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2017 Coastal Master Plan

Appendix C – Modeling

Attachment C3-4

Barrier Island Model Development (BIMODE)

Report: Version 1

Date: July 2015

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Coastal Protection and Restoration Authority

This document was prepared in support of the 2017 Coastal Master Plan being prepared by the Coastal Protection and Restoration Authority of Louisiana (CPRA). CPRA was established by the Louisiana Legislature in response to Hurricanes Katrina and Rita through Act 8 of the First Extraordinary Session of 2005. Act 8 of the First Extraordinary Session of 2005 expanded the membership, duties and responsibilities of CPRA and charged the new Authority to develop and implement a comprehensive coastal protection plan, consisting of a Master Plan (revised every 5 years) and annual plans. CPRA's mandate is to develop, implement and enforce a comprehensive coastal protection and restoration Master Plan.

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Executive Summary

Predicting the evolution of Louisiana's barrier islands is a critical component of the Coastal Protection and Restoration Authority of Louisiana (CPRA) 2017 Coastal Master Plan. The Integrated Compartment Model (ICM) to be utilized for the 2017 Coastal Master Plan is capable of efficiently simulating 50-year time periods and predicting project effects at the basin-scale. The Barrier Island Model Development (BIMODE) component was developed for integration with the ICM and improves upon the 2012 Coastal Master Plan (CPRA, 2012) barrier shoreline model by including additional physical processes (e.g., overwash), improving the capabilities of predicting change in island morphology, and incorporating realistic event-driven morphodynamic responses.

The scope of work included a literature review, model approach development, and model formulation, coding, and testing, along with working meetings, routine teleconferences, and reporting. The focus area includes the Chandeleur Islands on the eastern side of the Mississippi River active Balize Delta and from Scofield Island to Raccoon Island on the western side of the Mississippi River active Balize Delta.

Based upon the detailed literature review, knowledge and experience from restoration project design and field data collection, and professional judgment, the BIMODE Team selected the following key physical processes, forcing functions, and geomorphic forms for inclusion in the model: longshore sediment transport, cross-shore sediment transport, breaching, inlets and bays, post-storm recovery, subsidence, and eustatic sea level rise (ESLR). Descriptions of the processes, functions, and forms along with their respective analytical and / or empirical formulations are provided.

Due to the spatial scale of the focus area and the temporal scale of the ICM, complex island models that predict both longshore and cross-shore sediment transport are not viable. Therefore, a hybrid modeling approach was developed to account for the key physical processes of longshore and cross-shore sediment transport. The longshore transport model formulation includes a three-step wave transformation process using available hindcast data to yield representative breaking wave conditions. These wave data are used to estimate sediment transport rates employing the Coastal Engineering Research Center (CERC) transport formulation.

Sediment sinks are included by not allowing bypassing across specific inlets, that is, assuming zero transport onto the adjacent downdrift island. Shoreline retreat due to silt loss is computed based on the percent silt and clay in the erodible face. Varying sand / silt percentages are allowed on a profile-by-profile basis though uniform percentages were utilized for each island.

The cross-shore sediment transport formulation includes application of the one-dimensional Storm-induced BEAch CHange (SBEACH) model that simulates cross-shore morphologic response in response to tropical cyclone events (referred to herein as storms) based on measurement derived, empirical equations. While the code is not directly incorporated into the BIMODE model, the SBEACH model runs are recalled through look-up tables to determine the likely output profile given the starting input profile and storm characteristics. Input profiles are based on representative static submerged profiles from each of the regions along with combination of varying dune heights, dune widths and berm widths, some of which represent pre-restoration barrier island profiles. Barrier island breaching is incorporated into the BIMODE model by determining critical thresholds of minimum barrier island widths and minimum width to island length ratios through comparisons to historical data on barrier island breaching.

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Inlet and bay processes, specifically inlet expansion/enlargement, using equilibrium theory for inlet cross-sectional area as a function of tidal prism, are incorporated into BIMODE using the same formulation employed in the 2012 Coastal Master Plan barrier shoreline model (Hughes, et al., 2012).

Based upon experience in restoration project design, SBEACH tends to under predict storm erosion, which in some sense accounts for post-storm recovery processes. Accordingly, the BIMODE Team recommends the post-storm recovery processes are captured sufficiently through application of SBEACH.

Subsidence and ESLR are incorporated into the BIMODE model through manual adjustments following guidance documents prepared by CPRA.

The schematization of the BIMODE model outlines the procedure for how the selected physical processes are incorporated to develop the final output. The procedure includes reading in the profile and wave data inputs, determining longshore sediment transport, locating nodal points where sediment transport diverges, determining net erosion or accretion along each profile, and computing change in beach face profile specific to longshore transport; adjusting beach profiles to account for relative sea level rise, beach face profile retreat due to silt loss, and consolidation; accounting for cross-shore sediment transport for the given storm suite; eroding the bayward side of each profile; checking for and implementing breaching if the thresholds are met; and incorporating the inlet and bay model; and repeating these steps for the 50-year simulation period. The output is cross-sections at each emergent profile in the format of a Digital Elevation Model (DEM).

The BIMODE.f90 program, written in Fortran 90, simulates the physical processes described in the model schematization. The file structure consists of a main program file, which calls on several subroutines to run. Each subroutine was tested for functionality. The program in its entirety was also tested by running 50-year simulations including return interval storms and periods of average wave conditions. Test runs of the code were successful. Refinements of the code may be necessary based on the results of the calibration analysis. Calibration outcomes will be reported in Attachment C3-23 (ICM Calibration and Validation).

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List of Abbreviations

ADCIRC	ADvanced CIRCulation Model
BIMODE	Barrier Island Model Development
CB&I	Chicago Bridge and Iron Company
CEC	Coastal Engineering Consultants, Inc.
CEM	Coastal Engineering Manual
CERC	Coastal Engineering Research Center
CHE	Coast & Harbor Engineering, Inc.
cm	Centimeter
CPE	Coastal Planning and Engineering, Inc.
CPRA	Coastal Protection and Restoration Authority
DEM	Digital Elevation Model
DHI	Danish Hydraulic Institute
ESLR	Eustatic Sea Level Rise
FEMA	Federal Emergency Management Agency
g	Gram
hr	Hour
IPCC	Intergovernmental Panel on Climate Change
kg	Kilogram
Lat	Latitude
Long	Longitude
m	Meters
mm	Millimeters
NAVD	North American Vertical Datum of 1988
NOAA	National Oceanic and Atmospheric Administration
NOS	National Ocean Service

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NRC	National Research Council
RSLR	Relative Sea Level Rise
s	Second
SLR	Sea Level Rise
SBEACH	Storm-induced BEAch Change Model
STWAVE	Steady-State Spectral Wave Model
SWAN	Simulating WAves Nearshore Model
UNO	University of New Orleans
UnSWAN	Unstructured Simulating WAves Nearshore Model
USACE	U.S. Army Corps of Engineers
UTM	Universal Transverse Mercator
WIS	Wave Information Studies
yr	Year

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1.0 Introduction

1.1 Model Improvement Plan

The Coastal Protection and Restoration Authority of Louisiana (CPRA) embarked on the development and application of model improvements for the 2017 Coastal Master Plan. This effort was launched with the 2017 Model Improvement Plan (CPRA, 2013), which builds upon the modeling developed for the 2012 Coastal Master Plan (CPRA, 2012). The overall vision for the landscape modeling was to develop an Integrated Compartment Model (ICM) characterized by development of new process-based algorithms (e.g., marsh edge erosion and sediment distribution), integration of model code into a single common framework (e.g., all code integrated into Fortran), and increased resolution of the models (e.g., reducing the size of the 2012 Coastal Master Plan Eco-hydrology compartments). The ICM is designed to simulate 50-year time periods in an efficient manner and predict project effects at a basin-scale.

Barrier island restoration has been a focus of CPRA's coastal restoration and protection program for decades. The ability to predict barrier island morphological dynamics, including long-term sustainability, is a critical component of this effort. The 2012 barrier shoreline model (Hughes et al., 2012) was able to predict inlet area change and island movement based on processes such as wave climate. An external peer review identified that the 2012 barrier shoreline model lacked dynamic (physical) processes and stochastic events. The improvements identified for the 2017 barrier island model include the addition of physical processes (e.g. overwash), improving the capabilities of predicting change in island morphology, adding more realistic event-driven morphodynamic responses, and integration into the ICM.

1.2 Scope of Work

The scope of work for the 2017 Barrier Island Model Development (BIMODE) includes:

- Activity 1 – Summarize current literature and available modeling approaches;
- Activity 2 – Convene a working meeting to discuss and evaluate modeling approaches;
- Activity 3 – Develop the modeling approach and prepare a written summary of the proposed formulation/approach; and
- Activity 4 – Code the model, test the newly developed model, and report results.

This report discusses the physical processes, forcing functions, and geomorphic forms that affect barrier island evolution in Louisiana; summarizes the current literature specific to the process, function or form; outlines the analytical and empirical formulations; presents the modeling approach for the process, function, or form; documents the model schematization for the BIMODE model; and presents the development of the model coding and testing of the subroutines to confirm the functionality and accuracy of the program.

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1.3 Focus Area

The focus area (Figure 1) extends from the Chandeleur Islands to the eastern side of the active Mississippi River Balize Delta and from Scofield Island to Raccoon Island on the western side of the active Mississippi River Balize Delta. The study area is divided into the following six regions:

- Isles Dernieres;
- Timbalier;
- Caminada Headland and Grand Isle;
- Barataria Bay;
- Breton Island; and
- Chandeleur Island.

The study area was subdivided based upon the differing offshore characteristics and environmental forcings that affect the model inputs including but not limited to geomorphology, wave sheltering or profile slope. Figure 2 shows these regions highlighting the barrier islands in each region.

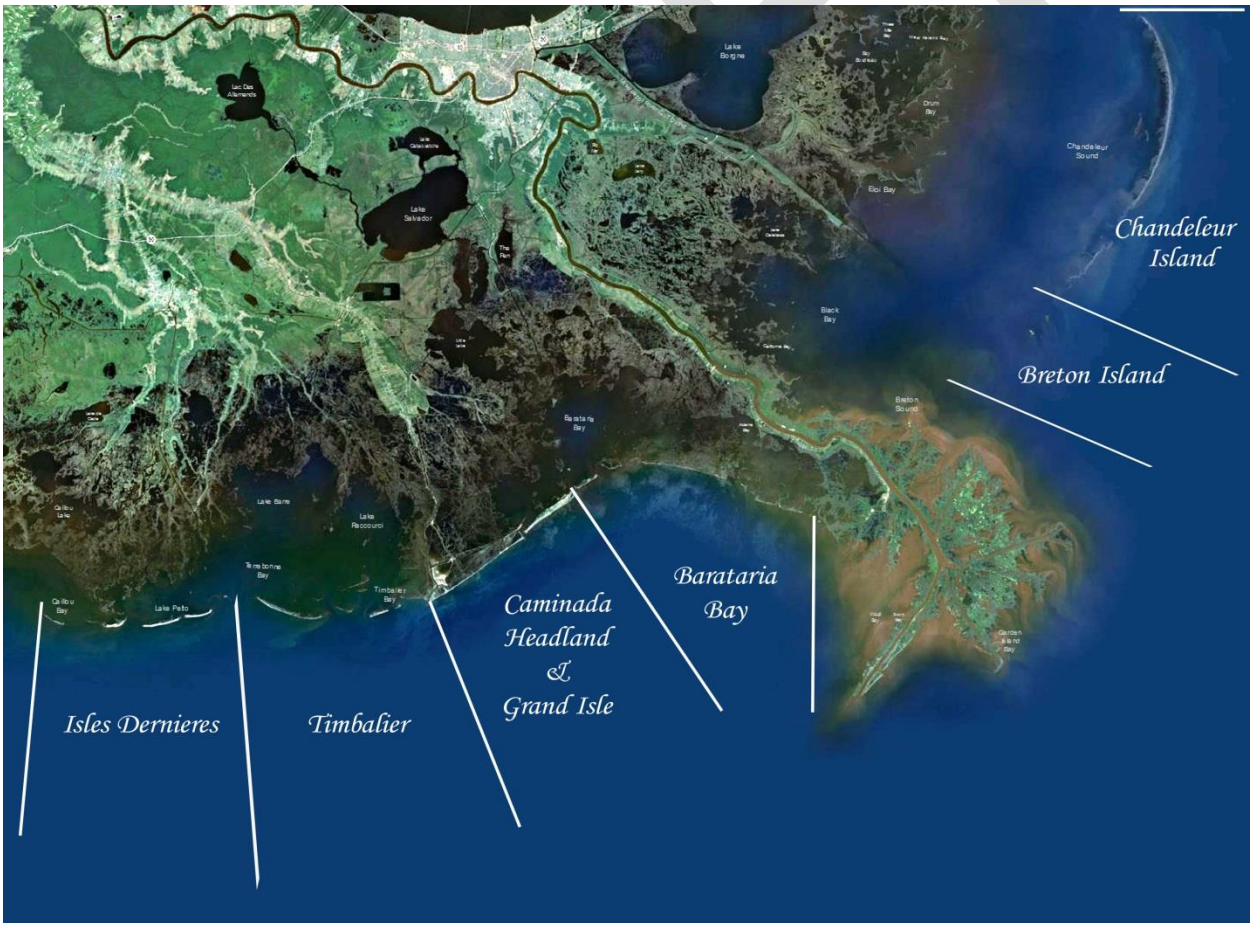

Figure 1: BIMODE Region Map.

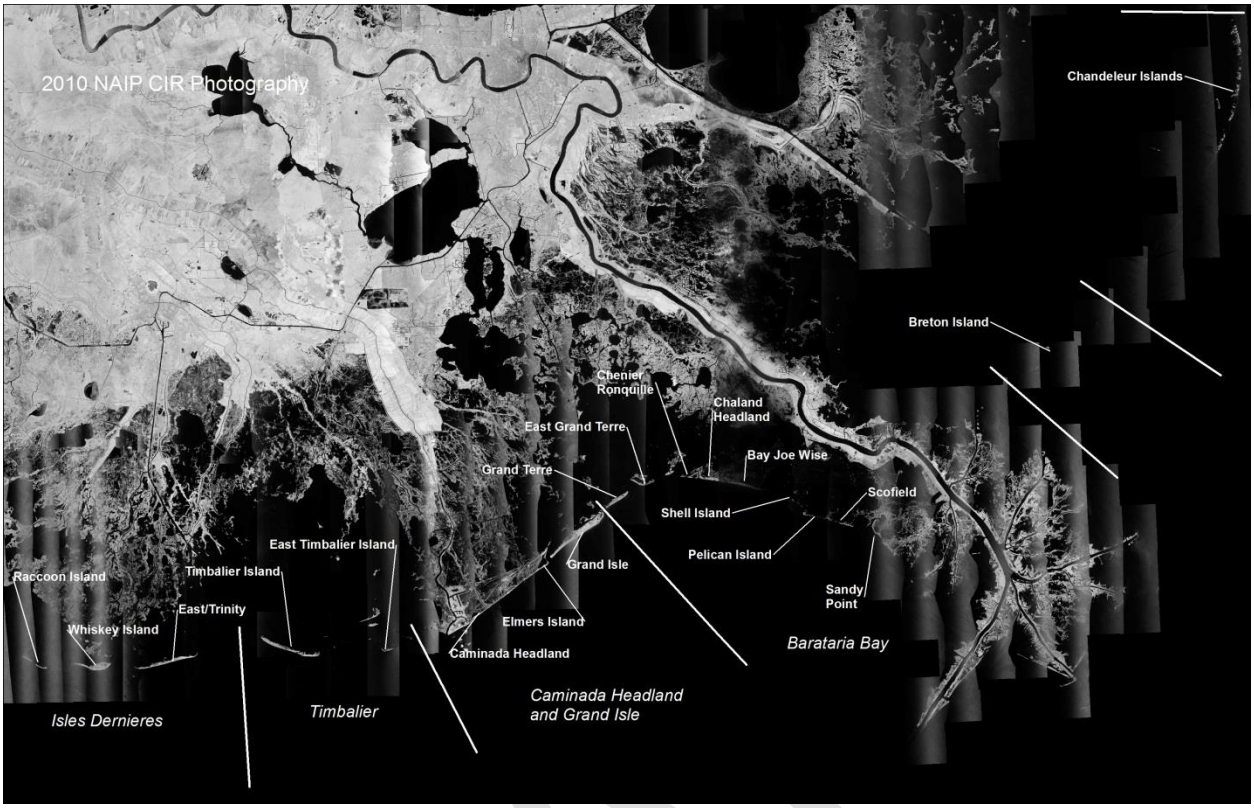

Figure 2: Study Area Map with Barrier Islands Listed.

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2.0 Barrier Island Evolution

The Louisiana barrier islands are the product of Mississippi River channel switching over the last 5,000 years. It is channel switching and complex interactions between anthropogenic events, sediment transport, storm impacts, and inlet dynamics that contribute to barrier island formation, migration, and erosion. Figure 3 presents the three-stage geomorphic model that summarizes the development and evolution of transgressive depositional systems in the Mississippi River Deltaic Plain including the formation of the barrier islands (Penland *et al*., 1988). Due to the lack of sediment supply, the barrier islands are eroding and degrading. The projected years of disappearance for the barrier islands are on decadal scales (USACE, 2010 and 2012).

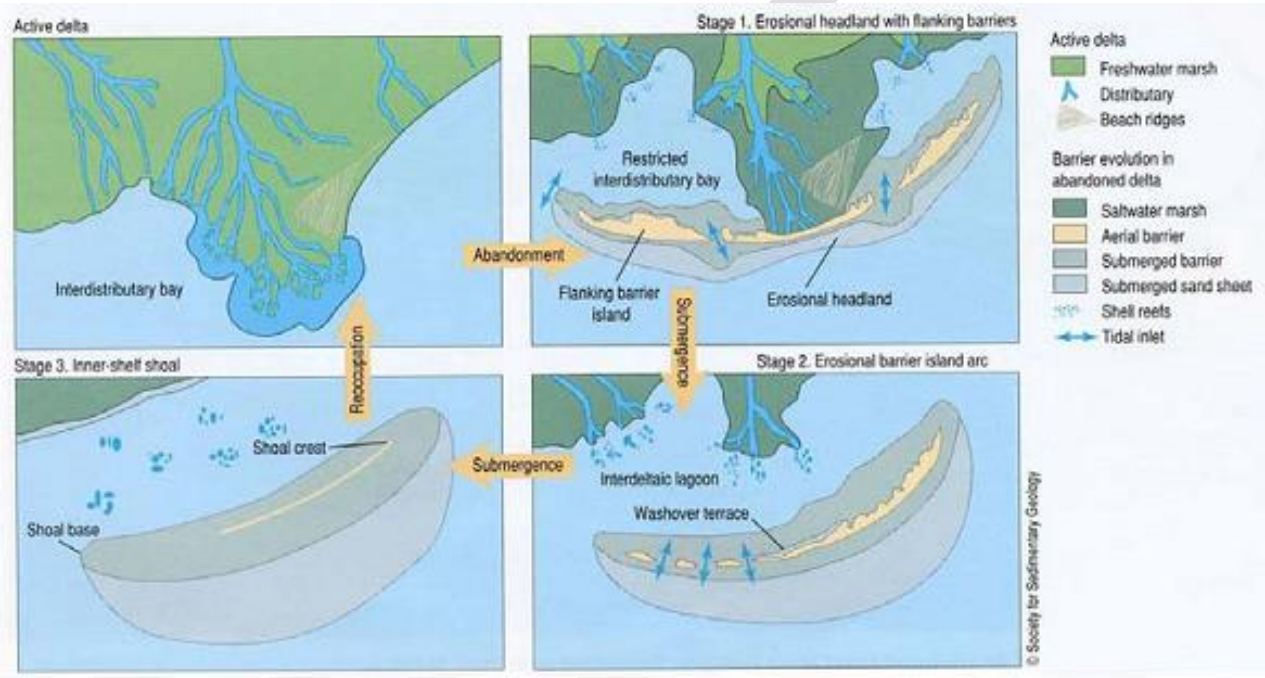

Figure 3: Three-Stage Geomorphic Model.

The evolution of Louisiana's barrier islands is well described in the literature (e.g., Williams *et al*., 1992; Penland *et al.*, 1988; Penland *et al*., 2005; Georgiou *et al*., 2005; Kulp *et al*., 2005; Rosati *et al*., 2006 & Rosati and Stone, 2009). Louisiana's barrier islands are typically low lying and comprised of three physical features, the beach, dune, and back-barrier marsh. Their geomorphic form acts as a buffer to reduce the full force and effects of wave action, saltwater intrusion, storm surge, and tidal currents on associated estuaries and wetlands. Further, the back-barrier marsh platform captures overwash sediments during episodic events; sediment that would otherwise be carried into back bay areas to form shoals or be lost into deeper waters. The marsh also serves as a roll over platform as the islands migrate landward. Their ecologic function provides wetland habitat for a diverse number of plant and animal species, and to help retain sediment. The beach and dune are comprised of a thin veneer of sand overlying poorly consolidated silts and clays. As the elevations of the islands are low, they are frequently overwashed during storms.

Forcing functions (e.g., winds, waves, tides, currents, subsidence, and eustatic sea level rise (ESLR)) transport sediment and / or evolve the land forms on a continual basis. Storms impact the barrier islands as sand is eroded from the Gulf shoreline, the underlying mixed sediments are exposed to wave attack, and overwash occurs. If a sufficiently wide marsh platform exists, the

islands will migrate in an inland direction as washover sediment is captured. As storms pass, the bayside shoreline or marsh edge may also erode due to waves that are generated on the bay which transport sediment into the back bay and remove it from the active littoral system. If the marsh platform is narrow or non-existent, breaches may occur.

In the wake of significant storm events, barrier islands may experience recovery periods, which are typically years in length and may represent prograding shorelines or may represent periods where shoreline erosion is less severe than during storm impact periods. While revegetation of the dune and overwash deposits may occur, the current deteriorated conditions of the majority of the barrier islands as well as insufficient time between storm events preclude significant recovery of their geomorphic form and ecologic function.

Louisiana's barrier islands have a limited sediment supply. In addition, over time the area of the interior bays has increased as a result of natural and anthropogenic factors (e.g., subsidence, oil and gas exploration) leading to increases in tidal prism. Increases in the tidal prism jet sediment further offshore, which increases the ebb shoal capacity and reduces sediment bypassing at inlets. The ebb shoals are drowned rather than bypassing sand or welding to the adjacent barriers (Georgiou *et al*., 2005). New breaches formed during storms typically grow into permanent inlets, further fragmenting the barrier islands.

For modeling barrier island evolution on decadal scales, Rosati *et al*. (2006) recommended accounting for the following: erosion of Gulfside and bayside sand, vegetation, and core sediments; overwash and washover deposits; breaching; partial recovery of sand along the Gulf shoreline; vegetation of dunes and wetlands; aeolian transport; longshore sediment transport; ESLR; subsidence; and consolidation of poorly-consolidated sediment. The approaches to model these processes are discussed in detail in the following sections of this report.

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3.0 Modeling Options for Barrier Island Evolution

3.1 Summary of 2012 Barrier Shoreline Model

The 2012 barrier shoreline model (Hughes *et al*., 2012) simulated coastline and inlet evolution in response to physical forcings. The model was applied to the sandy shorelines of Louisiana in two segments. The first segment included the barriers from the western Isle Dernieres (Raccoon Island) to Scofield Island. The second segment included the barrier islands east of the Mississippi River delta, including Breton Island and the Chandeleur Islands (Figure 2). The model encompassed long-term processes, such as response to sea level rise (SLR), subsidence, landward migration by beach and foreshore erosion and overwash processes, and offshore and longshore loss of sediment to deepwater sinks below mean annual wave base. The model operated in a one-dimensional (cross-shore) mode at a selected alongshore interval (~100 m) and geometrically translated a cross-shore profile based on the calculated processes.

The model used the sediment continuity equation to balance net import or export of sediment, and then used the deficit or gain to determine the shoreline erosion rate at each location. The model computed alongshore transport in plan form using an empirical relationship (USACE 2002), driven by offshore wave climate relative to a local shoreline angle. The model used an annual wave climate derived by analysis of hourly wave information obtained from archived data from the Wave Information Studies (WIS) project (Hubertz, 1992). The resulting wave climate was used to drive the longshore transport equation. Resulting net longshore transport was then balanced by pre-determined cross-shore transport rates, obtained during model calibration. The resulting mass balance subsequently produced accretion or erosion, depending on excess or a deficit in the sediment. The result from this procedure was a one-dimensional cross-shore translation of the shoreline. This process was repeated for each time-step. The model did not address predictions nearing a century or longer. Further, the model did not account for event driven (storm induced) change.

The following improvements were recommended for the 2012 barrier shoreline model (Hughes, 2012):

- Use of a full local wave model providing more accurate wave heights and directions for the longshore transport calculations,
- In the cross-shore dimension, improve the approach to more accurately account for overwash processes and removal of sediment offshore,
- Account for event driven (storm induced) change, and
- Implement more frequent coupling of the eco-hydrology model and the barrier shoreline model components.

3.2 Review of Model Options

The scope of work for BIMODE began with a review of options for the barrier island model component of the 2017 Coastal Master Plan ICM, taking into consideration the recommendations stemming from an external review of the 2012 barrier shoreline model. The BIMODE Team divided the review of model options into three categories:

- Wave Climate and Wave Transformation, Water Level, Tide, and Storm Surge;

- Sediment Transport and Morphological Change; and
- Tidal Inlets and Estuaries/Bays.

The review included the model name, brief description, methodology, pros and cons, and general discussion as well as summary and discussion on certain inputs for the BIMODE model. The review served as the first step in recommending the preferred model option for the key physical processes, forcing functions, and geomorphic forms of longshore sediment transport, cross-shore sediment transport, and inlets and bays. The selection of the preferred model option was formulated by outlining specific modeling steps and integrating them into a model schematization description. With respect to the longshore and cross-shore sediment transport processes, the BIMODE Team recommended they be handled through separate evaluations and combined through a hybrid approach.

The complete review is presented in Appendix 1.

3.3 Physical Processes, Forcing Functions, and Geomorphic Forms

Based upon review of pertinent available literature, knowledge and experience from restoration project design and field data collection, and professional judgment, the BIMODE Team selected the following physical processes, forcing functions, and geomorphic forms that affect the evolution of Louisiana's barrier islands for consideration in developing the modeling approach:

- Wave Transformation;
- Longshore Sediment Transport;
- Cross-shore Sediment Transport;
- Breaching;
- Inlets and Bays;
- Aeolian Processes;
- Subsidence;
- ESLR; and
- Post-Storm Recovery.

These physical processes, forcing functions, consideration of variation in sediment properties, and geomorphic forms are described in the following sections. The descriptions include pertinent references describing each process along with relevant literature on recent advances in modeling specific to BIMODE. The equations and formulations for each process, function or form incorporated in the BIMODE model are provided. The rationale for not incorporating certain processes, functions or forms in the BIMODE model is also provided.

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4.0 Wave Transformation

4.1 Input Data

4.1.1 Wave Climate

Wave data vary in time period and duration and generally include wave height, period, and direction. Hindcast data are generally longer term time series, e.g. 20-year record, that include deep water wave data that are generated from wind data. Wave gauge data available for the Louisiana coast include both deep water and intermediate water locations. Project-specific gauge data are typically short duration (e.g., monthly) and located in the nearshore. Deep water is defined where the water depth to wave length ratio is 0.5 or greater. Intermediate (transitional) water is defined where the water depth to wave length ratio is less than 0.5 and greater than 0.05. Shallow water is defined where the water depth to wave length ratio is less than 0.05 (USACE, 2002).

The primary sources of wave input data used in modeling for barrier island studies and project designs include WIS hindcast time series, Wavewatch III hindcast time series (Tolman, 2009), National Oceanic and Atmospheric Administration (NOAA) National Data Buoy Center (NDBC) wave buoys, offshore wave gauge data, project-specific wave measurements, and other model-generated data. These data sources provide the input to the longshore transport component of the BIMODE model.

Model generated wave data during tropical storm and hurricane events were produced for the 2012 Coastal Master Plan by ARCADIS using the ADvanced CIRCulation (ADCIRC) hydrodynamic model coupled with the Unstructured Simulating Waves Nearshore (UnSWAN) model (CPRA, 2012). Model output included time series of storm surge, water currents, wave height, wave period, and wave direction at every node in the computational mesh, as well as the maximum value at any given time step during the simulation. Available storm wave and storm surge output data was acquired and compiled by CPRA and The Water Institute of the Gulf for use in the 2017 Coastal Master Plan modeling. These data provide the input to the cross-shore transport component of the BIMODE model.

4.1.2 Water Level, Tide, and Storm Surge

The primary sources of water level and tide input data used in modeling for barrier island studies and project designs include NOAA National Ocean Service (NOS) tide gauge data, project-specific measurements, and other model-generated data. The NOS data generally provide continuous (6 minute or hourly) time series records over multi-year time intervals. Project specific measurements also provide continuous time series recordings, but are typically of shorter duration (e.g., days to months). In addition to daily observed astronomical tide elevation measurements, storm surge estimates for specific storm events may be generated from the NOS gauges by subtracting predicted astronomical tide elevations from the observed values.

Storm surge modeling performed for the State of Louisiana and for the Federal Emergency Management Agency (FEMA) was summarized in the Literature Review (Appendix 1). For Louisiana barrier island restoration project studies and design, water elevation and storm surge in cross-shore response modeling have primarily utilized computations and algorithms within the

cross-shore models. Storm-specific offshore wave data (from buoys, gauges, and hindcasts) and nearshore tide gauge data are used as model input.

As with the wave data, the availability of the 2012 Coastal Master Plan output data from the ADCIRC hydrodynamic model coupled with the UnSWAN wave transformation model was compiled by CPRA for use in the 2017 Coastal Master Plan modeling. The ADCIRC/UnSWAN output is used in the cross-shore model simulations for storm events. Non-storm event tidal fluctuations are incorporated within long-term (decadal) shoreline change simulations based on longshore sediment transport computations.

4.2 Model Options

Models that transform waves from deep to intermediate water and from intermediate to shallow water were reviewed and summarized in the initial review of model options (Appendix 1). The simplified WIS Phase III spectral wave transformation procedure (Jensen, 1983) can be used for wave transformation from deep water to intermediate water depths. Extensive wave transformation modeling has been performed as a part of Louisiana's barrier island restoration project studies and design (e.g., CPE, 2003; CPE, 2005; CHE, 2007; CEC and SJB, 2008; Thompson, 2008; USACE, 2010; CEC, 2011; and USACE, 2012). The two-dimensional spectral wave models STWAVE (Smith *et al.*, 2001) and SWAN (Booij *et al.*, 1996) have been primarily used for intermediate and shallow water wave transformations. Other models including MIKE21 (SW and NSW) (DHI, 2009) and Delft3D-Wave (Deltares, 2011) have been applied along the Louisiana coast for specific shallow water wave transformation modeling.

4.3 Summary and Recommendations

4.3.1 General

This section describes the recommended procedure for the wave transformation to be applied for the estimate of longshore sand transport rates. This procedure including the steps, techniques, and statistical analyses is based upon review of pertinent available literature, knowledge and experience from restoration project design, and professional judgment of the BIMODE Team. The procedure involves the following major steps, which are described in the following sections:

- Selection of Wave Data;
- WIS Phase III transformation and statistical analysis;
- Detail nearshore wave transformation; and
- Estimation of breaking wave conditions.

4.3.2 Wave Data

The BIMODE model requires long-term statistical wave information as input for the estimation of longshore sand transport rates. The WIS recently completed a comprehensive hindcast for the Gulf of Mexico for the interval 1980 through 2012. This 33-year wave hindcast is used as the primary source of wave information for the calculation of longshore sand transport rates in the BIMODE model. The WIS wave hindcast may be accessed and downloaded from the WIS website at http://wis.usace.army.mil/.

A single WIS hindcast station was identified within each of the six regions, and the WIS station located closest to the center of each sub-basin was selected. The following stations were included and are shown in Figure 4:

- Isles Dernieres: WIS Station 73124, 14 m depth, Lat 28.70 Long -90.80;
- Timbalier: WIS Station 73126, 18 m depth, Lat 28.70 Long -90.00;
- Caminada Headland and Grand Isle: WIS Station 73129, 21 m depth, Lat 29.00 Long -90.05;
- Barataria Bay: WIS Station 73131, 10 m depth, Lat 29.20 Long -89.75 ;
- Breton Island: 73139, 25 m depth, Lat 29.45 Long -88.75 ; and
- Chandeleur Island: WIS Station 73141, 27 m depth, Lat 29.75 Long -88.55.

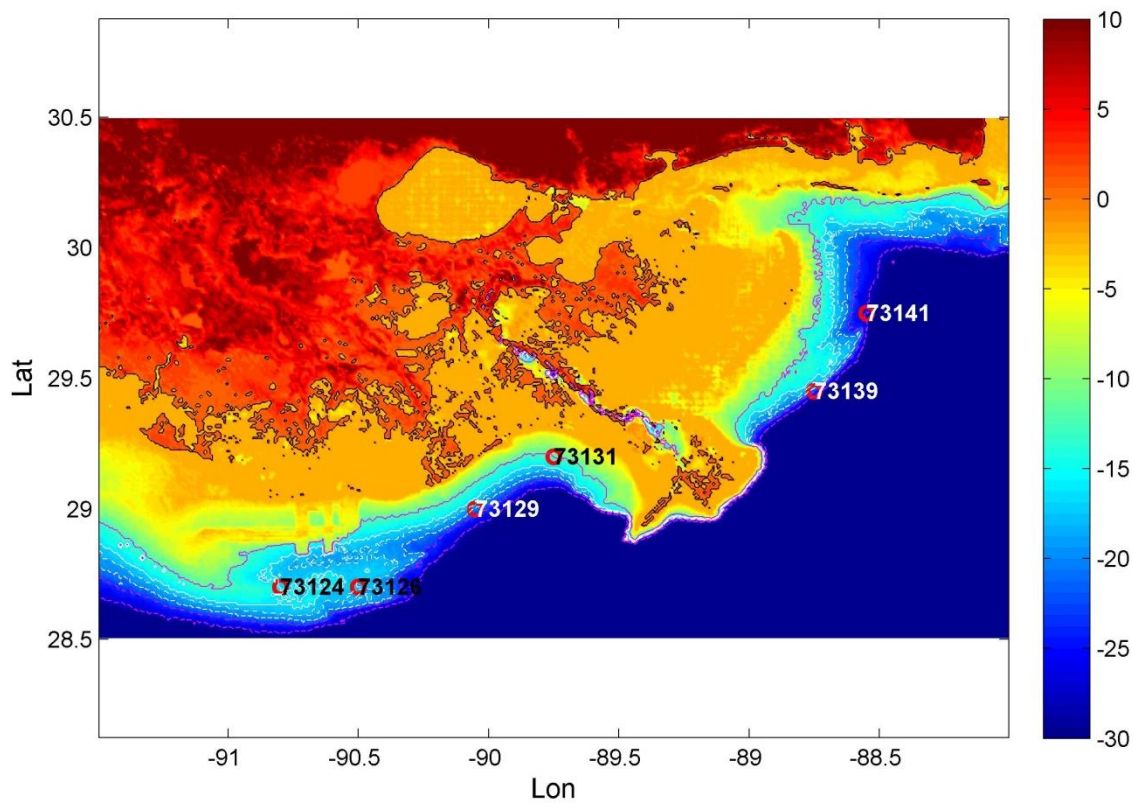

Figure 4: WIS station locations. Six stations (ST73124, ST73126, ST73129, ST73131, ST73139, ST73141) are used for wave transformation. The contour of each wave station depth is given in meters.

As WIS is an offshore database including ocean forcings (e.g., local wind generated waves) and swell, it is directly relevant to BIMODE. Other subroutines of the ICM (e.g., hydrology, morphology) may use other sources of wave data but due to the direct utility of the WIS database there is not a strong need to correlate the input wave data with data from those sources. However, to the greatest extent practicable, the input data employed within the BIMODE model was made consistent with other 2017 Coastal Master Plan ICM subroutines.

4.3.3 WIS Phase III Transformation and Statistical Analysis

The purpose of this step is twofold: first, the deepwater hindcast wave information is processed to remove offshore traveling wave conditions from the wave time series; and secondly, the transformed wave data are analyzed to identify statistically representative wave conditions for each month of the year. Identification and use of statistically representative wave conditions to characterize the offshore wave climate on a monthly basis is a form of input reduction and is viewed as imperative to the prediction of barrier island evolution over long time periods (50 years) to avoid excessive computation times.

The WIS Phase III transformation procedure (Jensen, 1983) is a point-to-point spectral wave transformation procedure that assumes no additional energy input from wind, and straight and parallel bottom contours. The waves are assumed to have a distribution of energy over a range of frequencies and directions. The energy spectrum is governed by the Texel, Marsen, and Arsloe spectral form (Hughes, 1984). The directional spread is given by the cosine function raised to the 4th power. The directional spectrum is discretized into frequency and direction components, and the components are treated independently. Due to the temporal and spatial scale of the ICM, the bottom contours between the starting depth and the shallower ending depth are assumed to be straight and parallel. Application of this assumption is validated through extensive calibration of the predicted longshore transport rates to measured transport rates. Use of this transformation procedure is viewed as superior to the alternative of applying a 180 degree cut-off for offshore traveling waves based on the spectral mean wave direction. In the WIS Phase III transformation procedure, only the energy in offshore traveling direction bins is removed from the highly oblique wave conditions and the onshore traveling wave energy is transformed to the breaking wave water depth of approximately 6 feet.

Selection of the regional shoreline orientation should be done with care as it directly affects the transformation process. The WIS Phase III transformation technique also allows for sheltering the shallow water point from wave energy approaching from specified wave directions. This capability may be important for some of the regions, in particular the Barataria Bay region (sheltering of wave energy from the east due to the Mississippi River delta), Breton Island region (sheltering of wave energy from the south and west due to the Mississippi River delta and sheltering of wave energy from the Mississippi Sound), and Chandeleur Island region (sheltering of wave energy from the Mississippi Sound).

The Phase III transformation technique is used to transform the offshore wave climate from the WIS hindcast station to obtain the onshore-directed wave climate at the offshore boundary of the nearshore transformation model. The Phase III transformation converts the wave angle convention from meteorological to a shoreline reference angle convention in which wave angles range between 0 and 180 degrees. In this direction convention, a wave angle of 0 degrees corresponds to a wave traveling parallel to the shoreline from right to left, a wave angle of 90 degrees corresponds to a wave moving directly on shore (perpendicular to the shoreline), and a wave angle of 180 degrees corresponds to a wave parallel to shoreline shoreline from left to right. To convert the wave direction convention to the typical shoreline referenced wave direction convention, wave angles ranging between +90 and -90 degrees, subtract 90 from the WIS Phase III wave angle.

After performing the Phase III transformation, the 1980 to 2012 WIS offshore wave time series is parsed on a monthly basis to obtain 33 data sets for each individual month (January, February, March, etc.). Each month is analyzed to determine statistically defensible wave conditions for that month. These conditions essentially represent weighted averages for a 33-year wave sequence noting the offshore waves are removed as described above. The end goal of the

statistical analysis is the identification of different representative wave conditions (based on bands of wave height, wave period, and incident wave direction) for each month of the year. Then the wave conditions of the 33 year wave time series are placed in one look-up table. Repeated wave conditions are neglected. In this way a total of 617 different wave conditions were defined to characterize the 33 year wave climate within each of the six regions.

Statistical analysis includes:

- Use of wave period bands: minimum period to 4 seconds, 4-6 seconds, 6-8 seconds, 8-10 seconds, 10-12 second, etc. up to maximum wave period
- Use of wave direction bands at 22.5° angles (N, NNE, NE, ENE… NNW)
- Wave height bands (for significant wave height) defined in 1m increments: 0-0.5m, 0.5-1.5m, 1.5-2.5m, 2.5-3.5m, etc., up to the maximum wave height

This is a typical wave breakdown for GENESIS modeling (Hanson and Kraus, 1991) and follows guidance for the hypercube method (Bonanata et al, 2010).

These divisional bands were selected to provide representative wave conditions in a manner that would provide computational efficiency given the geographical extent of the BIMODE model. The wave period division distinctly encompasses both more frequent, lower energy wave conditions, as well as, less frequent waves during more energetic conditions. Application of these monthly wave conditions incorporates seasonal and time sequencing influences into the wave conditions for the BIMODE model.

4.3.4 SWAN Nearshore Wave Transformation

The BIMODE Team considered both the Steady-State Spectral WAVE model (STWAVE) (Smith *et al.*, 2001) and Simulating WAves Nearshore (SWAN) model (Booij *et al.*, 1996) as candidate nearshore wave transformation models from the offshore boundary to near breaking conditions. Both models are robust computationally efficient tools for estimating the transformation of waves across an irregular nearshore bathymetry. The BIMODE Team decided to use the SWAN nearshore wave transformation model due to the familiarity with the model and previous use of SWAN in the design and performance evaluation of barrier island restoration projects in the focus area. The SWAN model is used to transform the representative wave conditions across the irregular nearshore bathymetry from the WIS Stations to near breaking conditions. The SWAN model includes wave damping, shoaling, refraction, and breaking. Further, storm surge is included in the SWAN model.

For these simulations, a unit input wave height is specified together with the mean wave period and mean wave direction computed from the statistical analysis. Pre-breaking wave conditions in the nearshore are saved corresponding to the specific profiles (shoreline segments) that evolve using the BIMODE model. By transforming a unit wave height, the resulting wave height in the nearshore can be viewed as a transformation coefficient (product of the refraction and shoaling coefficients) and can be multiplied by the mean wave height calculated for each of the wave height bands to obtain unique nearshore wave heights. The save stations for nearshore wave conditions should be located in pre-breaking water depths for the majority of the wave conditions. It is necessary that the save stations be located in pre-breaking water depths in order for the assumptions associated with the unit wave height transformation procedure to be valid. It was recommended that the save stations be located in water depths generally greater than 3 m and less than 5 m to the extent that this is possible and practical.

Output from this step of the wave transformation procedure is a database of nearshore wave information including wave height, wave period, wave angle, nearshore station depth, and percent occurrence for each month of the year. The number of required SWAN simulations depended on the number of statistically represented wave conditions identified in the statistical analysis of the offshore time series of wave conditions. The maximum was 120 conditions (two wave period bands by 5 wave direction bands by 12 months) for each of the six regions.

4.3.5 Estimation of Breaking Wave Conditions

Final wave transformation to breaking is performed within the BIMODE model using a breaking wave criteria, Snell's Law, and the conservation of wave energy. In this portion of the analysis, the wave angle with respect to the local shoreline orientation is estimated based on shoreline positions at adjacent modeled profiles. The nearshore waves are transformed to breaking with respect to the local shoreline orientation and the resulting breaking wave conditions are used to estimate longshore sand transport rates for each of the representative monthly wave conditions. Application of the breaking wave criteria is validated through extensive calibration of the longshore transport rates. Further, the uncertainties in the wave transformation process are far less than the overall calibration of longshore transport to obtain realistic transport rates.

The pertinent equations used in this phase of the wave transformation procedure are as follows:

<u>Conservation of Wave Energy</u>

$$E_1 C_g \cos\alpha_1 = E_2 C_g \cos\alpha_2 \qquad \text{(Eqn. 1)}$$

Where: E = wave energy density
C_g = wave group velocity
α = wave angle relative to shore normal
Subscripts $_1$ and $_2$ denote different water depths,

and

$$E = \frac{1}{8}\rho g H^2 \qquad \text{(Eqn. 2)}$$

where: ρ = mass density of water
g = gravitational acceleration
H = wave height,

and

$$C_g = Cn \qquad \text{(Eqn. 3)}$$

where: C = wave phase velocity
n = ratio of wave group velocity to wave phase velocity,

and

$$C = \frac{L}{T} \qquad \text{(Eqn. 4)}$$

where: L = wave length
T = wave period,

and

$$n = \frac{1}{2}\left[1 + \frac{2kh}{\sinh(2kh)}\right] \qquad \text{(Eqn. 5)}$$

where: k = wave number
h = water depth,

and

$$k = \frac{2\pi}{L} \qquad \text{(Eqn. 6)}$$

Breaking Wave Criterion

$$H_b = 0.78 h_b \qquad \text{(Eqn. 7)}$$

Where: H_b = Breaking wave height
h_b = water depth at breaking.

Snell's Law

$$\frac{\sin\alpha_1}{L_1} = \frac{\sin\alpha_2}{L_2} \qquad \text{(Eqn. 8)}$$

Wave Length

$$L = \frac{gT^2}{2\pi}\tanh\left(\frac{2\pi h}{L}\right) \qquad \text{(Eqn. 9)}$$

While more sophisticated wave breaking criteria are available, Hunt's equation (approximation) can be used to provide an explicit solution (Hunt, 1979). Based upon the detailed literature review, knowledge and experience from field data collection and numerical modeling of wave transformation and breaking, and professional judgment, the BIMODE Team deemed this approach sufficient for the temporal and spatial scales of the ICM.

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5.0 Longshore Sediment Transport

5.1 General

Longshore sediment transport is defined as the movement of sediment parallel to the shoreline occurring primarily within the surf zone under the forcing functions of breaking waves and surf combined with nearshore currents. This process is one of the key physical processes that controls beach morphology and is at the core of the BIMODE model. It interacts with the other key processes, forcing functions, and geomorphic forms including cross-shore sediment transport and inlets and bays.

Waves reach the shoreline from different directions and produce daily as well as seasonal reversals in transport direction. The gross transport rate is defined as the summation of sediment transport in both the left and right directions (along the shoreline) and may be used in estimating shoaling rates in inlets and channels. The net transport rate is defined as the difference between left and right directed sediment transport, the higher value indicating the net direction of transport. It is the gradient of the net sediment transport rate that is used to estimate the retreat or advance of the shoreline.

While the full longshore transport potential may not be realized on Louisiana's sediment starved coast, application of a longshore transport formulation with calibration to measured transport rates accounts for sediment deprivation. For the purpose of the model, it was assumed that barrier island recession releases a sufficient supply of sand to satisfy the longshore transport potential provided extensive calibration to published data is performed and the release and loss of silt is accounted for.

5.2 Model Options

5.2.1 Single Line Theory Models

The theory of Pelnard-Considère (1956) gives the basic equations describing the morphological processes of coastline evolution due to longshore sediment transport gradients (Figure 5a). These equations lead to the well-known diffusion equation derived below. For the single line theory, the coastal profile is schematized according to Figure 5.

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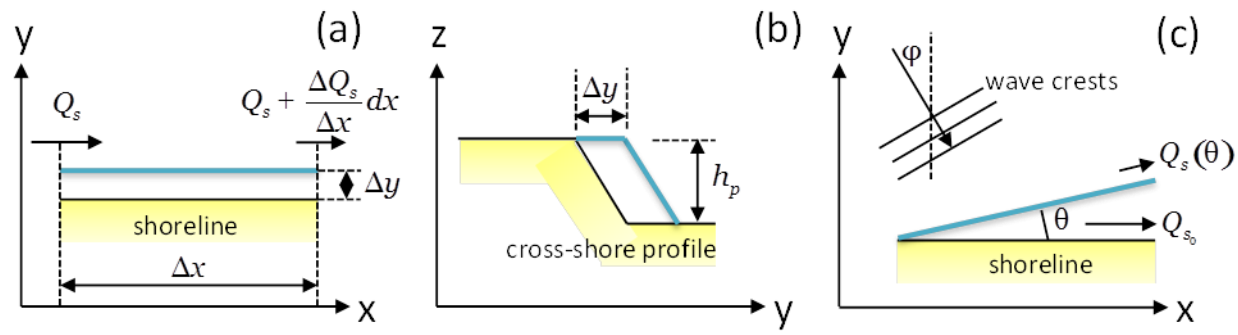

Figure 5: Single Line Theory According to Pelnard-Considère (1956).

Equating the sediments going into Q_s and out of the control area $\left(Q_s + \frac{\Delta Q_s}{\Delta x} dx\right)$ (control area is shown in Figure 5a) results in the continuity equation shown below:

$$\left(Q_s + \frac{\Delta Q_s}{\Delta x} dx\right) dt - Q_s dt = -\frac{\Delta y}{\Delta x} h_p dx dt + q_b h_p dx dt \qquad \text{(Eqn. 10)}$$

Where:
- x = longshore coordinate
- y = cross-shore coordinate
- t = time (years)
- d = indicates total (ordinary) derivative
- Δx = longshore length of the control area (m)
- Δy = cross-shore shoreline change of the control area (m)
- Q_s = total longshore transport (m^3/year)
- h_p = height of the active profile (i.e. the part of the profile that changes due to the longshore transport gradients) (m)
- q_b = source/sink parameter which can be used to represent effects of river discharges (source) or cross-shore erosion due sea level rise or overwash. (m^3/year)

The equation of motion can be derived from Figure 5c by assuming that the longshore transport is a (continuous) function of the coastline orientation (θ). This leads to:

$$Q_s(\theta) = Q_{s_0} + \theta \left(\frac{\partial Q_s}{\partial \theta}\right)_{\theta=0} + \frac{1}{2}\theta^2 \left(\frac{\partial^2 Q_s}{\partial \theta^2}\right)_{\theta=0} + \ldots \qquad \text{(Eqn. 11)}$$

Where:
- Q_{s_0} = longshore transport for the initial coastline orientation
- ∂ = indicates partial derivative
- θ = coastline orientation.

With the assumption that second order and higher terms can be neglected the above equations simplifies to:

$$Q_s(\theta) = Q_{s_0} + \theta \left(\frac{\partial Q_s}{\partial \theta}\right)_{\theta=0} \qquad \text{(Eqn. 12)}$$

Assuming small angles:

$$\theta = \tan\theta = \frac{\partial x}{\partial y} \qquad \text{(Eqn. 13)}$$

and defining

$$-\frac{\partial Q_s}{\partial \theta} = S_1 \qquad \text{(Eqn. 14)}$$

the longshore transport can be described as a function of the coastline orientation (equation of motion):

$$Q_s(\theta) = Q_{s_0} - S_1 \frac{\delta y}{\delta x} \qquad \text{(Eqn. 15)}$$

Where: S_1 = the variation of the transport as a function of the coastline orientation.

Combining Equations 10 and 15, a simple diffusion equation results (Equation 16) that describes the coastline behavior in combination with a source/sink term:

$$-\frac{\delta y}{\delta t} = \frac{S_1}{h_p}\frac{\delta^2 y}{\delta x^2} + q_b \qquad \text{(Eqn. 16)}$$

A detailed description of single line theory models including empirical, analytical and numerical approaches is found in USACE (2002).

Although single line theory models, termed coastline models herein, are a very useful tool for the prediction of long term coastal behavior on decadal time scales, some of the assumptions may limit their applicability in certain situations. Of major importance is the assumption that the shoreline erosion or accretion is derived from the horizontal movement of the cross-shore profile including the beach, defined as the toe of dune to mean low water, and the shoreface, defined from mean low water to point where beach sand actively oscillates due to wave conditions, is assumed to move horizontally over its entire active profile height, h_p. Refer also to Figure 5b. The beach slope, therefore, does not change. Also, beyond the active profile height, the bottom does not move. The shoreward limit of profile change is located at the top of the active profile. Important implications of this assumption are that only longshore sediment transports are accounted for and that the cross-shore profiles are assumed to be in equilibrium.

Additional processes that may influence the coastline development (e.g., interaction with adjacent inlets or breaching, overwash and post-storm recovery) can be incorporated in the source and sink term in the above equation (q_b). Only the aggregated sediment volume that affects the coastline response should be incorporated. This implies that the coupling of the coastline model to inlet models and/or cross-shore profile models requires the aggregation/transformation of potentially complex model outcomes to a single volume source or sink rate.

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5.2.2 Process Based Morphological Area Models

More advanced process based morphological area models are available (e.g., Delft3D, MIKE21, MIKE3). However, the spatial and temporal time scales of the 2017 modeling effort exceed their practical application range. Despite the fact that these models include many detailed hydrodynamic and transport processes, they are often unable to accurately describe the long term coastline evolution (e.g., Van Duin *et al*., 2004 and Grunnet *et al*., 2004). Although progress has been made to simulate cross-shore profile morphology within these morphological area models (e.g., Ruessink *et al*., 2007 and Walstra *et al*., 2012), such process based models require a significant calibration effort.

5.3 Longshore Transport Formulations

Many longshore transport formulations have been developed (e.g., see Bodge (1989) for an overview). All are based on the dual presence of a stirring mechanism (waves) and advective mechanism (longshore). The first transport formulations were based on the total transport concept (i.e., no distinction between suspended and bed load transport components) and usually considered the cross-shore integrated transports (referred to as bulk transports, such as the Coastal Engineering Research Center (CERC), 1984 and Kamphuis, 2000). More advanced transport formulations distinguished between bed load and suspended load (Bijker, 1967, 1971; Van Rijn,1993; and Soulsby, 1997) and even fine material (Van Rijn, 2007a and 2007b). The advanced transport formulations require estimates of the cross-shore wave height distribution, (breaking) wave induced longshore current, orbital velocities, etc. Furthermore, some formulations also include cross-shore transport processes due to wave asymmetry (Van Rijn, 2007a and 2007b).

- CERC (1984) bulk equation (only waves);
- Kamphuis (2000) bulk equation;
- Bijker (1967, 1971) bed and suspended load of sand;
- Van Rijn (1993) bed and suspended load of sand;
- Soulsby (1997) bed and suspended load of sand; and
- Van Rijn (2007a and 2007b) bed and suspended load of sand and fine sediment.

5.4 Summary

Using a single morphological area model application, e.g., MIKE21(DHI, 2009) or Delft3D-Wave (Deltares, 2011), covering the entire study area to simulate barrier shoreline change on a decadal scale would constitute an unprecedented (and impracticably large) computational effort. In contrast, a coastline model application, e.g. longshore transport formulation utilizing CERC (1984), was considered more suitable for the envisaged large spatial and temporal scale applications in the BIMODE model. However, care should be taken not to apply the BIMODE model or use its results beyond its applicability range.

Known limitations of utilizing a coastline model within BIMODE include:

- Assuming a similar alongshore grid resolution as the 2012 model of about 100 m, features or impacts on scales of less than 300 to 500 m cannot accurately be resolved.
- If longshore transport calculations are updated every time step to coincide with the monthly breaking wave output time steps described in Section 4, predicted temporal changes on similar or smaller time scales may be less accurate.

- Gradients in longshore transport should be the main driver of coastline change because coastline models assume a constant cross-shore profile shape. Therefore, breaching, overwash or adjacent inlets should have a relatively small effect on the longshore transport.

Successful calibrated shoreline change simulations on complex barrier islands using coastline models have been performed extensively (e.g., Leadon, 1991, 1995; USACE, 2004; CPE, 2005; CHE, 2007; and CEC, 2011). It should be noted that successful calibration of coastline models does require significant effort and care. The application of coastline modeling within the BIMODE modeling approach improves upon coastline modeling applied for the 2012 barrier shoreline model by including process-based modeling of wave transformation described in Section 4 and cross-shore sediment transport described in Section 6.

Despite the advances that have been made in recent years (e.g., Van Rijn *et al.,* 2013), longshore transport calculations (and as a result the coastline evolution considered here) still require a substantial calibration effort. Especially in complex coastal settings such as the Louisiana coast (e.g. multiple sediment types, inlets, extreme forcing conditions), the prediction uncertainties increase dramatically. This also applies to predictions based on advanced practical transport formulations, which would therefore still require a significant calibration. In other words, it is unlikely that advanced transport models would reduce the calibration effort. Furthermore, simple formulations such as CERC and Kamphuis have a predictable behavior, which facilitates the calibration effort. Complex formulations have the disadvantage of a relatively large number of model parameters and the (combined) effects of these on the model outcomes are not always clear.

Therefore, assuming that a calibration effort with historical shoreline changes is not influenced by the choice of the longshore transport formulation, the application of a simple transport formulation is preferred. The CERC equation is straightforward to code; was previously reviewed, accepted, and applied in the 2012 barrier shoreline model; and was preferred by the BIMODE Team based on personal experience.

Based on the above considerations, the CERC transport formulation is included in the BIMODE model with alongshore varying (site specific) calibration factors derived from an extensive calibration with observed shoreline change and longshore transport rates. Specifically the empirical coefficient (*K* value) in the transport formulation is calibrated to yield predicted transport rates on the same order of magnitude as the published longshore transport rates.

5.5 Calibration Data

A sediment budget is a method to track the location and movement of sediment within a system. The "system" can be broken into various cells, which along with the entire system, are defined by the developer of the sediment budget. The sediment budget can include sources that provide sediment to the system or sinks, which remove sediment from the system.

For the purposes of BIMODE, a sediment budget is applied to define the transport of sediment along various reaches and determine whether the inlets act as a complete sediment sink or whether there is sediment transport across the inlet. Rosati (2009) developed a sediment budget for all of coastal Louisiana, which included sediment within interior bays and sediment located beyond the depth of closure. Morang *et al.* (2013) expanded upon this budget and can provide

a basis for determining cell boundaries, including if and how they interact. Additional data is also available from design reports for various barrier islands restoration projects.

Table 1 defines the various compartments within the study area along with the intervening inlets and whether transport of sand is thought to occur across the inlet and still remain in the active beach profile (above the sand depth of closure). Table 1 was developed starting with the westernmost island, Raccoon Island, in the westernmost region, Isles Dernieres, and moving east through the Timbalier region, Caminada Headland and Grand Isle region, to the Barataria Bay region. Once at Scofield Island, the easternmost island in the Barataria Bay region, the cells were restarted at Breton Island within its region, and moved north through the Chandeleur Island region. Figure 2 shows the location and relation of each of these islands/headlands. Longshore transport rates documented in the literature are presented in Table 1. The longshore transport rates are provided in cubic meters per year (m^3/yr).

Table 1: Proposed Sediment Budget Cells for BIMODE.

Cell	Cell Components	Inlet (sink)	Reference
1	Raccoon Island (21,000-31,000 m^3/yr to west)		CPE, 2004; Stone and Zhang, 2001
		Coupe Colin	
2	Whiskey Island (40,000 m^3/yr loss to Coupe Colin)		Stone and Zhang, 2001
		Whiskey Pass	
3	Trinity Island (46,000 m^3/yr loss to Whiskey Pass) New Cut (periodic breach) East Island		Stone and Zhang, 2001
		Houma Navigation Canal / Cat Island Pass	
4	Timbalier Island (35,000 m^3/yr loss to Cat Island Pass)		Stone and Zhang, 2001
		Little Pass Timbalier	
5	East Timbalier Island (41,000 m^3/yr loss to Little Pass Timbalier)		Stone and Zhang, 2001
		Raccoon Pass	
6	West Belle Pass Barrier Headland (20,000 m^3/yr loss to Raccoon Pass		
		Belle Pass (300,000 cy/yr periodic dredging and bypassing)	Thomson *et al.*, 2009
7	Caminada Headland Caminada Pass (63,000 m^3/yr natural bypass W-E) Grand Isle		USACE, 2004
		Barataria Pass	

Cell	Cell Components	Inlet (sink)	Reference
8	West Grand Terre (23,000 m^3/yr loss into Pass Abel)		
		Pass Abel	
9	East Grand Terre (4,000 m^3/yr loss into Qautre Bayou Pass)		CPE, 2005
		Quatre Bayou Pass	
10	Grand Pierre		
		Long Bay	
11	Chenier Ronquille (31,000 m^3/yr loss to Long Bay) Pass La Mer (natural E-W bypassing between 2,500 m^3/yr and 45,000 m^3/yr) Chaland Headland Pass Chaland (natural E-W bypassing 29,000 m^3/yr) Pass Chaland to Grand Bayou (Bay Joe Wise) Grand Bayou (now closed and likely to remain so) Shell Island West (40,000 m^3/yr loss to Coupe Bob)		Thomson *et al.*, 2011 CPE, 2003 Thomson *et al.*, 2008
		Coupe Bob (estimated potential ebb shoal volume = 4.1M cy)	Thomson *et al.*, 2008
12	Shell Island East (40,000 m^3/yr loss to Coupe Bob)		Thomson *et al.*, 2008
		Empire Waterway	
13	Pelican Island Scofield Pass (8,000 m^3/yr to Scofield Pass) Scofield Island		CPE, 2003
		Mississippi River	
14	Breton Island (241,000 m^3/yr to north, 237,000 m^3/yr to south)		Thomson *et al.*, 2010
		Mississippi River Gulf Outlet Grand Gosier (currently shoals) Curlew Island (currently shoals)	
15	Chandeluer Islands (1,093,000 m^3/yr to the north and 795,000 m^3/yr to the south)		Thomson *et al.*, 2010
		Hewes Point	

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The estimates of sediment transport are used to calibrate longshore sediment transport developed in the BIMODE model. This calibration is for existing conditions only. The compartments listed above are used to determine the terminal end of longshore transport and essentially the terminus of the barrier system. These are applied at the start of the model with island breaching being applied at a later time step, as discussed in Section 7. The sediment transport rates are also used to determine growth at non-structured ends of the system. As the modeling effort proceeds, additional calibration data may be identified to complete blank cells.

It is noted the longshore transport rates for the Breton Island and Chandeleur Island regions are an order of magnitude greater than the other regions, which is attributed to the acute wave angle, relatively deep depth of closure on the order of 30 feet, and profile steepness.

5.6 Silt Loss

Louisiana's barrier islands are composed of sand, silt, and clay. The composition of the erodible face of the island must be considered when predicting future shoreline recession because silt and clay exposed along the Gulf shoreline face are placed in suspension and transported offshore, while the sand fraction remains behind. This sand fraction is then subjected to longshore transport. From a coastal engineering perspective, it is the volume of sand within the system that is important because the sand provides protection from wave attack. The cohesive nature of the silt/clay soil is ignored over the longer term. Marsh outcroppings are exposed along the shoreface following storm conditions suggesting that sand overwashes the island while the cohesive soils may survive the initial passage of the storm. However, the marsh outcrops are then eroded rapidly under average wave conditions reforming a sandy gulf shoreline face well landward of the pre-storm condition The shoreline retreat in the weeks following a storm has been observed to be as large as the retreat during the passage of the storm (Penland *et al.*, 2005).

A non-restored island has higher silt content in the erodible beach face than a restored island. Campbell (2005) suggested that marsh samples should be taken to estimate the silt content in the erodible face of a non-restored island. A sample from within the marsh is a better representation of the erodible face as the shoreline may at one point be at this location with the transient beach face. The silt content in the erodible face of a restored island varies depending on the silt content of the borrow area and whether the beach was constructed in front of the original island or on top of the original island.

Therefore, in addition to shoreline retreat that is determined from the longshore sediment transport rates, shoreline retreat due to silt loss is also computed within the BIMODE model. An estimate of the shoreline retreat is developed based on the percent silt and clay in the erodible face. For example, if a non-restored island with 50% silt and clay is expected to retreat 0.3 m due to longshore transport, the actual shoreline recession is estimated at 0.6 m (1/(1-50%)). However, a restored island with a silt content of 10% retreats 0.33 m for the same 0.3 m estimate of shoreline retreat due to longshore transport (1/(1-10%)).

This theory is based on the dynamic morphosedimentary model by Campbell (2005), which postulated that absent a catastrophic event, the shoreline recession during the storm is matched or exceeded by the recession in the months following the storm. This is attributed to the exposed cohesive sediment withstanding the larger waves due to the limited time element but then eroding under constant but smaller waves and the abrasiveness provided by the sand fraction remaining on the shoreface.

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6.0 Cross-shore Sediment Transport

6.1 General

Cross-shore sediment transport typically refers to a barrier island's profile response to storm events, though profile shaping and retreat also occur during quiescent periods. Given the low elevation of Louisiana's barrier islands, the storm surge and runup can exceed the island crest elevation during storm events. De Sonneville (2006) showed that once Louisiana's barrier islands are overtopped then the sediment transport is predominantly bayward resulting in overwash. Campbell (2005) suggested that overwash stripped the sand veneer from the face of Louisiana's barrier exposing the mixed deltaic sediments, which once exposed experienced high retreat rates until sufficient sand was released to reform the sand veneer. Campbell's theory postulated that the more cohesive sediment withstands the storm event better than the non-cohesive sediment (sand) but in the months following the passing of the storm, the cohesive sediment is essentially abraded away by sand being rubbed across the surface by regular waves. This releases more sand from the mixed deltaic sediment contained within the island core. Once there is sufficient sand on the shoreface, this loss of cohesive sediment slows as the sand covers it. Thus rebuilding Louisiana's barrier islands higher/wider with sand should increase sustainability and longevity.

Other cross-shore transport processes that can rebuild / add elevations include recovery after storms and aeolian processes, and are discussed separately in subsequent chapters.

As part of the model development, the BIMODE Team focused the model approach on the recommendations from the review of barrier island model options (Appendix 1). Specifically, the longshore and cross-shore sediment transport processes are handled separately through a hybrid approach. One of the primary recommendations for improving the 2012 barrier shoreline model was the inclusion of cross-shore processes (e.g., overwash) and thus the BIMODE Team focused a significant work effort on the addition of cross-shore transport processes.

6.2 Model Options

Overwash is one of the major cross-shore transport processes that drives the morphology of Louisiana's barrier islands. Several models are available that can predict the islands' response to storms. A discussion of these models follows.

EDUNE: EDUNE was developed by Kriebel (1995) with Robert Dean as an early collaborator. It is a cross-shore, one-dimensional model that is based on Dean's equilibrium profile theory and uses a finite difference solution. It is an open source code. While quick and easy to apply, it does not include overwash.

Beach-fx: Beach-fx (Gravens *et al.*, 2007) is the USACE's Monte Carlo simulation model for estimating the physical performance and economic benefits and costs of shore protection projects, particularly beach nourishment along sandy shores. It is a cross-shore, one-dimensional model that simulates cross-shore morphologic response to a storm event based on measurement derived, empirical equations. It is a widely used model that has been applied extensively along the Atlantic and Gulf of Mexico developed coastlines to estimate beach erosion and dune lowering and evaluate beach nourishment project performance. While not an open source code, it is possible to run hundreds of simulations quickly. Its limitation includes the

specified berm elevation is fixed and not allowed to vary throughout the simulated lifecycle. Further, breaching is not simulated in Beach-fx.

Delft3D: Delft3D (Deltares, 2011) is one of the more advanced two- or three-dimensional models available for modeling coastal processes. Delft3D incorporates the majority of coastal processes related to waves, winds, currents, water levels, and sediment transport. While it can incorporate overtopping and overwash of the islands, it is computationally intensive requiring longer run times. For example, running a 20-year wave climate for the Chenier Ronquille Barrier Island Restoration project required approximately one week (Thomson *et al*., 2011). It is an open source code.

XBeach: XBeach (Roelvink *et al.*, 2009) is a two-dimensional model for wave propagation, long waves and mean flow, sediment transport and morphological changes of the nearshore area, beaches, dunes and back-barrier during storms. It is an open source code model that has been developed with funding and support by the USACE and a consortium of UNESCO-IHE, Deltares (Delft Hydraulics), Delft University of Technology, and the University of Miami. The model solves coupled two-dimensional horizontal equations for wave propagation, flow, sediment transport and bottom changes, for varying (spectral) wave and flow boundary conditions. Because the model accounts for the temporal variation in wave height, it resolves the long-wave motions created by this variation. This so-called 'surf beat' is responsible for most of the swash waves that actually hit the dune front or overtop it. With this innovation, the XBeach model is better able to model the development of the dune erosion profile, to predict when a dune or barrier island will start overwashing and breaching, and to model the developments throughout these phases. However, this model has not been frequently applied to Louisiana's barrier islands; thus significant time and expense would be required to calibrate and validate its utilization for coastal Louisiana.

MIKE21 and MIKE3: MIKE21 and MIKE 3 (DHI, 2009) models are the two-dimensional and three-dimensional versions of the MIKE suite that use spectral waves and radiation stress to drive sediment transport. These models incorporate the majority of coastal processes related to waves, winds, currents, water levels, and sediment transport. While they can incorporate overtopping and overwash of the islands, the computing time is extensive and the run times are long. The model code is not open source.

SBEACH: SBEACH was developed by the USACE and is operated within the Coastal Engineering Design and Analysis System user interface (Larson and Kraus, 1989). It is a cross-shore, one-dimensional model that simulates cross-shore morphologic response in response to a storm event based on measurement derived, empirical equations. Within SBEACH, volume is conserved. It is a widely used model that has been applied extensively in coastal Louisiana to estimate dune lowering and overwash extents across barrier islands. While not an open source code, which negates the ability to include the code directly into the model, it is possible to run hundreds of simulations quickly. These runs can then be recalled through a look-up table to determine the likely output profile given the starting input profile and storm characteristics. The model has the ability to predict the cross-shore transport and overwash physical processes, has been used extensively in the design of Louisiana barrier island restoration projects, and is capable of running hundreds of simulations cost effectively with reasonable run times.

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6.3 Summary

6.3.1 Model Selection

The evolution of the barrier islands off the Louisiana coast involves the storm-driven overwash processes that produce barrier island rollover and a progressive lowering of barrier island elevations including the berm elevation. The barrier island rollover process and subsidence of the unconsolidated underlying marsh platform leads to narrowing of barrier island width and ultimate breaching of the island.

As EDUNE does not include overwash, and it is not recommended for the BIMODE model.

As some of the key processes cannot presently be simulated with Beach-fx and that the model is closed source precluding its direct integration within the model. Therefore, Beach-fx is not recommended for the BIMODE model. However, several of the concepts employed in the formulation of Beach-fx are incorporated into the BIMODE model, specifically the use of a pre-computed database of beach profile response to storm conditions is used to evolve the barrier island profiles through time within the BIMODE model.

Due to the spatial scale of the focus area and temporal scale of the ICM, and the complexity associated with integrating its code within the ICM, the use of Delft3D is not recommended.

Although XBeach is specifically designed to simulate storm/hurricane impact, its incorporation into the BIMODE model would increase the model simulation time and model complexity an order of magnitude or greater than the other one-dimensional cross-shore transport models considered herein. Perhaps in future applications of BIMODE, specific aggregated XBeach results could be used as local background erosion/retreat values.

Due to the spatial scale of the focus area and temporal scale of the ICM and that the models are closed source precluding their direct integration within the model, MIKE21 or MIKE3 are not recommended for the BIMODE model.

SBEACH is a cross-shore sediment transport model that predicts the response of the barrier islands to a variety of storm events including overwash. This model has been extensively applied during previous modeling efforts for Louisiana barrier island restoration projects and is relatively quick and easy to run. The drawback of the source code not being available can be overcome by running the model externally and then using look-up tables to return the expected post-storm profile for a given storm event. As SBEACH is a widely used and recognized model and the calibration parameters are readily available, SBEACH was the preferred choice for the BIMODE model. Further, the BIMODE Team improved calibration of the SBEACH model for coastal Louisiana to demonstrate the predictive capability of the model across the focus area for the selected range of storms.

Due to the spatial scale of the focus area and temporal scale of the ICM, and the complexity of the models required to predict sediment transport adjacent to inlets, bayward transport around the ends of the islands or through breaches is not accounted for in the model.

6.3.2 Calibration Data

Several barrier island restoration projects were under construction when Hurricane Isaac struck the Louisiana coastline in August 2012. Pre- and post- storm profile data were available for use in

improving the calibration of the coefficients employed within SBEACH for coastal Louisiana to yield more accurate predictions of overwash and erosion due to storms.

6.3.3 Model Implementation

The first phase was a proof of concept where a small subset of storms and profiles were modeled. In this proof of concept, there was a representative static submerged profile extending from mean low water gulfward defining the offshore profile shape, one for each region (Isles Dernieres, Timbalier, Caminada Headland and Grand Isle, Barataria Bay, Breton Island, and Chandeleur Island). On each base profile, 24 cross-sections were overlaid with a combination of varying dune heights, dune widths and berm widths. Several of the combinations represented pre-restoration barrier island profiles versus restored barrier profiles. Given six regions and 24 combinations, a total of 144 profiles were modeled. Seven storm events were developed (e.g., 1, 2, 5, 10, 25, 50 and 100-year return period). Thus a total of 1008 storms runs were performed.

Following the proof of concept, a wider array of storms and cross-sections were required. The typical restored barrier profiles were based upon the barrier island/headland conceptual design templates depicted in Appendix A of the 2012 Coastal Master Plan (CPRA, 2012). The standard templates were expanded upon to account for a full range of anticipated template parameters. The cross-sections for the final model have a minimum template of 7.6-m dune width. The dunes were increased at 7.6-m increments to a width of 120 m. The dune elevation was increased at 30-cm increments from +1 m, NAVD to +3 m, NAVD. A berm width for the Caminada Headland reach was added with a minimum width of 7.6 m increasing the width at 7.6-m increments up to 120 m wide. Combinations also represented pre-restoration barrier island profiles, which were covered in the suite of SBEACH cross-sections. This fell under starting conditions of contour widths.

The parameters that remained the same were the berm elevation = +0.9 m, NAVD, corresponding to barrier island berm elevations, which are fairly consistent across the coast as they relate to the average wave climate, marsh platform width of 300 m, and marsh platform elevation of +0.6 m, NAVD. The dune slopes also remained unchanged and are based on a post-storm (SBEACH) slope.

The range of storms for use in the final model was provided by CPRA.

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7.0 Breaching

7.1 General

In the context of the BIMODE model, barrier island breaching is defined as a new opening in the barrier island that allows water to flow between the Gulf of Mexico and the back bay. Breaching typically occurs on Louisiana's low-lying and narrow barrier islands when inundation during storm events causes strong currents to flow across the island and focus where dunes are absent or low. Breaching may occur from either the gulfside or the bayside. As barrier islands breach, their geomorphic form reduces and they lose their capacity to protect estuaries and bays; and the reduction in supratidal and intertidal land area diminishes the barrier islands' ecologic function. Further, the reduction in land area results in increased tidal prism. Breaches that remain open form new inlets, which capture part of the tidal prism. This combined with subsidence and sea level rise increases currents, thereby reducing sediment bypassing to adjacent islands and further fragmenting the barrier island system.

7.2 Model Options

Based upon the literature review, no industry standard empirical or theoretical numerical models existed for prediction of barrier island breaching along the Gulf coast. Options that were available for consideration in the BIMODE model include the following.

Basco and Shin (1999) developed a one-dimensional approximation of the physical processes involved in barrier island breaching. They defined a new inlet as a breach event whereby the low profile section lies below the Mean Lower Low Water elevation at the conclusion of the storm. For each successive time step, the tide cycle causes water to flow through the new inlet. They did not attempt to determine the complexity of whether the new inlet would remain open or if post-storm recovery and breach closure would occur. Their approach utilized SBEACH for dune/beach erosion, a Lax-Wendroff explicit scheme to simulate flood propagation on initially dry barrier islands, a Preissman implicit scheme for water motion, and a forward-time, centered-space explicit scheme for sediment motion to study the volume change and sediment motion of the cross-section profile for the selected storm suite. Sensitivity testing was performed and comparisons made to validate the integrated numerical model.

Kraus *et al*. (2002) conducted a literature review and found that while there are qualitative reports and case studies of barrier island breaching, there was little information on the physical processes and modeling of the processes regarding breaching. Their work included development of a susceptibility index to classify breaching potential by storm surge and inundation given by Equation 17. The basis for the index is that a barrier island will achieve an elevation on the order of the highest regular tide, wave and wind set up plus wave runup. If the storm surge accompanied by the setup and runup approach the diurnal tide range, then breaching is likely. The higher the index, the more likely a breach is to occur. They examined a case study in California as well as provided representative values of the index for the Atlantic and Gulf coast states.

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$$B = S_{10} / R \qquad \text{(Eqn. 17)}$$

Where: B = breach susceptibility index
S_{10} = effective surge level for the 10-year storm as defined by water level
R = diurnal tidal range.

As part of the Louisiana Coastal Area Study, the USACE and CPRA co-sponsored two major barrier shoreline integrated feasibility studies and environmental impact statements in the Barataria Basin (USACE, 2012) and Terrebonne Basin (USACE, 2010). Both studies examined the geomorphic and ecologic form and function of the barrier islands and defined the critical values, that is, minimal thresholds, for the beach, dune and marsh platform components through detailed coastal processes analyses, comparisons to historical barrier island physical characteristics, and application of historical barrier island evolution patterns. SBEACH modeling was conducted to evaluate post-storm conditions and confirm the minimal thresholds for the island components were retained after being subjected to the selected storm suite. The SBEACH results provided a means to examine a range of profile shapes (widths and elevations for both beach berm and dune) subjected to a range of probabilistic storms and determine the critical widths for barrier island breaching.

An analysis of barrier island breaching was conducted by Coastal Engineering Consultants (CEC) on behalf of CPRA. Utilizing available literature on barrier island breaching, barrier island restoration project data, measured shoreline positions over time, and scale photography along coastal Louisiana (e.g., CEC, 2013; USACE, 2012; USACE, 2010; Martinez, 2009; Thomson *et al.*, 2009; URS, 2008; SJB, 2007; CPE, 2003; McBride *et al.*, 1995; and Penland and Suter, 1984), historical breaches were identified that interrupt longshore sediment transport, thereby resulting in barrier island segregation and formation of a new inlet. The analysis measured the critical parameters pertaining to the identified breaches. These parameters include the pre-storm island width and updrift (distance from breach to updrift island end) and the post-storm breach width, and island length, as well as the ratios of island width to updrift length and breach width to total length (Table 2.)

Table 2. Barrier Island Breach Data and Breaching Criteria.

Island / Headland	**Pre-Storm**			**Post-Storm**		
	Min. Island Width (m)	**Updrift Length (m)**	**Width to Length Ratio**	**Breach Width (m)**	**Island Length (m)**	**Width to Length Ratio**
Raccoon	100	2,710	3.8%	670	5,430	12.4%
East Timbalier	90	2,010	4.5%	1,220	6,980	17.5%
West Belle Pass	90	2,830	3.2%	640	3,540	18.1%
Chaland Headland	30	3,720	0.8%	370	5,090	7.2%
Bay Joe Wise	50	2,620	1.9%	1,340	6,130	21.9%
Scofield	40	1,460	2.7%	950	3,440	27.4%

The other critical parameter to determine is the ratio of both updrift and downdrift length to island length. These should be greater than 27% or more from adjacent inlets. Dr. Ioannis Georgiou of the University of New Orleans (UNO) has conducted a similar analysis of the Chandeleur Islands, which yielded similar breaching criteria as the CEC analysis (Ioannis Georgiou, 2014, pers. comm.).

7.3 Summary

Based on review of available literature, knowledge and experience in design and monitoring of restoration projects along coastal Louisiana, and professional judgment, the BIMODE Team concluded that barrier island width and width to length ratio are the primary criteria for predicting if a breach will occur and interrupt longshore sediment transport, thereby forming a new inlet. The following breaching criteria are applied in BIMODE each time a storm event occurs within the simulation based on the breach data presented above:

- island width = 60 m;
- the ratio of both updrift and downdrift length to island length = 27%;
- island width to updrift length ratio (pre-storm) = 3%; and
- breach width to length ratio (post-storm) = 15%.

The critical values of island width, ratio of both updrift and downdrift length to island length, island width to updrift length ration and breach width to length ratio are checked one by one to determine whether a breach occurs.

The following process occurs once it is determined that a breach occurs. If the profiles do not exceed the critical width and width to length ratios it is assumed the breach "heals" itself and longshore transport continues. If the profiles exceed the critical width and ratio width to length sand are greater than 27% or more from the adjacent inlets, the profiles are "turned off" and treated as a new inlet. For additional information, refer to inlets and bays coding in Section 8.

The BIMODE Team also contemplated incorporating the geology, subsurface conditions, and site constraints into the model; however, consensus was this would be too challenging to code due to the number of variables including but not limited to the number of islands, geological diversity within each region, varying subsurface conditions both in the longshore as well as the cross-shore directions, and presence or absence of oil and gas infrastructure / canals.

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8.0 Inlets and Bays

8.1 General

Barrier chains, comprising 15% of the world's coastlines, consist of sandy islands separated by tidal inlets that allow water and sediment exchange between the back-barrier environment and coastal ocean (e.g., Ranasinghe *et al*., 2013). Tidal currents maintain a channel by removing wave-deposited sand and building ebb- and flood- deltas seaward and landward of the inlet throat, respectively (Hayes, 1979 and FitzGerald, 1984). Both inlet cross-sectional area and the volume of sand comprising the ebb delta shoal positively correlate to the tidal prism (Jarret, 1976; O'Brien, 1969; and Walton and Adams, 1976). Loss of back-barrier wetlands due to rising sea level increases tidal prism, thereby enlarging the volume of the ebb delta and dimensions of the inlet throat (FitzGerald *et al.*, 2008). The increasing water levels in the basin reduce frictional damping of the tidal wave, increasing the back-barrier tidal range, which further augments the prism (Howes *et al.*, 2013). Increased accommodation space in the back-barrier promotes the formation and enlargement of a flood-tidal delta. While some sand for the ebb and flood delta enlargements comes from incision and expansion of the inlet throat, most is removed from the adjacent barrier island shoreface littoral cells. The expanding capacity of the ebb-tidal delta in particular may greatly diminish the amount of sand bypassing the inlet through longshore transport, decreasing sediment supply to the downdrift barrier and hastening the transition to a transgressive island chain (FitzGerald, 1984 and FitzGerald *et al.*, 2008). The inference here is that as the tidal prism increases, the capacity of the ebb-tidal delta increases and in a limited sediment supply system, reduces bypassing because more sand goes to feed the ebb shoal.

8.2 Modeling Options

8.2.1 Inlet hydrodynamics

Inlets serve as conduits of tidal exchange between the coastal ocean and interior basins. Bruun and Bruun and Gerritsen (1960) gave this definition for a tidal inlet, which is the most common type of coastal inlet: "A tidal inlet is the waterway connection between the sea and a bay, a lagoon, or a river entrance through which tidal and other currents flow." Regardless of the inlet origin (e.g., geologic such as the Golden Gate, hydrological where a river enters the sea, or littoral such as openings through barrier islands), a tidal inlet must maintain sufficient velocity through its cross section to maintain the channel of the inlet; without tidal flow the channel closes. Knowledge of inlet hydrodynamics is critical to determining whether inlets remain open, enlarge, or close because of insufficient current to transport sediment through the inlet. The Eco-hydrology model used in the 2012 Coastal Master Plan modeling effort did not provide detailed hydrodynamics, although a single velocity for every time-step is available. For example, additional information to carry inlet stability calculations were reported by Escoffier (1940, 1977) as well as van de Kreeke (1990), and include tidal velocities, bottom shear stress, and cross sectional area at the inlet throat. These data can be used to estimate equilibrium shear stresses based on knowledge or friction factors at each inlet, following methodology presented by van de Kreeke (1990). This information is important in determining the ebb-jet size and structure, and helping evaluate sediment transport in the vicinity of the inlet and how hydrodynamics in the vicinity of inlets interrupt transport or alter sediment bypassing volumes (Kraus, 2000).

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8.2.2 Inlet Morphology

Morphology (e.g., the cross sectional and overall shape of an inlet) is governed by several parameters including inlet hydrodynamics and hydraulic characteristics. These include the hydraulic radius, shape of the cross section near the inlet throat and nearby environments, stratigraphy in the vicinity of the inlet including the depth of hard-to-erode substrate, presence/absence of anthropogenic structures (jetties or terminal groins), relative forces of tide versus wave dominance near the entrance, sediment supply and direction of the long shore transport, size and shape of the ebb-tidal delta, and orientation of the inlet throat (Hayes, 1979; FitzGerald, 1984; and FitzGerald *et al.*, 2000). One requirement for assessing the dynamics of an inlet's cross-sectional area is knowledge of the tidal prism of the receiving basin. If known, then the inlet can be adjusted using a minimum equilibrium cross section given by published relationships (e.g., Jarret, 1976 and O'Brien, 1969), which have been modified into what is known as the O'Brien–Jarrett–Marchi law (D'Alpaos *et al*., 2009). Additional models for inlet cross sectional evolution over time using analytical methods were developed and presented by Larson *et al*. (2011). The basic O'Brien relationships were implemented in the 2012 barrier shoreline modeling with their corresponding exponents representing un-jettied Gulf coast inlets. This includes the general form of the equation (Equation 18). 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 (D'Alpaos *et al*., 2009) given by:

$$A = kP^a \qquad \text{(Eqn. 18)}$$

Where A = inlet cross-sectional area
k = Gulf coast coefficient
P = maximum tidal prism
a = exponent for the Gulf coast inlets.

The total tidal prism for a basin is defined as:

$$P = A_1T_1 + .. + A_nT_n \qquad \text{(Eqn. 19)}$$

Where P = tidal prism for the basin (estuary)
T = tidal range (m) for the nth hydrodynamic cell in the basin
A = area (open water) of the cell
n = the number of cells which make up a given bay or estuary.

The application of these relationships within BIMODE is described in Section 8.3 below.

This simple implementation however neglects complex processes such as inlet migration, which in some Louisiana barrier islands can be important through the course of 25 to 50 years (Miner *et al*., 2009a and Miner *et al*., 2009b). Levin (1993) presented a classification scheme of Louisiana inlets, on the basis of previous work by Hubbard *et al.* (1979), which recognized wave, tidal or mixed morphology inlets. This approach however only approximately describes the planform and submerged morphology qualitatively. Using an in-depth analysis of tidal prism and inlet geometry, Howes *et al.* (2013) presented more specific quantitative metrics to classify inlet morphology on the basis of additional hydraulic characteristics and namely the hydraulic radius. The methodology proposed here, although simple, is very powerful and can be implemented immediately. Although the omissions appear significant, their relative contribution to inlet morphology is rather small compared to the dominant effect of the tidal prism, which is already

addressed. Furthermore, there is limited information to describe these additional dynamic process associated with inlet evolution, and collecting more data to develop relationships that better constrain first order response was not achievable within the time frame of this effort.

8.2.3 Interaction of Inlets with Nearby Environments

Obviously, since inlets connect the coastal ocean and interior bays, any model used to assess this interaction must be at least able to force exchange caused by pressure gradients across the inlet. Most models, including the Eco-hydrology model developed for the 2012 Coastal Master Plan, can already address this. This computation is critical for calculating tidal prism.

Inlets are often associated with ebb (and/or flood) deltas or shoals. Knowledge of ebb delta morphology and dimensions is critical for correctly interpreting processes in the nearshore environments near barriers. For example, sediment bypassing is a process associated with inlets; however, ebb deltas often control the temporal and spatial aspects of sediment bypassing inlets and impose additional sediment sinks/sources that could significantly affect the longshore sediment transport budget. FitzGerald *et al.* (2000) suggested natural mechanisms for sediment bypassing at tidal inlets. Their study, supplemented by additional data from previous research, concluded that the governing variables for sediment bypassing include tidal prism, inlet geometry, wave and tidal energy, sediment supply, spatial distribution of back-barrier channels, regional stratigraphy, slope of the nearshore, and engineering modifications (if present). Kraus (2000) extended this work further to develop a quantitative tool for ebb-shoal evolution and sediment bypassing at inlets. This mathematical model calculates the change in volume and sand-bypassing rate at ebb-tidal shoals. This is done by distinguishing bypassing bars from attachment bars, allowing for the transfer of sediment across the distal ebb-delta (shoal) (Figure 6). The volumes and bypassing rates of these morphologic entities are calculated by analogy to a reservoir system, where each reservoir can fill to a maximum (equilibrium) volume. The ratio of the input longshore sand transport rate and the equilibrium volume of the morphologic feature is found to be a key parameter governing morphologic evolution. The model was validated with observations in Ocean City inlet, Maryland, and used to test deviation in sediment bypassing volumes as a result of mining of the ebb-shoal through a hypothetical idealized scenario.

While the reservoir model presented in Kraus (2000) is robust and easy to implement, the data to validate this model along all inlets in coastal Louisiana is lacking. In Louisiana, there are several inlets (e.g. Coupe Colin, Whiskey Pass, Little Pass Timbalier) that are not well defined; they are transgressive systems and tend to be wave influenced and storm-dominated. These inlets are especially important for several reasons. First, although they are rather large inlets (3-5 km across), they have a narrow active channel and thalweg (1-2 km) and are flanked on one or both sides by a shallower subaqueous platform. The flow dynamics of the thalweg and adjacent platform areas have significant influence on sediment transport (both longshore and cross-shore), something that can critically affect barrier island evolution as well as the evolution of the ebb-delta. This made application of a reservoir type model difficult, without additional data to calibrate and validate. Thus the reservoir model (Kraus, 2000) was not recommended for utilization in BIMODE.

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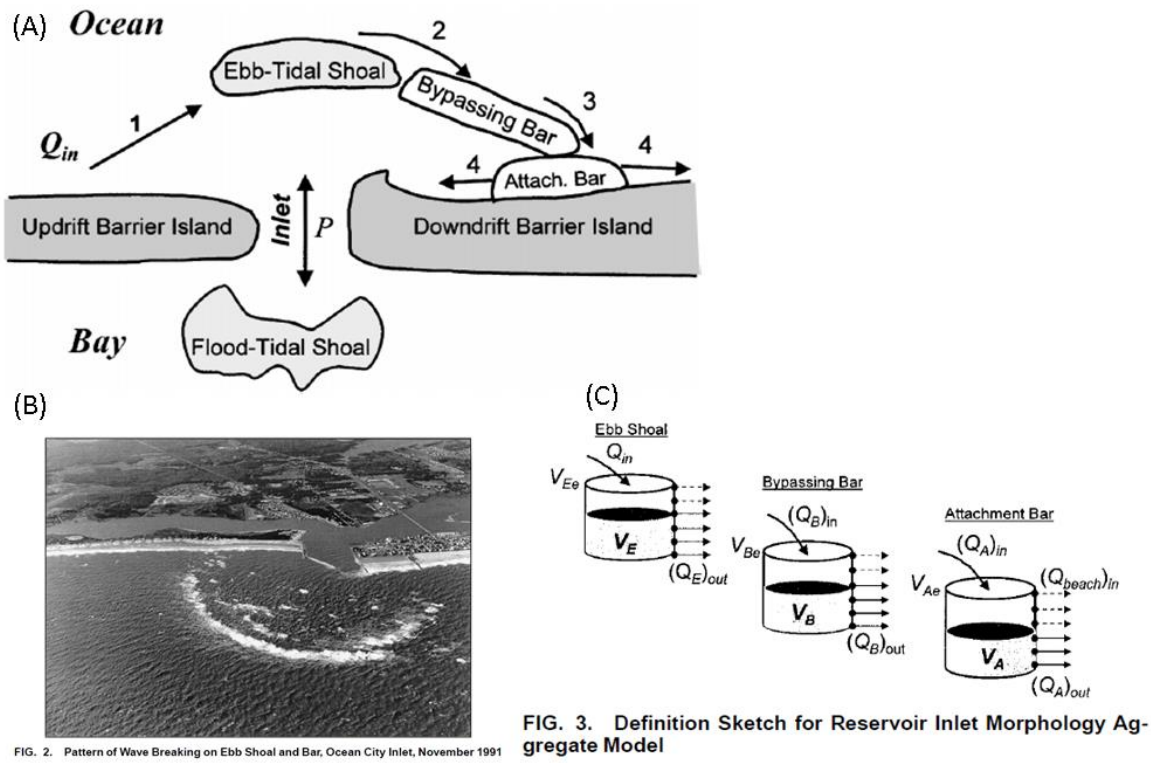

Figure 6: Reservoir Model for Ebb-Delta Growth and Sand Bypassing Volume Calculation (Kraus, 2000).

8.3 Summary

The following methodology based on equilibrium theory is included in the BIMODE model. The methodology remains similar to 2012 modeling and is listed again below.

Using equilibrium theory, the likely increase in the inlet cross-sectional area is computed using the Gulf coast version of the Jarrett-O'Brien-Marchi relationship (D'Alpaos *et al.*, 2009) given by Equations 18 and 19, recognizing that the Gulf coast relationship was derived from well-defined inlets.

In the 2012 model, this calculation was done using maximum monthly tidal range multiplied by the area of the corresponding Eco-hydrology model cell (or compartment), and integrated across the entire basin to compute the tidal prism every month. For the 2017 modeling, the annual mean tidal prism volumes for compartments contributing to the tidal flow into/out of each island's respective bays are calculated and passed to BIMODE. The daily tidal prism is calculated by the hydrology subroutine of the ICM for each hydrologic compartment as: daily tidal prism = (daily high water – daily low water)*(open water area). The annual mean value of these daily tidal prisms is calculated for each compartment and summed for the compartments designated as influencing each group of islands and their inlets. Therefore each group of BIMODE islands uses a different tidal prism volume that reflects the variation in tidal range across the interior bays.

9.0 Aeolian Processes

9.1 General

The liberation, transport and consequent deposition of sand by wind-driven processes occurs when sediment is available and sufficient strength winds are present (Kok et al., 2012). Along sandy coastal barrier systems aeolian processes are a mechanism of sediment transfer from the beach to supratidal dune systems and dune systems into lower tidal elevations such as the beach face and nearshore (Ritchie and Penland, 1990). Sediment transport by wind is a highly dynamic process that can result in the temporary (transport into the littoral zone) or longer time scale (fully developed supratidal dune fields) sequestration of sediment across a range of barrier shoreline environments.

The median grain size of Louisiana sandy barrier headlands and barrier island systems falls within the fine sand range of 0.09 mm to 0.14 mm (Campbell *et al*., 2005). This sediment class can readily be moved by aeolian forces and summer thunderstorm activity; tropical cyclones and pre-frontal south winds that accompany the passage of winter cold fronts and post-frontal north winds all generate sustained wind velocities that are capable of silt and sand transport along the Louisiana coast through suspension, saltation, or bed surface creep.

The depositional patterns and magnitude of aeolian transported sediment are however very poorly understood along the Louisiana coastal zone and adequate data do not currently exist to provide a calibrated numerical model of aeolian sediment movement. However, aeolian transport science does provide several methods and approaches to the calculation of aeolian sediment transport.

9.2 Model Options

There exists a variety of approaches to calculating sediment flux by wind driven transport. In general the existing quantitative approaches rely fundamentally on knowledge of wind speed, median grain size, and air density (variable by humidity) to determine critical values allowing for aeolian sediment motion.

9.2.1 Bagnold Method

According to the Bagnold equation (1941), the discharge of sediment in kg/s/m width is:

$$q = C\left(\frac{d}{D}\right)^{0.5}\left(\frac{\rho_a}{g}\right)U_*^{\,3} \qquad \text{(Eqn. 20)}$$

Where:

q	=	sediment discharge (kg/s/m)
C	=	a constant equal to 1.8 for dune sand
d	=	mean grain size diameter
D	=	reference grain size of 0.25 mm
g	=	acceleration due to gravity
ρ_a	=	air density
U_*	=	shear velocity (m/s).

For the temperature range of -10° C to 50° C, errors in air density due to humidity are less than 0.2%. Therefore, the effects on air density due to humidity can be ignored (Masamichi *et al.*, 2008). The value for shear velocity, U_*, can be found with the equation:

$$U_* = 0.4 \left[\frac{U_{5m}}{log\left(\frac{5}{Z_0}\right)}\right] \quad \text{(Eqn. 21)}$$

Where: U_{5m} = wind speed at 5 m
Z_0 = roughness length (assumed to be 0.02m).

Subsequently, Bagnold formulated a different equation for estimating q in metric tons/hr/m width:

$$q = 5.2 \times 10^{-4}(U - U_c)^3 \quad \text{(Eqn. 22)}$$

Where: q = sediment discharge (metric tons/hr/m)
U = wind speed in cm/s at 1 m above the ground surface
U_c = threshold velocity of 400 cm/s.

9.2.2 Hsu Method

Hsu (1974, 1987) formulated relationships connecting sediment transport to the Froude number given by the following equations:

$$q = H \left[\frac{U*}{(gd)^{0.5}}\right]^3 \quad \text{(Eqn. 23)}$$

Where: d = mean grain size diameter (cm)
U_* = shear velocity (cm/s)
g = accleration due to gravity (cm/s^2)
H = aeolian sand transport coefficient with same dimensions as q (g/cm-s) and can be found with the relationship:

$$\ln(H) = (-0.42 + 4.91 d_{lower}) \times 10^{-4} \quad \text{(Eqn. 24)}$$

Where: d_{lower} = grain size (mm).

For dry beaches, Hsu (1974, 1987) created a relationship between wind speeds at a height of 2 m and the shear velocity given by the following equation:

$$U_{2m,t} = \frac{U_{*t}}{0.044} \quad \text{(Eqn. 25)}$$

Where: $U_{2m,t}$ = threshold wind speed at height of 2 m
U_{*t} = threshold shear velocity.

Manipulation of drag coefficient equations yields the formula:

$$U_{5m,t} = \frac{\left[U_{*\mathrm{t}} ln\left(\frac{Z_2}{Z_1}\right)\right]}{k + U_{2m,t}} \qquad \text{(Eqn. 26)}$$

Where:

$U_{5m,t}$	=	threshold wind speed at height of 5 m
z_2	=	anemometer height of wind speed measurements
z_1	=	2 m (from Hsu's relationship)
k	=	von Karman's constant (0.4).

Wind speeds exceeding this value of $U_{5m,t}$ are able to transport sediment, whereas velocities smaller than the threshold wind speed are assumed to have a transport rate of zero. If $U_{5m} > U_{5m,t}$ the following equation is applied to find the shear velocity:

$$U_* = 0.044\, U_{5m} \qquad \text{(Eqn. 27)}$$

Where: $\mathrm{U_{5m}}$ = wind speed at 5 m and should be converted to cm/s to produce a U_* value (cm/s).

To calculate the sediment transport rate, a formula by Hsu (1987) states:

$$q = K\left[\frac{U_*}{(gd)^{0.5}}\right]^3 \qquad \text{(Eqn. 28)}$$

Where:

q	=	sediment transport rate (g/cm^{-s})
g	=	accleration due to gravity (cm/s^2)
U_*	=	shear velocity (cm/s)
d	=	median grain size diameter (cm)
K	=	dimensional aeolian transport coefficient with the same dimensions as q and calculated by:

$$K = e^{-9.63+4.91d} \qquad \text{(Eqn. 29)}$$

Where: d = median grain size diameter (mm), regardless of the units of K.

This equation for K cannot be applied if the mean grain size diameter exceeds 1.0 mm.

9.2.3 CEM Method

The Coastal Engineering Manual (CEM) (USACE, 2002) employs a method of calculating transport rates based primarily on Bagnold (1936, 1941) and Hsu (1974, 1987) transport rate equations. The CEM method first calculates the threshold wind speed or the wind speed required to initiate the movement of sand particles. This critical shear stress (or threshold wind speed) is provided by Bagnold (1941) with the equation:

$$U_{*\mathrm{t}} = A_t \left\{\frac{[(\rho_s - \rho_a)gd]}{\rho_a}\right\}^{0.5} \qquad \text{(Eqn. 30)}$$

Where: A_t = a dimensionless constant equal to 0.118
ρ_s = sediment's mass density
ρ_a = air density
g = acceleration due to gravity (m/s$^{2)}$
d = the lower limit grain size diameter (m).

This equation yields a threshold velocity in m/s for the dimensions specified.

The final step of the CEM Method requires the determination of a volumetric transport rate from the mass transport rate, indicating

$$q_v = \frac{q}{[p_s(1-p)]} \qquad \text{(Eqn. 31)}$$

Where: q_v = volumetric transport rate (cm^3/cm^{-s})
q = sediment transport rate (g/cm^{-s})
p_s = sediment mass density (g/cm^3)
p = porosity of the in situ sand (assume = 0.4).

This volumetric transport rate can be converted to m^3/m-s if multiplied by 10^{-6} and tons/hr/m if multiplied by 0.360.

9.3 Summary

Though these types of quantitative approaches provide estimates of aeolian transport, there exists a fundamental lack of parameters and data for the Louisiana sandy shoreline to effectively model aeolian transport patterns and sediment volumes.

First, there exists a wide range of variability in the average wind speed, wind patterns, and frequency of events that can generate velocities capable of aeolian sediment transport. In the absence of wind climate with good spatial and temporal variability, predicted rates would likely be unrealistic. Furthermore, information on the wind boundary layer is lacking and hence correct estimations of shear velocity are not achievable.

Second, there has been no comprehensive inventory of the sediment properties and characteristics of dune systems along Louisiana sandy barrier shorelines since the late 1980's to early 1990's (e.g., Ritchie, 1989 and Ritchie, *et al*., 1992). Consequently, there currently exists no fully compiled and current inventory of dune characteristics or the types of morphologic responses that Louisiana coastal dune systems have undergone in response to overwash processes and winds by which to calibrate and validate quantitative aeolian models.

Finally, information and data that are required to correctly characterize lag effects after storms associated with sand transport are limited. For instance, post-storm, formerly subaerial sand is often supply limited and stored offshore. Lag effects associated with the introduction of sand first into the littoral zone, then onto a deflated berm is also lacking, making modeling of these processes extremely challenging.

Based on the lack of data (e.g., wind boundary layer, inventory of dune characteristics and their types of morphological responses, and lag effects after storms), the BIMODE Team considered it

unreasonable to attempt incorporating aeolian transport equations into the BIMODE model. There is value however in considering that aeolian transport may play a positive role in barrier island longevity and supratidal elevation gain following barrier renourishment efforts when sufficient sand is available to the system, and several Louisiana barrier island restoration projects have incorporated aeolian concepts into renourishment engineering. For degraded barriers with limited sediment supply there appears to be no net benefit to the placement of dune fencing.

The 2017 Coastal Master Plan vegetation modeling team evaluated minimum elevations for the barrier island vegetated dune communities. Based on their evaluation (Jenneke Visser, 2012, pers. comm.), they established that dune vegetative species occur at the first point traveling landward of the Gulf where the elevation equals 0.698 m above mean sea level. Based upon the knowledge, experience, and professional judgment of the BIMODE Team, this is a conservative estimate and will support dune vegetation in the wake of significant storm impacts and overwash.

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10.0 Post-Storm Recovery

10.1 General

In the context of BIMODE, post-storm recovery is defined as the return of sediment (which was eroded during the storm) to the barrier island that contributes to the re-establishment of its geomorphic form and ecologic function from natural processes. Recovery of the barrier islands in the wake of significant storm events has been documented in the literature, e.g., Kahn (1986), Fearnley *et al.* (2009), and Martinez *et al.* (2009). These historical analyses demonstrate recovery periods whereby the shorelines accrete or experience less severe erosion compared to storm periods.

Dingler and Reiss (1995) reported that Hurricane Andrew, which passed directly over Isles Dernieres in 1992, stripped all the sand from Trinity Island's beach face, exposing the underlying mixed sediment core. It was estimated that the impact of the storm resulted in approximately 90 m of berm crest migration to the north and a sediment loss of approximately 80 m^3/m from the shoreline. Observations conducted one year after the hurricane's passage indicated the core remained exposed and the upper foreshore eroded over 24 m.

Stone *et al.* (2007) examined the impacts of Hurricanes Andrew (1992), Lili and Isidore (2002) and Katrina and Rita (2005), which all caused significant damages to the barrier islands within the study area. They reported that while post-storm recovery does occur, it is very slow and the multi-decadal increase in both storm frequency and intensity is resulting in a net loss in the overall sediment budget.

Fearnley *et al.* (2009) and Sallenger *et al.* (2009) analyzed the recovery potential of the Chandeleur Islands in the wake of Hurricanes Katrina and Rita that adversely impacted these islands in 2005. It was estimated that 86% of the surface area of the Chandeleur Islands was eroded by Hurricane Katrina. Immediate post-storm observations revealed that all of the sand visible from the air was removed, leaving only marshy outcroppings. Analyses of aerial photography taken two months after the storm concluded the islands were still rapidly eroding after the storm noting Hurricane Rita impacted the area during this time frame causing some of the erosion.

10.2 Model Options

Based upon the literature review, no industry standard empirical or theoretical numerical models exist to predict post-storm recovery of the barrier islands. The cross-shore model Beach-fx includes a post-storm recovery factor of 70% to 80% of the beach berm width (Mark Gravens, 2013, pers. comm.). As described in Section 6, this model was not recommended for the BIMODE model as it does not allow for certain processes that are viewed as essential for modeling the behavior of the barrier islands of Louisiana.

Knowledge and experience from restoration project design (e.g., CEC and SJB, 2008; USACE 2010; and USACE, 2012) indicates the SBEACH model under-predicts the amount of erosion and overwash due to storm events, and upon examining the islands and their recovery period, the SBEACH predictions more closely match the net change, that is, the combination of storm erosion and recovery.

10.3 Summary

The SBEACH model was the preferred model for the cross-shore processes, and experience has indicated that SBEACH tends to under predict storm erosion, which in some sense accounts for post-storm recovery processes. Accordingly, the BIMODE Team suggests the post-storm recovery processes are captured sufficiently through application of SBEACH.

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11.0 Subsidence

11.1 General

Subsidence is the gradual sinking or lowering of the land surface. It is one of the key physical processes affecting landforms within the focus area. With respect to coastal Louisiana, six primary processes cause subsidence (Reed and Yuill, 2009) including:

- Tectonic subsidence;
- Holocene sediment compaction;
- Sediment loading;
- Glacial isostatic adjustment;
- Fluid withdrawal; and
- Surface water drainage and management.

CPRA convened a panel of experts in 2010 to examine the causes of subsidence, review existing literature on historic subsidence rates, assess procedures for predicting subsidence, and render recommendations for future planning purposes including the 2012 Coastal Master Plan. The outcome of the panel's recommendations included a spatially defined map representing plausible ranges of subsidence over the next 50 years. The ranges of subsidence rates for coastal Louisiana are shown in Figure 7 and listed in Table 3 specific to the study area (CPRA, 2012). It is noted these ranges do not include ESLR or the compaction due to loading from future projects. These physical processes are addressed separately.

11.2 Application for BIMODE

Guidance from CPRA was to follow the same procedure for applying the effects of subsidence on barrier island evolution utilized in the 2012 Coastal Master Plan for coding and testing of the BIMODE model.

The barrier shoreline morphology model developed for the 2012 Coastal Master Plan accounted for the effects of subsidence through application of a simple one-dimensional relationship wherein the elevations along the cross-shore profile were lowered by the subsidence rate (Figure 8). Spatially variable subsidence was applied with one set of values applied for the moderate future scenario and one set of values for the less optimistic future scenario. For the moderate and less optimistic projections, CPRA utilized professional judgment to select the lower 20th percentile and 50th percentile of the plausible ranges of future subsidence rates, respectively, for each region (CPRA, 2012). The values applied for the study area are presented in Table 3.

The BIMODE model can updated if needed and future efforts will be coordinated with the broader 2017 Coastal Master Plan modeling effort.

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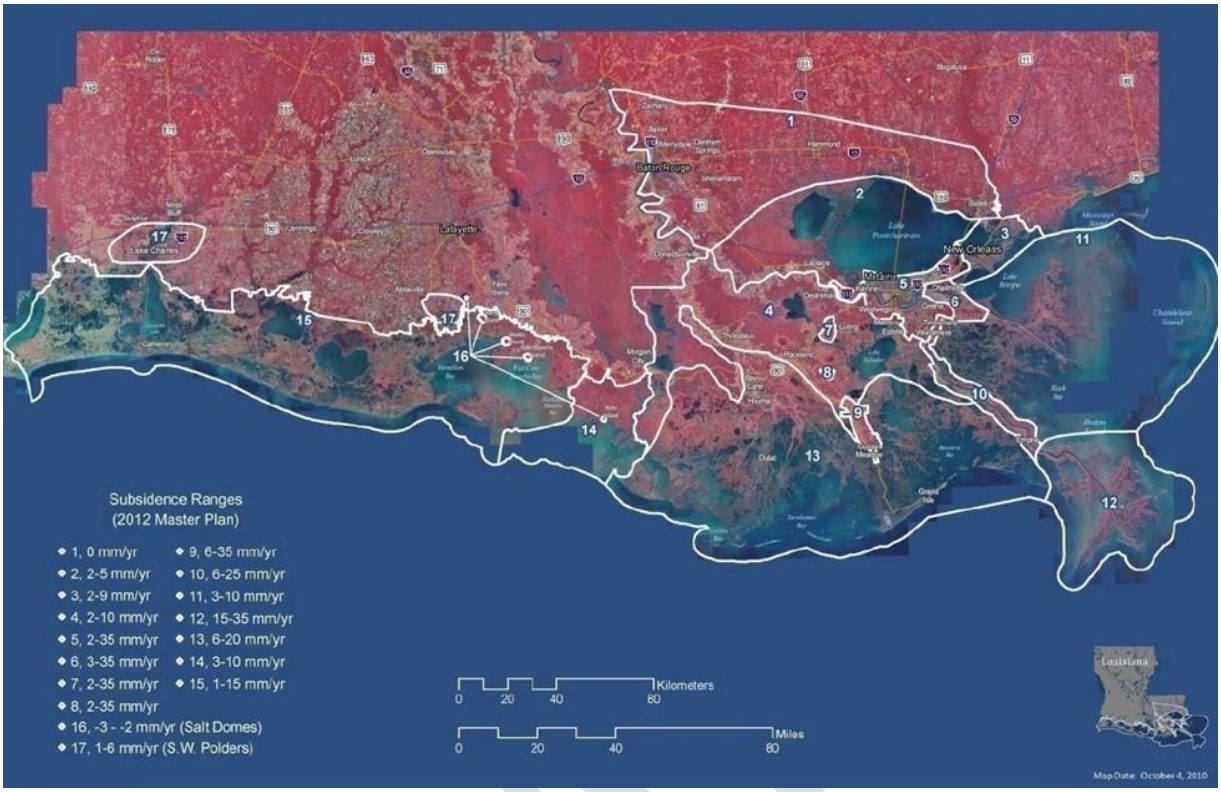

Figure 7: Map of Projected Subsidence Ranges for Southern Louisiana Generated by the Subsidence Advisory Panel for the 2012 Coastal Master Plan (CPRA, 2012).

Table 3: Subsidence Values used in 2012 Barrier Shoreline Morphology Model (CPRA, 2012).

Region	Designation	Range (mm/year)	Moderate Scenario (mm/year)	Less Optimistic Scenario (mm/year)
Isles Dernieres	13	6-20	8.8	13.0
Timbalier	13	6-20	8.8	13.0
Caminada Headland / Grand Isle	13	6-20	8.8	13.0
Barataria Bay (west)	13	6 - 20	8.8	13.0
Barataria Bay (east)	12	15 - 35	19.0	25.0
Breton Island	11	3 - 10	4.4	6.5
Chandeleur Island	11	3 - 10	4.4	6.5

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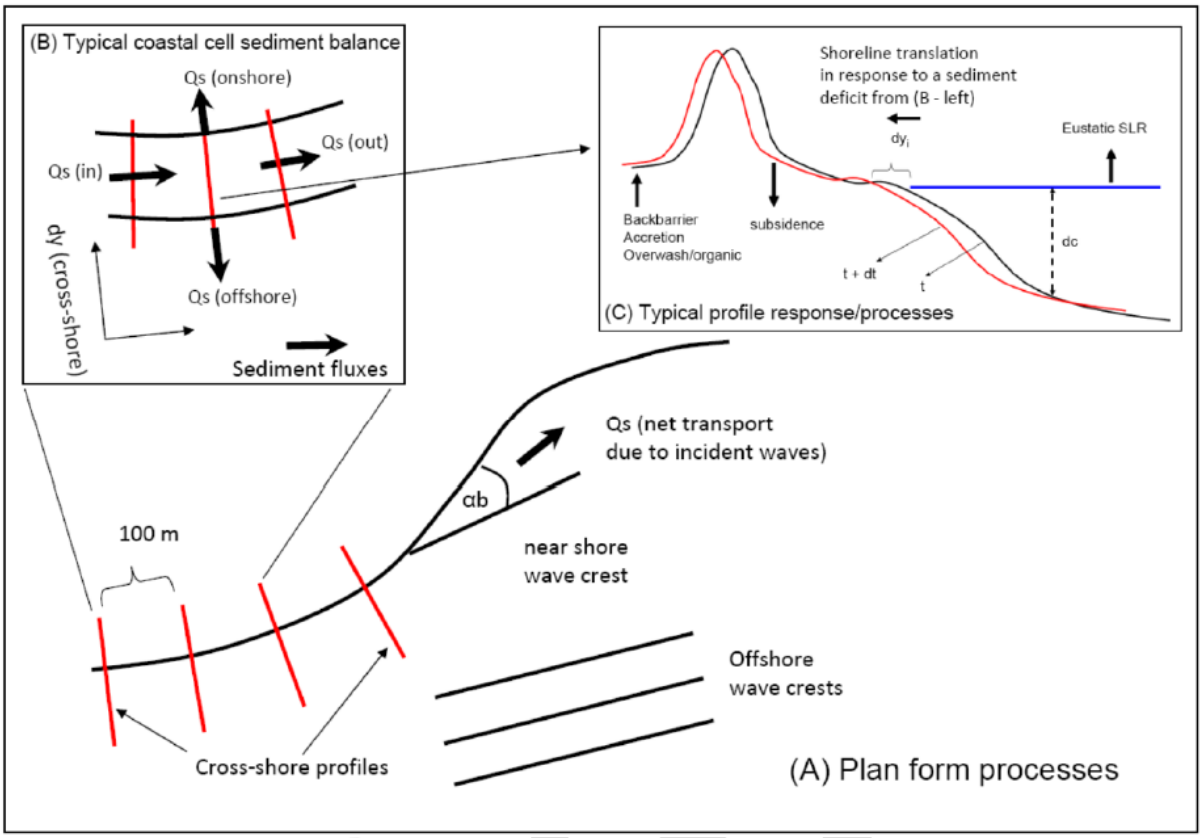

Figure 8: Model Schematic of Plan Form Processes, Mass Balance of Sediment Transport, and Corresponding Shoreline Response from the 2012 Coastal Master Plan (Hughes et al., 2012).

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12.0 Eustatic Sea Level Rise

Relative sea-level refers to the height of sea level as measured from a particular point or area on the earth's surface. The National Research Council (NRC) (1987) initially developed an equation and values to estimate relative sea level rise (RSLR) which is the combination of ESLR and subsidence. The USACE (2009, 2011) updated this equation and shifted the base year from 1987 to 1992. The Intergovernmental Panel on Climate Change (IPCC) developed SLR trends based on recent climate research (IPCC, 2007).

For the 2012 Coastal Master Plan, the plausible range of sea level rise over 50 years utilized a low boundary of 3.1 mm/yr equal to 0.155 m over 50 years taken from IPCC (2007), and a high boundary assuming an acceleration of 1.005 x 10^{-4} consistent with NRC (1987) and USACE (2009) equal to 0.65 m over 50 years. Moderate and less optimistic projections were chosen for the landscape models and were determined utilizing the generalized equation for SLR given by:

$$E\ (t_2 - 1986) - E(t_1 - 1986) = a([t_2 - 1986] - [t_1 - 1986]) + b([t_2 - 1986]^2 - [t_1 - 1986]^2)$$

(Eqn. 32)

Where:	E	=	change in ESLR at time t
	a	=	historical linear rate of global SLR = 0.0031
	b	=	acceleration constant for predicted global SLR
		=	2.36 x 10-5 (moderate) and 6.2 x 10-5 (less optimistic) (CPRA, 2012).

CPRA will provide updated projections for use in the 2017 modeling. The BIMODE model will be updated accordingly, and future efforts will be coordinated with the broader 2017 Coastal Master Plan modeling effort.

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13.0 Model Schematization

This section discusses the schematization of the BIMODE model and outlines how the selected physical processes are incorporated to develop the final output.

Step 1. Establish littoral cells. Create profiles from available data. Convert x,y,z data into profile based data. Determine azimuth for each profile and store so that profile data can be converted back to x,y,z format.

Step 2. Prepare input parameters for each profile including silt content, initial active profile height, and post-restoration profile. Data is included as a look-up table.

Step 3. Select wave climate for period between storm events. Select an appropriate WIS hindcast station for the barrier island domain of interest. Transform the full 33-year WIS time series from the hindcast station to the offshore depth of the SWAN grid using the WIS Phase 3 transformation technique and specifying the regional shoreline orientation and sheltering angles as appropriate. Then, the transformed time series is parsed by month in preparation for performing the monthly statistical characterization. The time series is grouped by specified angle bands and period bands. The monthly statistical analysis results in the identification of a limited number of "characteristic" wave conditions for each month. The monthly wave data series are provided as input for BIMODE on a monthly time step.

Step 4. Develop a database of nearshore wave conditions for each of the model segments (transects) by transforming waves from offshore location to a depth contour before breaking (-6 foot contour suggested) using SWAN. This process contains both offshore wave transformation (WIS Phase III) and nearshore wave transformation before breaking. Select representative monthly wave data and create a look-up table for each offshore wave condition to output a nearshore wave condition. The last part of wave transformation to wave breaking is performed within BIMODE. The wave height, period and direction at breaking location are used for longshore sediment transport. This step is only performed once using existing available bathymetry. It is assumed that the impact of relative sea level rise on wave transformation is minimal compared to other modeled processes.

Step 5. Develop look-up tables for cross-shore storm model runs. For proof of concept, 1008 runs were performed as described in Section 14.0 (7 storm events run on 6 different profile lines with 24 different cross-sections). Look-up tables are either based on cross-shore profile or a tabulation of retreat of various contours along the beach face and tracking of overwash distance on the bay side.

Step 6. Check whether the profile still has a subaerial component. If yes, then continue; if not, then move to next profile and repeat Step 6.

Step 7. Compute longshore transport rate from each of the monthly representative wave conditions for each emergent profile for the given time interval. Read local wave height, period and direction at each timestep of the wave record using wave transformation from Step 4. Determine longshore transport rate based on the CERC equation for sediment transport. Calculate cumulative longshore gross transport values (e.g. sum of easterly transport and sum of westerly transport) as well as net sediment transport and direction for the month. Repeat for all months in the year.

Step 8. Locate divergence of sediment transport within each littoral cell (nodal point). Variable nodal points are calculated. Sum net transport rates changes going away from the nodal point to determine erosion or accretion at each profile line. Check whether the profile is adjacent to a pass such that gross transport into the pass is lost from system. (Alternate option is to sum transport loss to the pass and estimate whether subaerial growth could occur).

Step 9. Change beach face profile location by equating sediment transport loss or gain to shoreline retreat or advance. Read in active profile height from profile (probably fix depth of closure specific to each region and then read either dune crest or estimate berm elevation from cross-section). (Volume = Distance between profiles times active profile height times change in shoreline location.)

Step 10. Account for profile elevation adjustments due to sea level rise and subsidence in given time period. Read in sea level rise from a table to account for variability with time. Read in subsidence and/or primary consolidation due to project construction to account for variability with time. Adjust elevations of points along beach profile to account for consolidation.

Step 11. Account for silt loss. Increase the shoreline retreat by the percentage of silt in the beach face.

Step 12. Combine shoreline changes due to longshore transport and silt loss. Retreat the beach face profile by the combined change.

Step 13. Reduce elevation of each point along the cross-section uniformly to account for subsidence. (Detritus can be added to the subsidence value either implicitly or explicitly as its own table. The value would be included in this step.)

Step 14. Repeat Step 9 through Step 13 for each profile.

Step 15. Is a storm predicted within this time period? If no, then skip to Step 20. If yes, then determine profile values for berm width, dune height, and dune width. Access the look-up table to find the input profile that most closely matches these values and the storm event that most closely matches the specified storm. Overwrite the input profile with the post-storm profile from the look-up table. Use the seaward high tide line to locate the profile. This step accounts for the storm-induced shoreline change due to cross-shore sand transport. Overwash beyond the marsh platform is also encompassed in the SBEACH look-up tables. (This may be changed to track only a few contours and develop a look-up table for the retreat of those contours.)

Step 16. Repeat for all profiles.

Step 17. Is another storm predicted in this time period and can longshore processes be excluded between storm events? If so, return to Step 16.

Step 18. Smooth the shoreline.

Step 19. Erode the bayward side of the profile if applicable. This is based on the marsh edge erosion subroutine of the ICM.

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Step 20. Check whether each island exceeds the island breaching thresholds. The first step is to determine profiles with island width less than 60 m, which can potentially breach. Then confirm the potential breach is far-field from island ends (the ratio of both updrift and downdrift length to island length are 27% or more from adjacent inlets). The other criterion is to check for the critical width to updrift length ratio. If the ratio is less than 3%, the island can potentially breach. For the profiles with both of the criteria satisfied, the breach is initiated. If the breaching thresholds are exceeded, determine which profiles are most likely to breach and label the number of consecutive profiles equal to the critical width as being submerged (no longshore transport). Reset the definition of island for subsequent breach evaluations.

Step 21. Incorporate the inlet and bay module at the specified time step. One-year intervals are currently preferred.

Return to Step 6 and repeat until 50-year simulation period is complete.

Output is a cross-section at each emergent profile in the format of a DEM.

For the future with project scenarios, BIMODE has the ability to input a restoration project in the 50-year simulation or add renourishment of a previously restored island at a specific target year. The goal is to automate this procedure; however, it is understood that the design template will have to be positioned in relationship to the island position at the specified target year noting the landward migration of the barrier islands due to overwash and other erosional processes. The details of this are currently in progress.

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14.0 BIMODE Code Development & Testing

14.1 Overview

This section describes the routines developed to simulate the steps outlined in the previous Model Schematization section and the quality control testing performed to confirm the functionality and accuracy of the program. The code in its entirety was submitted to CPRA (as Appendix 2).

14.2 BIMODE Code

The BIMODE code was written in Fortran 90. It consists of a single main program, BIMODE.f90, which calls on an input file, a global variable file and several subroutines to perform the necessary computations. The format of the input and output for the program is an ASCII grid file in .XYZ format and a text file with input/ output parameters. The datum of the input and output files is in Universal Transverse Mercator (UTM) 15 coordinates in meters. The elevation datum is NAVD 88 (Geoid '09) in meters.

14.2.1 File Structure

The BIMODE code requires the following files to run:

- *BIMODE.f90* is the main program file. It calls the input file, variable file, and subroutines necessary to run the program.

- *Mod_global.f90* defines the parameters necessary for computation i.e. gravity, sediment density, density of water and coefficients in the CERC equation. It also allocates variables for assignment in the subroutines.

- The file *mod_util.f90* provides utility to read input and is only used in subroutine "read_input" in the following section.

- *Input.txt* is the input parameter file for the program. It governs the start and end time of the model, the grid spacing, the profile naming, reading the wave data look-up table, reading the SBEACH look-up table and the input parameters. The input parameters include sea level rise rate, subsidence rate, silt content, breaching criteria and marsh erosion rate.

- Excel_Date_Table_1900to3100.txt is the date code file starting from 1900 to 3100. All the time points in BIMODE are expressed in terms of days according to this file.

- *Storm_event.prn* is a text file listing the storm occurrences for the simulation. Time of occurrence is set as Year, Month, Day, Hour and Minute that a storm is to occur during the simulation.

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- The SBEACH look-up table is stored in *SBEACH.tab*. This table contains the initial pre-storm profiles and the post-storm transformation correlated to storm event and initial profile.

- The wave look-up table is stored in *WIS_station_name_WIS.tab* (for example ST73141_WIS.tab). There were four WIS stations selected to develop the average wave climate. Each wave case contains the significant wave height, wave period, wave direction and the depth.

- The wave time series from each WIS station is saved as *WIS_station_name_WIS_reformat.prn* (for example ST73141_WIS_reformat.prn).

- A survey file in.XYZ format contains profile number, coordinates (x,y) and elevation (z) and is required to run the program.

- A survey control file in control.prn contains the starting coordinates and profile azimuth.

14.2.2 Main Subroutines

The first step in running BIMODE is to read the input file, .XYZ data file, survey control file, look-up tables, storm event control file and wave time series, using subroutine "read_input." This subroutine calls on the file mod_util.f90 to read and format the input file parameters.

Next, the subroutine "allocate_variables" is called to allocate space for and assign initial values to the variables in all of the other subroutines. The program then checks for subaerial points along each profile, using "check_subaerial." A subaerial point was defined as any point with an elevation above 0 meters NAVD88.

The following subroutine, "check_island," is used to determine if the profile aligns with an island. An island has seaside submerged points and bayside submerged points. If an island does exist, the island width is calculated for use later for breaching criteria. The island width is defined as the distance from the seaside zero-contour to the northern-most zero-contour. Note that the .XYZ data file may contain missing data points. In order to eliminate all missing points, LIDAR data are applied first; then, linear interpolation is performed to fill in the remaining missing points. If LIDAR data is applied, the program smoothes the cross-shore profile data based on a 21 point smoothing algorithm.

To compute the final wave transformation from the nearshore to the breaking point, the subroutine "wave_transform" is run. The wave height, wave period and wave direction are read in from wave data look-up table. The look-up table contains wave data developed from the Hypercube analysis of the WIS data for each WIS station. In the Hypercube analysis, the wave transformation is performed for a number of wave cases with various height bands, period bands and direction bands. Then the 3D linear interpolation is used to obtain the wave refraction coefficients for any other wave cases. The WIS data record extended from January 1, 1980 to December 31, 2012 (33 years). In order to complete a 50-year simulation, the wave record was repeated, providing 66 years of data.

The subroutine "longshore_transport" is used to calculate longshore transport by waves based on CERC (1984). First, the cumulative longshore gross transport rate is calculated. The direction of transport depends on the wave angle. Then, the net transport at each cell (area between profiles) is calculated. The net longshore transport is smoothed across profiles using the inverse-distance weighted method (Lam, 1983). For each target profile, the smoothed net longshore transport is weighted by transports at both the target profile and the adjacent profiles. The further profile from the target profile makes less contribution to the transport. This avoids a feedback loop in the model because shoreline change affects wave angle and thus drives further change.

The following three subroutines calculate shoreline retreat rates and update the profiles. The subroutines below are applied after longshore transport at each time step (monthly).

- "silt_loss": accounts for silt loss based on silt content (Default is 0.3)
- "sea_level_rise": calculates sea level rise rate as a function of time
- "land_subsidence": calculates land subsidence, affects entire profile.

The subroutine "crossshore_transport" updates the profiles based on storm-induced cross-shore transport applied by referencing the transformations stored in the SBEACH look-up table. The program knows a storm occurs based on the sequence of storm events saved in the storm_event.prn file. When a storm occurs, the program compares the existing profile to the idealized initial profiles stored in the SBEACH look-up table. The middle point of the maximum dune height of the idealized profile is aligned over the existing profile for comparison. Then, the program selects the idealized profile with the minimum difference from the existing profile. Based on this selected idealized profile and the given storm event, the SBEACH look-up table is used to identify the profile transformation that was simulated in SBEACH (outside of BIMODE) to occur. Hundreds of idealized profiles with maximum dune heights that vary by 0.1 meters and varying dune widths were simulated in SBEACH with varying return period storms to provide data for the SBEACH look-up table. Finally, the profile transformation is applied to the active portion of the existing profile and a post-storm profile is generated inside BIMODE.

The shoreline position is updated at each time step by the "update_shoreline" routine. Based on profile changes, the seaside shoreline either advances or retreats. The bayside shoreline is also updated but as a result of the marsh erosion function.

The "check_breaching" subroutine is used to check the breaching threshold of an island based on two criteria: barrier island width and the island width to length ratio. The critical values of these criteria were set as constants in the code. The critical width (less than 60 m) is firstly determined among all the profiles. The potential breach is far-field from island ends, which is 27% or more from adjacent inlets. The critical width to updrift length ratio is set as 3%. In general, for the profile that is less than 60 m wide from gulf mean high water to bay mean high water, is located greater than 27% of the total island length from both adjacent inlets, and its width to updrift length ratio is less than 3%, a breach is initiated.

The subroutine "write_output" generates the output files. The first output file is the XYZ file (Profile_0001), which contains the final profile data. Next, the text file containing the cumulative longshore transport is generated *Qsum_0001*. Finally, a time series of shoreline retreat and advance is printed, *time_series.txt*. At the same time, a running log file is generated during the calculation.

There are other subroutines and functions in the program to support the functions of the main subroutine. These subroutines include:

- Gmt2datecode: converts date and time from input.txt into a time table date number.
- Exist_error: prints error messages if necessary while reading input file data.
- Several linear interpolation methods based on nearest points.
- Solv_disprsn: solves dispersion equation for wave length using the Newton-Raphson iteration method (Press et al., 1992).

14.3 Testing

A series of tests were conducted on the BIMODE program to examine the functionality and performance of the individual subroutines and the code in its entirety.

14.3.1 Profile Data

To test the ability of BIMODE to read in and process data, the profile data for the 4 regions west of the Mississippi River, Chandeleur and Breton Islands were used. The data set was sourced from the initial survey data used in the 2012 Coastal Master Plan model (Hughes *et al.*, 2012). The data were surveyed into the North American Datum of 1983 (Horizontal) and NAVD88 (Vertical) using the GEOID model reference frame. The format of data file consisted of the following:

- pNum - profile id, from west to east
- x - easting in UTM 15 meters
- y - northing in UTM 15 meters
- z - elevation in NAVD88 meters

The source of data for testing was the Barrier Island Comprehensive Monitoring Program (BICM) bathymetry for all regions. LIDAR data (Nayegandhi, 2010) was used to fill in areas missing data. For the areas still missing data, linear interpolation was applied. The final profile data was interpolated to generate profiles with cross-shore resolution of 2 meters and longshore spacing of 100 meters between profiles. The initial survey data used for testing is shown in Figure 9.

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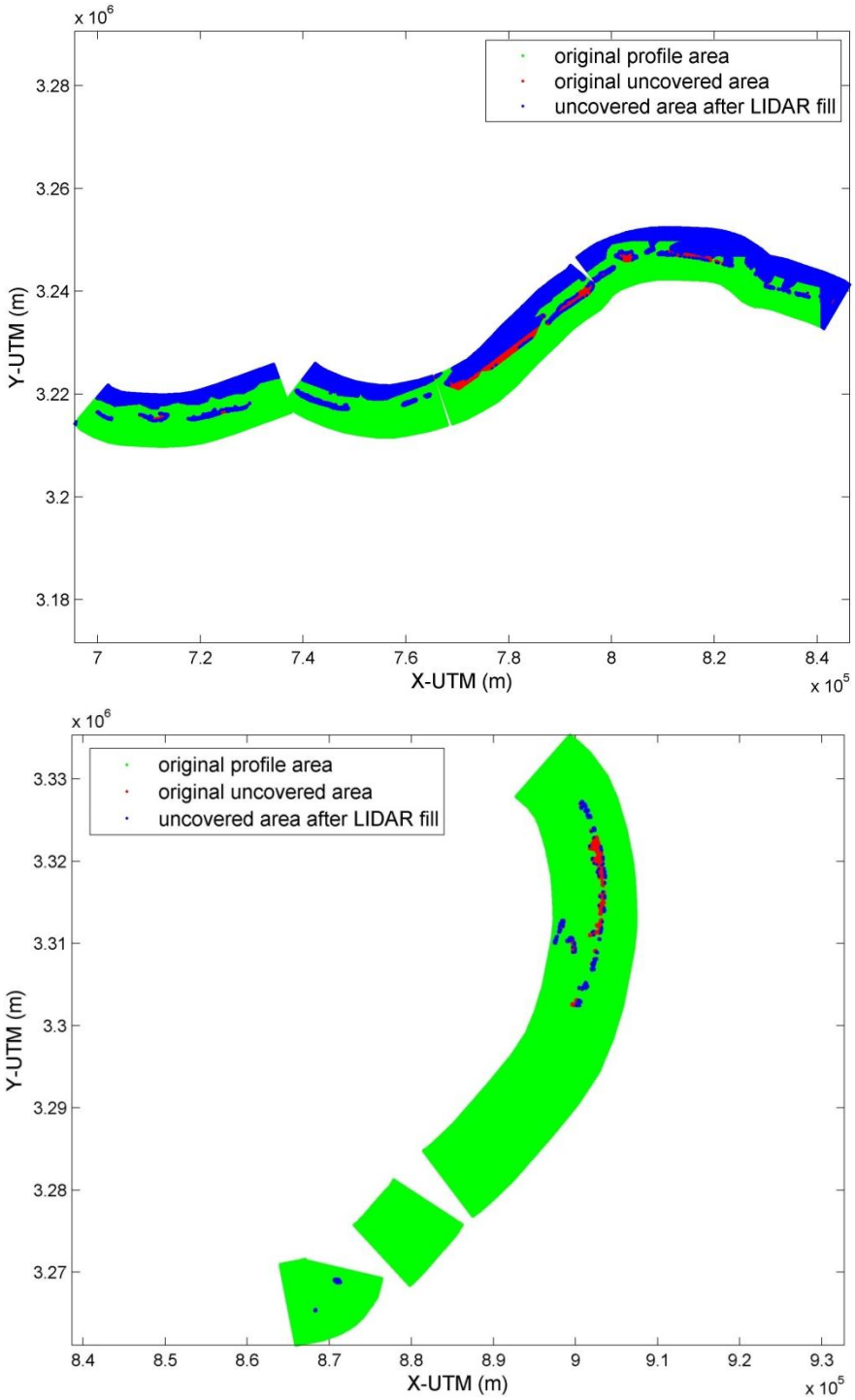

Figure 9: Plan View of Initial Profile Data Used in Testing, Southern Louisiana and Chandeleur Island and Breton Island. Input data was colored green. Original missing points were colored in red. Areas requiring linear interpolation after LIDAR fill were colored in blue.

14.3.2 Wave Transformation

Hindcast data from six WIS stations was used as input to drive the wave transformation using SWAN. The locations of the WIS stations are shown in *Figure 4* WIS stations 73124 and 73126, 73129 and 73131 were selected as the wave condition source for Isles Dernieres, Timbalier, Caminada Headland and Grand Isle, Barataria Bay, respectively. WIS stations 73141 and 73139 were selected for Chandeleur and Breton Islands. The wave data time series extends from January 1, 1980 to December 31, 2012, a period of 33 years with hourly record intervals. Figure 10 through Figure 15 include the hourly wave data distribution for the 33-year record at the six WIS stations. The distinct values selected to classify the wave bands are listed in Table 4.

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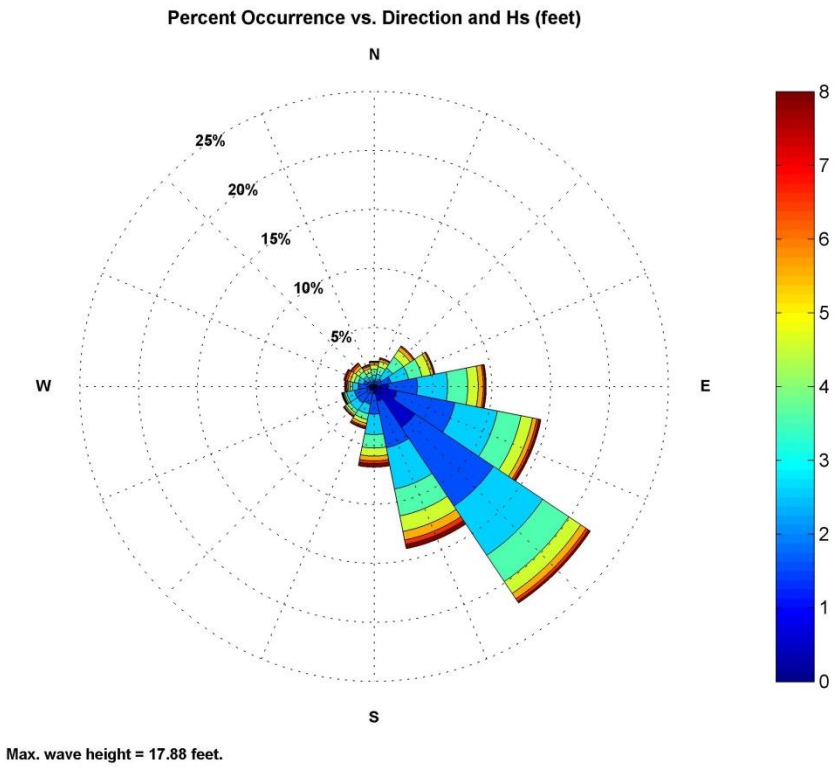


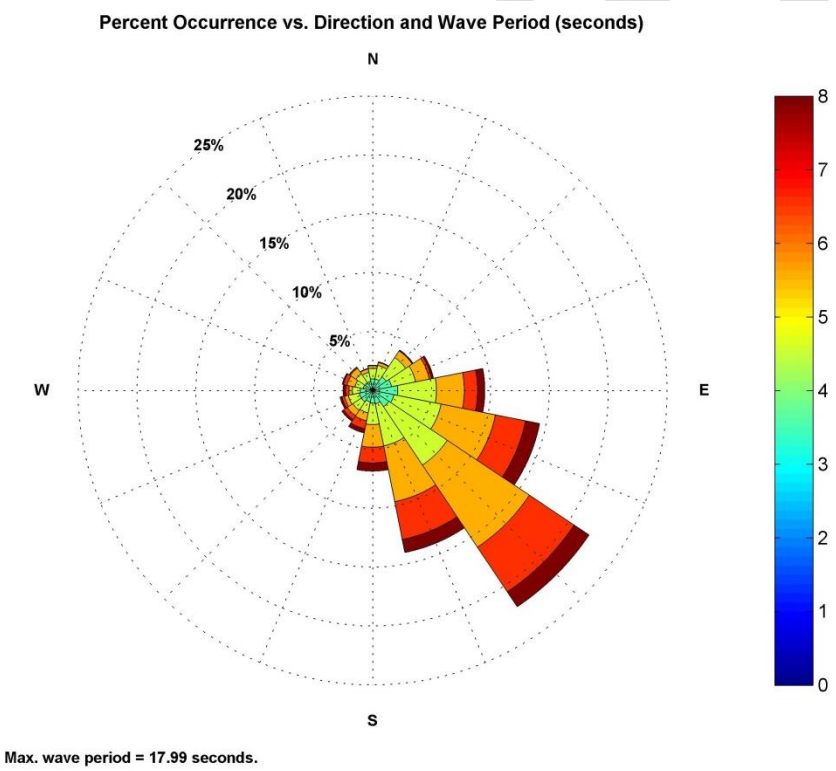
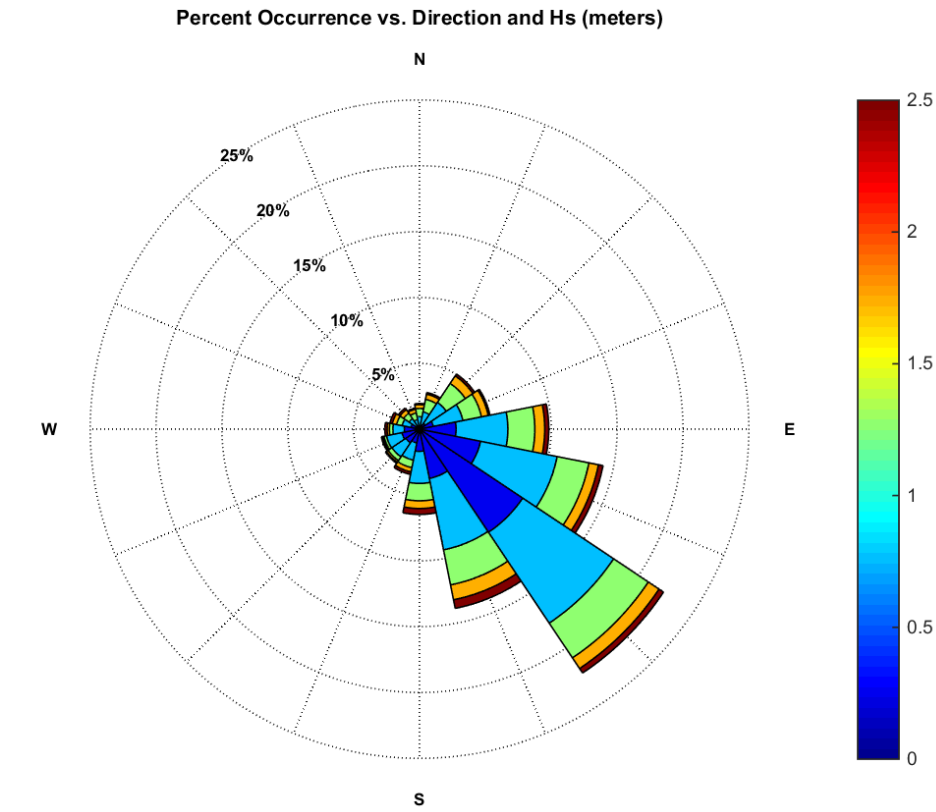


Figure 10: ST73124 Hourly Directional Wave Statistics from Jan. 1, 1980 to Dec. 31, 2012.



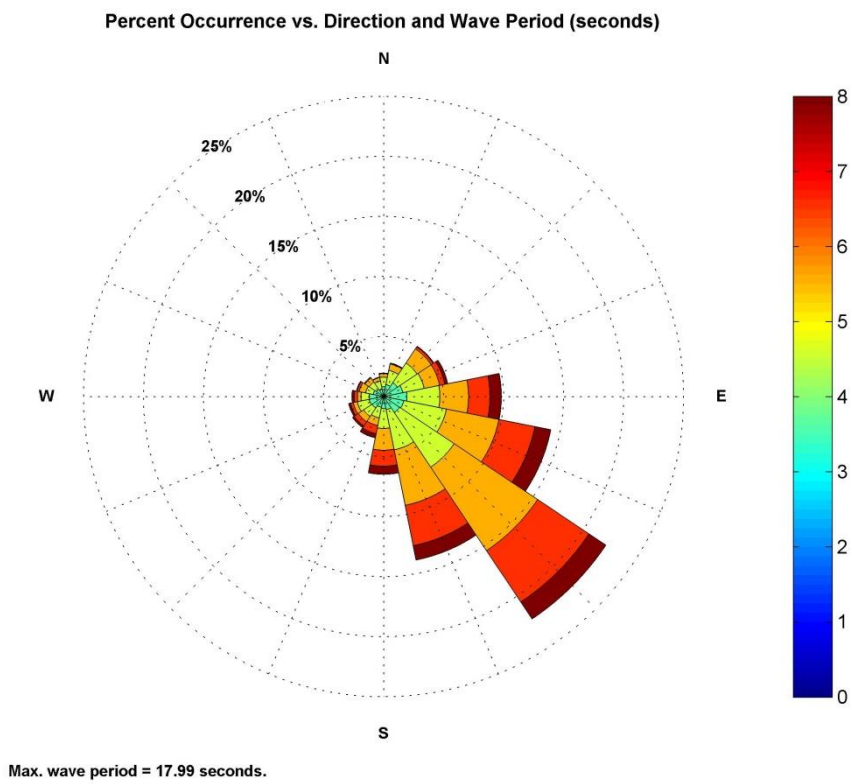
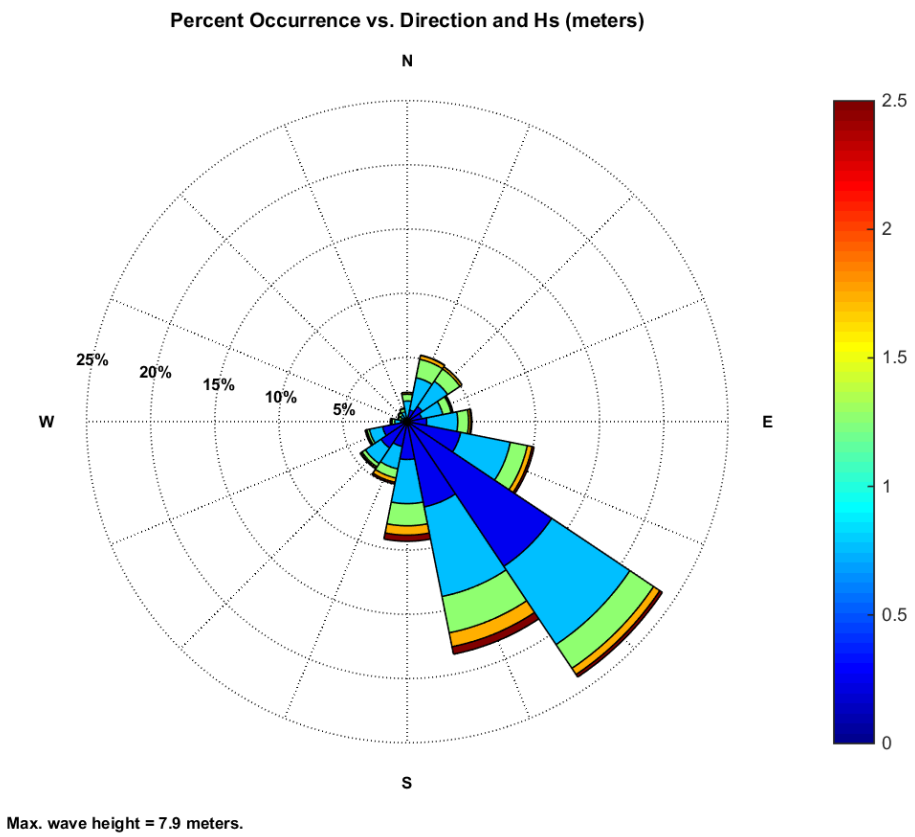


Figure 11: ST73126 Hourly Directional Wave Statistics from Jan. 1, 1980 to Dec. 31, 2012.



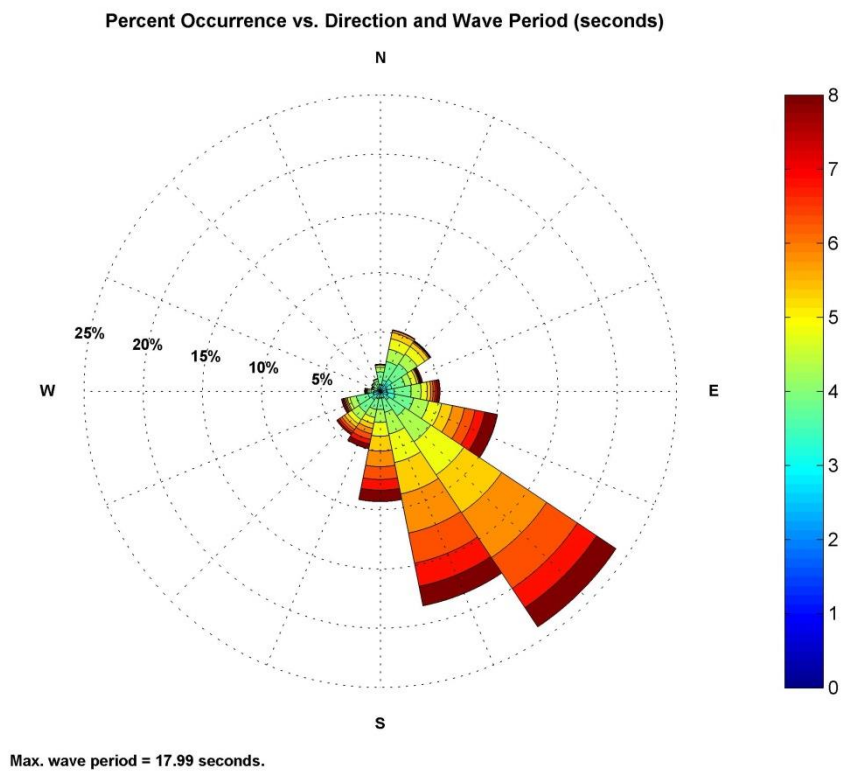
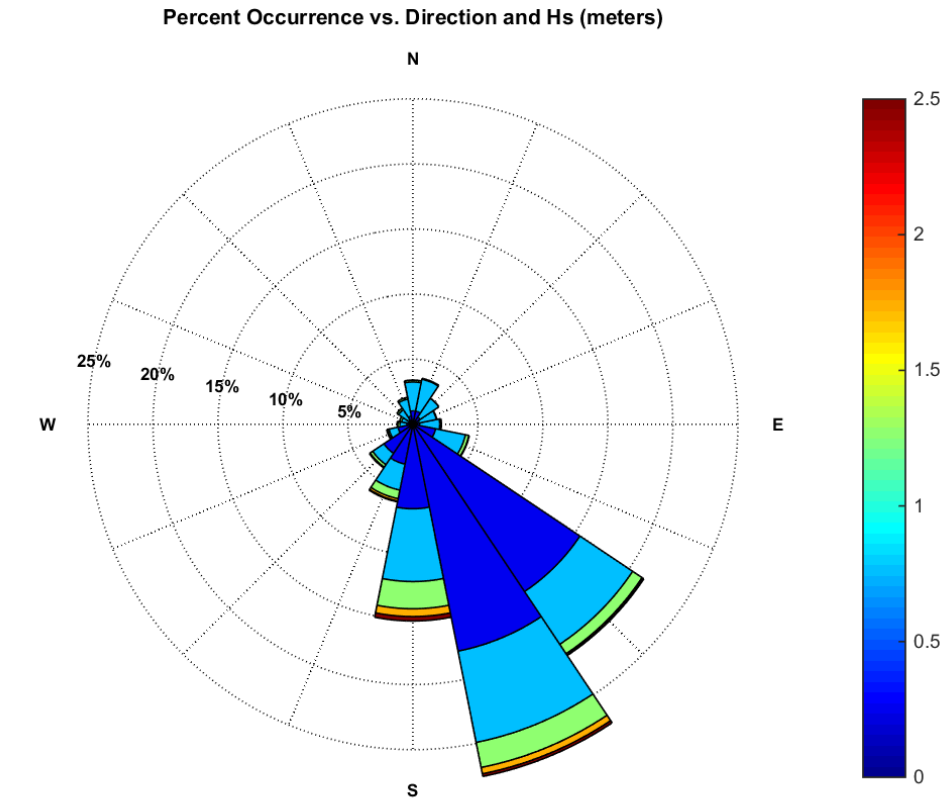


Figure 12: ST73129 Hourly Directional Wave Statistics from Jan. 1, 1980 to Dec. 31, 2012.



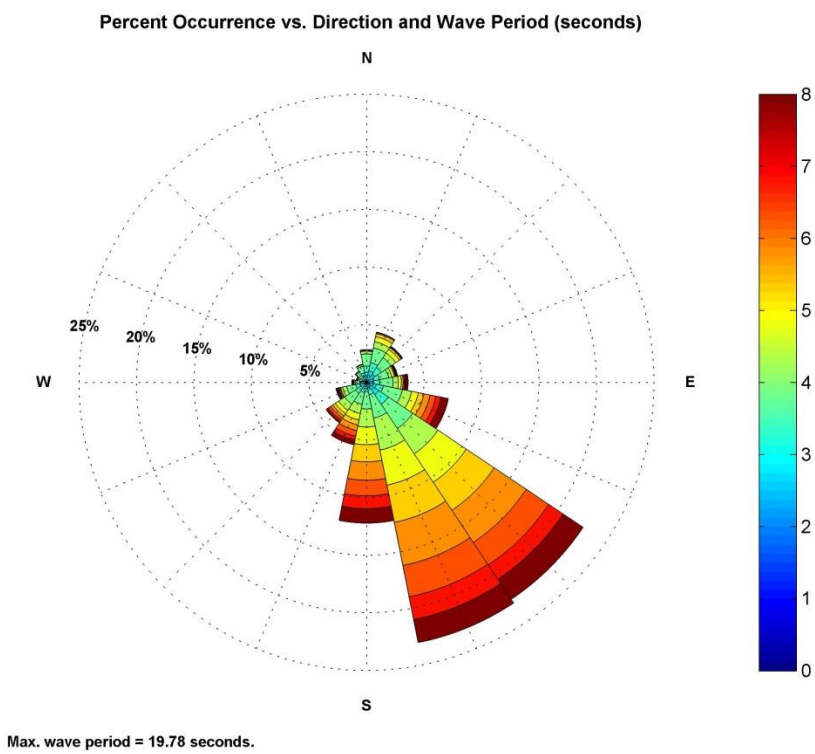
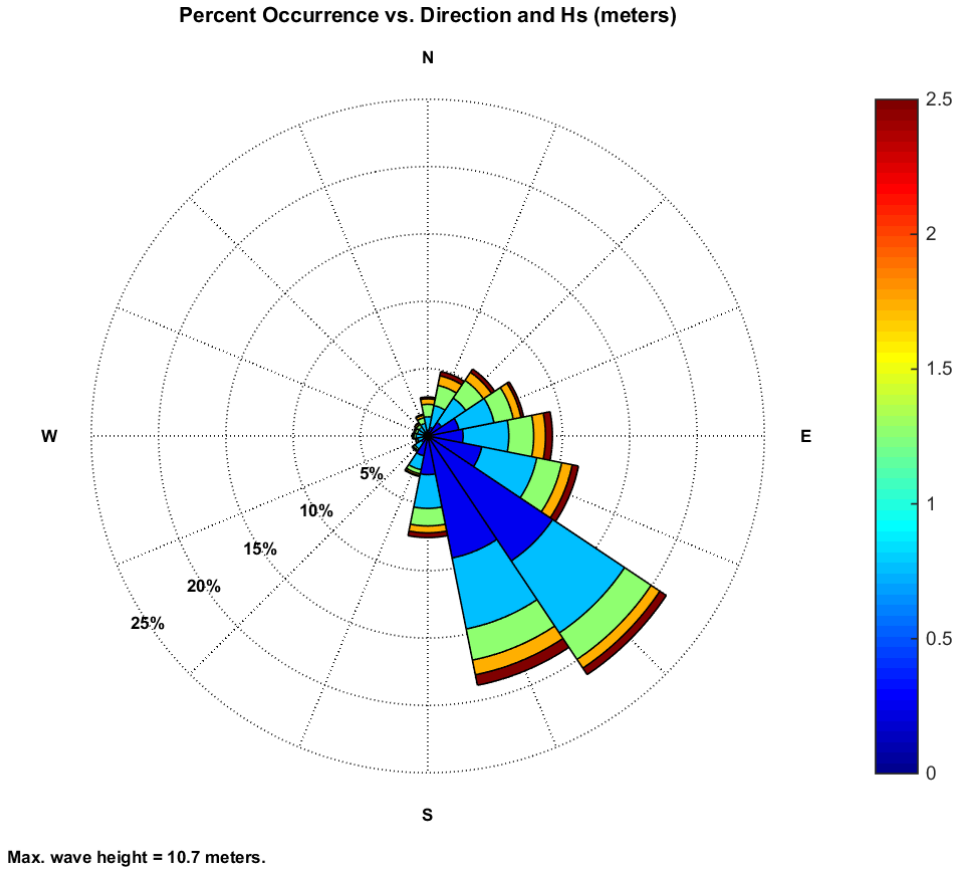


Figure 13: ST73131 Hourly Directional Wave Statistics from Jan. 1, 1980 to Dec. 31, 2012.



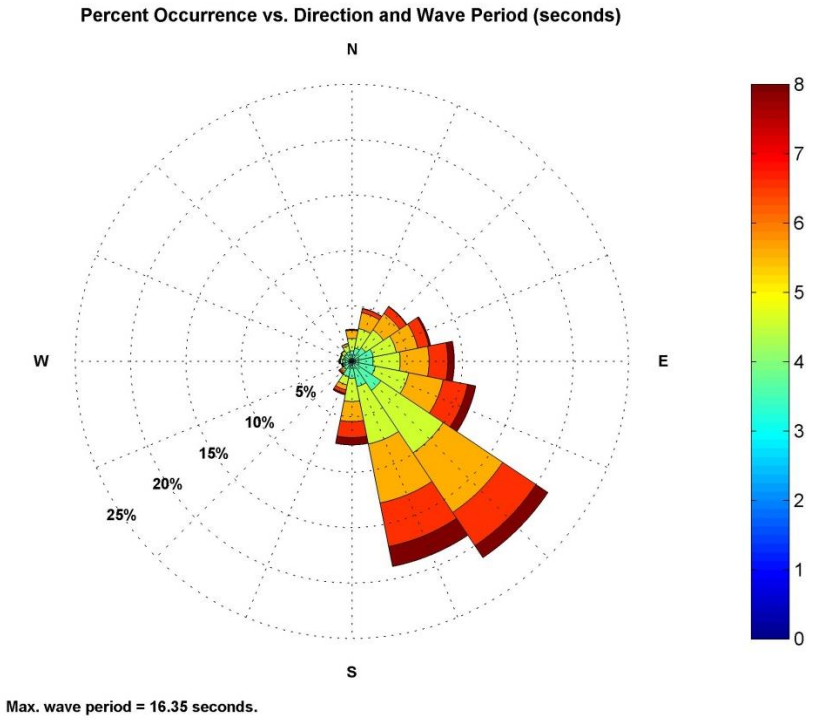
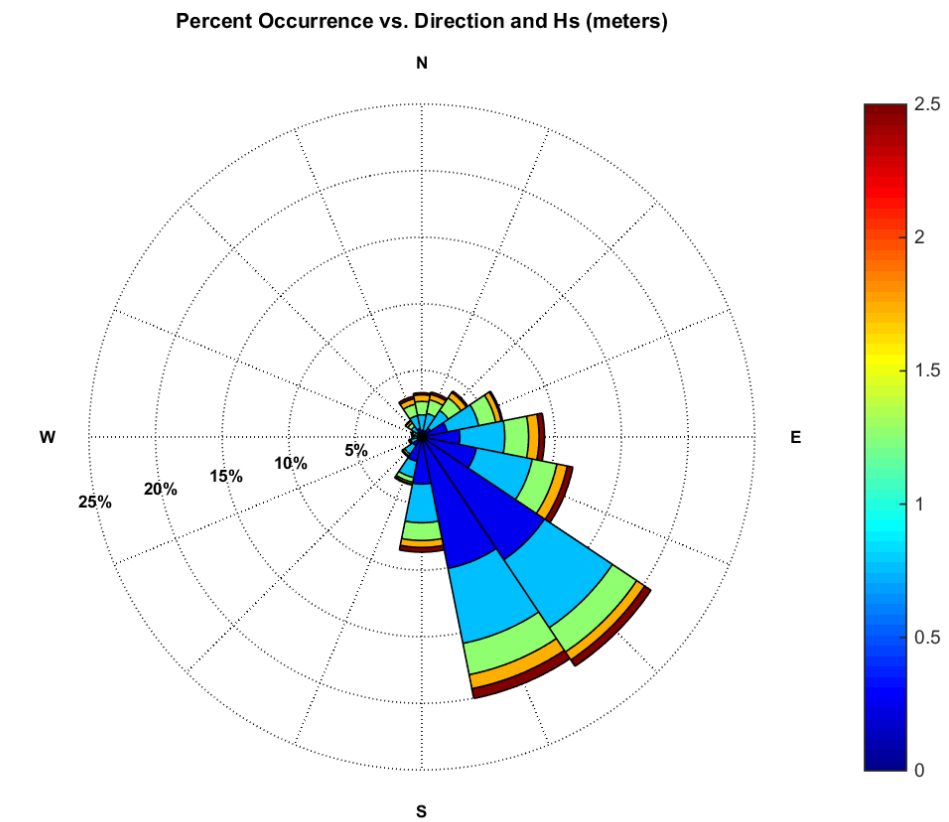


Figure 14: ST73139 Hourly Directional Wave Statistics from Jan. 1, 1980 to Dec. 31, 2012



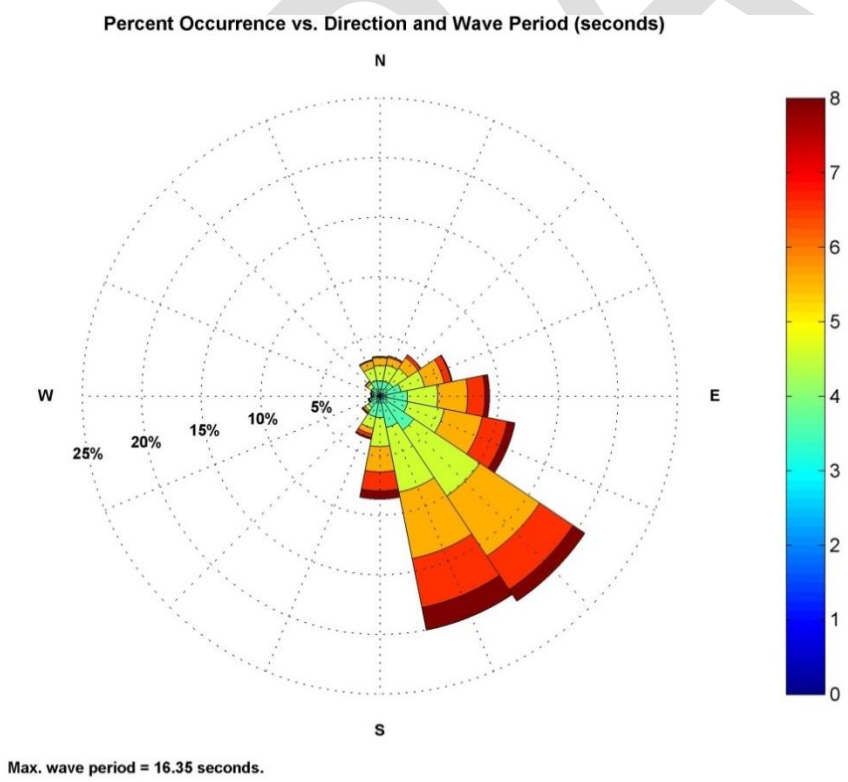


Figure 15: ST73141 Hourly Directional Wave Statistics from Jan. 1, 1980 to Dec. 31, 2012.

Table 4: Bands of Wave Parameters for Wave Roses.

Wave Parameter*	Bands
Hs (m)	<0.5, 0.5 to 1.5, 1.5 to 2.5, 2.5 to 3.5, 3.5 to 4.5, 4.5 to 5.5, 5.5 to 6.5, >6.5
T (s)	<4.0, 4.0 to 6.0, 6.0 to 8.0, 8.0 to 10.0, 10.0 to 12.0, 12.0 to 14.0, 14.0 to 16.0, >16.0
Dir (degrees)	0, 22.5, 45, 67.5, 90, 122.5, 135, 157.5, 180, 202.5, 225, 247.5, 270, 292.5, 315, 337.5

* Hs denotes significant wave height, T denotes wave period, and Dir denotes direction relative to true north.

To obtain input data for the testing of BIMODE, the offshore waves were transformed using SWAN. For the models west of the Mississippi River, the nearshore bathymetry was based on both profile data and National Geophysical Data Center coastal DEM metadata. The nearshore bathymetry for Chandeleur and Breton Island was based on profile data described in the previous section. The offshore bathymetry data was obtained from Chandeleur Island Sound surveys collected between 1934 and 2009 (obtained from NOAA in 2014). The bathymetry used in the SWAN test run is shown in Figure 16 through Figure 19.

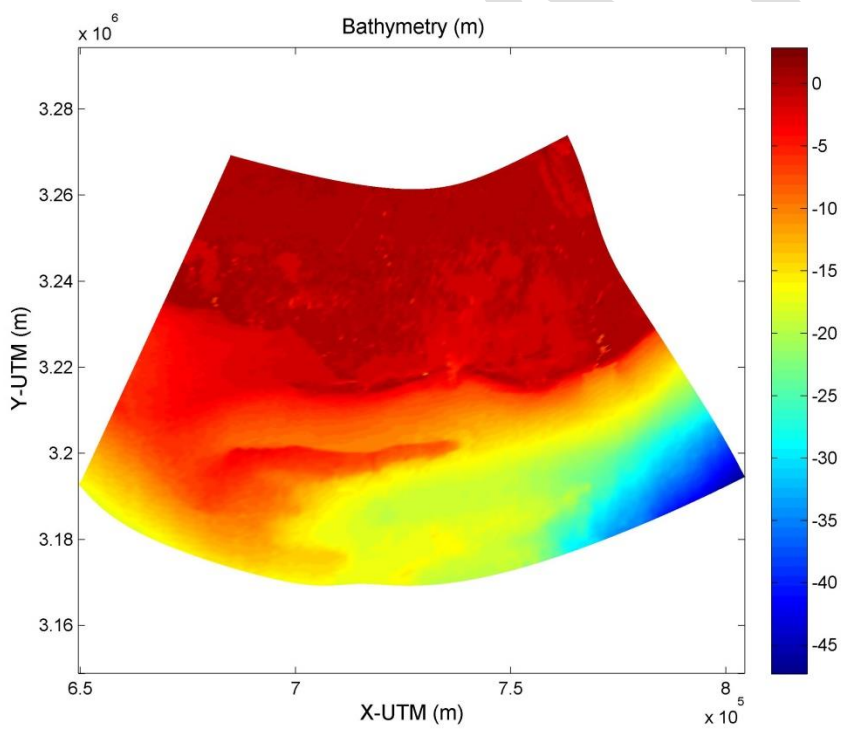


Figure 16: SWAN Grid Bathymetry for Isles Dernieres and Timbalier Test.

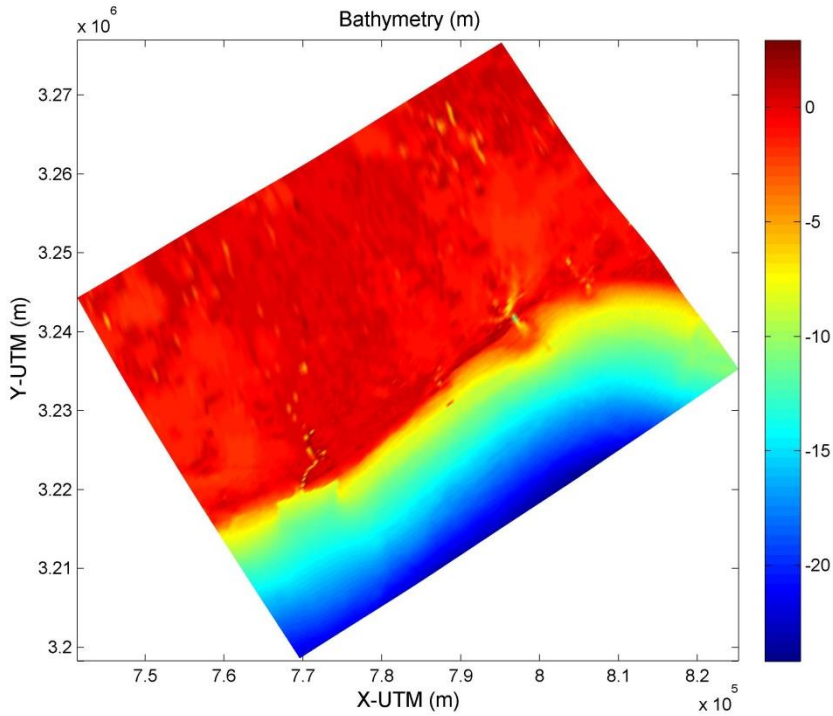


Figure 17: SWAN Grid Bathymetry for Caminada Headland and Grand Isle Test.

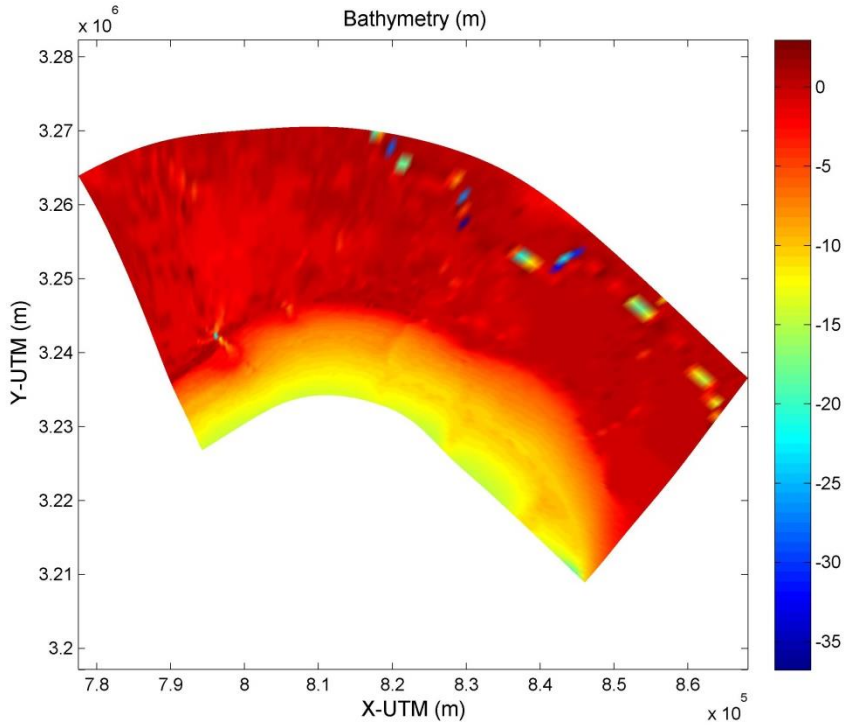


Figure 18: SWAN Grid Bathymetry for Barataria Bay Test.

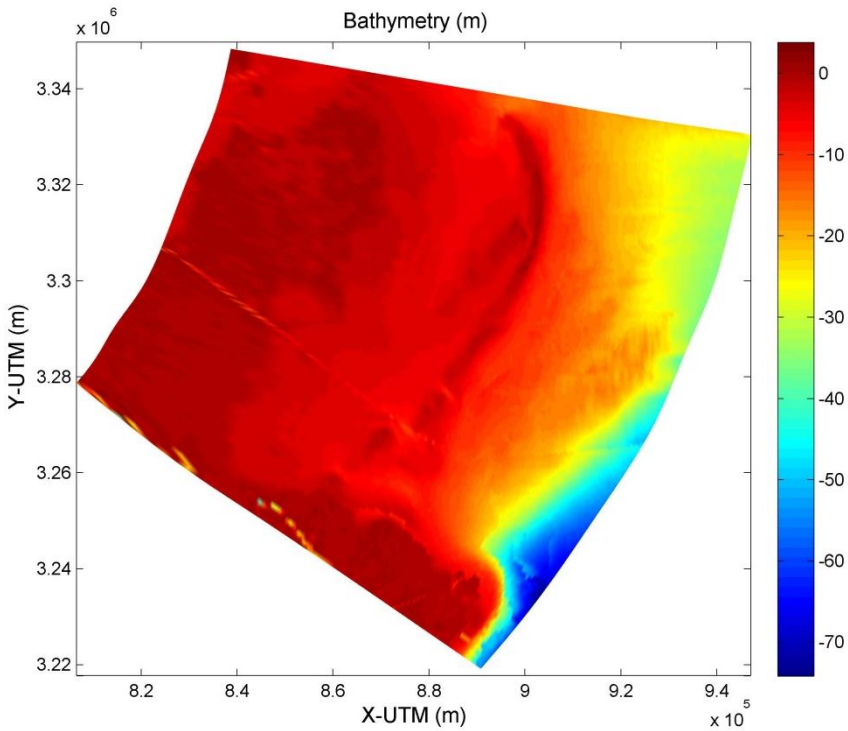


Figure 19: SWAN Grid Bathymetry for Chandeleur Island and Breton Island Test.

Using the SWAN model, the waves were transformed from the offshore boundary using WIS station data to a depth contour of 4 meters for models west of the Mississippi River and 5 meters for Chandeleur Island and Breton Island. Figure 20 through Figure 23 show the wave transformation of direction and significant wave height for one example wave case at individual locations.

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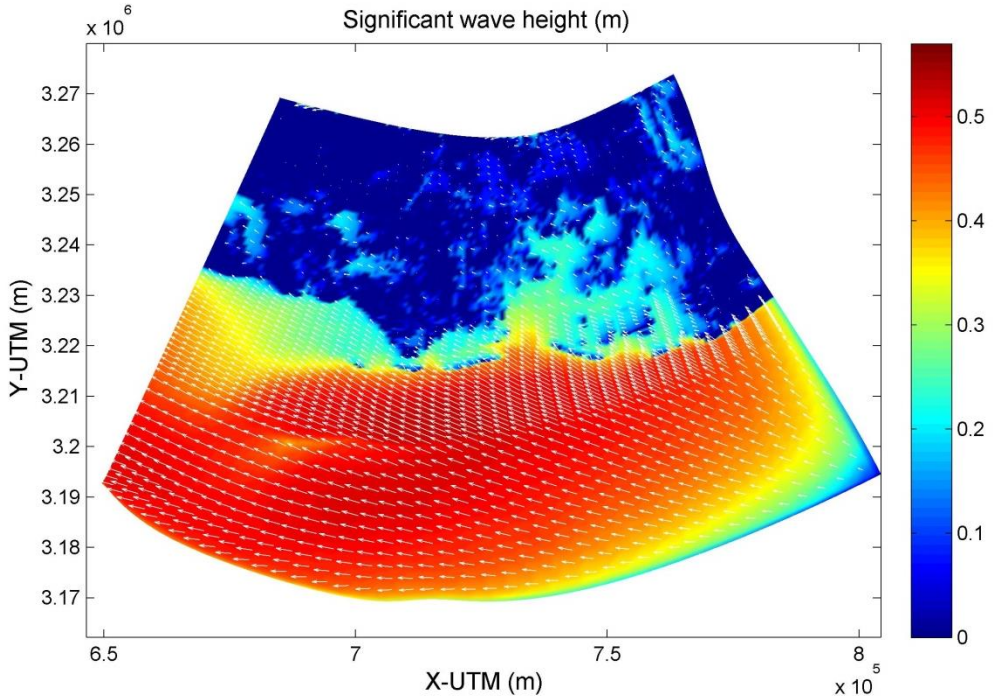

Figure 20: SWAN Results of Isles Dernieres and Timbalier for a Single Wave Case.

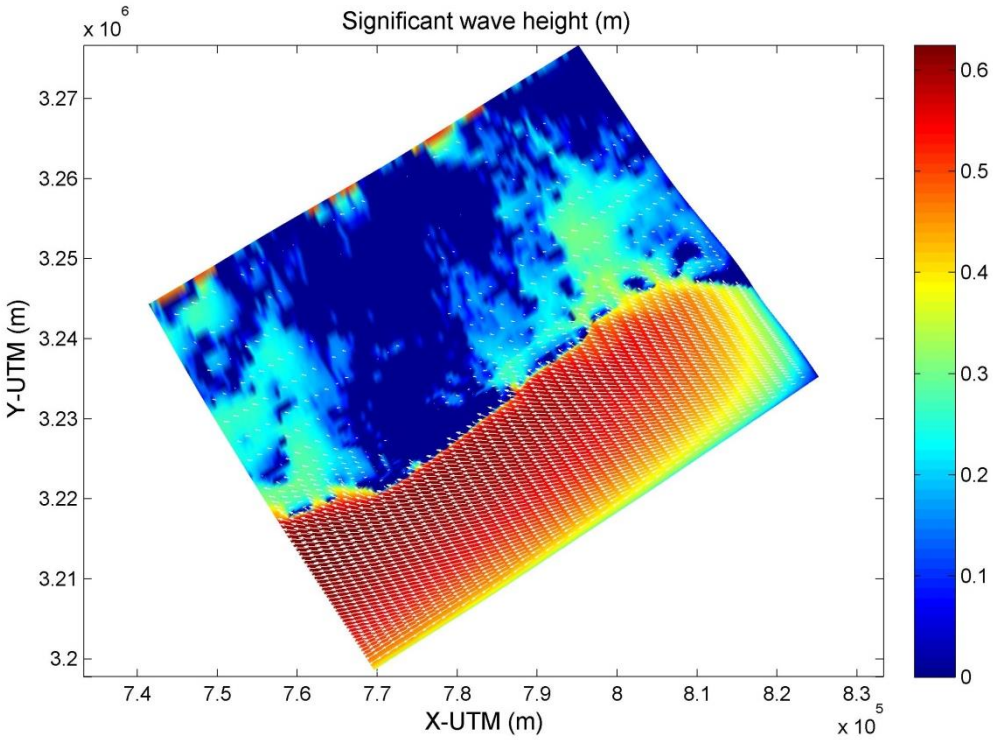

Figure 21: SWAN Results of Caminada Headland and Grand Isle for a Single Wave Case.

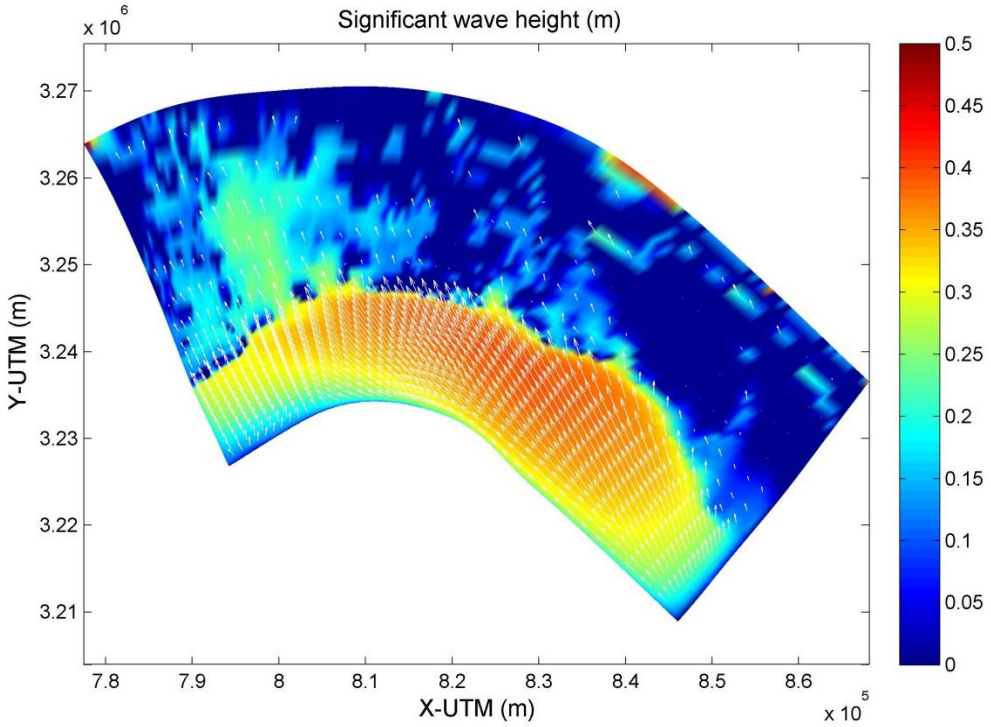

Figure 22: SWAN Results of Barataria Bay for a Single Wave Case.

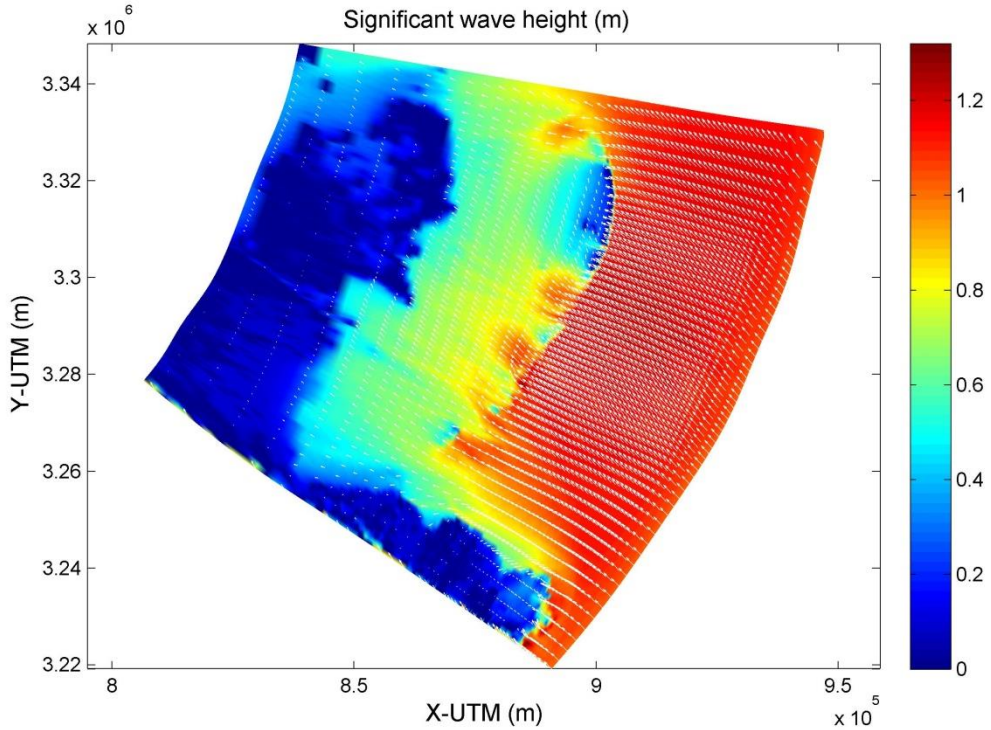

Figure 23: SWAN Results of Chandeleur Island and Breton Island for a Single Wave Case.

Wave transformation from the -4m depth contour to the wave breaking location is performed within BIMODE as described in Section 4.3.5 based on profile input data. An example of the results of this wave transformation from the offshore to breaking depth is shown in the monthly wave statistics from the year 1980 presented in Figure 24, 25, 26, and 27. Prior to computation, the program verifies the depth contour to start the BIMODE wave transformation exists along the profile. The representative monthly breaking wave height, period, direction, as well as water depth were used to calculate longshore sediment transport using the CERC equation as described in Chapter 5 of this report. The wave angle used in the CERC equation was determined by the SWAN output wave direction and profile azimuth. Testing of wave transformation in SWAN and processing of data within BIMODE proved the program to be functional and free of program errors.

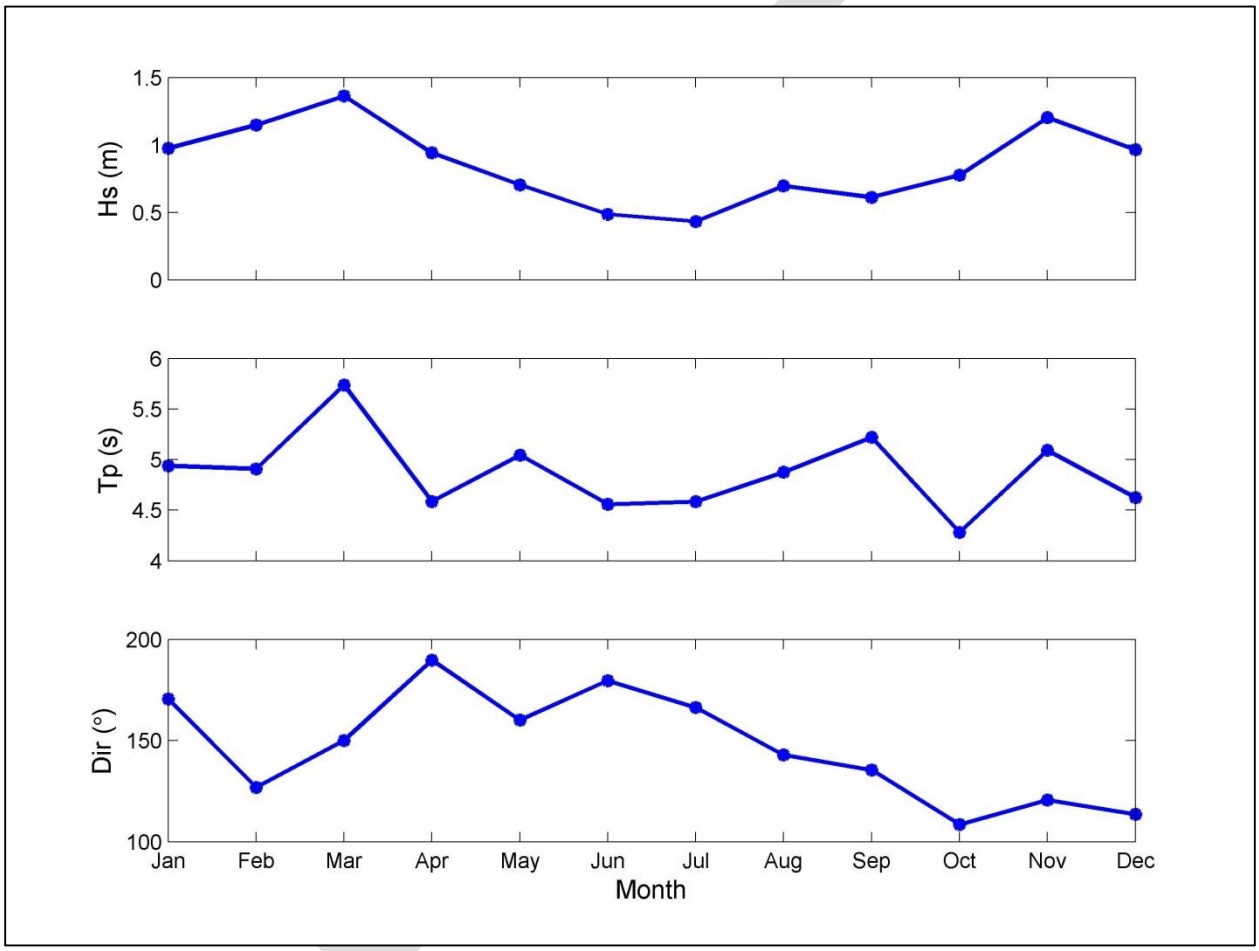

Figure 24: ST71341 Monthly Offshore Wave Distribution for the Year 1980.

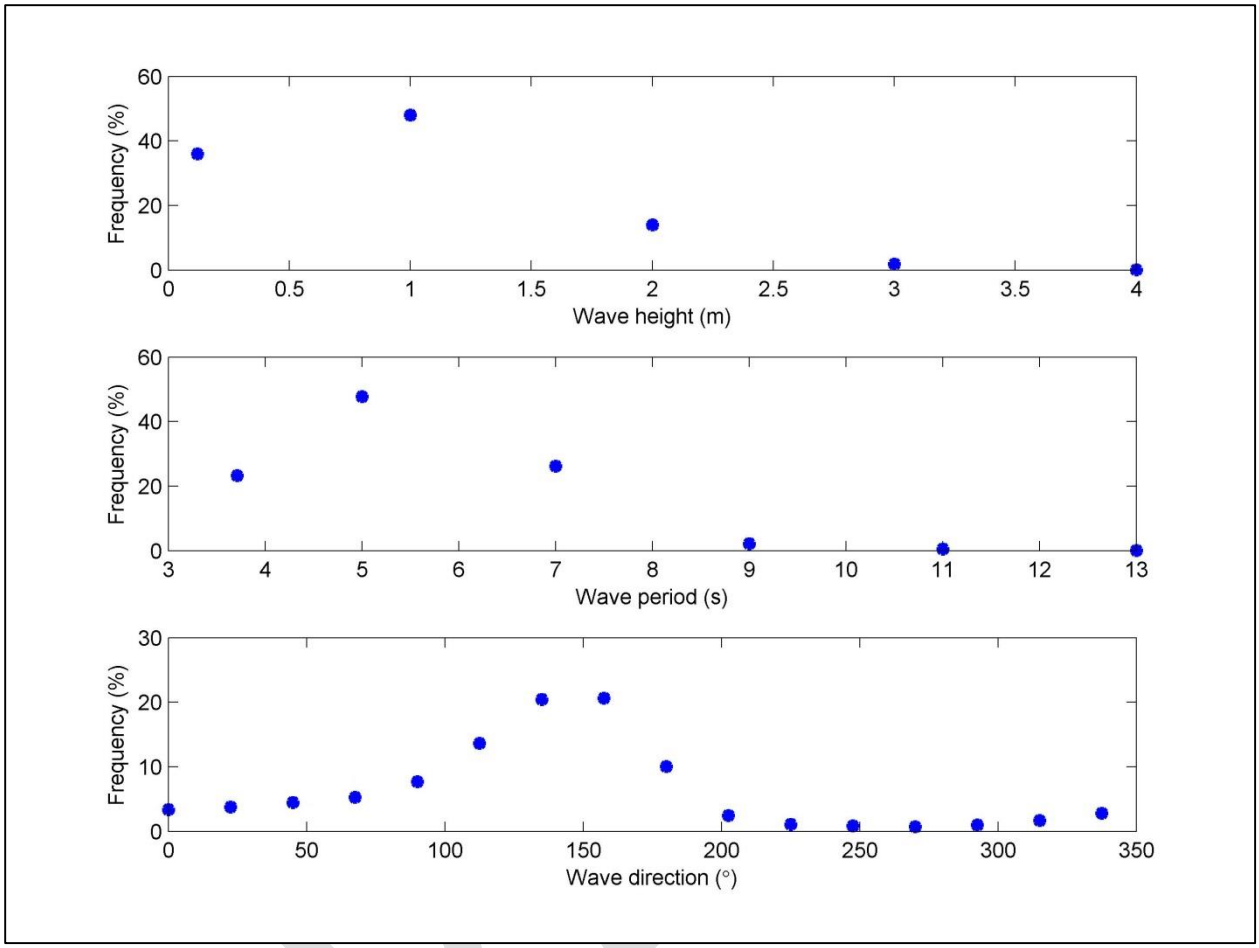

Figure 25: ST73141 Frequency Distribution of Offshore Wave Statistics for the Year 1980.

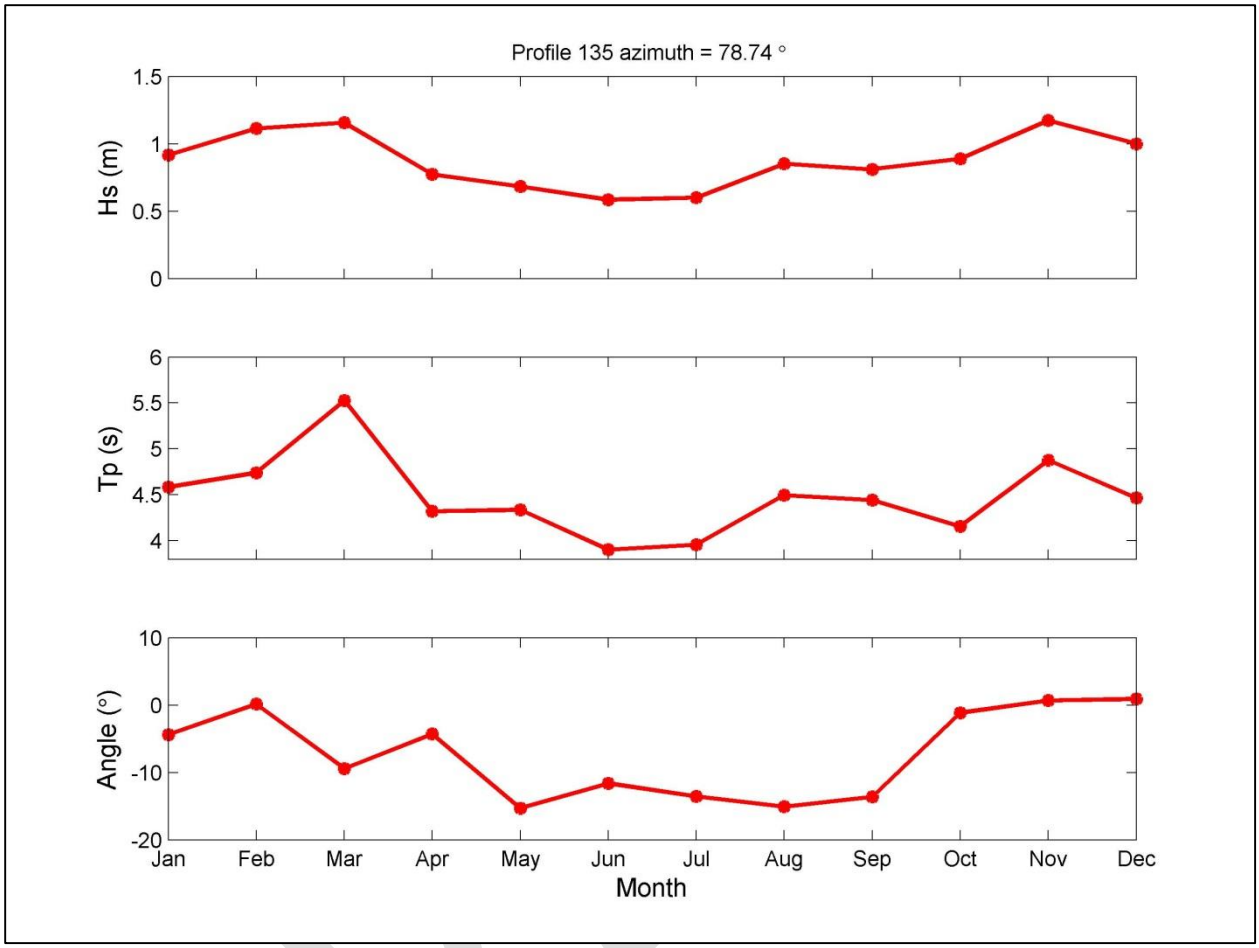

Figure 26: Monthly Breaking Wave Distribution for Year 1980 at Profile 135 in the Chandeleur Islands.

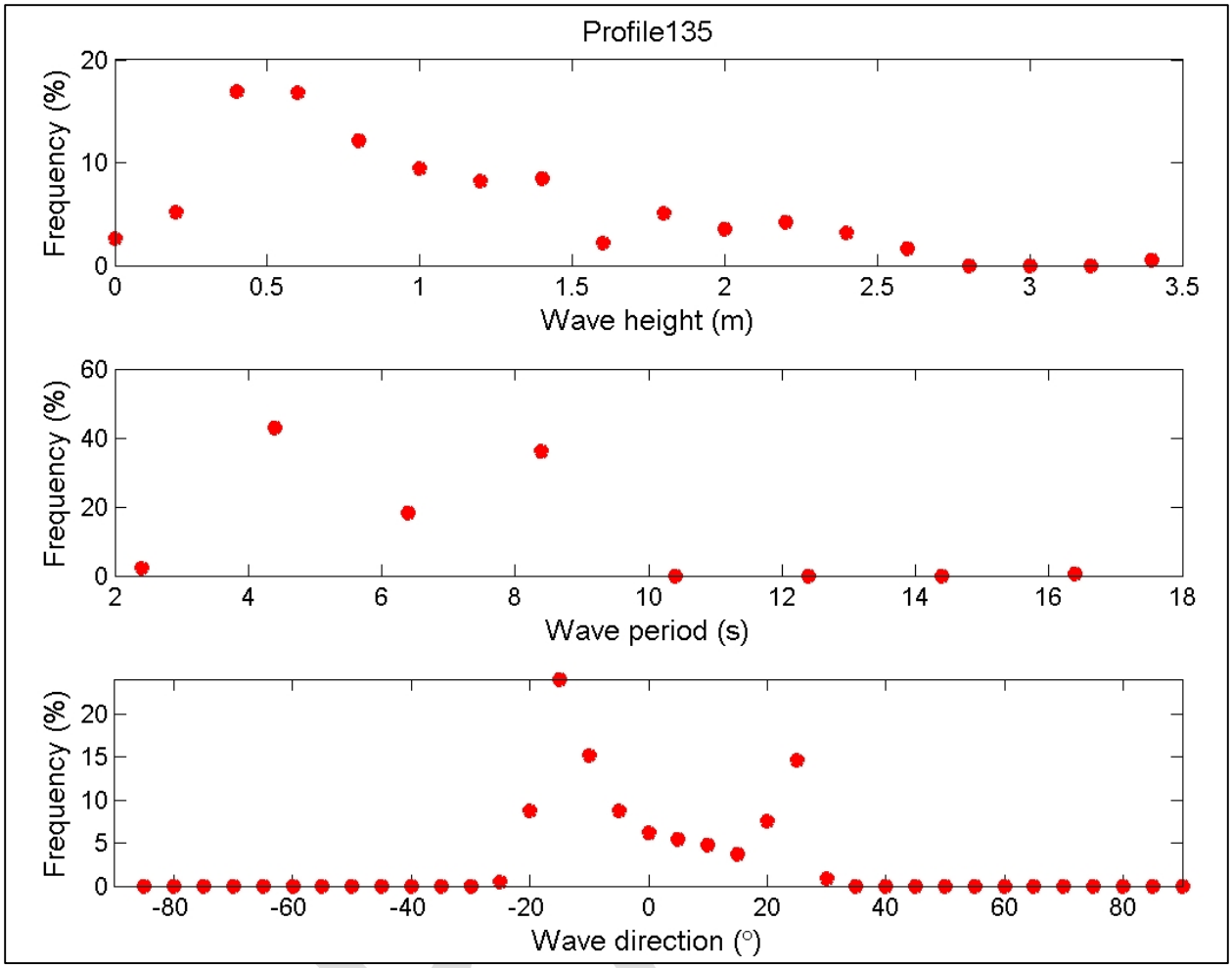

Figure 27: Frequency Distribution of Breaking Wave Statistics for Year 1980 at Profile 135 in the Chandeleur Islands.

14.3.3 Cross-shore Sediment Transport

In order to test the cross-shore transport subroutine and SBEACH look-up table function, 16 example profile cases were developed and two storm scenarios were simulated in SBEACH to provide data for the table. The example profile cases were combinations of maximum dune heights of 1.2 meters, 1.8 meters, 2.4 meters and 3 meters and dune widths of 30.5 meters, 61 meters, 91 meters, and 122 meters. The two storms simulated were a 5-year and a 20-year storm. The storm data was sourced from Cobell et al. (2013).

The following figures describe the contents of the SBEACH look-up table. Figure 28 below shows an example profile case with a maximum dune height of 1.2 meters and a dune width of 122 meters after 5-year storm and 20-year storm. The lower plot in Figure 28 shows the elevation difference before and after storm. The elevation difference is stored in the SBEACH look-up table as the storm transformation function.

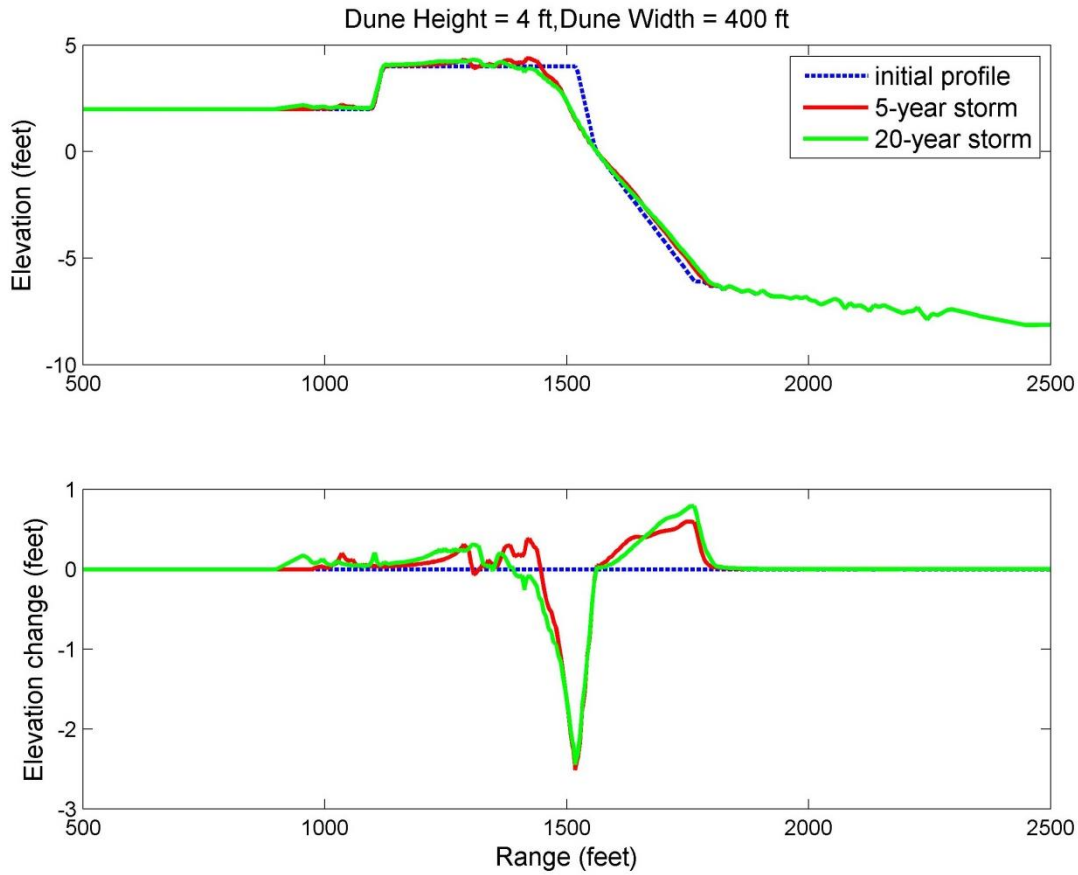

Figure 28: SBEACH Results & Transformation Applied in BIMODE. SBEACH results for an example profile after a 5 and 20-year storm event (top); difference between the initial profile and the post-storm profile, known as the transformation (bottom).

The initial step of the SBEACH look-up table function is to match an idealized profile case to the existing profile (Figure 29). In the test, the measured profiles were compared to the 16 idealized example profile cases. The matching idealized profile had the least difference from the existing profile. The storm transformation of the idealized profile linked to the specific storm period was then applied to the existing profile. Figure 29 shows the output of the test of the application of the transformation for the 5 and 20-year storm event examples.

Figure 30 shows the shoreline after running the cross-shore transport subroutine for a 5-year and 20-year storm event. Testing of the cross-shore transport subroutine and SBEACH look-up table function within BIMODE proved the program to be functional and free of program errors.

Breaching is checked after each storm event to remove the breached area from longshore transport calculation. The methodology is described in both Section 13 and the beginning of this section. Due to the limited availability of profile shapes in the current SBEACH look-up table, the breaching process validation is not provided. The storms used in testing (5-year storm and 20-year storm) did not cause profile changes that led to beaching in the scenarios simulated. The breaching process will be tested during BIMODE code integration with the ICM, when sufficient SBEACH profile types are provided.

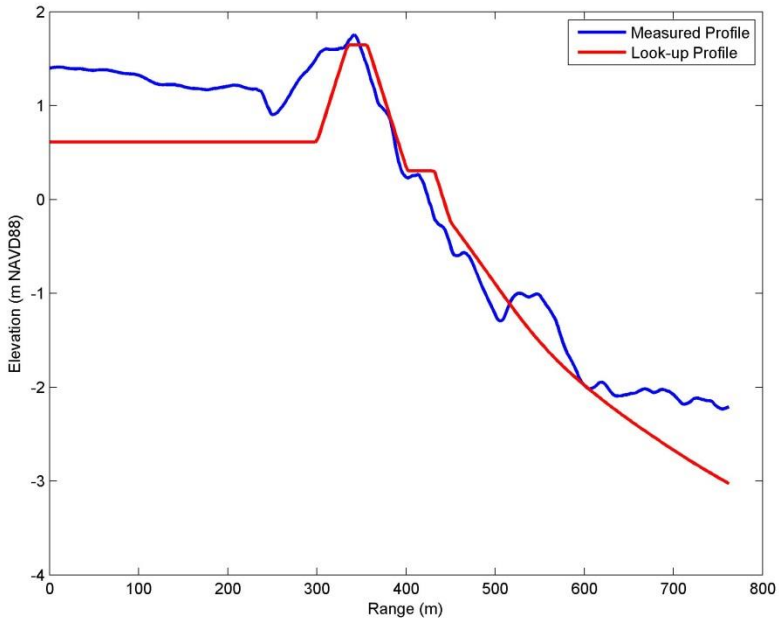

Figure 29: Test Output: Profile Matching in BIMODE.

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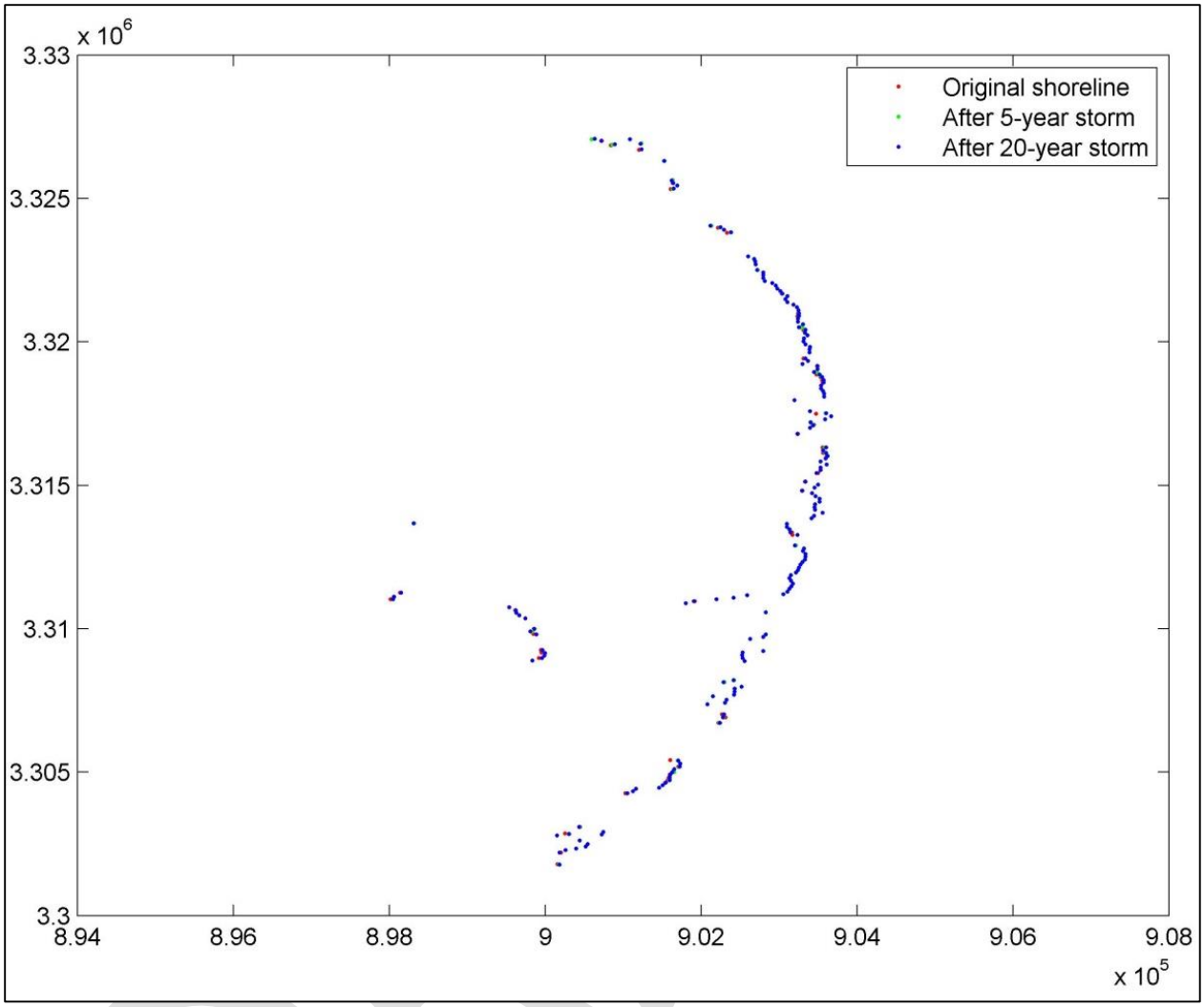

Figure 30: Test Output: Application of Transformation in BIMODE.

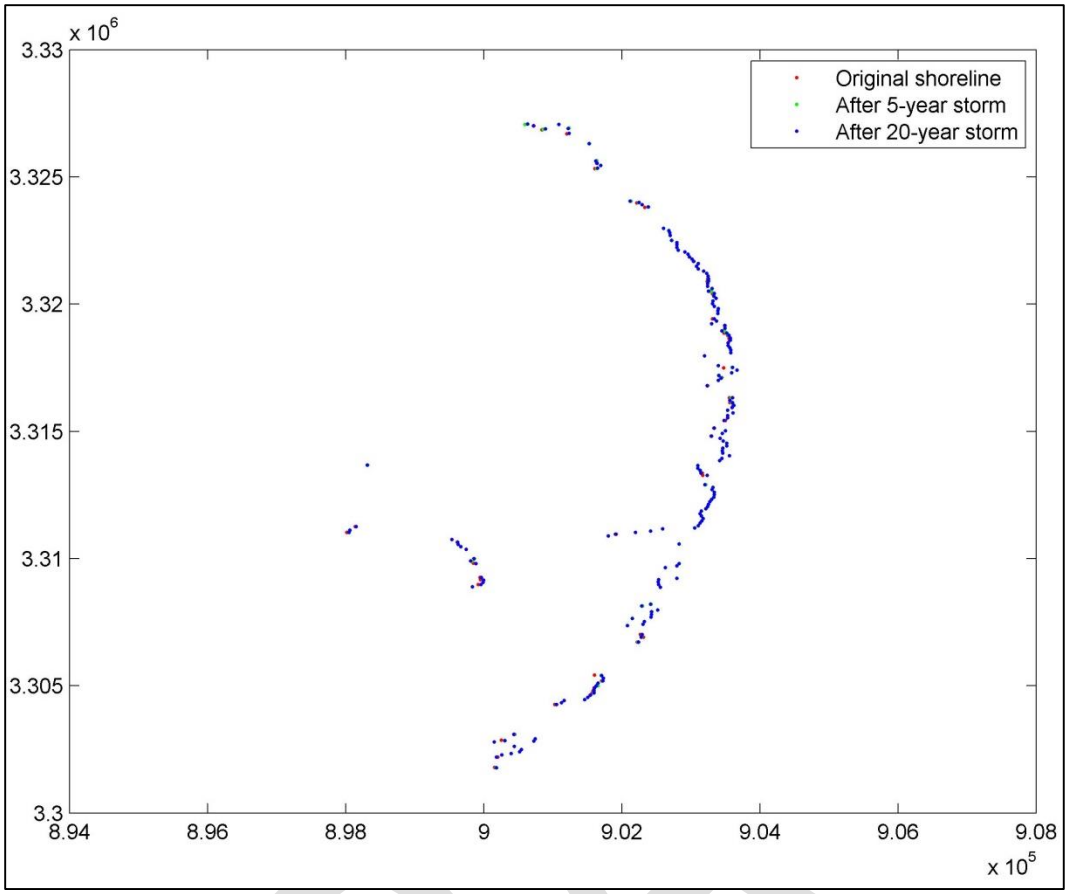

Figure 31: Test Output: Plan View of Shoreline After a 5-Year Storm Event and 20-Year Storm Event.

14.3.4 Longshore Sediment Transport

According to the CERC equation, the longshore transport is calculated for each profile based on wave parameters. The net longshore transport in each cell (area between two adjacent profiles) was calculated and smoothed using inverse-distance weighted method. To smooth the longshore transport at the target profile, the transport rates were considered at both the target profile and the adjacent profiles. The transport rate is then weighted by the distance between target profile and adjacent profile. More distant profiles contribute less to the transport rate of the target profile.

The definition of longshore sediment transport direction is similar to GENESIS. When sitting on the beach, facing seaward, if one sees waves come from left to right, the wave direction is positive and so is the longshore transport. Two adjacent profiles form one cell. There is longshore transport at each cell. The net transport at each cell is then calculated. For the area where longshore transport leaving the cell is greater than the longshore transport entering the cell, there was a sediment loss in the cell, which results in the profile retreat as shown in Figure 32. The profile retreated from the maximum elevation location seaward to the depth of closure (5 meters). As the shoreline retreated, the slope behind the maximum elevation location steepened. This happens because the profile has discrete points. As the highest point is shifted landward, if it does not extend beyond the next point, it gets closer to it. Since the elevations of

the two points remain the same but they are closer together, the slope becomes steeper. Testing of the program identified the need to apply a slope threshold to prevent unrealistic or near vertical slopes from occurring. In the program, any slope greater than π/6) (= 30°) are removed and interpolated.

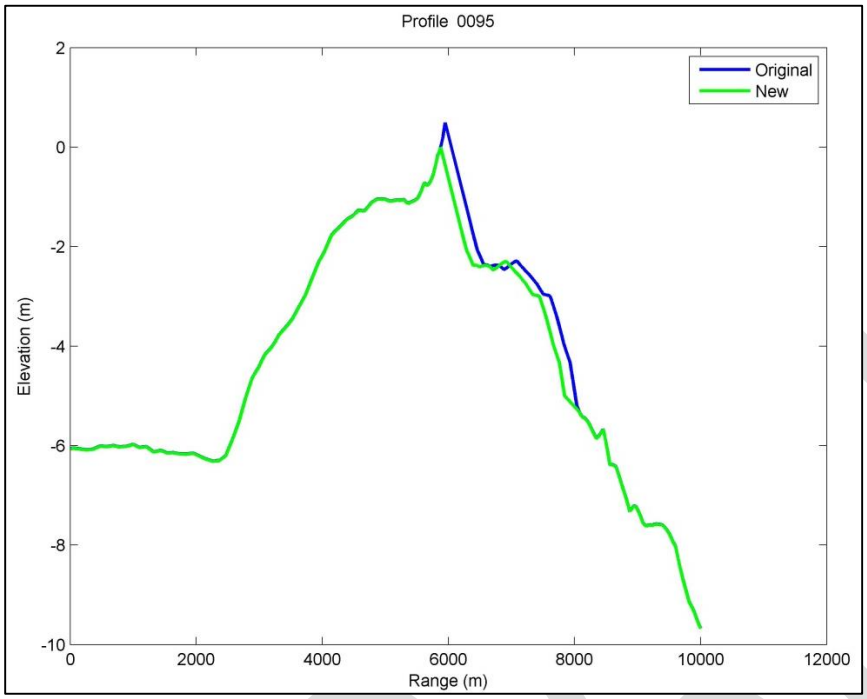

Figure 32: Test Output: Shoreline Retreat Resulting from Longshore Transport Losses.

For areas with positive net longshore transport, where longshore transport entering the cell is greater than the longshore transport leaving the cell, a gain of sediment occurred in the cell. The profile was advanced from the maximum elevation location to the depth of closure. Figure 33 is an example of a test where dune width increased as the profile advanced.

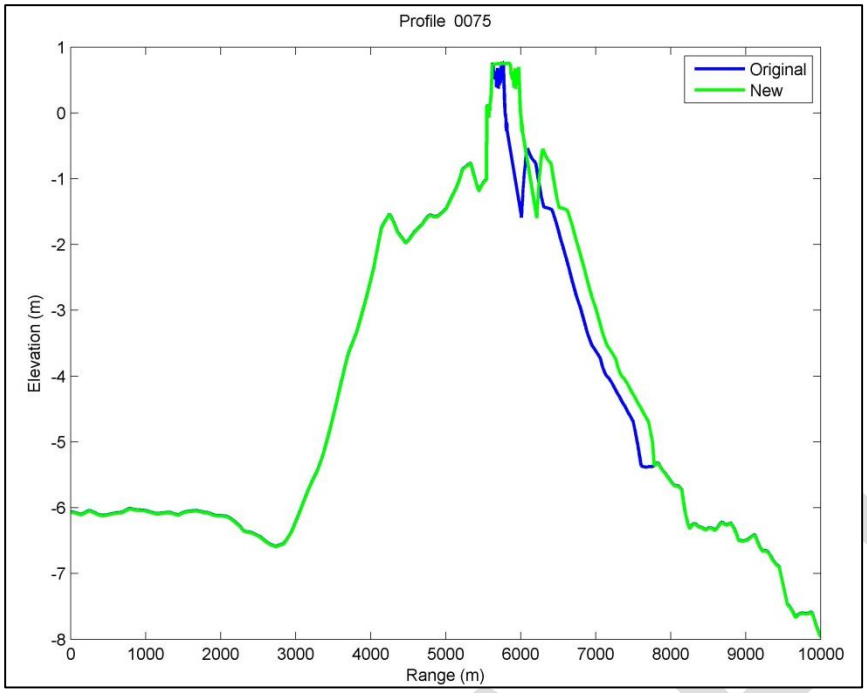

Figure 33: Test Output: Shoreline Advancement from Longshore Transport Gains.

BIMODE outputs a time series of wave-induced shoreline retreat or advance at a specified profile ID. An example of output from the test of the shoreline retreat/advance rate (m/day) subroutine is shown in Figure 34. Positive value indicates shoreline retreat. The result is based on monthly wave data series between 2006 and 2014. The shoreline retreat/advance induced by each wave case is calculated. The monthly retreat is the sum of each retreat rate times its occurrence time. The alternation in shoreline retreat and advancement in the time series is a function of the monthly changes in wave height, period and direction.

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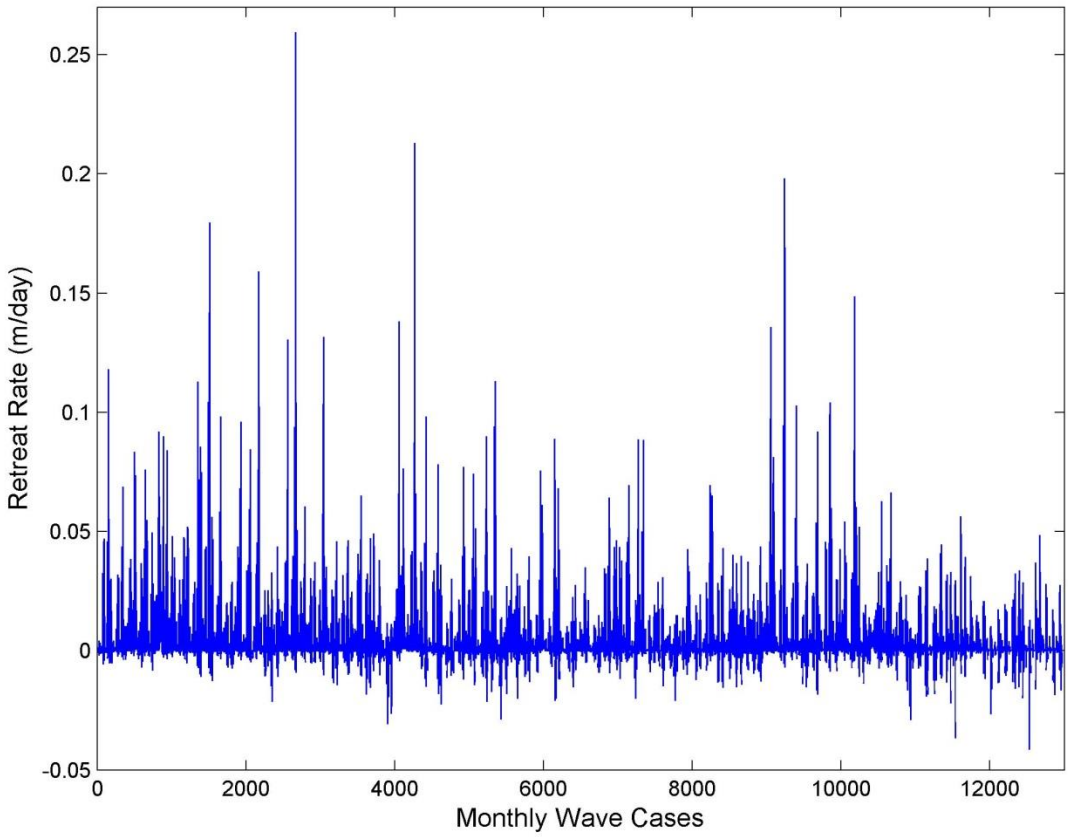

Figure 34: Test Output: Time Series of Shoreline Retreat/Advance.

The results of the shoreline change after a one year simulation and the computation of longshore transport along a stretch of shoreline along Chandeleur Island is shown in Figure *35*.

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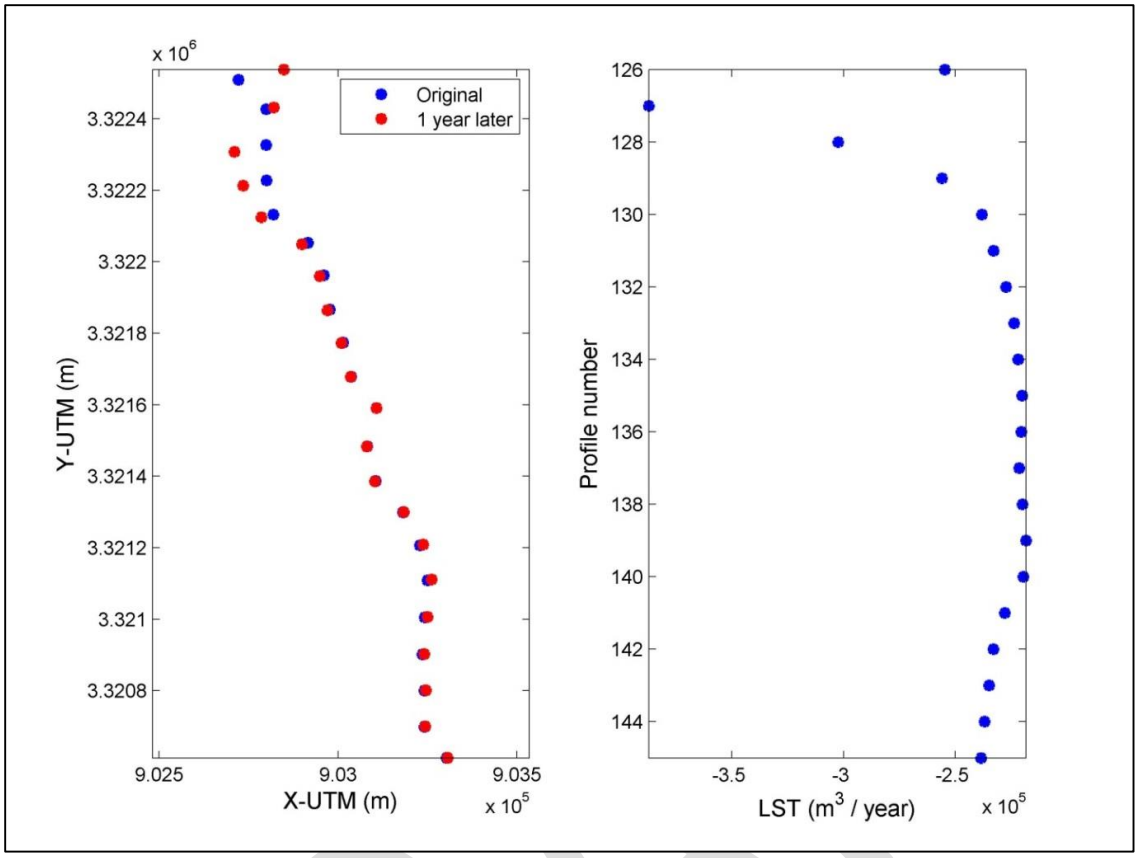


Figure 35: Shoreline change after a year of simulation along a section of shoreline on Chandeleur Island without storm events (left) and the corresponding longshore transport rate (right).

14.3.5 50-year Test Run Based on Monthly Statistic WIS Wave Data

A BIMODE test run was set up for both southern Louisiana and the Chandeleur Island and Breton Island regions with monthly representative WIS wave data for 50 years. The model run began on January 1, 1980 and ended January 1, 2030. Since the wave data record only covers January 1, 1980 to December 31, 2012, the time series was repeated after 2012. The monthly statistics of wave data was formatted in terms of wave cases by the frequency of occurrence. Therefore, the monthly statistics may contain 4-150 representative wave cases. Each of the wave cases within the month was transformed to depth of breaking (using SWAN offshore and internal module in the nearshore), calculated for longshore sediment transport and added according to the frequency of occurrence. In detail, the wave data series is parsed by month in preparation for performing the monthly statistical characterization. The monthly statistical analysis results in identification of some limited number of characteristic wave conditions for each month. SWAN was used to simulate each of the representative wave conditions develop a database of nearshore wave conditions. The final wave transformation to the breaking point and the sediment transport contribution from each of these representative wave conditions are computed by BIMODE. Finally, the resulting transport rates are summed to obtain the net and gross transport rates for the month. The output included shoreline location and cumulative longshore transport every 10 years. Figure 36 through Figure 46 show the shoreline change and longshore transport for both southern Louisiana and Chandeleur Island and Breton Island test areas.

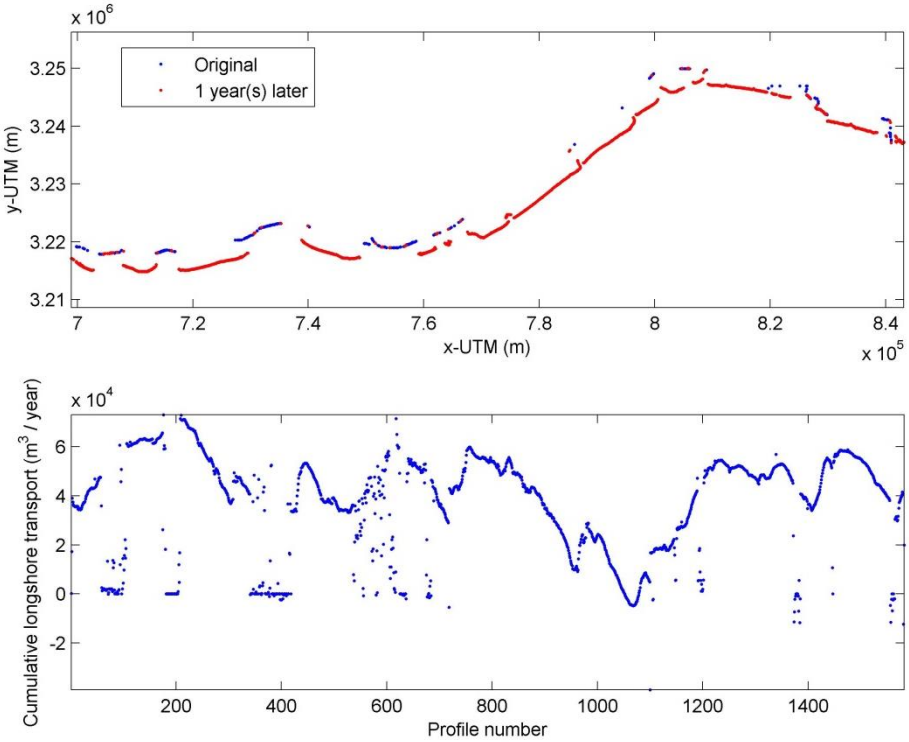


Figure 36: Shoreline and Cumulative Longshore Transport West of Mississippi River (Year 1).

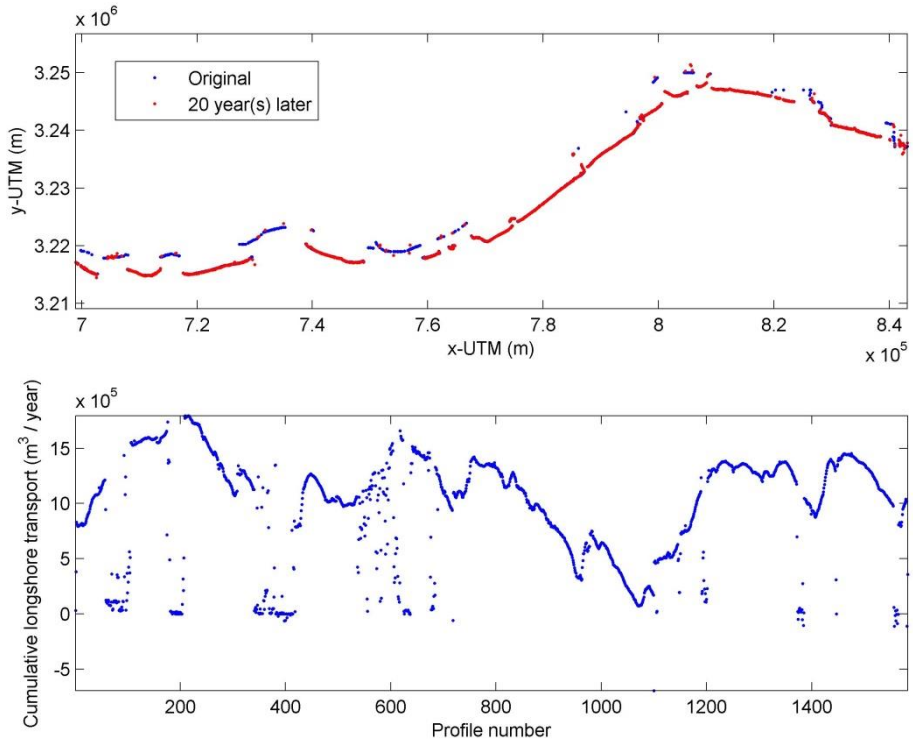


Figure 37: Shoreline and Cumulative Longshore Transport West of Mississippi River (Year 20).

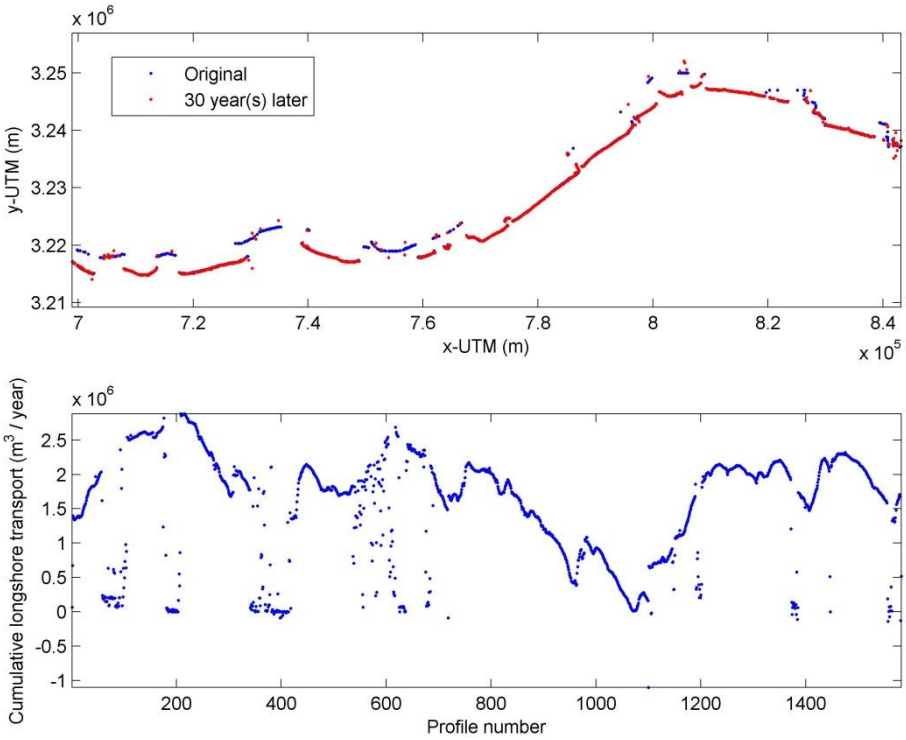


Figure 38: Shoreline and Cumulative Longshore Transport West of Mississippi River (Year 30).

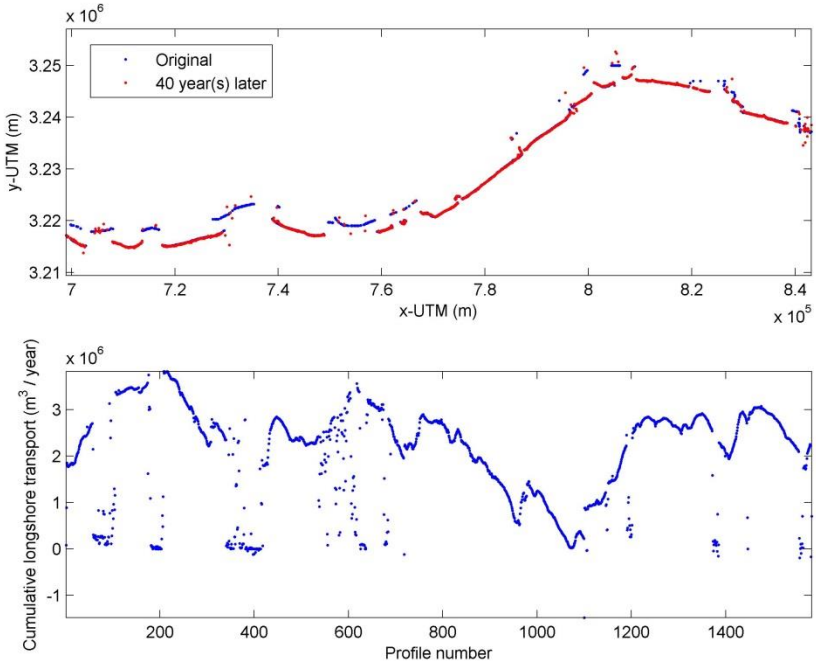


Figure 39: Shoreline and Cumulative Longshore Transport West of Mississippi River (Year 40).

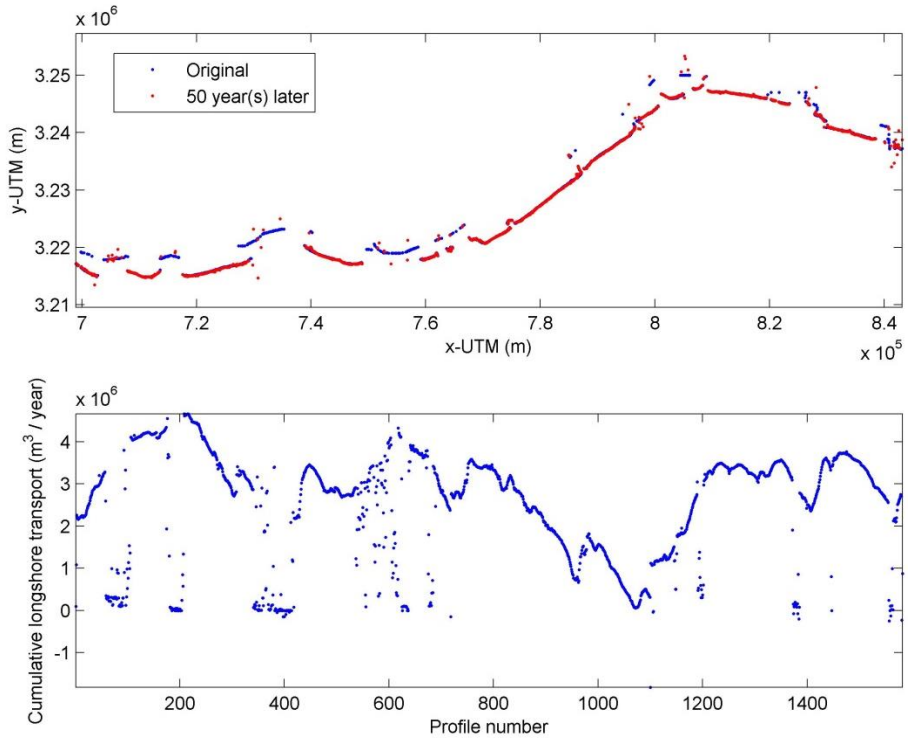


Figure 40: Shoreline and Cumulative Longshore Transport West of Mississippi River (Year 50).

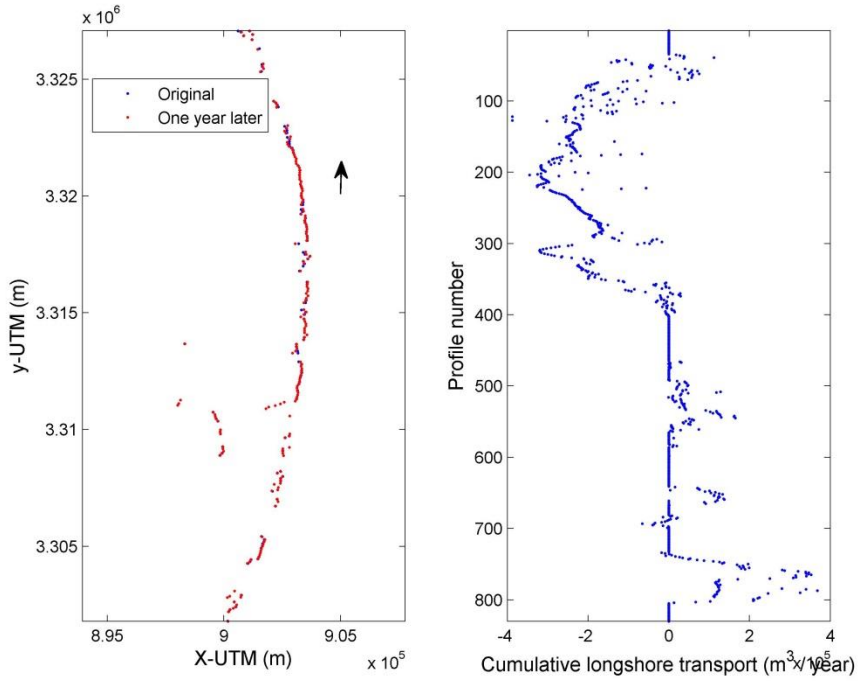


Figure 41: Shoreline and Cumulative Longshore Transport at Chandeleur Island (Year 1).

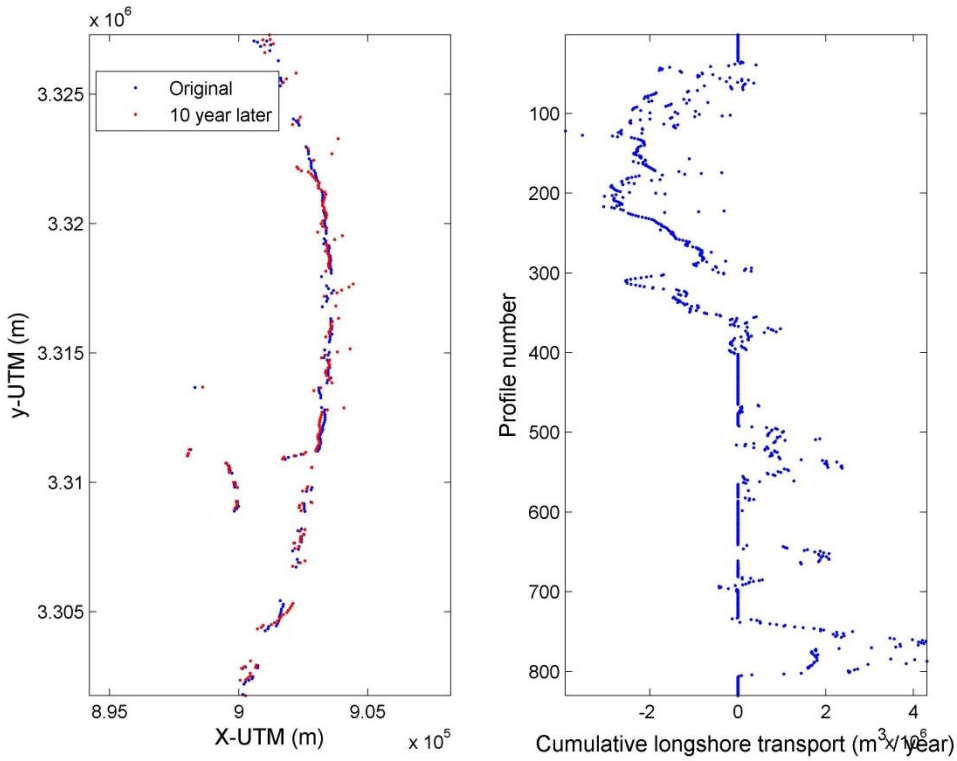


Figure 42: Shoreline and Cumulative Longshore Transport at Chandeleur Island (Year 10).

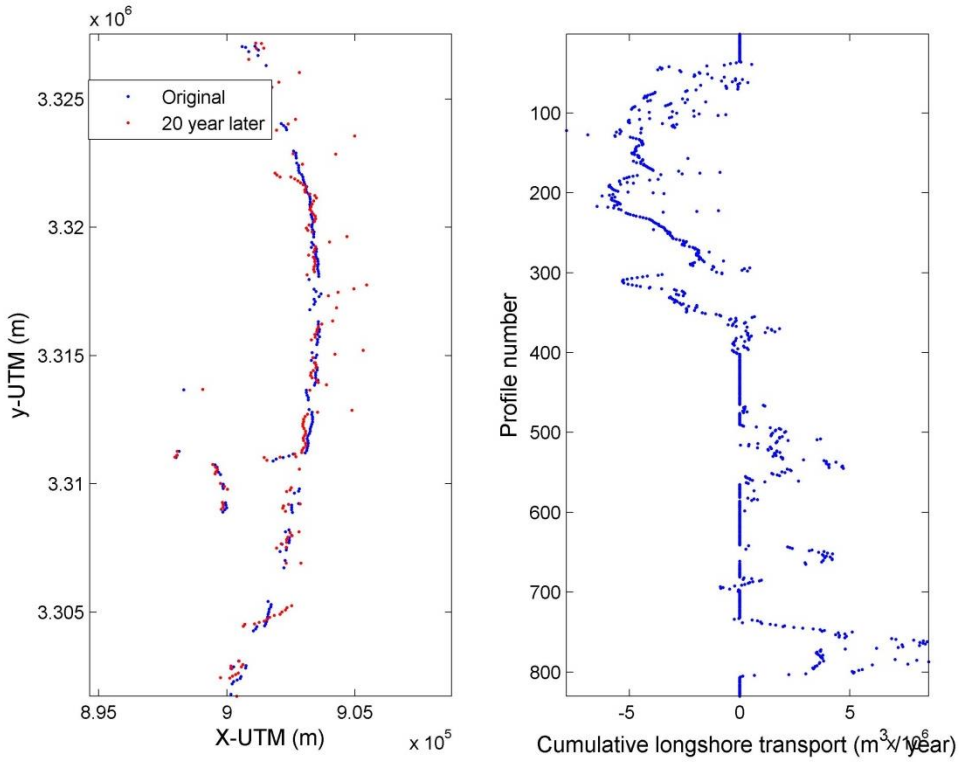


Figure 43: Shoreline and Cumulative Longshore Transport at Chandeleur Island (Year 20).

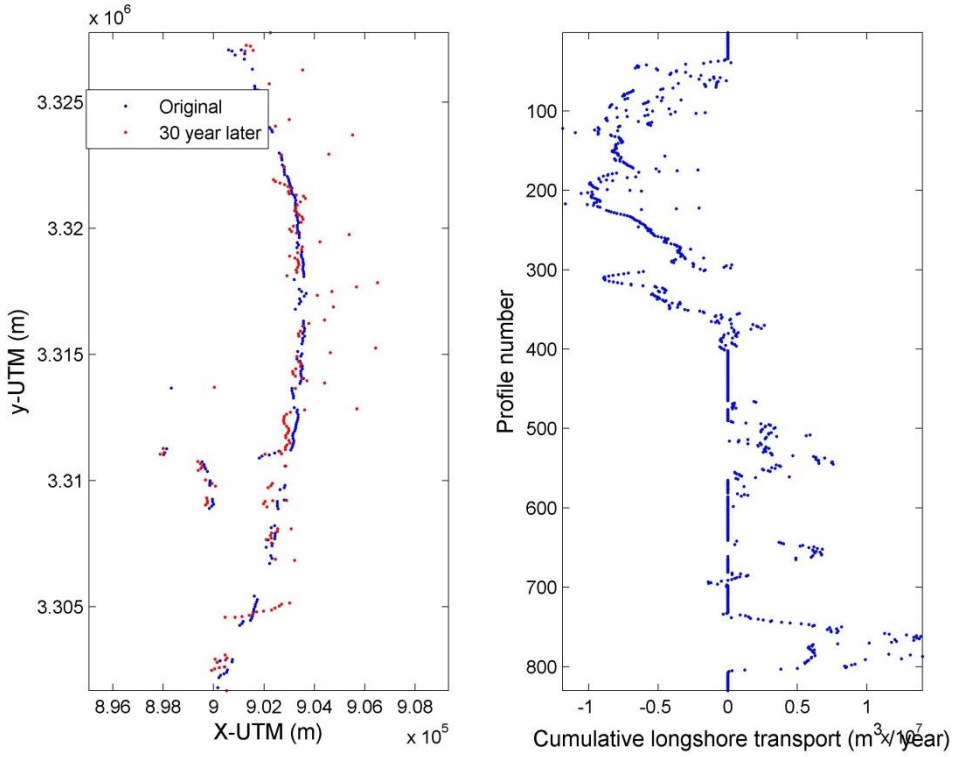


Figure 44: Shoreline and Cumulative Longshore Transport at Chandeleur Island (Year 30).

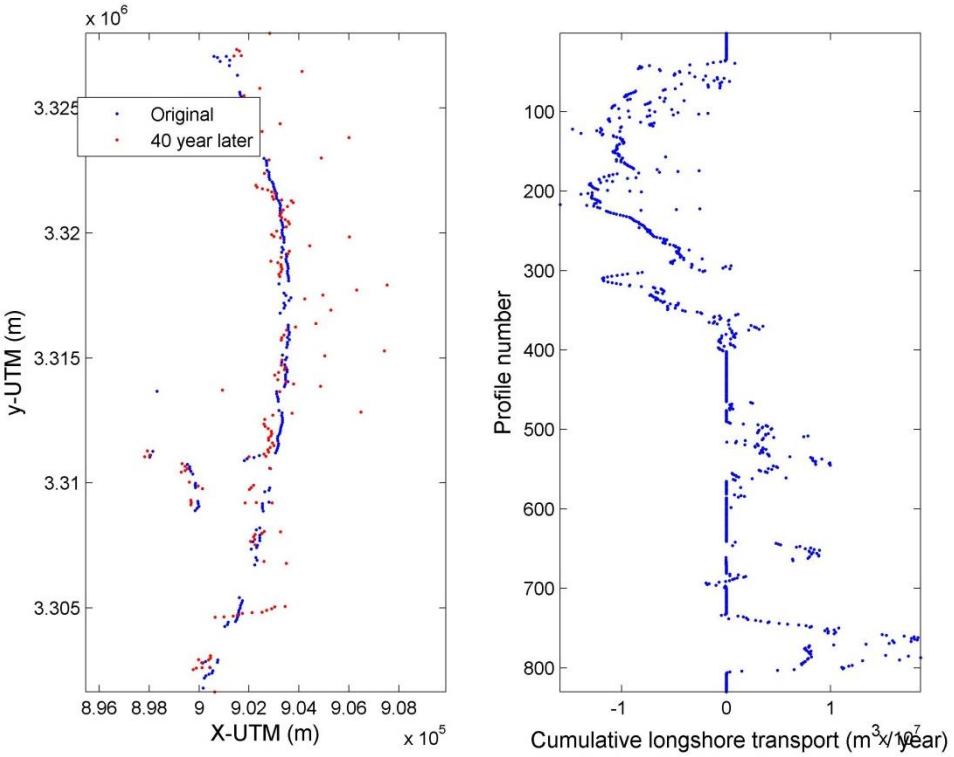


Figure 45: Shoreline and Cumulative Longshore Transport at Chandeleur Island (Year 40).

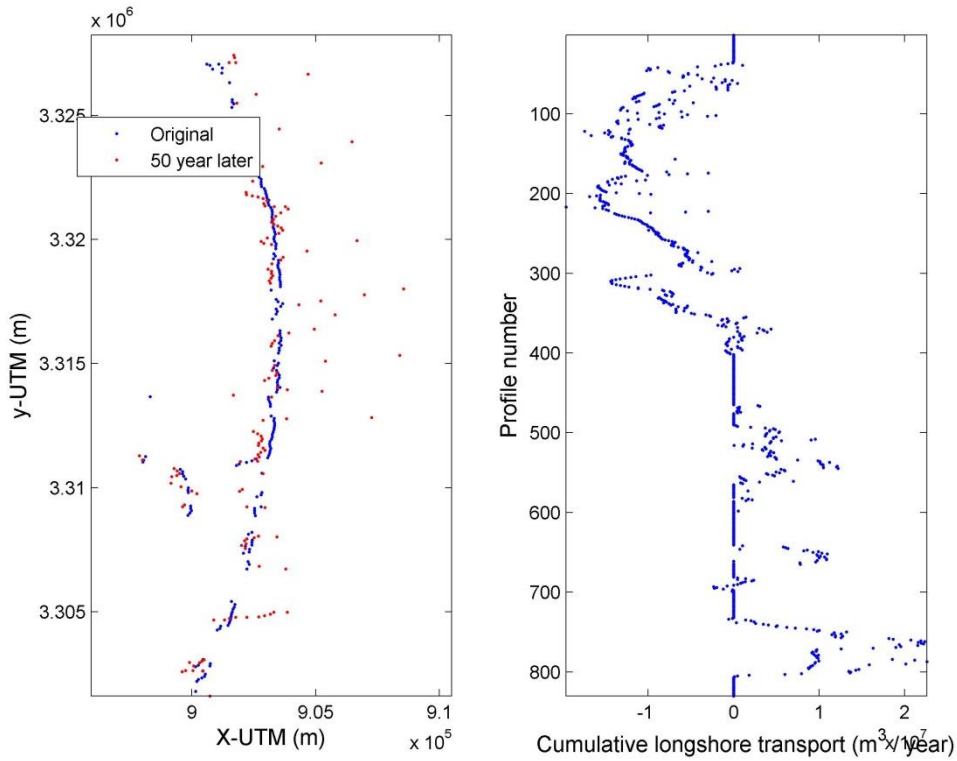


Figure 46: Shoreline and Cumulative Longshore Transport at Chandeleur Island (Year 50).

For the model domain west of the Mississippi River, the longshore sediment transport was mostly continuous along these barrier islands. Therefore, the shoreline location changed smoothly over years. However, for Chandeleur Island and Breton Island, the longshore sediment transport calculation was usually interrupted by the breached areas and inlets along the barrier islands. In BIMODE, a restricted depth was set below which no longshore transport was calculated. Since the shoreline retreat/advance was calculated by the net longshore transport between two adjacent profiles, longshore transport at breached areas and inlets caused abrupt changes in shoreline location. The code for simulating shoreline change adjacent to breaches and inlets may need to be further modified during the calibration and sensitivity analysis phase.

14.3.6 Inlet and Bay Model Integration

The inlet and bay model was integrated in BIMODE to predict inlet morphology change. The model was based on the 2012 Coastal Master Plan Inlet and Morphology Model (Hughes *et al.*, 2012). Two subroutines of the main structure of the inlet and bay model were included in BIMODE. Further integration and validation may be necessary in the phases following model development.

14.3.7 Program Messages from BIMODE

When running the BIMODE program, the user can first expect to see the successful reading in of the input.txt file (Figure 47). If the reading in was not successful, an error message will appear. Then, the screen will show the input file information. When the model runs, the computation time and wave case information is printed on screen at each monthly time step (

Figure 48). At the same time, the log file running_log.txt which contains the same information as screen printout is created. If the program runs and terminates without errors, a message of normal termination appears at the end (Figure 49). The print to screen function can be disabled in order to increase run times.

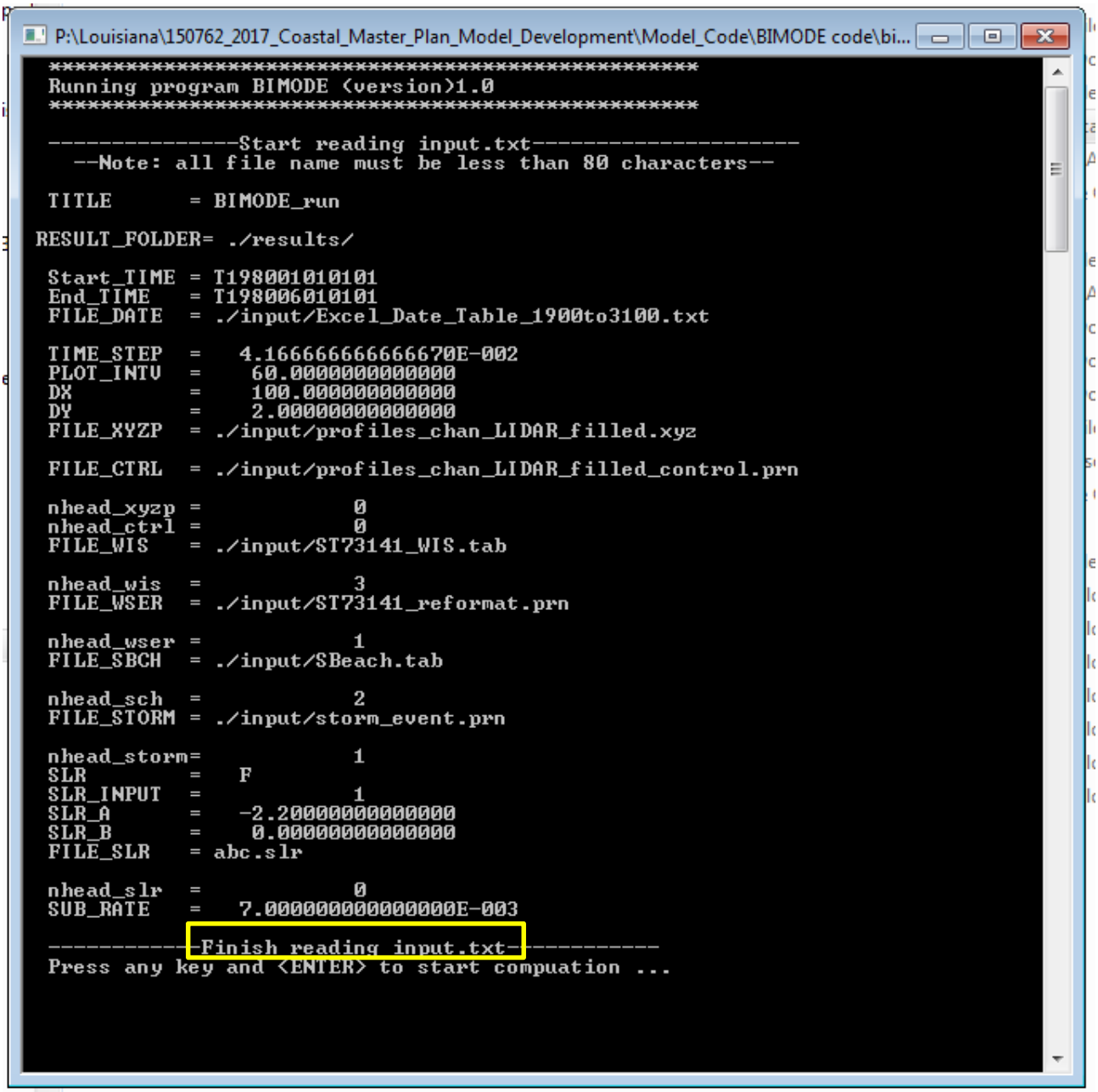


Figure 47: Successful Reading of Input File.

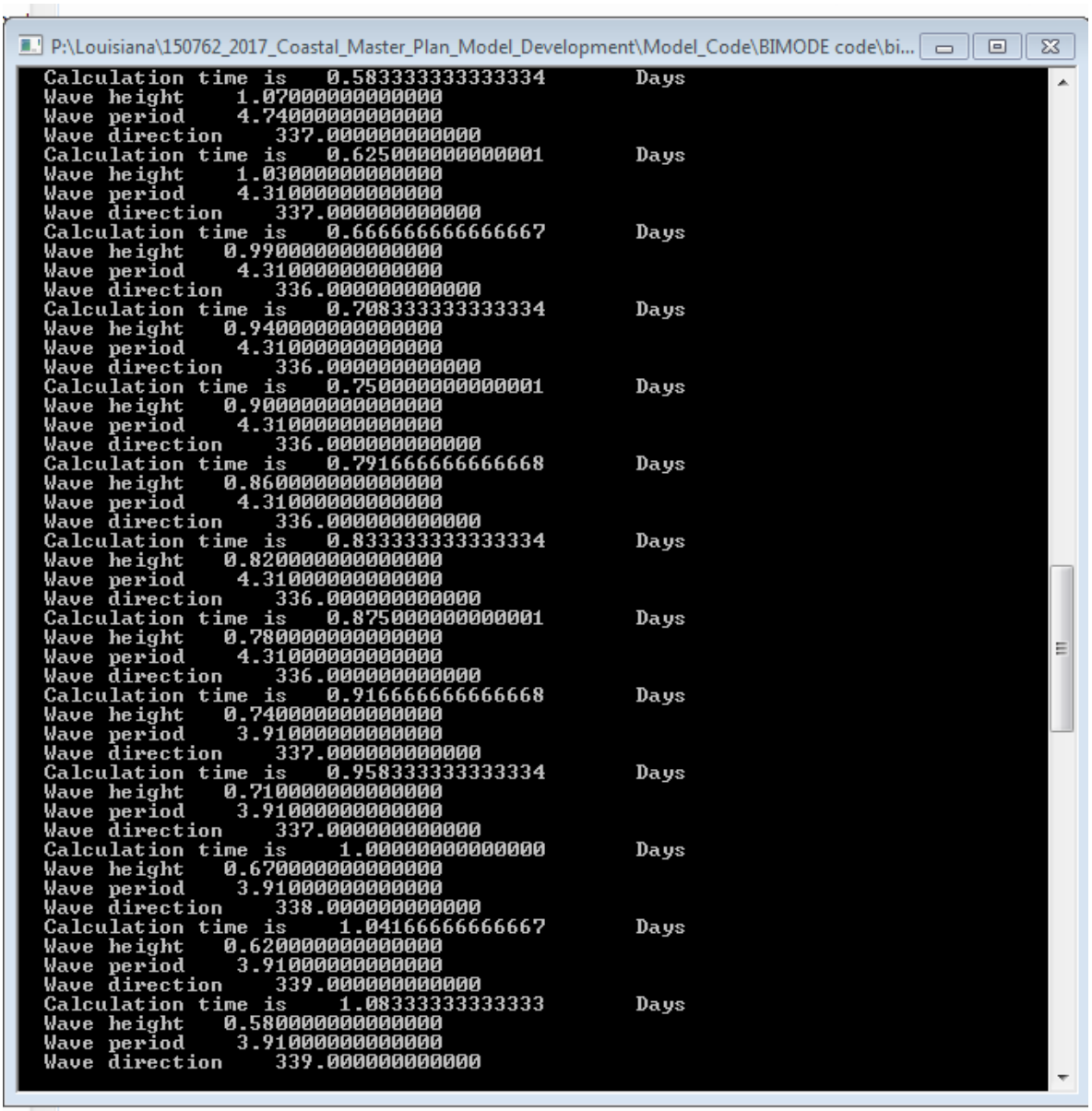
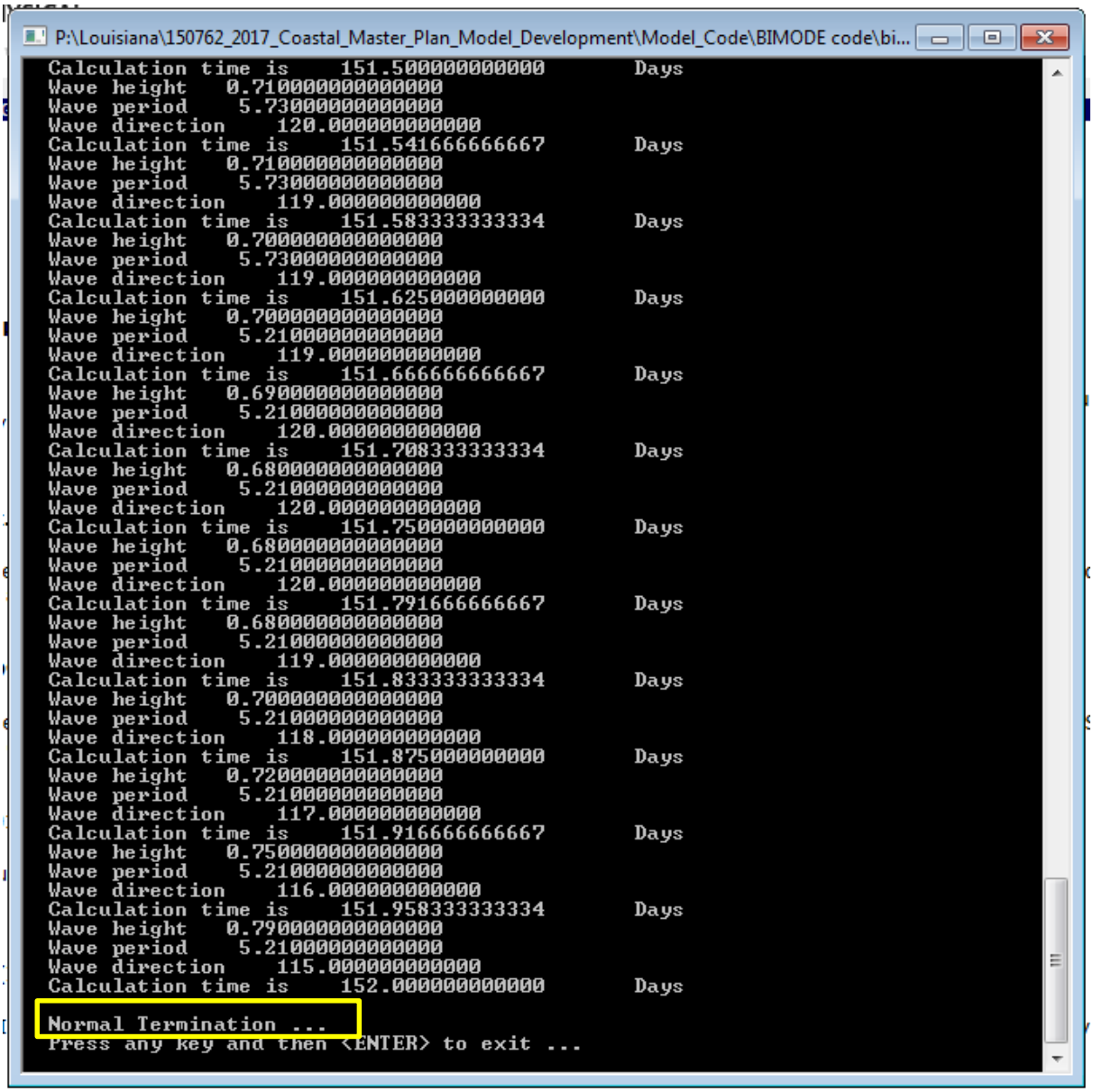


Figure 48: Screen View of Program Running.



```
P:\Louisiana\150762_2017_Coastal_Master_Plan_Model_Development\Model_Code\BIMODE code\bi...
Calculation time is     151.500000000000        Days
Wave height    0.710000000000000
Wave period     5.73000000000000
Wave direction     120.000000000000
Calculation time is     151.541666666667        Days
Wave height    0.710000000000000
Wave period     5.73000000000000
Wave direction     119.000000000000
Calculation time is     151.583333333334        Days
Wave height    0.700000000000000
Wave period     5.73000000000000
Wave direction     119.000000000000
Calculation time is     151.625000000000        Days
Wave height    0.700000000000000
Wave period     5.21000000000000
Wave direction     119.000000000000
Calculation time is     151.666666666667        Days
Wave height    0.690000000000000
Wave period     5.21000000000000
Wave direction     120.000000000000
Calculation time is     151.708333333334        Days
Wave height    0.680000000000000
Wave period     5.21000000000000
Wave direction     120.000000000000
Calculation time is     151.750000000000        Days
Wave height    0.680000000000000
Wave period     5.21000000000000
Wave direction     120.000000000000
Calculation time is     151.791666666667        Days
Wave height    0.680000000000000
Wave period     5.21000000000000
Wave direction     119.000000000000
Calculation time is     151.833333333334        Days
Wave height    0.700000000000000
Wave period     5.21000000000000
Wave direction     118.000000000000
Calculation time is     151.875000000000        Days
Wave height    0.720000000000000
Wave period     5.21000000000000
Wave direction     117.000000000000
Calculation time is     151.916666666667        Days
Wave height    0.750000000000000
Wave period     5.21000000000000
Wave direction     116.000000000000
Calculation time is     151.958333333334        Days
Wave height    0.790000000000000
Wave period     5.21000000000000
Wave direction     115.000000000000
Calculation time is     152.000000000000        Days

Normal Termination ...
Press any key and then <ENTER> to exit ...
```

Figure 49: Normal Termination of Program.

14.3.8 Performance

Fifty year test runs were conducted to test the performance and functionality of the BIMODE program. The fifty year simulation included the occurrence of a 5-year storm event every 5 years starting in year 5 (10 events) and a 20-year storm event every 20 years (2 events), for a total of 12 storm events. Tests were conducted on both test regions. The run time depends on the amount of selected wave cases in each month and number of profiles in the test region. The final run time is recorded in the file running_log.txt. The total time to run a 50-year of simulation with this setup was approximately 15 hours on an Intel i5-4570, Quad-core Processor (3.2 GHz, 16.0 GB, 64 bit Operating System).

15.0 Conclusions

A critical component of 2017 Coastal Master Plan is predicting the evolution of Louisiana's barrier islands. The 2017 Model Improvement Plan (CPRA, 2013) builds upon the modeling developed for the 2012 Coastal Master Plan (CPRA, 2012). Models must be capable of simulating 50-year time periods in an efficient manner and predicting project effects at a basin-scale. Specifically, the BIMODE improvements include modeling additional physical processes (e.g., overwash), improving the capabilities of predicting change in island morphology, and incorporating realistic event-driven morphodynamic responses. Another key advantage of BIMODE is the ability to be integrated into the ICM. The scope of this effort included a literature review; model approach development; and model formulation, coding, and testing; along with working meetings, routine teleconferences, and reporting. The focus area includes from the Chandeleur Islands to the eastern side of the Mississippi River active Balize Delta and from Scofield Island to Raccoon Island on the western side of the Mississippi River active Balize Delta.

Based upon a detailed review of pertinent available literature, knowledge and experience from restoration project design and field data collection, and professional judgment, the BIMODE Team selected the following physical processes, forcing functions, and geomorphic forms that affect the evolution of Louisiana's barrier islands for consideration in developing the modeling approach: wave transformation, longshore sediment transport, cross-shore sediment transport, breaching, inlets and bays, post-storm recovery, subsidence, and ESLR. Aeolian processes are not included in the BIMODE model, and the rationale for not incorporating this process is provided herein.

A hybrid modeling approach was developed to account for the key physical processes of longshore and cross-shore sediment transport. The longshore transport model formulation includes a three step wave transformation process using available hindcast data to yield representative breaking wave conditions. Wave data are used to estimate sediment transport rates employing the CERC transport formulation. Calibration of the longshore transport rates will be accomplished through comparisons to published data; note: calibration procedure and outcomes will be documented separately. The cross-shore sediment transport formulation includes application of the one-dimensional model SBEACH that simulates cross-shore morphologic response to a storm event based on measurement derived, empirical equations. The SBEACH model runs are recalled through look-up tables to determine the likely output profile given the starting input profile and storm characteristics. Input profiles are based on representative static submerged profiles from each of the regions along with combination of varying dune heights, dune widths and berm widths, some of which will represent pre-restoration barrier island profiles. The cross-shore transport formulation will be calibrated to demonstrate the predictive capability of the model across the study area for the selected range of storms.

Based upon experience in restoration project design, SBEACH tends to under predict storm erosion, which in some sense accounts for post-storm recovery processes. Accordingly, the BIMODE Team suggests the post-storm recovery processes are captured sufficiently through application of SBEACH.

Barrier island breaching is incorporated into the BIMODE model by determining critical thresholds of minimum barrier island widths and minimum width to island length ratios through application of historical data on barrier island breaching.

Subsidence and ESLR are incorporated into the BIMODE model through manual adjustments per guidance provided by CPRA.

The barrier shoreline model employed in the 2012 modeling accounted for inlet and bay processes, specifically inlet expansion/enlargement, using equilibrium theory for inlet cross-sectional area as a function of tidal prism. The BIMODE model utilizes the 2012 model formulation for inlets and bays, and can be coupled with the hydrology subroutine of the ICM more frequently, e.g., yearly, than was possible in 2012.

The procedure for the BIMODE model includes reading in the profile and wave data inputs, determining longshore sediment transport, locating nodal points where sediment transport diverges, determining net erosion or accretion within each cell formed by two adjacent profiles, and computing change in beach face profile specific to longshore transport; adjusting beach profiles to account for relative sea level rise, beach face profile retreat due to silt loss, and consolidation; accounting for cross-shore sediment transport for the given storm suite; eroding bayward side of profile; checking for and implementing breaching if the thresholds are met; and incorporating the inlet and bay model; and repeating for the 50-year simulation period. Output is cross-sections at each emergent profile in the format of a DEM.

BIMODE.f90 is the executable program developed to simulate the physical processes outlined in the procedures. BIMODE was written in Fortran 90. The file structure of the program consists of a main program file, which calls on several process-based subroutines to run. Quality control testing of the functionality and performance of the individual subroutines and code in its entirety was performed. Fifty year test runs were set up for two regions, Southern Louisiana and the Chandeleur Island and Breton Island complex, and included the occurrence of 12 return-interval storm events. In the final tests, the program ran to completion successfully and without program errors. Based on the input data used for testing and the results, additional model validation and modification may be necessary to refine the processes included in the model and to integrate BIMODE into the ICM. Validation of the breaching process is necessary since only a limited number of profile shapes were included in the SBEACH look-up table used for testing. Further integration and validation of the inlet and bay model is necessary in the following phases of model development. In correlation, the code for simulating shoreline change adjacent to breaches and inlets may need to be further modified based on the results of the calibration and sensitivity phase.

DRAFT

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Appendices

Appendix 1: Review of Barrier Island Model Options

Appendix 2: BIMODE Code in Fortran 90 – submitted separately to CPRA for integration into the ICM and for archiving.

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Appendix 1: Review of Barrier Island Model Options

September 30, 2013

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Prepared by:

BIMODE {**B**arrier **I**sland **MO**del **DE**velopment Team } Team

I. Introduction

The Water Institute and the Coastal Protection and Restoration Authority of Louisiana (CPRA) have embarked on the development and application of the Modeling Program for the 2017 Coastal Master Plan. The 2017 modeling program shall build upon the modeling program developed for the 2012 Coastal Master Plan and improve upon the 2012 modeling program with a focus on project interactions and sequencing. The 2017 models shall be designed to simulate 50-year time periods in an efficient manner and be capable of predicting project effects at a basin-scale.

The first four subtasks of the model development include Sediment Distribution, Marsh Edge Erosion, Barrier Islands, and Vegetative Communities. These subtasks involve refining the existing modeling tools and / or developing new tools to improve upon the 2012 modeling program. The overall vision is to develop Integrated Compartment Models characterized by development of new process-based algorithms (e.g., marsh edge erosion and sediment distribution), integration of model code into a single common framework (e.g., all code integrated into Fortran), and increased resolution of the models (e.g., reducing the size of the 2012 Coastal Master Plan Eco-hydrology compartments).

Barrier island restoration has been a primary focus of CPRA's coastal restoration and protection program for over a decade. The ability to predict the barrier islands morphological dynamics, including long-term sustainability, is a critical component of this effort. The 2012 barrier shoreline model was able to predict inlet area change and island movement based on processes such as wave climate. The external peer review identified that the 2012 model lacked dynamic (physical) processes and stochastic events. The improvements identified for the 2017 model include the addition of physical processes (e.g. overwash), improving the capabilities of predicting change in island morphology, and the addition of more realistic event-driven morphodynamic responses.

This report presents the review of model options for the **B**arrier **I**sland **MO**del **DE**velopment (BIMODE), Subtask 4.3. The BIMODE Team includes:

- Subtask Leader: Michael Poff (CEC)
- Modeling: Gordon Thomson (CBI) (Barrier Islands), Ioannis Georgiou and Mark Kulp (UNO) (Inlets and Bays)
- Technical Support: Dirk Jan-Walstra (Deltares), Mark Gravens (USACE), Mark Leadon (CPRA), and Darin Lee (CPRA)
- Guidance/Oversight: Ehab Meselhe, Denise Reed, and Alaina Owens (The Water Institute of the Gulf), Mandy Green (CPRA), and Mark Leadon (CPRA)

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II. Scope of Work

The scope of work for BIMODE includes:

- Activity 1 – Summarize current literature and available modeling approaches;
- Activity 2 – Convene a working meeting to discuss and evaluate modeling approaches;
- Activity 3 – Develop the modeling approach and prepare a written summary of the proposed formulation/approach; and
- Activity 4 – Code the model, test the newly developed model, and report results.

The scope of work for Activity 1 included summarizing the current literature and available modeling approaches for the barrier island model component of the 2017 modeling program. Specific to the review of model options, the BIMODE Model Team divided the review into three categories:

- Wave Climate and Wave Transformation; Water Level, Tides and Storm Surge – Compiled by Mark Leadon and Mark Gravens
- Sediment Transport and Morphological Change – Compiled by Gordon Thomson
- Tidal Inlets and Estuaries/bays – Compiled by Ioannis Georgiou and Mark Kulp

The following sections present the reviews by category. The reviews included the model name, brief description, methodology, pros and cons, and general discussion as well as summary and discussion on certain inputs for the modeling program.

III. Wave Climate and Wave Transformation; Water Level, Tides, and Storm Surge

This section summarizes and discusses wave, tides and water level data and input sources; and presents a summary of wave transformation and storm surge models that are commonly applied in coastal engineering studies.

A. WAVES

1. Wave input sources (GOM)

a. Measurements – Long duration (years): NOAA-NDBC buoys, LSU-WAVCIS; Short-duration (months): LA project and/or study-specific related shallow water wave gage measurements
b. Hindcast – USACE-WIS; NOAA-Wavewatch III
c. Other model-generated archives – ADCIRC coupled with UnSWAN (SWAN with an unstructured grid) for various hypothetical storm event suites for wave attenuation/storm damage estimates for the LA Master Plan; previous related studies (re: FEMA/USACE Flood Insurance Study, IPET, Joint Storm Surge (JSS) Analysis in Southern LA, etc.)

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Summary:

- Wave measurements vary in time period/duration; generally short(er) duration (i.e., 10-20 years); NDBC buoys include deep water storm/hurricane wave height, period, direction time-series data at 1-hr intervals; WAVCIS gages include hourly nearshore, shallow-water short-duration (i.e., 1-5 years) time-series data including storm/hurricane data.
- Wave Information Studies (WIS) wave hindcast data generated from wind records compiled at numerous nearshore stations along the LA coast; include wave height, period, direction time-series data on 3-hr intervals; 20-year time duration (1980-1999).
- NOAA Wavewatch III wave data information includes wave hindcast output (height, period, direction) from August 1999 through present; data for current conditions and forecast also accessible.
- Hindcast time series provides long-term wave input for barrier shoreline/geomorphic response models; both hindcast and measurement data are applicable to short-duration cross-shore storm event response.
- WAVCIS data includes ADCP wave gage measurements from a series of gages located in intermediate water depths off the LA coast over varying time periods of operation from the early 2000's through the present.
- Project-specific wave gage installations have obtained time-series wave height, period, and directions data measurements for specific wave transformation model calibration.
- The ADCIRC coupled with UnSWAN model runs by Arcadis for the 2012 Coastal Master Plan generated storm surge, water currents, wave height, wave period, and wave direction at every node in the mesh at every time step. At the end of each simulation, the model created output files which contain time series information for these parameters, as well as the maximum value at any given time step during the simulation (2012 Coastal Master Plan Appendix D-24).
- Availability of water level and wave output from Arcadis modeling with ADCIRC and UnSWAN is being pursued by CPRA and WI staff.
- In conjunction with pursuing hypothetical storm suites compiled and used by Arcadis, further inquiry regarding overlap and inclusion of IPET and other similar source information will be considered.

Discussion:

- In addition to barrier island geomorphology modeling for the 2012 Coastal Master Plan, extensive modeling has been performed as a part of LA barrier island/headland restoration project studies and design. Predominant sources of wave data used in modeling for project studies and design are WIS hindcast time series wave data supplemented by Wavewatch III hindcast time series wave data, as well as, NDBC, WAVCIS, and project-specific wave measurements.
- A database of representative or plausible storm conditions (storm surge hydrographs and wind waves) should be developed to characterize the storm climatology and can be used (or sampled) to generate future sequences of storms that drive barrier island evolution.
- The contribution of astronomical tides to the total water level can be handled by a number of different techniques which may include random sequencing of astronomical tides with the storm surge hydrograph or a statistical sequencing of a representative tide signal with the storm surge hydrograph [three tide ranges; mean of upper quartile tide range, mean of lower quartile tide range and mean of central half of tide range] storms associated with the central half tide range are double weighted (relative probability) compared to those associated with upper and lower quartile tide ranges]. Phasing the

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storm surge hydrograph with the tide signal such that peak surge aligns with peak high tide, mean tide falling, low tide, and mean tide rising. The result of this technique is the generation of 12 plausible representations of each event.

- ADCIRC coupled with UnSWAN model-generated wave output from studies by Arcadis associated with the 2012 Coastal Master Plan and related work which may be available for use in the 2017 Coastal Master Plan modeling efforts may provide benefits to the 2017 modeling program in multiple ways.

2. Wave Transformation

a. Deep to intermediate water: STWAVE (USACE-CHL); SWAN (Deltares); CMS (USACE-CHL); WISPH3
b. Intermediate to shallow water; shallow water: STWAVE, SWAN; Delft3D-WAVE; MIKE21 (DHI); CGWAVE

Summary:

- STWAVE and SWAN are widely-used 2D finite difference models for transformation of time-series wave parameters (height, period, direction) from deep and intermediate water depths to shallow water for nearshore wave analyses and input to barrier island models
- CMS (Coastal Modeling System), part of the USACE Surface Water Modeling System (SMS), uses a wave model similar to STWAVE
- Delft3D-WAVE is coupled with SWAN for wave transformation modeling
- MIKE 21 from Danish Hydraulics Institute includes a series of wave models for various wave transformation conditions and applications
- WISPH3 is used for wave transformation of wave height, period, and direction parameters from deep to intermediate water
- CGWAVE is used predominantly for shallow water wave transformation including wave breaking

Discussion:

- In addition to barrier island geomorphology modeling for the 2012 Coastal Master Plan, extensive modeling has been performed as a part of LA barrier island/headland restoration project studies and design. Wave transformation models used in project studies and design have predominantly used STWAVE and SWAN for intermediate and shallow water wave transformation. To a more limited extent, Delft3D and MIKE21 have been applied for specific shallow water wave transformation modeling associated with wider application of these two models.
- The 2012 barrier island modeling program estimates longshore sand transport rates based on an annual statistical representation of offshore wave conditions. Recommend that the 2017 barrier island modeling program employ a more rigorous treatment of wave transformation to include a maximum model/wave time step of 24 hours. Recommend a more detailed treatment of nearshore wave transformation to take into account wave transformation across an irregular nearshore bathymetry. Nearshore wave transformation is necessary to better characterize irregular nearshore breaking wave conditions that produce local longshore sand transport gradients which are important drivers of barrier island evolution.
- If the ADCIRC coupled with UnSWAN model-generated wave output from studies by Arcadis associated with the 2012 Coastal Master Plan and related work is available for use in the 2017 Coastal Master Plan modeling efforts, then that output may provide wave

input for the 2017 modeling program. This may provide a reduction in 2017 modeling work needed to generate nearshore wave conditions.

B. WATER LEVEL, TIDES, AND STORM SURGE

1. Water Level/Tide Input

a. Measurements – Long duration (years): NOAA-NOS tide gages (i.e., Grand Isle), USACE tide gages in coastal LA; Short-duration (months): LA project and/or study-specific related shallow-water water elevation gage measurements
b. Model-generated - 2012 and 2017 Coastal Master Plan-Arcadis (ADCIRC); FEMA/USACE Flood Insurance Study, IPET, Joint Storm Surge (JSS) Analysis in Southern LA, etc.
c. RSL – CPRA (re: J. Pahl) & USACE technical guidance (see bibliography)

Summary:

- NOAA-NOS tide gages record 6-minute and/or hourly water elevation measurements; measurements include astronomical tide and storm surge; predicted astronomical tides can be used to determine storm surge; open coast gages are located inland in protected waters, not in the open GOM.
- LA restoration project-specific tide gage installations have obtained time-series water elevation/tide data. Project-specific wave gage installations may provide water surface elevation time-series in addition to the wave height, period, and direction data measurements obtained by the wave gage.
- The ADCIRC and UnSWAN models calculate storm surge, water currents, wave height, wave period, and wave direction at every node in the mesh at every time step. At the end of each simulation, the model creates output files which contain time series information for these parameters, as well as the maximum value at any given time step during the simulation (2012 Coastal Master Plan, Appendix D-24).
- CPRA and USACE technical guidance documents summarize available tide gages and data sources for RSLR considerations.

Discussion:

- In addition to barrier island geomorphology modeling for the 2012 Coastal Master Plan, extensive modeling has been performed as a part of LA barrier island/headland restoration project studies and design. Water elevation and storm surge hydrograph measurements used in cross-shore modeling have predominantly been obtained from NOS tide gages, such as at Grand Isle. Other NOS gage data, USACE tide gage data, and project-specific tide gage data has been used to a lesser extent.
- If the ADCIRC coupled with UnSWAN model-generated water elevation and storm surge output from studies by Arcadis associated with the 2012 Coastal Master Plan and related work is available for use in the 2017 Coastal Master Plan modeling efforts, then that output may provide water elevation and storm surge input for the 2017 modeling. This may provide a reduction in 2017 modeling work needed to generate nearshore water elevation and storm surge conditions.

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2. Storm Surge Modeling:

a. ADCIRC coupled with UnSWAN (SWAN with an unstructured grid) for hypothetical storm event suites for wave attenuation/storm damage estimates for the LA Master Plan
b. FEMA/USACE Flood Insurance Study, IPET, Joint Storm Surge (JSS) Analysis in Southern LA, etc.
c. Restoration project-specific: Based on tide gage measurements, cross-shore response model related computations and algorithms generate cross-shore water elevations and storm surge

Summary:

- The ADCIRC and UnSWAN models calculate storm surge, water currents, wave height, wave period, and wave direction at every node in the mesh at every time step. At the end of each simulation, the model creates output files which contain time series information for these parameters, as well as the maximum value at any given time step during the simulation (2012 Coastal Master Plan Appendix D-24).
- For LA barrier island/headland restoration project studies and design, water elevation and storm surge in cross-shore response modeling have predominantly utilized computations and algorithms within the cross-shore models. Storm-specific offshore NDBC buoy, WIS and Wavewatch III hindcast, and/or nearshore tide gage data have been used as model input.

Discussion:

- If the ADCIRC coupled with UnSWAN model-generated water elevation and storm surge output from studies by Arcadis associated with the 2012 Coastal Master Plan and related work is available for use in the 2017 Coastal Master Plan modeling efforts, then that output may provide water elevation and storm surge input for the 2017 modeling. This may provide a reduction in 2017 modeling work needed to generate nearshore water elevation and storm surge conditions.
- Cross-shore response models used in LA barrier island/headland restoration project studies and design have generated water elevation and storm surge from computations and algorithms within the cross-shore models. Storm-specific offshore NDBC buoy, WIS and Wavewatch III hindcast, and/or nearshore tide gage data have been used as model input.

IV. Sediment Transport and Morphological Change

This section summarizes various sediment transport and morphologic change models that are commonly applied in coastal engineering studies.

A. GENESIS – GENEralized Model for SImulating Shoreline Change

GENESIS is the classic shoreline change model, which while older, is still frequently used to model shoreline change. It is based on assuming a constant cross-shore profile and is thus termed a "one-line" model as following any contour on that profile indicates the movement of every other contour given the fixed cross-section.

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Methodology/Assumptions

- Beach profile shape is constant (1D model)
- Seaward and shoreward limits of profile are constant
- Longshore sand transport is due to wave action
- Finite difference solution scheme using Crank-Nicholson implicit scheme

Pros

- Classic methodology for simulating shoreline changes based on wave input and sediment transport rate equations
- Widely used and tested methodology
- Relatively simple in terms of coding
- Can handle long-term simulations (decadal)
- Critical input available from USACE

Cons

- Can't handle fundamental change in composition of beach face (i.e. switching percentage of silt and sand in the beach face that occurs in Louisiana when a barrier island is restored
- Manual adjustments needed to account for overwash and lowering of berm/dune elevation observed in Louisiana following large storm events
- Doesn't handle sand loss to inlets or tidal current driven transport
- Doesn't account for offshore loss of silt due to suspension
- One line model doesn't allow for acreage calculations or overwash benefits
- Not open source

B. LitPack

LitPack, developed by DHI, contains several modules within it to cover various coastal processes. STP models non-cohesive sediment transport by waves and currents; LitDrift models longshore currents and longshore transport; LitLine addresses coastal evolution.

Methodology

- Model basis is turbulent wave-current boundary layer (Fredsoe, 1984).
- Interpolation and finite difference techniques
- Solves basic continuity equation

Pros

- Can handle suspended sediment
- Widely used and tested methodology
- Relatively simple in terms of coding

Cons

- Not open source
- One line model doesn't allow for acreage calculations or overwash benefits
- Unclear as to run time for long term simulations
- Unclear as to how it can deal with overwash and lowering of dune

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C. AdH Model

The ADH model was developed by USACE ERDC. It adds a time varying component capability to ADCIRC and STWAVE and can be used in conjunction with the Surface Water Modeling System (SMS) as a pre- and post-processor.

Methodology

- Unstructured finite element mesh, which can be dynamically refined in areas where more resolution is needed.
- Quasi-3D shallow water hydrodynamically driven model using 2D shallow water equations.
- Probabilistic representation of sediment transport that includes wave and current transport of bed and suspended load.

Pros

- Critical input/technical support available from USACE.
- Can handle transport of mixed sediment systems (sand and clays)
- Incorporates many of the complex coastal processes required to predict overtopping, longshore transport and losses

Cons

- Integration with other portions of the 2017 Coastal Master Plan model could be difficult.
- Limited duration of modeled period (1-2 years) because computationally intensive
- Linkage with STWAVE only available in beta version at present time.
- Open source?

D. Delft3D

Delft3D is one of the more advanced three-dimensional models on the market for modeling coastal processes. It is a three dimensional model and can track morphologic change over entire basins and even the State depending on grid size and computing power. It has multiple modules to deal with wave transformation (SWAN). It has recently opened the code though the GUI must still be purchased.

Methodology

- Finite difference model that can be run in full 3D, 2D-H, or 2D-V mode.
- Incorporates majority of coastal processes related to waves, winds, currents, water levels, and sediment transport.
- Relies on a morphologic factor (morfac) to decrease computing time. The morfac equals the length of the study period x percent occurrence for each wave case/ duration of the wave case in the model simulation.

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Pros

- Incorporates many of the complex coastal processes required to predict overtopping, longshore transport and losses
- Morphologic model that can account for islands, bays and inlets.
- Can model long durations (several years to decades) due to the application of the morfac.
- Can handle mixed sediment systems though it drives computing time up.

Cons

- Integration with other portions of the 2017 Coastal Master Plan model could be difficult.
- Computationally intensive with very long run times
- Does not include subaerial rebuilding resulting in continued island elevation loss over time.
- Not a model upon which we could base our code.
- Does not allow unstructured grid, which is better suited for irregular coastlines.

E. MIKE-21 and MIKE-3

MIKE-21 and MIKE-3 were developed by DHI. As with other complex models, it is composed of several modules that examine wave transformation (SW), sediment transport

Methodology

- Model basis is spectral wave and radiation stress.
- Uses mean horizontal velocities and radiation stress to drive bed load sediment transport and
- Solves basic continuity equation.

Pros

- Morphologic change model that can account for islands, bays and inlets.
- Can handle suspended sediment and
- Widely used and tested methodology
- Relatively simple in terms of coding

Cons

- Not open source
- Limited model duration 1-2 years
- Unclear as to how it can deal with overwash and lowering of dune

F. SBEACH

SBEACH (Storm-induced BEAch CHange model) was developed by the USACE and is operated within the CEDAS user interface. It is a cross-shore, 2D model that models cross-shore morphologic response in response to a storm event based on measurement derived, empirical equations. It is a widely used model that has been applied extensively in coastal Louisiana to estimate dune lowering and overwash extents across barrier islands.

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Methodology

- The model is based on equation of mass conservation and uses empirical relationships derived from measurements.
- Contains a wave transformation component that is based on small amplitude wave theory up to breaking and then the breaker decay model (Dally, 1980).
- Assumes that there is no gradient in longshore transport (essentially ignoring longshore transport).
- It is uses Fortran 77 and C++ programming languages.

Pros

- Widely used and recognized model. Calibration parameters are readily available.
- Relatively quick to perform a storm run with easy input and output parameters.
- Variable grid available to allow more detailed elevation following in swash and overwash zones.
- Critical input available from USACE.

Cons

- Not open source.
- Doesn't have island elevation rebuilding mechanism during quiescent periods beyond the wave runup limit.
- Doesn't account for mixed sediment system that is being eroded. It has been observed that there is a sandy veneer along Louisiana's barrier islands. This is overwashed during storm events exposing the cohesive mixed sediments that can survive storm. However, regular wave action then erodes the beach face, reforming the sandy veneer in the weeks to months following the storm event (Campbell, 2005).
- Doesn't account for change in material at the commonly observed break in slope on profiles west of the river. Above this elevation (typically -1.2 to -2.1 meters, NAVD) the material is sandy while below this elevation the sediment is typically composed of silt and clay. This does not appear to be a critical issue given the flat offshore slopes initiate breaking and have a wide breaker zone except that it excludes wave damping by a fluid mud layer.

G. Beach-*fx*

Beach-*fx* was developed by the USACE as an engineering-economic planning tool. Essentially, it greatly expands upon a single SBEACH run at a single profile to thousands of storm events along multiple profiles and combines them with upland property value to estimate damage values. This probabilistic outcome is an improvement upon the single storm outcome of SBEACH but increases computational time.

Methodology

- Cross-shore results use SBEACH as underlying coastal engineering model but enhanced with an event based Monte Carlo life-cycle simulation of storm events.
- An MS Access database builds in upland infrastructure information with a GIS and GUI interface.

Pros

- As storm response is based on the SBEACH model, the positive aspects of the SBEACH model are achieved.
- It takes the single SBEACH run and develops a Monte Carlo simulation of runs to determine a probabilistic outcome rather than single result.

Cons

- The damage portion of the program is not required for the work that is proposed for the 2017 Coastal Master Plan.
- As storm response is based on the SBEACH model, the drawbacks are similar.
- Storm damages are not sequential (i.e. a 5-year storm following a 20-year storm). Given the sensitivity of Louisiana barrier islands to overtopping this is concern.
- To apply a Monte Carlo simulation of storm events requires that 50-year runs be performed with integration of longshore components on an annual basis. Computing time for this approach is increased.
- Open source?

H. EDUNE

EDUNE was developed by Dave Kriebel (with Robert Dean an early collaborator). It is a cross-shore, 2D model that is based on Dean's equilibrium profile theory and uses a finite difference solution.

Methodology:

- Based on Dean's equilibrium profile theory and solving for energy dissipation.

Pros

- Relatively quick and easy to apply.
- Open source

Cons

- Developed for the case of high dunes that extend infinitely landward and thus does not include the major coastal process of overwash that drives Louisiana barrier island morphology change.
- Requires external wave transformation model to provide breaking wave height though sediment transport is based on exceeding the equilibrium dissipation

I. Coastal Planning & Engineering (CPE) In-house Analytic Model

CPE has applied an in-house model to estimate shoreline and acreage changes over decadal time periods. It is an MS-Excel based analytic model based on averaging shoreline retreat rates and a single storm event history.

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Methodology

- Spreadsheet based, analytic model accounting for multiple coastal processes
- Based on average conditions of shoreline (gulf and bay) retreat, RSLR, etc., except for discrete storm events causing overwash and lowering of the dune
- Incorporates cross-shore modeling from SBEACH

Pros

- Easy to follow, explain and incorporate additional processes
- Easy to update for various islands under with and without project conditions (change in sand content)
- Provides acreage and shoreline length outputs
- Can be readily adapted to a Fortran code

Cons

- Not a peer reviewed model
- Doesn't directly incorporate waves and tides or fundamental coastal equations into the model
- Extrapolates averaged conditions to a longer timescale
- Limited to single island runs and doesn't account for inlet processes

Discussion of Sediment Transport and Morphologic Change

A simple one-line model is insufficient to meet the expectations of CPRA. While a comprehensive 3D model would provide the most robust solution, it is unlikely that a full 3D model could be developed within the timeline required for enhancement of the barrier island modeling task. Run times for these types of models can also be excessive, which makes them impractical for the 50-year predictions that CPRA is seeking. Combing a 2D longshore model and 2D cross-shore event storm event driven model is an achievable goal and could meet CPRA's expectations.

Most of the models include a GUI (graphic user interface). Given that a commercial model is not required, this should not be a requirement of the modeling team. More importantly, it may allow CPRA to request the underlying code driving the coastal engineering principles, if it is not already open source. This could save considerable time and improve the final model by allowing time to be focused on revising, integrating and testing the model code rather than starting from the beginning.

None of the models reviewed incorporate subaerial rebuilding due to aeolian transport. Given the relationship between overwash and island elevation, this process should be incorporated into the BIMODE modeling effort.

Most of the reviewed models cannot effectively handle mixed sediment systems, such as occurs along coastal Louisiana.

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V. Tidal Inlets and Estuaries/Bays

This section summarizes various models capable of simulating estuarine circulation, sediment transport, and associated inlet processes that are commonly applied in coastal engineering studies.

A. AdH Model

The ADH model was developed by USACE ERDC. It adds a time varying component capability to ADCIRC and STWAVE and can be used in conjunction with the Surface Water Modeling System (SMS).

Methodology

- Unstructured finite element mesh, which can be dynamically refined in areas where more resolution is needed.
- Quasi-3D shallow water hydrodynamically driven model using 2D shallow water equations.
- Probabilistic representation of sediment transport that includes wave and current transport of bed and suspended load.

Pros

- Critical input available from USACE.
- Can handle transport of mixed sediment systems (sand and clays)
- Incorporates many of the complex coastal processes required to predict overtopping, longshore transport and losses
- Adaptive mesh improves computational efficiency

Cons

- Integration with other portions of the Master Plan model could be difficult.
- Limited duration of modeled period (1-2 years)
- Linkage with STWAVE only available in beta version at present time.
- Open source?

B. Delft3D

Delft3D is one of the more advanced three-dimensional models on the market for modeling coastal processes. It is a three-dimensional model and can track morphologic change over entire basins and even the State depending on grid size and computer power. It has multiple modules to deal with wave transformation (SWAN), hydrodynamics (FLOW), and sediment transport (MORPHO). Although the code has recently been opened, the GUI source remains closed.

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Methodology

- Finite difference model that can be run in full 3D, 2D-H, or 2D-V mode.
- Incorporates majority of coastal processes related to waves, winds, currents, water levels, and sediment transport.
- Relies on a morphological acceleration factor (MORFAC) to decrease computing time. The morphological acceleration factor is a factor, which multiplies the bathymetric and topographic changes in a given time step, so that, for example, a 14 day model simulation can be used to simulate 1 year of bathymetric and topographic changes. In this particular example, a 14 day simulation with a MORFAC of 26 can be used to simulate 1 year of bathymetric change (26 = 365/14).

Pros

- Incorporates many of the complex coastal processes required to predict overtopping, longshore transport and losses
- Morphologic model that can account for islands, bays and inlets.
- Can model long durations (several years to decades) due to the application of the morfac.
- Can handle mixed sediment systems though it increases computing time.

Cons

- Integration with other portions of the Master Plan model could be difficult.
- Computationally intensive with very long run times.
- Does not include subaerial rebuilding resulting in continued island elevation loss over time.
- Not a model upon which we could base our code.
- The SWAN model, which is the companion wave transformation model for Delft3D, has been judged by some experts to be computationally slow (William Dally, 2012, pers. comm.).

C. MIKE-21 and MIKE-3

MIKE-21 and MIKE-3 were developed by DHI. As with other complex models, it is composed of several modules that examine wave transformation (SW), hydrodynamic module (HD), and the sand and mud transport modules (ST and MT).

Methodology:

- Model basis is spectral wave and radiation stress.
- Uses mean horizontal velocities and radiation stress to drive bed load sediment transport and
- Solves basic continuity equation.

Pros

- Optional unstructured finite element mesh, which can be refined in areas where more resolution is needed.
- Morphologic change model that can account for islands, bays and inlets.
- Can compute suspended sediment.
- Widely used and tested methodology.

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- MIKE21SW wave model has a fast and computationally efficient solution scheme.
- A new version of the MIKE21/MIKE3 flow model has been introduced to run on the GPU cards developed for video games. This could speed up run time substantially (Mikkel Andersen, 2013, pers. comm.)

Cons

- Not an open source.
- In the traditional, CPU version, the model duration is limited to 1-2 years due to strictly sequential wave forcing
- Unclear as to how it can deal with overwash and lowering of dune during storms

D. ECOMSED/EFDC/FVCOM/RMA2/3 others

These are from the family of estuarine models that can address hydrodynamics and salinity and temperature transport, and some of them can also address tracers and sediment. All these models are similar in capability to Delft3D and they are rather advanced two- and three-dimensional models. Although sediment transport with mobile bed options is available in most of these models, they do not have the advantage of morphological upscaling (similar to Delft3D) and hence are relatively slow.

Methodology

- Finite difference, finite element and/or finite volume in 3D or 2D modes.
- Incorporate majority of coastal processes related to waves, winds, currents, water levels, and sediment transport.

Pros

- Can handle mixed sediment systems though it increases computing time.

Cons

- Integration with other portions of the Master Plan model could be difficult.
- Computationally intensive with very long run times

E. ASMITA or similar

This is a simple box-type model that treats the basin, tidal flats, inlets, and coastal ocean in a dynamic way. Because it lacks sufficient spatial resolution, this model cannot be used to infer circulation patterns within an estuary or bay, but can sufficiently and accurately help infer tidal prism changes over long periods, because of its short execution times (for simulations over centuries).

Methodology

- Finite difference methods (largely ordinary linear differential equations)
- Can incorporate or address major exchange processes between the ocean and bay (and hence basic hydraulics at inlets connecting the two basins.

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Pros

- Runs quickly
- Good estimate of the tidal prism changes over time
- Tracks estuarine depth, and tidal flat and marsh elevation, and hence can account for tidal prism in a dynamic way.

Cons

- Lack of spatial resolution
- Could misrepresent circulation patterns (if needed or required)
- Likely ignores short duration events, such as entrainment of sediment from individual storms, or wind driven effects on the estuary/bay circulation.
- Ignores sub-grid scale inlet processes

F. Link node models (also known as box models)

Similar to ASMITA these models are very similar to those used by the eco-hydrology team in the 2012 Coastal Master Plan. Because they have reduced spatial resolution, they can run much faster and represent bulk processes (such as tidal propagation and other constituent transport through a basin).

Methodology

- Finite difference methods (largely ordinary linear differential equations)
- Can incorporate or address major processes

Pros

- Runs quickly
- Good estimate of the tidal prism changes over time

Cons

- Lack of spatial resolution
- Could misrepresent circulation patterns
- Ignores sub-grid scale inlet processes

G. Simple inlet equilibrium relationships

These are simple algebraic equations based on the work of Jarrett (1976) and O'Brien (1931, 1969). Input to these models is the tidal prism and the result or output is inlet geometry (i.e., inlet throat cross-sectional area).

Methodology

- Simple algebraic equations

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Pros

- Runs quickly
- Good estimate of the inlet cross-sectional due to a change in the tidal prism over time

Cons

- Lack of spatial resolution
- Ignores sub-grid scale inlet processes

H. Simple 1-D inlet hydrodynamics

These models are analytical or numerical solutions of inlet hydrodynamic and resulting bay – ocean exchange, with the objective of predicting inlet morphologic evolution.

Methodology

- Using knowledge of tides at the ocean, these models use pressure gradient calculations, and density gradient effects to estimate flux of water and mass through inlet for a desired period.

Pros

- Often run relatively quickly, because they only consider standardize idealized areas rather than specific geographic areas.
- Good estimate of the inlet cross-sectional area change, because of a change in the tidal prism over time
- May provide additional information on velocity variation at inlet, and perhaps better infer inlet morphology.

Cons

- Lack of spatial resolution
- Ignores sub-grid scale inlet processes as well as estuary processes.

** The above models have different capabilities and limitations and there are others that have similar application that have not been discussed.

Discussion of Processes at Inlets and Estuaries (that models should account for)

Inlet hydrodynamics

Knowledge of inlet hydrodynamics is critical to determine whether inlets will remain open, enlarge, or close, because of insufficient current to transport sediment through the inlet. Current models in the 2012 Coastal Master Plan do not provide detail hydrodynamics, although a single velocity for every time-step is known and can be used if needed. This information may also be important in determining the ebb-jet size and structure and perhaps help with additional information regarding sediment transport in the vicinity of the inlet.

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Inlet morphology

One requirement for assessing the dynamics of an inlet's cross-sectional area is knowledge of its tidal prism. If known, then the inlet can be adjusted using a minimum equilibrium cross section given by relationship (Jarret 1976, and O'Brien, 1931; 1969). This code was performed for the 2012 Coastal Master Plan, but the inlets were static in time. However, information from the ocean-estuary exchange can be used to infer these processes further, and assist in determining morphological evolution at more frequent time-steps using more process-based variables, such as shear velocity.

A challenging scenario would be the case where inlets open or barriers breach during storms (assuming that the new barrier models can predict that). It will be important to pass this information to the eco-hydrology teams who deal with estuary processes, but we note that this is a challenging step, because the links representing inlets in those models are held constant in time (i.e. no new inlets will be allowed once the simulation begins).

Interaction of Inlets with nearby environments

Obviously, since inlets connect the coastal ocean and interior bays, any model used to assess this interaction must be at least able to force exchange caused by pressure gradients across the inlet. Most models, including current 2012 Coastal Master Plan eco-hydrology models, can already address this. This computation is critical for calculating tidal prism. In the 2012 modeling program this calculation was done using maximum monthly tidal range multiplied by the area of the corresponding box, and integrated across the entire basin to compute the tidal prism. Whatever tool exists for the 2017 modeling program must be able to address at least this step, but doing so more frequently so that the process of inlet expansion/enlargement is coupled.

Inlets are often associated with ebb (and/or flood) deltas. Knowledge of ebb delta morphology and dimensions is critical for correctly interpreting processes in the nearshore environments near barriers. For example, sediment bypassing is a process associated with inlets; however, ebb deltas often control the temporal and spatial aspects of sediment bypassing inlets and impose additional sediment sinks/sources that could significantly affect the longshore sediment transport budget. It is recommended that some of these processes are included in the barrier model for more realistic representation of the system.

In Louisiana, there are several inlets that are not well defined; they are transgressive systems and tend to be wave influenced and storm-dominated. These inlets are especially important for several reasons. First, although they are rather large inlets (3-5 km across), they have a narrow active channel and thalweg (1-2 km) and flanked on one or both sides by a shallower platform. The flow dynamics of the thalweg and adjacent platform areas have significant influence on sediment transport (both alongshore and cross-shore), and something that can critically affect barrier island evolution.

The shoreface fronting barriers in Louisiana are highly erosional and in disequilibrium with the wave energy exhibited by large sediment deficits, which believed to be caused by storms. These areas are well beyond closure depths, and therefore if there is interest to include this process in

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the 2017 modeling program, additional routines (or perhaps extending the cross-shore profiles farther offshore) must be considered to account for this trend.

Estuarine hydrodynamics or circulation

Estuarine circulation can be determined by many of the models presented herein and, to some extent, by models currently available from the 2012 Coastal Master Plan. Assuming that the approach remains the same for 2017 Coastal Master Plan for estuaries, the inlets should be coupled with the estuary models on a standard basis, such that updates on inlet morphology (cross-sectional area) as a minimum are transferred back to the estuary models immediately (during the 2012 modeling program this was done every 25 years, but doing so every year will be beneficial).

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