ABSTRACT

KURUM, MUSTAFA ONUR. Improved Post-storm Model Predictions of Barrier Island Response to Extreme Events by Including Land Cover Effects on Sediment Transport Capacity. (Under the direction of Margery Overton.)

The objective of this thesis is to present geospatial and numerical tools and methods to study short term barrier island evolution. The first stage in this is achieved by raster based techniques used to assess the barrier island evolution in a decadal time frame by analyzing time series of coastal elevation data in order to extract spatial patterns of barrier island evolution dynamics. Multiple storm events may happen in a decadal time frame which are dominant factors in shaping barrier island morphology. Therefore in the second stage, the eXtreme Beach behavior (XBeach) model is used to simulate the process of barrier island response (e.g., beach and dune erosion, overwash and breaching). It is shown that under inundation overwash conditions XBeach reproduces common overwash features however the amount of erosions were calculated to be higher than the measured erosion and the model exhibited high sensitivity to total surge levels and surge level gradients across the barrier island. The main cause of the problem was identified as the traditional representation of a study location as consisting only sand in the numerical model domain. To address the problem, a methodology was implemented to mimic the effects of land cover features on the sediment transport capacity. The effects of the land cover effect implementation were validated by simulating two breaching cases occurred on the Outer Banks of North Carolina barrier islands during Hurricane Irene. After validation, hypothetical but realistic scenarios were tested in order to demonstrate the usefulness of the modeling framework to stakeholders interested in developing barrier island management and protection strategies. The improvements on the prediction capacity by including land cover effects were also shown to be valid in widely used 1D applications.
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Improved Post-storm Model Predictions of Barrier Island Response to Extreme Events by Including Land Cover Effects on Sediment Transport Capacity

by
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A dissertation submitted to the Graduate Faculty of North Carolina State University in partial fulfillment of the requirements for the Degree of Doctor of Philosophy

Civil Engineering

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DEDICATION

My family, their love and trust in me provide an environment which makes anything possible. Dedicating a work is much too modest a way of recognising the magnitude of contributions of my family - but I hope it draws attention to the high regard in which I hold them. Without their support, none of this could have been possible.
BIOGRAPHY

Mustafa Onur Kurum grew up in Istanbul, Turkey. He received his Bachelor of Science degree in civil engineering form Middle East Technical University, Ankara, Turkey in 2006. In 2008, he received his Master of Science degree in coastal and harbour engineering from the same university. He continued his graduate studies towards a Ph.D. degree by joining the Department of Civil, Construction and Environmental Engineering at North Carolina State University as a graduate research assistant under the direction of Dr. Margery Overton.
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Barrier islands are highly dynamic landforms that are susceptible to erosion and migration by the natural forces of wind, sea level, tides and waves. With the increasing population density in the coasts, understanding the short term barrier island evolution has become more critical in order to establish coastal planning and management strategies aimed to protect both human life and infrastructure. Short term barrier island evolution can be identified as the changes the barrier island is experiencing in a decadal time frame. However, extensive morphological change, such as breaching, can occur in a time scale of hours under certain storm and topographic conditions.

This dissertation is presented in four chapters that were being developed as potential manuscripts. In the first chapter, application of modern mapping technology and robust raster-based geospatial analysis that provided new insights (dynamic layer and trends in elevation change using per cell linear regression) into short term evolution of coastal topography at a barrier island section on the North Carolina coast is presented. The results gathered using the
geospatial analysis of the study location indicate significant variability in volume and shoreline change over the 6 years period (1997-pre Isabel 2003) examined. The results of the geospatial analysis also indicate that the elevation change trends are in line with traditional barrier island landward migration where foredunes are experiencing trends of decreasing elevation while the landward side of the dunes exhibits moderate increasing elevation trends. Also, knowledge on geospatial tools and techniques acquired during this study enabled high detailed visualizations of the terrains in question, revealing critical topographic features (e.g. beach access on dunes, parking lot behind dunes) that may effect the processes that takes place around them. In terms of the modeling efforts, the spatial distribution of these critical topographic features is important as it dominates the decisions behind model grid resolution and placement. This paper was an in depth look at the breached section of the barrier island near Hatteras during Hurricane Isabel in 2003. This location was used to initiate breach modeling efforts.

During the course of this study, in 2011, Hurricane Irene breached two sections of the barrier island and the availability of the pre and post storm topographic and hydrodynamic data made these locations robust testbeds for numerical modelling. The initial modelling effort started at Hatteras was therefore extended to the new breached locations. In the second chapter, to study the processes that takes place during extreme storm events and investigate practices to reduce or prevent the damage induced by them, the eXtreme Beach behavior (XBeach) model is used to simulate the process of breaching by implementing the effects of land cover features on the process. XBeach has become increasingly popular in coastal morphological modeling as a robust and flexible environment. Although, recent studies showed good capability in simulating cases where the storm induced damage was limited to the dune face erosion and overwash induced erosion, the capability decreases simulating case studies where inundation played a critical role on the post storm configuration. The main cause of the problem was identified as the traditional representation of a study location as consisting only sand in the numerical model domains.
Here, two breaching cases occurred on the Outer Banks of North Carolina barrier islands during Hurricane Irene were studied. The land cover features (sand, vegetation, hard to erode surfaces) were extracted from orthoimagery and implemented into the model simulations by defining sediment characteristics and factors that effect the sediment transport capacity and assigning them to model domain nodes. It was found that the implementation of the land cover effects increases modeling capabilities to simulate breaching. By successfully simulating the breaching events that took place during Hurricane Irene, the processes that takes place during such events were examined. It was found that the difference in erodibility introduced by different land cover classes leads to different erosion patterns thus different hydraulic gradient distributions which eventually has an important role on the post storm configuration. Moreover, high flow velocities that may be present under a combination of certain topographic and hydrodynamic conditions may play a critical role on the channelization and incipient breaching. The methodology developed in this chapter was then applied to the initial testbed at Hatteras where a breach occurred during Hurricane Isabel in 2003. More information about the Hatteras breach simulation is presented in Appendix A.1

In the third chapter, based on the high barrier island response prediction capacity achieved with the implementation of land cover effects, hypothetical but realistic scenarios were tested in order to study the breaching function and demonstrate the usefulness of the modeling framework to stakeholders interested in developing barrier island management and protection strategies. For this purpose, first, hypothetical topographic and hydrodynamic scenarios were created as variations of the pre Irene topography and Hurricane Irene (soundside event) conditions respectively. The results show that breaching function is influenced by the variations in the hydraulic head difference between connecting water bodies. Second, Hurricane Isabel (ocean side event) was simulated on pre Irene topographic conditions. Mitigation of the damage induced by Hurricane Isabel on pre Irene topography was studied by creating various scenarios based
on changes made to the pre Irene topography. It was found that there are several combinations that can be applied to the study location in order to reduce the erosion of the dunes and damage to infrastructure inland and the presented modeling framework can be used to design, test and optimize different re-construction/protection methods under hypothetical storm forces.

Finally, despite the fact that 1D applications does not take the alongshore variability and its effects on the coastal sediment transport into account, it is a widely used practice due to its practicality. Therefore, the implementation of land cover effects was tested in a 1D XBeach application over profiles selected at the Pea Island breach location. Model results were compared to measured elevation data and simulation results from Cross-Shore Numerical model (CSHORE), a 1D cross shore evolution model that The Federal Emergency Management Agency (FEMA) has shown interest in implementing into its flood mapping workflow. It was found that XBeach has a higher capacity in predicting cross shore profile response with and without the implementation of land cover effects while implementing the land cover effects improves the simulation results.
CHAPTER 2

Geospatial techniques to derive short term dynamics of coastal morphology


2.1 Abstract

Availability of frequent and high quality lidar data provides the ability to develop and improve geospatial techniques to derive short term dynamics of coastal morphology. These techniques can be used to investigate temporal evolution of the barrier island systems and to provide inputs for the numerical model studies of coastal morphological change. This paper presents some
of the techniques used to investigate the coastal morphology dynamics at the Hatteras Island, NC, USA where a breach was opened due to Hurricane Isabel in September, 2003. Results of morphological change from 1997 to pre Hurricane Isabel 2003 are presented. Pre and post Hurricane Isabel topobathy are created and compared to investigate the sand distribution caused by the breaching. Further numerical model studies are underway to simulate the breach opening dynamics.

2.2 Introduction

The availability of the high quality and frequent lidar data provides the ability to extract new information about spatial patterns of coastal landform dynamics through the use of geospatial analysis (Mitasova et al., 2009). Raster based measures such as stable core surface, maximum surface and dynamic layer along with regression slopes and standard deviations can be derived from lidar data using a raster-based geospatial methodology (Mitasova et al., 2010). The derived maps can be used to provide new insights into short term evolution of coastal morphology and input for numerical simulations and case studies. This work concentrates on the use of geospatial techniques for quantifying and visualizing the coastal morphology changes. Our case study focuses on the breach that occurred on Hatteras Island, NC during Hurricane Isabel in 2003 (Figure 3.1). This paper presents the morphological evolution of the breach location from 1997 to pre Isabel 2003 as well as the pre and post Isabel sand distribution. An introduction to the numerical modelling effort is underway and briefly discussed in the Numerical Approach section.
2.3 General Methods to Derive Coastal Dynamics

Using the methods outlined in Mitasova et al. (2010), the maximum surface is derived from lidar data sets dating from 1997 through 2008. Figure 2.2 illustrates the antecedent beach and dune conditions (orange), post storm reconstruction and recovery under the derived maximum (beige). Note that the apparent double dune line is the artifact of the pre and post storm dune conditions creating maxima. The cross section used for the visualization is through the breach. Thus, there is no beach and dune in the post Isabel inset in Figure 2.2. It should also be noted that the digital elevation models (DEMs) used in this study were interpolated at 0.5 meter resolution and the systematic errors were corrected following the methods mentioned above.

The geomorphological evolution of the barrier island in the breach location reveals that the dune barrier was receding towards the sound side and the dune heights were getting smaller meaning a decrease in the dune volume. To quantify the volume changes, sand volumes have
been calculated in a region bounded by the road (NC12) and the shoreline for the given year as illustrated in Figure 2.3. The road has been selected as the sound side boundary for volume calculation because the extent of the data for 2003 pre Isabel dataset is limiting the volume calculation area.
The shorelines were extracted at MHW. Since the DEMs use the vertical datum NAVD88, MHW to NAVD88 conversion was necessary. This conversion has been carried out using the datum data given for the Cape Hatteras Fishing Pier, NC (NOAA). For this location the shorelines were considered to be at the 0.32 m contour level. Using the shorelines and the fixed road boundary, masks for each year were created and used to extract the region where the sand volume changes will be taken into account. This region is approximately 1500 m long and 100 m wide. The resolution of the region was set to 1 m in order to calculate the volumes by multiplying the per cell elevation by the unit cell area (1 m$^2$). Figure 2.4 illustrates the volumes calculated and the changes from 1997 to 2003 pre Isabel. The changes between years may not be linear as indicated in Figure 2.4. The lines were plotted to demonstrate the declining volume trends. The change from 1999 to 2003 is indicated by a dashed line to indicate that the volumes are not known for years 2000, 2001 and 2002.

![Figure 2.4: Sand volume change from 1997 to 2003 pre Isabel](image)

Figure 2.4: Sand volume change from 1997 to 2003 pre Isabel
To further investigate the temporal changes that occurred during the evolution of our study region which eventually led to the breach occurred during Hurricane Isabel in 2003, dune crests for each year (1999 to 2003 pre Isa.) were manually digitized as vector lines. Cross shore transects are created at every 20 m using a simple Python code and intersected with the dune crest vectors in order to monitor the dune crest movement horizontally and vertically on the transect plane. The vertical and horizontal shifts are plotted on the post Isabel shoreline vector to study the relation of the temporal evolution of the extracted region to the breach location caused by Hurricane Isabel. Figure 2.5 illustrates the horizontal regression (movement towards the sound side of the barrier island) of the dune crest line along the shore perpendicular transects. The bars in the graph can be considered to show the transect location and alignment for simplicity. The post Isabel shoreline vector is placed in this figure just for location referencing. This figure shows that the breach area was more prone to dune regression than its surrounding areas for this particular region.

Figure 2.5: Horizontal shift of dune crest along the transects
Figure 2.6.a illustrates the 1997 and 2003 pre Isabel dune crest elevations. Figure 2.6.b illustrates the dune crest elevation change aligned on transect planes from 1997 to 2003 pre Isabel. Note that Figure 2.6.a and 2.6.a.b are aligned with each other to make comparison easier for the reader. Also, as in Figure 2.5, the post Isabel shoreline vector is placed in this figure just for location referencing. It can be seen that the distribution of dune crest elevation change does not necessarily align with the breach channel locations. However, one should look at
Figure 2.6.a and 2.6.b together to see that although the dune crest elevation has decreased more on some of the transects in the breach location, the final dune crest elevation minimums are coinciding with the breach channel locations.

Using the raster based time series analysis Mitasova et al. (2010), the standard deviation map (Figure 2.7) and the regression slope map (Figure 2.8) for the Hatteras breach location are presented to further investigate the short term (1997 to 2003 pre Isabel) coastal dynamics. Both maps can be used to identify stability in the selected region but each map is quantifying the stability with different metrics. (Figure 2.7), illustrates the deviation in meters however it does not represent the sign of the change, not explaining whether the change is erosion or accretion. Therefore, one can only derive a measure of stability for the selected region. As can be seen
from Figure 7, the foredune system is highly dynamic, deviation reaching 1.83 m. Inland from the foredunes, stability increases as presented by the blue color used in this map. The higher is the calculated standard deviation, the lower is the stability.

Figure 2.8 illustrates the regression slope map. In other words, the map representing the elevation changes per year for the selected region and period of time. Regression slope calculation needs equal time intervals between the input rasters. Assuming 1997, 1998 and 1999 data are 1 year apart, dummy maps (maps of null points) had to be created for years 2000, 2001 and 2003. Both the standard deviation map (Figure 2.7) and the regression slope map (Figure 2.8) have similar patterns of stability; the difference of the regression slope map is the ability to put a sign on the stability. It can be seen from Figure 8 that, the highest elevation change rates are on the foredune system and the values are negative meaning erosion. This lost sand has been recovered at the back of the foredune system and this is indicated by the green areas on the
figure meaning accretion. The amount of lost sand in the foredune system is not equal to the amount of sand recovered and this can be explained by the limited extent of data. To be able to make such a study requires a large topographic and bathymetric data.

2.3.1 A closer look at Hatteras Breach

To quantify and visualize three dimensional characteristics of the breach, pre and post Isabel lidar data were merged with bathymetry data to develop topobathy raster maps for the breach area (Figure 2.9). Since the post Isabel lidar data does not contain bathymetric information, the breach DEM is created by interpolating (Kurum et al., 2010) the USACE bathymetry survey data (Wamsley and Hathaway, 2004) taken after the storm into the existing DEM.

![Figure 2.9: Pre and Post Isabel lidar merged with bathymetry data](image)

The derived topobathy maps are divided into three regions to investigate the sand volume changes at the breach, the sound side of the island and the ocean side of the island. The volumes are computed for each region by using per cell analysis of the topobathy raster maps. The results of the per cell analysis are presented in Table 2.1. Results show that there is net sand loss at the
study location.

<table>
<thead>
<tr>
<th></th>
<th>Below Sea Level (m$^3$)</th>
<th>Above Sea Level (m$^3$)</th>
<th>Total (m$^3$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Breach Area</td>
<td>75923</td>
<td>103653</td>
<td>179576</td>
</tr>
<tr>
<td>Sound Side</td>
<td>221861</td>
<td>0</td>
<td>221861</td>
</tr>
<tr>
<td>Ocean Side</td>
<td>27578</td>
<td>39292</td>
<td>66870</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>325362</strong></td>
<td><strong>142945</strong></td>
<td><strong>468307</strong></td>
</tr>
</tbody>
</table>

Per cell analysis was used to demonstrate the sand distribution, erosion (red) and accretion (green) at the breach location by computing the elevation differences at each cell in Figure 2.10.a. The pattern of erosion suggests that the lost sand was carried outside the survey extent accounting for the losses quantified in Table 2.1. In addition, the overwash pattern was evident in the post storm ortho photo in Figure 2.10.b, also suggesting sand movement towards the sound side.

Figure 2.10: a. Erosion (red) and accretion (green) at the breach location (in meters) b. Post storm ortho photo
2.4 Modelling Approach

Numerical modelling provides us the ability to simulate and try to understand different real or hypothetical cases. In addition to deriving short term dynamics of coastal morphology, geospatial techniques can be used to create input for several different case studies to investigate the effect of changing coastal landforms on coastal hydrodynamics such as storm surge (Kurum et al., 2010). For this study, in order to understand the processes that take place during the time of first overwashing and breach opening, a numerical model based study has been initiated.

Initially, in order to understand the gravity of the water elevations in front of the breach location, a basic graphical illustration was made (Figure 2.11) by superposing the maximum water elevation output from ADCIRC on the pre Isabel topography (Figure 2.11.b). The maximum water elevation is extracted just in front of the dunes, and is the maximum recorded (2.5 m) during the Hurricane Isabel ADCIRC run. This run was built on the North Carolina Floodplain ADCIRC grid as described in Luettich and Blanton (2008). The run duration was 5.5 days, starting September 14th, 2003, with the hurricane Isabel winds that were modeled as reported in Vickery and Blanton (2008). Note that the maximum water elevation includes the storm surge and the astronomical tide.

We can see from Figure 2.11.b that the storm surge and tide elevation at their maximum gets very close (approximately a minimum of 50 cm) to the dune crest. SWAN output at the same location (just in front of the dunes) indicates that the maximum wave height reached 2.5 m. Thanks to the availability of pre and post Isabel LIDAR data, Hatteras breach location is a very suitable location to use and test models that are capable of calculating coastal morphological changes and dynamics. In this sense, as an ongoing effort to model the Hatteras breach, XBeach model is being used. XBeach, stands for eXtreme Beach behavior, is an open-source program that has been developed to model the nearshore response to hurricane impacts. The
model includes wave breaking, surf and swash zone processes, dune erosion, overwashing and breaching (Roelvink et al., 2009). XBeach needs a staggered grid to run. The pre Isabel topobathy was created using the same geospatial techniques that were used to create the post Isabel topobathy as discussed above. The pre Isabel topobathy was then used as the source of XBeach grid cell attributes. The grid modifications are simplified by developed workflows that integrate geospatial and numerical codes. Figure 2.12 presents the Hatteras breach domain used for the XBeach runs.

XBeach can be forced from the offshore boundary with JONSWAP spectrums describing the wave conditions offshore. Also, it is possible to assign the boundary corners varying surge and tide levels. In this case, Hurricane Isabel storm surge and the accompanying tide are extracted from the previously mentioned ADCIRC run. For preliminary XBeach runs, the wave condition spectrums were created using the USACE FRF wave data for Hurricane Isabel. Figure 2.13
Figure 2.12: XBeach Hatteras breach domain

presents an intermediate time step during XBeach test runs. Modeling the Hatteras breach is an ongoing effort. Test runs are being carried out to better understand the model capabilities and requirements. Additionally, offshore wave conditions will be extracted from a coupled ADCIRC - SWAN model to improve the input precision.

**Acknowledgements** The authors would like to acknowledge the support of the agencies funding the research: the US Department of Homeland security (award 2008-ST-061-ND 0001), along with agencies involved in data collection (USGS - pre and post Isabel LIDAR data, NCFMP) and the NOAA CSC for providing access to the data. In addition the authors would like to thank Dr. Nick Kraus, U.S Army Corps of Engineers, for making available the post Isabel breach survey data. Brian Blanton for working with us on the ADCIRC grid and storm input files.
Figure 2.13: XBeach Hatteras breach location overwash and flooding

**Disclaimer** The views and conclusions contained in this document are those of the authors and should not be interpreted as necessarily representing the official policies, either expressed or implied, of the US Department of Homeland Security.
CHAPTER 3

The effect of the land cover on the response of the coastal zone numerical morphology modeling


3.1 Introduction

It is believed that the increase in the Atlantic hurricane related coastal hazard events are either related to climate change, the natural climate cycle, i.e., Atlantic Multidecadal Oscillation (Goldenberg et al., 2001) or a combination of both. Scientific Assessment of the Effects of Global Change on the United States report states that climate change will worsen natural events,
intensifying storms, floods, droughts and cause sea level rise (SLR) due to climate change. Specifically, hurricane power dissipation is found to be correlated to the sea surface temperature and with the increasing temperatures the potential of destructiveness will increase (Emanuel, 2005). Knutson et al. (2010) suggests that the globally averaged intensity of tropical cyclones will increase 2 to 11% by year 2100. In addition, Tebaldi et al. (2012) suggests that if the rate of SLR accelerates as much as expected, at about a third of the 55 sites distributed along the coasts of the contiguous United States, a 100 year return levels of annual storm surges would become a 10 year return event by 2050. In some locations, this shift in the return periods is identified as a 100 year event becoming an annual event. Moreover, coastal counties constitute only 17 percent of the total land area of the United States (not including Alaska), but account for 53 percent of the total population. This population is expected to increase by an average of 3,600 people per day, reaching 165 million by the year 2015 (Culliton, 1998). According to Strauss et al. (2012), 3.7 million people who live along the US coastline are within 1 m of the present high tide line. A total inundation of 2,600 km$^2$ for the coastal states from Virginia to Massachusetts by 2100 considering approximately 1 m SLR is estimated. This inundation area increases to 3,800 km$^2$ at high tide if local tidal ranges are incorporated in the analysis (Wu et al., 2009). Taking the potential increase in the coastal hazard and coastal population growth trends into account, the importance of understanding coastal vulnerability and predicting the coastal morphological response is evident. This goal motivated the development of variety of models in the past decades while the prediction capacity has increased over time. Kriebel and Dean (1985), Kraus and Wise (1993), Larson and Kraus (1989), Larson et al. (1990, 2001, 2004, 2005), Roelvink (1993) and Vellinga (1983, 1986) introduced beach profile evolution models to predict coastal response to storms. Empirical based models evolved to process based models over time, however, widely used profile based models and applications lacked the ability to assess the complexity introduced by the possibility of significant alongshore variability.
Advancements in two-dimensional, depth-averaged (2DH) models (e.g., Lesser et al., 2004; Reniers et al., 2004, 2006; Dongeren et al., 2003; Roelvink et al., 2009) and the increasing availability of computational power, it became a more widely used approach to use numerical simulation models that can solve the physics based processes that take place in the form of erosion, overwashing and breaching. While the 2D applications of modeling studies enabled taking all the topographic complexity and hydrodynamic conditions into consideration, the ability to represent the landcover variability on a given study site is not a readily available capability of the models. This is consistent with the fact that the numerical models developed and used to simulate coastal response to storms concentrate on resolving the sediment transport processes that take place in the coastal area, where the flow can be assumed to be interacting with sandy topography. However, in certain cases, the storm induced water level may exceed site specific critical levels and overtopping occurs. For barrier islands, the overtopping leads to flow into the coastal hinterland with the potential of reaching the water body separated by the barrier, typically the estuarine or the sound. If the duration of inundation is sufficient and a strong flow condition between the water bodies develops, the flow induced cross shore scouring leads to breaching of the barrier island landmass (Wamsley and Kraus, 2005). Naturally the amount of erosion on the cross shore direction of the island determines whether the initial channelization will develop into a breach channel or not. Along the hydrodynamic conditions, the amount of erosion also depends on the topographic conditions the overland flow will be interacting; although barrier islands maybe considered mostly sandy, the particular stretch of the barrier island in question may be developed (e.g., roads, buildings) and/or vegetated. The vegetation types, densities and sediment properties play an important role on the morphological change patterns (Wang et al., 2006; Wang and Horwitz, 2007). In essence, the vegetation cover will often decrease the surface erosion by changing the flow characteristics (e.g. blocking the flow, increase the resistance by introducing roughness and soil compaction due to root density)
which effectively changes the sediment transport and stream morphology (Neary et al., 2012). Roads or such hard to erode surface layers (e.g., building foundations, parking lots) may get damaged during overwash and inundation conditions by being subjected to direct wave attack, flow across and along them. While the damage occurs, the morphological change around these features is also affected by their erodibility, e.g., the weir effect of a road during overwash causing supercritical flow over the road and scour on the opposite edge of the road (Chaney, 2007; Douglass et al., 2004; Houser, 2009).

We used the eXtreme Beach behavior (XBeach) model to simulate the process of breaching and the effect of land cover on the process by studying two breaching cases occurred on the Outer Banks of North Carolina barrier islands during Hurricane Irene. XBeach is a 2DH morphodynamic numerical model developed with focus on the nearshore response to wave breaking, surf and swash zone processes, dune erosion, overwash, inundation and breaching driven by the time-varying extreme conditions such as storms and hurricanes (Roelvink et al., 2009). Similar studies using the same model and dealing with barrier island response under overwash and inundation conditions have been carried out recently (McCall et al., 2010; Lindemer et al., 2010). Particularly, McCall et al. (2010) investigates the effect of Hurricane Ivan on the morphological response of Santa Rosa Island and discusses a sheet flow sediment transport limiter, a proxy to improve simulation results by accounting for the lack of erosion resistance in a study domain represented by model nodes assigned sand sediment characteristics. In this study, our motivation is to extend such detailed coastal numerical simulations by incorporating the effect of the land cover to our modeling effort to serve as the sediment transport limiter where necessary by using simple tools and empirical set of parameters to mimic the land cover effects on coastal response to extreme events including incipient breaching.
3.2 Study sites

Most distinct feature of coastal North Carolina is the Outer Banks (OBX) barrier island system that separates the Atlantic Ocean from Pamlico Sound (Figure 3.1). According to Birkemeier

Figure 3.1: North Carolina coast; study locations and Hurricane Irene track
et al. (1984), it was thought that the OBX were covered with trees, shrubs, vines and grass in the early 1800s but the grazing and lumbering in the 1800s lead to the denudation, inundation during high tides and erosion of the islands. In 1930s, a public project was initiated to create a continuous line of vegetated dunes from the North Carolina - Virginia state border to the Ocracoke Inlet in the south. In 1950s, with the establishment of the Cape Hatteras National Seashore and the hurricanes occurred in 1954 and 1955, the dune stabilization project regained focus and the dunes built in 1930s were rebuilt and extended. However in the 1970s, due to economic implications and the persistent erosion problems, Cape Hatteras National Seashore ceased the dune stabilization project. Since then, the ocean front dunes have primarily been subjected to natural processes and long term shoreline erosion has reduced the width of the beach and exposed the dunes to the natural impact of storm waves and surge. Hurricane Irene made landfall near Cape Lookout, North Carolina on August 27th, 2011 and travelled north through the Pamlico and Albemarle Sound while breaching two locations on the North Carolina OBX. The first breach location is 10 km south of Oregon Inlet and is within the U.S. Fish and Wildlife Service (USFWS) Pea Island National Wildlife Refuge. Therefore this study location is essentially undeveloped with the exception of the two-lane highway (NC 12) and three USFWS maintenance buildings and its paved parking lots. Pre Hurricane Irene, the Pea Island breach location exhibited severe erosion and overwash deposits caused by the storm conditions induced by Nor’Ida in 2009. In fact, the location of one of the overwash fans created by Nor’Ida coincides with breach channel created by Hurricane Irene in 2011. Having assessed the damage at this breach location after Irene, the North Carolina Department of Transportation (NCDOT) decided to construct a temporary bridge at the Pea Island breach location to restore transportation along NC 12. The second breach location is at Mirlo Beach Rodanthe, 20 km south of Oregon Inlet. The breach at this site did not stay open and was naturally closed. NCDOT repaired the dunes and the roadbed at this location. In contrast to the Pea Island breach
location, the Rodanthe breach location was developed with residential buildings and the NC 12. The OBX barrier island width varies from a minimum of 170 m just north of Rodanthe breach location to a maximum of 1800 m north of Pea Island breach location (Overton, 2012). The thickness of the island at the study sites is approximately 300 m, among the thinnest parts of the barrier island. Both locations have vegetated dunes, especially landward of dune crest where available.

3.3 Hurricane Irene

Hurricane Irene was not a record breaking storm in terms of wave energy and ocean side surge levels. It was noteworthy because the flooding that led to the opening of two breaches came from the sound side of the barrier island. Perhaps, the most influential sound side event for the Outer Banks was recorded in 1846. Barnes (1995) states that "A remarkable surge of water, driven by continuous northeast winds, pushed far into the Pamlico and Albemarle Sounds, flooding rivers and creeks for miles inland. Then, as the hurricane passed and its winds rotated to the southwest, this massive expanse of water rushed back toward the sea, overwashing the Outer Banks from west to east. On the night of September 7, a new inlet was created by these events, known today as Hatteras Inlet. The next day, a second inlet was formed just south of Roanoke Island. This inlet soon became navigable and was named Oregon Inlet for the first large boat to pass through it, the Oregon". Hatteras Inlet and Oregon Inlet are still open to this day. Another significant sound side event closely related to the Pea Island breach location was recorded in 1932. After the 1932 nor’easter had passed, shifted winds pushed the sound side water towards the barrier island and tide reached a level of approximately 3.6 meters eventually breaching the island at five locations, northernmost channel being at approximately the same location as the breach caused by Hurricane Irene (Clinch et al., 2012). The largest channel created by the 1932 storm was
naturally closed in 1945. The hydrodynamic storm conditions for the storms mentioned above differ in magnitude but they are all characterized by a large storm surge from the sound side that led to breaching of the barrier islands. Figure 3.2 and Figure 3.3 depicts the hydrodynamic conditions for Hurricane Irene between the dates August 26th, 2011 and August 30th, 2011 (UTC) recorded at the U.S Army Corps of Engineers (USACE) Field Research Facility (FRF) at Duck, NC. In Figure 3.2, the timing of the shifting winds is shown. Accordingly, the sound side water level starts to increase (Figure 3.3). According to the hydrodynamic data collected at the FRF, maximum observed storm surge (including astronomical tides) on the ocean side was approximately 1 m, NAVD88 (Figure 3.3). The maximum observed storm surge on the sound side was measured as approximately 2 m, NAVD88 and is the highest water level measured in the sound at the FRF since observations began in 1979. In Figure 3.3, significant wave height recorded at 17 m (Waverider, ID 630, seaward of the FRF pier) depth peaked at 5.6 m and the wave height recorded at 2 m depth peaked at 2 m. The average measured post Hurricane Irene wrack line at the landward dune face was 2.4 m (NAVD88, 0.4 m standard deviation). This value is in line with the measured sound side water level at FRF considering the wave action during

![Figure 3.2: Wind and mean wave direction at Duck, NC FRF during Hurricane Irene](image-url)
Figure 3.3: Measured wave heights, periods and water levels at Duck, NC FRF during Hurricane Irene

the sound side flooding. There was no wave record for the sound side, however local accounts and the Hurricane Irene now-cast by The Coastal Emergency Risks Assessment (CERA) group suggest that sound side waves peaked at 1.5 meters around the study sites.

3.4 Model setup

The availability of the pre and post storm elevation data and the measured hydrodynamic conditions of Hurricane Irene makes the Pea Island and Rodanthe breach locations a robust test bed for the purposes of this study. XBeach provides the necessary capabilities to represent both the topographic and land cover variability in the model domain and simulate the storm conditions of Hurricane Irene to resolve the processes that took place during the breaching of the barrier island. For detailed model description and formulation of XBeach, see Roelvink et al., 2008, 2009. Herein the creation of model domain (Section 3.4.1) and the implementation
of the land cover use (Section 3.4.2) are presented for the Pea Island breach location only. Same procedures were repeated to create the Rodanthe breach location case and will not be repeated here. The hydrodynamic boundary conditions used for both study locations are briefly described in Section 3.4.3. After the completion of the model setup, the model parameters are modified based on the comparison of the results to the post storm surveys and images. The procedure is repeated to calibrate the model parameters to yield realistic results. The results for both cases are presented and discussed in the Results and Discussion section (Section 3.5).

3.4.1 Model domain

The area covered by the model domain for the Pea Island breach location is approximately 2 \( km^2 \). The domain nodes are laid on a varying size grid. The maximum resolution in both the cross shore and alongshore direction is 2 m whereas the minimum resolution is 10 m in the alongshore direction and 20 m in the cross shore direction. In the cross shore direction, the domain was extended beyond the limit of expected sediment transport at the offshore and sound side boundaries. The depth at the ocean side offshore boundary was limited (approximately at 17 m) by the depth where the hydrodynamic conditions were extracted from the buoy. In order to increase model stability around the lateral boundaries, the elevation profiles were replicated in the alongshore direction, effectively minimizing the topographic gradients that could potentially initiate sediment transport at or around the lateral boundaries. The elevation and bathymetry information to create the model domains were extracted from a digital elevation model (DEM) compiled by merging the 2011 NCDOT photogrammetrically collected pre and post storm terrain elevation data, the 2004 USACE Topo/Bathy Lidar data and the 2009 USACE Joint Airborne Lidar Bathymetry Technical Center of Expertise (JALBTCX) Lidar data for North Carolina (see Table 3.1). The Lidar data mentioned were downloaded from the National
Oceanic and Atmospheric Administration (NOAA) data distribution portal Digital Coast website (NOAA, 2011). The photogrammetric elevation data was provided by NCDOT through personal contacts.

Table 3.1: Dates and agencies that conducted lidar missions used in the study

<table>
<thead>
<tr>
<th>Date</th>
<th>Agency</th>
<th>Accuracy</th>
<th>Resolution</th>
</tr>
</thead>
<tbody>
<tr>
<td>April - September 2004</td>
<td>USACE</td>
<td>0.15 m vertical / 0.8 m horizontal</td>
<td>3 m</td>
</tr>
<tr>
<td>August 2009</td>
<td>USACE (JALBTCX)</td>
<td>0.2 m vertical / 0.75 m horizontal</td>
<td>2 m</td>
</tr>
<tr>
<td>August 2nd 2011</td>
<td>NCDOT</td>
<td>0.05 m vertical / 0.01 m horizontal</td>
<td>1 - 3 m</td>
</tr>
<tr>
<td>August 30th 2011</td>
<td>NCDOT</td>
<td>0.05 m vertical / 0.01 m horizontal</td>
<td>1 - 3 m</td>
</tr>
</tbody>
</table>

All Lidar elevation, bathymetry and the photogrammetric point data were converted to the same coordinate system (North Carolina State Plane System, SPCS 3200) and the same vertical datum (NAVD88) where necessary using the Vertical Datum Transformation tool (VDatum; Parker et al. 2003). The point clouds were merged giving the NCDOT photogrammetric data priority over the other two datasets based on the accuracy of each dataset. The merged point cloud was then interpolated to a 1 m resolution DEM using the regularized spline tension interpolation method (Mitasova et al., 2005). The elevation accuracy of the final DEM was verified using the high accuracy NCDOT benchmarks along NC 12. Using elevation data from different dates and agencies makes the verification step important as systematic error may exist in Lidar data (Mitasova et al., 2010). The DEM have been edited to incorporate all the land cover (e.g. parking lots, USFWS maintenance buildings) features of the location in order to ensure highest possible accuracy of the compared results. Finally, the model nodes are assigned their elevations from the created DEM. Figure 3.4 depicts the final model domains that represent the pre Hurricane Irene conditions for the Pea Island breach location and the
Figure 3.4: Model grids for Pea Island breach location (left panel) and Rodanthe breach location (right panel). NC 12 is marked with dotted line. U.S. Fish and Wildlife Service maintenance buildings (left panel) and residential buildings (right panel) are marked with rounded rectangle boxes. Ocean side (top), sound side (bottom).

Rodanthe breach location. For reference, NC 12 (dotted line) and the USFWS National Wildlife Refuge maintenance buildings and residential buildings (rounded rectangle box) are noted in the figure. The axes of the model grids are populated with the local model coordinates in meter and oriented to have the ocean side at the top of the figure. The workflow to create the pre storm configuration, as described above, was followed to create the DEMs representing the post storm configurations which served as the source of elevation data to create the post storm model grids for both study locations for comparison purposes. However it should be noted that the
post storm elevation data from NCDOT did not include any bathymetric data, except in the case of the Pea Island breach location where the NCDOT surveyed the main breach channel in the proximity of NC 12 to assess the damage and react on a solution to restore transportation. In order to simplify the interpolation process, other channels created in both locations were assigned depths manually based on the visual evidence from the orthoimagery.

3.4.2 Land cover implementation

Mostly the parts of the coast in interest to coastal response studies are the nearshore, foreshore and foredune locations. In this sense, it is reasonable and justified that the modeling efforts to study the coastal response to storm conditions represent the location in question by defining all model nodes as sand nodes. This application is not limited to the cited case studies modelled with XBeach and is very common in coastal morphological modeling as it is practical and reasonable given the areas of interest. However, the storm induced flow does not always interact with the sandy coastal area. Especially in situations where the overwash flow interacts with the coastal hinterland, the effect of the land cover features are important in changing rates of sediment transport and in influencing the development of the pathways of flow which in turn impact the amount of erosion (or accretion) experienced. In this study, through the case studies at Pea Island and Rodanthe breach locations, the aim is to provide insight on the effect of land cover including sub surface sediment layers in improving the prediction of post storm coastal morphological configuration and breaching. To emphasize the effect of the land cover on the post storm morphology, model parameters were first set to represent all nodes in the model domain as sand. These cases will be referred to as "all sand" cases. The results of the all sand cases were then compared to the results of "land cover" cases. The land cover cases refer to the simulations where all nodes are represented with their corresponding land cover feature
extracted from color orthoimagery. Using supervised radiometric classification procedures within a GIS on the pre storm orthoimagery, the study area is divided into areas categorized by the land cover features. Using visual interpretation, the user defines different land cover classes (e.g., vegetation, hard surfaces, sand) by defining small areas on the color orthoimagery. The GIS workflow then processes the entire image into a raster of the defined classes (Figure 3.5). For simplicity, both locations were assumed to be represented by defining three land cover classes consisting sandy areas on the nearshore, foreshore and foreshore locations, vegetated and paved/concrete areas in coastal hinterland. Using the processed land cover class raster, each model node was assigned a $D_{50}$, $D_{90}$ and the sediment calibration factor (a parameter that influences the rate of sediment transport) based on the land cover class it belonged. This was made possible by a feature in XBeach originally developed to model multiple sediment layers in overwash cases. This feature provides the ability to track the sediment while enabling the user to assign different sediment characteristics and distribution in each node of the model domain. It is assumed that a top layer of sediment is readily available for sediment pick-up and it is made of fractions of different sediment types as defined by the user. The sedimentation and erosion related to each sediment class fraction is calculated and used to change the composition of the sediment classes on the top layer. As the top layer thickness changes, the sediment is moved up or down from the layers below to the top layer, keeping the top layer thickness fixed. This is made possible by a variable layer below the top layer that can change in thickness based on erosion or deposition on the top layer (Roelvink et al., 2008). Essentially, the number of land cover classes, the number of layers to represent each land cover class from surface to a defined depth by the thickness of each layer and the number of layers are configurable. The configuration used in this study is presented in Table 3.2. Conceptually, the model domain is defined in three layers (surface layer, sub layer 1, sub layer 2) of 0.4 m in thickness for each land cover class defined (model parameters: $ngd = 3$, $nd = 3$, $dzg = 0.4$). That is, if a model node is
defined as sand on the surface layer of the domain, it will remain as a sand node for the first sub layer and the second sub layer. A pavement/concrete node will change into a sand node after the erosion of the surface pavement/concrete layer. A vegetation node will change into a sand node only after the surface and the first sub layer is eroded. The idea behind having only one concrete/pavement layer is to mimic the pavement sitting on sand whereas a vegetation node changes into a sand node after the erosion of both the surface and the first sub layer to imitate
the effect of root density. Sand and vegetation nodes use the same sediment characteristics (medium sand; $D_{50} = 0.0002 \text{ m}, D_{90} = 0.0004 \text{ m}$) with different sediment calibration factors sedcal = 1 and sedcal = 0.2, respectively. The concrete/pavement nodes use significantly larger sediment characteristics (cobble; $D_{50} = D_{90} = 0.256 \text{ m}$) and smaller sediment calibration factor (sedcal = 0.01). The sediment characteristics and the calibration factors for the vegetation and concrete/pavement classes are empirical and have no physical meaning other than trying to imitate the behavior of such land cover features, e.g., a vegetated dune may erode more slowly than an unvegetated dune, a paved area will not erode until the pavement is removed. These parameters were calibrated using the Pea Island breach case and applied to the Rodanthe breach case without change. It should be noted that the sediment calibration factors are applied to each node after the corresponding equilibrium bed and suspended concentrations are calculated at each time step of the simulation whereas the sediment characteristics have the influence over the calculation of the threshold velocities to initiate sediment displacement at each time step.

**Sediment characteristics and calibration factors sensitivity analysis**

A sensitivity analysis was carried out in order to study the effects of changing the sediment characteristics and calibration factors on the eroded volume over the eroded area. For this purpose a test domain was created with a uniform dune separating two water bodies on each side (Figure 3.6; left panel). The dune crest height was kept constant at 3.8 m alongshore with a gap

<table>
<thead>
<tr>
<th>Land Cover Class (Surface Layer)</th>
<th>D50 (m)</th>
<th>D90 (m)</th>
<th>Sed. Cal. Factor (sedcal)</th>
<th>Sub Layer 1</th>
<th>Sub Layer 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sand</td>
<td>0.0002</td>
<td>0.0004</td>
<td>1</td>
<td>Sand</td>
<td>Sand</td>
</tr>
<tr>
<td>Vegetation</td>
<td>0.0002</td>
<td>0.0004</td>
<td>0.2</td>
<td>Vegetation</td>
<td>Sand</td>
</tr>
<tr>
<td>Concrete/Pavement</td>
<td>0.256</td>
<td>0.256</td>
<td>0.01</td>
<td>Sand</td>
<td>Sand</td>
</tr>
</tbody>
</table>
Figure 3.6: Sensitivity test domain. Initial state (left panel) and last time step for the sand, sedcal = 0.25 case (right panel)

left in the center of the domain at 2 m height. This test domain was schematized to represent the gap in the dunes at the Pea Island breach location coinciding with the location of the main breach channel Hurricane Irene induced. On one boundary the water level was raised from 1.9 m to 2.2 m in 1.5 hours to overwash the gap in the dune then incrementally lowered back to 1 m level in the next 3 hours whereas on the other boundary the initial water level 1.9 m was incrementally lowered to 1.3 m over the course of the full run (4.5 hours). Constant 1 m waves ($H_{rms}$) were also applied from the boundary where the water level was raised. The boundary conditions and the model parameters were kept constant through all tests where sediment characteristics for sand ($D_{50} = 0.0002$ m, $D_{90} = 0.0004$ m) and cobble ($D_{50} = D_{90} = 0.256$ m) were tested with changing sediment calibration factors varying between 0.001 and 1. Model parameters that were used in the breach case studies were used for the sensitivity tests for consistency. The results of the sensitivity tests were presented in Figure 3.7. The volumes eroded for each case were calculated over the area eroded for that particular case, that is, the eroded areas were case specific and changed based on the effected areas. It can be seen on the vertical logarithmic scale in Figure 3.7 that the rates of change of the eroded areas for both cases are linear compared to
the rates of change of the eroded volumes, especially in the lower range of sediment calibration factors tested (sedcal = 0.001, 0.005, 0.01, 0.025, 0.05, 0.1). The higher rate of change on the eroded volumes points to the channelization process taking place, i.e., the effected area does not get larger while the channel gets deeper. For the higher range of the sediment calibration factors tested (sedcal = 0.25, 0.5, 0.75, 1), both the eroded area and the eroded volume trends for sand and cobble exhibit constant rate of change. When the same eroded area and volume results are plotted on a linear vertical scale (Figure 3.8), it can be seen that the eroded areas and the volumes for the sand cases increase linearly with the increasing sediment calibration factors whereas the initiation of sediment motion hampered by the larger grain sizes of the cobble cases restricts the same linearly increasing trend as in the sand cases. Therefore, using larger sediment grain sizes in combination with small sediment calibration factors to represent hard to erode
Figure 3.8: Sensitivity tests results graph. Eroded areas and volumes calculated for all cases on the linear vertical scale surfaces in the model helps mimic the effect of such features may have on the flow and erosion patters, e.g., high velocities developing over the roads and their weir effect (scouring along the edge of the road) during flooding conditions.

3.4.3 Hydrodynamic boundary conditions

For consistency, models for both study locations were forced for the same period of time starting approximately at the time when the sound side water levels starts to rise on 27 August 2011 21:00 UTC (Figure 3.3) ending on 30 August 2011 09:00 UTC, a total of 60 hours. The significance of the simulation end time is that on 30 August 2011, NCDOT collected orthoimagery and photogrammetric ground elevation data for both study sites along with the bathymetric survey at the Pea Island main breach channel location which provides the ability to quantitatively compare
the model results against. For the cases of barrier island morphological evolution with XBeach under such conditions as Hurricane Irene where the hydrodynamic conditions at the sound side of the barrier island were dominant, the wave forcing at the sound side boundary may be more influential on the final outcome than the wave forcing at the ocean side boundary and it may be needed to be given priority over the wave forcing at the ocean boundary since it is not possible to generate waves from both the sound and ocean boundaries at the same time in the same model domain. In order to decide on the final set of hydrodynamic boundary conditions to be used as forcing input for both the Pea Island and Rodanthe cases, preliminary model runs were carried out to assess the contribution of the waves on the post storm configuration. That is, for both study locations two runs were carried out where the corresponding wave forcing from the sound side and the corresponding wave forcing from the ocean side were applied separately along with the corresponding water level boundary conditions present at the ocean and sound side boundaries. The water level boundary conditions and the ocean side wave forcing data were extracted from the hydrodynamic data measurements from FRF presented in Section 3.3. The sound side wave forces were not measured however the ADCIRC+SWAN coupled (Dietrich et al., 2012) now-cast model runs produced by CERA were available to generate wave forcing boundary conditions. It was concluded from the preliminary model runs that for the Pea Island breach case, applying the corresponding wave forcing from the ocean boundary did not have significant effect on the post storm configuration of this particular location. The ocean side waves were dissipated in the nearshore and failed to overwash the dunes via run-up. This observation from the preliminary run was justified by local accounts and by the time stamped video recordings of the area during Hurricane Irene. Therefore, for the Pea Island breach case, the wave forcing was applied at the sound side boundary along with the water level signals at the sound and ocean boundaries. For the Rodanthe breach case however, the wave forcing applied at the ocean side boundary had more significant effect on the post
storm configuration compared to applying the wave forces at the sound side boundary. The wave forcing from the ocean side for this particular location led to overwashing of the dunes and weakening parts of the dune line against the sound side surge. This difference between two study locations is assumed to be a function of the pre storm topographic and bathymetric configuration, e.g., the dune line at Rodanthe had overall lower crest elevations compared to Pea Island breach location, the waves had to travel on a wider and vegetated stretch of the barrier island at Rodanthe thus dissipating more energy, the bathymetry differences for each study location resulting in different wave transformation for each location. The wave forces were applied at 3 hours intervals using JONSWAP spectrums defined by the wave height \(H_{m0}\), peak period \(T_p\) and the wave direction information gathered at the FRF along with the peak enhancement factor in the spectrum \((\text{gammajsp} = 3.3)\), directional spreading coefficient \((s = 20)\) and the highest frequency used to create the spectrum \((\text{fnyq} = 1)\). The water level signals were applied as time series of water surface elevation at 30 minutes intervals from both the sound and the ocean side boundaries.

### 3.5 Results and Discussion

#### 3.5.1 Qualitative results

As explained in Section 3.4.2, to illustrate the improvement in the modeling results made by using land cover classes, model results for the all sand and land cover cases are depicted next to the pre and post storm NCDOT orthoimagery for both the Pea Island breach location (Figure 3.9) and the Rodanthe breach location (Figure 3.10). The qualitative comparison of the results aims to visually confirm the prediction of the breach channel locations and to compare the overall morphological changes occurred at the given location versus the simulated changes. First
Figure 3.9: Pea Island breach location results. Pre storm orthoimagery (NCDOT, 08/02/2011) (a). Pre storm model domain (a.1). Post storm orthoimagery (NCDOT, 08/30/2011) (b). All sand case model results (b.1). Post storm model domain (c). Land cover case model results (c.1)
Figure 3.10: Rodanthe breach location results. Pre storm orthoimagery (NCDOT, 08/02/2011) (a). Pre storm model domain (a.1). Post storm orthoimagery (NCDOT, 08/30/2011) (b). All sand case model results (b.1). Post storm model domain (c). Land cover case model results (c.1)
row of images in Figures 3.9 and 3.10 depict pre storm orthoimagery (a) and its representation in the model domain (a.1) with local model coordinates in meters along with the black frame box indicating the coverage of the orthoimagery. Topography is illustrated with shades of brown and the bathymetry is illustrated as shades of blue; lower elevations and shallower depths are lighter shades. It is possible to note some features in the orthoimagery on the model domain visualization such as the curved road bed and the remnant dune features along the coast in the Pea Island breach location. In addition, the maintenance and residential buildings are easy to differentiate by the darker shades of brown for both model domains as these features represent the highest elevations in both model domains. Model domains presented in Figures 3.9.a.1 and Figure 3.10.a.1 were used as the initial conditions for both the all sand and land cover cases of both study sites. The second rows of images depict the post storm orthoimagery (b) and the model result at the last time step of the simulation of the all sand cases (b.1). Finally, the last rows of images depict the real post storm configuration represented in the model domain (c) and the model result at the last time step of the simulation of the land cover cases (c.1). It is immediately visible from Figure 3.9 and 3.10 that the all sand case results overestimated the morphological change occurred in the study locations. For the Pea Island breach location, it is clear that two channels were formed in correct locations (Figure 3.9.b.1), however the widths and depths of the simulated channels appear to be much extensive in contrast to the post storm orthoimagery (Figure 3.9.b) and its representation in the model domain (Figure 3.9.c). The comparison of the depths is presented in Section 3.5.2. The secondary channel, right hand side in Figure 3.9.b.1, was not only wider but almost extended to the sound side water body to form a second breach channel. For the Rodanthe breach location, the simulated erosion for the all sand case exhibited unrealistic erosion. Low points on the dune line present at this study locations led to excessive overwash and erosion that eventually wiped out of the dunes leading to multiple breach channels.
The implementation of land cover classes as described in Section 3.4.2 into the model runs visibly improved model results. For the Pea Island breach case, the extensive vegetation both on the seaward and landward sides (the spatial distribution of these classes was illustrated in Figure 3.5) of the road and the road itself provided mitigating properties and prevented the extensive widening and extension of the secondary channel seen in the all sand case results presented in Figure 3.9.b.1. More detail on the location and shape of the channels and erosion patterns were achieved by employing different sediment classes mimicking the effect of the land cover features. The main channel width and depths observed in the land cover case and the channelization patterns (Figure 3.9.c.1) were more in line in contrast with the post storm model domain (Figure 3.9.c) and what was visible in the orthoimagery of the post storm conditions (Figure 3.9.b). For the Rodanthe breach location, the simulated erosion for the land cover case (Figure 3.10.c.1) was a considerable improvement over the all sand case results (Figure 3.10.c.1). The implementation of land cover classes, mainly vegetation, improved the stability of the flat portion on the left side of the study site domain, preventing the multiple channel breaching seen in the all sand case results. However, it can be also seen from Figure 3.10.b and 3.10.c that the erosion behind the houses on the shoreline in the upper right hand side of the domain and the channelization of the breached dune were more extensive in contrast to the simulated results of the land cover case. Similarly for the Pea Island breach location, it can be seen from Figure 3.9.b and 3.9.c that in some spots the erosion landward of the road and the channelization in the proximity of the left side lateral boundary were more extensive in contrast to the simulated results of the land cover case. The underestimation of the erosion in the sections mentioned above is attributed to the limitations of the model domain sizes. The extent of the storm covered most of the barrier island; however it was not feasible to incorporate the full barrier island system into the model. The effects of overwash from the ocean side, flooding and flowing along the road and/or the surging flow from the sound side flooding some parts of the island.
before other parts and possibly advancing into the modeled domain are excluded by the lateral boundaries. In such a barrier island system, the lateral boundaries of both model domains act as a barriers against the possible alongshore overland flow moving into the modeled domain and influencing the erosion patterns. As an example, the underestimated erosion behind the homes on the shoreline in the upper right side of the domain in the Rodanthe breach land cover case (Figure 3.10.c.1) is most likely the result of the lacking flow that could have been flowing from the immediate neighborhood of the model domain excluded by the right side lateral boundary. The grade of the road at this particular location also suggested that the lowest point in elevation was right where the breach occurred and the road bed elevation increased in both directions away from this point. Similarly, the underestimated erosion behind the dunes near the left side lateral boundary for the Pea Island land cover case (Figure 3.9.c.1) can be attributed to the processes blocked by the lateral boundary. It is assumed here that the effect of the lateral boundaries on the final simulated configurations is negligible since the cross shore processes are more dominant in incipient breaching.

### 3.5.2 Quantitative results

**Survey elevation comparison**

While the location and morphology of the new channels are important in understanding vulnerable landform exhibiting tipping point behavior, the depth of channelization (for channels that breach the island) will determine the hydraulic capacity for remaining open as an inlet. As mentioned in Section 3.4.3, the storm event was simulated as a 60 hours event ending on 30 August 2011 09:00 UTC when the NCDOT conducted a bathymetric survey in the proximity of the NC 12 highway at the Pea Island breach location in order to determine alternatives for repairing the road to restore transportation along the barrier island. This data provided the ability
to compare the all sand and land cover case results along a transect on the road to the surveyed elevations and calibrate the model parameters of the Pea Island land cover case for this location. These model parameters were kept constant for the Rodanthe breach case. Figure 3.11 depicts the 470 m long surveyed transect along NC 12 over the post storm orthoimagery taken the same day (top panel) and the graph (bottom panel) providing a cross sectional view with distance along the road on x-axis and elevations (NAVD88, m) on the y-axis comparing the results of

![Figure 3.11: Post storm road survey at the Pea Island breach location. Surveyed transect along NC 12 (dashed line from A to B) overlaid on orthoimagery (30 August 2011, NCDOT) (top panel). Comparison graph of results along the survey transect (bottom panel).](image)

Figure 3.11: Post storm road survey at the Pea Island breach location. Surveyed transect along NC 12 (dashed line from A to B) overlaid on orthoimagery (30 August 2011, NCDOT) (top panel). Comparison graph of results along the survey transect (bottom panel).
the all sand (dashed line) and land cover (solid line) case to the surveyed elevations (dash-dot line). The all sand case was consistent in illustrating a greater tendency to erode. The depth reached in the main channel for the all sand case was approximately 6 m, about three times deeper than the post storm survey. The field survey did not extend to the secondary channel so it was not possible to compare depths developed at that location. The land cover case was in very good agreement with the surveyed elevations in the main channel, an expected result since the parameters related to the land cover implementation were calibrated based on the model results. Erosion and channelization was underestimated on and around the road in the proximity of the left hand side lateral boundary of the study domain (approximately between x = 20–120 m, bottom panel in Figure 3.11). As discussed earlier, one reasonable explanation for this is the effect of the lateral boundary being close to this particular location and blocking the processes that may had influenced the channelization and erosion patterns.

Flow velocities driving sediment transport

Hydrodynamic conditions induced by Hurricane Irene presents a situation where the surge from the sound side flooded the barrier island and exceeded the low elevations at certain parts of the dune line. The topographic conditions at the low lying portions of the dune line for each study site exhibited flat to mild slopes landward of the dunes compared to the beach face slopes. In addition, the low tide on the ocean side coinciding with the time the sound side surge flooded and incipient overwash occurred, increased the hydraulic head difference at the interface where the water bodies from the two sides met. The overwash by overflow where water flowed constantly over the low lying portions of the dunes during the time of higher water levels in the sound side, with the additional effects of topographic and hydrodynamic conditions, led to accelerated flow conditions, similar to high velocity sheet flow conditions, causing severe erosion of the dune and eventually breaching. The sediment transport routine implemented in XBeach is based on
the Soulsby-van Rijn total load transport by waves and currents sediment transport formulation (Soulsby, 1997). Based on the formulation, the sediment is set in motion when the stirring velocities exceed a threshold transport velocity based on Shields (van Rijn, 1993). In the model, the stirring velocity is a combination of the Eulerian mean and infragravity velocities and the near bed short wave orbital velocity calculated in XBeach (Roelvink et al., 2009). Under certain hydrodynamic conditions, high stirring velocities may occur and lead the sediment transport formulation to overestimate the erosion because the effect of soil dilatancy and the effects of sheet flow conditions reducing bottom shear stress and suspended sediment transport are not accounted for in the formulation. To account for this limitation, a Shields value ($s_{\text{max}}$) to act as the sheet flow transport limiter can be set to limit stirring velocities. For instance McCall et al. (2010) uses $s_{\text{max}}$ to be equal to 1.0 (Shields value corresponding to start of sheet flow) to significantly improve the model skill compared to not using the sheet flow transport limiter. In essence, whenever the internally calculated Shields parameter exceeds $s_{\text{max}}$, it is set equal to $s_{\text{max}}$ leading to a constant stirring velocity fixed at the initiation of the sheet flow limit ($s_{\text{max}} = 1$) for all instances where the stirring velocities actually exceeded the set limits.

In the model runs carried out for this study, the Shields parameter limiter was not used, thus the calculated velocities were not capped. However, an all sand case with $s_{\text{max}}$ parameter set to 1.0 was carried out to study the effects of the limiter on the simulated results of the Pea Island breach location. This case will be referred as the $s_{\text{max}}$ case for the remainder of this paper. Figure 3.12 depicts the maximum velocities recorded at each model node during the simulation of the land cover, $s_{\text{max}}$ and all sand cases of the Pea Island breach location. It can be seen from Figure 3.12 that the maximum recorded velocities for the all sand and land cover cases are overall larger than the $s_{\text{max}}$ case. As a result of the limited velocities, the simulated erosion for the $s_{\text{max}}$ case was not enough to cause channelization leading to breaching of the barrier island. The topographic and hydrodynamic conditions for the Pea Island breach location presents a
scenario where the duration of the sound side water levels to reach its recorded maximum and lower back down should have been long enough to induce enough erosion to develop a channel that will allow constant flow from the sound side to the ocean side even with the decreasing sound side water levels as the storm moves away from the breach location. Figure 3.13 depicts the elevation, water depth and flow velocities recorded at a model node (at x=500, y=1050 in local model coordinates, see Figure 3.4) in the Pea Island main breach channel for the land cover and smax cases. For both cases, the erosion starts with the overwash by overflow (at output time step 50; model outputs were recorded every 300 seconds) however over time the erosion rates exhibit significantly different behavior. In Figure 3.14.a, the profile view depicts the condition corresponding to the start of the overflow (output time step 50). In panel b,c and d of Figure 3.14, the profiles showing the conditions for the land cover, smax and the all sand cases are presented respectively. The time step selected (output time step 165) to present the evolution of all cases corresponds to the moment where the sound side water level dropped to a level
below the highest elevation of the simulated profile during the smax case simulation (Figure 3.14.c) thus the flow from the sound side to the ocean side was blocked for the remainder of this simulation. It can be seen that the overestimated erosion of the all sand case (Figure 3.14.d) was controlled by using the sheet flow transport limiter however for the given topographic and hydrodynamic conditions for this study location during Hurricane Irene, the implementation of the land cover effects without applying a limit on the velocities resulted in a better simulation of the event. Limiting the erosion by implementing a limiter on the flow velocities turned out to have a critical effect on the outcome of the model results since the limited erosion prevented the incipient channelization which eventually prevented breaching. At this output time step, it is also possible to note the effect of the NC 12 road resisting erosion and creating the weir effect discussed in the Introduction section (Figure 3.14.b). High velocities developed due to this effect along NC 12 during the land cover case simulation reveals the location of the road in Figure 3.12.a.
3.6 Conclusions

This paper focused on how the land cover features such as pavement/concrete and vegetation have been conceptualised and how it has been operationalised in the XBeach 2DH morphodynamic numerical model. The model is used to simulate the process of breaching and the effects of land cover features on the process by studying two breaching cases occurred on the Outer Banks of North Carolina barrier islands during Hurricane Irene. First, model parameters associated with the land cover implementation are calibrated and validated qualitatively and quantitatively.
for the Pea Island breach location as presented in the Results and Discussion section. With a limited sensitivity study, the effect of changing sediment characteristics and the calibration factors on the model reaction on erosion is presented. Based on the sensitivity tests and the calibration of the associated parameters using the Pea Island breach case, pavement/concrete features were represented with large sediment grain sizes \( D_{50} = D_{90} = 0.256 \text{ m} \) and a low sediment calibration factor \( \text{sedcal} = 0.01 \) and vegetation features were represented with the same sediment grain size as sand features \( D_{50} = 0.0002, D_{90} = 0.0004 \text{ m} \) with a sediment calibration factor equal to 0.2. In addition, the subsurface layer configuration is set up to have pavement/concrete surface layers to be followed by sand sub layers (mimicking e.g., a road sitting on sand) whereas the vegetation layers are followed by a subsequent vegetation sub layer before being followed by a sand sub layer (mimicking e.g., vegetation root density). The derived sediment characteristics and calibration factors along with the surface/sub layer configuration were applied to the Rodanthe breach location and realistic modeling capacity was achieved.

Successful prediction of post-storm breach morphology of the Pea Island and Rodanthe breach locations through the implementation of antecedent topographic and land cover conditions and the underlying sediment layers shows that XBeach is capable of modeling the hydrodynamic conditions such as flooding, overwash and inundation and simulating the morphological change such as channelization and breaching associated with them. This capacity can help answer critical questions on where and how breaches occur during storm events and help communities facing post-storm repair decisions and developing long-term comprehensive land use plans. Also, the simulations provided insight on the processes that take place during barrier island breaching. For instance, the difference in erodibility introduced by different land cover classes leads to different erosion patterns thus different hydraulic gradient distributions which eventually has an important role on the post storm configuration. Moreover, high flow velocities that may be present under a combination of certain topographic and hydrodynamic
conditions may play a critical role on the channelization and incipient breaching.

Acknowledgements

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Abstract accepted, paper will be published as: Kurum, M.O., and Overton, M.F. (2013). Scenario testing at Pea Island. Proceedings of the Coastal Dynamics Conference 2013

4.1 Introduction

Long stretches of the coastal barrier island chain known as the Outer Banks of North Carolina, USA from Oregon Inlet to Hatteras Inlet have been characterized as on or on the verge of a threshold (Gutierrez et al., 2007). The Outer Banks has a long and rich history of inlet openings and closings over the last several centuries. Possibly the most influential event on the shape of the Outer Banks is the 1846 storm. The storm induced water levels overwashed the barrier island from the soundsie and created two navigable inlets, the Hatteras Inlet and the Oregon Inlet, which remained as the major inlets in the Outer Banks to this day (Clinch et al., 2012) (Figure
4.1). The vehicular access to the Outer Banks is currently provided by the Bonner Bridge on North Carolina Highway 12 (NC 12) crossing the Oregon Inlet. NC 12 lies along the barrier islands and is the only paved road connecting the villages of the Outer Banks to the mainland. The development of the Outer Banks is dominantly fueled by the tourism industry, especially after Bonner Bridge was opened in 1963, as many areas of the barrier islands are national and

Figure 4.1: Outer Banks of North Carolina, USA
international destinations of recreation. Therefore, NC 12 highway is a critical infrastructure for the stakeholders of the Outer Banks. Accordingly, maintenance of the road is essential in preserving the continuous transportation link for the barrier islands. The problem is that the coastal highways on barrier island systems are subject to repetitive natural coastal processes such as hurricane and storm induced storm surge and waves that can cause overtopping and overwash on the low elevation parts of the barrier islands. In some cases, the overwash flow can lead to breaching of the barrier island and forming a new inlet. In 1933, a storm event created five channels on the barrier island approximately 10 km south of the Oregon Inlet (Markham, 1935). This inlet was named after another historical inlet close to this location that was open from the 1730s until 1922, the New Inlet. Four of the channels were closed naturally by 1935. The remaining main channel migrated south, narrowed and subsequently closed by 1945. During this period, the transportation was shifted landward of the barrier island by connecting small islands with bridges that would allow bypassing the channel locations. More recently, in 2003, overwash induced by Hurricane Isabel conditions caused portions of the barrier island between Buxton and Hatteras villages (Figure 4.1) to be breached from the ocean side and form a new inlet of three channels (simulation of Hatteras breach was included in the Appendix A.1). In this case the channels were artificially filled to allow for the reconstruction of the removed portion of the road. The breach isolated more than 300 people in Hatteras Village. The village was without electricity, water, food and medical supplies which had to be ferried. Eventually temporary power and water lines were installed and a ferry service, using commercial fishing boats, was set up for residents. But access for tourists, which fueled the local tourist industry, and the transport of needed rebuilding supplies, had to wait until the breach was closed and road rebuilt (Wutkowski, 2004). In 2011, Hurricane Irene breached the island from the soundside approximately at the same location as one of the channels created during the 1933 storm. The breach channel stayed open and the transportation was restored by a temporary bridge installed
in two months at the location. The temporary bridge is still present to this day however the short term breach channel evolution indicates a possible natural closing of the channel it crosses. During Hurricane Irene, the barrier island was also overwashed near Rodanthe, the dunes were breached yet no island breaching occurred and the transportation was restored by repairing the damaged road. Shortly after that event, in 2012, Hurricane Sandy induced storm surge and waves overwashed the same location in Rodanthe, damaged the road and removed the ocean side dunes. This portion of the road remained exposed to the ocean and was flooded numerous times at high tide hindering the transportation along the island until December 2012.

Although breaching of the barrier island cases where critical infrastructure such as the transportation link NC 12 for Outer Banks is under removal threat are relatively seldom events, the possible interruption and damage to transportation is not only limited to breaching. More often, the storm induced surge and waves causes overwash of the low elevation portions of the dunes. The overwash causes the erosion of the sand from the dunes and deposition inland called overwash fans. In the case of barrier islands, due to limited width of the island, the overwash fans may have a greater chance to extend inland to cover the roads with large sediment layers interrupting transportation and requiring frequent repairs and/or maintenance. Moreover, the storm induced damage in barrier islands is not only limited to the roads. Over the years, several beach houses were lost or damaged along the Outer Banks, people lost their lives or got injured due to severe storm induced conditions. The protection of critical coastal infrastructure, in this case NC 12, becomes more evident when its role on evacuation and emergency response efficiency are also factored in.

In the light of its history and recent events, Outer Banks is and will remain to be a dynamic and vulnerable coastal zone susceptible to storm and hurricane induced damage. A recent short term time series analysis of elevation data collected at Rodanthe and Hatteras shows a relatively small stable core in both study areas, with beaches and the ocean side of the dunes
exhibiting systematic high rates of elevation loss (Mitasova et al. (2010) presented in Chapter 2). These trends are considered to increase the potential vulnerability of the barrier island and the infrastructure that resides on it against storm and hurricane events. Therefore it is essential to study the processes (e.g., dune and shoreline erosion, overwash, breaching) that may take place during storm and hurricane events and provide alternatives and solutions to the related problems that may present a threat against both important infrastructure and human life.

Since barrier islands are under the threat of both soundside and ocean side events, the study is divided into two sections; Hurricane Irene (soundside event) scenarios and Hurricane Isabel (ocean side event) scenarios. In the first section, . These scenarios were analyzed in terms of their effects on the breaching function by comparing the results of the scenarios to the original Hurricane Irene at Pea Island simulation developed in Chapter 3. In the second section, Hurricane Isabel was simulated on pre Irene topographic conditions. Additionally, by creating various scenarios based on changes made to the pre Irene topography, hypothetical barrier island protection practices were tested under Hurricane Isabel hydrodynamic conditions.

### 4.2 Hurricane Irene Scenarios

The breached portion of the barrier island during Hurricane Irene is under protection of the U.S. Fish and Wildlife Service (USFWS) as part of the Pea Island National Wildlife Refuge. Therefore, large scale, long term, dune repair and beach nourishment are not allowed. However, The North Carolina Department of Transportation (NCDOT) is allowed to remove storm overwash deposits from NC 12 and rebuild artificial dunes within its right-of-way, defined as approximately 30 meters on each side of the centerline of the road. At this location, the natural beach and dune formation is well outside the right-of-way, therefore have been subject to repetitive storm action without maintenance. After Hurricane Isabel in 2003, multiple overwash
fans were formed. The Thanksgiving Day storm in November 2006 and the Veteran’s Day storm in 2009 further eroded the dunes and flattened previous overwash fan locations. In 2009, the shoreline resided landward of the location of the dune ridge in 1996 (Hardin et al., 2012). Weakened by the ocean side storms over time, this location was finally breached from the soundside during Hurricane Irene in August 2011.

Formation of the Pea Island breach can be defined as a function of the site specific initial topographic conditions and the event specific hydrodynamic conditions. On the initial topographic conditions; the history and the evolution of this location suggests that the topographic conditions played an important role in the Pea Island breach formation. During Hurricane Irene, risen soundside water body overflowed previously overwashed low portions of the pre Irene topography. The main channel of the Pea Island breach was formed exactly on one of the overwash fans created by the 2009 storm (Figure 4.2). Secondary channels were also formed where the dunes were degraded by previous storms.

Figure 4.2: Orthoimagery of the study location in December 2009. Courtesy of Clinch et al. (2012).
On the hydrodynamic conditions induced by Hurricane Irene; the soundside water level reached its maximum at a time coinciding with low ocean side water level conditions. The hydraulic head difference created by the hydrodynamic conditions at the time overflow began led to high velocity flows with high sediment transport capacity during incipient overflow.

We investigated the effects of topographic and hydrodynamic conditions on breaching separately. For the topographic conditions side, two new model domains were created where topographic conditions at the study location were improved by 1) repairing the dunes and 2) applying beach nourishment. Both of the model domains were tested under Hurricane Irene hydrodynamic conditions. For the hydrodynamic conditions side, two ocean side water level scenarios specifically developed to reduce the hydraulic head difference between the ocean side and soundside water bodies were created and simulated on the pre Irene topography. Figure 4.3 depicts the time series of the recorded ocean and side water levels along with the two ocean side water level scenarios created. Looking at the first 24 hours of the simulated event, the

![Figure 4.3: Recorded and hypothetical water levels during Hurricane Irene](image)

Figure 4.3: Recorded and hypothetical water levels during Hurricane Irene

average head difference between the recorded ocean and soundside water levels is 1.17 m with a
maximum head difference of 2.4 m. In the ocean side water level scenario 1, the average was reduced to 0.84 m, and the maximum to 1.48 m. Finally, in the ocean side water level scenario 2, the average head difference was reduced to 0.61 m, with maximum at 1m.

Figure 4.4 summarizes the inputs and outputs of the simulations of all Hurricane Irene scenarios described above. On the upper left panel, the pre Hurricane Irene conditions of the study site are illustrated. In this panel the ocean is on the left and the soundside is on the right. This orientation and this footprint is used repeatedly in all the results figures. The black dashed line is the location of the cross section profiles where the elevations for each case were extracted and plotted in the graph at the bottom panel. This location was selected so that it captured the breach formations simulated in these scenarios. In the middle left panel, the post Hurricane Irene conditions of the site are illustrated. This panel along with the corresponding profile plotted in at the bottom panel, serve as a comparison base to all the hypothetical scenarios. Note that in the pre Irene cross section profile, maximum elevation is approximately 1.7 m (NAVD88) with no dune formation visible. The post Irene cross section profile is indicated with a solid red line in the graph at the bottom panel and represents the deepest channelization achieved among the scenario results. On the upper right, initial topographic conditions for the dune repair scenario are illustrated. The dimensions of the built dune can be seen in the plot at the bottom panel. The initial topographic conditions for the beach nourishment application to the pre Irene topography is not illustrated however the cross section plot provides an insight about its dimensions. Beach nourishment was placed just below the dune toe as an approximately 60 m wide strip of sand.

As stated before, the Pea Island breach was induced by overflow from the sound side. In the dune repair scenario, the overflow was blocked by the dunes preventing flow across the island from the soundside to the ocean side. Therefore, no breaching occurred. Erosion that was caused by the flows developed during the initial inundation of the soundside was observed along the soundside shoreline and the ocean side of the road. The resulting cross section profile
Figure 4.4: Hurricane Irene scenarios: Pre Irene conditions and simulation results
looked almost exactly like the initial dune repair profile, therefore it is not plotted in the graph at the bottom panel. In contrast to the dune repair scenario, water flowed across the island in the nourishment and two ocean side water level scenarios resulting in different erosion patterns, either a breach occurred or the island was overwashed. Different erosion patterns are directly related to flow velocities developed during the simulation of the scenarios. To examine this relation, the maximum velocities calculated at each model node during the simulation of each scenario are illustrated in Figure 4.5. In the nourishment scenario, the flow velocities were slightly reduced (Figure 3.5, upper right panel) compared to the post Irene results (Figure 3.5, upper left panel). The effects of the nourishment on the post storm configuration can be seen more clearly by comparing the post Irene profile to the nourishment scenario profile plotted in

Figure 4.5: Hurricane Irene scenarios: Maximum recorded velocities
the graph at the bottom panel of Figure 4.4. The slightly reduced flow velocities resulted in lower sediment transport. The effect of the change in flow velocity magnitudes on the post storm configuration is emphasized by the results of the ocean side water level scenarios. In water level scenario 1, a breach channel was observed with shallower depths (Figure 4.4, bottom graph) and width (Figure 4.4, bottom left panel) compared to the post Irene results. Further reducing the hydraulic head difference between the ocean and soundside in water level scenario 2, breach channel formation was prevented (Figure 4.4, bottom right panel). The effect of changing the hydraulic head difference between the water bodies can be seen more clearly in Figure 4.5.

In this section, scenarios as variations of the pre Irene topography and Hurricane Irene hydrodynamic conditions were tested. The dune repair scenario results shows that the topographic conditions that would not allow the overflow from the sound side could have prevented breaching and extensive damage on the island including the road. Also, higher ocean side water levels coinciding with the incipient soundside overflow could have reduced the erosion and channelization. According to the modeled results, beach nourishment would not change the outcome of Hurricane Irene at the study location. However, beach nourishment is not a soundside event prevention and/or stabilization practice. Its effect on the post storm configuration is discussed in the next section where an ocean side event was simulated on the pre Irene topography.

### 4.3 Hurricane Isabel Scenarios

In this section, different barrier island protection scenarios were tested under ocean side event conditions, Hurricane Isabel. Hurricane Isabel was a significant event that breached the OBX barrier island in Hatteras and damaged various locations by overwash along the island including this study location (Figure 4.6). Maximum wave heights ranged between 2.7 - 3.3 m at the model ocean boundary and the maximum storm surge reached 1.7 m.
First, Hurricane Isabel on the pre Irene topography is simulated and presented in Figure 4.7. In the upper left panel of the figure, the simulated post storm configuration is illustrated. At the bottom panel, three cross section profiles of the post storm configuration are plotted. Dashed lines in the profile plots indicate initial conditions whereas the colored lines are the simulated profiles taken at the transects with matching colors overlaid on the upper left panel. Finally, in the upper right panel, simulated elevation change is illustrated to present erosion/deposition patterns and magnitudes. In Figure 4.7, it can be seen that Hurricane Isabel simulation did not create a breach channel on pre Irene topography. Most dunes were breached and flattened exhibiting erosion patterns similar to the visual evidence in the 2003 orthoimagery in Figure 4.6. However, especially at the area that was breached during Hurricane Irene, the erosion appear to extend landward of the road, damaging it during the process.

In order to investigate possible practices that could have prevented such extensive damage, three dune repair alternatives were tested. The dunes were built at locations to ensure the new dunes were not seaward of the current dune toe positions. Dune repair alternatives were defined
Figure 4.7: Hurricane Isabel scenario model results

based on their crest elevations (3.0 m, 4.6 m and 6.1 m - NAVD88) above the road bed elevation (1.5 m - NAVD88) (See Figure A.9 for illustration of dune repair alternatives). In all alternatives, the dunes were built with a 1:3 slope on the ocean side, 1:5 on the soundside and with a flat dune top with a minimum width of approximately 4.5 m. Beach nourishment as explained in Section 4.2 was applied to each dune repair alternative to create additional three scenarios representing more comprehensive practices to increase resilience to erosion. The results of the dune repair and beach nourishment scenarios are presented in the following six Figures (4.8; 4.9; 4.10; 4.11; 4.12; 4.13). The figures were followed by the discussion of results.

Simulation results of the dune repair scenario where the dune crest height was set at 4.5 m exhibited very similar erosion and deposition patterns to the Hurricane Isabel scenario results. During Hurricane Irene, same dune repair scenario was able to prevent breaching and minimize
Figure 4.8: Hurricane Isabel simulation results. Domain with dune crest @ 4.5 m

Figure 4.9: Hurricane Isabel simulation results. Domain with dune crest @ 4.5 m and nourishment
Figure 4.10: Hurricane Isabel simulation results. Domain with dune crest @ 6.1 m

Figure 4.11: Hurricane Isabel simulation results. Domain with dune crest @ 6.1 m and nourishment
Figure 4.12: Hurricane Isabel simulation results. Domain with dune crest @ 7.6 m

Figure 4.13: Hurricane Isabel simulation results. Domain with dune crest @ 7.6 m and nourishment
damage since it only needed to prevent the overflow from the soundside. However, under Hurricane Isabel conditions, the dunes were breached in multiple locations. Especially in the bottom part of the study site that can be identified as the region between the magenta and blue profile lines (Figure 4.8), similar to the Hurricane Isabel scenario, material moved from this region was deposited into the channel connected to the soundside water body. Also in this region, high erosion around the road was observed. Based on the volume calculations of the initial and post conditions, 17,527 m$^3$ was added to the base scenario (pre Hurricane Irene conditions; average dune crest height 3 m) to construct a 4.5 m high continuous dune line (Table 4.1). Volume calculations in Table 4.1 are limited to the extent of the model domain visible in the figures. First, the footprint of each dune construction alternative was extracted, named as dune section. Areas seaward of this footprint was named as beach section and areas landward of this footprint was named as inland section. At each section, available volumes in the pre Irene topography, sand needed (added) to create each scenario’s initial (pre) conditions, simulation results (post) and the corresponding subaerial (above zero NAVD88) erosion was calculated and listed in Table 4.1.

Addition of the beach nourishment to the 4.5 m high dunes resulted in reduced sediment transport behind the dune line (Figure 4.9). Most of the breached dunes in the previous scenario survived the storm, however the dunes at the bottom part of the domain were still breached and most of the material removed was deposited between the dune line and the road. Net volume increase inland for this scenario was calculated as 918 m$^3$. The erosion on and around the road was observed to be negligible. However parts of the road was covered with deposited material.

Removing the beach nourishment and raising the dune crest height to 6.1 m yielded similar erosion and deposition patterns behind the dunes (Figure 4.10) as in the previous case with 4.5 m dunes and nourishment. The difference between these scenarios is that the removal of the beach nourishment leaves the dune line exposed to direct wave attack. This can seen more
clearly when comparing the erosion magnitudes and distribution pattern results of the scenarios with the same dune height with and without beach nourishment. In the nourishment scenarios, most of the material from the nourishment is transported seaward (as deposition in the ocean side), creating a milder sloped shallower bed over which wave energy dissipates more before reaching the dune line. Net volume increase inland for this scenario was calculated as 1286 $m^3$. The erosion on and around the road was observed to be negligible. However parts of the road was covered with deposited material.

In the 6.1 m dune repair with beach nourishment scenario results (Figure 4.11), overwash and dune breaching were prevented. This configuration was able to withstand the simulated storm conditions, the erosion was limited to seaward of the dune crest where the volume lost, in this case all volume lost is sand volume, was calculated to be, 92241 $m^3$, less than the sand volume added, 102141$m^3$, to create the scenario initial conditions (Table 4.1). Similarly, the results of the 7.6 m high dune repair with and without dune nourishment (Figure 4.13 and Figure 4.12 respectively) also show that the overwash and dune breaching were prevented. Although the same outcome, protection of the coastal hinterland, was achieved, the efficiencies of the configurations are different. For instance, approximately the same amount of sand was added to the system to create the 6.1 m dunes and nourishment scenario as in the 7.6 m dunes only scenario. However, less volume was lost as a result of the simulation in the latter. Also, the results of the 7.6 m dunes with nourishment scenario indicate that 50% more sand was added to the system (to the beach) to achieve the same performance in terms of lost volume and protection of the coastal hinterland as in 6.1 m dunes with nourishment. It should however be noted that additional sand remaining in the system can serve as protection in case of frequent storm events.
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</tr>
<tr>
<td>Sand Added</td>
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<td>100,854</td>
</tr>
<tr>
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<td>183,013</td>
</tr>
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<tr>
<td>Percentage Lost (Eroded/Pre)</td>
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<td>13%</td>
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4.4 Conclusions

In this paper, we tested variations of hypothetical barrier island topographic conditions under different hypothetical storm scenarios in order to identify critical aspects of the topographic and hydrodynamics conditions that effect barrier island response to storms. Results of the scenarios based on the soundside event Hurricane Irene suggest that certain topographic and hydrodynamic conditions under which high velocity flows occur between the ocean side and soundside water bodies results in increased sediment transport capacity therefore higher erosion. In situations where these flow velocities were reduced, whether as a result of the topographic or hydrodynamic conditions, the amount of erosion was reduced. For instance, prevention of the flow across the island by repairing the dunes at the Pea Island breach location prevented breaching and damage to NC 12. Results of the scenarios based on the ocean side event Hurricane Isabel suggest that barrier island protection can be achieved by applying commonly used practices such as dune repair and beach nourishment. Nourishing/replenishing the beach moves the erosion concentration seaward and helps with dune survival. Increasing the dune height prevents initial overwash that may lead to channelization but it is also possible to over design a dune that does not offer increased protection performance.

Even with the assumption of 'ability to accurately predict coastal response and vulnerability', the decision making processes may impede preventative action due to political and environmental constraints. Immediate action is usually taken without constraints when critical coastal infrastructure is under instantaneous threat or needs to be restored after failure. In terms of dunes that provide protection to landward infrastructure, re-construction methods can be developed to prevent repetitive failure based on failing conditions including pre failure dune design and the hydrodynamic characteristics that caused it. The presented modeling framework can be used to design, test and optimize different re-construction/protection methods under
hypothetical storm forces.

Acknowledgements The authors would like to thank the NC Department of Transportation and Renaissance Computing Institute for providing datasets and computational resources to make this study possible. This material is based upon work supported by the Coastal Hazards Center of Excellence, a US Department of Homeland Security Science and Technology Center of Excellence under Award Number: 2008-ST-061-ND 0001. DISCLAIMER: The views and conclusions contained in this document are those of the authors and should not be interpreted as necessarily representing the official policies, either expressed or implied, of the U.S. Department of Homeland Security.
This work was carried out in support of the project objective of the funding agency

The previous chapters emphasized the significance of the ability to predict the barrier island response to storms in terms of erosion of the beach and dune face and/or breaching of the island. The applications presented were in 2DH in order to take the alongshore variability and complexity into account. However, profile based (1D) applications still have a wide use since the simplicity makes them easy to apply, which is valuable in the initial stage. 1D application is also less computationally expensive which makes it more accessible. In this sense, this chapter presents the simulation of Hurricane Isabel using XBeach in 1D over 33 profiles selected at the Pea Island breach location (Figure 5.1). The results of the XBeach simulations were compared to field measurements and to Cross-Shore Numerical model (CSHORE) simulations over the same profiles. Selection of CSHORE among other 1D numerical models capable of simulating cross shore processes is that The Federal Emergency Management Agency (FEMA) has shown
interest in implementing CSHORE model into their flood mapping program (Johnson, 2012).

The profiles were selected to be approximately 50 m apart, however as can be seen from Figure 5.1, some sections of the island were not covered by the profiles. Mainly, the area between profile 28 and profile 29 was left out since this is where the Wildlife Refuge maintenance buildings reside. Profiles coinciding with pre-existing overwash fans were also excluded from the model simulations (the gaps between profiles 22-23 and profiles 29-30).

![Figure 5.1: Profiles selected for 1D XBeach application at Pea Island breach location](image)

Although the 1D application was only tested at this particular location, the selected profiles’ dune crest heights vary between 4.8 - 9.3 meters, also the positions of the dune toes and dune heels vary in a 100 meters horizontal range which changes the dune width and beach width accordingly. In Figure 5.2, all profiles are plotted with their shorelines aligned at zero of the x-axis, four profiles were emphasized to demonstrate dune variability. In combination, these
variables created a profile set that covers a wide range of possible dune profile formations that presumably represents a wide selection of possible case study locations.

XBeach 1D application was carried out in two stages. First stage; all profiles were represented as sand, a very common approach applied in coastal morphological change modeling practices. In the second stage, the land cover application as explained in previous chapters, was used in order to check its validity in 1D application (XBeach model parameters are presented in Appendix C.2). Same profiles were also input to the CSHORE model to simulate the effect of Hurricane Isabel on the study location. CSHORE was originally developed to calculate the irregular non-linear wave transformation in combination with a non-Gaussian probability distribution of the free surface elevation (Kobayashi and Johnson, 1998; Kearney and Kobayashi, 2000; Johnson and Kobayashi, 2000). Over time the model capability has been extended with the inclusion of cross shore and longshore sediment transport predictions, wave runup and overtopping on dunes (Figlus et al., 2011). The scientific description and the governing equations of XBeach and CSHORE are given in Roelvink et al. (2009) and Johnson et al. (2012) respectively and are not repeated here. The simulation results from both models were compared to the measured erosion to quantify the model performance. These results are presented in Section 5.3.
5.1 Model Setup

Both models have been applied to simulate the dune erosion along the Pea Island National Wildlife Refuge, approximately 8 km north of Mirlo Beach, Outer Banks (OBX) of North Carolina due to Hurricane Isabel in 2003. The hydrodynamic condition data for Hurricane Isabel was extracted from the Datawell Directional Waverider, ID 630, located offshore at approximately 17 m depth from the US Army Corps of Engineers Field Research Facility (FRF) pier, Duck NC (Figure 5.3).

![Figure 5.3: Measured wave heights, periods and surge level at FRF Buoy 630](image)

In XBeach, the hurricane offshore wave boundary conditions were represented with 72 hourly JONSWAP spectrums, covering three days with the peak of the Hurricane centered in the hydrograph. In CSHORE, the same hydrograph was applied except the wave heights were converted to root mean square wave heights and were input as a time series with 15 minutes
intervals. As can be seen from Figure 5.3, the storm surge level reached 1.75 meters and the wave height reached 8.1 meters at the peak of the storm. The offshore extent of the profiles was limited to reach -17 meters (matching the depth of the buoy where the hydrographs were extracted). In XBeach, the profiles were represented with a varying size grid where the distance between nodes ranged from 20 meters offshore to 1 meter nearshore and over the dunes. In CSHORE, the distance between nodes were kept constant at 0.5 meters. The bed material in both models was selected as D50 = 0.0003 m, D90 = 0.0005 m sand.

5.2 Model Parameter Sensitivity

CSHORE model parameters were not calibrated and the parameter values used in this study are taken from the sensitivity tests, calibration and model validation to field data study carried out for Atlantic coast cases (Johnson et al., 2012).

Multiple parameters are required to be defined for XBeach to perform the simulations. These parameters are mostly associated with physical processes and reference values are readily available in a report for all XBeach testbed cases and real case studies published as of February 2011 (Van Thiel de Vries and Van Dongeren, 2011). The report also contains all the sensitivity and validation analysis carried out. In this study, recommended settings for sandy beaches have been used for the parameter setup with the exception of the wave skewness and asymmetry parameters. A sensitivity analysis is carried out to demonstrate the effects of changing these parameters and results were presented using Profile 1. The selection of the parameters however, was carried out considering the effect over all the profiles selected to represent the study site.

First, using the default set of parameters and studying the erosion process that takes place over time (Figure 5.4) reveals that at hour 20, before the peak of the storm comes into effect, the scarping at the beach had already created a 2.5 meters deep new dune face like feature. At hour
30, this new feature had moved landward (approximately 50 meters) and reached a depth of 3 meters. As the effects of the peak of the storm hits the existing profile, the process turns into an avalanching process which leads to the over prediction of the eroded material from the profile.

Figure 5.5 and Figure 5.6 depict the effect of changing the wave skewness (facSk) and wave asymmetry (facAs) factors by 0.1 increments between 0.1 (default XBeach value) and 0.9. Both factors were kept equal as the values were inclemently changed. It can be seen from Figure 5.5
Figure 5.6: Effect of wave skewness (facSk) and asymmetry (facAs) factors (0.6-0.9) on computed bed Profile 1

that with the default values (facSk = facAs = 0.1), the erosion is largely overestimated.

Figure B.24 and Figure B.25 depicts the effect of changing the wave skewness while keeping the wave asymmetry factor constant at 0.1. It can be seen from both figures that the effect of

Figure 5.7: Effect of wave skewness (facSk) factor (0.1-0.5) on computed bed Profile 1 (facAs = 0.1 - constant)

changing the wave skewness parameter while keeping the wave asymmetry at a minimum, does
not have a mitigating impact on the over predicted erosion. This can be explained by the fact that the skewness in waves increase as the deep water sinusoidal waves start shoaling. The skewed waves transform into asymmetric waves as they enter the surf zone. Therefore, increasing the wave skewness factor in our case does not mitigate the early erosion process in the surfzone and foreshore that leads to the new dune face like feature.

To mitigate the formation of the new steep dune face like feature, the net offshore bedload transport needed to be decreased. Increasing the wave asymmetry factor essentially increases the landward bedload transport caused by the landward leaning asymmetric waves (Watanabe and Sato, 2004). In effect, the net offshore sediment transport is decreased, mitigating the early over erosion in the surf zone and foreshore therefore delaying the avalanching process to start when the peak of the storm conditions are in effect and the associated storm surge and waves are interacting with the real dune face.

Profile 1 is used to demonstrate the effect of wave asymmetry and skewness factor on mitigating the premature scarping of the foreshore (Figure 5.9). In this sense, factors for wave asymmetry and wave skewness were selected as 0.3 based on the improvements on the erosion
5.3 Results and Discussion

The results of the model runs were compared based on the measured eroded areas and the simulated eroded areas per transect. The vertical extent of the eroded area calculation for the pre-storm, post-storm and simulated profiles were limited by the still water flood level (SWFL) associated with the storm (Figure 5.10, SWFL = 1.74 meters for Hurricane Isabel). The horizontal extent was limited by the intersection point of all pre, post and simulated profiles (Figure 5.10). All areas calculated under the profiles and within the vertical and horizontal limits mentioned above are listed in Table 5.1. The measured eroded areas were also plotted (Figure 5.11) against the simulated eroded areas for each model run (XBeach (sand), XBeach (veg.) and CSHORE) where the trends for each can be observed relative to the perfect prediction line.

Figure 5.9: Modelled Profile 1 after 10, 20, 30, 40 and 50 hours of storm action (facAs = facSk = 0.3)
From Figure 5.11, by looking at the resulting scatter point data, we see that both XBeach cases are on the over estimating side of the perfect prediction line whereas CSHORE result scatter is on the other side of the line, underestimating the erosion. Based on the linear fits for each case, XBeach (sand) and CSHORE trends are parallel, however XBeach predictions improve on profiles where larger amount of erosion was measured. On the other hand, CSHORE predictions gets worse on profiles where large amount of erosion was measured. Within the XBeach cases, introduction of the vegetation cover effect increases the prediction capacity of simulation results. The scatter and its trend line for the XBeach vegetation case is more concentrated and parallel to the perfect prediction line. The median error in prediction over all
profiles for XBeach (sand) was calculated as 7.87% over prediction, XBeach (veg.) 3% over prediction and CSHORE 21.1% under prediction.

Additionally, the vertical extent of the eroded area calculation for the pre-storm, post-storm and simulated profiles was shifted to the dune toe elevation for each profile to investigate the simulation performance where only the dune was in focus (See Table 5.2 and Figure 5.12). The results based on eroded areas calculated above the dune toe show that the simulated erosion data scatter and trends concentrate around the perfect prediction line. The median error in prediction over all profiles for XBeach (sand) was calculated as 6.5% over prediction, XBeach (veg.) 1.8% under prediction and CSHORE 12.6% under prediction.
Table 5.2: Measured and simulated erosion areas ($m^3/m$) above dune toe elevation for all profiles

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<th>XBeach (veg.)</th>
<th>CSHORE</th>
<th>Measured (XBeach (sand))</th>
<th>XBeach (veg.)</th>
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<th>Measured (XBeach (sand))</th>
<th>XBeach (veg.)</th>
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Figure 5.12: Results based on areas calculated above dune toe
5.4 Conclusions

Over the selected profiles, simulating the effects of Hurricane Isabel, XBeach simulation results exhibit overall over predicting behavior with improving simulation results where higher amounts of erosion were measured. CSHORE simulation results, on the contrary, exhibit overall under predicting behavior with better simulation results where lower amounts of erosion were measured. The plots presenting all pre, post and modeled profiles for XBeach (sand), XBeach (veg.) and CSHORE cases are presented in the Appendix B.1, B.2 and B.3 respectively.

Prediction capacity of both models seems to improve when the erosion was calculated only in the dune area. Although shifting the vertical extent of the area calculations from the SWFL to the dune toe elevation reduces the overall error, this reduction might be partly caused by the fact that the areas calculated in smaller windows (higher vertical extent) have smaller chance of introducing simulation errors. It should be kept in mind that this does not undermine the poor performance in simulating the erosion of the beach face and nearshore, as shown in the sensitivity analysis section. In XBeach, premature erosion of the beach face created sharp changes in elevations in the nearshore/dune face region which in return changes the wave energy dissipation patterns, effecting the simulation results of the post storm configuration.

As in the 2D applications of XBeach, it is shown that using the land cover effects also improved the prediction performance of XBeach 1D applications regardless of the extent of the eroded area calculations.
CHAPTER 6

Summary of conclusions

In summary, Chapter 1 demonstrates that geospatial techniques to derive short term dynamics of coastal morphology can be used to investigate temporal evolution of the barrier island systems and to provide inputs for the numerical model studies of coastal morphological change. At the study location near Hatteras it was found that the foredune system is highly dynamic, deviation reaching 1.83 m. The highest elevation change rates are negative and on the foredune system meaning erosion. This lost sand has been recovered at the back of the foredune system and this is indicated by the positive rates meaning accretion. Also, knowledge on geospatial tools and techniques acquired during this study enabled high detailed visualizations of the terrains in question, revealing critical topographic features (e.g. beach access on dunes, parking lot behind dunes) that may effect the processes that takes place around them. In terms of the modeling efforts, the spatial distribution of these critical topographic features is important as it dominates the decisions behind model grid resolution and placement. Incorporating the potential
topographic detail that influences the post storm configuration into model grid proved to be an important step in improving simulation results and therefore implemented in all modeling cases throughout this study.

Chapter 2 demonstrates how land cover features such as pavement/concrete and vegetation have been conceptualised and how it has been operationalised in the XBeach 2DH morphodynamic numerical model. Based on the sensitivity tests and the calibration of the associated parameters using the Pea Island breach case, pavement/concrete features were represented with large sediment grain sizes \( D_{50} = D_{90} = 0.256 \text{ m} \) and a low sediment calibration factor (sedcal = 0.01) whereas vegetation features were represented with the same sediment grain size as sand features \( D_{50} = 0.0002, D_{90} = 0.0004 \text{ m} \) with a sediment calibration factor equal to 0.2. In addition, the subsurface layer configuration is set up to have pavement/concrete surface layers to be followed by sand sub layers (mimicking e.g., a road sitting on sand) whereas the vegetation layers are followed by a subsequent vegetation sub layer before being followed by a sand sub layer (mimicking e.g., vegetation root density). The derived sediment characteristics and calibration factors along with the surface/sub layer configuration were applied to the Rodanthe breach location and realistic modeling capacity was achieved. Therefore, the calibrated values can serve as a starting point if calibration is needed for applications in other locations.

In Chapter 3, variations of hypothetical barrier island topographic conditions under different hypothetical storm scenarios in order to identify critical aspects of the topographic and hydrodynamics conditions that effect barrier island response to storms were tested. Results of the scenarios based on the soundside event Hurricane Irene suggest that certain topographic and hydrodynamic conditions under which high velocity flows occur between the ocean side and soundside water bodies results in increased sediment transport capacity therefore higher erosion. In situations where these flow velocities were reduced, whether as a result of the topographic or hydrodynamic conditions, the amount of erosion was reduced. For instance, prevention of
the flow across the island by repairing the dunes at the Pea Island breach location prevented breaching and damage to NC 12. Results of the scenarios based on the ocean side event Hurricane Isabel suggest that barrier island protection can be achieved by applying commonly used practices such as dune repair and beach nourishment. Nourishing/replenishing the beach moves the erosion concentration seaward and helps with dune survival. Under Hurricane Isabel conditions, the simulation results show that dunes built with 6.1 m crest height in combination with 60 m seaward beach replenishment below dune toe would have prevented the dune breaching. Without beach replenishment, a dune crest height of 7.6 m would be needed to prevent similar damage.

Finally, Chapter 4 shows that in 1D, XBeach simulation results exhibit overall over predicting behavior with improving simulation results where higher amounts of erosion were measured. CSHORE simulation results, on the contrary, exhibit overall under predicting behavior with better simulation results where lower amounts of erosion were measured. As in the 2D applications of XBeach, it is shown that using the land cover effects also improved the prediction performance of XBeach 1D applications regardless of the extent of the eroded area calculations.
REFERENCES


Markham, E. (1935). Beach erosion at Kitty Hawk, Nags Head and Oregon Inlet, NC. Technical Report 1-40, Office of the Chief of Engineers, Beach Erosion Board, United States Army.


Scenario testing additional material

A.1 Hurricane Isabel Hatteras breach simulation

The implementation of the land cover effects was essentially inspired during the simulation efforts of the Hatteras breach caused by Hurricane Isabel. Below are some of the important aspects of Hurricane Isabel, model grid generation and results of simulations.

A.1.1 Study site

The study site selected for this work is the breach location on Hatteras Island (Figure A.1). Hurricane Isabel made landfall on the North Carolina Outer Banks between Cape Lookout and Cape Hatteras (Figure A.1, upper right) on Thursday afternoon, September 18th, 2003, generating record wave heights reaching approximately 8 m and storm surge reaching 1.5 m at
the US Army Corps of Engineers (USACE), Field Research Facility (FRF), located at Duck, NC, 145 km northeast of landfall (Wamsley and Birkemeier, 2004).

Accordingly, the storm caused significant damage to the Outer Banks and to NC 12 highway connecting villages of the Outer Banks in the form of washovers, dune erosion and breaching on Hatteras Island (Overton and Fisher, 2004). Based on the topo/bathy surveys conducted at the breach location after the storm, the breach contains three channels (see Figure A.1, bottom right). Approximately, the west channel is 100 m wide, 2-3 m deep. The mid channel is 70 m wide and 1.5 m deep and the main channel is 100 m wide, 6 m deep (Wamsley and Birkemeier (2004); Freeman et al. (2004)). The barrier island at the breach location is partly vegetated and 160 - 200 m wide. The dune field at the area of interest has a range of 2.5 - 4.5 m in elevation. There are also two parking lots inside the area of interest. One on the ocean side of the NC 12, approximately 250 m west of the west channel where the dune field elevation is at its minimum. The other is on the sound side of NC 12 and partly coincides with the main channel location.

A.1.2 Initial model grid

The topography and bathymetry data used in this study is collected by various agencies. Pre and post Hurricane Isabel LiDAR point data was collected as part of the NASA / USGS Experimental Advanced Airborne Research LiDAR (EAARL, September 16th -21st, 2003) program. The locations where the pre and post Hurricane Isabel LiDAR data did not cover the whole extent of the barrier island were represented using the North Carolina Floodplain Mapping Program (NCFMP, February 2001) LiDAR point data set. The data was gathered from USGS Center for Lidar information Coordination and Knowledge 2009 and NOAA Coastal Services Center 2010 in NC State Plane horizontal coordinate system with North American Vertical Datum 1988 (NAVD88) in units of meters. The bathymetry data is gathered from the DEM developed as
part of the National Flood Insurance Program (NFIP) storm surge study (reference section2). The post storm LiDAR data did not include bathymetry information. The USACE bathymetry survey data taken after the storm is integrated into the available bathymetry data to represent the breach. All point data were transformed to the state plane horizontal coordinate system with the vertical datum NAVD88. Where necessary, the vertical datum transformation was carried out using the Vertical Datum Transformation tool (VDatum; Parker et al., 2003). Finally the point data sets are used to create seamless pre and post Hurricane Isabel digital surface models (DSMs) by integrating topography and bathymetry data together and interpolating to generate 0.5 meter resolution DSMs. The DSMs have been edited to incorporate all the land cover (e.g.
parking lots, beach access on dune) features of the location in order to ensure highest possible accuracy of the compared results.

The bathymetry data is gathered from the DEM developed as part of the National Flood Insurance Program (NFIP) storm surge study. The post storm LiDAR data did not include bathymetry information. The USACE bathymetry survey data taken after the storm is integrated into the available bathymetry data to represent the breach. All point data were transformed to the state plane horizontal coordinate system with the vertical datum NAVD88. Where necessary, the vertical datum transformation was carried out using the Vertical Datum Transformation tool (VDatum; Parker et al. (2003)). Finally the point data sets are used to create seamless pre and post Hurricane Isabel digital surface models (DSMs) by integrating topography and bathymetry data together and interpolating to generate 0.5 meter resolution DSMs. The DSMs have been edited to incorporate all the land cover (e.g. parking lots, beach access on dune) features of the location in order to ensure highest possible accuracy of the compared results.

The finalized DSMs (Figure A.2) are utilized as the source of elevation data for each model node making the model grid. The grid covers approximately 1.4 km in alongshore direction, centering the breach location and 2.4 km in the cross shore direction. Domain grid size varies between 2 m and 15 m in the alongshore direction and 2 m and 48 m in the cross shore direction. The ocean and sound side model grid nodes are set up to match the locations where the boundary condition data is gathered, discussed in more detail in the Hydrodynamic boundary conditions section.

A.1.3 Land cover features at Hatteras breach location

To classify the pre Hurricane Isabel land cover features for the study area, unsupervised classification coupled with the maximum likelihood classifier was used to classify the Dare
County, NC 2002 Digital ortho photo (NC OneMap http://data.nconemap.com/geoportal/) into sand and vegetation classes. Land cover features such as roads, parking lots and houses are hand digitized as a separate class (Figure A.3).

The sub aquatic vegetation (SAV) classification is based on the SAV feature map developed as part of the North Carolina Department of Environment and Natural Resources (NCDENR) Submerged Aquatic Vegetation Mapping Project. The density of the SAV was classified as dense, patchy or absent. The patchy and dense vegetation features are merged to represent the sound side SAV. The absent SAV density is assumed to represent sandy bed of the sound side. SAV classification raster is merged with the land cover raster and finalized by assuming the ocean side bed has the same sand characteristics. The final classification raster is then used as the source of classification data while creating the class distribution model input files (gdist). For each class, distribution files are created to represent the land cover feature in the model run in three 0.4 m thick layers. The assignment of sand and vegetation at the top layer is unchanged in the layers below whereas the assignment of developed areas switches to sand after the erosion of the top layer.
A.1.4 Hydrodynamic boundary conditions

Hydrodynamic data used in the XBeach model as boundary conditions include the wave height, wave period, wave direction and water level; extracted from a large scale coupled SWAN + ADCIRC model run forced with Hurricane Isabel winds. The coupled model system runs sequentially in time, sharing the same unstructured grid (Dietrich et al., 2011).

For the study location, no wave direction or water level data is available at the National Data Buoy Center (NDBC) Station 41025, the closest NDBC Station to the study location. Therefore,
the wave directions and the water levels extracted from the coupled SWAN + ADCIRC model are compared with the corresponding data extracted from the NDBC Station 44056 at Duck, NC (Figure A.4, top panel). The dashed lines in Figure A.4 correspond to values extracted at the offshore boundary of the XBeach model domain. The duration of the XBeach simulation is chosen to be 36 hours, Sept 18th, 2003 00:00AM UTC - Sept 19th, 2003 12:00PM UTC, including the peak of the storm surge at the center of the input hydrodynamic data time series. The simulated maximum water level at the offshore model boundary of the study location is approximately 1.7 meters (NAVD88), on September 18th, 2003 17:00 UTC. The water level includes the astronomical tides and the storm surge, the wave setup effect on the water level is removed. The dominant wave direction at the offshore model boundary varies between 146-162
Although there was no wave direction or water level data available at the NDBC Station 41025, the wave height and wave period data were collected until the buoy stopped measuring. The available data is used to compare the simulated wave height and period data to the observational data (Figure A.5). The simulated wave heights at the offshore model boundary of the study location during the simulation duration vary between 2.6 - 3.6 meters. The simulated wave periods for the same location and duration vary between 10 - 17 seconds.

It is considered that the comparison of the simulated and observational data is consistent
and the results of the SWAN + ADCIRC model can be used to represent the Hurricane Isabel hydrodynamic conditions at the study location. For the sound side boundary of the model, the simulation indicates that the part of the model domain that lies on the sound side was dry due to winds pushing the water away from the sound side shoreline. To simulate this effect, the water level signal for the sound side model boundary is lowered to a level as if the water was pushed away until after the peak of the storm surge has passed. Then, the water level has been incrementally raised back to Mean Sea Level (MSL) by the end of the simulation.

**A.1.5 Results**

The results of the Hatteras breach simulation were compared to the breach survey elevations collected post storm. Figure A.6 illustrates the post storm imagery overlaid with the surface generated using the breach survey elevations. The transects (transect 1 and transect 2) over which the elevations were extracted and plotted at the bottom panel is indicated with the white dashed lines. The ocean side is at the bottom side and the soundside is on the top side of the illustration.

Figure A.7 illustrates model simulation results of the Hatteras breach. On the top panel, the resulting post storm configuration is presented. The same transects where the survey elevations were extracted are overlaid on the post storm surface. Simulation results were extracted at these transects are plotted in the bottom panel of Figure A.7.

In terms of distinct channel depths, it can be seen from the results that a high prediction capacity was reached by the implementation of the land cover effects. Comparing the surveyed elevations surface (Figure A.6, top panel) to the modeled post storm survey (Figure A.7, top panel), it can be seen that the channel orientations were skewed (towards the left side of the figure) in the real case. This orientation was not captured during the simulation of the breach
channels. This problem is attributed to the lack of ocean side and soundside alongshore currents that may have influenced the flow patterns in the ocean-barrier island-sound direction.

Figure A.6: Survey results at Hatteras breach location
Figure A.7: Simulation results of the Hatteras breach
A.2 Additional scenarios for Hurricane Irene

In addition to the presented scenarios in Chapter 4, Section 4.2, two additional hypothetical conditions have been modeled: 1) increased vegetation and 2) increased sea level. The results of the additional scenarios are presented here alongside a dune repair case and the Hurricane Irene simulation presented in Chapter 3. The ocean front dune was repaired by building the ridge to a common elevation and filling in the alongshore gaps in the pre-storm topography. The land cover was enhanced by uniformly filling in the sparse areas of vegetation and extending vegetation to the dune crest (Figure A.8, bottom left panel). Sea-level rise was simulated by raising the background water level by 0.5 m. Figure A.8, right panel illustrates the spatial distribution of the modeled maximum velocity (top) and the resulting topography (bottom).

Figure A.8: Panel 1: Pre-storm land cover, top & extended vegetation, bottom. Panel 2: Maximum velocity map, top & post-storm morphology maps, bottom.
The cases are ordered left to right with increasing hydraulics highs. Case c is the calibrated simulation for Irene. Repairing the dune, case a, eliminated the topographic lows and prevented flow through the dune field and subsequent channelization. Increasing vegetation also reduced the high velocity/erosion feedback loop that otherwise would occur, case b. Increasing sea level allows additional topographic lows to fill and channelize, case d.
A.3 Dune repair and nourishment scenarios: Summary of initial conditions

Figure A.9: Sections of the study location showing different dune construction alternatives
Figure A.10: Sections of the study location showing different dune construction alternatives with beach nourishment
A.4 Additional beach nourishment scenario

In addition to the beach nourishment scenarios presented in Chapter 4, Section 4.3, a more realistic beach nourishment application scenario was tested. In Figure A.11, bottom panel, the dimension of the nourishment placed is shown (pre nourishment 2, solid black line). Here, same dune (dune crest @ 4.5 m) and berm placement (approximately 60 m wide) is used as in the scenario with dune crest @ 4.5 m and nourishment presented in Chapter 4, Section 4.3 (referred to as Pre Nourishment 1 in Figure A.11, bottom panel, dashed black line). The difference between these two scenarios is that the berm for this additional beach nourishment scenario was connected to the bed using the equilibrium profile concept by Dean (1991). The resulting erosion/deposition map (middle panel) indicate that the eroded material from the berm and dunes were moved offshore to an extent to reach the pre existing sandbar formation. The results of both nourishment scenarios are plotted in the bottom panel of Figure A.11. The elevations of the profile plots were extracted along the transect overlaid in the top panel (thick red solid line).

The results of this additional scenario indicate that this application is more robust in terms of preventing dune breaching and protection of the coastal hinterland. To create the pre nourishment 1 case, 68030 \( m^3 \) sand was added to the pre Irene topography, mostly placed above zero NAVD88. For the pre Nourishment 2 scenario, a total of 456131 \( m^3 \) was added to the system (above and below zero NAVD88) over an alongshore length of approximately 680 m.
Figure A.11: Comparison of beach nourishment scenarios
APPENDIX B

1D XBeach Applications - All Profiles
B.1 Model: XBeach; No Land Cover

Figure B.1: Profiles 1-5, XBeach (blue), Pre Isabel (dotted), Post Isabel (red)
Figure B.2: Profiles 6-10, XBeach (blue), Pre Isabel (dotted), Post Isabel (red)
Figure B.3: Profiles 11-15, XBeach (blue), Pre Isabel (dotted), Post Isabel (red)
Figure B.4: Profiles 16-20, XBeach (blue), Pre Isabel (dotted), Post Isabel (red)
Figure B.5: Profiles 21-25, XBeach (blue), Pre Isabel (dotted), Post Isabel (red)
Figure B.6: Profiles 26-30, XBeach (blue), Pre Isabel (dotted), Post Isabel (red)
Figure B.7: Profiles 33-33, XBeach (blue), Pre Isabel (dotted), Post Isabel (red)
B.2 Model: XBeach; Land Cover

Figure B.8: Profiles 1-5, XBeach (blue), Pre Isabel (dotted), Post Isabel (red)
Figure B.9: Profiles 6-10, XBeach (blue), Pre Isabel (dotted), Post Isabel (red)
Figure B.10: Profiles 11-15, XBeach (blue), Pre Isabel (dotted), Post Isabel (red)
Figure B.11: Profiles 16-20, XBeach (blue), Pre Isabel (dotted), Post Isabel (red)
Figure B.12: Profiles 21-25, XBeach (blue), Pre Isabel (dotted), Post Isabel (red)
Figure B.13: Profiles 26-30, XBeach (blue), Pre Isabel (dotted), Post Isabel (red)
Figure B.14: Profiles 33-33, XBeach (blue), Pre Isabel (dotted), Post Isabel (red)
B.3 Model: CShore; No Land Cover

Figure B.15: Profiles 1-5, XBeach (blue), Pre Isabel (dotted), Post Isabel (red)
Figure B.16: Profiles 6-10, XBeach (blue), Pre Isabel (dotted), Post Isabel (red)
Figure B.17: Profiles 11-15, XBeach (blue), Pre Isabel (dotted), Post Isabel (red)
Figure B.18: Profiles 16-20, XBeach (blue), Pre Isabel (dotted), Post Isabel (red)
Figure B.19: Profiles 21-25, XBeach (blue), Pre Isabel (dotted), Post Isabel (red)
Figure B.20: Profiles 26-30, XBeach (blue), Pre Isabel (dotted), Post Isabel (red)
Figure B.21: Profiles 33-33, XBeach (blue), Pre Isabel (dotted), Post Isabel (red)
B.4 Wave Skewness and Asymmetry Sensitivity

Figure B.22: Effect of wave asymmetry (facAs) factor (0.1-0.5) on computed bed Profile 1 (facSk = 0.1 - constant)

Figure B.23: Effect of wave asymmetry (facAs) factor (0.6-0.9) on computed bed Profile 1 (facSk = 0.1 - constant)
Figure B.24: Effect of wave skewness (facSk) factor (0.1-0.5) on computed bed Profile 1 (facAs = 0.1 - constant)

Figure B.25: Effect of wave skewness (facSk) factor (0.6-0.9) on computed bed Profile 1 (facAs = 0.1 - constant)
APPENDIX C

Model parameters
C.1 Model parameters used in Land cover and scenario testing runs

Reading input parameters:
--------------------------------
Physical processes:
XBeach reading fromparams.txt
swave = 1
lwave = 1
flow = 1
sedtrans = 1
morphology = 1
avalanching = 1
nonh = 0
gwflow = 0
q3d = 0
swrunup = 0
ships = 0
bchwiz = 0
--------------------------------
Grid parameters:
gridform = xbeach
xori = 0.0000
yori = 0.0000
alfa = 0.0000
nx = 626
ny = 342
posdwn = 0.0000
depfile = *filename vary between runs*
vardx = 1
dx = -1.0000
dy = -1.0000
xfile = *filename vary between runs*
yfile = *filename vary between runs*
theta = 217.5000 Warning: value > recommended value of 180.0000
theta = 15.0000
thetanaut = 1
--------------------------------
Model time parameters:
CFL = 0.6000
tstop = 140400.0000 (for Isabel scenarios)
tstop = 217800.0000 (for Irene scenarios)
--------------------------------
Physical constants:
rho = 1025.0000
g = 9.8100
depthscale = 1.0000
--------------------------------
Initial conditions:
zsinitfile = zsinitfile.txt
hotstartflo = 0
--------------------------------
Wave boundary condition parameters:
instat = jons
bcfile = wave_lst.txt
taper = 100.0000
nmax = 0.8000
leftwave = wavecrest
rightwave = wavecrest
--------------------------------
Wave-spectrum boundary condition parameters:
nonhspectru = 0
random = 1
fcutoff = 0.0000
nspr = 0
trepsac = 0.0100
spredthr = 0.0800
oldwbc = 0
correctHm0 = 1
--------------------------------
oldnyq = 0
Tm01switch = 0
wbcversion = 2

--------------------------------
Flow boundary condition parameters:
  front = abs_2d
  left = neumann
  right = neumann
  back = abs_2d
  ARC = 1
  order = 2.0000
  carspan = 0
  freewave = 0
  epsi = 0.0000
  nc = 383
  tidetype = velocity

--------------------------------
Tide boundary conditions:
  tideloc = 2
  paulrevere = land
  zs0file = tide.txt

--------------------------------
Discharge boundary conditions:
  disch_loc_f = None specified
  disch_times = None specified
  ndischarge = 0
  ntdischarge = 0

--------------------------------
Wave breaking parameters:
  break = roelvink_daly
  gamma = 0.5500
  gamma2 = 0.3000
  alpha = 1.0000
  n = 10.0000
  gammmax = 2.0000
  delta = 0.0000
  fw = 0.0000
  fwcutoff = 1000.0000
  breakerdela = 1
  shoaldelay = 0
  facsd = 1.0000
  facrun = 1.0000

--------------------------------
Roller parameters:
  roller = 1
  beta = 0.1000
  rfb = 0

--------------------------------
Wave-current interaction parameters:
  wci = 0
  hwci = 0.1000
  cats = 4.0000

--------------------------------
Flow parameters:
  bedfriction = chezy
  bedfricfile = None specified
  C = 55.0000
  huh = 0.1000
  nuhfac = 1.0000
  huhv = 1.0000
  smag = 1

--------------------------------
Coriolis force parameters:
  wearth = 0.0417
  lat = 0.0000

--------------------------------
Wind parameters:
  rhoa = 1.2500
  Cd = 0.0020
  windfile = None specified
  windv = 0.0000
  windth = 270.0000

--------------------------------
Bed composition parameters:
  ngd = 3
  nd = 3
  por = 0.4000
  D50 = 0.0002
  D50 = 0.0002
  D50 = 0.2560 Warning: value > recommended value of 0.0008
  D50 = 0.0002
  D90 = 0.0004
  D90 = 0.0004
  D90 = 0.2560 Warning: value > recommended value of 0.0015
  rhos = 2650.0000
Sediment transport parameters:
form = vanthiel_vanrijn
waveform = vanthiel
sws = 1
lws = 1
B Rafac = 1.0000
facsl = 1.6000
z0 = 0.0060
smax = -1.0000
tsfac = 0.1000
facua = 0.1000
facSk = 0.1500
facAs = 0.1500
turb = bore_averaged
Tb fac = 1.0000
Tsmin = 0.5000
lwt = 0
betad = 1.0000
sus = 1
bed = 1
bulk = 0
facDc = 1.0000

Morphology parameters:
morfac = 10.0000
morfacopt = 1
morstart = 120.0000
morstop = 140400.0000
wetslp = 0.8000
dryslp = 1.8000
hswitch = 0.0500
dzmax = 0.0500

Output variables:
timings = 1
tunits = None specified
projection = None specified
rotate = 1
tstart = 0.0000
tint = 1.0000
tsglobal = None specified
tintg = 300.0000
nglobalvar = 4
nglobalvar: Will generate global output for variable: zs
nglobalvar: Will generate global output for variable: zb
nglobalvar: Will generate global output for variable: u
nglobalvar: Will generate global output for variable: v
npoints = 0
npointvar = 0
rugdepth = 0.0000
mmeanvar = 0
ncross = 0
outputforma = fortran
ncfilename = None specified
netcdf output to: xboutput.nc

Drifters parameters:
drifterfile = None specified
ndrifter = 0

Shipwaves parameters:
shipfile = None specified
Wave numerics parameters:
    scheme = upwind_2
-----------------------------
Flow numerics parameters:
    eps = 0.0010
    umin = 0.0000
    hmin = 0.0500
    secorder = 1
    oldhu = 0
-----------------------------
Sediment transport numerics parameters:
    thetanum = 1.0000
    sourcesink = 0
-----------------------------
cmax = 0.1000
-----------------------------
Bed update numerics parameters:
    frac_dz = 0.7000
Warning: variable nd_var1 < recommended value of 2
    split = 1.0100
    merge = 0.0100
-----------------------------
MPI parameters:
    mpiboundary = auto
-----------------------------
Finished reading input parameters
C.2 Model parameters used in 1D application runs

--- Reading input parameters: ---

### Physical processes:
- **XBeach reading from params.txt**
  - `swave = 1`
  - `lwave = 1`
  - `flow = 1`
  - `sedtrans = 1`
  - `morphology = 1`
  - `avalanching = 1`
- `nonh = 0`
- `gwflow = 0`
- `q3d = 0`
- `swrunup = 0`
- `ships = 0`
- `bchwiz = 0`

### Grid parameters:
- `gridform = xbeach`
- `xori = 0.0000`
- `yori = 0.0000`
- `alfa = 0.0000`
- `nx = 800`
- `ny = 0`
- `posdwn = 0.0000`
- `depfile = *filename vary between runs*`
- `vardx = 1`
- `dx = -1.0000`
- `dy = -1.0000`
- `xfile = *filename vary between runs*`
- `yfile = None specified`

### Model time parameters:
- `CFL = 0.6000`
- `tstop = 257400.0000`

---

### Physical constants:
- `rho = 1025.0000`
- `g = 9.8100`
- `depthscale = 1.0000`

---

### Initial conditions:
- `zsinitfile = None specified`
- `hotstartflo = 0`

---

### Wave boundary condition parameters:
- `instat = jons`
- `bcfile = wave_lst_isabel.txt`
- `taper = 100.0000`
- `nmax = 0.8000`
- `leftwave = neumann`
- `rightwave = neumann`

---

### Wave-spectrum boundary condition parameters:
- `nonhspectru = 0`
- `random = 0`
- `fcutoff = 0.0000`
- `nspr = 0`
- `trepfac = 0.0100`
- `sprdthr = 0.0800`
- `oldwbc = 0`
- `correctHm0 = 1`
- `oldnyq = 0`
- `Tm01switch = 0`
- `wbversion = 2`

---

### Flow boundary condition parameters:
- `front = abs_2d`
- `left = wall`
- `right = wall`
- `back = abs_2d`
- `ARC = 1`
order = 2.0000

carspan = 0

freewave = 0
epsi = 0.0005
nc = 1
tidetype = velocity

---------------------------------------------

Tide boundary conditions:
tideloc = 2
paulrevere = land
zs0file = bc_tide_isabel.txt

---------------------------------------------

Discharge boundary conditions:
disch_loc_f = None specified
disch_times = None specified
ndischarge = 0
ntdischarge = 0

---------------------------------------------

Wave breaking parameters:
break = roelvink_daly
gamma = 0.7800
gamma2 = 0.5000
alpha = 1.0000
n = 10.0000
gamma = 5.0000
delta = 0.0000
fw = 0.0000
fw_cutoff = 1000.0000
breakerdela = 1
shoaldelay = 0
facsd = 1.0000
facrun = 1.0000

---------------------------------------------

Roller parameters:
roller = 1
beta = 0.1000
rfb = 1

---------------------------------------------

Wave-current interaction parameters:
wci = 0
hwci = 0.1000
cats = 4.0000

---------------------------------------------

Flow parameters:

bedfriction = chezy
bedfricfile =

nuh = 0.1000
nuhfac = 1.0000
nuhv = 1.0000
smag = 1

---------------------------------------------

Coriolis force parameters:

wearth = 0.0417
lat = 0.0000

---------------------------------------------

Wind parameters:

rhoa = 1.2500
Cd = 0.0020
windfile = None specified
windv = 0.0000
windth = 270.0000

---------------------------------------------

Bed composition parameters:

ngd = 1 (2 for veg.)
nd = 16
por = 0.4000
D50 = 0.0003
D50 = 0.0003*
D90 = 0.0005
D90 = 0.0005*
rhos = 2650.0000
dzg = 0.0500
dzg1 = 0.0500
dzg2 = 0.0500
dzg3 = 0.0500
sedcal = 1.0000
sedcal = 0.0300*
ucrcal = 1.0000
ucrcal = 1.0000*
* only used in veg. cases

---------------------------------------------

Sediment transport parameters:

form = vanthiel_vanrijn
waveform = vanthiel
sws = 1
lws = 1
BRfac =1.0000
facsl =1.6000
z0 =0.0060
smax =-1.0000
tsfac =0.1000
facua =0.1000
facSk =0.3000
facAs =0.3000
turb =bore_averaged
Tbfac =1.0000
Tsmin =0.5000
lwt =0
betad =1.0000
sus =1
bed =1
bulk =0
facDc =1.0000
tintm =257400.0000
nglobalvar =3
nglobalvar: Will generate global output for variable:zb
nglobalvar: Will generate global output for variable:zs
nglobalvar: Will generate global output for variable:hh
npoints =0
mrugauge =0
npointvar =0
rugdepth =0.0000
mmeanvar =0
ncross =0
outputforma =fortran
ncfilename = None specified
netcdf output to:xboutput.nc
-----------------------------------------------
Morphology parameters:
morfac =5.0000
morfacopt =1
morstart =120.0000
morstop =257400.0000
wetslp =0.3000
dryslp =1.0000
hswitch =0.1000
dzmax =0.0500
struct =0
-----------------------------------------------
Output variables:
timings =1
tunits = None specified
projection = None specified
rotate =1
tstart =0.0000
tint =1.0000
tsglobal = None specified
tintg =300.0000
tspoints = None specified
tintp =1.0000
tscross = None specified
tintc =1.0000
tsmean = None specified
nglobalvar: Will generate global output for variable:zb
nglobalvar: Will generate global output for variable:zs
nglobalvar: Will generate global output for variable:hh
npoints =0
ncross =0
ncfilename = None specified
netcdf output to:xboutput.nc
-----------------------------------------------
Drifters parameters:
drifterfile = None specified
ndrifter =0
-----------------------------------------------
Shipwaves parameters:
shipfile = None specified
-----------------------------------------------
Wave numerics parameters:
scheme =upwind_2
-----------------------------------------------
Flow numerics parameters:
eps =0.0010
umin =0.0000
hmin =0.2000
secorder =1
oldhu =0
-----------------------------------------------
Sediment transport numerics parameters:
theta =1.0000
sourcesink =0
cmax =0.1000
-----------------------------------------------
Bed update numerics parameters:
frac_dz =0.7000
Warning: variable nd_var1 < recommended
-----------------------------------------------
value of 2
    split = 1.0100
    merge = 0.0100

--------------------------------
MPI parameters:

mpiboundary = auto

--------------------------------
Finished reading input parameters