Before using the models to project future conditions, we demonstrated their ability to simulate past behavior of the system. For calibration, we used a 1978 habitat map from FWS to initialize the MDM and a data series from 1978 to 1988 to simulate 10 years of habitat change. We compared the resulting 1988 habitat map to a 1988 FWS habitat map. We quantified the agreement between the two maps with a goodness-of-fit spatial statistics routine that compares the spatial pattern of habitat cells at multiple resolutions (Costanza 1989), which returned a value of 94.9 out of a possible 100 (Martin 2000). The multiple resolution approach allows a more complete analysis of the way in which the spatial patterns match (Turner

Table 1. Key attributes of Mississippi Delta landscape models.

<table>
<thead>
<tr>
<th>Model</th>
<th>Study location</th>
<th>Area (km²)</th>
<th>Water movement (spatial, temporal resolution)</th>
<th>Future simulation Period</th>
<th>Land building</th>
<th>Habitats</th>
</tr>
</thead>
<tbody>
<tr>
<td>CELSS</td>
<td>Western Terrebonne basin</td>
<td>2479</td>
<td>Mass-balance model (1 km², variable)</td>
<td>1983–2033 (50 yrs)</td>
<td>Yes</td>
<td>Fresh, brackish, salt marsh, swamp, upland, open water</td>
</tr>
<tr>
<td>BTELSS</td>
<td>Barataria basin</td>
<td>6101</td>
<td>Hydrodynamic model (100 km², 1 hr)</td>
<td>1988–2018 (30 yrs)</td>
<td>No</td>
<td>Fresh, brackish, salt marsh, swamp, upland, open water</td>
</tr>
<tr>
<td>MDM</td>
<td>Western Terrebonne to freshwater bayou</td>
<td>8604</td>
<td>Hydrodynamic model (1 km², variable)</td>
<td>1988–2058 (70 yrs)</td>
<td>Yes</td>
<td>Fresh, intermediate, brackish, salt marsh, swamp, open water</td>
</tr>
</tbody>
</table>
The algorithm gradually degrades the resolution with which the fit is measured by gradually increasing the size of the sampling window in which the fit is calculated (Costanza et al. 1990). The total fit is a weighted average of the fit at all window sizes, with the smaller windows given the most weight. We obtained a validation value of 95.4 when we initialized the MDM in 1988, ran it for 10 years, and compared it to the 1998 FWS habitat map (Martin 2000). All six habitat types of the MDM (Table 1) were accounted for in the calibration and validation procedures. The BTELSS returned values of 89.3 and 74.4 for calibration and validation simulations, respectively (Reyes et al. 2000). Further calibration and validation of the models included comparing predicted habitat trends with historic rates of change and comparing recorded and predicted salinity and suspended sediment concentrations at specific locations (Martin 2000, Reyes et al. 2000).

The output of the models was designed to be easily interpreted through both visual inspection and quantitative results. We formatted variables tracked by the models into maps at chosen time intervals, producing a sequence of images portraying the dynamics of landscape components at a 1 km² resolution. In addition to maps showing habitat change, we also produced a map series of productivity, salinity, flood duration, water depth, water velocity, elevation, and suspended sediments. Results from these models are best understood by viewing animated map sequences of the various parameters (11 March 2002; http://130.39.20.51/projects.html). The figures in this article are examples of images that were generated at the conclusion of MDM simulations.

In previous scenarios, we evaluated the uncertainty of data inputs to the models and the uncertainty of the resulting predictions. The Manning coefficient, in particular, is difficult to estimate yet has the potential to affect water movement. We therefore investigated the uncertainty of model results caused by variations of Manning values. This analysis (Reyes et al. 2000) showed that the zone between fresh and saline marshes is most affected by variations in Manning values. For the Barataria–Terrebonne Ecological Landscape Spatial Simulation, the amount of habitat change increased with greater variations in Manning values (Reyes et al. 2000). Other parameters evaluated for uncertainty are variations of forcing functions, initial marsh elevation, sediment resuspension constants, and sediment size distributions (Martin 2000, Reyes et al. 2000).

Scenario analysis
How will different management alternatives affect Mississippi Delta marshes?

Current conditions scenarios. Current conditions scenarios simulated the continuation of current trends and patterns for each study area (starting in 1988) without management actions and offered a baseline of comparison for other simulations. The outcomes of these scenarios were markedly different for the MDM and BTELSS. In the simulation of Barataria Basin with the BTELSS, total marsh coverage de-
clined by more than 56% during the 30-year current conditions scenario (Table 2; Martin et al. 2000). This marsh loss is caused by the interaction of natural processes, such as high rates of relative sea-level rise that characterize the Barataria Basin (Penland and Ramsey 1990), and human modifications, such as elevated levees, that eliminate the input of river sediments (Martin et al. 2000). In fact, the ability to simulate marsh creation was not included in BTELSS because little, if any, land gain is expected in the Barataria Basin without management action. By contrast, the MDM study area experienced a 13.5% gain in marsh during the 70-year current conditions scenario, primarily because of the expansion of fresh marsh coverage associated with the progradation of the Atchafalaya Delta (Figure 3, Table 2).

The contrast in habitat change in these two areas is predominately due to regional differences in riverine inputs. Because inputs from the Mississippi River have been eliminated by elevated levees and closure of distributaries, the marshes of Barataria Basin cannot keep pace with relative sea-

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**Table 2. Changes in marsh coverage due to scenarios simulated with the BTELSS and MDM models.**

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Year</th>
<th>Marsh coverage (km²)</th>
<th>Percentage change from 1988</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Barataria Basin (BTELSS simulations)</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Initial conditions</td>
<td>1988</td>
<td>1949</td>
<td></td>
</tr>
<tr>
<td>CCS (RSLR = 1.2 cm per yr)</td>
<td>2018</td>
<td>849</td>
<td>−56.4</td>
</tr>
<tr>
<td>RSLR = 2.2 cm per yr</td>
<td>2018</td>
<td>196</td>
<td>−89.9</td>
</tr>
<tr>
<td><strong>Mississippi Delta Model (MDM) study area</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Initial conditions</td>
<td>1988</td>
<td>1696</td>
<td></td>
</tr>
<tr>
<td>CCS (RSLR = 0.5 cm per yr)</td>
<td>2058</td>
<td>1925</td>
<td>13.5</td>
</tr>
<tr>
<td>Half river input</td>
<td>2058</td>
<td>1713</td>
<td>1.0</td>
</tr>
<tr>
<td>Double river input</td>
<td>2058</td>
<td>2117</td>
<td>24.8</td>
</tr>
<tr>
<td>No river input</td>
<td>2058</td>
<td>1345</td>
<td>−20.7</td>
</tr>
<tr>
<td>RSLR = 1.2 cm per yr</td>
<td>2058</td>
<td>1596</td>
<td>−5.9</td>
</tr>
<tr>
<td>RSLR = 1.2 cm per yr and double river input</td>
<td>2058</td>
<td>2021</td>
<td>19.2</td>
</tr>
<tr>
<td>RSLR = 2.2 cm per yr</td>
<td>2058</td>
<td>1041</td>
<td>−38.6</td>
</tr>
<tr>
<td>RSLR = 2.2 cm per yr and double river input</td>
<td>2058</td>
<td>1641</td>
<td>−3.2</td>
</tr>
</tbody>
</table>

Note: CCS, current conditions scenario; RSLR, relative sea-level rise.

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Figure 4. Three maps of conditions in 2058 resulting from the following 70-year Mississippi Delta Model scenarios: (a) Atchafalaya River and Wax Lake outlet flows doubled, (b) Atchafalaya River and Wax Lake outlet flows halved, and (c) Atchafalaya River and Wax Lake outlet flows eliminated. The white line denotes the shoreline in 1988. Refer to Table 3 for habitat coverages.
level rise and will continue to subside and convert to open water. By contrast, the Atchafalaya River deposits riverine sediments in its delta, raising the elevation of substrate in open water areas until flooding durations decrease, permitting vegetative colonization. Subsequent organic soil formation leads to additional gains in elevation and eventual habitat change from open water to marsh. The predicted growth rate of the Atchafalaya Delta over the 70-year current conditions scenario, which is 1.84 km² per yr, is less than the 3.5 km² per yr actual rate of progradation that occurred during its first 18 years of existence (Roberts 1997). Such a decrease is expected as the delta matures while inputs are held constant. Although the MDM study area as a whole experienced land gain, marshes more distant from the river mouth, such as those in Pointe au Fer and Marsh Island (see Figure 1), suffered losses of marsh in the current conditions scenario (Figure 3). These areas received less riverine input and could not keep pace with the relative sea-level rise of 0.5 cm per yr that is characteristic of the study area (Penland and Ramsey 1990).

**River alterations in the Mississippi Delta Model.** Simulations performed with the MDM, in which Atchafalaya River inputs were doubled, halved, or eliminated, demonstrate the importance of river flow in sustaining marsh habitats across the study area. Doubling flows increased both the water and sediment delivered to the estuary and increased the growth of the Atchafalaya Delta by 125 km², compared with the current conditions scenario (Figure 4). In addition, marshes farther removed from the delta experienced greater accretion, which reversed the trend in these areas from marsh loss in the current conditions scenario to marsh gain. Pointe au Fer and Marsh Island gained 17 and 31 km² of marsh, respectively, in this scenario. Across the study area, a total of 421 km² of marsh was gained when flows were doubled (Table 2). Reducing Atchafalaya River flow by one-half decreased the growth of the Atchafalaya Delta by 125 km², compared with the current conditions scenario (Figure 4). Alterations in riverine inputs that have taken place in the Mississippi Delta and other deltas throughout the world demonstrate the relevance of these scenarios. As a result of natural and anthropogenic changes, the amount of sediment input to the Nile, Indus, and Ebro Deltas has been reduced by over 90%; for the Po and the Mississippi, the reduction is about 75%; and for the Rhone, the reduction is greater than 50% (Day et al. 1997, Kesel 1988). The scenario eliminating river inputs (Figure 4), exemplified by the current situation in the Nile Delta (Stanley and Warne 1993, Fanos 1995) and Barataria Basin, resulted in increased marsh salinization and loss across the MDM study area (Table 2).

Great increases in river input have also taken place, as in the case of the Atchafalaya River, which has gone from negligible flow...
to one third of the total flow of the Mississippi River over the past two centuries (Roberts 1997). Current projects, such as the Three Gorges Dam along the Yangtze River, ensure continued alterations of riverine inputs and impacts on delta evolution. The ability of models such as the MDM to simulate the linkages and feedbacks between hydrodynamics and ecological processes across large areas for long time periods renders these tools critical for quantitatively assessing the consequences of historical and future river and marine alterations on delta growth and regression.

**Sea-level rise—Mississippi Delta Model.** Further scenarios demonstrate that during the anticipated acceleration of sea-level rise, maximizing riverine inputs will be critical for maintaining coverage of the world’s deltas. Holocene marine deltas, such as the Mississippi and Nile, were initiated during a deceleration of sea-level rise and are very susceptible to changes in sea level (Day and Templet 1989, Stanley and Warne 1994). Subsidence combined with accelerated sea-level rise will amplify relative sea-level rise rates across low-lying deltas over the next 100 years, jeopardizing the economic and environmental services provided by these systems (Milliman et al. 1989, Day et al. 1995). The BTELSS predicted that marsh loss would increase to 89.9% in the isolated Barataria Basin if the relative sea-level rise increased from the current conditions rate of 1.2 cm per yr to 2.2 cm per yr (Table 2). In the MDM study area, the trend of marsh gain was reversed to marsh loss when relative sea-level rise was increased from the current conditions value of 0.5 cm per yr to 1.2 and 2.2 cm per yr (Table 2). Simulations at these elevated rates of relative sea-level rise with doubled river flows show potential to mitigate the loss of marshes due to increased sea-level rise. With doubled river flows and a relative sea-level rise of 1.2 cm per yr, the MDM predicted the amount of newly created land to surpass the current conditions scenario by 96 km² (Figure 5, Table 2). These results imply that with adequate sediment inputs, healthy delta marshes may serve as a buffer against moderate rates of sea-level rise.

**Management proposals—Mississippi Delta Model.** We used the MDM to analyze two management proposals for varying the flow distribution between the Wax Lake outlet and lower Atchafalaya River and one proposal to minimize salinity changes in Vermilion and Cote Blanche Bays (Figure 1; Martin 2000). The US Army Corps of Engineers and other management groups were considering these proposals in an effort to address flooding problems and habitat changes in the area. The first flood control plan would direct exceedingly high flows toward the Wax Lake outlet, but overall it would direct 10% more volume annually toward the Atchafalaya Delta. We did not activate this change until 2008, making the first 20 years of the simulation identical to the current conditions scenario. The second flood protection plan also alters the flow distribution between the Wax Lake outlet and Atchafalaya Delta. This plan would accelerate the natural movement of flow toward the Wax Lake outlet by guiding 20% more of the flow toward this channel, at the expense of the Atchafalaya Delta, in 2028. In the current conditions scenario, the shift of flow toward the Wax Lake outlet occurred 20 years later, in 2048.

A series of jetty plans have also been proposed, to diminish freshwater riverine inputs to Vermilion and west Cote Blanche Bay (Figure 1) and to preserve higher salinities in these bays. We used the MDM to analyze the most drastic of these plans, a jetty stretching from Marsh Island to the mainland that would eliminate flow between Atchafalaya Bay and Cote Blanche Bay. We simulated the jetty at an elevation 1.6 meters above mean water level beginning in 1988 (Figure 6). An additional component of this plan was to stop riverine water from flowing westward along the Gulf Intracoastal Water Way (GIWW) to the western bays. We distinguished the effects of each plan from natural changes through comparison with the current conditions scenario.

Because the flow alterations of each flood plan were relatively small compared with the current conditions scenario, they had little effect on the marsh and open water balance across the study area. Compared with the current conditions scenario, the first flood control plan resulted in 14 km² more marsh coverage, whereas the second plan increased open water coverage by 10 km² (Table 3). Both flood options increased fresh and brackish marsh coverage and decreased April 2002 / Vol. 52 No. 4 • BioScience 363
the amount of intermediate marsh (Table 3). In contrast to the larger changes in flow previously evaluated (Table 1), these minimal habitat impacts suggest that the delta system has the capacity to absorb smaller changes in river inputs without experiencing major ecosystem change.

The jetty was successful at maintaining salinities that were annually 1 to 5 primary salinity units greater than the current conditions scenario across Vermilion and Cote Blanche Bays (Martin 2000). Large areas that were fresh or intermediate marsh at the end of the current conditions scenario, but were brackish marsh following the jetty simulation, demonstrate that the jetty also preserved saline habitats surrounding these bays (Figure 6). However, all riverine inputs, not only salinity, were systematically reduced to the areas west of the jetty. This led to declines in suspended sediment concentrations in Vermilion and west Cote Blanche Bays. Consequently, marsh coverage declined relative to the current conditions scenario by 67 km² (Table 3), as decreases in suspended sediment concentrations lessened sediment deposition in the surrounding marshes (Figure 6). Eliminating westward riverine flows in the GIWW precluded the development of a small delta at the point of contact between the GIWW and west Cote Blanche Bay (Figure 6).

Previous studies have shown that jetties and similar structures that alter hydrology have the potential to affect distribution of marsh habitat (Sklar and Browder 1998, Martin et al. 2000). Impounded wetlands suffer isolation from riverine sediments and exhibit lower rates of deposition (Cahoon 1994). Hensel et al. 1998) and increased land loss (Swenson and Hensel 2000). Impounded wetlands suffer isolation from riverine sediments and exhibit lower rates of deposition (Cahoon 1994). Hensel et al. 1998) and increased land loss (Swenson and Hensel 2000). Eliminating westward riverine flows in the GIWW precluded the development of a small delta at the point of contact between the GIWW and west Cote Blanche Bay (Figure 6).

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Conclusions

Although human settlement and use of delta environments make it impossible to revert to the natural delta cycle, the models we reviewed provide quantitative predictions of the effects of various alternatives for balancing human needs and long-term vitality of delta systems. The results demonstrate that the maintenance and restoration of natural riverine inputs can create and preserve deltaic marshes and mitigate present and future deterioration of deltaic ecosystems. Scenarios in which riverine inputs were reduced resulted in losses of marsh coverage, underscoring the need to include deltaic impacts in evaluations of upstream river alterations. Increases in riverine inputs created new marsh, demonstrating the potential to sustain deltaic marshes despite accelerated rates of sea-level rise. The analysis of the jetty plan illustrates the environmental costs of imposing linear barriers in estuarine settings.

These scenarios exemplify the potential of landscape models such as the MDM and BTELSS to quantitatively evaluate proposed management plans in conjunction with natural alterations and lead to a more precise understanding of deltaic response to perturbations. During the 15-year development of these models (Sklar et al. 1985, Costanza et al. 1990, Reyes et al. 2000), and in current applications in the Everglades (Fitz and Sklar 1999) and Chesapeake Bay (Voinov et al. 1999), the goal has been to predict large-scale temporal and spatial patterns resulting from regional impacts. Such models can predict effects of complex interactions over lengthy time periods and across entire landscapes and are unique in their ability to predict the growth and regression of deltas for multiple decades.

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