Model Name: Barrier Shoreline Morphology Model

Functional Area: Barrier Shoreline Morphology

Model Proponents: Coastal Protection and Restoration Authority

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1. *Background*

a. Purpose of Model

This model was developed specifically for the Louisiana 2012 Coastal Master Plan for barrier shoreline and inlet evolution at a decadal scale. The motivation to develop a new model was driven by the complexity of the issues required by the master plan and the anticipated matrix of projects to be simulated. Although commercial models are available to perform a similar task (GENESIS - Hanson and Krauss, 1989, and UNIBEST-CL – WL|Delft Hydraulics, 1994), to avoid licensing concerns and possible limitations due to un-availability of the source code, and because of the short modeling timeline, a new model was developed. The model, however, is modular, and aspects of the calculations can be improved internally or externally as required.

The model presented in this report can (a) help forecast the response of barrier islands (shorelines) to long-term forcing such as relative sea-level-rise, and (b) predict the morphological response of tidal inlets to interior wetland loss. Taken together, the results produced by the model present the final position of the barrier shorelines and their respective inlets in response to long-term forcing at yearly time-steps.

This model can help determine the response of a sandy coastline to long-term wave climate and relative sea-level-rise forcing, and can provide the final barrier position at time-scales of one year to several decades. The targeted audience and expected users of this model are coastal planners with the need to manage a large coastline segment rather than an individual island, and who have to view and consider the regional response of such systems (including interior wetland loss, non-linear subsidence and eustatic sea level rise) under various scenarios of climate forcing and sediment supply (See Appendix C-Environmental Scenarios for more information).

The benefit of using this model is twofold. First, the simulation times allow the end user the opportunity to simulate decadal processes and document annual change of shorelines, inlets, and barrier area. Second, the output generated by this model, after analysis, provides a quantitative metric for barrier islands and their inlets over time, as a function of varying environmental conditions (sea-level-rise rates, subsidence) and specific restoration plans including projects on the barriers themselves (construction and nourishment) and other sites.

b. Model Description and Depiction

The Barrier Shoreline Morphology Model, referred to herein as the Coastal Morphology Model (CMM) simulates coastline and inlet evolution in response to physical forcing such as offshore wave climate, sea-level-rise and storms. The model was applied to the sandy shorelines of Louisiana in two segments. The first segment covers the barriers from the western Isle Derniere (Raccoon Island) to Sandy Point (See Figure 1). The second segment includes the barrier islands east of the Mississippi River delta, and includes Breton Island and the Chandeleur Islands (Figure 1).

The model encompasses long-term processes, such as response to sea-level-rise, subsidence, landward migration by beach and foreshore erosion and overwash processes, and the offshore and longshore loss of sediment to deepwater sinks below mean annual wave base. The model operates in a one-dimensional mode at a selected alongshore interval (~100 m) and geometrically translates a cross-shore profile based on the calculated processes. The model uses the sediment continuity equation (see Section 2a, eq. 4) to balance net import or export of sediment, and then uses the deficit or gain to determine the shoreline erosion rate at each location. The sediment continuity is governed by a mass balance of cross-shore and alongshore sediment transport. The model computes alongshore transport in plan form using an empirical relationship (USACE 2002), driven by offshore wave climate relative to a local shoreline angle. The shoreline angle is obtained dynamically at the intersection of sea-level and the coastline using the topo-bathymetric dataset. The model uses an annual wave climate derived by analysis of hourly wave information obtained from archived data from the Wave Information Studies (WIS - Hubertz and Brooks, 1992). To establish the annual frequency of occurrence for the wave height used in the transport equation, waves were separated into 8 magnitudes of wave heights, and 16 directional increments of 22.5 degrees. The resulting climate was used to drive the long-shore transport equation at an interval of 100 m along the modeled segment of the coast). Resulting net long-shore transport (on an annual basis) was then balanced by pre-determined cross-shore transport rates, obtained during model calibration (using a 20 year period). The resulting mass balance subsequently produced accretion or erosion, depending on excess or a deficit in the sediment, within the 100 m coastal segment. The result from this procedure is a one-dimensional translation of the shoreline. This process is repeated for each time-step (one year). While annual sediment budgets are used herein, modification of the input wave climate can be made to account for seasonal differences. The intra-annual variations of wave climate are not considered so that the model executes faster. This means that beach rotation and winter to summer changes in the shoreline erosion are not captured; only the net annual change is captured. The time-step of one year does not affect the results since the transport equation is not in deferential form.

The Coastal Morphology Model (CMM) has two components, the Inlet Morphology Model (IMM) module and the Barrier Morphology Model (BMM) module. The two modules are executed separately, as well as forced or driven separately (using different input data and forcing) and provide feedback with each other at a selected time frequency. For example, for the 2012 Coastal Master Plan modeling effort, the feedback was performed every 25 years, according to constraints from other models and overall modeling schedule. Exchange between modules is user defined and can be more frequent; however, the feedback process is not automated and is somewhat time-consuming. For instance, inlet cross-sectional area does not change as rapidly as the shoreline erodes. Therefore, coupling at an annual time-scale with the Barrier Morphology Model would not provide more accurate results, and is not entirely necessary. Alternatively, during intervals of approximately 25 years, there are changes of the order of 8 – 10 % in inlet cross sectional area, thereby mandating a feedback frequency shorter than the one used herein. It is noted, however, that the feedback frequency does not affect the Barrier Morphology Model results.

The IMM relies on equilibrium relationships to establish stable inlet morphology in response to a change in the estuary tidal prism, which is an input variable to the IMM model. Model derived tidal range and the geometry (or area) of the computational stencil (or grid) from the Eco-Hydrology Model are used as input (see Figure 2). The tidal range is used in conjunction with the computational domain (summation of the areas of the boxes which comprise a bay) to compute the tidal prism, and the maximum prism during spring tides is selected as the governing driver (the model actually uses the maximum annual tidal range using the daily tidal range observations from the Eco-Hydrology Model). Using an equilibrium relationship (Jarrett, 1976; O'Brien, 1969), the IMM computes the inlet cross-sectional area given an increase in the tidal prism. At the selected frequency (currently every 25 years; this exchange period is used for all interacting models within the master plan effort), the IMM interacts with output from the Barrier Morphology Model to produce a final digital elevation model (DEM) for the coast (Figure 3). The DEM is an interpolated surface derived from the combined cross-shore segments and inlet output to create one surface. The presence of a DEM does not imply that the resulting morphology accounts for two or three-dimensional processes.

This model is very similar to other one-dimensional shoreline erosion models (GENESIS - Hanson and Krauss, 1989, UNIBEST-CL – WL|Delft Hydraulics, 1994, and GEOMBEST, Stolper et al., 2005). This model is unique, however, in that the shoreline angle is evaluated at each time step (1 year) and always used in relation to wave climate. This enables the model to calculate a new longshore transport rate in plan form, which is used to determine the alongshore fluxes in the sediment continuity equation. Furthermore, the ability of the model to automatically calculate the shoreline angle is a good fit for scenarios that have relative sea-level-rise variations since rising sea-levels or subsidence may affect the angle (because of antecedent topography) independently of shoreline erosion, and hence dictate transport dominance.

Perhaps the biggest limitation of the model is that nearshore transformation processes impacting waves are simplistic, and in areas with high refraction, these processes may be over simplified (this includes areas with large ebb tidal deltas, inlets, and areas where a significant variation in bathymetry is present relative to the approaching waves). Thus, the model does not capture localized transport reversals, or transport hot-spots, but rather captures the trend of the shoreline migration.

c. Contribution to Planning Effort

The CMM is capable of long-term simulations of sandy shoreline (barrier shoreline) response to incident waves, and simultaneous relative sea-level-rise forcing. The use of long-term herein is taken to mean a few decades. This model does not address, in its present form, predictions nearing a century or longer. The model does not account for event driven (storm induced) change. Although not a long-term process per se, cumulative impacts from multiple storms (such as those observed from impacts during hurricanes Ivan and Katrina at the Chandeleur Islands) can have morphological implications that affect the sediment supply in the littoral zone, but such changes would not be captured by this model. It should be noted that this deficit in sediment supply could have significant impacts, such as changing the transport regime of the barrier, potentially leading to rapid collapse of the system.

d. Description of Input Data

Model Input data

1. Initial Conditions

This Section describes the input data at the starting point of the model run before the simulation begins. These data are only used once in the model, and represent “existing conditions”, or conditions at the beginning of the simulation.

Barrier Morphology Model

Bathymetry and topography: The most recent topography and bathymetry for the modeled regions are required. For this effort, data from the Barrier Island Comprehensive Monitoring (BICM) Program dataset were used (Miner et al, 2009) to define this surface. For topography, more recent data were used and were overlaid in the dataset. Newer LiDAR data as a rule replaced previous topography if overlap existed between the two datasets. The LiDAR data used included surveys conducted in 2008 (central coast) and 2010 (Chandeleur Islands) using the EARRL LiDAR system operated by the USGS (Sallenger et al, 2009). The resulting composite surface provided the final footprint of the barrier shorelines (both emergent and submerged portion). Cross-shore transects (Figure 4) are then extracted from the topo-bathymetric dataset, at the desired alongshore interval that the user wishes to operate the model. For this application, the interval was 100 m.

Grain size diameter: The median grain size diameter per coastline segment is an input. If this value is not known for each segment, one global median grain diameter can be used. For the effort herein, we used spatially constant values of 0.1 mm (Flocks et al., 2009). The model can accept a mean diameter for every 100 m segment if such information is available.

Closure depth (dc): Closure depth can be selected based on knowledge of the actual closure depth in the area. For this study, we used data derived by analysis from List et al (1997). Closure depth values vary spatially from 4 m in the western barriers (Isle Dernieres) to more than 10 m near the Caminada Headland (for more details, a digital appendix can be provided upon request). While data from List et al. (1997) were used for closure depth, the bathymetry, topography and grain size data were from more recent sources (Miner et al., 2009; Flocks et al., 2009).

Water level and shoreline angles: Water elevation for the initial identification of the shoreline, was provided by the master plan project team in NAVD88, and was selected to be the initial water elevation for all participating groups in the master plan modeling effort. In subsequent years, sea-level-rise was applied to the ‘new’ shoreline (as determined by the erosion or accretion rate) prior to the calculation of a new shoreline angle.

Inlet Morphology Model

Initial (2010) cross-sectional area of major inlets in the modeled area: This includes all inlets present in the BICM bathymetric surveys, as identified by Miner et al (2009). Other input data include the selection of the appropriate equilibrium relationship and coefficients (see Section 2a. eq. 2) from Jarrett (1976) and O’Brien (1969). The coefficients used were those for un-jettied inlets in the Gulf Coast Region. Sensitivity and uncertainty analysis (see Section 7) was carried out to establish the variance in these predictions.

2. Boundary Conditions

Barrier Morphology Model

Wave Climate: For the master plan modeling effort, the long-shore sediment transport equations were driven using WIS data (20 years, from 1989 - 2009). For the 50 year simulation, this period was recycled (by repeating the wave climate such that 2010 was modeled as 1989, 2011 was modeled as 1990 and so on). The model may be driven however by either forecast wave fields or field observations (if available).

Sea-Level rise rate: Sea-level rise values were specified by CPRA (see Appendix C – Environmental Scenarios). Temporally variable (i.e., curve, not straight line) sea level was applied to the model, with one sea level rise rate applied for the moderate future scenario and a higher sea level rise rate applied for the less optimistic future scenario (see Appendix C – Environmental Scenarios).

Subsidence rate: Subsidence values were specified by CPRA (see Appendix C – Environmental Scenarios). Spatially variable subsidence was applied to the model, with one set of subsidence values applied for the moderate future scenario and another set of subsidence values applied for the less optimistic future scenario (see Appendix C – Environmental Scenarios).

Back-barrier marsh accretion rate: A constant accretion rate was applied at each time step (Morris and Calhoon, 2002).

3. Constants

Sediment density: Sediment density for quartz sand (2650 kg/m^3) is used (Dean and Darlymple, 2002).

Parameter beta (β): This is a calibration parameter in the longshore transport equation (see Section 2, eq. 3), to account for a sediment density other than pure sand, or to account for the presence of fine sediment that once eroded is lost from the littoral zone (see Section 8 below for more information on uncertainty analysis).

4. Other

Other parameters to run the model include the length of the run (for this effort 25 or 50 years was used depending on the exchanged period between models) and temporally variable inputs for moderate and less optimistic future scenarios. In addition, project runs, such as those that reflect a restoration project within the system, must be prepared *a priori*. In other words, the original bathymetry or topography must be modified on the basis of the project, and new cross-shore profiles must be extracted to update the data structures prior to performing any model runs.

e. Description of Output Data

Output data from this model include (1) transformed wave conditions computed and used for sediment transport and shoreline change analysis for each computational time step, (2) alongshore and cross-shore sediment transport rates/volumes generated for each time step, (3) shoreline angles generated for each time step, (4) percent increase of the inlet cross-sectional area. Finally, the resulting shoreline transformation, accompanied by changes in the inlet cross sectional area was interpolated onto a digital elevation model (DEM) in NAVD88 meters.

Example output is shown in Figures 5 and 6. Figure 5 shows the initial surface and Figure 6 shows the initial surface (Figure 6 upper panel) used as the model initial condition, the final surface, generated after interpolation of the model results (middle panel), and the difference of the two surfaces (lower panel) produced by differencing the two surfaces. A digital appendix with output transport rates, shoreline angles, and other output parameters is available upon request.

Model output can be provided in standard ASCII format, in column format, row format, or matrix format. Transient output (such as shoreline angles for every year, and singular shoreline erosion for each year) are also stored as output and can be used further. Generally, the output for a singular parameter (e.g. shoreline position) is in array form, starting from the westernmost cross-shore profile to the easternmost profile (1,500 profiles exist for the central coast) and from year 1 to year 50. Therefore, this array will have dimensions of 1,500 x 50. Similar parameters are also stored in similar format (although not written to a file, they are stored in memory). Details of the file formats are provided in Section 3e).

The cross-shore profile elevations (i.e., elevations describing the profile are every 2 m in the horizontal direction along the length of each island) for each of the 1500 profiles, are modified depending on the scenario run, and the new elevations resulting from each time-step are stored in ASCII format (x,y,z). The elevations, supplemented by inlet information (percent increase) are ultimately used to prepare the DEM.

f. Statement on the capabilities and limitations of the model

The model is capable of estimating the migration rate of a barrier island and adjacent shorelines in response to a long-term wave climate and relative sea-level-rise. It does so by use of a longshore transport equation (see Section 2, eq. 3) to evaluate alongshore fluxes, which are balanced by cross-shore processes (over-wash, offshore loss) using the sediment continuity equation (see Section 2, eq. 4) to predict a one-dimensional shoreline erosion/accretion. Performed over several time-steps, the model eventually estimates the final location of the shoreline. Given sufficient resolution in the alongshore dimension, a spatial interpolation algorithm builds the final form of the barrier unit as a DEM (for instance, the alongshore resolution of 100 m, and the cross-shore resolution of 2 m is sufficient to produce a 30 m resolution surface).

Limitations related to the theory and assumptions include, among others, ignoring local wave refraction and other nearshore processes. This will affect the way local waves are transformed, and result in errors in the prediction of the longshore sediment transport. These errors are not expected to be large – generally less than 10% - but could provide local reversals of transport in areas with nearshore coastal features such as nearshore bars, shallow ebb deltas, oblique isobaths etc. They could produce hot spots of erosion/accretion not captured herein. Given the distribution of waves approaching the coast, taken over one year, these reversals are likely not a significant source of error. The shoreline angle is computed every time-step, using adjacent shoreline locations (typically ~100 m in either direction). The shoreline angle is smoothed prior to execution of the next time-step. Therefore, local hot spots, and local small-scale reversals are not resolved by the model, but the overall shoreline trend is captured. The offshore wave climate frequency is determined by adding the magnitudes in 8 bins and the directions in 16 bines (bins are increments of 22.5 degrees). Defining the bins by slightly different angles or using more/less directional bins may result in slightly different transport, although this effect is expected to be small. What may actually be more significant, in this effort, is the use of the WIS dataset to drive shoreline erosion. The WIS data used herein were integrated into annual average data rather than being used as an hourly time series (in order to reduce computation time), and, thus, do not explicitly include storm events within the input conditions. Moreover, using an annual average wave rose to determine to frequency of occurrence of a particular wave height or period to determine sediment transport, may further suppress the effects of individual storms (see Section 2 for more detail). Hence, the model can be considered capable of addressing a response to sea-level rise and some equilibrium response to waves, rather than individual storms. For more detail on the methodology see Section 2.

g. Description of model development process including documentation on testing conducted (Alpha and Beta tests)

Model development was initiated following the compilation of the governing theory and methodology (see Section 2). Coding of the equations that were identified for inclusion (detailed in Section 2) is relatively straightforward. The model's performance and testing were performed using the shoreline of Louisiana (the study area) because a substantial dataset on historic shorelines (from digitized aerial photographs) topography and bathymetry spanning over decades already exists. As a result, the developers tested the model in a challenging and rapidly changing environment. A fast changing environment presents additional challenges, such as the lower shoreface response. Lower shoreface processes respond to storm events and storm wave base, therefore, since this modeling effort does not deal with storm-induced transport, capturing this response is a challenge. Ultimately, alpha tests were performed to accurately predict reasonable transport rates (when compared to previous studies; e.g. Georgiou et al., 2005; Ellis and Stone, 2006, Rosati and Stone, 2009) and shoreline response (e.g. Fearnley et al., 2009). Calibration was also the single most stringent test we performed, to ensure that the model, given reasonable input and constants that agreed with theory, was adjusted to reproduce historic shorelines. Calibration results and model skill is shown in Section 2.

2. *Technical Quality*

a. Theory

The Coastal Morphology Model (CMM) consists of two separate components: the Inlet Morphology Model (IMM) and the Barrier Morphology Model (BMM).

Inlet Morphology Model: The IMM accepts input from both the Wetland Morphology and the Eco-Hydrology models. For example, for a specific scenario simulated, the land/water ratio from the Wetland Morphology Model is used to compute the active bay area contributing to the tidal prism (for instance, Barataria Bay is composed of several hydrology boxes). Eco-Hydrology output (specifically the tidal range) for each individual box is used to identify the volume of water exchanged during a tide for the period of interest (see Appendix D-1 Eco-Hydrology Model Technical Report). Therefore, the total tidal prism for a basin is defined as:

$$P = \sum_{i=1}^{n} (\max\left|T_{range}\right| * A_b) \quad (1)$$

where T_{range} is the tidal range (m) for the n^{th} hydrodynamic cell, A_b is the area (open water) of the cell, and n is the number of cells which make up a given bay or estuary. Using equilibrium theory, the likely increase in the inlet cross-sectional area is then computed using the Gulf Coast version of the Jarrett-O'Brien-Marchi relationship given by:

$$A = kP^a \quad (2)$$

where *A* is the inlet cross-sectional area, *k* is the gulf coast coefficient, *P* is the maximum annual tidal prism, and *a* is the exponent for the gulf coast inlets. The result is compared to the previous cross-sectional area from the earlier period and the final result (output) to the Eco-Hydrology team is reported as a percent increase or decrease in cross-sectional area. The uncertainty for this step is calculated using the 95% confidence interval as reported in O'Brien (1969) and Jarrett (1976). For instance, Figure 7 shows the annual percent increase of the combined inlet cross-sectional for Terrebonne Bay for two different master plan scenarios.

Barrier Morphology Model: The model for barrier island erosion and shoreline evolution is a simple, one-dimensional plan form model. Through use of offshore wave climate (20 years – from 1989 through 2009 of hourly wave heights, wave periods), wave forcing was produced to drive the shoreline change. For instance, to determine the frequency that a wave occurs during one year, waves were grouped into 8 wave height magnitudes, and in 16 directions using the hourly records (hence 8765 records per year were used). Upon completion, a probability (in percent of annum) is known for each of the wave heights, in each given direction; examples of annual average wave rose are shown in Figure 8.

Waves are transformed using a simple shoaling transformation and eventually break locally (USACE 2002). For a given group of waves with wave heights with magnitude *j* approaching from direction *i*, the probability of those waves occurring in one year is $P_{i,j}$. Therefore, the resulting longshore transport rate per year, for a given segment of the coast can be represented using the following formula:

$$Q_{i,j} = P_{i,j}\left[\sum_{i=1}^{7}\sum_{i=1}^{24}[K\frac{\rho(g^{0.5})}{16k^{0.5}(\rho_s-\rho)(1-n)}H_{rms}^{(\frac{5}{2})}\cos(\alpha b)^{\frac{1}{4}}\sin(2\alpha b)]\right] \quad (3)$$

where $P_{i,j}$ is the frequency for a given wave height *i* occurring from a given direction *j*), ρ is the water density, ρs is the sediment density, αb is the incident wave angle relative to the shoreline, $K = \beta 1.4 e^{-2.5(D_{50})}$, in which D_{50} is the mean grain diameter, β is a calibration parameter (which represents the presence of mud or fines in the system), *k* is the breaker index set to 0.78, and *n* is the sediment porosity. The indices *i,* and *j* indicate, respectively, the magnitude and directional bins used to determine the frequency of an individual wave type from WIS data. The resulting net transport rate (from the 7 x 24 = 168 calculations per year) is then differenced across an alongshore coastal cell (Figure 9), and is balanced using the sediment continuity (eq. 4) with both offshore and overwash fluxes. The resulting volume is then divided by the alongshore shoreline segment, and the closure depth obtained from List et al. (1997) to produce a one-dimensional model which has the form of

$$\frac{dy_i}{dt} = -\frac{1}{d_c}\frac{dQ_{i,j}}{dx} - S \qquad (4)$$

where $Q_{i,j}$ is obtained from eq. 4, d_c is the closure depth, and *S* the source terms, defined as

$$S = \left(\frac{dQ_{offshore}}{dx} + \frac{dQ_{overwash}}{dx}\right)\frac{1}{d_c} \qquad (5)$$

A schematic of this procedure is shown in Figure 9.

At each annual time-step, the elevations along a cross-shore profile were modified by applying a simple one-dimensional model such that

$$\frac{dh}{dt} = -\frac{dSub}{dt} + \frac{dAcr}{dt} \qquad (6)$$

where h is the local elevation along a cross-shore barrier profile, Sub is the subsidence rate per annum, and Acr is the accretion rate (Figure 9).

The eustatic term $\frac{d\zeta}{dt}$ (where ζ is the eustatic sea level) does not directly affect the elevation of the seabed, but is used to compute the shoreline angle before the second year of calculations is carried out. The local shoreline angle is then calculated by using the adjacent coastal cells shoreline position, and assuming a linear fit between them.

b. Description of system being represented by the model

The model represents a segment of a Louisiana's sandy shoreline (Figure 1) with barrier islands, described in Section 1b. The model operates in the plan form (Figure 9A) to produce sediment transport rates, subsequently differenced (Figure 9B) to yield an erosional or accretional profile (Figure 9C). The cross-shore or profile transformations are geometric and follow the Bruune Rule as shown in Komar (2002) and FitzGerald et al. (2008). The system represented by the model is a coastline segment, with sandy barriers, where transport within the littoral zone, indicated by the closure depth, takes place in the alongshore dimension (Figure 9 A, B, and C). The area between the barriers, the tidal inlets, is represented by the IMM. This model computes the change in the inlet cross-sectional area due to changes in the tidal prism, as a result of interior wetland loss, marsh creation, or other projects (this aspect of the model is driven by Eco-Hydrology Model output).

c. Analytical requirements

Model skill assessment was performed, first to ensure that the model although simple, had an inherent capability to reproduce a present shoreline position starting from a known historical shoreline position. Since shoreline positions along the modeled region are available for 1989, this year was used as the starting year during the calibration. The objective was to reproduce the 2009 and 2010 shoreline positions throughout Louisiana (for the modeled region, Figure 1), without adjusting the source terms (Figure 10a). Since offshore fluxes are largely unknown in the study area, the source term, *S,* (Section 2a. eq. 4) is used as a calibration parameter in conjunction with parameter β (Section 2a). Figure 10 (upper panel) shows the model performance without adjustment, while figure 10 (lower panel) shows the improvement of the prediction after calibration was completed.

Specifically, for the central coast, the most recent shoreline extracted from the topographic-bathymetric composite surface was from 2009 given the recent LiDAR used. Figure 11 shows the model predicted shoreline during calibration in plan form. For the Chandeleur chain on the other hand, we see a similar result with the performance shown in Figure 12. The only difference between the two regions is that the most recent shoreline position for this chain was obtained from LiDAR in 2010 rather than 2009.

d. Assumptions

i. The mean grain diameter (D_{50}) is constant in time and space (0.1 mm; Flocks et al., 2009). Information on grain size diameter is sparse, but the assumption of a representative diameter, invariant in time and space is appropriate given the large time-step of one year. This implies that the model does not capture small scale, or short turbulent driven processes; therefore, the selection of the grain size will only affect the transport rate, and overall erosion proportionally, with a predictable behavior.

ii. The cross-shore profile is geometrically similar inside the closure depth up to the dune crest. This means that the model is not capable of predicting local changes to the cross-shore profile due to a local nearshore process, but rather treats the profile as being in equilibrium the entire time. Since the time-step is one year, intra-annual changes in profile shape due to intra-annual changes in wind and wave patterns are not captured. Therefore, the assumption is made that a cross-shore profile will return to equilibrium each year. This assumption is reasonable based on work by Dean (1991) and is largely a function of local sediment characteristics.

iii. Dune erosion is empirical and dune crests are symmetrically and geometrically eroded. The assumption here is that the dune must follow similar rules to those of the shoreline. Dunes can only exist landward of the shoreline, within the same distance from the shoreline during a model run, and retain their shape in time. Since the model does not resolve nearshore processes, there is no information to asymmetrically erode the dune.

iv. Backbarrier deposition/accretion is empirical and at a constant rate (Morris and Calhoon, 2002) to mimic natural overwash and organic accumulation (for non-sandy marshes).

v. No explicit storms are simulated, except for storm wave climate that already exists in the offshore forcing (WIS Stations).

vi. Lower shoreface response and processes are ignored. The lower shoreface is not affected by day-to-day processes but rather responses to storms. Since the model does not simulate individual event driven transport, lower shoreface processes were neglected.

vii. Offshore fluxes in the sediment continuity equation and the accretion terms were calibrated for the period of 1989-2009. All barrier shoreline models were first calibrated to reproduce the present shoreline starting from 1989. In some cases, no subaerial elevations were available; hence, a dune height of 1.0 – 1.5 m was selected to avoid a non-breaking wave and to complete the calibration. Approximately 10% of the modeled region did not have subaerial elevation. For instance, at Breton Island a value of 1.5 m height was selected based on a previous 2006 LiDAR survey conducted by the USGS. For the area near Pelican Island and vicinity, a value of 1.5 m was selected. The same value was used for other areas missing subaerial information.

viii. Shoreline angles were smoothed using a simple filter to prevent oscillations and unrealistic perturbations prior to executing the next year of simulation.

ix. Final DEM output is spatially interpolated and could include unrealistic features and artifacts of the interpolation algorithm. This includes a singular high elevation, which appears as a spike in the dataset. Other features may include a small step near the transition from an area with high activity (erosion or accretion) to an area with low change. Such features may occur because the third dimension is not explicitly simulated using any realistic processes, or numerical equations. Caution is encouraged to use the final datasets within their uncertainty.

e. Identification of formulas used in the model and proof that the computations are appropriate and done correctly

The theoretical formulas used in the model are shown in Section 2. The coded or discretized formulas in the MatLab® environment (standard engineering software) were tested, often by more than one developer. Tests to ensure that output was reasonable were performed (compared to literature or against observations and/or by performing calculations performed in a spreadsheet – also see Section 2b and 2c for more detail). Additionally, comparison with real-world examples was conducted to ensure plausible predictions (see Section 2c). The source code is available, and serves as the basis to verify and test that the formulas are indeed correct. Source code will be available by CPRA upon request by a potential user.

3. System Quality

a. Description and rationale for selection of supporting software tool/programming language and hardware platform

The model was written entirely in the MatLab® scientific software, due to the inherent capability of the language in accessing multiple files from multiple folders, and the software ability to handle data structures. Most initial and boundary conditions exist in data structures.

b. Proof that the programming was done correctly

Although it is possible that a small code error may exist, developers frequently checked each other's work to ensure that theory and implementation of theory was done accurately and transferred correctly to the programming language and that output results were reasonable. If an error does exist, it is likely small and will not affect the results significantly. An example of the observed response from a 50 year simulation is shown in Figure 13. The 50 year simulation results, subtracted from the initial 2010 condition (Figure 12A) shows similar erosional spots with the longer-term erosion volumes reported in Miner et al. (2009) (Figure 13B). More erosion is evident in Figure 13B (and expected), since the period of comparison is two and one-half times longer (approximately 130 years).

c. Availability of software and hardware required by model

The model uses the MatLab® environment to run all the modules, therefore a licensed version of MatLab® is required to run the model. Additionally, freely available algorithms are used to interpolate and form the DEM. For example, the interpolation algorithm used herein is only available in the MatLab® version of 2010. The model does not need any other software to perform simulations, however, the final DEM files are written in a georeferenced grid (the standard for ESRI® ArcGIS) that can be viewed using ArcGIS. No other software is required to run the model, or view the output. Alternatively, since the output is written in ASCII format, other formats can be incorporated with additional coding.

d. Description of process used to test and validate model

The model post-development was calibrated using real datasets from the entire coastline of southeast Louisiana. The datasets were developed by the University of New Orleans under the Barrier Island Comprehensive Monitoring (BICM) Program. The model was driven with wave climate for a similar period for which shorelines were available. The model was calibrated to reproduce observations for a dataset representing a long-term change from 1989 to 2009/10 (a full description of calibration is provided in Section 2c). The 3D interpolation of the model results was also compared to the results of Miner et al. (2009), again with favorable results (see Section 3b). With the model's success in capturing shoreline response during calibration, it is expected that future shoreline positions can be reasonably forecasted using the same coefficients and constants. The success of this exercise lies in the availability of multiple shorelines during a relatively short (seasonal to annual) and long (decades) time period. This facilitates accurate testing of the short and long-term response of the shoreline erosion algorithms.

e. Discussion of the ability to import data into other software analysis tools (interoperability issue)

Presently, the model both accepts input data and exports output data using MatLab® structures. MatLab® can easily export to or import from text files (any delimiter), XML or spreadsheet formats. Thus, the input data structures can be compiled with minimal effort within MatLab® from ASCII or excel files. Equally easily, the code can be altered to accept data in other formats. The benefit of using data structures (which act like a database) is that variables may be called by name, rather than needing to be stored in a specific order and then called from the appropriate columns or row from an ASCII or EXCEL formatted file. Therefore, as the BMM is currently written, two input files are required, that for wave data and that for shoreline data. The shoreline data input file must be a structure with a layer for each cross-shore transect within the length of shoreline being considered. The model uses the length of this structure to determine the length of the shoreline and set up all output structures or calculation loops. The BMM shoreline data input structure must contain the following inputs (format in parenthesizes) for each alongshore transect::

i. 'dc', depth of closure (positive downward in m)
ii. 'WISdata' column in wave data structure to be used for each transect, this is synonymous with the WIS station being used to force each position alongshore (positive integer)
iii. 'bf####', where #### is the date or name of the data set, this input provides the coordinates describing each transect (Position of landward end X, position of landward end Y, position of back shoreline of barrier X, position of back shoreline of barrier Y, position of the front shoreline of barrier X, position of the front shore of barrier Y, distance from landward end to back shoreline along transect, distance from the landward end to the front shoreline along the transect in m, for the master plan effort Easting and Northing, UTM Zone 15 were used).
iv. 'm' the beach slope (positive sloping offshore and unitless as is a gradient).
v. 'Z', the elevation with respect to mean sea level every 2 m along the cross-shore transect from the landward end, ([5001 x 1], in m).

The wave data structure is expected to contain the following data:

i. 'date', year represented by the data (YYYY)
ii. 'WISdata', sub structure with two categories containing the annual average probabilities calculated for 8 wave height (H) and wave period (T) categories in each of the 16 directional bins
iii. 'T' the wave period (8 x 16, the total grid should sum to 1)
iv. 'H' the wave height categories for (8 x 16, the total grid should sum to 1)
v. 'id', station identification number (positive integer)
vi. 'd', water depth at station (positive downward, m)
vii. 'wnum', wave number – calculated from each of the 8 wave periods considered and station water depth (for this effort a method by Hunt (1979) to solve the dispersion relation and obtain the wave number) [(8 x 1], unitless real number)
viii. 'L', wavelength – calculated from the wave number using standard linear wave theory (Dean and Dalrymple, 2002). ([8 x 1], m).

ix. 'C', wave celerity – calculated from the wave number using standard linear wave theory (Dean and Dalrymple, 2002). ([8 x 1], m).

A setup module is available to help construct and calculated these terms.

For the IMM the inputs are:

i. 'A', cross-sectional area of the combined inlets (m^2)
ii. 'P', a structure with the tidal prism for each year calculated from the Eco-Hydrology output (tidal range and Bay Area) (m^3).

Output data from the IMM is provided in an ASCII format:

i. 'dX', percent change in cross-sectional area for each year (%)

There are two outputs from the BMM. The outputs are single structures, with the data in each layer of the structure representing a variable for the entire shoreline length (i.e. having the same number of rows as there are transects along the shore and, therefore, layers in the input structure). The first output is a structure has the following categories (see digital appendix for examples):

i. 'year' , the year being considered (YYYY)
ii. 'Q', the alongshore transport for each shoreline section (m^3/yr)
iii. 'delta', the cross shore change in position (positive seaward, m)
iv. 'delta2'. the cross shore change in position incorporating relative sea-level changes (positive seaward, m)
v. 'new', new coordinates of the front shoreline of the barrier (X,Y, m).
vi. 'ang', the new shoreline angle (post smoothing, (see Section 1f) (degrees).

The second output is a matrix of cross-shore elevations (to mean sea level, adjusted for shoreline erosion and relative sea-level changes) for each cross-shore transect. This output will have dimensions 5,001 rows, by the number of transects along the length of the shoreline being considered.

The output structures can be easily output in database or ASCII format using MatLab®, likewise the topo-bathy grid can be converted to a DEM and from here export as, for example, a grid structure compatible with GIS software. A DEM export module (MatLab® function) was created as part of the master plan project to provide a correctly formatted input to another team.

Interoperability is relatively low as this was not part of the present scope, thus developers did not have enough time to develop modules to translate data to other models beyond the DEM builder. The simplicity of the output structures and the use of MatLab®, however, allows for relatively easy translation to any required format. In the case of the master plan project, text input data from the Eco-Hydrology Model was easily manipulated in MatLab® for input to the IMM, and the interpolated DEM from the BMM was output as a .grd format (ArcMap grid), for the Wetland Morphology Model.

4. *Usability*

a. Availability of input data necessary to support the model

The minimum input data to drive the model is wave climate. The easiest way to access such data is through the Wave Information System (WIS) operated by the Army Corps of Engineers. The WIS data were chosen because they are consistently available, in a standard format for all regions around the United States and have been shown to be a reliable hindcast (Hubertz and Brooks, 1992). WIS data are also preferable because the model requires a sufficiently long and accurate record of wave climate (long enough to capture both day-to-day conditions and also various storms ~ 10 years), The data must be prepared (by binning) in 8 magnitude bins, and 22.5 degree directional bins into a data structure *a priori* (as described in Section 3). Both period and wave height data are required.

Additionally, initial topography and bathymetry for the region of interest must be available, and data structures, such as cross-shore transects, must be built and prepared *a priori*. Alongshore resolution of 100 m, and the cross-shore resolution of 2 m is sufficient to produce a 30 m resolution surface.

For the purpose of performing scenario simulations, the model must first be calibrated with historic shorelines, by varying some constants and source terms (see Section 2, eq. 4) until historic shorelines are reproduced successfully. This implies that the user has some experience analyzing shoreline change, and some data to test the model skill in a new area.

In addition, accurate bathymetry and topography are also important in order to verify the accurate depth in the nearshore, the shape of the cross-shore profile, and most importantly the closure depth (dc), as well as providing a reasonable profile of the sub-aerial barrier island components (dune shape, proximity to the beach). The availability of these data will vary depending on region, for Louisiana, the BICM project provided extremely high resolution data.

Other input data requirements include: grain size information with alongshore; some information on overwash volumes or rates for a moderate storm, and finally some idea on the sand-mud fraction of the littoral zone to use in the beta calibration term (in the longshore transport equation; eq. 3). Again, the availability of these data will vary depending on region but these are variables commonly found in the literature as part of coastal engineering studies.

b. Formatting of output in an understandable manner

The output of the model is an interpolated DEM, which can be viewed in ArcGIS or other geospatial application. We use the standard ESRI® grid format (common among master plan groups and any GIS software), and files are binary format. A user can load one simulation (i.e. moderate scenario for one project group) as a reference and another simulation from a different environmental scenario (or a different project groups) for comparison. By subtracting elevations produced from each simulation, a surface showing volumetric change can be generated and further analyzed, where one can see erosion and deposition zones (e.g. Figure 13A).

c. Usefulness of results to support project analysis

The model provides a useful estimate of shoreline position, but the data can also be used to identify regions most at risk from erosion and shoreline retreat. The CMM also provides important information concerning the size and position of inlets (important in terms of navigation and tidal exchange).

d. Ability to export results into project reports

The present capability to export results has been implemented to address the current need of master plan team members, and a standard (for this study as well as an ERSI® standard for viewing geospatial data). However, if specific guidelines on the type of information needed are available, since the source code is available and MatLab® is very flexible in its export options, output can be customized to generate datasets with additional information (including xml, xls and ASCII text with any required delimiter).

e. Training availability

This model was developed at the University of New Orleans in collaboration with Boston University on a budget constraint. No training is available under the current task, but training can be arranged given a reasonable time and a budget to develop and respond to the request.

f. Users documentation availability and whether it is user friendly and complete

No documentation is available (user manual or technical manual). The models are simplistic in theory, and the relative ease of data structures provides for a reasonable learning curve for the experienced user in the MatLab® environment. The user does not necessarily need be an expert on barrier morphology, although knowledge of processes in the coastal zone can help the user select appropriate datasets for future simulations, testing, and analysis. Finally, clear and complete documentation containing all input, output tabulations and graphical illustrations and plots, assumptions, boundary conditions, empirical values, and procedural steps from start to finish plus model software code will be provided to CPRA.

g. Technical support availability

Technical support for this model is not available under the current contract. Support, training, workshops, and manuals can be developed upon request with additional time and resources.

h. Software/hardware platform availability to all or most users

A functioning recent version of MatLab® is required (version 2010 was tested). MatLab® is available from Mathworks©; therefore, the model can be executed on any platform that MatLab® is available. The user may be restricted to Windows® platforms for viewing the output, since ERSI® ArcGIS is not available on non-Windows® platforms. The output, however, is a standard grid, and therefore should be accessible from other GIS software (such as GRASS). Additionally, the model output could also be exported to any geospatial software with the appropriate additions to the model source code.

i. Accessibility of the model

The model was developed at the University of New Orleans and Boston University, as part of this modeling effort. The source code can be distributed freely upon request.

j. Transparency of model and how it allows for easy verification of calculations and outputs
The code is modular (consisting of 'functions' called by a central program), and clearly noted throughout; thus, it is relatively simple to follow. The fundamental and governing equations are marked and relatively easy to follow, and descriptions of the equations and the input file formats are given in Sections 2 and 3 of this document.

The MatLab® will indicate errors in file formats or coding using the debug function within the software. In order to test that the model is working properly, a calibration and validation should be undertaken, comparing the output to a known (historic) shoreline change (see Section 2e for details on calibration terms).

5. Sources of model uncertainty

Uncertainty in the output of the BMM and the IMM potentially arises from several different areas, including: error or uncertainty in model inputs, numerical instability or coding errors, or errors related to the assumptions upon which the models are constructed.

a. Input data.

Inputs to the BMM include:

Shore normal profiles of bathymetry and topography: Input data for the baseline modern bathymetry was drawn from the BICM Study (Miner el al., 2009) and used in conjunction with Experimental Advanced Airborne LiDAR (EAARL) data, collected by the United State Geological Survey (USGS), to produce a combined DEM along the modern barrier shorelines. The USGS flights were conducted on September 2008 for the central coast and September 2010 for the Chandeleur Islands. Cross-shore profiles were extracted from an interpolated grid at an alongshore spacing of 100 m with a resolution of 2 m along-transect. The trajectory of the each profile was determined according to the angle of the shoreline for each 100 m section.

Accuracy of the BICM bathymetry at collection is reported as being 0.07 m (RMS error) horizontally (a function of DGPS measurements). Vertical uncertainty is of the order of 0.09 m (inherent fathometer uncertainty) and further uncertainty, introduced by the gridding process, was optimized by gridding at a resolution of 100 m (Miner et al, 2009). The EAARL data have a vertical accuracy of 0.14 m (RMS error) to bare earth measurements; the accuracy is reduced to 0.47 m (RMS error) in the presence of vegetation. Further uncertainty may be introduced by the re-interpolation of these data onto the profiles, but is likely of a similar order to the original gridding error. A conservative estimate of ±0.3 m vertical is placed on the resulting profile data.

Historical bathymetry data were obtained from List et al. (1994). This dataset was used for model calibration and for the extraction of historical shorelines. Historical bathymetry was converted into a common horizontal and vertical datum: UTM zone 15 meters, NAVD 88 meters as a component of the BICM project. Uncertainty in these data vary as they were compiled from a variety of sources including hydrographic charts and T-Sheets. List et al (1994) make a conservative estimate of ±0.5 m vertically.

Shoreline position: Shoreline positions were determined automatically from either shore normal bathymetry or from aerial photographs. When the bathymetry was used, the mean sea level (MSL) value was used to determine the shoreline. Several types of error or uncertainty may occur during this procedure, the first relates to the underlying bathymetric data used (as described above). An uncertainty of the order of ± 0.3 m in the bathymetry would also produce an error in the shoreline position; this error would vary based on the gradient of the shoreline, a lower gradient would produce a relatively larger horizontal error for the shoreline position. The average upper shoreface bed slope for the modeled shoreline (calculated from MSL to the 2 m isobath) is 0.012 and is associated with a horizontal translation of the shoreline of ± 25 m (this is a very conservative estimate, in reality the nearshore slope or beach slope is much steeper and will result in smaller errors). This however, only occurs once at the beginning of the simulation and it does not affect the simulation beyond this point. A known starting shoreline position (for a selected year) can be used instead and will eliminate this initial error altogether (the last verified shoreline was post hurricane Katrina, and since the starting point for simulations is 2010, initial shoreline position was estimated using bathymetry from BICM, which itself is from 2006 or 2007. In areas where LiDAR data were available, that dataset was used instead, and the error in the shoreline position for those areas is less than 5 m).

Further error may potentially be introduced during the extraction of a shoreline as a result of the selection of an unrealistic shoreline data point. As shoreline position was established on the basis of the first MSL position in the onshore direction along the profile, it was possible for large offshore bars or marsh islands in the backbarrier (where the barrier shoreline was breached) to contaminate the shoreline. To ensure this did not happen, controls were set in the automated extraction (limiting the onshore-offshore distance between proximate shoreline points). In addition, quality control assessments were carried out by eye through comparison to aerial photographs and shorelines were corrected where errors were found.

Wave climate data: Wave data used in the model were obtained from the WIS database. Ten WIS locations along the modeled region were used and are shown in Figure 1. These data provide information on the offshore wave height, period and direction. To determine the frequency of occurrence of each wave height, and it associated direction, the data were separated into 8 magnitude bins and 16 directional bins (increments of 22.5 degrees). Selecting more bins (e.g., every 10 degrees) may improve estimates of the transport rates. Additionally, performing the analysis on a seasonal, rather than a yearly time frame, may improve results further, and possibly capture intra-annual variability. This however, was intentionally omitted in this effort due to emphasis on longer time scales by the state. Offshore wave climate along the central coast (from Raccoon Island to Sandy Point segment) was similar post analysis of the data as described above, and as a result one WIS station central to the area was used. A different one was used for the Breton-Chandeleur chain. Averaging direction in increments of 22.5 degrees, and using that to determine frequency, introduces small errors in direction and transport rates. This component can be improved by using more offshore wave locations. For future work, emphasis on expanding field observations could improve knowledge of offshore wave climate.

Inlet Morphology Model

The input to the Inlet Morphology Model is the maximum annual tidal prism, obtained from the Eco-Hydrology Model. Errors associated with this input are reported elsewhere. However, the post processing of the data into the correct format to input to the IMM were automated and to ensure no error was introduced, the calculation was tested for the correct response before automation proceeded. Input equations and coding were assessed and verified by a team member other than the programmer

b. Numerical process

Numerical methods have the potential for introducing error through coding mistakes and numerical instabilities. The longshore transport component of the shoreline model was prone to instabilities relating to shoreline angle fluctuations, and in some cases it was necessary to apply a smoothing function to relax this instability. However, uncertainty related to the numerical process was reduced through QA/QC and through the calibration and validation process. Each calculation within the model was tested individually for the correct response before automation proceeded. The equations and coding were assessed and verified by a team member other than the programmer.

c. Model assumptions:

Several assumptions inherent to the individual barrier and inlet morphology models may introduce uncertainty into the final model output.
Barrier Morphology Model

The use of offshore waves rather than describing the refraction and energy changes as the waves shoaled (as described in Sections 1 b and f) could result in skewed outputs. Moreover, the static translation of a section of the shoreline on or offshore rather than process driven morphological change (as described in Sections 1 f and 2 d), could also introduce error into the final outputs. Finally, overwash and accretion were only accounted for indirectly (i.e. not through a process based calculation).

Inlet Morphology Model

One of the major uncertainties in the inlet model is associated with the fundamental equations that were used. The logarithmic nature of the equations implies that the spread of the data, and thus the spacing of the error bars, are large (O'Brien, 1969; Jarrett, 1976).

In addition to uncertainty within the calculation, there is the assumption that the inlets can be considered as a cumulative area, rather than individually. On the basis of studies by Howes (2009), this represents a reasonable assumption.

6. Suggested model improvements

There are several improvements that can be made to the model, and given no time-constraints in execution, additional processes, such as those listed below, can be represented to better simulate realistic response. If and where available, physics-based or process-based algorithms can replace the existing geometric algorithms. However, some of the most critical updates and improvements include:

i. Use of a full local wave model providing more accurate wave heights and directions for the longshore transport calculations, or use of transformation equations in addition to breaking and shoaling, can also improve the plan form transport calculations. This can be further improved by more accurate sediment budgets at tidal inlets.
ii. In the cross-shore dimension, the model only addresses changes within the depth of closure geometrically (i.e., it does not modify the profile as a function of a continuously transformed wave as it moves onshore). This aspect can be improved by simulating the cross-shore response separately to better account for overwash processes and removal of material offshore.
iii. Better coupling of the IMM and BMM models should be considered in future iterations. These models are now coupled every 25 years. The sediment transport near inlets is not accurately captured at the moment (i.e. inlet bypassing, or terminal groin behavior is empirical and constant in time). Better and more frequent integration of the two models is recommended, once more information is known on these processes.

7. Quality review

Specific quality review (QR) procedures for the Coastal Morphology Model to support the 2012 Coastal Master Plan included the following:

a. Assessments and review of input data
b. Testing, sensitivity and calibration of model components against observations
c. Assessments of output for instabilities and propagated errors.

Although external reviewers were not enlisted for the QR process, as separate tasks were assigned to team members from each institution, cross-checks and quality control assessments were undertaken by individuals external to each sub-group. Specifically, input Bathymetry and LIDAR data were combined to provide profiles every 100 m alongshore and were visually inspected for erratic elevation data and corrected to represent a realistic geomorphology of the barrier islands. Input shoreline data automatically generated from elevation data or through image analyses were each inspected for errors or deviations that might instigate instabilities and were corrected by hand. Wave climate (wave heights and wave periods and directions) obtained from the WIS database were also inspected for anomalies both at download and after processing to the correct input format for the model. This step is critical since probability of occurrence was separated into 8 magnitudes (for wave height) and 16 directions (increments of 22.5 degrees).

Throughout the development of both the BMM and the IMM models, each calculation was tested individually for the correct response before automation proceeded. Input equations and coding was assessed and verified by a team member other than the programmer. Likewise, output data were assessed for instabilities and unrealistic behavior as part of the calibration and validation process. For instance, this step included addressing shoreline instability at the terminal part of a barrier island, where the shoreline angle abruptly changes over time.

The model output DEMs were visually inspected for the 25 and 50 output years. Irregularities in the shoreline behavior over time were identified and, if significant enough (compared to adjacent shoreline position), the model was re-run after the cause had been identified and corrected (e.g. some inflections of the shoreline became unstable over time due to a high incident wave angle which in turn included a high transport rate, but a smoothing of model input at a reasonable scale (alongshore) removed these perturbations). Small scale and intermittent discontinuities and irregularities in the DEM surface were recognized as a limitation of the model's ability to generate a 3D surface using 1D calculations and with respect to the scope of what the intended use of model output.

8. Uncertainty analysis

The CMM simulates barrier shoreline and inlet evolution in response to physical forcing such as offshore wave climate, and relative sea level rise. The two components of the CMM: IMM and BMM were addressed separately for uncertainty.

Uncertain Parameters/Relationships Identified for the Uncertainty Analysis

The following parameters were identified and selected for the uncertainty analysis. Tables 1 and 2 provide the different uncertainty settings selected for these parameters:

Parameters in the Barrier Morphology Model (BMM):

Parameter beta (β) that specifies the sand/mud fraction
Closure depth (d_c)
Mean grain diameter (D_{50})

Parameters in the Inlet Morphology Model (IMM):

Exponent for the gulf coast inlets (a)
Gulf coast coefficient (k)

where parameters (k) and (a) are used to compute the likely increase in the inlet cross-sectional area based on the Gulf Coast version of the Jarrett-O'Brien relationship (Jarrett, 1976, O'Brien, 1969) given by $A = kP^a$ where P is the maximum annual tidal prism.

The reader is referred to Appendix D-27 - Model Uncertainty Analysis where more detail on the uncertainty simulations can be found.

9. Model Results

Model results from two of the scenarios simulated are shown herein. The results are intended to demonstrate the output as a function of change in forcing (ie seal-level-rise) over time and space. For this section, results from the moderate scenario S12 and the less optimistic scenario S13 are shown. Furthermore, the group number associated with these results is G01 for the future without action (ie no projects, fowa), as well as group 3 (G03) which includes barrier island projects from Barataria Pass to Sandy Point (per parent report). For simulations in the central coast, from the Caminada Headland, to Sandy point, it is apparent that erosion rates are slightly higher for S12 and S13 (Figure 14 lower panel), resulting in larger landward migration of shorelines (Figure 14 middle panel).

Project effects are visible when comparing the resulting shorelines between G01 and G03 (Figure 15). It is apparent that projects in the vicinity of Grand Isle through the eastern part of East Grande

Terre, have reduced the erosion rate over the 50 year period (Figure 15 lower panel) and resulting in less landward migration of the shoreline.

Other ways to demonstrate model results is to provide a summary of sediment (volume) lost during the simulation (see example data in Table 3) or by comparison of subareal area of any barrier coastline. For example, sand in shallow deposits is re-worked easier and can remain in the littoral zone thereby extending the period which the barrier island can benefit. Rapid erosion on the other hand can cause some sand deposits to remain outside this zone, and as a result not benefit the barrier. Barrier restoration and nourishment projects will result in a sand infusion to the barrier thereby increasing the longevity of the system. Table 3 summarizes benefits resulting from restoration project between Barataria and Sandy Point (G03) between the two scenarios (moderate -S12 and less optimistic S13). Notice that despite the scenario (S12 or S13) the resulting sediment volume gained (at 25 and 50 years) is higher compared to that with no projects (G01). Despite the entire coast losing sediment, this rate is slowed by projects. The benefit to the barriers however, is perhaps more evident when we inspect the subareal area of the barrier (the area above sea level at that time). We note that sea level is dynamic (ie is increasing) and the model only account (in Table 4 that is) for area that is above mean sea level at the specific simulation year. In it obvious that restoration on barrier shorelines is boosted by projects, when one compares the area of barrier in the out years as a function of scenarios (S12 and S13). For instance, for the moderate scenario, barrier area is decreasing uniformly as a function of environmental conditions at ~ 15% for S12 and ~20% for S13. This makes sense since S13 is the less optimistic scenario. When projects are implemented, the 25-year rate of descrease for S12 is reduced to ~10%, and further reduced to ~8% by the end of the 50-year simulation, while for the less optimistic scenario with projects, the rate of area decrease is slowed to ~12%, but remains constant through the 50 years.

10. References

Dean, R.G. (1991) Equilibrium Beach Profile: Characteristics and Applications, J. of Coastal Research, Vol. 7, No. 1, pp 53-84.

Dean, R.G., Dalrymple, R.A. (2002) Coastal Processes with Engineering Applications, Cambridge University Press, 475 pp.

Ellis, J., and Stone, G.W., (2006) Numerical simulation of net longshore sediment transport and granulometry of surficial sediments along Chandeleur Island, Louisiana, USA. *Marine Geology,* 232, 115-129.

Fearnley, S., Miner, M., Kulp, M., Bohling, C., Martinez, L., and Penland, S., (2009), Chapter A. Hurricane impact and recovery shoreline change analysis and historical island configuration—1700s to 2005, *in* Lavoie, D., ed., Sand resources, regional geology, and coastal processes of the Chandeleur Islands coastal system—an evaluation of the Breton National Wildlife Refuge: U.S. Geological Survey Scientific Investigations Report 2009–5252, p. 7–26.

FitzGerald, D.M., Fenster, M.S., Argow, B.A., and Buynevich, I.V., (2008) Coastal Impacts Due to Sea-Level Rise. *Annual Review of Earth and Planetary Sciences*, pp.604-47.

Flocks JG, Twichell DC, Sanford J, Pendleton E, Baldwin W (2009) Sediment sampling analysis to define quality of sand resources. In: Lavoie D (ed) Sand resources, regional geology, and coastal processes of the Chandeleur Island coastal system—An evaluation of the resilience of the Breton National Wildlife Refuge. U.S. Geological Survey Scientific Investigation Report 2009 – 5252, pp. 99 – 124.

Georgiou, I. Y., Fitzgerald, D.M., and Stone, G.W., (2005). The Impact of Physical Processes along the

Louisiana Coast. *Journal of Coastal Research*, 44, 72-89.
Hanson, H., Krauss, N.C. (1989) GENESIS: Generalized model for simulating shoreline change, Report 1, Technical Reference, Army Corps of Engineers, Washington DC, 11 pp.
Howes (2009) The impact of wetland loss on inlet morphology and tidal range within Barataria Bay, Louisiana, MS Thesis, Boston University, 100pp.
Hubertz, J.M., Brooks, R.M. (1992) Verification of the Gulf of Mexico hindcast wave information, Wave Information Studies (WIS) Report 28, Department of the Army, US Army Corps of Engineers, Washington DC, 35 pp.
Hunt, J. N. (1979) Direct Solution of Wave Dispersion Equation. ASCE Jour. Waterw., Port, Coastal and Ocean Engr., Vol 105, pp 457-459.
Jarrett, J.T.(1976) Tidal prism-inlet area relationships, U.S. Army Corps of Engineers, GITI Report 3, 32 pp.
Komar, P.D. (2002) Beach Processes and Sedimentation (2nd edition), Prentice Hall, Prentice hall, New Jersey 07458, 544 pp.
List, J.H.; Jaffe, B.E.; Sallenger, A.H., Jr.; Williamss, .J.; Mcbride, R.A., And Penland, S., (1994) Louisiana Barrier Island Erosion Study: atlas of sea-floor changes from 1878 to 1989. US. Geological Survey Misc. Invest. Series I-2150-B, 82p.List et al. (1994). Louisiana Barrier Island Erosion Study: Atlas of Seafloor Changes from 1878 to 1989
Miner M.D., Kulp M.A., Flocks J., Twichell D., Penland S., Weathers D., Martinez L., Motti J., DeWitt N., Reynolds B.J., Baldwin W., Danforth B., Worley C., Bergeron E., Ferina N., McCarty P., Brown M., Torres J., (2009) Louisiana Barrier Island Comprehensive Monitoring program (BICM), vol 3. Bathymetry and historical seafloor change 1869–2007. Part 1. South-central Louisiana and northern Chandeleur Islands, bathymetry methods and uncertainty analysis. Univ. New Orleans Pontchartrain Inst. Environ Sci. Tech Rep. http://dnr.louisiana.gov/crm/coastres/project.asp?id=BICM
O'Brien, M.P., 1969. Equilibrium flow areas of inlets on sandy coasts. Journal of Waterway, Port, Coastal, and Ocean Engineering, 95, 43–55.
Rosati, J.D., and Stone, G.W. (2009) Geomorphologic Evolution of Barrier Islands along the Northern U.S. Gulf of Mexico and Implications for Engineering Design in Barrier Restoration. *Journal of Coastal Research* 25(1), 8-22.
Stolper, D., List, J.H., and Thieler, E.R. (2005) Simulating the evolution of coastal morphology and stratigraphy with a new morphological-behavior model (GEOMBEST): Marine Geology, v. 218, p. 17-36.
U.S. Army Corps of Engineers (2002) Coastal Engineering Manual. Engineer Manual 1110-2-1100, U.S. Army Corps of Engineers, Washington, D.C. (in 6 volumes).
WL|Delft Hydraulics (1994) UNIBEST, A software suite for the simulation of sediment transport processes and related morphodynamics of beach profiles and coastline evolution, Programme manual. WL|Delft Hydraulics, Delft, The Netherlands, pp. 39.

Attachment A: Figures and Tables

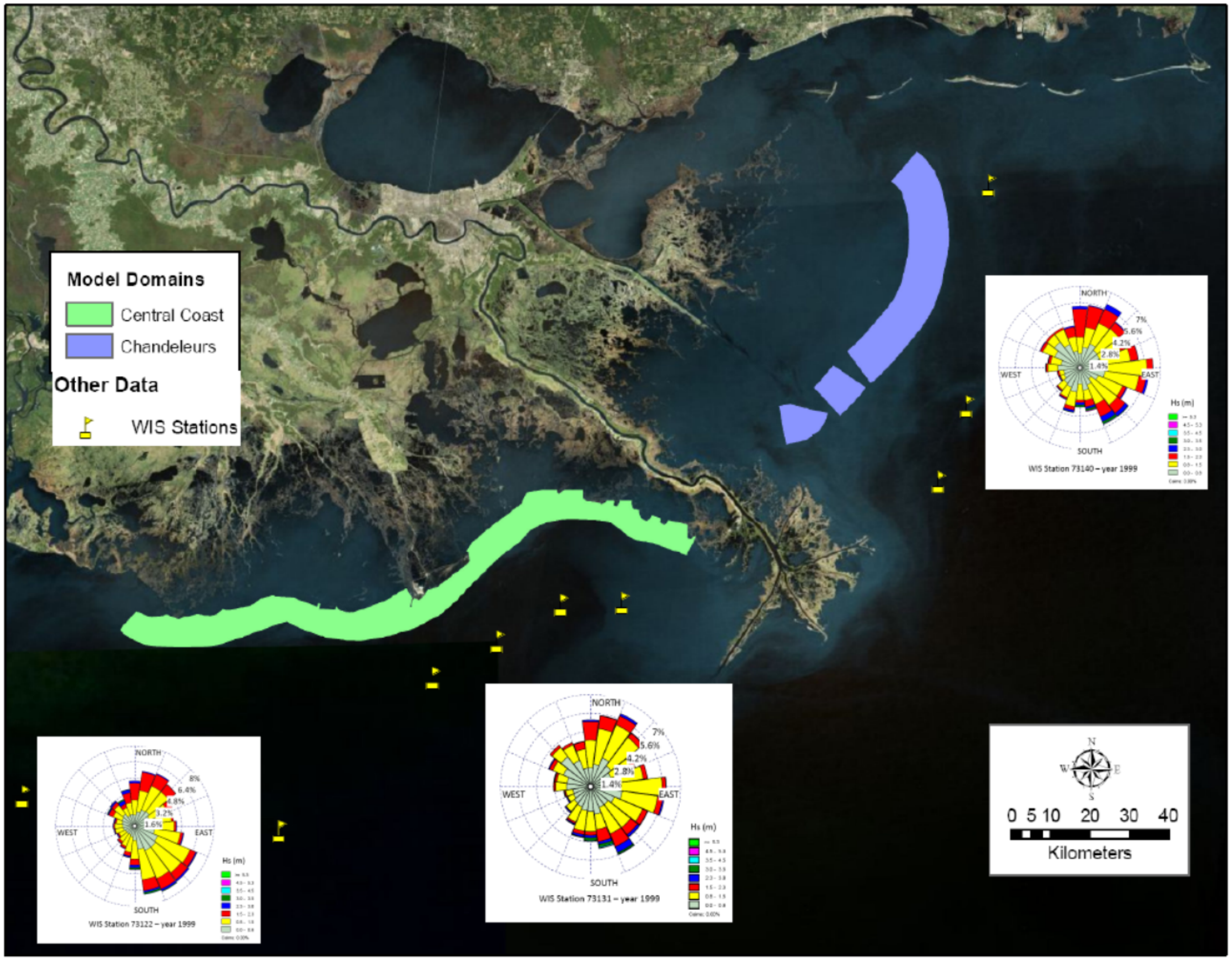

Figure 1 Map of the study area, showing the regions where the models were applied. Also shown (yellow flags) are the locations where (WIS) waves are available. Inserts show examples of wave climate resulting from the frequency analysis of hourly wave data, used to drive the longshore transport equation.

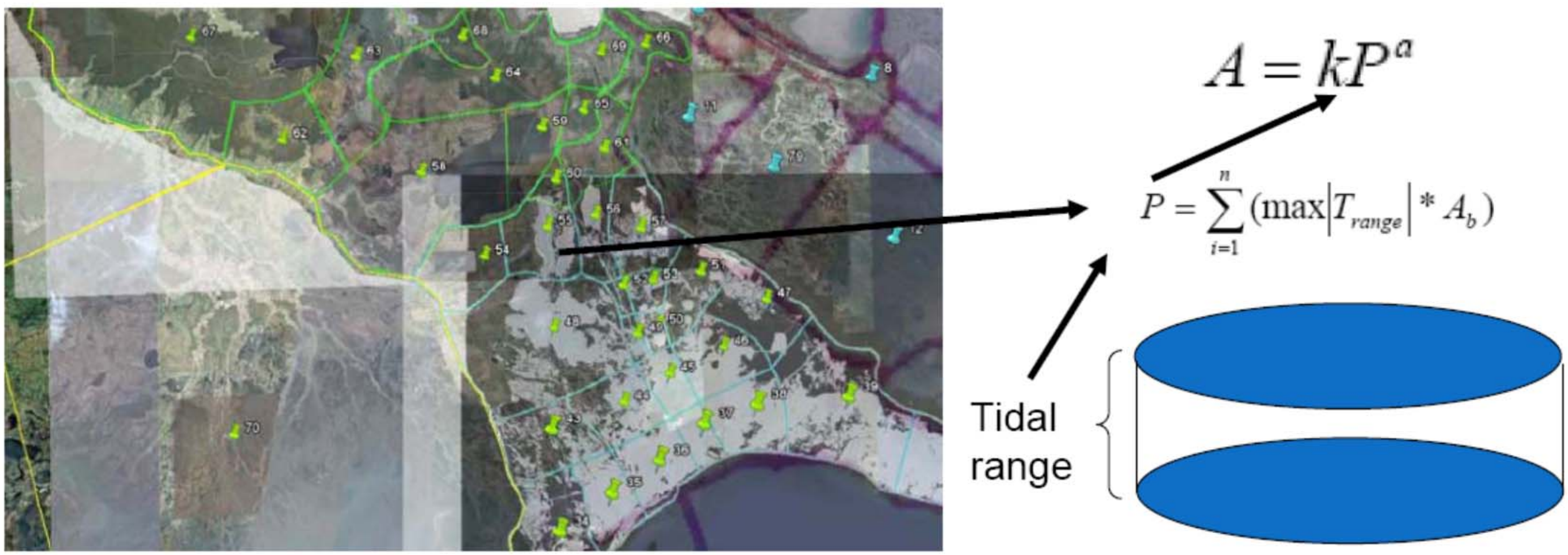

Figure 2 Schematic showing how the Eco-Hydrology grid and corresponding boxes are used to determine the maximum annual tidal prism, and how the corresponding inlet cross-sectional area is computed.

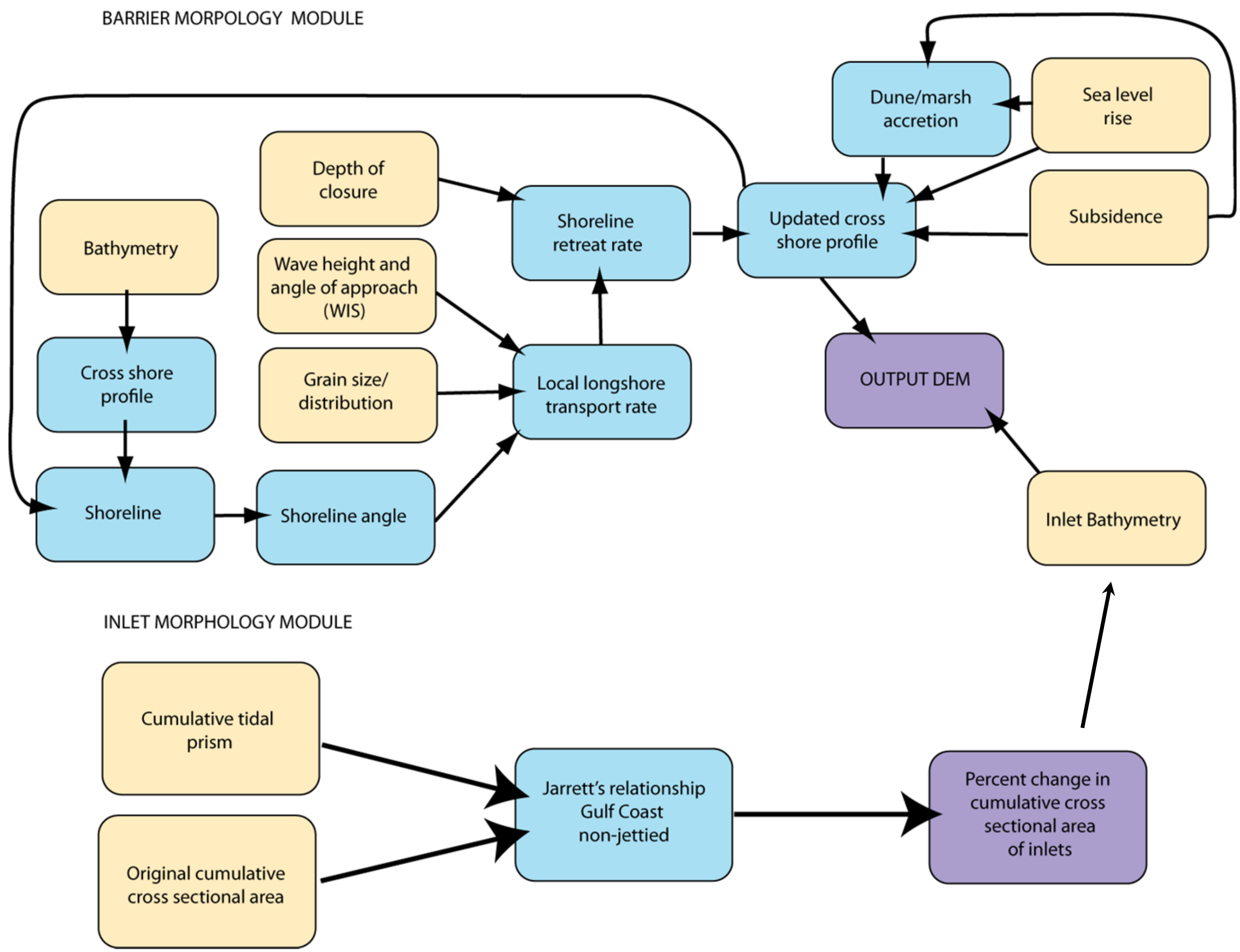

Figure 3 Model flow chart showing input, calculation and output for the BMM and IMM modules and their interaction. Input data are shown in yellow, model components and calculations are shown in blue, and final model ouput are shown in purple.

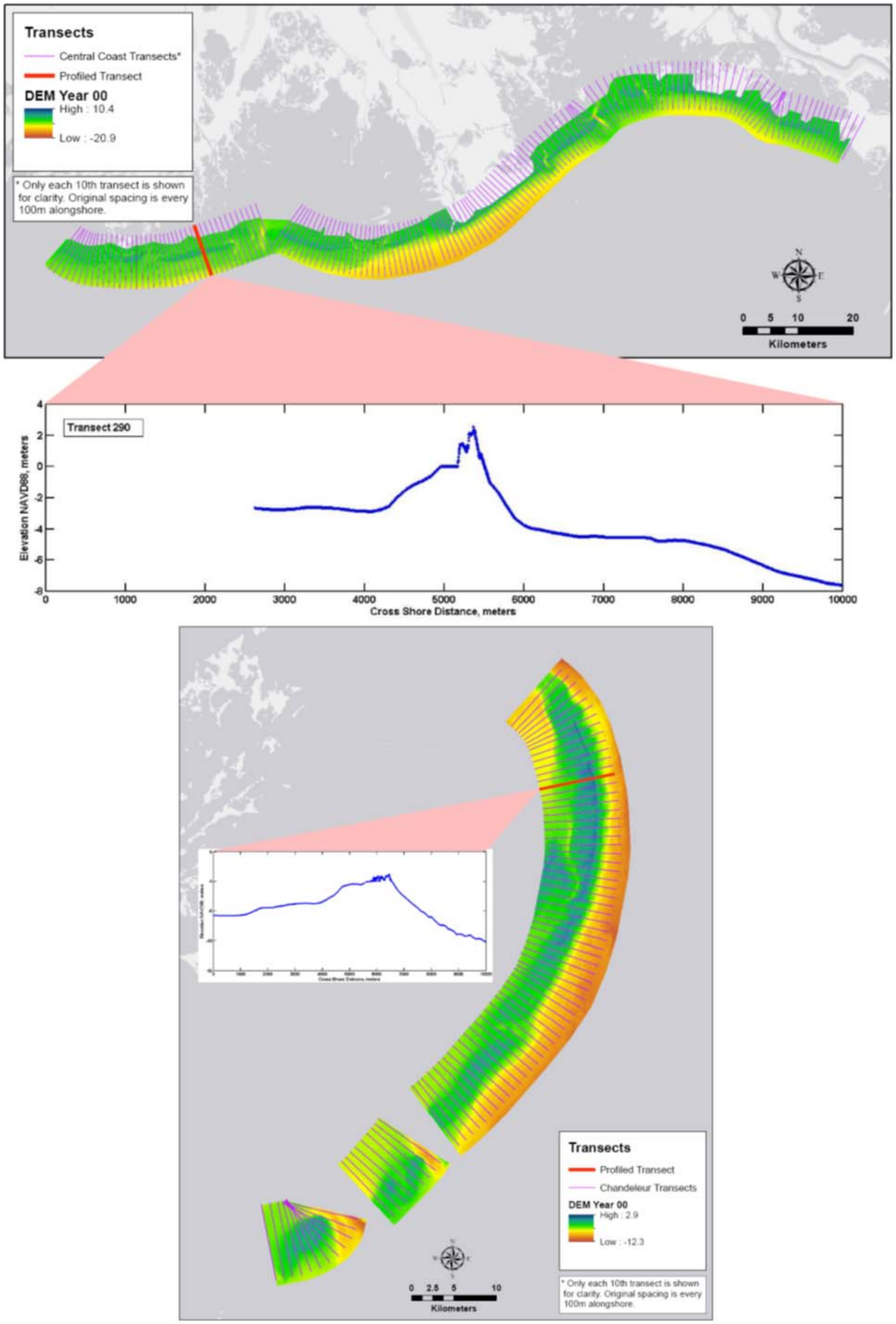

Figure 4 Cross-shore transects extracted from the topo-bathymetric composite DEM (A – for central coast, and B for the Chandeleur Chain). For clarity, every 10th transect is shown. The profile for the highlighted transect (shown in red) is shown in the lower panel for each modeled region.

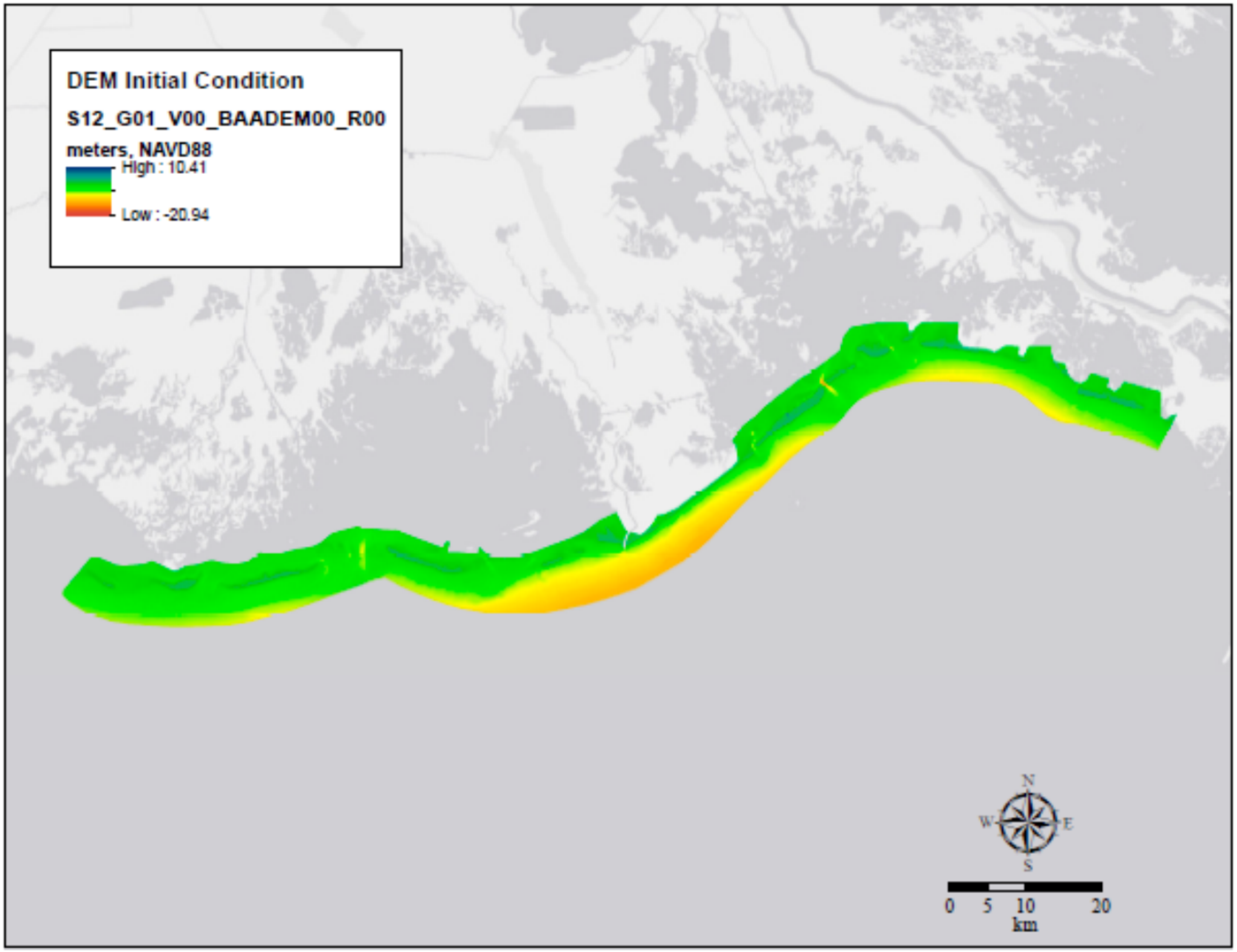

Figure 5 Model initial condition (initial bathymetry).

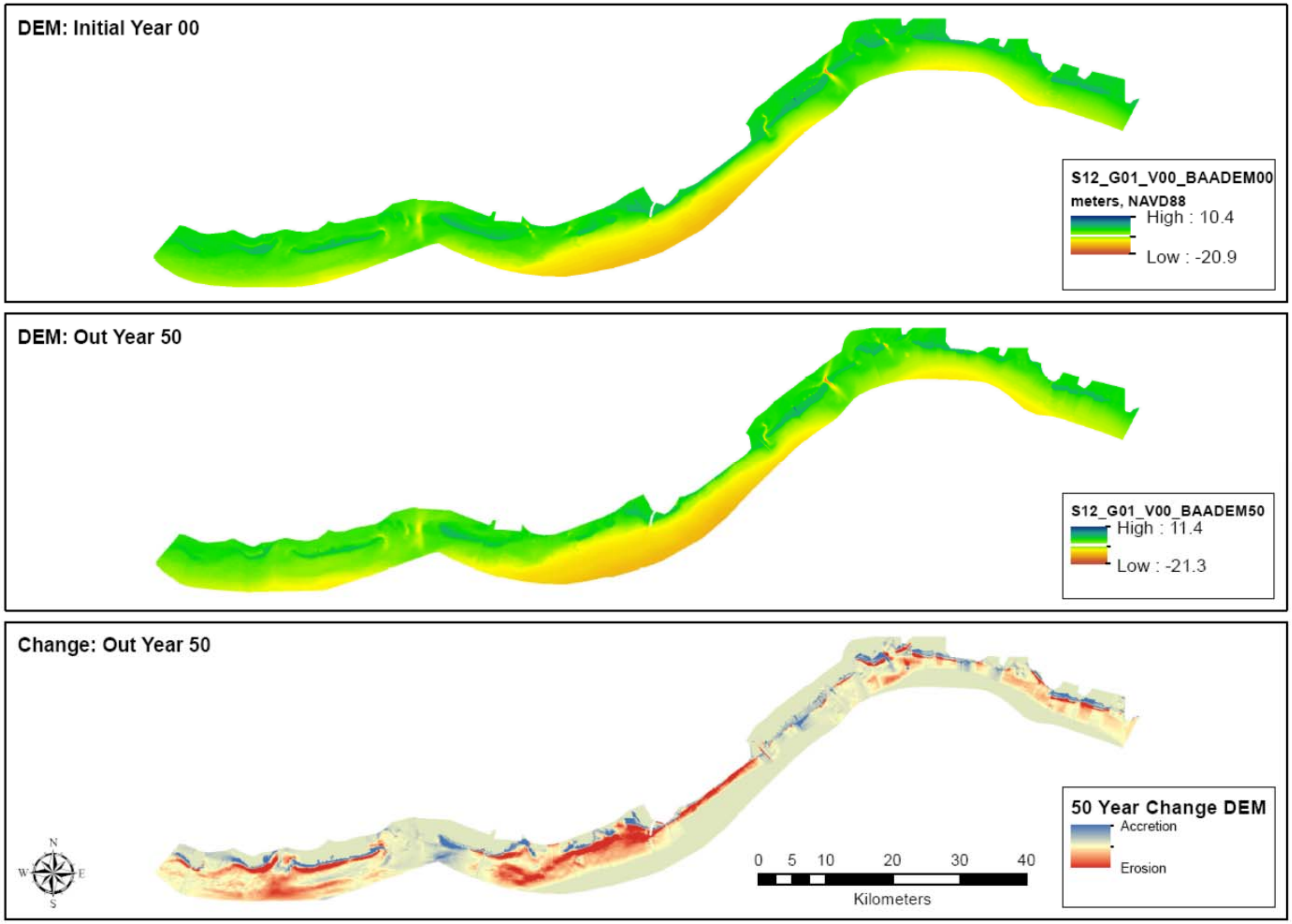

Figure 6 Model initial condition (initial bathymetry - upper panel), and simulated model results after 50 years of simulation for scenario 12 (i.e., the moderate future scenario) along the central coast (middle panel). The resulting accretion or erosion is shown in the lower panel.

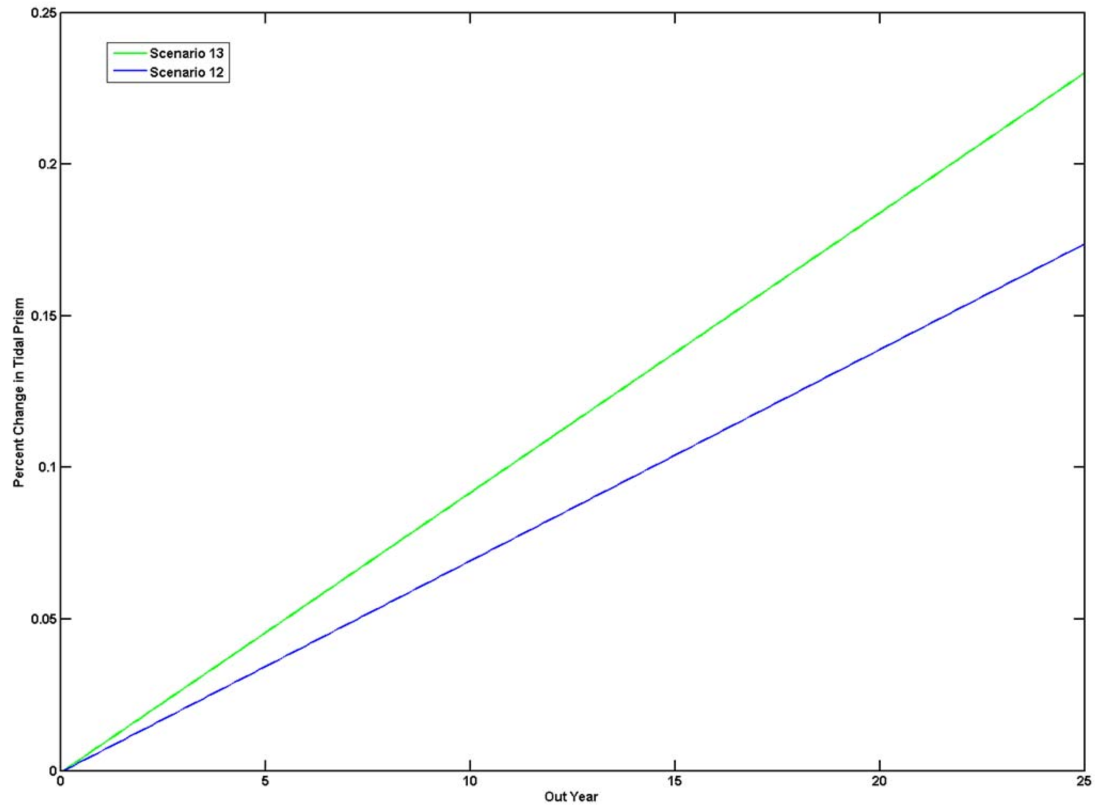

Figure 7 Percent increase in tidal prism in the Terrebonne Basin for two scenarios simulated over a 25 year simulation period. S12 represents a moderate set of future conditions, and S13 represents a less optimistic set of future conditions.

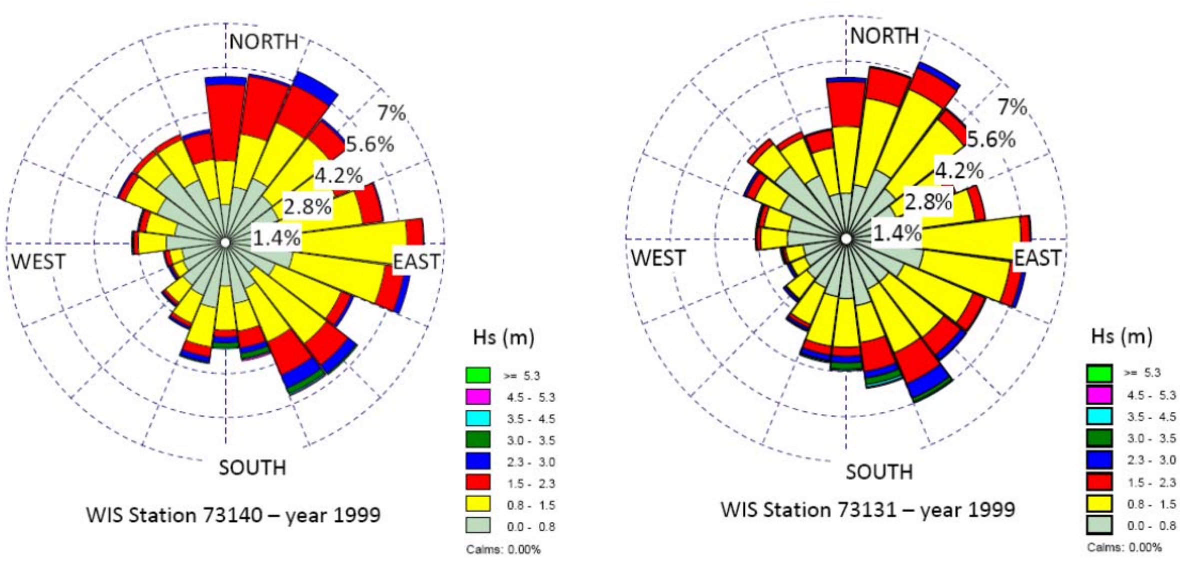

Figure 8 Frequency distribution of processed WIS station wave data used to drive the longshore transport calculations. For this example, wave data are grouped into 24 directional bins rather than 16.

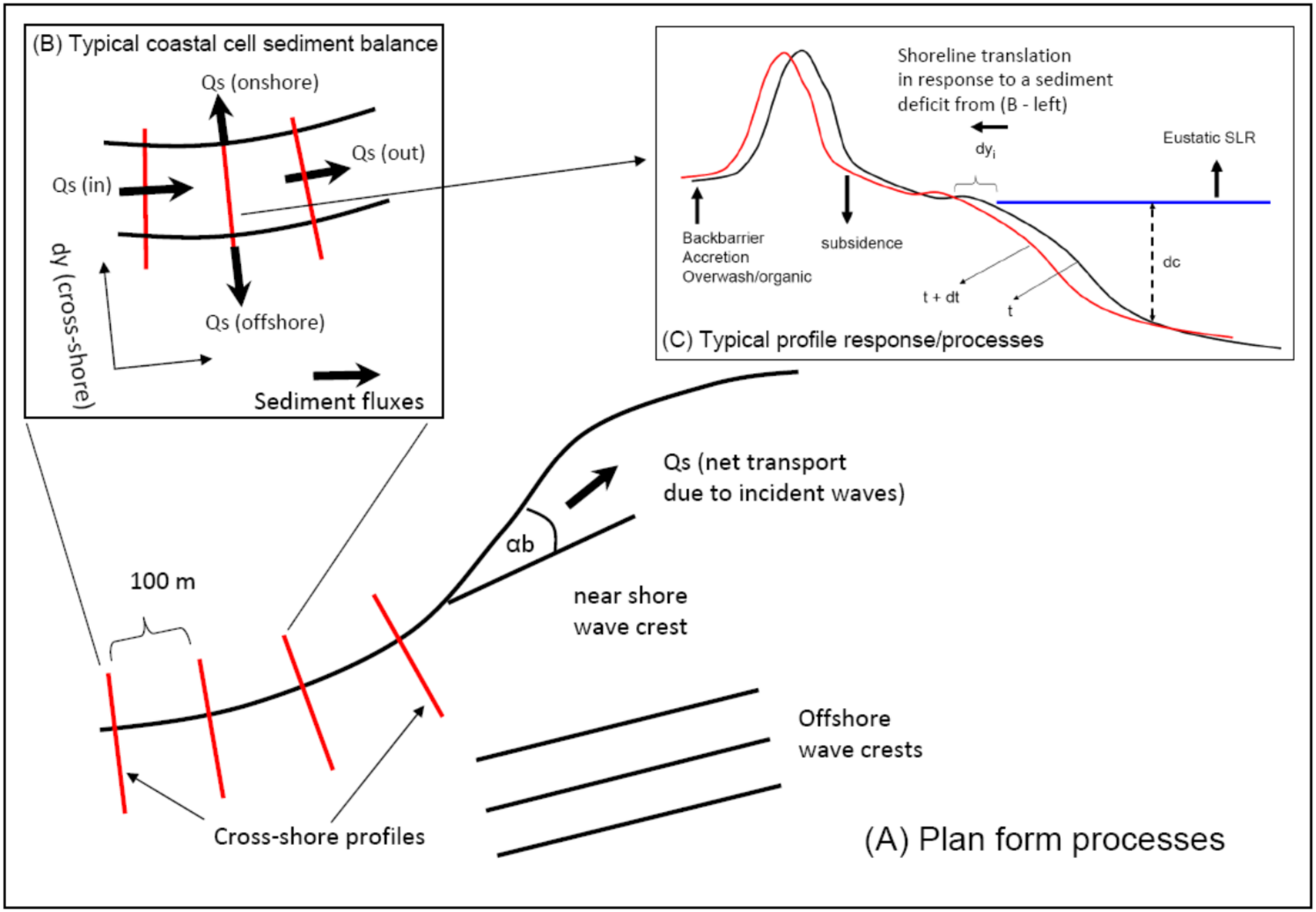

Figure 9 Model schematic showing the plan form process of approaching waves that are transformed to breaking (A), (B) the resulting mass balance of sediment transport, and (C) the corresponding shoreline response (t represents preset time, and t+dt the next time step).

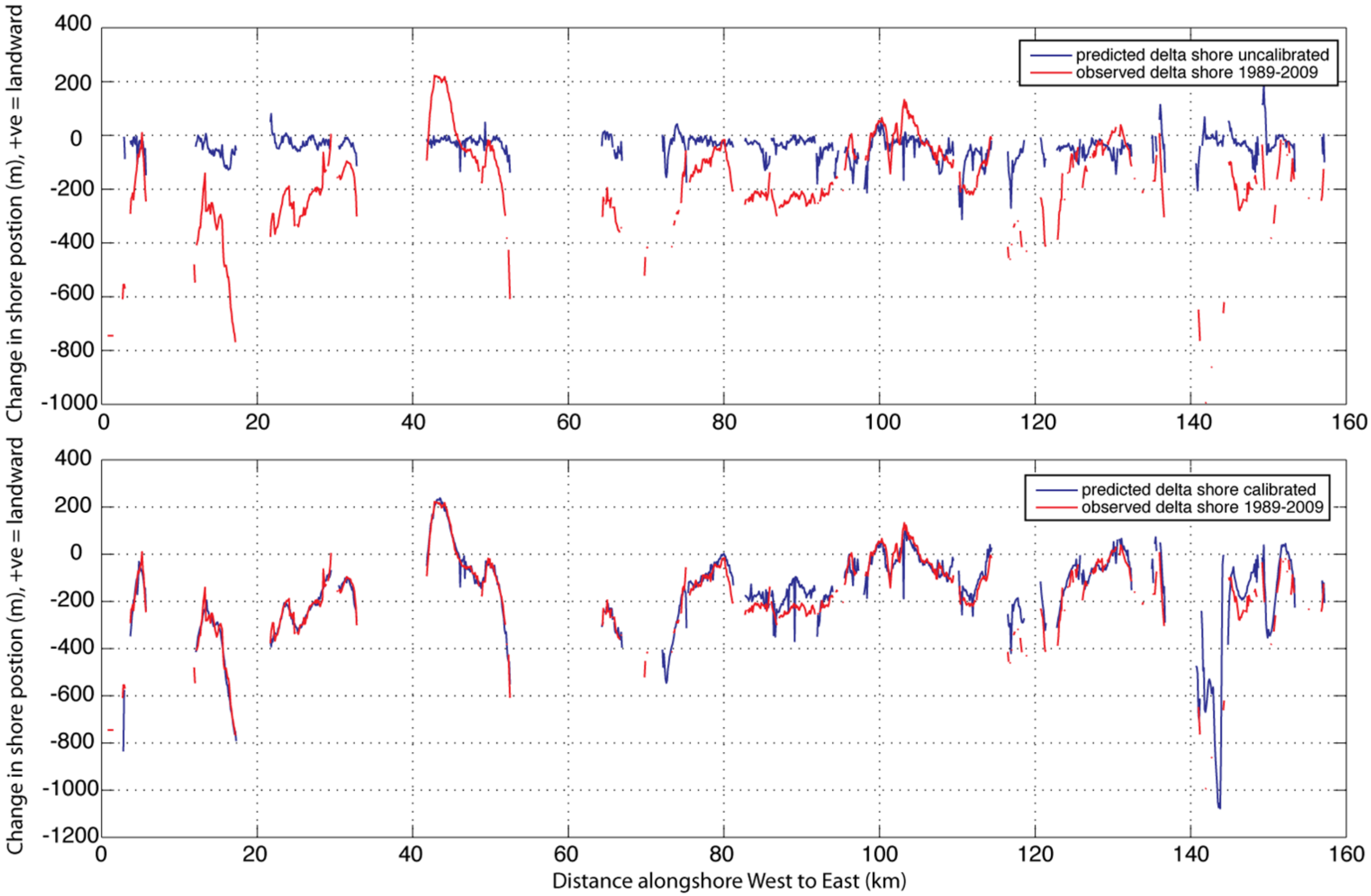

Figure 10 Model skill assessment during calibration without adjusting source terms (upper panel), and after adjusting source terms (lower panel); The lower panel performance was the one retained for use during the master plan simulations, and no further adjustment of these terms was performed post calibration.

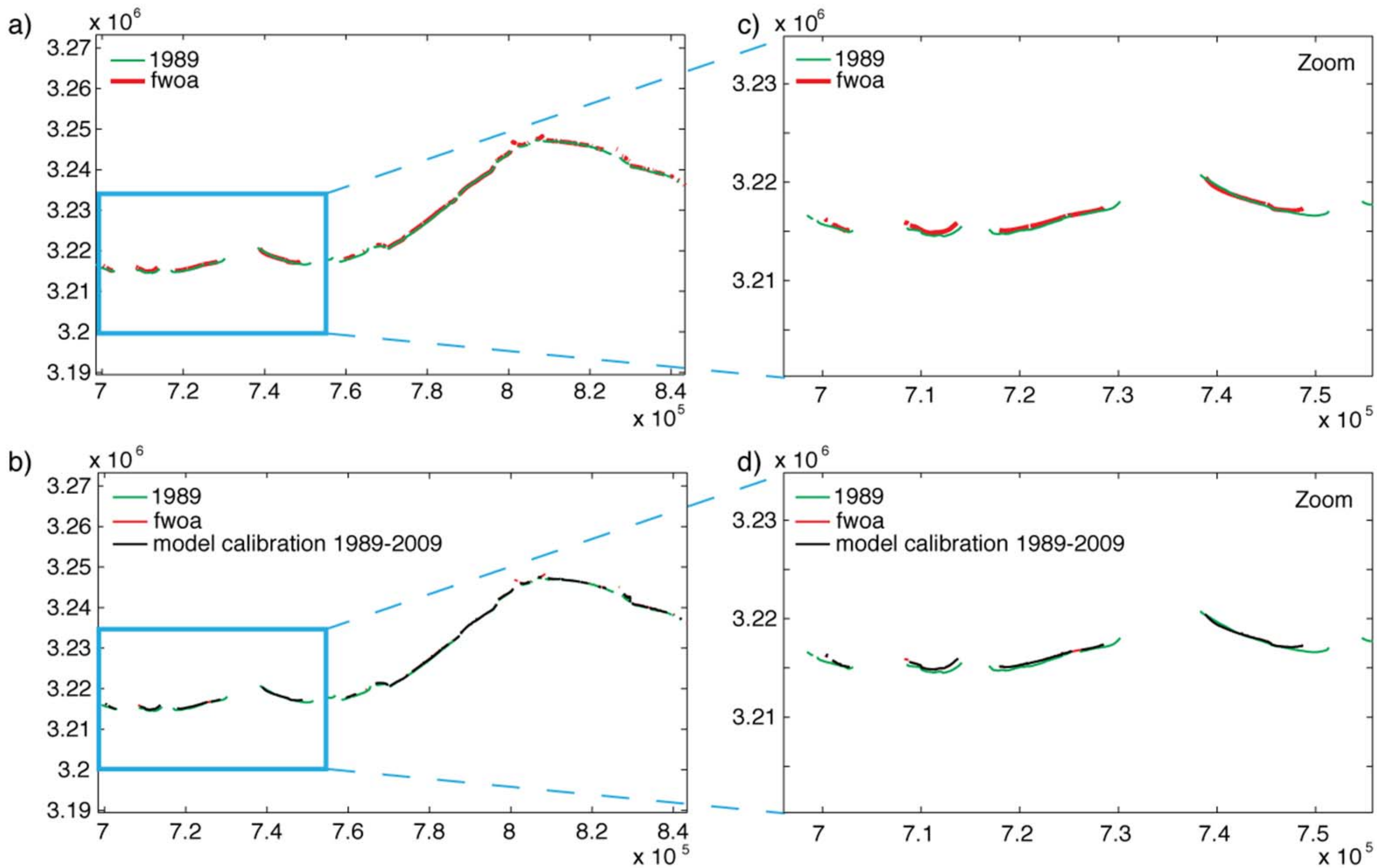

Figure 11 Model Calibration for the central coast. In (a) the future without action initial shoreline is shown with a zoom-in section in (c); In panel (b), the model prediction is clearly noted in solid black line, with a zoom-in of this section in panel (d).

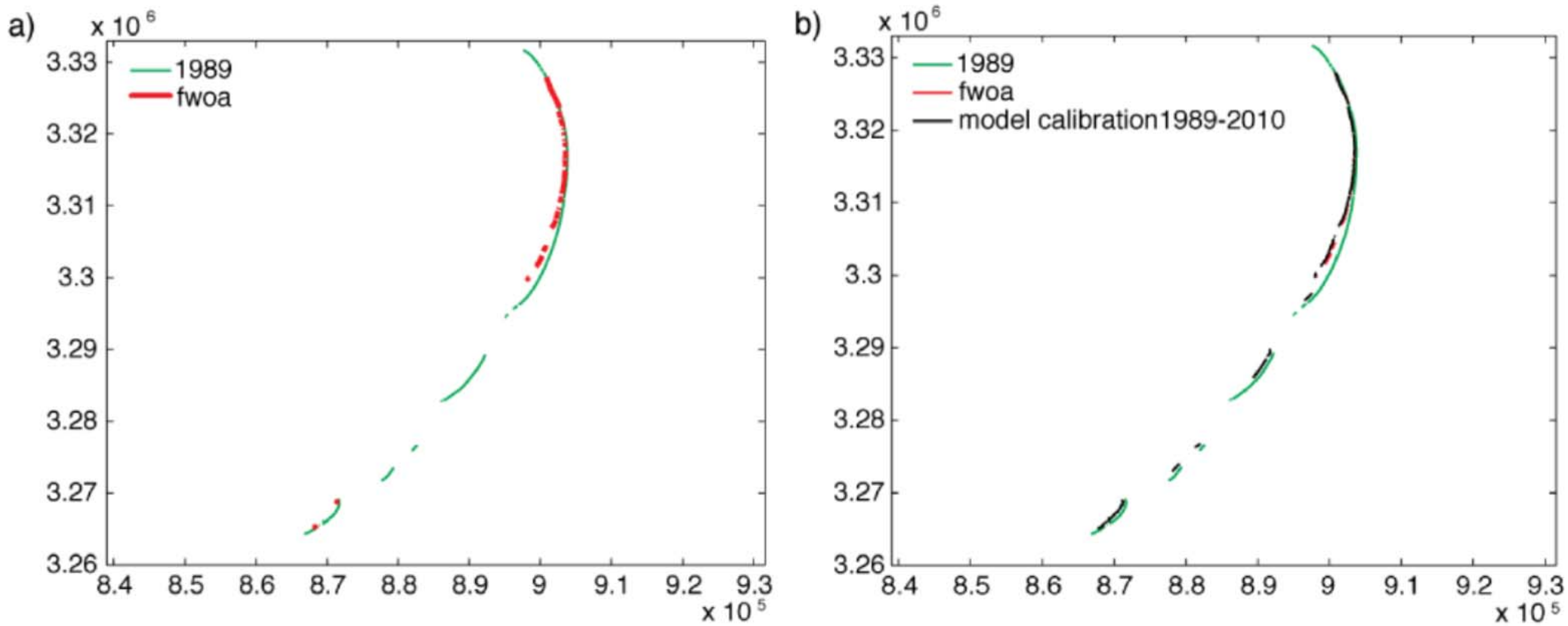

Figure 12 Model skill assessment during calibration of the model along the Chandeleur Island chain.

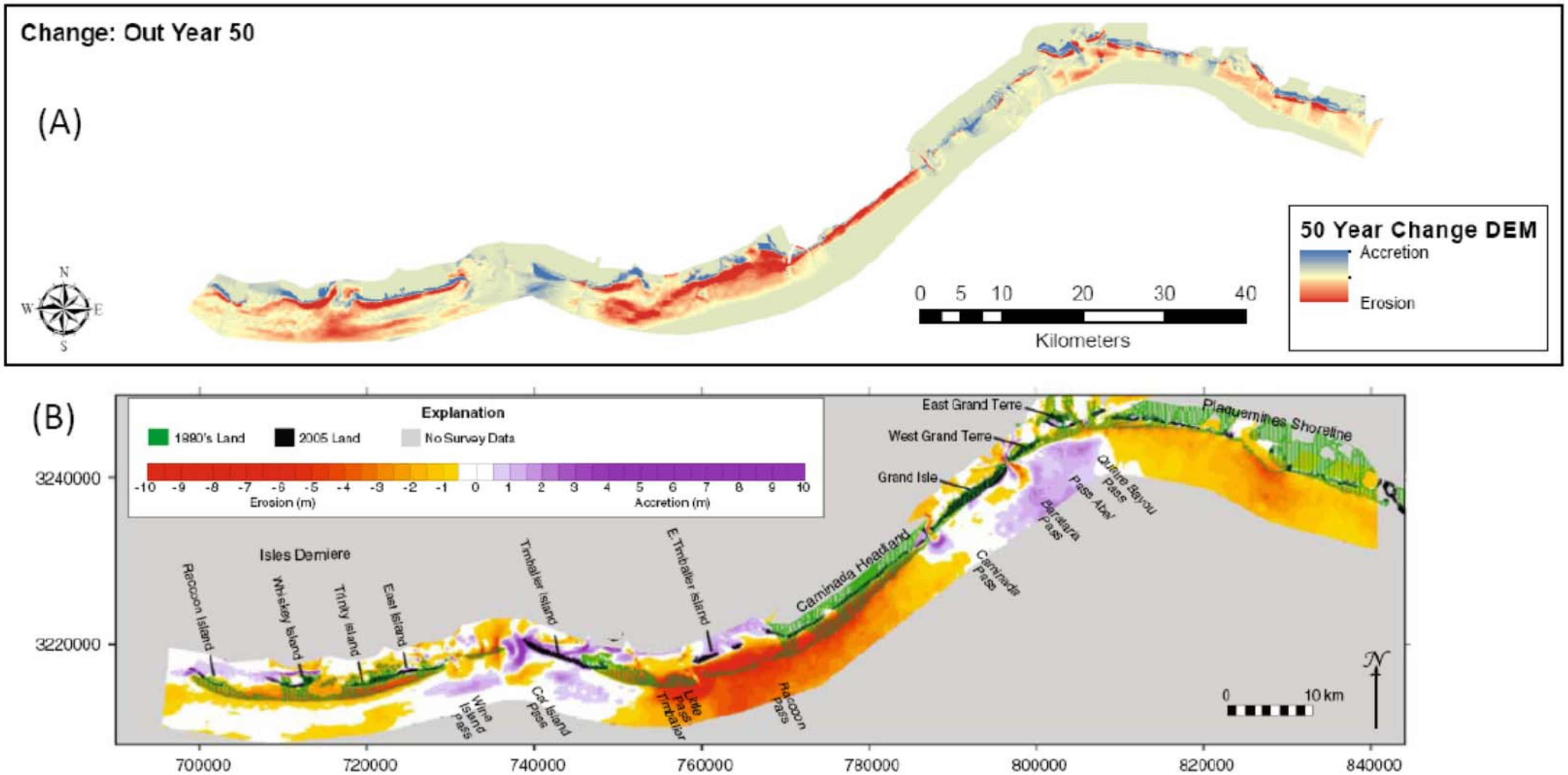

Figure 13 Example model output (A) subtracted from the initial condition showing a migration or erosion rate which is in agreement with historical erosion rates reported in Miner et al. (2009); In (B) notice the large-scale erosion in similar areas as those predicted by the model (B adopted from Miner et al., 2009).

Table 1: Uncertainty settings for the parameters of the Barrier Morphology Model (BMM)

Run # (RXX)	R01	R02	R00	R03	R04
parameter	Minimum impact	Intermediate minimum impact	Most likely value	Intermediate maximum impact	Maximum impact
D50	0.2	0.15	0.1	0.08	0.0625
beta	0.01	0.0225	0.05	0.1	0.17
dc_Caminada (m)	-15	-12.5	-10	-8.5	-7.5
dc_R2S (m)	-10	-8	-6	-5	-4
dc_Chan (m)	-15	-11	-8	-6.5	-5

Table 2: Uncertainty settings for the parameters of the Inlet Morphology Model (IMM)

Run # (RXX)	R01	R02	R00	R03	R04
parameter	Minimum impact	Intermediate minimum impact	Most likely value	Intermediate maximum impact	Maximum impact
alpha ('a')	0.73	0.83	0.86	0.93	0.99
kappa ('k')	0.000297	0.000324	0.000351	0.000384	0.000416

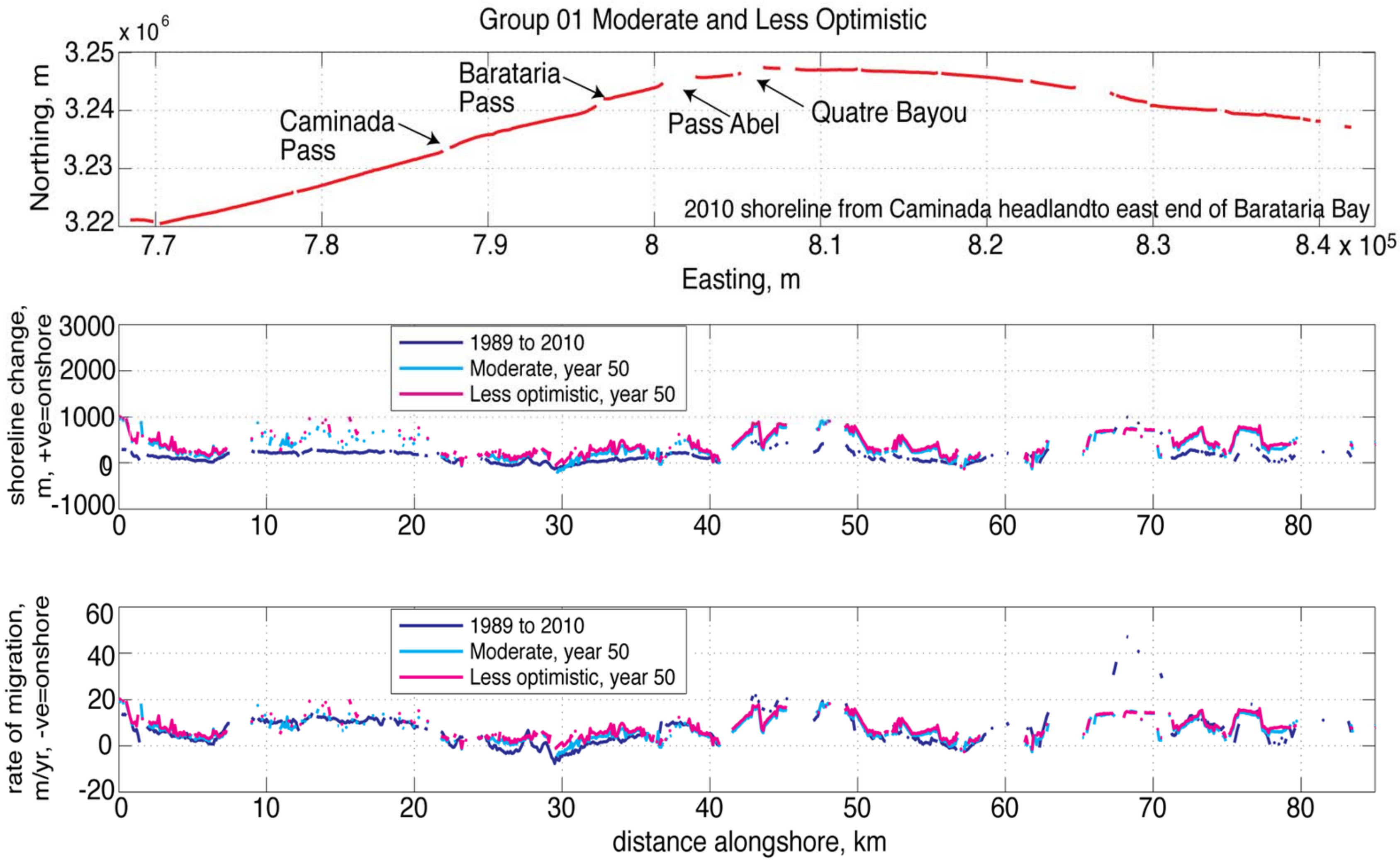

Figure 14. Shoreline response from the no action or no projects simulation, showing differences between the most recent change since 1989 (from model calibration) compared with the moderate and the less optimistic scenario.

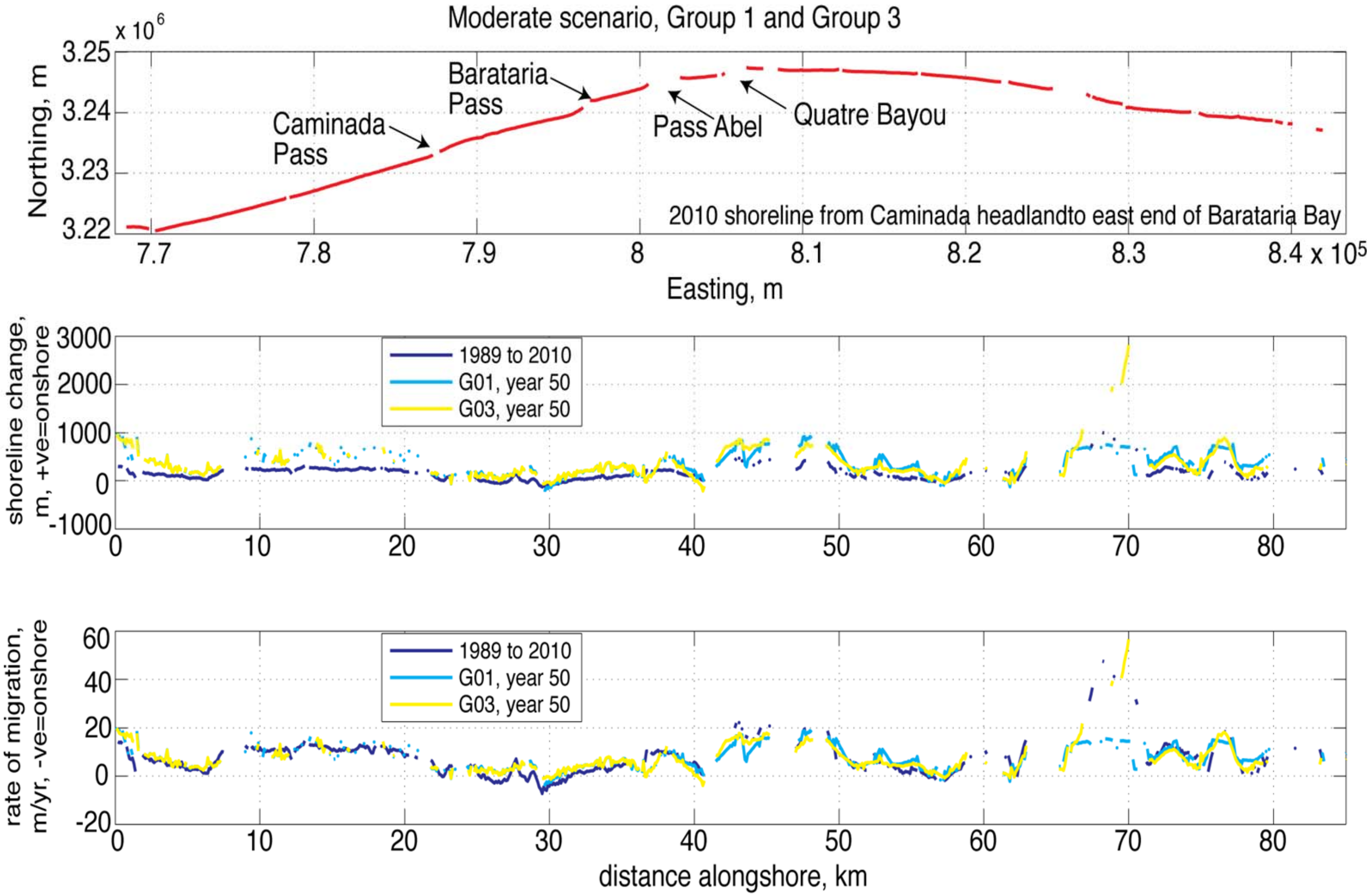

Figure 15. Shoreline response from the no action or no projects simulation compared against restoration projects under G03.

Table 3. System-wide sediment loss along the Central Coast.

G01 S12				G01 S13			
	Gain (million m^3)	Loss (million m^3)	Net Change (million m^3)		Gain (million m^3)	Loss (million m^3)	Net Change (million m^3)
25	44.5	-477.9	-433.4	25	40.7	-583.9	-543.2
50	42.8	-452.7	-409.9	50	39.6	-564.2	-524.6

G03 S12				G03 S13			
	Gain (million m^3)	Loss (million m^3)	Net Change (million m^3)		Gain (million m^3)	Loss (million m^3)	Net Change (million m^3)
25	55.2	-475.6	-420.4	25	52.1	-583.4	-531.3
50	53.9	-454.5	-400.6	50	53.9	-565.6	-511.7

Table 4. System-wide subareal area of barrier along the Central Coast.

G01	Barrier Area m^2		G03	Barrier Area m^2	
Time	S12	S13	Time	S12	S13
0	45.3	45.3	0	61.7	61.7
25	38.1	36.3	25	55.2	53.7
50	32.7	29.3	50	50.4	47.2