Evaluation of the feeder nourishment concept for the Atlantic southeast coast of the United States.

A case study for Hilton Head Island, South Carolina.

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in partial fulfilment of the requirements for the degree of

Master of Science
in Hydraulic Engineering

at the Delft University of Technology,
to be defended publicly on Monday August 31, 2020 at 16:00.

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Preface

With this master thesis I conclude my Master of Science program in Hydraulic Engineering at the Civil Engineering and Geosciences faculty at the Technical University of Delft (TU Delft). I was forced to combine my role as a student, with that off a full-time employee at an engineering firm. A hard task, which resulted in many late nights and delays. However, in order to achieve something that you desire, you need to be prepared to make sacrifices. And the satisfaction is that much larger when you know that you have given it your all. This thesis marks the end of my career as my student. A career which has known its ups and downs. But most importantly a career which I look back to with great pride. My time at the TU Delft has shown me that nothing is impossible, as long as you put in the work.

Nothing is achieved on your own. Therefore, I need to thank some people that have helped me during this process. First, I would like to thank Julia Hopkins in particular, for her role as my day-to-day supervisor. Your guidance during our weekly meetings was invaluable, and your enthusiasm contagious. I would not have made it without you, thank you. I would also like to thank Mathieu de Schipper, Brian McFall, and Stefan Aarninkhof for their patience, guidance, and valuable advice during the progress meetings we had. And I would like to thank Joep Storms for his willingness to join my graduation committee on such short notice.

Finally, I would like to thank my parents. I am the first one in our family to follow an education, and this was only possible through your support, both financially and emotionally. Thank you for always believing in me, I will be forever in your debt, and I hope that I have made you proud.

C.J.M. (Roy) Crielaard
Volendam, July 2020.

Summary

About 80-90% of U.S. East Coast barrier beaches have experienced erosion in the last 100 years. South Carolina's coastline forms no exception, a third of its developed shoreline experiences erosion. Among these eroding shorelines is Hilton Head Island, the second largest barrier island on the U.S. East Coast. Until now, erosion here has been addressed through traditional local beach nourishments.

An alternative approach to the traditional nourishment method, are so-called feeder nourishments or feeder beaches. The potential advantages of the feeder nourishment concept over the traditional method are reduction of the nourishment frequency, containment of the ecological stress in a relatively small area, and a short to medium term increase of local available space for recreation and the environment. Given the potential advantages above, the residents of Hilton Head Island asked TU Delft to investigate the possibility of applying a feeder nourishment at their shoreline.

Currently, a pilot project known as "The Sand Engine" is examined along the Dutch coast. Several studies into its morphological behaviour show that this feeder nourishment can be beneficial to the sediment budget of a larger coastal cell. Because of the promising results at the Sand Engine pilot project, it is tempting to state that a feeder-nourishment could also be applied at Hilton Head Island. The problem, however, is that the conditions at Hilton Head Island and the Sand Engine are different.

There are two main differences between Hilton Head Island and the Sand Engine. First, Hilton Head is subjected to a relative calm wave climate in comparison to the Sand Engine. Second, the presence of two tidal inlets at Hilton Head, compared to a relative straight and uninterrupted coastline at the Sand Engine. As a result, the conclusions drawn from the Sand Engine pilot project do not necessarily hold for Hilton Head Island as well.

The main objective of this thesis is to analyse the morphological behaviour of a feeder nourishment located at Hilton Head Island. First, to study its potential as a measure against erosion at Hilton Head. Second, to compare its morphological behaviour to that of the Sand Engine. And third, to be able to examine the potential of the concept for the Atlantic southeast coast of the U.S. in general.

The morphological development of a feeder nourishment at Hilton Head Island was simulated with Delft3D over the course of 1 year for different model scenarios, with varying forcing conditions and varying bathymetric features. The effect of the relative calm wave climate at Hilton Head Island in comparison to the Sand Engine is twofold. First, the contribution of wave forcing to the total erosional volume of the feeder nourishment after 1 year is smaller as compared to the Sand Engine. Eliminating all driving forces besides wave forcing reduces the total erosional volume to 58% at Hilton Head, in comparison to 75% at the Sand Engine. Second, the contribution of storm events to the total erosional volume after 1 year from the feeder nourishment is smaller at Hilton Head compared to the Sand Engine. It measures 23% at Hilton Head, in comparison to 60% at the Sand Engine. To assess the impact of the two tidal inlets on the feeder nourishment, they were closed off. Closing of the tidal inlets eliminates any (potential) residual currents. This reduces the total amount of sediment that is eroded from the feeder nourishment by 7% compared to a reference scenario with open tidal inlets.

Before construction of the feeder nourishment the coastline south of the nourishment experienced a net sediment outflux of approximately 4000 m^3/year. After construction of the feeder nourishment, the southern section experiences a net import of sediment of approximately 100.000 m^3/year. Meaning that the southern section, on average, has transitioned from being erosive to accreting. Up

to 500 meter away from the nourishment the cross-shore profile shows a seaward movement of the shoreline position of approximately 25 m compared to the original situation without nourishment.

Before construction of the feeder nourishment the coastline north of the nourishment experienced a net sediment outflux of approximately 40.000 m^3/year. After construction of the feeder nourishment, this net outflux of sediment has decreased to approximately 25.000 m^3/year. This shows that the feeder nourishment is feeding sediment to the northern section, but at a rate that is not sufficient to keep up with the underlying erosion rate. The northern domain, on average, still experiences a sediment outflux and stays erosive. Roughly 50 m of coastline directly north of the feeder nourishment experiences a seaward movement of the shoreline position. However, moving further away from the nourishment, the shoreline remains erosive.

The Atlantic southeast coast of the United States is made up of North Carolina, South Carolina, Georgia and Florida’s east coast. The South Carolina and Georgia coastline are comparable in both hydrodynamic conditions and geomorphological setting. They are mixed-energy coasts, broken up by numerous tidal inlets, and home to short barrier islands with complex sediment transport patterns. North Carolina’s and Florida’s east coast are wave-dominated, with relative straight shorelines. Which is distinctly differences from the conditions found at Hilton Head Island. Therefore, the potential of the feeder nourishment concept is only analysed for South Carolina’s and Georgia’s coastline. The presence of numerous tidal inlets leads to strongly varying conditions along the coastlines of both states. The developed locations along South Carolina’s coastline that require erosion mitigating measures are south Debidue beach, North Island, Hunting Island and Daufuskie Island. Along Georgia’s coastline there are only some erosion hotspots along Sea Island’s coastline that require erosion mitigation measures. The wave climate at all the above mentioned location is similar to Hilton Head. A southeast swell, with a narrow range of directions and an annual wave height of roughly 1,0 m. The same goes for the tidal range. The results at Hilton Head show that erosion on adjacent coastal sections can be lessened and/or prevented by constructing a feeder nourishment. Given that these locations are subjected to similar conditions, the construction of a feeder nourishment could potentially be an effective measure to prevent or lessen the occurring erosion.

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1 Introduction

1.1. Background

About 80-90% of U.S. East Coast barrier beaches have experienced erosion in the last 100 years [Galgano et al., 1998]. South Carolina's coastline forms no exception, a third of its developed shoreline experiences erosion [Kana, 1988]. Among these eroding shorelines is Hilton Head Island, the second largest barrier island on the U.S. East Coast. The pristine beaches of Hilton Head make it a popular vacation destination, resulting in the presence of numerous luxury resorts, vacation homes, golf courses, etc. The development often reaches right up to the edge of the beach front, which is why the erosion poses a problem, it threatens the existence of the properties [Hilton Head Island Beaches, 2019].

The erosion is mainly focussed around the central part of the island's coastline, here shoreline retreat rates of up to 6,0 m per year occur [Olsen Associates, 2014]. Until now, the erosion has been addressed through traditional local beach nourishments. A common practice, where sediment is added to the sub aerial beach and/or dune system to directly address the occurring erosion and prevent further coastline degradation. Between 1969 and 2010, five different nourishment events have occurred to prevent sand loss from the centre of the island. In total, approximately 8,0 million m^3 of sediment has been added to the beaches during these five events. The nourishment frequency equals roughly every 7 to 10 years [Kana et al., 2013].

While effective, the traditional beach nourishment approach is relatively expensive, and no long-term solution against erosion [Dane, 2020]. An alternative approach to the traditional nourishment method, are so-called feeder nourishments or feeder beaches. This solution comprises the concentrated placement of (relatively) large volumes of sediment at a specific location, with the aim to gradually feed the surrounding coast. Wind, waves, and currents will spread the sediments along the coast [Publicwiki Deltares, 2020].

According to Stive et al. (2013), the potential advantages of the feeder nourishment concept over the traditional method are:

i. Reduction of the nourishment frequency
ii. The nourishment will slowly diffuse and advance the shoreline in a more natural fashion.
iii. The large initial perturbation will result in a short to medium term increase of local available space for recreation and the environment.
iv. The ecological stress, while considerable at the project location, is contained in a relatively small area.

Given the potential advantages above, the residents of Hilton Head Island asked TU Delft if they could investigate the possibility of applying a feeder nourishment at their shoreline.

The use of feeder nourishments is not new, they have been successfully applied to prevent erosion in both the United States and the Netherlands for decades [Coastal Engineering Manual, 2012; Publicwiki Deltares, 2020]. Currently, a pilot project known as "The Sand Engine" is examined along the Dutch coast. The Sand Engine is a massive 21,5 million m^3 feeder nourishment, which aims to widen beaches along a 10 to 20 km stretch over a period of 20 years [Brown et al., 2016]. Due to is large size, compared to other feeder beaches, it is often referred to as a mega (feeder) nourishment. Since its construction, the Sand Engine is intensively monitored to track the morphological development. De Schipper et al. (2016) conducted research into the spreading of the Sand Engine in the first 18 months after its construction. The study shows that the majority (72%) of the volumetric losses in sediment on the mega-nourishment was compensated by accretion on adjacent coastal sections and dunes. Another research, conducted over a period of 5 years by De Vries et al. (2018), confirms this feeding ability of the Sand-Engine. It states that mega feeder nourishment supplies sediment to a stretch of coast that is several times the initial length of the nourishment. The plan-form shape of the peninsula is reworked and found to gradually widen over time. The study concludes with the statement, that a mega-feeder nourishment can be beneficial to the sediment budget of a larger coastal cell.

1.2. Problem formulation

Because of the promising results at the Sand Engine pilot project, it is tempting to state that a feeder-nourishment could also be applied at Hilton Head Island. The problem, however, is that the conditions at Hilton Head Island and the Sand-Engine are different. First, the Sand-Engine is located on a straight, uninterrupted coastal stretch. Hilton Head Island on the other hand, is a barrier island, bordered by two tidal inlets. Furthermore, other conditions, such as wave climate, tidal climate, bathymetry, and sediment properties are of course also location specific. As a result, the conclusions drawn from the Sand Engine pilot project do not necessarily hold for Hilton Head Island.

1.3. Research goals

The main objective of this thesis is to analyse the morphological behaviour of a feeder nourishment located at Hilton Head Island. First, this enables us to assess the potential of the feeder nourishment concept as a measure against erosion at Hilton Head. Second, it allows for a comparison between the morphological behaviour of a feeder nourishment located at Hilton Head and The Sand Engine. Two locations with different conditions. Third, the results at Hilton Head Island can be used to examine the potential of the feeder nourishment concept for the Atlantic southeast coast of the U.S.

1.4. Research questions

To achieve the research goals, the following research questions need to be answered:

i. How do the hydrodynamic conditions and geomorphological setting at Hilton Head Island differ from those found at the Sand Engine pilot project?
ii. How do the differences in hydrodynamic conditions and geomorphological setting between Hilton Head and the Sand Engine affect the morphological development of a feeder nourishment?
iii. Can a feeder nourishment at Hilton Head Island supply sediment to adjacent coastal sections at a rate that is sufficient to prevent erosion?
iv. What do the results at Hilton Head Island mean for the Atlantic southeast coast of the United States?

1.5. Research approach

The hydrodynamic conditions and geomorphological setting at Hilton Head Island and the Sand-Engine are determined by means of a literature study. This involves a study of the wave climate, tidal climate, sediment properties, bathymetry, and sediment transport characteristics. A comparison between these characteristics for Hilton Head and the Sand Engine provides us with the answer to the first research question: how do the hydrodynamic conditions and geomorphological setting at Hilton Head Island differ from those found at the Sand Engine pilot project?

The second research question states: how do the differences in hydrodynamic conditions and geomorphological setting between Hilton Head and the Sand Engine affect the morphological development of a feeder nourishment? To answer this question, the morphological development of a feeder nourishment at Hilton Head Island is simulated. The applied model is Delft3D, a process-based numerical model. The model can carry out simulations of flows, sediment transports, waves, and morphological changes. In Delft3D, a depth-averaged two-dimensional model is set up, that recreates the conditions at Hilton Head Island. The goal of the model is to reproduce the sediment transport pattern and morphological behaviour at Hilton Head's coastline. To determine how the differences between the two locations affect the behaviour of a feeder nourishment, its morphological development is simulated over the course of 1 year for different model scenarios, with varying forcing conditions and bathymetric features. These results are compared to the morphological behaviour of the Sand Engine, to answer the second research question.

The third research question asks: can a feeder nourishment at Hilton Head Island supply sediment to adjacent coastal sections at a rate that is sufficient to prevent erosion? To be able to answer this question, first a 1-year reference scenario is run in Delft3D, which simulates the situation before construction of the nourishment. Then a second 1-year scenario is run, which simulates the situation after construction of a feeder nourishment. A comparison of the sediment budgets and cross-shore profiles changes between these two scenarios allows us to determine if the sediment supply from the nourishment is enough to prevent erosion in the adjacent coastal sections.

The fourth research question is, again, answered through means of a literature study. First an assessment is made of the hydrodynamic conditions and geomorphological setting of the coastlines that make up the Atlantic southeast coast of the United States: South Carolina, North Carolina, Georgia and Florida's east coast. This provides insight into the representativeness of the conditions at Hilton Head compared to the remainder of the Atlantic southeast coast of the United States. Second, the morphological behaviour (erosion/accretion) of the coastlines of the different states is analysed. This gives some insight into the potential/necessity of applying a feeder nourishment at these locations. Together these analyses provide the answer to the fourth research question: what do the results at Hilton Head Island mean for the Atlantic southeast coast of the United States?

2 Literature study

2.1. Hilton Head Island

Hilton Head Island is one of the many beach ridge barrier islands located along the Atlantic Coast of Beaufort County, South Carolina (Figure 1). The island is approximately 19 km long, 8 km wide, and it occupies an area of almost 140 km^2. This makes it the second largest barrier island on the US East Coast [Beach Renourishment Brochure, 2016]. Hilton Head's pristine beaches make it a popular vacation destination, as a result the island is home to numerous luxury resorts, vacation homes, golf courses, etc. Most of them built right up to the edge of the beach front [Hilton Head Island beaches, 2019].

*Figure 1: **Left:** Satellite image of a segment of the U.S East Coast, the red box indicates the location of Hilton Head Island. **Right:** Satellite image of the topography in the red box, it displays Hilton Head Island and the two tidal inlets that border it. Port Royal Sound to the north, and Calibogue Sound to the south. [Source: Google Earth]*

Bathymetry

Hilton Head Island is a transgressive relic coastal barrier, which has migrated landward over the last several centuries due to rising sea-levels. Most of the beach erosion is thus a naturally occurring phenomenon [Beach Management Plan, 2019]. The island is situated between two tidal inlets: Port Royal Sound (north) and Calibogue Sound (south). Both Nummedal & Humphries (1978) and Fitzgerald (1984) note that most of the tidal inlets along South Carolina's coast tend to be ebb dominant. This also includes Port Royal Sound and Calibogue Sound. In case a tidal inlet is ebb-dominant, the net sediment transport is directed seaward. The deposited sand forms shoals at the seaward mouth of the inlet, these are often referred to as the ebb-tidal delta [Kana et al., 2013]. The size of ebb-tidal delta is determined by the size of the tidal inlet itself and the balance between tidal currents and breakings waves [Kana, 1988]. The Port Royal Sound ebb-tidal delta is a massive estuarine entrance shoal that projects far out onto the continental shelf (Figure 2) [Hayes & Michel, 2008]. Also notice the so-called low stand delta at the edge of the continental shelf in Figure 2. This is a remnant from a period when sea-levels were lower, and the actual coastline was near the edge of the present continental shelf. This shows just how much the coastline has transgressed landward over the centuries.

The massive Port Royal Sound ebb-tidal delta accommodates an elaborate shoal system which envelops the island's entire coastline (Figure 3). The resulting shoreline profile is that of a relative steep initial foreshore slope (1:40), which transitions into a flat shoal system that extends on average roughly one kilometre offshore (Figure 4).

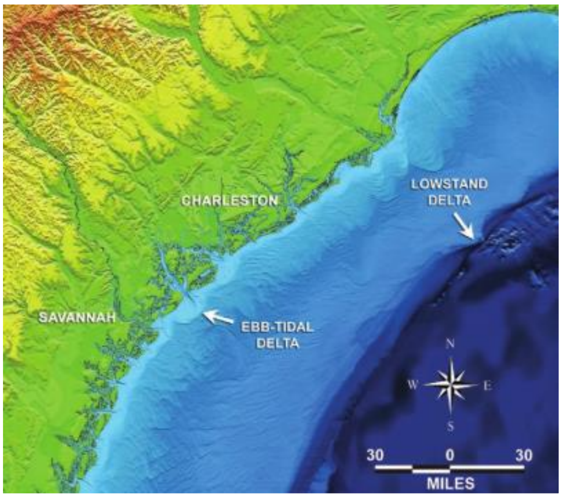


Figure 2: Bathymetry of the continental shelf off South Carolina's coastline. The massive ebb-tidal delta (arrow) of the Port Royal Sound tidal inlet is clearly visible. The blue colours represent water, while green, yellow and orange represent land. [Source: Hayes & Michel, 2008]

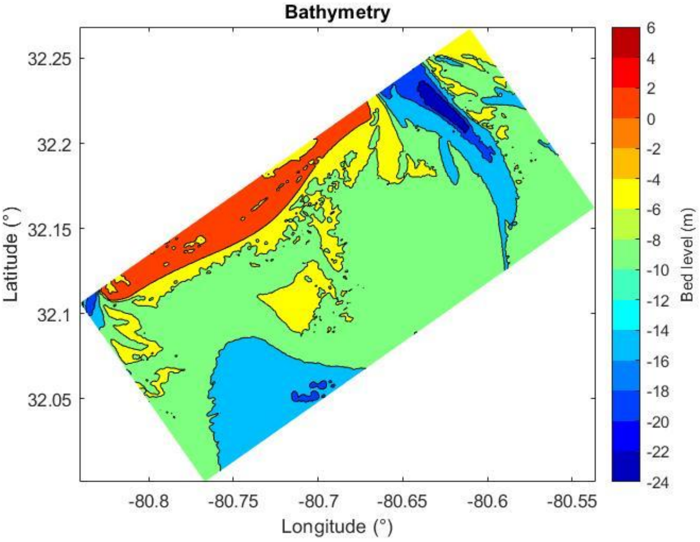


Figure 3: Plot of Hilton Head Island's coastline and its offshore bathymetry.

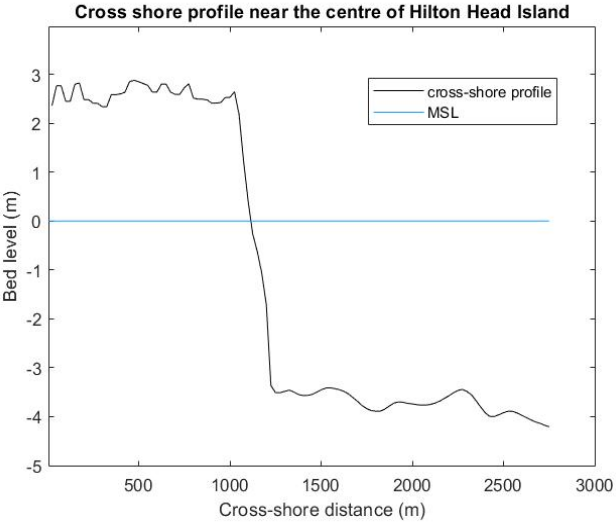


Figure 4: Cross-shore profile (80,73°; 32,15°) near the centre of Hilton Head Island.

Figure 5: Location of the different measuring stations. 1 = Station ID: 8669167 ; 2 = Station ID: ACT7186; 3 = Station ID: 63668

Tidal climate

The tidal climate is defined by two parameters: vertical tide and horizontal tide. The vertical tide, or tidal range, is the height difference between high tide and low tide. In conjunction with the fall and rise of the tide, alongshore tidal currents occur, which are referred to as the horizontal tide. Both the vertical tide and the horizontal tide are retrieved from the National Oceanic and Atmospheric Administration (NOAA) Tides & Currents Application [NOAA Tides & Currents, 2019]. The vertical tide is retrieved with the NOAA Tide Prediction Application [NOAA Tide Prediction, 2019]. The data is obtained from a measuring station (Station ID: 8669167) that is located within the Port Royal Sound tidal inlet (Figure 5). The data shows that the mean tidal range at the station equals approximately 1,9 m. This is in line with observations made by Kana (2013), who mentions a mean tidal range in the range of 1,8 m to 2,1 m for South Carolina's coast in general.

The horizontal tide is retrieved with the NOAA Current Prediction Application [NOAA Current Prediction, 2019]. The data is obtained from a measuring station (Station ID: ACT7186) that is located just off the northern tip of Hilton Head Island (Figure 5). The maximum flood tidal currents are predicted to measure approximately 1,00 m/s, and the maximum ebb tidal currents are predicted to measure approximately 1,50 m/s. Note that the measuring station is located close to the main channel of the tidal inlet. Inside the main channel the tidal currents reach their maximum value. Therefore, it is expected that the magnitude of the alongshore tidal currents is smaller than the values that are presented above.

Wave climate

The wave climate is derived from the wave information studies or WIS program [WIS USACE, 2019]. Near Hilton Head multiple wave hindcast stations are present. The data of the station closest to the island (Station ID: 63668) is used to determine the wave climate. This station is located approximately 25 km offshore from the centre of Hilton Head Island, outside of the shallow ebb-tidal delta at a water depth of 15 m (Figure 5). The annual mean significant wave height measures 1,0 m and the annual mean wave period measures 8,4 s. The calculation of these values is presented in Appendix A1. The waves at Hilton Head Island display a narrow range of directions. Almost all waves arrive between the nautical angles of 67,5° and 180° (Figure 6). Furthermore, a comparison of the wave and wind rose teaches us that the dominant wind directions do not coincide with the dominant wave directions. Both are indicators of a swell wave climate [Holthuijsen, 2007]. Hilton Head Island is thus predominantly subjected to a southeast swell.

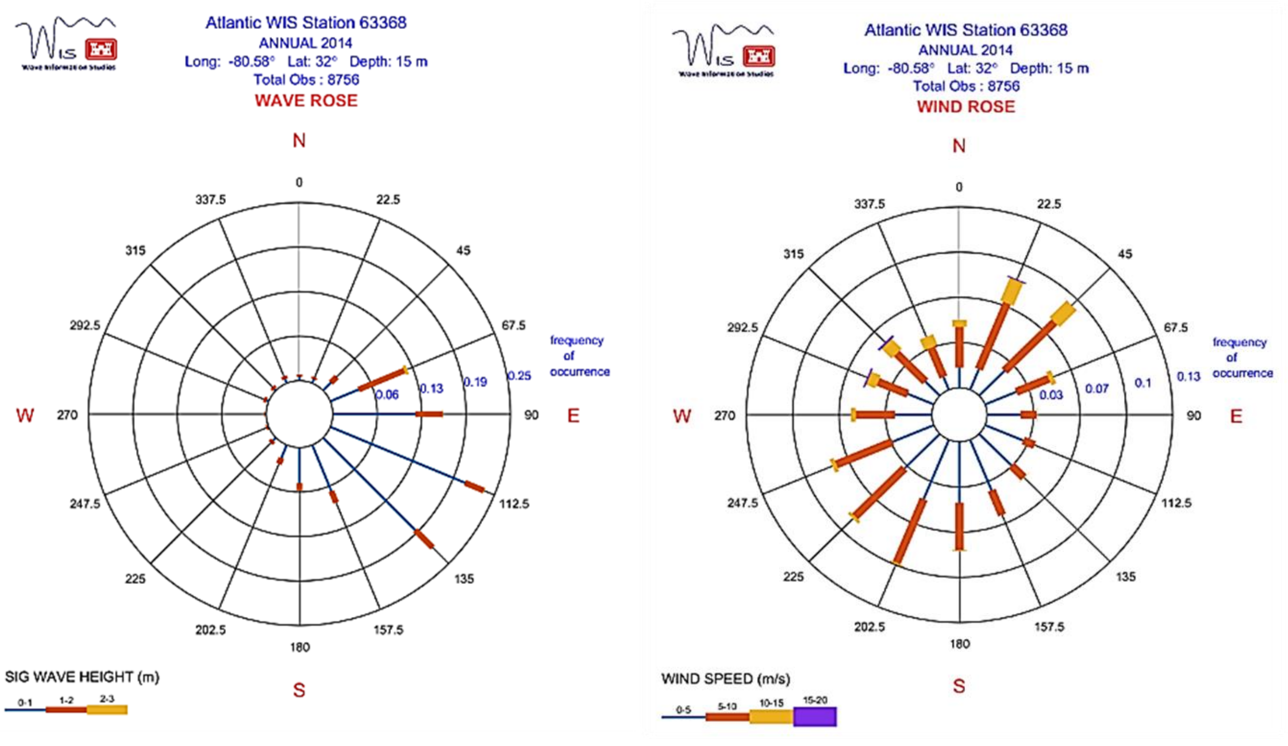


*Figure 6: **Left:** Wave rose of 2014, displaying the frequency of occurrence of wave directions for station ID 63368. **Right:** Wind rose of 2014, displaying the frequency of occurrence of the wind directions for station ID 63368. [Source: USACE WIS, 2019]*

Figure 7 shows a hindcast of the 1999 wave conditions for station ID 63668. 1999 is chosen because of its relatively large number of storms compared to other years. Almost every year, South Carolina's coast is affected by tropical storms and hurricanes during the Atlantic hurricane season. The hurricane season runs from June 1st to November 30th, with the peak period running from early August through the end of October. On the U.S. East Coast, an event is considered as a storm, if it boosts a maximum wave height larger than 3,0 meter [Komar & Allan, 2007]. The dataset of 1999 contains four of these storm events. Emily (24-28 August) is a tropical storm, Floyd (7-17 September) and Irene (13-19 October) are hurricanes.

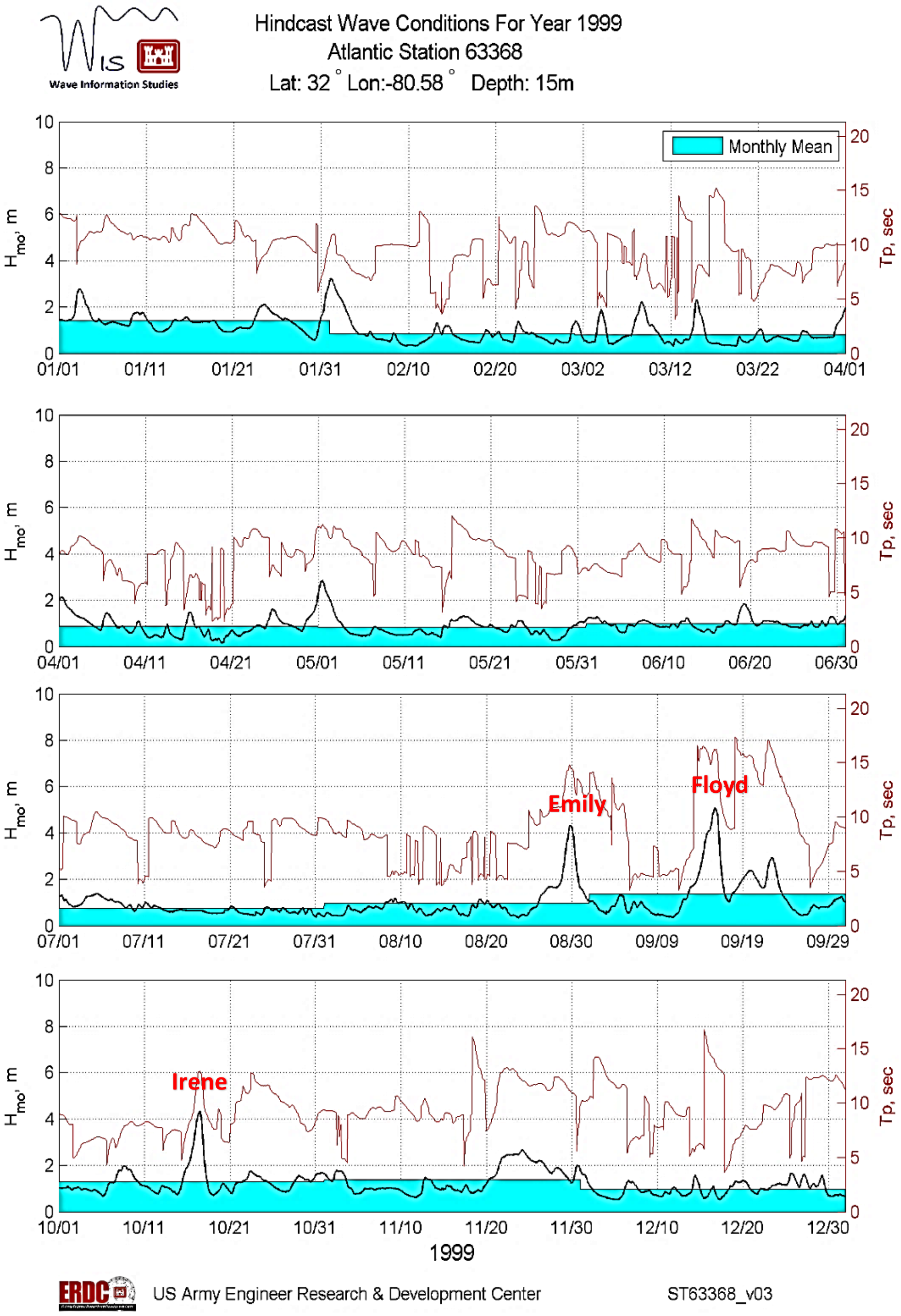


Figure 7: Hindcast of the 1999 wave conditions for station ID 63668. [Source: WIS, USACE 2019]

Sediment properties

In Appendix A2 the grain size distribution for typical beach sand on Hilton Head Island is presented. The value for D_{50} is estimated to be approximately 0,2 mm at Hilton Head. D_{50} represents the median particle diameter, which is defined as the sediment particle diameter for which 50% by weight is finer. D_{50} is an important parameter for sediment transport [Bosboom and Stive, 2015].

Depth of closure

The depth of closure (DOC) is an important parameter for the calculation of sediment transport rates. It is the depth beyond which no significant longshore or cross-shore transports take place due to littoral transport processes. The closure depth can thus be defined as the seaward boundary of the littoral zone [Bosboom and Stive, 2015]. One way to determine the DOC, is by studying changes in the profile. By examining the coastal profiles for a standard deviation of change that approaches zero, empirical evidence can be gathered to determine the DOC. Numerous profile surveys of South Carolina's coastline have been done since the eighties. Analysis of these profiles shows that the DOC at all locations lies within the -4,5 m contour on decadal scales [Kana et al., 2013]. Appendix A3 elaborates upon the determination of the DOC.

Sediment transport characteristics

Hayes and Michel (2008) provide an elaborate description of South Carolina's coast. The general azimuth of the coast is NE–SW. Parallel to the two principal wind directions. But local shoreline orientations can vary between north south to east west, which influences the sediment transport directions. The net sediment transport along South Carolina's coast is generally directed to the southwest. However, due to the presence of ebb-tidal deltas, numerous drift reversals can be found all along the state's coastline [Kana et al., 2013]. At Hilton Head, such a drift reversal occurs near the centre of the island's shoreline. The net sediment transport direction reverses here from the southeast to the northeast (Figure 8). The numerous drift reversals along South Carolina's coast are associated with wave transformation and sheltering around ebb-tidal deltas. Through a process called refraction, irregularities in offshore shoals can change the direction of incoming waves and focus wave energy on a given section of beach producing erosion, while wave energy is lessened in another spot nearby, causing accretion [Kana, 1988]. As a result of the drift reversal, the principal erosion signature at Hilton Head Island has been dispersion and transport of sand from its centre to each end of the island [Olsen Associates, 2014]. Consequently, wide beaches occur on the northern and southern ends of the island, and a narrow beach mid-island [Beach Management Plan, 2017]. Figure 9 confirms that erosion indeed occurs predominantly at the mid-island shoreline. Roughly a 7,5 km stretch of coast between 'Alder Lane' and 'The Folly' is subjected to erosion. The erosion rates along this stretch of coast vary between 5 to 20 feet per year, and the erosion is most severe near the centre of the island, where the transport reversal occurs. This relatively strong erosion near the

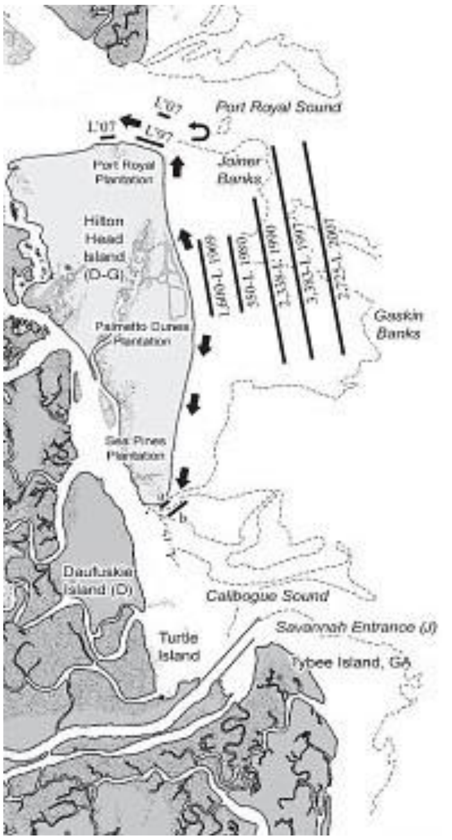


Figure 8: Schematic overview of the historic net sediment transport pattern at Hilton Head Island. The black arrows indicate the direction of the sediment transport. Past nourishment events at Hilton Head Island, are represented by the black lines. The length of the black lines represents the extent of the nourishment and is accompanied by their respective year of execution. [Source: Kana et al., 2013]

centre of the island also coincides with a relatively small beach width (<200 m). Making the centre of the island a vulnerable location. The beaches adjacent to the mid-island section, in general, either remain stable or experience accretion (both to the north and south). There are, however, also some local erosion hotspots. These are associated with shoal bypassing events and/or the construction of groins [Kana et al., 2013].

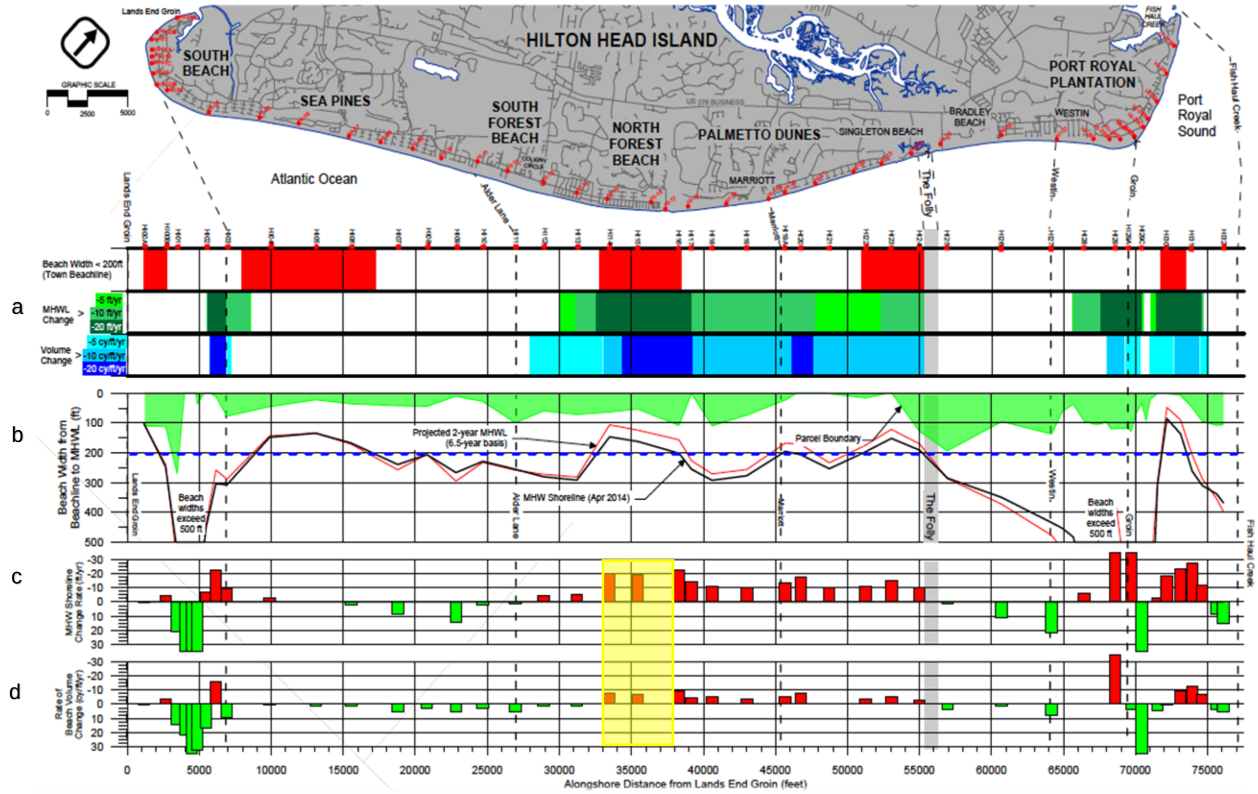


Figure 9: Overview of the morphological development at Hilton Head Island between March 2007 and April 2014. The translucent yellow square indicates the location of a control domain that is used later on in the research during the model calibration. [Source: Olsen Associates, 2014]

Panel a) ***above:*** *areas with a beach width less than 60 m (red) ;* ***middle:*** *MHWL change (light green = - 1,5 m/year ; green = - 3,0 m/year; dark green = - 6,0 m/year) ;* ***bottom:*** *volume change (light blue = - 12 m^3/year ; blue = - 24 m^3/year ; dark blue = - 48 m^3/year)*

Panel b) beach width from MHWL to the beachline in feet. The black line is the beach width on April 2014, the red line is the projected beach width in two years' time.

Panel c) MHW shoreline change rate in feet per year. Red blocks indicate a shoreline retreat and green blocks indicate a seaward movement of the shoreline.

Panel d) rate of beach volume change in cubic yard per feet per year. Red blocks indicate erosion and green blocks indicate accretion

Nourishment history

Until now, erosion has been addressed through traditional small-scale local beach nourishments. A common practice, where sediment is added to the sub aerial beach and/or dune system to directly address the occurring erosion and prevent further coastal retreat. Between 1969 and 2010, five nourishment events have added approximately 8,0 million m^3 of sand along 14 km of coast to counter sand losses from the centre of the island. The nourishment frequency is roughly every 7 to 10 years for the island's central shoreline. The nourishment rate over the past 30 years has been roughly twice the underlying erosion rate, leaving Hilton Head Island with significantly more beach/dune area in 2010 compared to 1980. Omitting the 1969 project, the average fill density between 1980 and 2010 has been approximately 500 m^3/m [Kana et al., 2013]. Given the statement above, that the nourishment rate has been twice the underlying erosion rate. This would mean that the underlying erosion rate measures 250 m^3/m along the centre of the island.

2.2. The Sand Engine pilot project

Part of this research is the evaluation of a feeder nourishment's performance by comparing it with a (mega) feeder nourishment located on the Dutch Coast, the Sand-Engine. The Sand Engine was constructed in 2011 along the coast of Delfland (Figure 10). This man-made peninsula consists of 17,2 million m^3 sand and covers an area of roughly 128 ha. The initial alongshore width measured approximately 2500 m, combined with a cross-shore extent of roughly 1000 meter. It is expected that over the next two decades the sediment will be redistributed trough natural coastal processes (marine and aeolian) between Hoek van Holland and Scheveningen [Luijendijk et al., 2016].

Since its construction in 2011, several studies into the behaviour of the Sand-Engine have been conducted. Analysis of project site data by De Schipper et al. (2016) concludes that after 18 months of monitoring the majority (70%) of the volumetric sediment losses were found to be compensated by accretion on adjacent coastal sections and dunes, confirming the feeder property of the nourishment. Based on five year of high-resolution topographical surveys, De Roest et al. (2018) concludes that sediments are redistributed in both alongshore and cross-shore direction over the coastal cell. Of the initial nourished volume of 17,5 million m^3, 4,2 million m^3 has been redistributed after 5 years. The decrease in cross-shore extent is fastest around MSL and decreases to almost zero at the depth of closure. The profiles are adjusting rapidly, with a maximum morphological activity in the intertidal zone. The morphological response shows limited morphodynamic activity around or below the DOC. Volumes that are deposited here may react on much larger timescale than intended. Therefore, the feeding characteristics of a mega-nourishment should be assessed using the nourished volume above the DOC, rather than the total volume. The first year morphodynamic response was much stronger than in any subsequent year. The results show that the Sand Engine spreads alongshore and feeds the adjacent coastal sections in the five years after construction.

*Figure 10: **A:** Location of the Sand Engine (Sand Motor) at the Dutch coast. **B**: The Delfland coastal cell including a sketch of the Sand Engine. **C:** The Sand Engine after completion in 2011. (Source: Luijendijk et al., 2016)*

Bathymetry

The Sand-Engine is located on an uninterrupted, and relative straight coastline. The slope of the profile in the intertidal and surf zone, prior to all the nourishments works, was 1:55 in this coastal stretch [De Schipper et al., 2016].

Tidal climate

The mean tidal range at the location of the Sand-Engine is 1,7 meter, and the horizontal tidal velocities measure in the order of 0,5 m/s [De Schipper et al., 2016].

Wave climate

The wave climate along the southern Dutch coast is wind sea dominated. The average annual wave height measures 1,3 m, and the wave period varies typically between 5 to 6 s. Usually, storm events occur in autumn and winter. Storms with a return period of once every year have a significant wave height of 4,0 m [De Schipper et al., 2016]. Figure 11 displays a time series of the observed significant wave heights at a measuring station (Europlatform) off the coast of Hoek van Holland between August 2011 and August 2012.

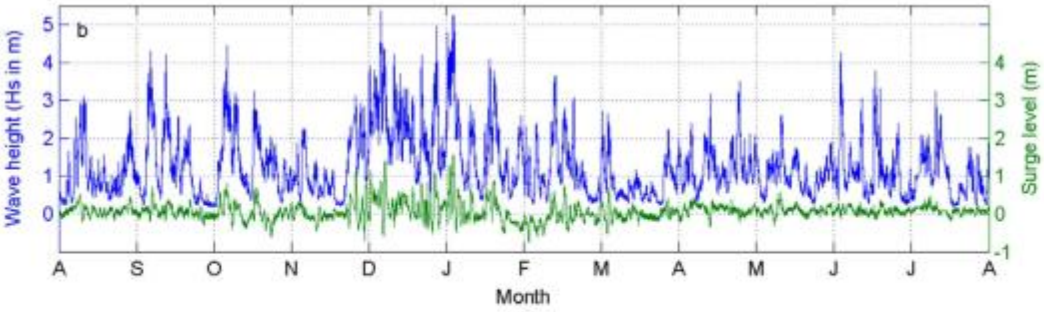


Figure 11: Time series (blue) of the observed concurrent significant wave heights at Europlatform from August 2011 till August 2012. Europlatform is an offshore measuring station in the vicinitiy of Hoek van Holland. The green line represents the surge level at Europlatform during the same time period [Source: Luijendijk et al., 2016]

Sediment properties

The beaches at the Sand-Engine consist of sand with an average median grain size (D_{50}) of roughly 0,24 mm [Olsen Associates, 2015].

2.3. Comparison of conditions

In Table 1 the studied conditions at Hilton Head Island and the Sand-Engine are summarized. A comparison between the two provides us with the answer to the first research question: how do the conditions at Hilton Head Island differ from the Sand-Engine pilot project?

Table 1: Summary of the conditions at Hilton Head Island and the Sand-Engine.

Hydrodynamic conditions	**Hilton Head Island**	**Sand-Engine**
Bathymetry	barrier island bordered by tidal inlets	straight uninterrupted coastline
Slope	1:40	1:55
Tidal pattern	semi-diurnal	semi-diurnal
Mean tidal range	1,9 m	1,7 m
Alongshore tidal velocities	*O* (1,0 m/s)	*O* (0,5 m/s)
Wave climate	swell wave dominated	wind wave dominated
Annual mean wave height	1,0 m	1,3 m
Annual mean wave period	8,0 – 9.0 s	5,0 – 6,0 s
Median particle diameter	0,20 mm	0,24 mm
Type of sediment	sand	sand

Note that the annual mean wave height at Hilton Head is calculated based on H_{m0}, while at the Sand Engine the annual mean wave height is calculated based on $H_{1/3}$. $H_{1/3}$ is the average height of the third-highest waves in a record of time period. H_{m0} is determined based on the variance of the record or the integral of the variance in the spectrum. While $H_{1/3}$ is a direct measure of Hs, H_{m0} is only an estimate of the significant wave height (H_s). In general, in deep water $H_{1/3}$ and H_{m0} are close in value and are both considered good estimates of H_s. Studies comparing the two estimates have shown that H_{m0} slightly overestimates the significant wave height by approximately 5% [Coastal Engineering Manual, 2020].

The first difference in conditions between the two locations is formed by the bathymetry. The Sand-Engine is constructed on a straight, uninterrupted coastline. Hilton Head, however, is part of South Carolina's barrier island chain. Tidal inlets divide this coastline, separating one barrier island from another. Resulting in a complex and compartmentalized coastline. The slopes of the profiles in the intertidal and surf zone is comparable for both locations, with the slope at Hilton Head Island being slightly steeper. The tidal conditions (pattern, range and alongshore velocities) at both locations are comparable as well. The wave climate, however, shows some distinct differences. Hilton Head is exposed to a swell wave climate, while a wind sea dominated wave climate is found at the Sand-Engine. As a result, the annual wave height and annual wave period at Hilton Head are respectively lower and longer. Another important difference regarding the wave climate is the so-called storminess. In general, an event is considered as a storm on the U.S. East Coast, when it boosts a maximum wave height larger than 3,0 m [Komar & Allan, 2007]. If this threshold is also applied to location of the Sand-Engine, then the annual number of storms at the Sand-Engine is significantly larger than the number of storms at Hilton Head. While 1999 is one of the stormiest years ever recorded at Hilton Head Island, it only boosts a total of 4 storm events that surpass the threshold of $H_{max} > 3,0$ m (Figure 6). The wave time-series between August 2011 and August 2012 at the Sand-Engine (Figure 11) counts more than a dozen storm events. Finally, the sediment properties at both locations are almost identical.

Of course, there is a certain degree of difference between all studied conditions for the two locations. However, two of them clearly stand out from the rest. These are the presence of two tidal inlets, and the subjection to a calmer swell wave climate. These are the two differences that will be subject of analysis in the second research question:

2.4. Tidal inlets

The influence of a nearby tidal inlet system on the development of a feeder nourishment is researched in a study by Dane (2020). The results of this numerical modelling study show, that there will be additional erosion near a tidal inlet if the feeder nourishment is located inside the influence area of the tidal inlet. Residual currents can occur if the tidal currents in the inlet are strong enough to form a tidal jet. The residual flow pattern is always directed towards the inlet, both in flood- and ebb-conditions (Figure 12). The extent of the influence area is dependent on both the tidal prism and the incident wave angle. An increase in the tidal prism, leads to an increase in the magnitude of the residual currents. As a result, the extent of the influence area becomes larger. In this study, the influence area increased from 2200 m for a tidal range of 1,5 m, to an influence area of 3100 m for a tidal range of 3,0 m. The influence area or reach is defined as the alongshore distance where the total alongshore sediment transport is larger than 50 m^3/6y/m, this threshold is assumed to be the limit of the noise in the results. However, the incident wave angle is the governing process, for both mild and storm conditions. An oblique wave angle, directed towards the tidal inlet, with the feeder-nourishment upstream of the tidal inlet, will reduce the reach. In this study, the influence area reduced to 1070 m for oblique wave conditions [Dane, 2020].

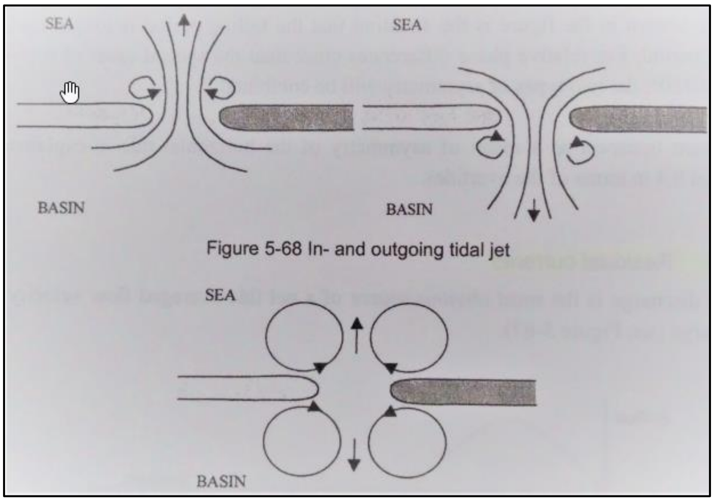


Figure 12: Schematized residual currents at a tidal inlet. [Source: Bosboom and Stive, 2015]

2.5. Morphological response Sand-Engine

De Vries et al. (2018) explains that the morphologic response at the Sand-Engine shows a clear signature of wave-driven hydrodynamics. Suggesting that wave forcing dominates over the effect of tidal currents and aeolian sediment transport. This is in line with the results of modelling studies by Luijendijk et al. (2016). According to this research, the total amount of sediment that is eroded from the feeder nourishment in the first year in a scenario with only wave forcing, measures approximately 75% relative to the total amount of sediment that is eroded in a scenario that includes all driving forces (waves, tide, wind and surge). The integrated erosion volume of the 12 biggest storm events accounts for approximately 60% of the total eroded volume after one year. So, it seems, that among wave forcing, storm events are the most important contributor to the erosional capacity. Vertical tidal fluctuations come in at a second place. The total amount of sediment that is eroded from the feeder nourishment in the first year in a scenario with only vertical tidal forcing, measures approximately 17% relative to the total amount of sediment that is eroded in a scenario that includes all driving forces (waves, tide, wind and surge). It is expected that the vertical tide influences the active part of the cross-shore profile, and as such influences the erosional volume. Horizontal tide, surge levels and wind-driven currents all amount to less than 5% of the total erosional volume after 1 year, compared to the amount of sediment that is eroded in a situation that includes all driving forces (waves, tide, wind and surge). The feeder property is related to the wave-forcing, such that high-energy waves result in more alongshore spreading and low-energy waves resulted mostly in cross-shore movement of the sediment and consequently no feeding of the adjacent coasts [De Schipper et al., 2016].

2.6. Research hypotheses

Based on the literature study above, the following research hypotheses are formulated for the remaining research questions.

RQ 2: How do the differences in hydrodynamic conditions and geomorphological setting between Hilton Head and the Sand Engine affect the morphological development of a feeder nourishment?
Since Hilton Head Island experiences a calmer swell wave climate, and wave forcing seems to be the most dominant contributor to the total erosional volume at the Sand-Engine. It is expected that the total amount of sediment that is eroded by wave forcing and/or storms, relative to the total erosional volume from the feeder nourishment by all driving forces (waves, tide, wind and surge), is smaller at Hilton Head Island in comparison to the Sand-Engine.

The nourishment will be constructed somewhere near the centre of the island, given that is where the erosion predominantly occurs. This places the nourishment at least several kilometres away from both tidal inlets. Therefore, it is not expected, that residual currents (if present) influence the behaviour of the feeder nourishment. However, the extent of the influence area found in the study by Dane (2020) is of course site specific and might be larger (or smaller) in the case of Hilton Head Island.

RQ 3: Can a feeder nourishment at Hilton Head Island supply sediment to adjacent coastal sections at a rate that is sufficient to prevent erosion?
Whether or not the supply of sediment outpaces the underlying erosion rates along the centre of the island (250 m^3/m), and can prevent coastal retreat, is probably highly dependent on the erosional volume during storm events. Given that storms are the dominant contributor to the total erosion volume at the Sand Engine in the first year (60%).

RQ 4: What do the results at Hilton Head Island mean for the Atlantic southeast coast of the United States?
About 80-90% of U.S. East Coast barrier beaches have experienced erosion in the last 100 years [Galgano et al., 1998]. Therefore, it is expected that there certainly is a need for an erosion mitigating measure like a feeder nourishment along the Atlantic southeast coast of the U.S. However, just like we cannot directly translate the findings of the Sand Engine pilot to the shoreline of Hilton Head Island. The same can be said for applying the results found at Hilton Head to the remainder of the Atlantic Southeast coast of the U.S. The representativeness of the conditions at Hilton Head Island compared to the remainder of the coastline plays an important role here. The presence of numerous tidal inlets might result in locally strongly varying conditions.

3 Research Method

The morphological evolution of Hilton Head Island will be modelled with Delft3D, a depth averaged two-dimensional model. The aim of this chapter is to calibrate the model, and set-up the model scenarios necessary to answer the research questions.

3.1. Model set-up

The applied model is Delft3D, a process-based numerical model. The model can carry out simulations of flows, sediment transports, waves, and morphological changes, amongst other things. It is composed of several modules which can interact with one another. The modules used in this research are: Delft3D-FLOW, Delft3D-WAVE and Delft3D-MORPHOLOGY

D3D-FLOW calculates non-steady flow and transport phenomena that result from wave and tidal forcing [D3D-FLOW manual, 2019]. D3D-WAVE is used to simulate the evolution of wind-generated waves in coastal waters. It has a dynamic interaction with the FLOW module, through this coupling, both the effect of waves on current and the effect of flow on waves are accounted for [D3D-WAVE manual, 2019]. D3D-MOR is part of the D3D-FLOW, it computes sediment transport and morphological changes. An important feature of the MOR module is the feedback loop with the FLOW and WAVE modules, this allow the generated flows and waves to adjust themselves to the local bathymetry [D3D-FLOW manual, 2019].

3.1.1. Computational grid and bathymetry

Figure 13 shows the location and size of the overall grid that is used in used in the FLOW and WAVE module. The grid cut-out represents the size and location of the local nested grid. The grid lay-out depends on the hydrodynamic processes, bathymetrical features, and the orientation of the coastline. Gridlines should preferably be orientated perpendicular/parallel to these features [Publicwiki Deltares, 2020]. Therefore, the grid is rotated 35° about the north, to align the grids with the orientation of the shoreline. The grid coverage is linked to the important bathymetric features that are present at Hilton Head Island. It includes a large part of the ebb-tidal delta, the shallow shoal systems, and the tidal channel of the Port Royal Sound inlet. The reason being that these bathymetric features directly influence the nature of the waves and tide, not including them would give an inaccurate representation of the processes at Hilton Head Island. The length of the grid in the alongshore direction measures approximately 30 km, and 18 km in the cross-shore direction.

The overall (rough) grid consists of 109 grid cells in the longshore direction and 68 cells in the cross-shore direction, this results in a grid resolution of roughly 275 by 275 meters. This overall grid size is established by systematically refining the grid resolution until a balance is found between the necessary accuracy level and the resulting computational effort. The finest overall grid resolution that was applied measured 100 by 100 meters. This significantly increased the computational time but did not result in a significant increase in detail/accuracy.

Within the overall (rough) grid, a smaller and more refined grid is nested. This grid is nested along the island’s central coastline, covering the reach of shoreline that is prone to erosion, and the area where the feeder nourishment will be constructed. The refined nested grid allows us to analyse the processes in the vicinity of the feeder nourishment in more detail. Applying this level of grid resolution to the entire grid would result in a too large computational effort. The length of the nested grid in the alongshore direction measures roughly 6 km, and 2,5 km in the cross-shore direction. With 266 grid cells in the alongshore direction, and 111 in the cross-shore direction, this results in a nested grid resolution of approximately 25 by 25 meters.

The aim of this study is to analyse the morphological development of the feeder nourishment and the adjacent coastlines. The characteristic length scale of these bathymetric features is in the order of several hundred of meters. A rule of thumb is that important bathymetrical features should be covered by a minimum of 5-10 grid cells [Publicwiki Deltares, 2020]. A grid cell resolution of 25 by 25 meters meets that criterium. It is also important to have adequate resolution of grid cells that undergo drying and flooding at land-boundary. Sufficient resolution will result in smoother current patterns during flooding / drying and consequently smoother bed level changes [Publicwiki Deltares, 2020]. The finest grid resolution that was applied measured 10 by 10 meters. This significantly increased the simulation time but did not result in smoother current or sediment transport patterns Therefore, it is assumed that a grid cell resolution of 25 by 25 meters is sufficient to cover the processes around the land boundary.

The bathymetry data is retrieved from the Digital Elevation Model (DEM) of the National Oceanic and Atmospheric Administration [NOAA DEM, 2019]. The resolution of the DEM is 1/3 arc second, which equals a resolution of approximately 10 meters.

Figure 13: Location, lay-out and size of the computational grid that is used in used in both the FLOW and WAVE module. The grid cut-out represents the size and location of the finer nested grid.

3.1.2. Boundary conditions

No boundary conditions need to be set at the ocean surface and/or bottom, given that the model is a depth-averaged two-dimensional model. This means that only lateral boundary conditions need to be imposed. Wave and tidal forcing are responsible for more than 90% of the total erosional volume at the Sand-Engine in the first year, therefore the decision is made to only include these two drivers in the model. And to exclude other drivers as aeolian transport and surge from the model.

The boundary conditions of D3D-FLOW consist of tidal constituents. The tidal constituents are generated with Delft Dashboard, a MATLAB-based graphical user interface (GUI). The dataset that Delft Dashboard utilizes to generate the tidal constituents is the TPXO 7.2 Global Inverse Tide Model. The tool automatically divides the four sides of the grid into open and closed boundary sections. The generated boundary conditions consist of an amplitude and a phase for the different tidal constituents.

The boundary conditions of D3D-WAVE consist of wave characteristics (height, period, direction, and directional spreading). The wave data is retrieved from the database of USACE’s Wave Information Studies program [USACE WIS, 2019]. This program provides us with hourly wave time-series for over 30 years. Several wave stations are present at Hilton Head Island, the station closest to the open boundaries is Atlantic Station 63368. Figure 7 shows the obtained wave time-series of 1999, which is chosen as the data source for the boundary conditions. The year 1999 was chosen for its relatively large number of storms compared to other years.

3.2. Model calibration

For the project site, only limited quantitative data sources are available to calibrate the model to. Figure 9 provides the MHW shoreline change rate (feet/year) and the rate of beach volume change (cubic yards/feet/year) for certain cross-sections. Second, there is the nourishment history at Hilton Head, which provides us with nourishment volumes for the separate nourishment events between 1970 and 2010. Other characteristics like sediment transport rates or current velocities are unavailable. Figure 8 provides a qualitative data source: the historic diverging sediment transport pattern. Both are used to calibrate the model.

3.2.1. Morphological acceleration factor

The simulation time of the calibration runs measures one month, for which the wave conditions of January 1999 are used as boundary conditions (Figure 14). Applying the full wave climate requires a large computational effort. To speed up the model, the wave conditions are first represented by a statistical representation and then reduced by applying a morphological scale factor or MorFac. This process is known as wave input reduction or WIR. The extent of reduction in wave conditions depends on the value of the MorFac. The MorFac is used to cope with the different timescales on which hydrodynamic and morphological developments take place. It works by multiplying the bel level changes with a constant factor, thereby effectively extending the morphological time step. This means that long morphological runs can be performed, using hydrodynamic simulations of only a fraction of the actual duration [Ranasinghe et al, 2010].

The applied MorFac during calibration equals 6, therefore the number of wave conditions in each bin is reduced by a factor 6. As result, the simulation time is shortened from one month to approximately 5 days. Figure 15 presents original the wave height distribution for January 1999, and Figure 16 presents the reduced wave height distribution for January 1999 after applying a MorFac of 6. When comparing Figures 15 and 16, one might notice that it is inherent to this process of wave input reduction, that events with a relative low frequency of occurrence are eliminated. Essentially, eliminating extreme storm conditions from the data set.

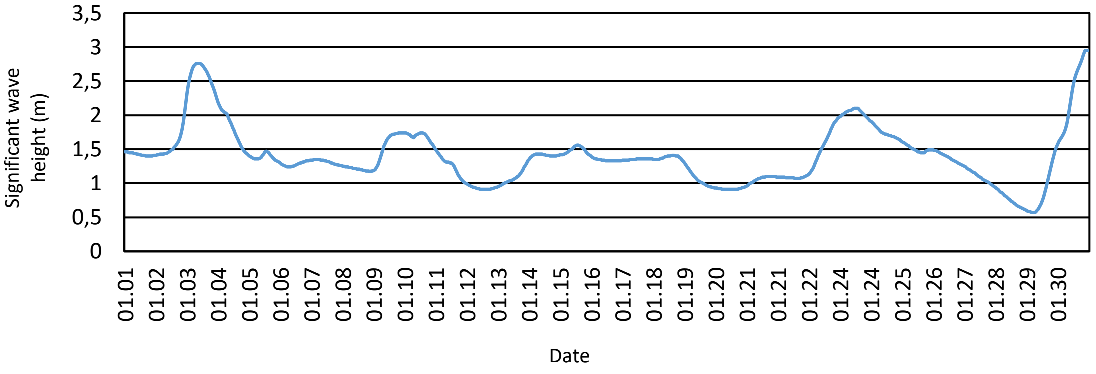


Figure 14: Wave time-series between January 1st, 1999 and January 31st, 1999

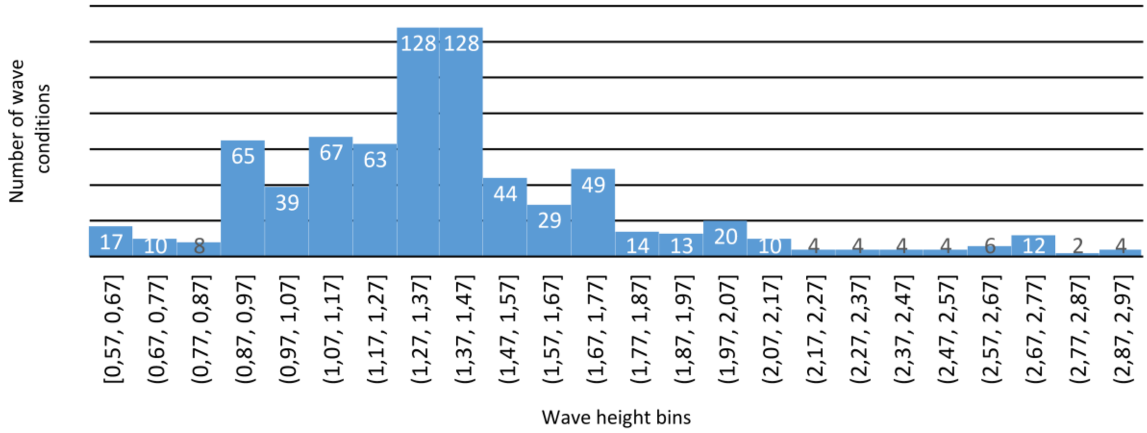


Figure 15: Wave height distribution for the original wave time-series of January 1999.

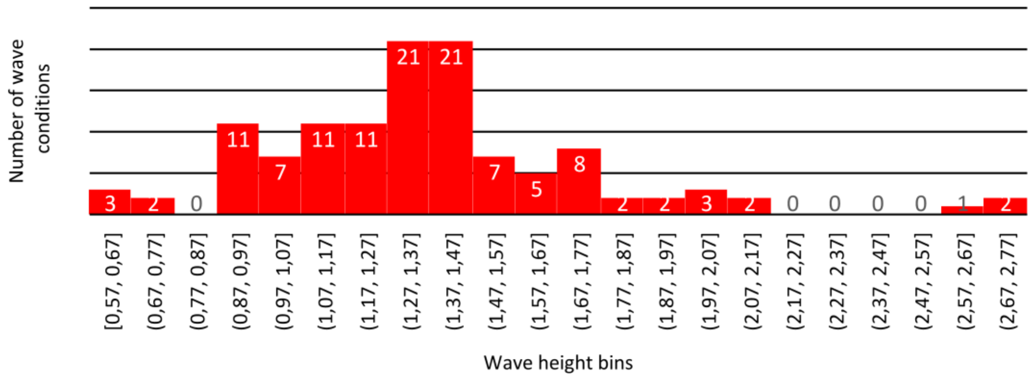


Figure 16: Wave height distribution for the reduced wave time-series of January 1999, after applying a MorFac of 6.

While the MorFac concept is a great tool for reducing the simulation time, there are limitations. A MorFac that is too high may lead to unrealistic results. To determine a safe upper limit, the resulting morphology of a benchmark case (MorFac =1) is compared to the computed morphology of simulations with a higher MorFac. The critical MorFac is then defined as highest MorFac that results in a morphology that is like that predicted by the benchmark case [Ranasinghe et al, 2010].

The cross-shore profile changes for a MorFac of 1, 6 and 12 display the same general behaviour, sediment is being deposited in the upper part of the profile (Figure 17). With increasing MorFac, however, the amount of sediment that is deposited in the upper part of the profile seems to decrease. This is confirmed by the computed volume changes in the control domain. It shows that for a MorFac of 1 the influx of sediment is largest, and that it decreases for an increase in MorFac. The volumetric differences are however relatively small in comparison to the size of the domain (112,5 ha). The results above lead to the assumption that the resulting differences in morphological behaviour are small enough to safely apply a MorFac of 12 without large consequences. The critical MorFac is therefore set to 12.

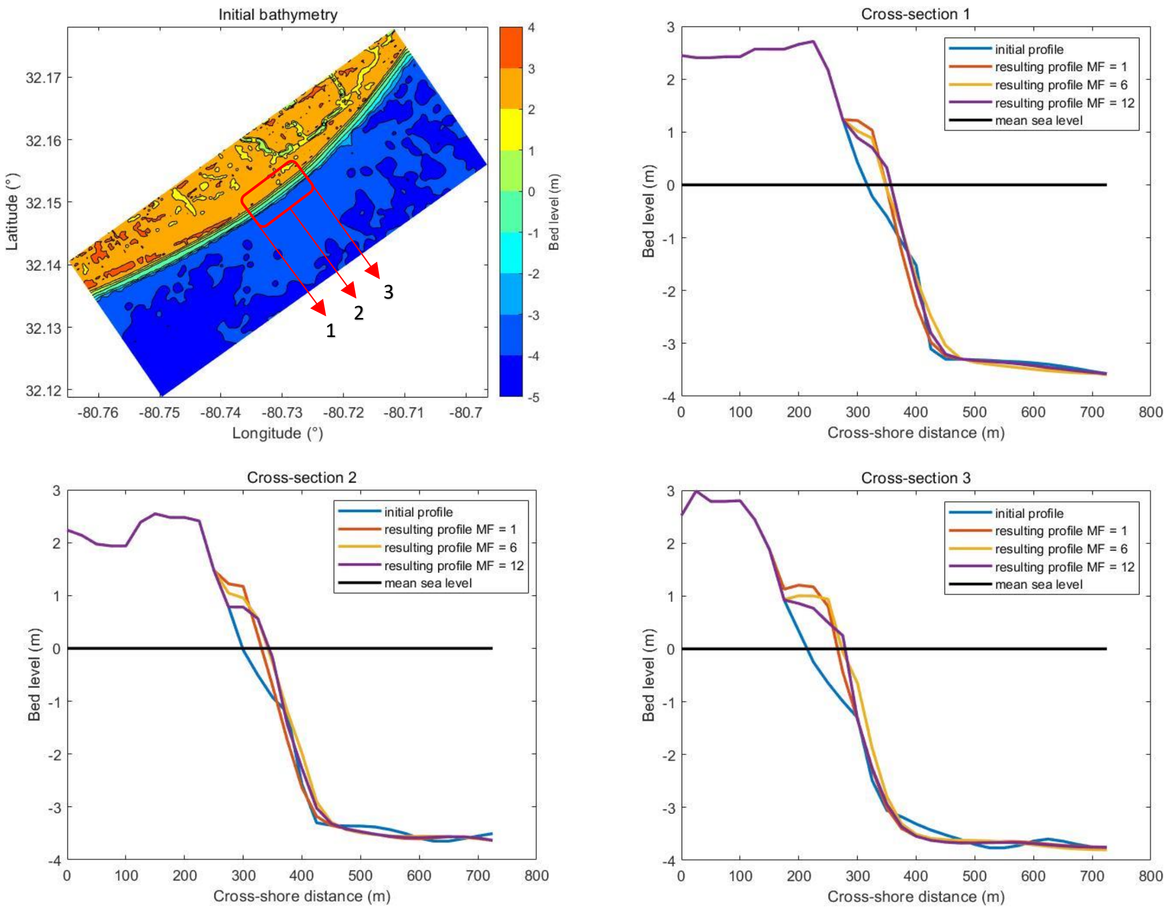


*Figure 17: **Left upper corner**: initial bathymetry and the location of the control domain (red square) and the cross-sections (red arrows). **Right upper corner**: cross-shore profile changes in cross-section 1. **Lower left corner:** cross-shore profile changes in cross-section 2. **Right lower corner:** cross-shore profile changes in cross-section 3.*

Table 2: Volume changes in the control domain for the different applied MorFac's

Applied Morfac	**Volume change (m³)**
1	150.740
6	135.220
12	122.660

3.2.2. Changes to the Delft3D default model-settings

While most model input parameters are kept at their default value, some are changed. Below, some of these parameter changes are explained in more detail.

Delft3D contains several types of bottom friction models (JONSWAP, Collins, Madsen et al.) The default model is the JONSWAP bottom friction model, which is also applied in this research. The bottom friction coefficient (C_b) of the JONSWAP model is decreased from its default value of 0,067 m^2s^{-3} to 0,038 m^2s^{-3}. Vledder et al. (2011) suggests that for sandy bottoms a value of 0,067 m^2s^{-3} is too high, and that much better results can be achieved by using C_b = 0,038 m^2s^{-3}. It also suggest that C_b = 0,038 m^2s^{-3} can be used for a wide range of bottom materials and independent of whether the waves are wind-sea or swell.

The number of directions of the directional space is increased from its default value of 36 to 72. This results in frequency bins of 5° (360°/72) instead of 10° (360°/ 36). These smaller frequency bins better suit the swell waves, given their relatively low directional spreading compared to wind sea waves [D3D modelling guidelines, 2019]

Luijendijk et al. (2016) states that the following two model input parameters are crucial for the calibration of D3D-MOR: dry cell erosion and sediment transport model. The factor for erosion of adjacent dry cells distributes the erosion of the most landward wet cell amongst its adjacent dry cells. This allows dry cells to be gradually eroded and become active wet cells. The default value is zero, which means that none of the erosion in the wet cell is transferred to the adjacent dry cell. For a value of one, all the erosion in the wet cell is transferred to the adjacent dry cell. [Luijendijk et al. 2016].

Several transport formulations are available in Delft3D. Van Rijn 1993 (TR1993-model) is set as the default sediment transport model in Delft3D. The sediment transport formulation applied in this case is Van Rijn 2004 (TR2004-model). TR2004 is an updated version of the TR1993 model. The most important improvement involves the refinement of predictors for the bed roughness and suspended sediment size [Van Rijn et al., 2004].

The computed sediment transport in Delft3d consists of 4 contributions: current-related bedload transport, wave-related bedload transport, current-related suspended load transport and wave-related suspended load transport. The morphology module contains 4 scale factors that determine their respective contribution to the total transport: BED, BEDW, SUS, SUSW. By default, the value for all four scale factors is 1. However, there are several studies that recommend deviating values for the wave related transport factors. Both Walstra et al. (2004) and Walstra (2008), advice a value of 0.3 for SUSW and BEDW in their morphology studies. On the OSS Deltares D3D-forum is stated that SUSW and BEDW are commonly decreased from its default value of 1 to values between 0,1 and 0,3. The argument is that in depth-averaged solutions the undertow due to waves is not fully resolved. Therefore, only the onshore transport component remains, resulting in an unrealistic sedimentation/accretion pattern along the shoreline. Table 3 summarizes the above mentioned, and other changes to the default Delft3D parameter values.

Table 3: Overview of the changes to the default Delft3D parameter values.

Module	**Parameter/setting**	**Value**
Flow/Wave	Timestep	0,5 min
	Bottom friction coefficient	0,038 m^2/s^3
	Water density	1025 kg/m^3
	Horizontal eddy diffusivity	1,0 m^2/s
	Minimum depth	0,30 m
Morphology & Sediment	Transport formula	Van Rijn 2004
	Minimum depth for sediment calculation	0,30 m
	Threshold sediment thickness	0,30 m
	Factor for erosion of adjacent dry cells	1,00 (-)
	Wave-related bedload transport factor (BEDW)	0,30 (-)
	Wave-related suspended transport factor (SUSW)	0,30 (-)

3.2.3. Model calibration results

According to Figure 18, the default Delft3D model-settings result in accretion along the entire coastal section. The resulting cross-shore profiles for the default model settings (Figure 19) show the same accreting pattern. Relatively large volumes of sediment are being deposited in the upper part of the profile, resulting in a significant seaward migration of the shoreline position (MSL = 0). This accretional behaviour can be explained by the relatively large onshore directed sediment transport outside of the surfzone (Figure 18). Luijendijk et al. (2016) already warned, that for the default settings in depth-averaged solutions, the undertow due to waves is not fully resolved. As a result, the onshore transport component is dominant, resulting in an unrealistic accretion pattern along the shoreline. The accretional behaviour of the shoreline also becomes apparent from the sediment budget of the control domain. To determine the volume change in this domain, for each grid cell the cumulative sedimentation/erosion is multiplied by the grid cell area. Over the course of 1 month, the control domain has experienced a net sediment influx of 93.830 m^3. This behaviour is in contradiction with the observed morphological behaviour at Hilton Head Island between March 2007 and April 2014. As, according to Figure 9, the control domain is subjected to erosion, and act as a source of sediment, rather than a sink.

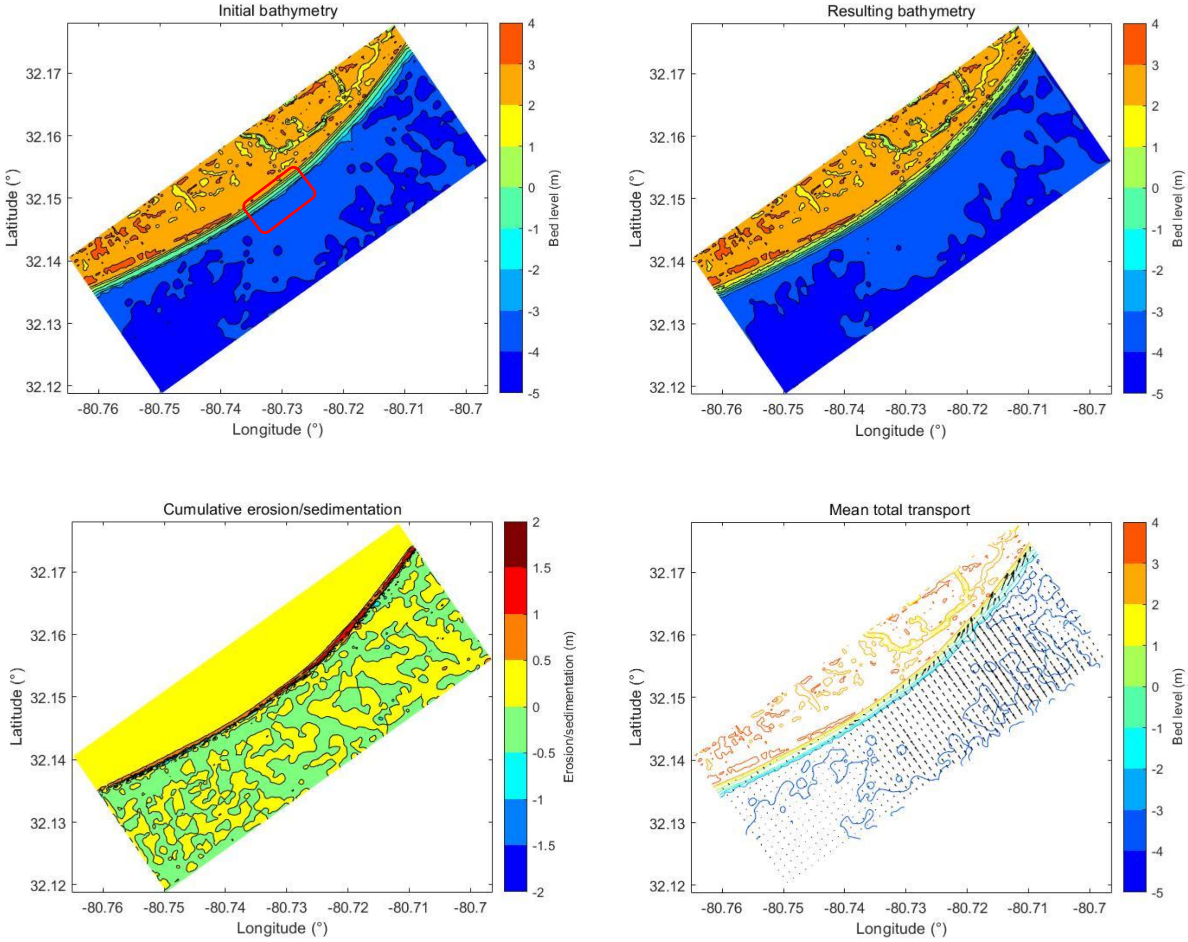


Figure 18: ***Upper left corner:*** *initial bathymetry in the nested grid domain, in which the red area indicates the location of the control domain.* ***Upper right corner:*** *resulting bathymetry after 1 month of simulation for the default Delft3D parameter values****.*** ***Lower left corner****: cumulative erosion/sedimentation pattern after 1 month of simulation for the default Delft3D parameter values****.*** ***Lower right corner****: mean total transport after 1 month of simulation for the default Delft3D parameter values. The black arrows indicate both the direction and the magnitude of the mean total sediment transport.*

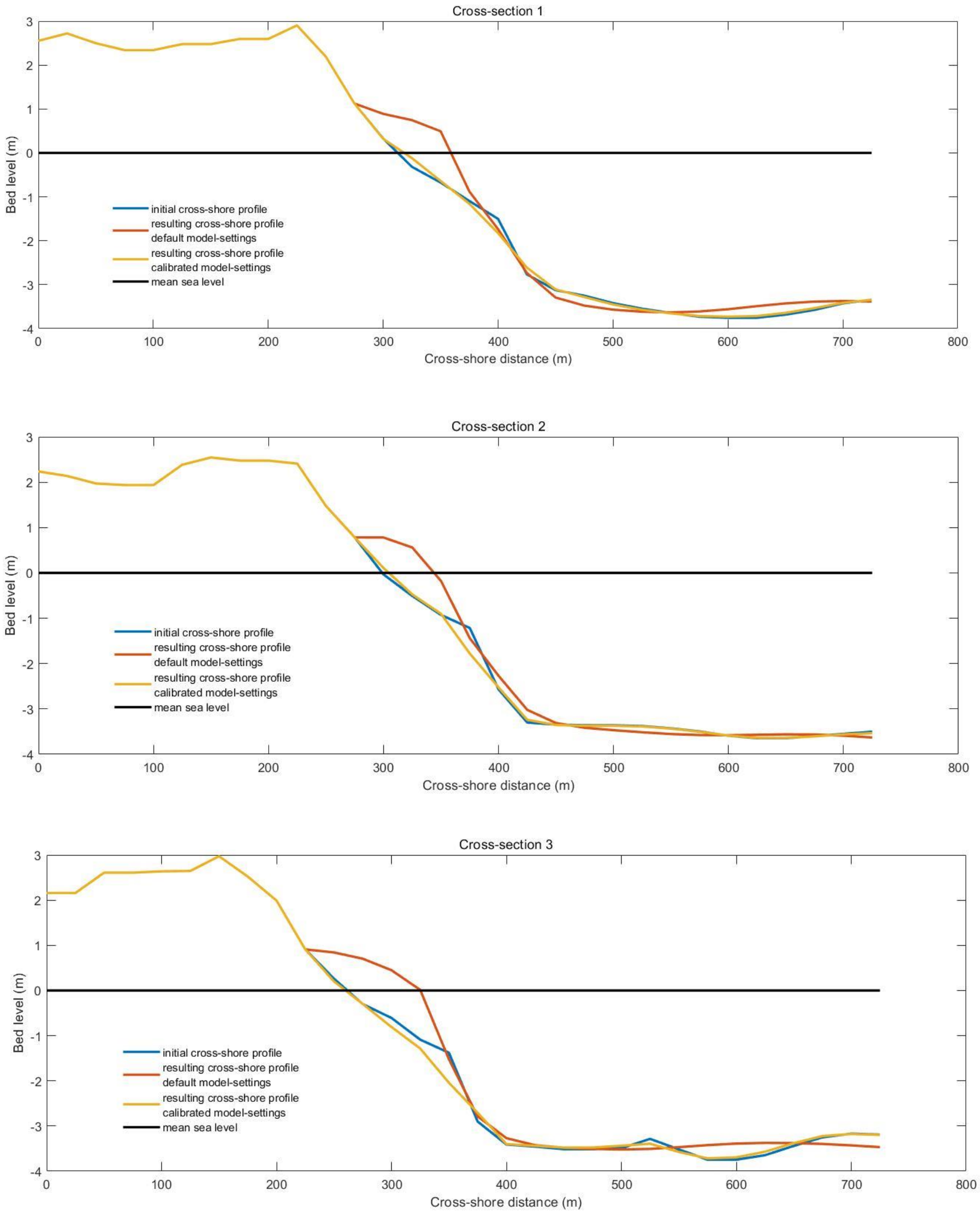


Figure 19: ***Above:*** *initial and resulting cross-shore profiles at the left edge of the control domain.* ***Middle:*** *initial and resulting cross-shore profiles at the centre of the control domain.* ***Below:*** *initial and resulting cross-shore profiles at the right edge of the control domain*

A different morphological reaction is observed for the calibrated model-settings (Figure 20). Compared to the default settings, the strong accretional pattern that occurred along the entire shoreline has disappeared. The resulting cross-shore profiles (Figure 19) show that the large deposition of sediment in the upper part of the profile has been resolved. Instead, the foreshore slope is now reworked to a smoother profile through redistribution of sediment. In cross-section 1 and 2 this is accompanied by a seaward movement of the shoreline position (MSL = 0). And in cross-section 3 the shoreline position more or less remains its original position. Using the same method as before, the volume change in the control domain is determined. Over the course of 1 month, the control domain experiences a net sediment outflux of -11.675 m^3, instead of the previously observed net sediment influx. Which agrees with the actual observed morphological behaviour within the control domain, namely that of an eroding coastline.

Extrapolation of the computed monthly volume change of -11.675 m^3, to a yearly value, results in a sediment outflux of approximately 140.000 m^3 out of the control domain. To get insight into the sediment volume changes near the centre of the island, the nourishment history at the island is consulted. Between 1970 and 2010, a total amount of 8.100.495 m^3 sediment is nourished at island's central shoreline, which comes down to a nourishment rate of approximately 200.000 m^3/year. This nourishment rate is assumed to be equal to the sediment need of the island's central coastline. Or formulated differently, the erosion rate of the island's central coastline. A comparison between the computed sediment outflux of 140.000 m^3/year, and the value of 200.000 m^3/year based on the nourishment history, teaches us that the computed sediment outflux underestimates the assumed sediment outflux.

However, there are two things that one needs to keep in mind. First, the value of 140.000 m^3/year is extrapolated based on just a single month (January). This value could both be larger or smaller when a full year is considered. Second, the nourishments between 1970 and 2010 have left Hilton Head Island with significant more beach area in 2010 compared to 1970. This means that the nourishment rate actually outpaces the underlying erosion rate, and that the value of 200.000 m^3/year overestimates the actually occurring erosion rate at the centre of the island.

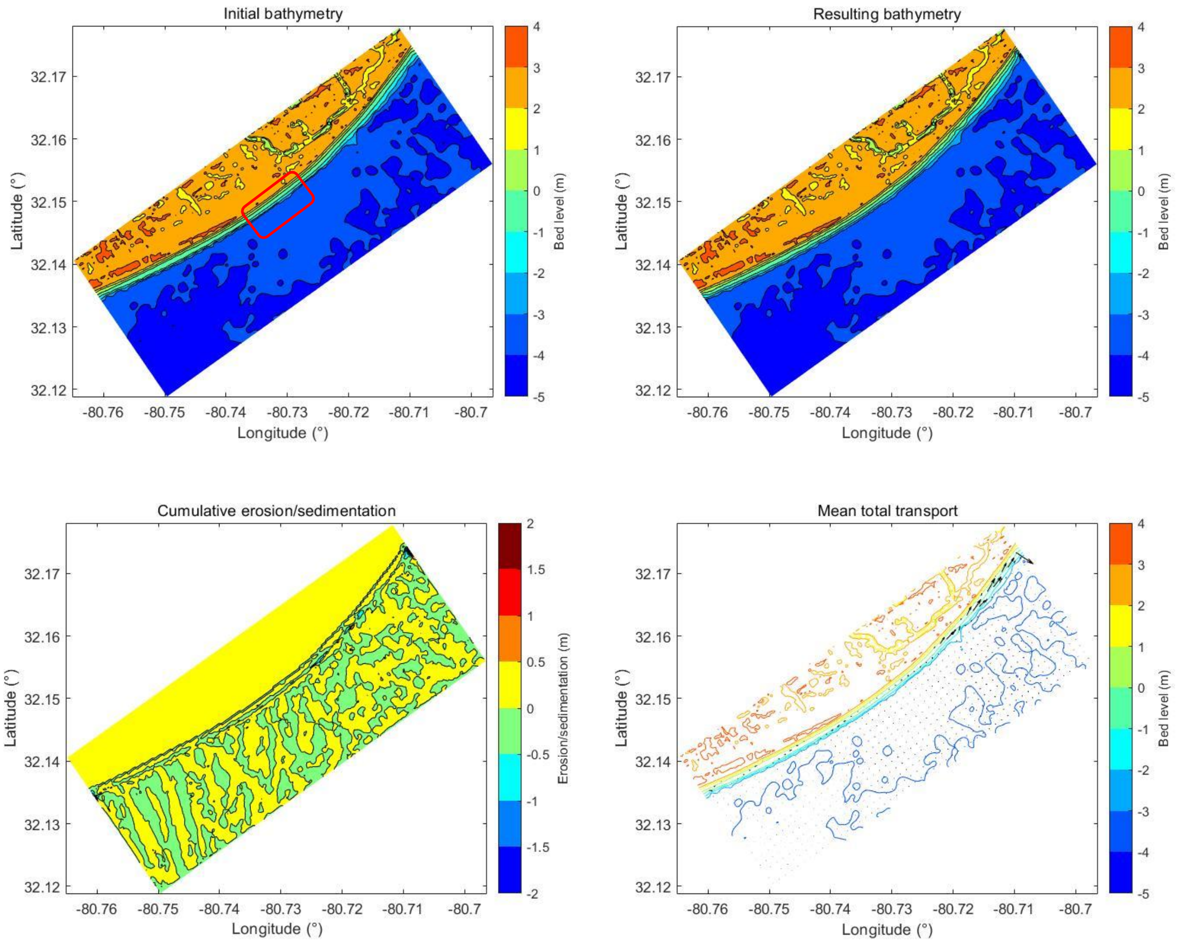


*Figure 20 : **Upper left corner:** initial bathymetry in the nested grid domain, in which the red area indicates the location of the control domain. **Upper right corner**: resulting bathymetry after 1 month of simulation for the calibrated Delft3D parameter values. **Lower left corner**: cumulative erosion/sedimentation pattern after 1 month of simulation for the calibrated Delft3D parameter values. **Lower right corner**: mean total transport after 1 month of simulation for the calibrated Delft3D parameter values. The black arrows indicate both the direction and the magnitude of the mean total sediment transport.*

A comparison between the mean total transport directions (Figure 18 and 20) shows that the onshore directed transport component outside of the surf-zone has disappeared, and that the sediment transport is now (more or less) limited to surfzone. At the centre of the island the sediment transport directions diverges into a northeast directed component, and a southwest directed component. Which agrees with the diverging pattern displayed in Figure 7 and described in Kana (1998). The magnitude of the sediment transport in the northeast direction is significantly larger than the transport in the southwest direction. Figure 8 shows that the magnitude of the MHW shoreline change rate and rate of beach volume change northeast of the centre are relatively large compared to the changes southwest of the centre. Indicating that also in reality, the magnitude of the sediment transport probably is larger in the northeast direction than in the southwest direction

A simulation run with no wave boundary conditions, and only tidal constituents, results in computed depth averaged alongshore tidal velocities at the centre of the island with a magnitude in the range of 0,1 – 0,30 m/s.

Summarized
First, the model predicts a net export of sediment out of the control domain, which agrees with the actual morphological behaviour at Hilton Head Island (Figure 9). Second, the computed order of magnitude of sediment export out of the control domain (140.000 m^3/year), is roughly in the same order as the value that is determined based on the historic nourishment events (200.000 m^3/year). Third, the calibrated model can reproduce a net transport pattern which shows similarities to the historic diverging transport pattern (Figure 8). Even though the quantitative nature of the calibration is limited, and the calibration partially relies on qualitative assessments. The results above indicate that the model is reliable enough to give an indication of the morphological development of a feeder nourishment at Hilton Head Island.

3.3. Research approach

Below the research approach applied to research questions 2 and 3 is explained.

RQ 2: How do the differences in hydrodynamic conditions and geomorphological setting between Hilton Head and the Sand Engine affect the morphological development of a feeder nourishment?
The two (major) differences between Hilton Head Island and the Sand Engine are the calmer wave climate and the presence of two tidal inlets. To determine the impact of the calmer wave climate on the feeder nourishment, the volume of sediment eroded from the feeder nourishment is compared for two scenarios. The first scenario includes both tidal forcing and wave forcing, while the second scenario only includes wave forcing. The amount of sediment that erodes from the feeder nourishment in the first year as a result of solely wave forcing, is expressed as a percentage of the total erosional volume in the first year caused by all driving forces (waves and tide). This value is compared to the value that is found at the Sand Engine. Second, the total erosional volume during the different storm events (Hs > 3,0 m) is determined and expressed as a percentage of the total erosional volume after 1 year from the feeder nourishment (scenario 1). This value is also compared to the value that is found at the Sand Engine. To assess the impact of the tidal inlets, a scenario is run in which the tidal inlets are closed off. By closing of the tidal inlets, the occurrence of tidal jets and consequently residual

currents is eliminated. Comparing the erosional volume from the feeder nourishment in a situation with closed off tidal inlets, to a reference situation with open tidal inlets, allows one to determine if the residual currents have an impact on the amount of sediment that is eroded from the feeder nourishment.

RQ 3: Can a feeder nourishment at Hilton Head Island supply sediment to adjacent coastal sections at a rate that is sufficient to prevent erosion
To be able to answer this question, first a reference scenario was run, which simulates the situation before construction of the nourishment. Then another scenario is run, which simulates the situation after construction of the nourishment. Comparison of the sediment budget in the adjacent coastal sections for both scenarios gives insight into the sediment budget of the adjacent coastal sections (erosive or accreting). Comparison of the cross-shore profiles in multiple cross-sections for both situations allows us to determine the reaction of shoreline position (retreating, moving seaward or maintaining its position).

3.4. Model scenarios

To answer the research questions, different model scenarios were simulated. Below the aim and the set-up of these scenarios is described.

3.4.1. Reference scenario

The aim of this scenario is to determine the underlying sediment volume changes and cross-shore profile changes in the three control domains before construction of a feeder nourishment. The morphological development is simulated over a time-period of 12 months. The obtained 1999 wave time-series is selected to supply the boundary conditions (Figure 6). The 12-month wave time-series is reduced to roughly one month by applying a MorFac of 12. As stated before, inherent to this specific technique of wave input reduction, is that events with a relative low frequency of occurrence are eliminated. Especially, the extreme wave heights during storms, that by nature have a low frequency of occurrence, are victim to elimination. Given the hypothesis that storms play a major role in the feeding behaviour of the nourishment, it is important to simulate storm events correctly. To achieve this, a time dependent MorFac is applied. During storm events, the default value of 1 is used for the MorFac. This means that there is no reduction of the number of wave conditions, which ensures that 'storms' are represented properly during the simulation. For the 'regular' conditions, the predetermined MorFac of 12 is applied.

According to De Schipper et al (2016), the morphological changes at the Sand-Engine pilot project were most pronounced during the first 6 months after placement. A modelling study by Halbmeijer (2019) into the development of a mega-nourishment at the Florida coastline, states that most of the morphological changes there occurred within the first 12 months after placement. Therefore, it is assumed that a 12-month simulation should suffice to get a decent insight into the morphological development at Hilton Head Island as well.

3.4.2. Feeder nourishment scenario 1

The aim of this scenario is to determine the underlying sediment volume changes and cross-shore profile changes in the three control domains after construction of a feeder nourishment. The boundary conditions, simulation time and MorFac are the same as in the reference scenario, the only difference is that the bathymetry now includes a feeder nourishment.

3.3.3. Feeder nourishment scenario 2

The aim of this scenario is to establish the percentage of wave induced erosion, relative to the total erosional volume from the feeder nourishment after 1 year caused by all driving forces (waves and tide). The boundary conditions, simulation time and MorFac are the same as in feeder nourishment scenario 1, the only difference is that tidal forcing is eliminated from the simulation as a driving force.

3.3.4. Feeder nourishment scenario 3

The aim of this scenario is to discern the impact of residual currents on the feeder nourishment. The boundary conditions, simulation time and MorFac are the same as in feeder nourishment scenario 1. The only difference is that the tidal inlets are closed off. Closing of the tidal inlets eliminates tidal jets and the potential accompanying residual currents, while the horizontal and vertical tide remain part of the simulation. The tidal channels and ebb-tidal delta owe their existence to the tidal inlets and closing of the inlets would also impact these bathymetrical features. Most likely, closing of the inlets would result in the disappearance of the tidal channels and the ebb-tidal over time. In an effort to let the bathymetry fit better to the new situation, the tidal channels are filled in with sediment and the ebb-tidal delta is smoothed to get a more gradual transition in the cross-shore direction. It has to be noted, however, that this new bathymetry does not accurately represent the bathymetry that would occur in a situation with closed off inlets, and that it is merely an approximation. Therefore, one has to be careful with the interpretation of these results. As the bathymetry can have a significant impact on the character of the flow pattern and/or sediment transport pattern. Furthermore, both inlets are closed off at once. Therefore, it is unknown what the separate impact of each tidal inlet is on the behaviour of the feeder nourishment.

Table 4 provides an overview of the different model scenarios and their characteristics (forcing, bathymetry, and run-time).

Table 4: Overview of the different model scenarios

Scenario	Wave forcing	Tidal forcing	Feeder-nourishment	Tidal inlets	Run-time
Reference	Yes	Yes	No	Open	12 months
Feeder nourishment 1	Yes	Yes	Yes	Open	12 months
Feeder nourishment 2	Yes	No	Yes	Open	12 months
Feeder nourishment 3	Yes	Yes	Yes	Closed	12 months

3.5. Design feeder nourishment

The design of the nourishment depends on its location, the necessary volume, the occurring depth of closure and its shape. All these characteristics are treated below, after which a basic design is presented for the nourishment

Location

The erosion predominantly occurs along a stretch of the mid-island shoreline (Figure 9). This is a result of the diverging net sediment transport pattern that redistributes sand from the centre to both ends of the island (Figure 8). The most logical solution would be to construct the feeder nourishment at the location of the transport reversal. First, this the area where the strongest erosional capacity is expected to occur. As on average sediment is transported out of this area in both southern and northern direction, with no or limited influx of sediment. Resulting in large transport gradients and consequently large volume changes (erosion). Secondly, the diverging transport pattern would hypothetically enable the nourishment to feed both the sediment starving coastlines to the northeast and southwest. If we do not make use of the transport reversal and locate the nourishment more to the south or north. The possibility increases that the nourishment is only capable of feeding sediment at a sufficient rate to just one of the adjacent coastlines, instead of both.

Volume feeder nourishment

Between 1980 and 2010, a total amount of 7.065.175 m3 sediment is nourished at island's central shoreline. This comes down to a nourishment rate of 235.500 m^3 per year. Currently, traditional nourishments occur at a frequency of every 7-10 years. One of the aims of a feeder nourishment is to reduce the nourishment frequency compared to the traditional methods, which means that the intended lifetime should at least be 10 years in this case. By multiplying the intended lifetime and the historic yearly nourishment rate, the required sediment volume can be approximated. For a mega-nourishment with an intended lifetime of 15 years, this would result in a required sediment volume of roughly 3,5 million m^3.

Depth of closure

The assumed DOC at Hilton Head Island (- 4,5 m) is small compared to the DOC at the Sand-Engine pilot project (- 8,0 m). One would think that this results in a relatively narrow literal zone, however, the opposite is true. The shallow shoals off Hilton Head's coastline extend on average approximately a kilometre offshore, facilitating a wide surf zone which is comparable in width to the surf zone at the Sand Engine (roughly 1000 meters). This wide surf zone is to our advantage, as it does not limit the cross-shore extent of a nourishment like a narrow surf zone would.

Shape

Regarding the geometric shape of the feeder nourishment, virtually unlimited design choices can be made curved, rectangular, triangular, etc. Different shapes could possibly have a different effect on the feeding properties. In this case the choice is made to give the nourishment a curved (Gaussian) shape. This shape has already proven successful in other applications of feeder nourishments along the U.S. East Coast (Maglio et al., 2015). And it also shows some similarity to the shape of the Sand-Engine, which has also proven its effectiveness. Optimization of the geometric shape could be an interesting topic for further research.

Design

Figure 21 presents the design of a 3,5 million m^3 feeder nourishment with an intended lifetime of 15 years. The alongshore length measures roughly 1500 meters, and the maximum cross shore extent measures approximately 500 meters. One can observe that all the sediment is placed on the shallow shoals, within the depth of closure, following the advice given in the research by Roest et al (2018).

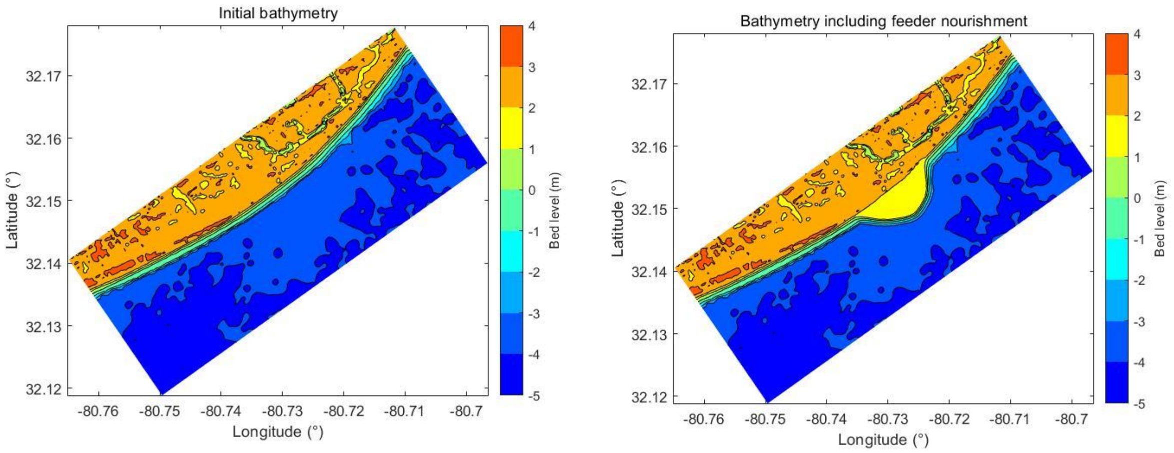


*Figure 21: **Left:** Initial bathymetry in the nested grid domain. **Right:** Bathymetry including feeder nourishment.*

4 Model results

4.1. Reference scenario

The aim of this scenario is to gain insight into the morphological behaviour of the area before construction of the feeder nourishment. This behaviour is used both as a reference for the next model scenarios that include the construction of a feeder nourishment, and for further validation of the numerical model. Figure 22 presents the initial bathymetry in the nested grid domain, the resulting bathymetry after 12 months of simulation, the cumulative erosion/sedimentation pattern, and the mean total sediment transport pattern.

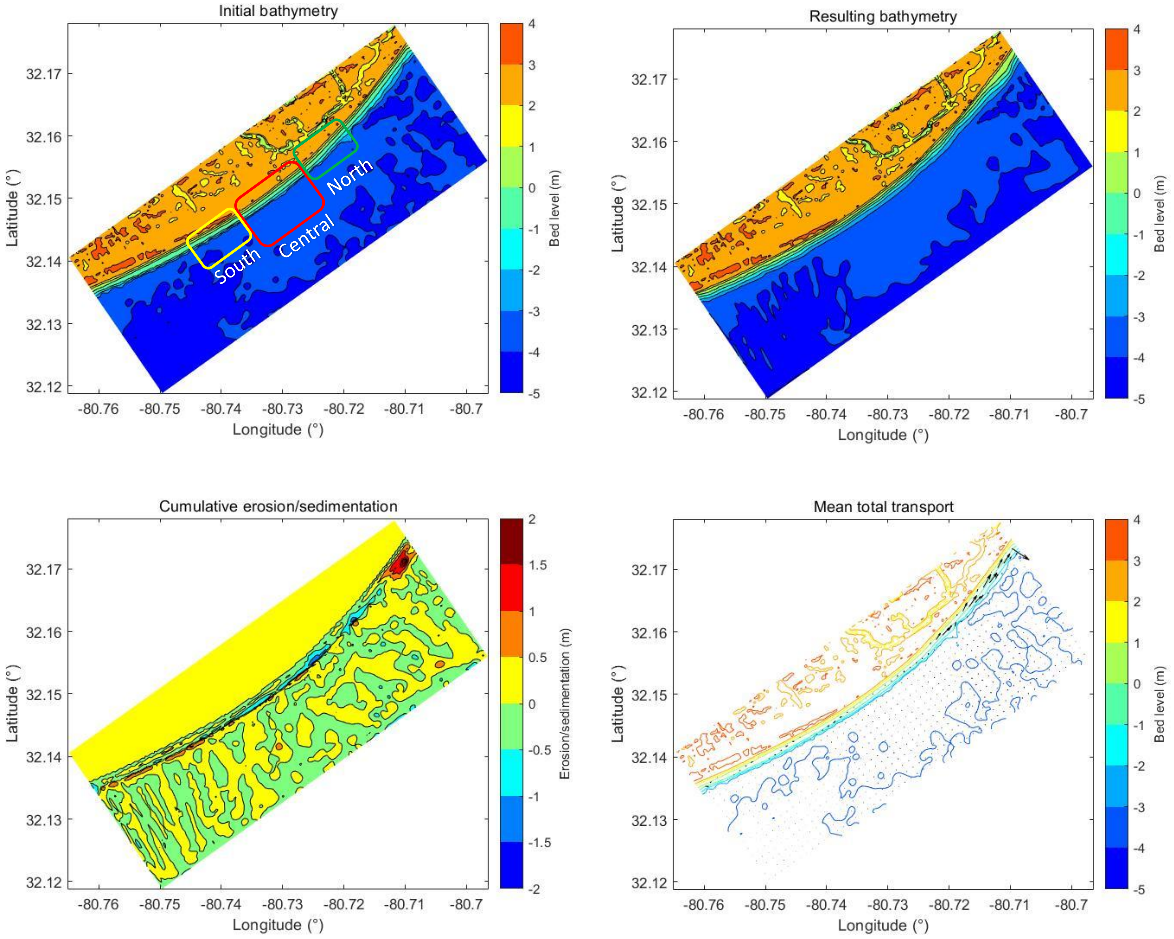


*Figure 22: **Left upper corner**: Initial bathymetry in the nested grid domain, including the three control domains: south, central, and north. **Right upper corner:** Resulting bathymetry after 12 months of simulation. **Left lower corner:** Cumulative erosion/sedimentation pattern after 12 months of simulation. **Right lower corner:** mean total transport after 12 months of simulation. The black arrows indicate both the direction and the magnitude of the mean total sediment transport.*

A comparison between the initial and the resulting bathymetry indicates that the foreshore slope is being reworked to a flatter profile. To obtain a more detailed look into the morphological development of the foreshore slope the cross-shore profiles are analysed. Figures 23, 24 and 25 present the initial cross-shore profile and the resulting cross-shore profile after 12 months of simulation for respectively the southern, central, and northern control domain. The cross-shore profile changes confirm the suspicion that the slope is being reworked. In all cross-sections the irregular initial foreshore slope transitions into a smoother profile, which is in most cases accompanied by a flatter slope. The comparison between the initial and the resulting bathymetry also teaches us that there is significant morphological activity outside of the surfzone. The shallow shoals are being reworked into a different pattern . Which results in the spotted “leopard” like pattern of the cumulative/erosion sedimentation plot outside of the surfzone.

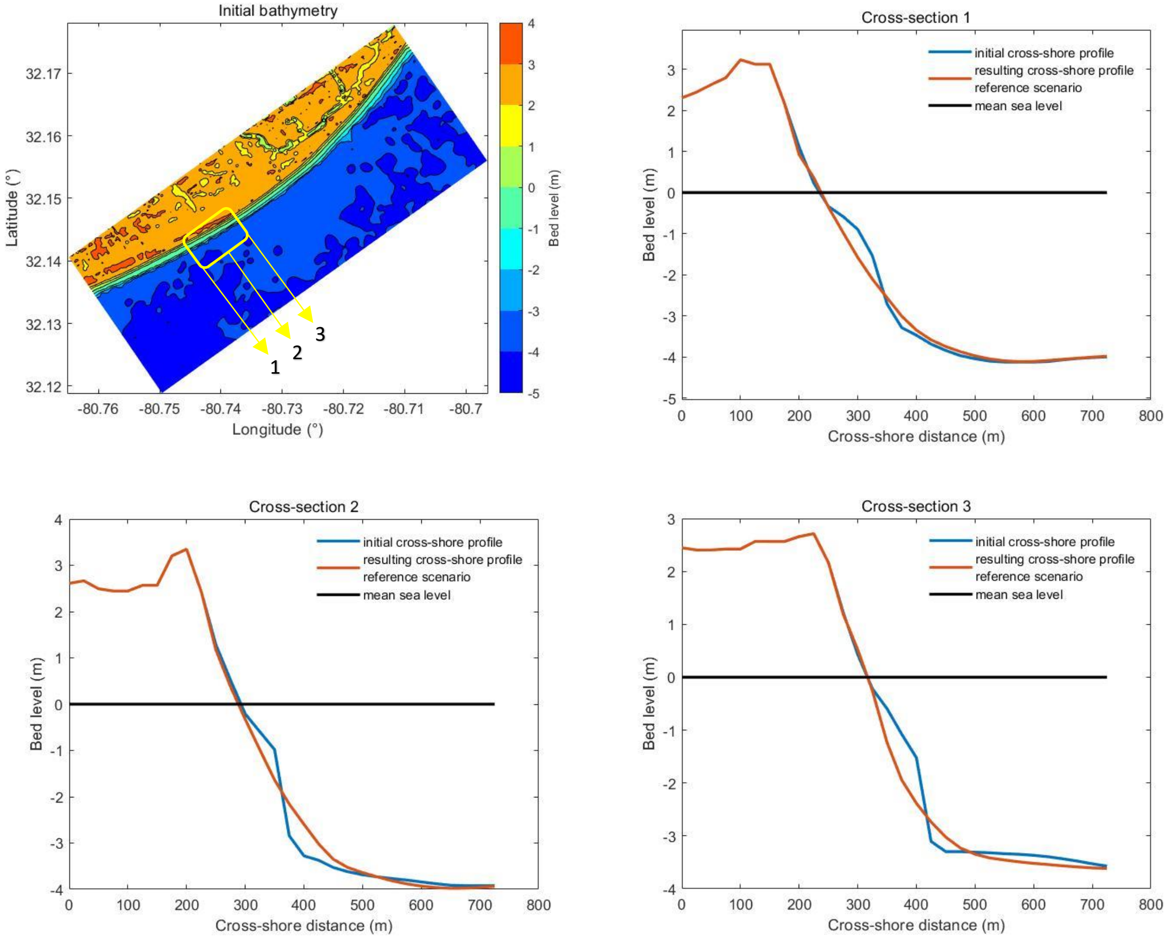
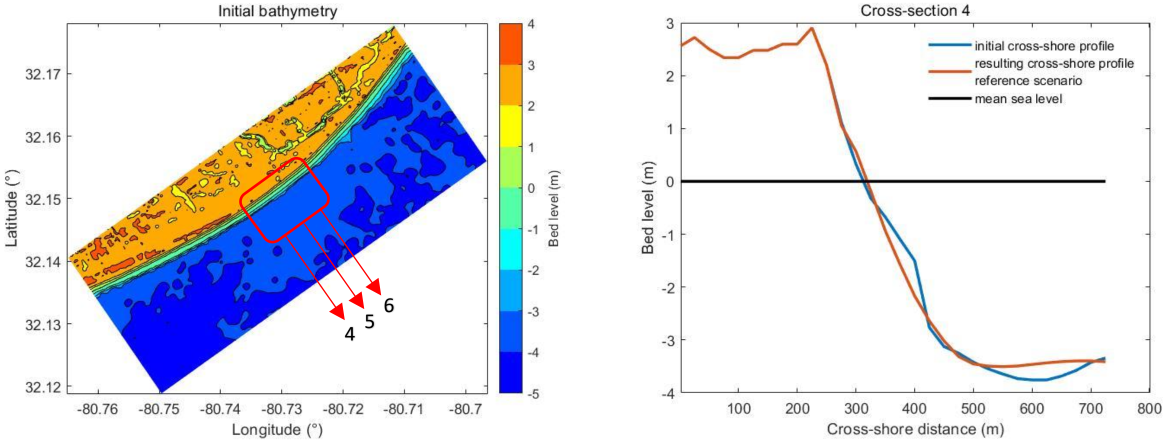


*Figure 23: **Left upper corner:** Location of cross-sections 1,2 and 3 in the southern domain. **Right upper corner:** Cross-shore profiles in cross-section 1. **Left lower corner:** Cross-shore profiles in cross-section 2. **Right lower corner:** Cross-shore profiles in cross-section3*



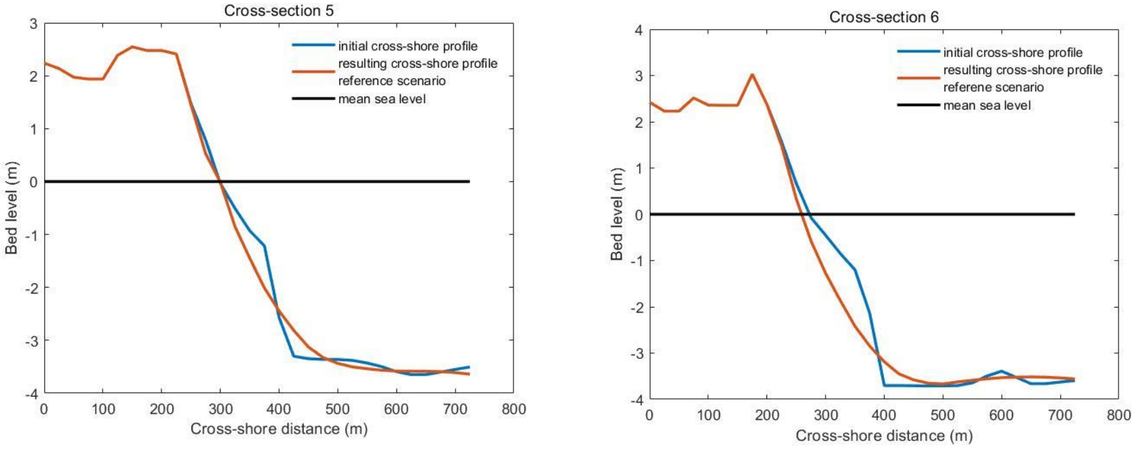


*Figure 24: **Left upper corner:** Location of cross-sections 4,5 and 6 in the central domain. **Right upper corner:** Cross-shore profiles in cross-section 4. **Left lower corner:** Cross-shore profiles in cross-section 5. **Right lower corner:** Cross-shore profiles in cross-section 6*

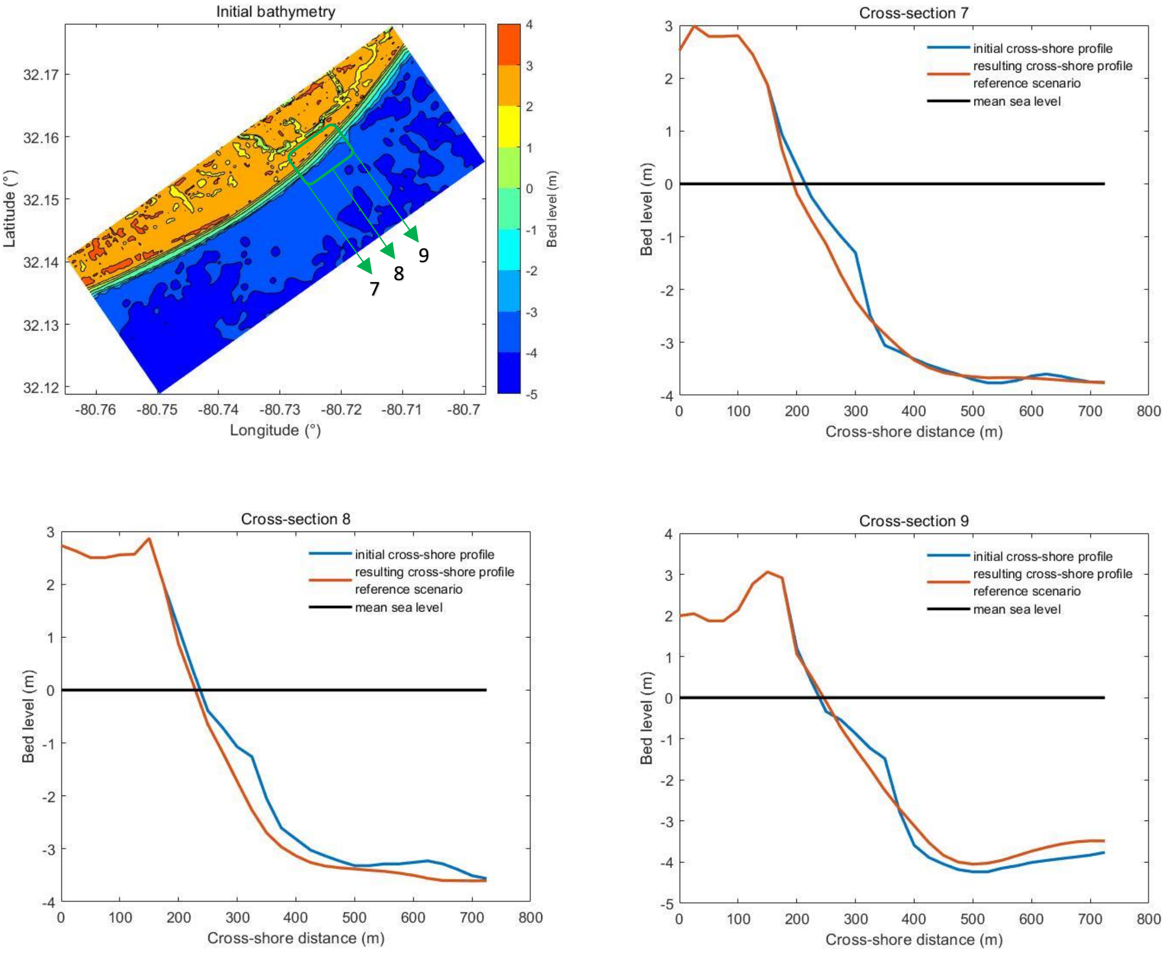


*Figure 25: **Left upper corner:** Location of cross-sections 7, 8 and 9 in the northern domain. **Right upper corner:** Cross-shore profiles in cross-section 7. **Left lower corner:** Cross-shore profiles in cross-section 8. **Right lower corner:** Cross-shore profiles in cross-section 9*

To be able to determine the volume changes at the feeder nourishment, and in the adjacent coastal sections, control domains were established (Figure 22). The central domain is used in the following model scenarios to determine the volume changes at the feeder nourishment, and is designed to cover the entire nourishment, it measures 1500 by 1250 meter. The southern and northern domains are used to determine the volume changes in the adjacent coastal sections to the north and south of the nourishment. Both are equal in size, and measure 750 meter in the cross-shore direction, and 1000 meter in the alongshore direction. The alongshore length of the southern and northern domain is based on the experiences at the Sand-Engine. Here adjacent coastal sections up to approximately a kilometre away from the nourishment experienced volume changes related to the nourishment in the first year after placement. Figure 26 presents the cumulative volume changes in the three control domains.

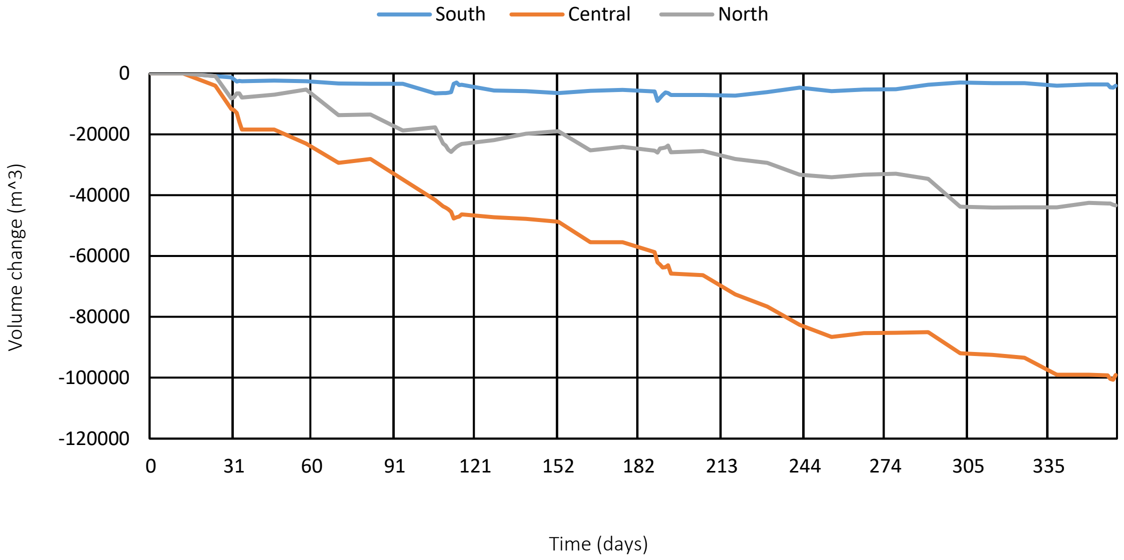


Figure 26: Cumulative volume changes in the reference scenario for the three control domains: south, central and north.

Figure 26 shows that the model predicts a net outflux of sediment out of all three control domains. The locations of the three control domains (south, north and central) are indicated in Figure 27. In panel d of this figure one can observe that in reality the central and northern domain also experience a net sediment outflux (red bars). The southern domain, however, should experience a net influx of sediment according to panel d of Figure 27 (green bars). The model, however, predicts a net sediment outflux out of the southern domain. Nonetheless, in the second part of the simulation, after approximately 200 days, the trend changes and the southern domain indeed experiences a sediment influx rather than a sediment outflux. The volume changes in the southern domain are significantly smaller in magnitude compared to the other two domains. This is the result of the relatively small alongshore transport capacity in the southern control domain (Figure 22). The above further validates the assumption that the model is reliable enough to give an indication of the morphological development of a feeder nourishment at Hilton Head Island.

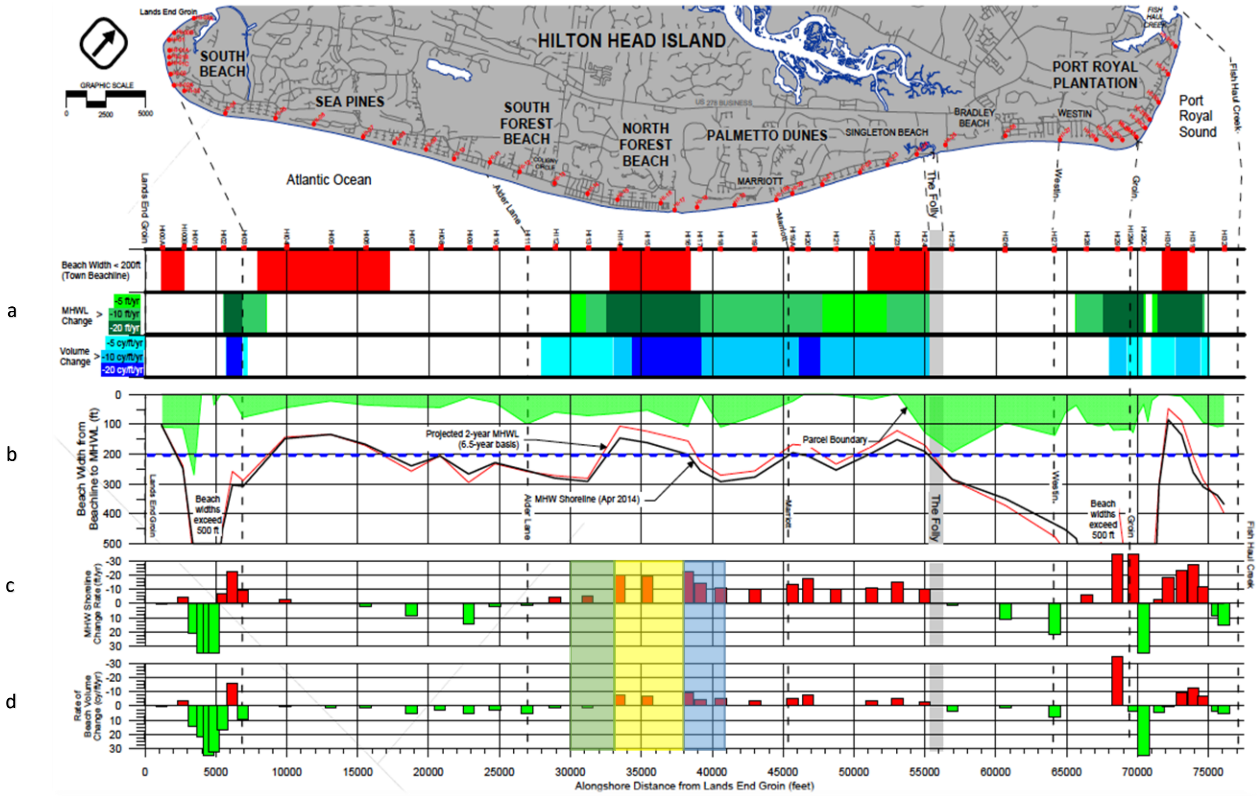


Figure 27: Overview of the morphological development at Hilton Head Island between March 2007 and April 2014. The translucent green square area indicates the location of the southern domain, the yellow square the location of the central domain, and the blue square the location of the northern domain. [Source: Olsen Associates, 2014].

Panel a) ***above:*** *areas with a beach width less than 60 m (red) ;* ***middle:*** *MHWL change (light green = - 1,5 m/year ; green = - 3,0 m/year; dark green = - 6,0 m/year) ;* ***bottom:*** *volume change (light blue = - 12 m^3/year ; blue = - 24 m^3/year ; dark blue = - 48 m^3/year)*

Panel b) beach width from MHWL to the beachline in feet. The black line is the beach width on April 2014, the red line is the projected beach width in two years' time.

Panel c) shoreline change rate in feet per year. Red blocks indicate a shoreline retreat and green blocks indicate a seaward movement of the shoreline.

Panel d) rate of beach volume change in cubic yard per feet per year. Red blocks indicate erosion and green blocks indicate accretion

4.2. Feeder nourishment scenario 1

The aim of this scenario is to determine the morphological development of the coastline after construction of the feeder nourishment. Figure 28 presents the initial bathymetry in the nested grid domain, the resulting bathymetry after 12 months of simulation, the cumulative erosion/sedimentation pattern, and the mean total transport pattern.

A comparison between the initial and the resulting bathymetry shows that the feeder nourishment is experiencing a retreat in the cross-shore direction. This cross-shore retreat also become apparent from the cumulative erosion/sedimentation pattern, which shows erosion along almost the entire outer perimeter of the nourishment. The resulting bathymetry further indicates that the nourishment is widening in the alongshore direction. The widening seems to be dominant in the southern direction.

This assumption is confirmed by the cumulative erosion/sedimentation pattern, which shows strong accretion on the south side of the nourishment and relatively low accretion on the north side.

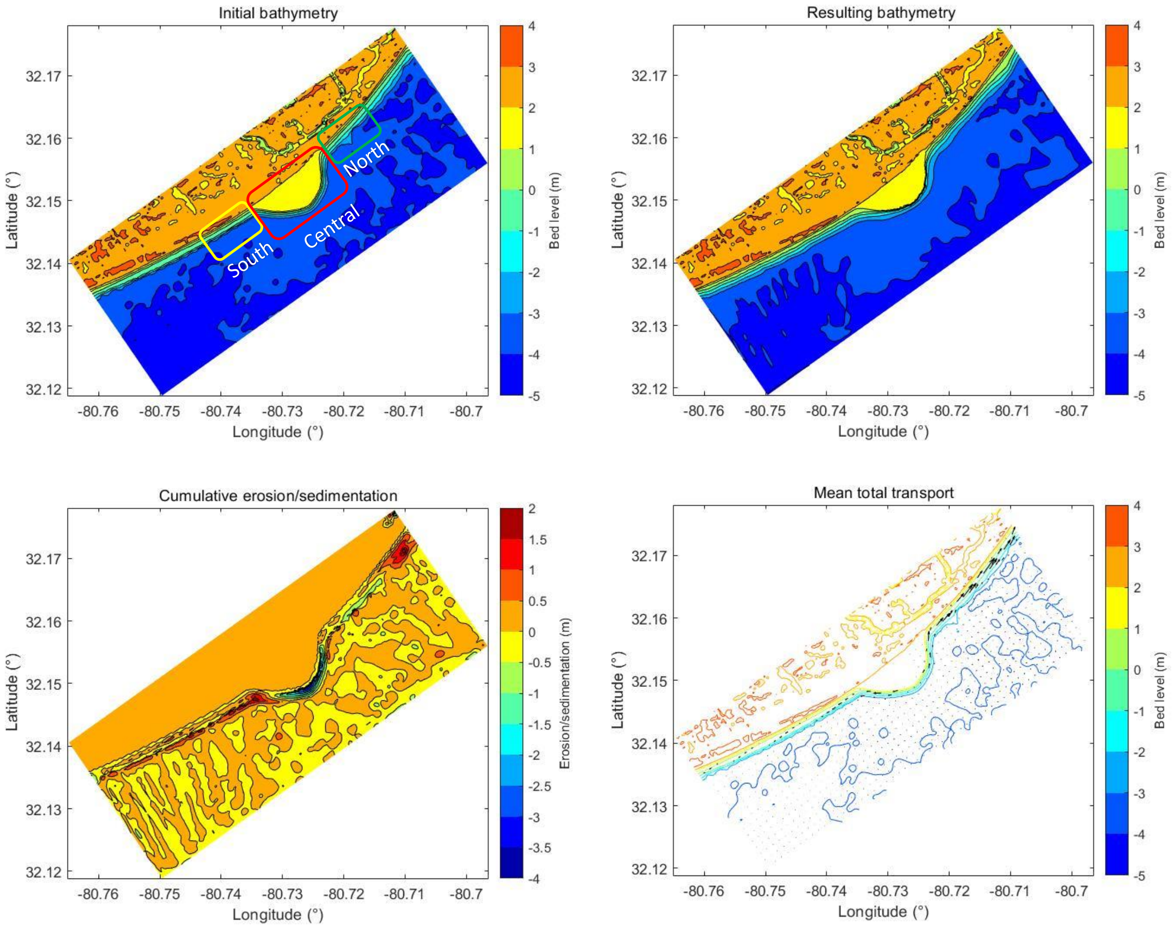


*Figure 28: **Left upper corner**: Initial bathymetry in the nested grid domain, including the three control domains: south, central, and north. **Right upper corner**: Resulting bathymetry after 12 months of simulation. **Left lower corner**: Cumulative erosion/sedimentation pattern after 12 months of simulation. **Right lower corner:** mean total transport after 12 months of simulation. The black arrows indicate both the direction and the magnitude of the mean total sediment transport.*

Sediment is being transported from the feeder nourishment in both directions. The magnitude of the sediment transport is larger in the northern direction than in the southern direction, just like in the reference scenario. To the south of the nourishment the transport capacity quickly decreases, such a decrease (negative gradient) in transport capacity generally leads to accretion. Which is exactly what we observe on the south side of the nourishment. Almost the entire southern domain seems to experience accretion. To the north of the nourishment the transport pattern is different. In the northern direction, the transport capacity does not decrease, and even seems to increase in magnitude. As a result, there is relative low accretion to the north of the nourishment, and some areas even seem to experience erosion. Again, there is also significant morphological activity outside of the surfzone. The resulting cumulative/erosion sedimentation pattern outside of the surfzone is practically identical to that of the reference scenario (Figure 22)

A more detailed look into the morphological development of the feeder nourishment is provided by the cross-sections of Figures 29.

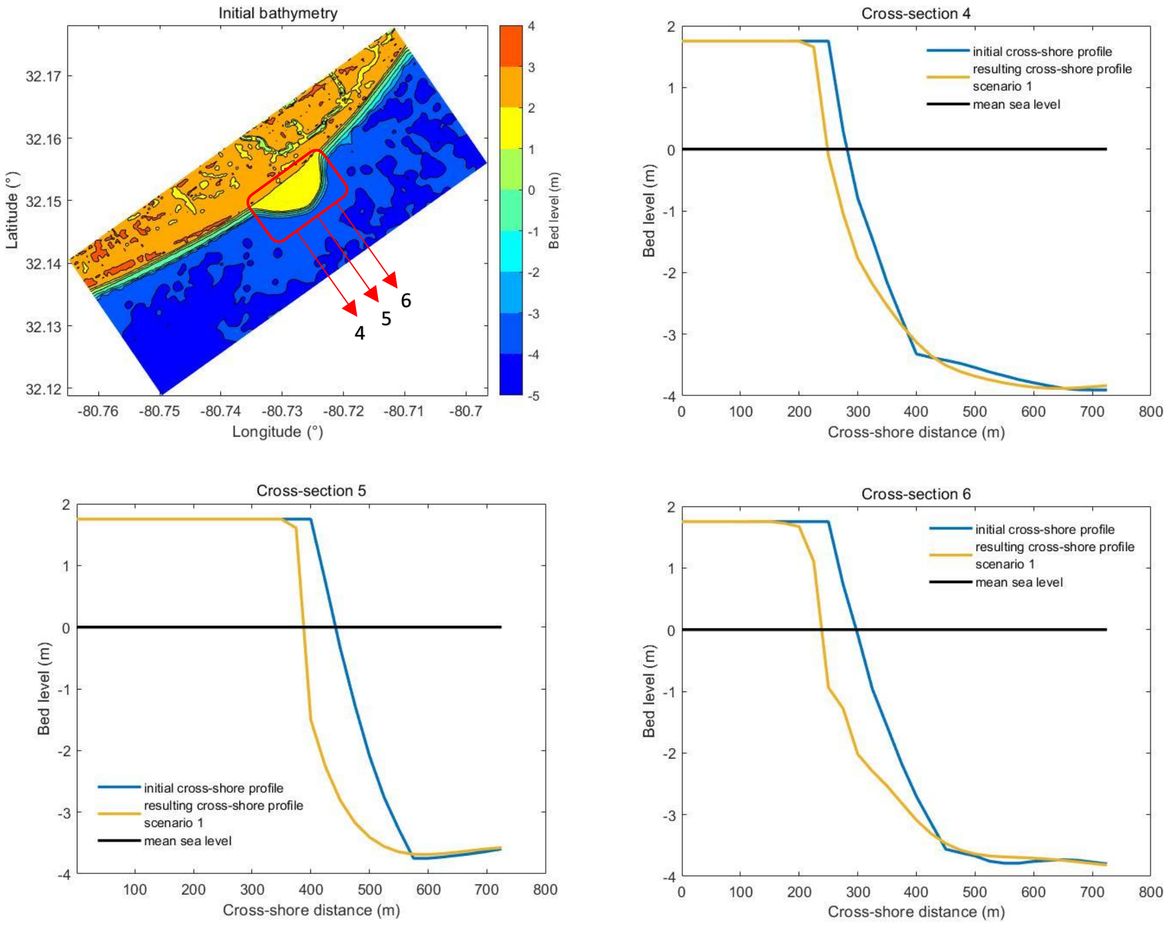


*Figure 29: **Left upper corner**: Location of cross-sections 4, 5 and 6 in the central domain. **Right upper corner**: Cross-shore profiles in cross-section 4. **Left lower corner**: Cross-shore profiles in cross-section 5. **Right lower corner**: Cross-shore profiles in cross-section 6*

All three cross-sections display a significant retreat in the cross-shore direction, which varies in magnitude between approximately 25 to 75 meters. Given its exposure, one would expect that the erosional volume and cross-shore retreat in cross-section 5 (the most seaward point of the nourishment) would be largest. However, this not the case. The cross-shore retreat is actually the largest in cross-section 6 and reduces in magnitude in the southern direction. Second, a visual comparison between the cross-sections indicates that the erosional volume in cross-section 5 is comparable in magnitude to that of cross-section 6. The erosional volume in cross-section 4 is significantly smaller in magnitude. This again agrees with the relatively large, and seemingly increasing alongshore transport capacity in the northern direction from the centre. And the relatively small and decreasing alongshore transport capacity in the southern direction from the centre. Finally, the resulting slope of the nourishment shows distinct differences in shape for the three cross-sections. What the three cross-sections do have in common, is that resulting slopes are relatively steep compared to computed slopes for this section of coastline in the reference scenario (Figure 24).

Figures 30 and 31 present the development of the cross-sections in the southern domain and northern domain, combined with the development of these cross-sections in the reference scenario (without nourishment).

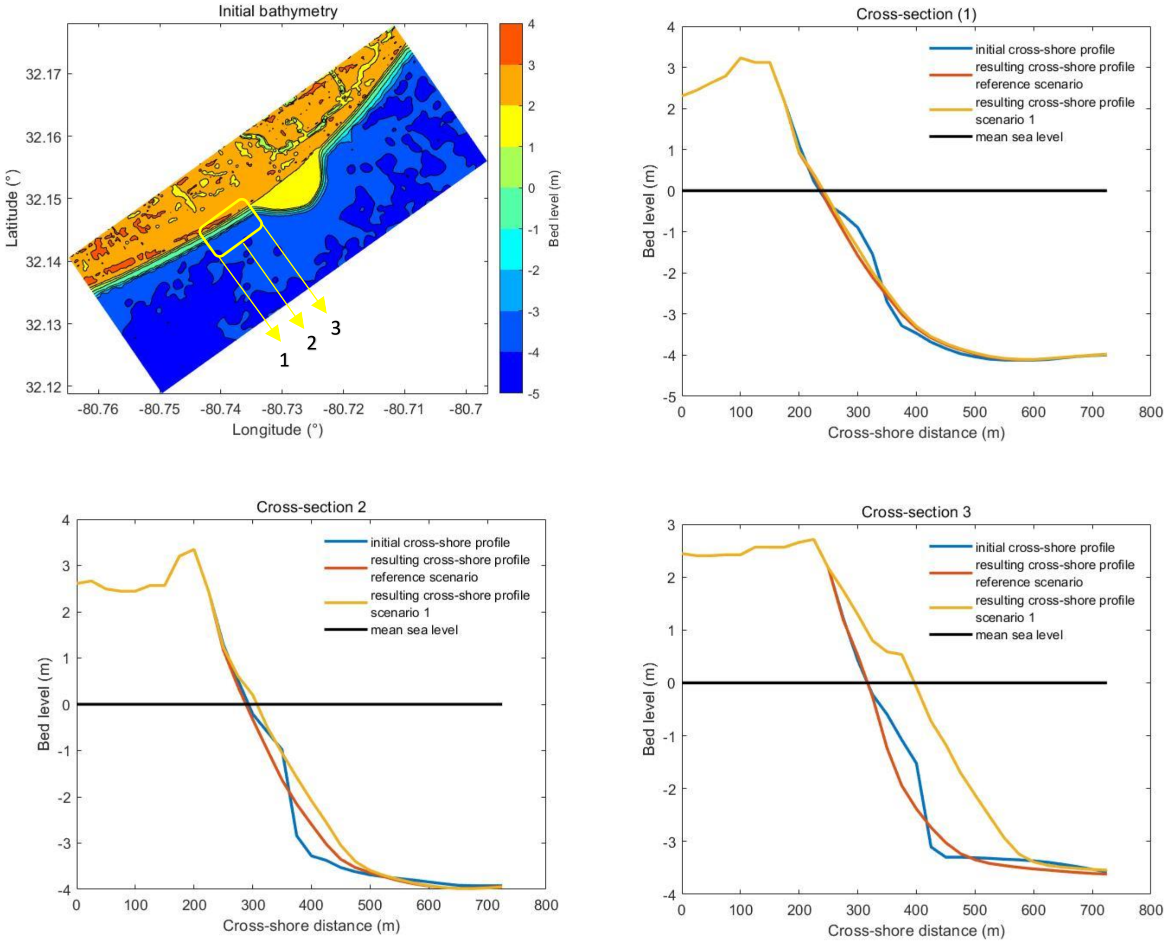
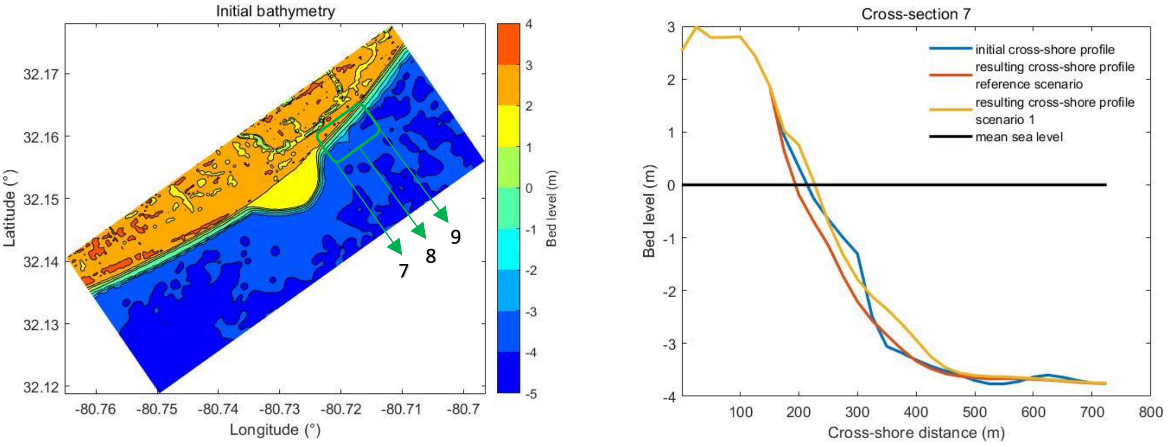


Figure 30: ***Left upper corner:*** *Location of cross-sections 1, 2 and 3 in the southern domain.* ***Right upper corner:*** *Cross-shore profiles in cross-section 1.* ***Left lower corner:*** *Cross-shore profiles in cross-section 2.* ***Right lower corner:*** *Cross-shore profiles in cross-section 3*



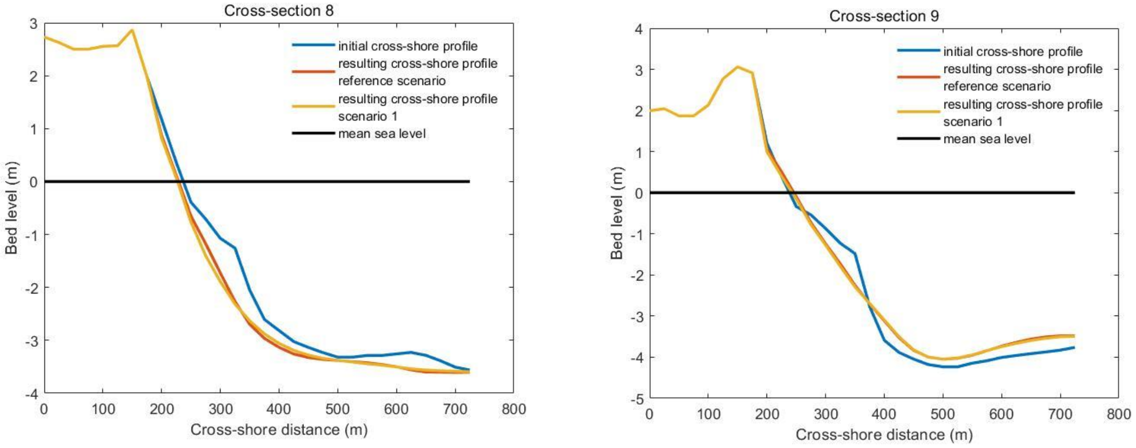


*Figure 31: **Left upper corner**: Location of cross-sections 7, 8 and in the northern domain. **Right upper corner**: Cross-shore profiles in cross-section 7. **Left lower corner**: Cross-shore profiles in cross-section 8. **Right lower corner**: Cross-shore profiles in cross-section 9.*

The cross-shore profile changes in the southern control domain (Figure 30) show that both cross-sections 2 and 3 experience a significant amount of accretion compared to the reference scenario. The profile in cross-section 1 is more or less similar to that of the reference scenario, showing only the minimum amount of accretion. The seaward movement of the shoreline position (MSL = 0) in cross-section 3 measures approximately 100 meters. It then reduces to approximately 25 meters in cross-section 2 and becomes approximately 0 meter in cross-section 3. This accretional behaviour of the southern control domain also becomes apparent from the sediment budget (Figure 32). In the reference scenario the southern domain is subjected to a relatively small amount of erosion. Over the course of 1 year the domain has lost roughly 4000 m^3 of sediment. However, after construction of the feeder nourishment, the domain experiences a net import of sediment of approximately 100.000 m^3. Meaning that the domain, on average, has transitioned from being slightly erosive to accreting. And that the feeding rate of the nourishment, outpaces the underlying erosion rate in this domain. This behaviour agrees with the observed cumulative erosion/sedimentation pattern (Figure 28). Which shows a relatively strong accretional pattern in almost the entire southern domain.

The cross-shore profile changes in the northern domain (Figure 31) show that only cross-section 7 experiences accretion compared to the reference scenario. The seaward movement of the shoreline position (MSL = 0) measures approximately 25 meters. Cross-section 8 shows signs of being slightly erosive, and cross-section 9 seems to remain stable. In both cases there is no observable change in the position of the shoreline position. The volume changes in the northern domain (Figure 32) show that the outflux of sediment out of the domain has reduced from -40.000 m^3 in the reference scenario, to approximately -25.000 m^3 after construction of the feeder nourishment. This means that the feeder nourishment is feeding sediment to this domain, but at a rate that is not large enough to keep up with the underlying erosion rate. As a result, the domain, on average, still experiences a sediment outflux and stays erosive. This behaviour agrees with the observed cumulative erosion/sedimentation pattern (Figure 28). Which displayed relatively small amounts of accretion in some areas of the domain, and erosion in others.

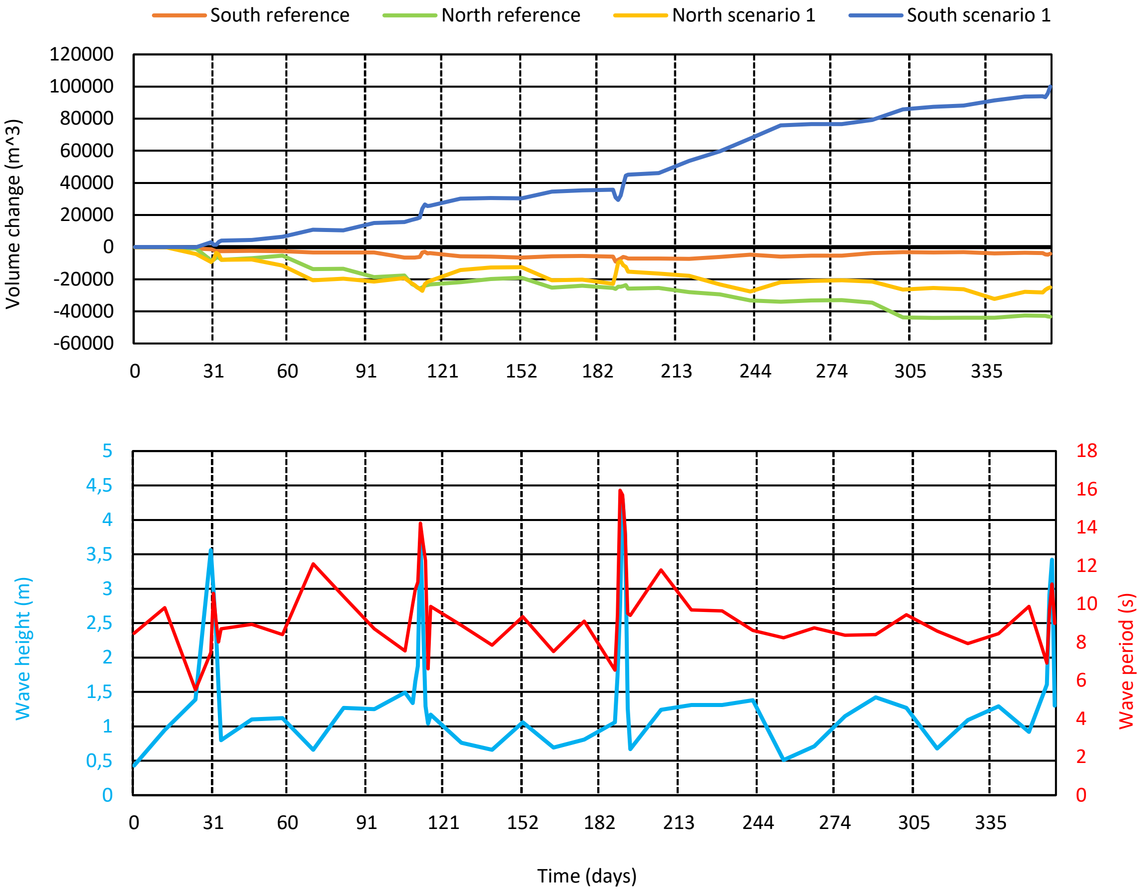


*Figure 32: **Above:** Cumulative volume changes in the southern domain and northern domain for the reference scenario and feeder nourishment scenario 1. **Below:** The simulated wave time-series (wave period height and wave period).*

No clear trend between the volume changes in the domains and either wave height or wave period becomes apparent from Figure 32. During storms, however, relative steep gradients occur in the volume changes. The reaction of the southern and the northern domain during these storms is exactly opposite. If one domain experiences an influx of sediment, the other experiences an outflux of sediment, and vice versa. This is because the storms events tend to originate from different directions, resulting in different transport patterns. The waves at Hilton Head Island display a narrow range of directions, with almost all waves arriving between the nautical angles of 67,5° and 180°. However, despite the limited range in wave directions, there are no less than three distinctly different sediment transport patterns. Waves originating between 67,5° and 120° generate a southwest directed sediment transport. Waves originating between 130° and 180° generate a northeast directed transport. Between 120° and 130° there is a "sweet spot" where the sediment transport diverges at the centre and simultaneously a southwest and northeast directed transport occurs. This phenomenon occurs during the last storm of the simulated wave time-series, and both adjacent coastal sections experience an influx of sediment.

Figure 33 displays the cumulative volume changes at the feeder nourishment (central domain) and the sum of the cumulative volume changes in the adjacent northern and southern sections. Now we can discern a trend between the wave height and the volume changes. Periods of relatively large wave heights result in an increased amount of sediment that is eroded from the nourishment. The steepest increase in erosional volume occurs during storm events. The total erosional volume during storm events measures approximately 50.000 m^3. This amounts to 23% of the total erosional volume after one year, which measures approximately 215.000 m^3 (Figure 33).

The second observation that can be made is that the amount of sediment that is eroded from the nourishment, does not equal the amount of sediment that accretes in the northern and southern domain. The total amount of sediment that is eroded from the nourishment measures roughly 215.000 m^3. The combined amount that accretes in the southern and northern domain equals approximately 125.000 m^3. This indicates that roughly 90.000 m^3 of sediment has been transported outside of the control domains. Which could either be transported further alongshore or in the cross-shore direction.

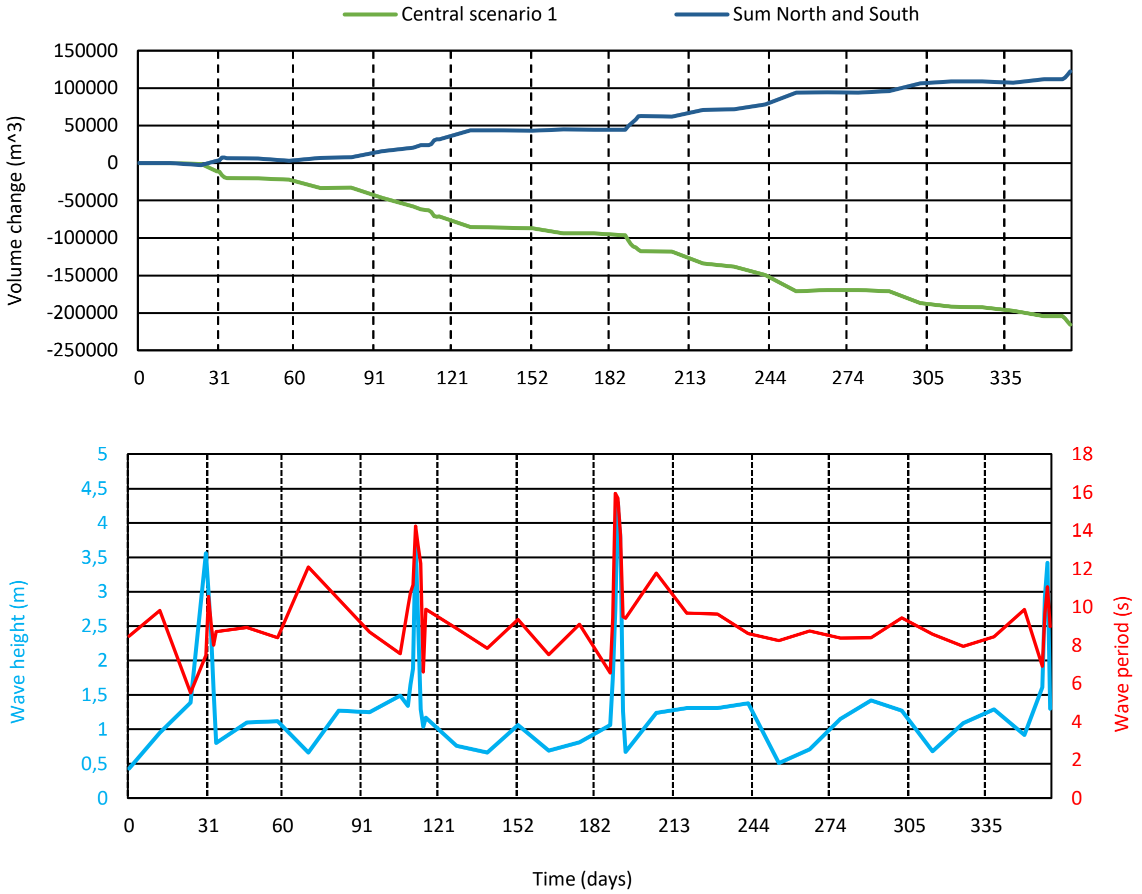


*Figure 33: **Above:** cumulative volume changes in the central domain, and the sum of the cumulative volume changes in the adjacent domains for feeder nourishment scenario 1. **Below:** The simulated wave time-series (wave period height and wave period).*

The assumption is that the observed difference between the amount of sediment eroded from the nourishment, and the amount of sediment accreting in the adjacent control domains, is a result of sediment being deposited outside of the northern control domain. This assumption is based on the relatively large and increasing alongshore transport magnitude in the northern direction (Figure 28). To assess this assumption, the cumulative erosion/sedimentation behaviour of the reference scenario is subtracted from the cumulative erosion/sedimentation behaviour of the feeder nourishment scenario (Figure 34). If sediment is transported and deposited further alongshore outside of the northern domain, one would expect an increase in accretion there, compared to the reference scenario. However, this is not the case. Also, outside of the nested grid domain, no significant increase in accretion is observed. Which indicates that the initial assumption is incorrect. The same can be said for the coastline to the south from the southern control domain. Again, no significant increase in accretion along the shoreline compared to the reference scenario is observed. In the cross-shore direction also no significant increases in accretion are observed compared to the reference scenario. Therefore, it is uncertain where the sediment that is lost from the control domains is transported to. One possibility is that the sediment is transported to the tidal inlets and subsequently deposited outside of the main grid. Another possibility is that the missing volume is preserved in the model as suspended sediment.

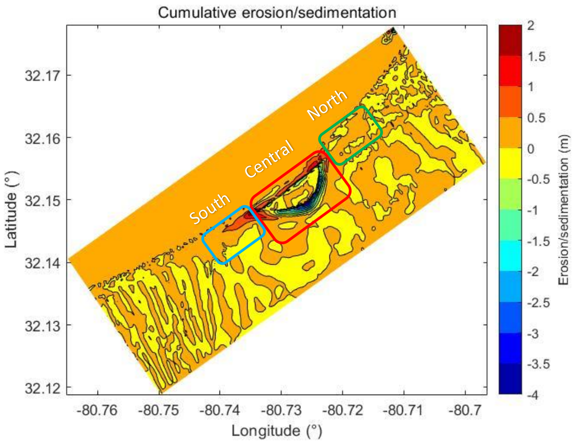


Figure 34: Difference between the computed cumulative erosion/sedimentation of the reference scenario and the feeder nourishment scenario, including the location/outline of the three control domains: south, central, and north.

4.3. Feeder nourishment scenario 2

The aim of this scenario is to establish the percentage of wave induced erosion, relative to the total erosional volume from the feeder nourishment after 1 year caused by all driving forces (waves and tide combined). The boundary conditions, simulation time and MorFac are the same as in feeder nourishment scenario 1, the only difference is that the tidal forcing is eliminated from the simulation. Figure 35 presents the cumulative erosion/sedimentation pattern for both scenario 1 and 2.

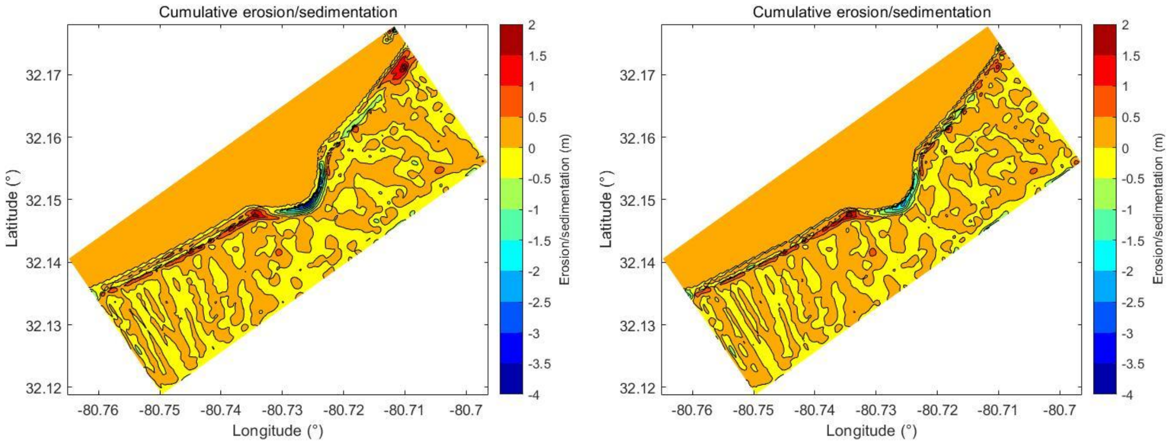


*Figure 35: **Left:** cumulative erosion/sedimentation pattern feeder nourishment scenario 1. **Right:** cumulative erosion /sedimentation pattern feeder nourishment scenario 2.*

A comparison between the cumulative erosion/sedimentation patterns for both scenarios indicates that there is a reduction in erosion along the outer perimeter of the feeder nourishment in scenario 2. The second observation that can be made is that there seems to be an increase in accretion in the both of the adjacent coastal sections in scenario 2. This increase in accretion appears to be the strongest to the north of the nourishment. The cross-shore profile changes in the central domain confirm that there is indeed a significant decrease in erosion from the nourishment in scenario 2 (Figure 37). In the southern domain the expected increase in accretion is not readily confirmable from the profile changes (Figure 36). While cross-section 2 experiences an increase in accretion, cross-section 3 is more erosive, and cross-section 1 remains unchanged. The cross-shore profile changes in the northern domain confirm that there is indeed a significant increase in accretion in this domain compared to scenario 1 (Figure 38).

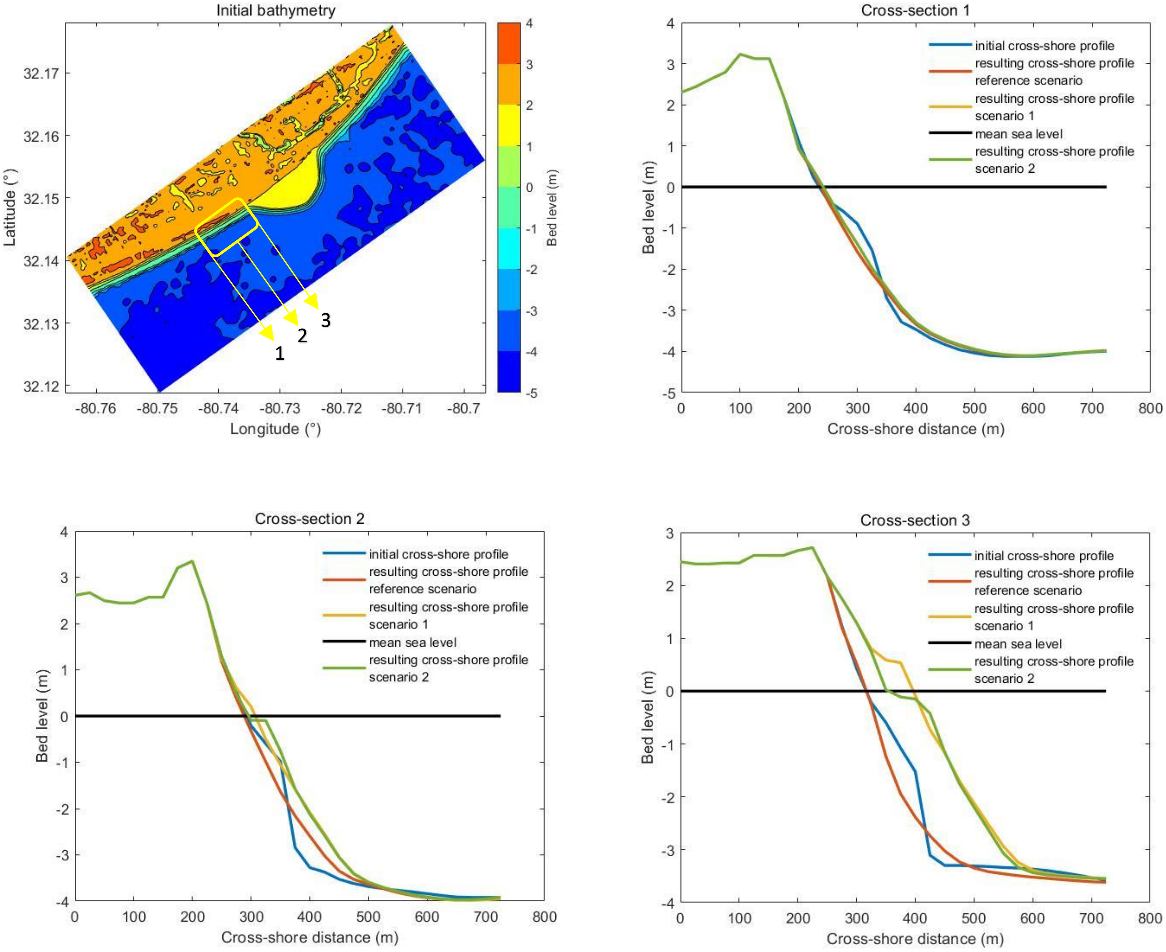


*Figure 36: **Left upper corner**: Location of cross-sections 1, 2 and 3 in the southern domain**.** **Right upper corner**: Cross-shore profiles in cross-section 1. **Left lower corner**: Cross-shore profiles in cross-section 2. **Right lower corner**: Cross-shore profiles in cross-section 3.*

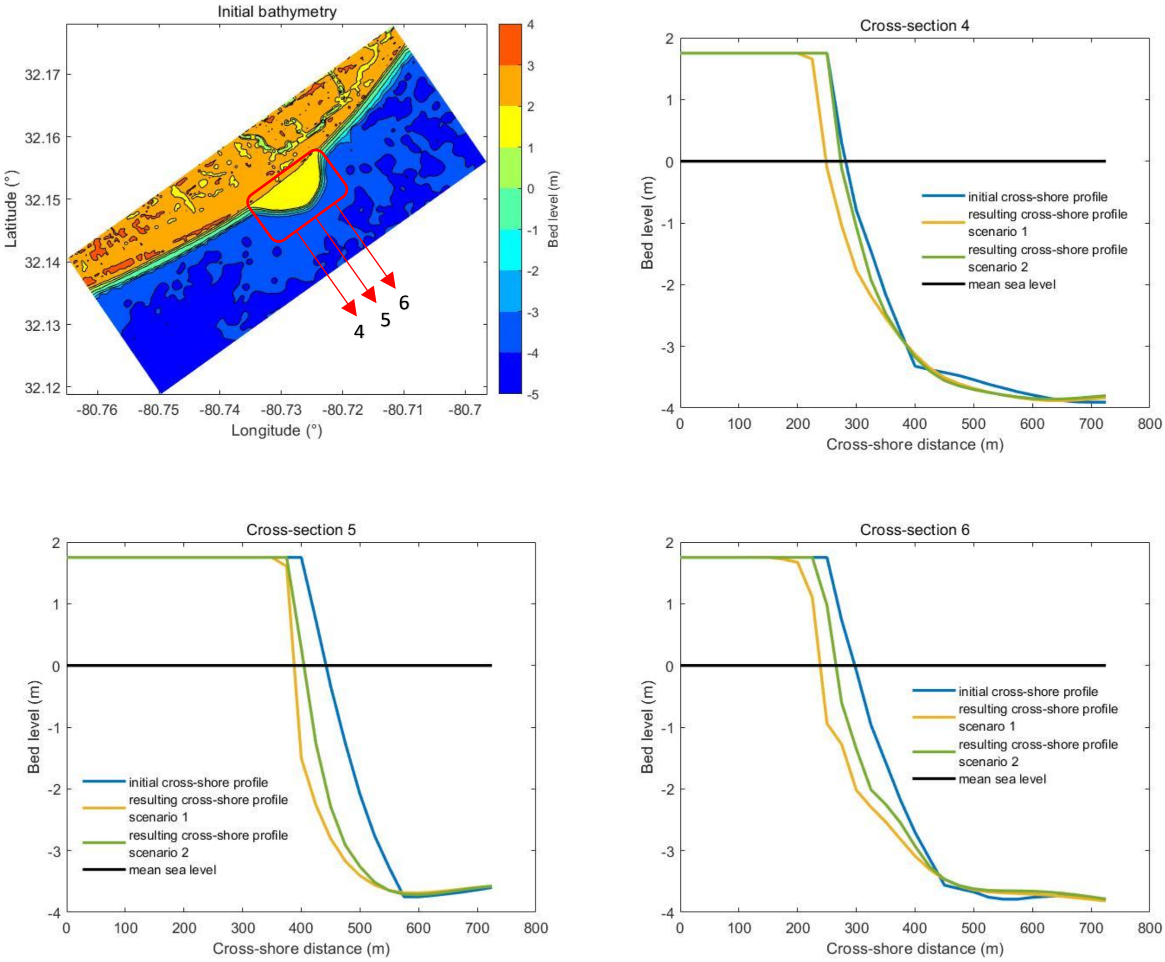
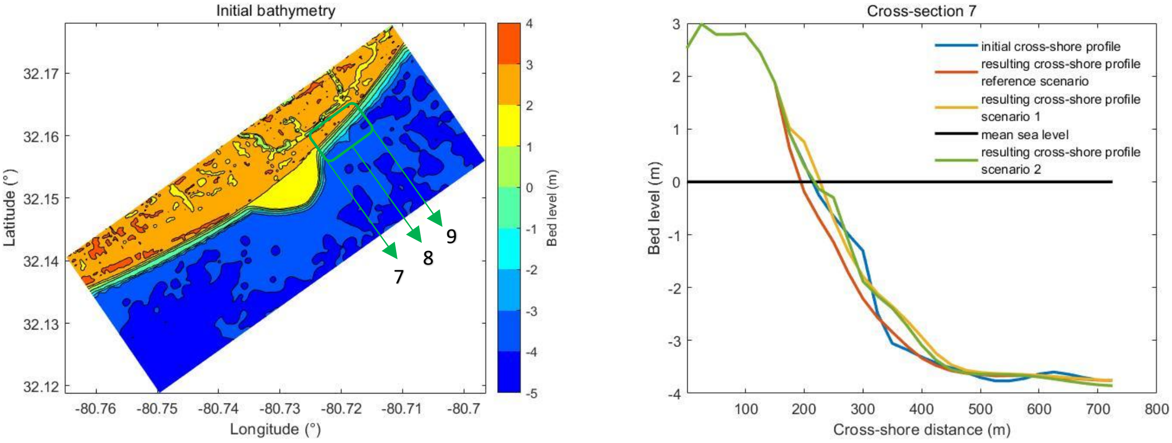


*Figure 37: **Left upper corner**: Location of cross-sections 4, 5 and 6 in the central domain. **Right upper corner**: Cross-shore profiles in cross-section 4. **Left lower corner**: Cross-shore profiles in cross-section 5. **Right lower corner**: Cross-shore profiles in cross-section 6.*



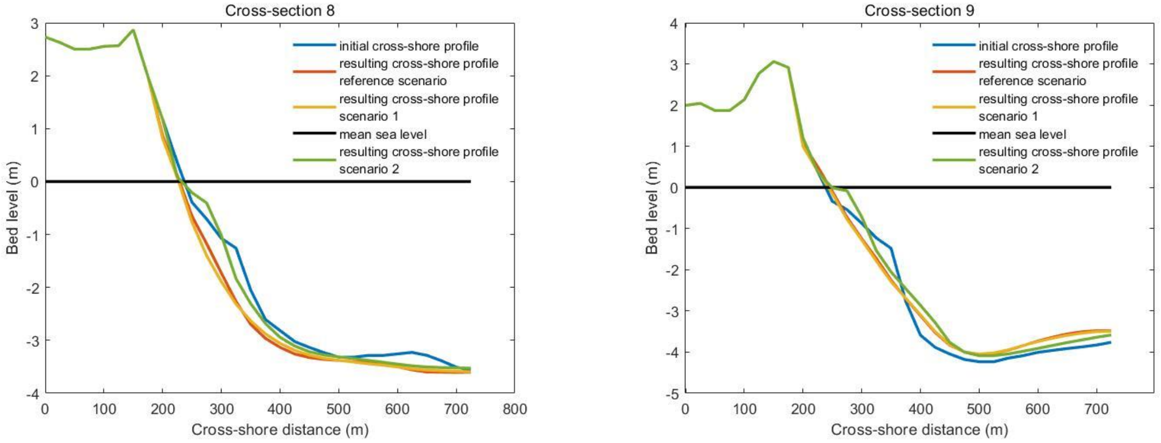


Figure 38: ***Left upper corner****: Location of cross-sections 7, 8 and 9 in the northern domain****.*** ***Right upper corner****: Cross-shore profiles in cross-section 7.* ***Left lower corner****: Cross-shore profiles in cross-section 8.* ***Right lower corner****: Cross-shore profiles in cross-section 9.*

The volume changes in the central domain (Figure 39) also confirm that the amount of volume eroded from the nourishment is significantly smaller. The amount of sediment eroded from the nourishment in feeder nourishment scenario 1 measures approximately 215.000 m^3. The erosional volume in feeder nourishment scenario 2 measures approximately 125.000 m^3.

The transport reversal at the centre of the island is present in both scenario 1 and 2. Which means that without tidal forcing the transport divergence still occurs, and that wave forcing is responsible for the occurring transport reversal. However, tidal forcing still does have a significant impact on the sediment transport. This becomes apparent from the significant differences in morphological behaviour compared to scenario 1, including tidal forcing.

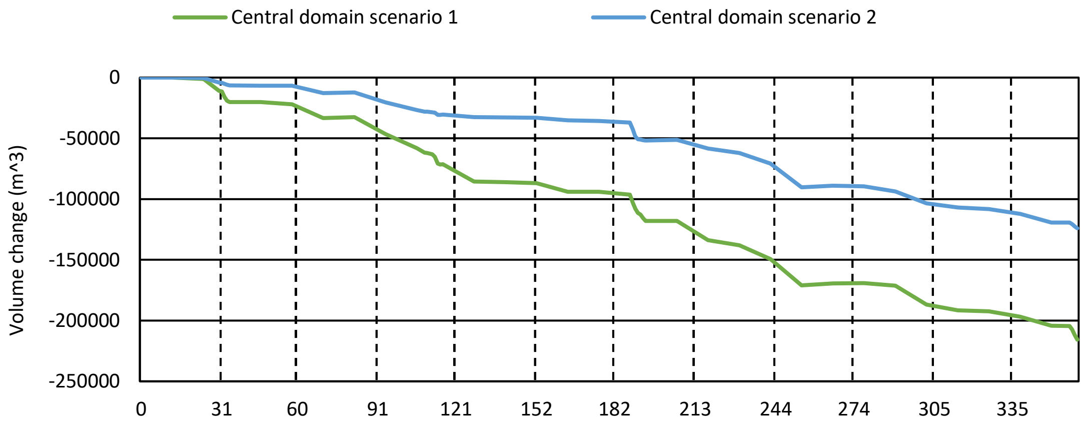


Figure 39: cumulative volume changes in the central domain for feeder nourishment scenario 1 and feeder nourishment scenario 2.

4.4. Feeder nourishment scenario 3

The aim of this scenario is to discern the (potential) impact of residual currents on the feeder nourishment. The boundary conditions, simulation time and MorFac are the same as in feeder nourishment scenario 1. The only difference is that the tidal inlets are closed off. Closing of the tidal inlets eliminates tidal jets and the potentially accompanying residual currents, while the horizontal and vertical tide remain part of the simulation.

A comparison between the volume changes in the central domain (Figure 40) for both scenarios shows that the amount of sediment that is eroded from the nourishment decreases from approximately 215.000 m^3 to roughly 200.000 m^3, a reduction of 7%.

With closed of tidal inlets, the sediment transport pattern still displays the same diverging pattern at the centre of the island. This further strengthens the assumption that wave forcing is responsible for the occurring transport reversal.

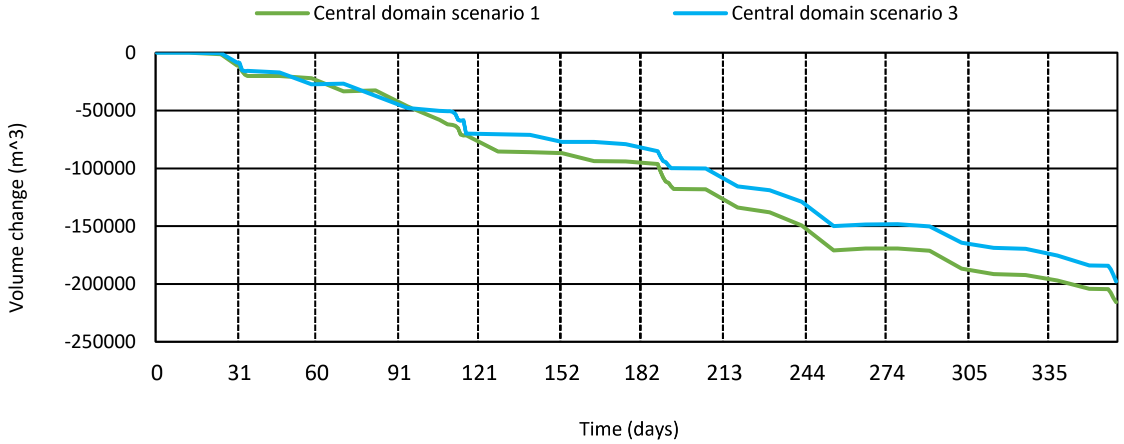


Figure 40: cumulative volume changes in the central domain for feeder nourishment scenario 1 and the cumulative volume changes in the central domain for feeder nourishment scenario 3.

4.5. Summarization results model scenarios

The total amount of sediment that is eroded from the nourishment measures roughly 215.000 m^3. The combined amount that accretes in the southern and northern domain equals approximately 125.000 m^3. So, 58% of the volumetric losses in sediment of the feeder nourishment was compensated by accretion in the adjacent control domains, and roughly 90.000 m^3 of sediment has been transported outside of the control domains. Which could either be transported further alongshore or in the cross-shore direction. It is uncertain where the sediment that is lost from the control domains is deposited, as both the nested grid domain, and the main grid, show no clear signs of increased accretion after construction of the feeder nourishment compared to the reference scenario.

The volume of sediment eroded from the feeder nourishment after 1 year solely due to wave forcing measures 58% of the total volume of sediment that is eroded from the feeder nourishment due to wave- and tidal-forcing combined. The integrated erosion volume of all (4) storm events (Hmax > 3.0 m) accounts for 23% of the total eroded volume after 1 year. Furthermore, the feeder property is related to wave-forcing such that high energy wave events result in a larger erosional volume than low energy wave events. Closing of the tidal inlets and eliminating (potential) residual currents decreases the total erosional volume from the nourishment by 7%. Eliminating tidal forcing and closing of the tidal inlets, does not change the occurring sediment transport pattern. The reversal in the sediment transport direction at the centre of the island still occurs. So, the transport reversal is wave driven, probably in conjunction with the occurring bathymetry.

The morphological behaviour in the two adjacent coastal sections is different. Before construction of the feeder nourishment the southern domain experienced a net sediment outflux of approximately 4000 m^3/year. After construction of the feeder nourishment, the domain experiences a net import of sediment of approximately 100.000 m^3/year. Meaning that the domain, on average, has transitioned from being slightly erosive to accreting. So, the feeding rate of the nourishment, outpaces the underlying erosion rate in this domain. Up to 500 meter away from the nourishment the cross-shore profile shows a significant seaward movement of the shoreline position (MSL = 0) compared to the original situation.

Before construction of the feeder nourishment the northern domain experienced a net sediment outflux of approximately 40.000 m^3/year. After construction of the feeder nourishment, this net outflux of sediment has decreased to approximately 25.000 m^3/year. This indicates that the feeder nourishment is feeding sediment to the domain, but at a rate that is not large enough to keep up with the underlying erosion rate. As a result, the domain, on average, still experiences a sediment outflux and stays erosive. Roughly 50 meter of coastline directly north of the feeder nourishment experiences a seaward movement of the shoreline position (MSL = 0). However, moving further away from the nourishment, the shoreline position remains erosive. And in some occasions, it recedes even more than it did in the original situation, without nourishment.

So, for the southern domain, which only experienced a relatively small amount of erosion to begin with, the construction of a feeder nourishment prevents erosion and transitions the domain from being erosive to accretional. For the northern domain, subjected to a relatively large amount of erosion, the construction of a feeder nourishment only decreases the amount of erosion. The feeding rate is not large enough to outpace the underlying erosion rate and transition the northern domain from being erosive to accretional.

5 Discussion

5.1. Research scope

The main objective of this thesis was to analyse the functioning of a feeder nourishment located at Hilton Head Island. In order to reach this goal, the hydrodynamic processes at Hilton Head were simulated using a numerical model (Delft3D). This showed that a feeder nourishment could prevent erosion in one adjacent coastal section and reduce it in the other. So, from a morphological standpoint the construction of a feeder nourishment at Hilton Head does indeed show potential. However, besides its feeding ability, there are also other criteria that determine the effectiveness/applicability of the feeder nourishment concept.

The first is the availability of sediment for the construction of the feeder nourishment. As mentioned before, an elaborate shoal system envelops Hilton Head's entire shoreline, providing an abundance of sediment. In the past, four different areas have been used as borrow areas for nourishment projects: Gaskin Banks, Joiner Shoals, Barret Shoals and Baypoint Shoals (Figure 41). All four of these locations provide a source of compatible sand, which is reasonably close to the project area, and accessible by a cutter-suction pipeline dredge [Olsen Associates, 2014].

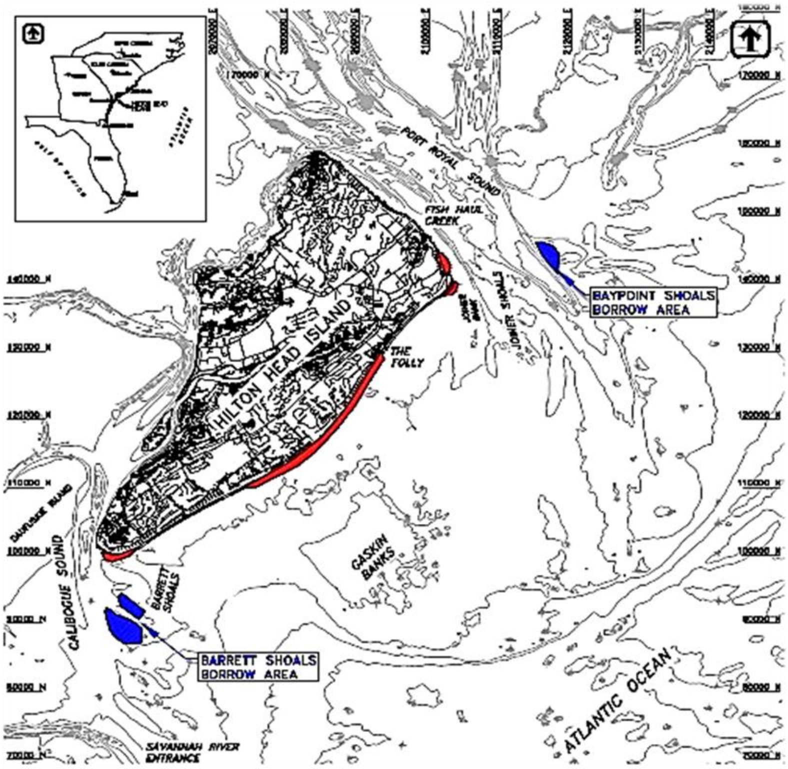


Figure 41: Schematic overview of Hilton Head Island and its offshore bathymetry. The four previously used borrow areas are indicated in the map: Barret Shoals, Gaskin Banks, Joiner Shoals and Baypoint Shoals. [Source: Olsen Associates, 2014].

After dredging, sediment conditions can sometimes change significantly in a borrow area. While some borrow areas refill relatively quick with compatible sand, others do not refill or are partially refilled with fine material (e.g. silt, clay, organic matter). Failure to refill, or a partial refill with fine sediments, can prevent the reuse of a borrow area as a source for sediment and it also negatively impacts the recovery time of benthic communities [Bergquist et al., 2009]. The organisms of the benthic community play an important role in the re-working of sediments, structuring habitat, processing nutrients and materials and serving as prey for larger invertebrates and vertebrates [Bergquist et al., 2009]. The South Carolina Department of Resources has monitored the sediment conditions and benthic community in the borrow areas mentioned above. With the goal of determining the impact associated with dredging and to determine whether the borrow areas showed evidence of recovering over a one-year period after dredging. The seabed level, with respect to MSL, for the four different borrow areas varies between -2,5 and -6,1 m [Bergquist, 2009].

Gaskin Banks, located near the middle of the island, was used as a borrowing area for the nourishment projects of 1990 and 1997. After the 1990 project, the borrow area experienced no major changes in sediment composition and a relatively short recovery time of benthic communities (6 months). After the 1997 project, however, the borrow area had a higher fine material content, and 2 year later the benthic community composition was still different from control areas [Bergquist et al., 2009].

Joiner shoals, located near the entrance of the Port Royal Sound, was also used a borrowing area during the nourishment projects of 1990 and 1997. After the 1990 project, the borrow area was filled in with a substantial amount of fine material and the composition of the benthic community was still significantly altered one to two year later. The same happened after the 1997 project. It is likely that ebb tidal transport from Port Royal Sound acted as the source of fine sediment to this borrow area. Therefore, Joiner shoals is not a sustainable source for sediment and should not be used as a borrow area in future projects [Bergquist et al., 2009].

Barret Shoals, located on the south end of the island near the inlet of Calibogue Sound, was first used as a borrow area during the nourishment project of 2006. For a different nourishment project at the neighbouring Daufuskie island, Barret shoals was also used as a borrow area. In both cases there was a rapid recovery of sediment conditions and benthic communities [Olsen Associates, 2014].

Baypoint Shoals, located on the eastern side of the Port Royal Sound tidal channel, was first used as a borrow area in 2012. After the dredging there was a rapid recovery of sediment conditions and benthic communities. This rapid recovery is linked to the tendency of the entire shoal system to migrate towards the borrowing area and the exposure of the site to the strong tidal flows generated by the tidal inlet [Olsen Associates, 2014].

The results of the study into the recovery of borrow areas show, that both Barret Shoals and Baypoint Shoals could be used as sustainable source for sediment. Joiner Shoals is not a sustainable sand source and should not be used as a borrow area in future projects. Due to the varying results at Gaskin Banks, following two different projects, it is advised not to use this location as a borrow area without further research.

An alternative to dredging offshore borrowing areas, is to use upland sand sources and transport the sediment by truck to the project site. Downside of this method is that the anticipated duration of construction using an upland sand source is much longer compared to using offshore sand sources. No guidelines for the allowed amount of sediment subtraction from these areas were found during the literature study. So, it is unknown if the necessary amount of 3,5 million m^3 sand can be fully subtracted from Barret Shoals and Baypoint shoals.

Secondly, there is the environmental impact of the feeder nourishment. The environmental impact falls outside the scope of this research but can be a decisive factor in the applicability of the concept at Hilton Head Island. Certainly, given the state and federally protected species with the potential to occur within the project area. In previous nourishment projects the town of Hilton Head has indicated that the following species and designated critical habitat may be potentially affected by nourishment projects (Olsen Associates, 2015): Piping plover, Rufa red knot, Wood Stork, Least stern, Wilson's plover, Loggerhead sea turtle, Green sea turtle, Leatherback sea turtle, Kemp's ridley sea turtle, Shortnose sturgeon, and the West Indian manatee. Before a nourishment can be constructed, a biological assessment (BA) has to made that evaluates the potential impact of such a nourishment on the above listed endangered species and designated critical habitats.

Furthermore, there are also the financial and political aspect that can determine the effectiveness/applicability of the feeder nourishment concept. Both are not part of the scope of this research but can nevertheless be decisive.

The above illustrates that besides the feeding ability of the nourishment, there is a multitude of other factors that determine the effectiveness/applicability of the concept. And that it is premature to make conclusions based on the results of a study into the feeding behaviour alone.

5.2. Model methodology

In Delft3D, a depth-averaged two-dimensional model is set up, to recreate the conditions at Hilton Head Island. Inherent to numerical modelling is the need to make certain simplifications, and there are also model and/or input related limitations. These limitations and simplifications are elaborated upon below.

The first limitation is related to the bathymetric data. The bathymetric data is retrieved from the Digital Elevation Model (DEM) of the National Oceanic and Atmospheric Administration. The resolution of the DEM is 1/3 arc second, which equals a resolution of approximately 10 meters. Which is sufficient in relation to the purpose of this research. However, the bathymetric data originates from 2006. After 2006 there have been two large renourishment projects at the centre of the island. And several smaller hurricane related emergency renourishments at other locations. This could result in a wider beach at some locations, but no major changes in the offshore bathymetry are expected. And therefore, it is also not expected that this influences the computed sediment transport pattern, or the computed morphological behaviour in general in any major way.

The choice was made to only include wave forcing and tidal forcing as driving forces. This excludes aeolian transport and surge as driving forces from the model. The reason for this choice is that including surge and aeolian transport increases the complexity and computational effort of the model significantly. At the Sand-Engine pilot project wave forcing and tidal forcing are responsible for more than 90% of the total erosional volume the first year. And surge and aeolian transport both contributed less than 5%. Indicating that the consequences of omitting aeolian transport and surge are limited. However, this only consider the first year after construction. One could imagine that over time, as the nourishment is being reworked to a smoother, less protrusive form, the contribution of the tidal and wave forcing become less. And that the contribution of the aeolian transport to the erosional volume increases. The most likely the outcome is that the amount of sediment transport is being underestimated.

The second simplification concerns the applied wave boundary conditions. The wave conditions of 1999 served as the source for the boundary conditions. Applying the full wave climate requires a large computational effort. To speed up the model a morphological acceleration factor of MorFac was applied. There are however limitations to the application of a MorFac. The upper limit for the MorFac was established at 12. The differences in morphological behaviour between a Morfac of 1 and a Morfac of 12 were small enough to assume that the model is still able to give a good indication of the morphological development of the feeder nourishment.

1999 was a year with a relatively high frequency of storms compared to other years. Between 1980 and 2014, Hilton Head Island was on average subjected to roughly two storm events (H_s > 3,0 m) per year. 1999 contained four storm events. The choice for 1999 was made to be able to get more insight into the impact that storms have on the feeding behaviour of a nourishment. A consequence of choosing such a relatively high wave energy year is that the feeding capacity of the nourishment might be overestimated. However, the results show that storm events were (only) responsible for 23% of the total erosional volume from the feeder nourishment after 1 year. A significant smaller percentage than found at the Sand Engine (>60%). And therefore, the significance of overestimating the feeding capacity of the feeder nourishment due to a relatively large number of storms in 1999 compared to other years also decreases.

The morphological behaviour of the nourishment is simulated over a time-period of 12 months. A longer simulation requires a run-time that is too long for the timeframe of this research. It is therefore impossible to say whether or not all the sediment of the feeder nourishment will be dispersed to the adjacent coastal sections during its lifetime. However, the morphological changes at the Sand-Engine pilot project were most pronounced during the first 6 months after placement. Furthermore, a modelling study by Halbmeijer (2019) into the development of a mega-nourishment at the Florida coastline, states that most of the morphological changes there occurred within the first 12 months after placement. Therefore, it is assumed that a 12-month simulation should suffice to get a decent insight into the morphological development at Hilton Head Island as well.

5.3. Model calibration

First, the model predicts an export of sediment out of the control domain, which agrees with the observed morphological behaviour at the centre of Hilton Head Island. Second, the computed order of magnitude of sediment export out of the control domain (140.000 m^3/year), is roughly in the same order as the value that is determined based on the historic nourishment rates (200.000 m^3/year). Third, the calibrated model can reproduce a net transport pattern which shows similarities to the historic diverging transport pattern.

For the project site, only limited quantitative data sources are available to calibrate the model to. Figure 9 provides the MHW shoreline change rate (feet/year) and the rate of beach volume change (cubic yards/feet/year) for certain cross-sections. Second, there is the nourishment history at Hilton Head, which provides us with nourishment volumes for the separate nourishment events between 1980 and 2010. Other characteristics like sediment transport rates or current velocities are unavailable. Figure 8 provides a qualitative data source: the historic diverging sediment transport pattern. Both are used to calibrate the model.

The limited amount of hard quantitative data makes it difficult to establish the reliability of the model. Because it only allows for a narrow comparison between observed and computed values. However, while the quantitative nature of the calibration is limited, and the calibration partially relies on qualitative assessments. However, the model calibration results show that the model is reliable enough to give at least an indication of the morphological development of a feeder nourishment at Hilton Head Island.

5.4. Comparison with the Sand Engine pilot project

Since its construction, the Sand Engine is being intensively monitored. The obtained data has led to several studies into the morphological behaviour of the Sand Engine. Below, the most important conclusions from these studies are summarized. The results from these studies are compared to the findings in this research study.

- Wave forcing accounts for approximately 75% of the total erosional volume after the first year [Luijendijk et al., 2016]
- Vertical tidal fluctuations contribute 17% to the total erosional volume after 1 year [Luijendijk et al., 2016]
- Horizontal tide, surge levels and wind-driven currents all contribute less than 5% to the total erosional volume after 1 year [Luijendijk et al, 2016].
- The integrated erosion volume of the 12 biggest storm events accounts for approximately 60% of the total eroded volume after one year [Luijendijk et al., 2016]
- 72% of the volumetric losses in sediment on the mega-nourishment was compensated by accretion on adjacent coastal sections and dunes [De Schipper et al., 2016].
- The feeder property is related to the wave-forcing, such that high-energy waves result in more alongshore spreading and low-energy waves resulted mostly in cross-shore movement of the sediment [De Schipper et al., 2016].

The volume of sediment eroded from the feeder nourishment after 1 year solely due to wave forcing amounts to 58% of the total volume of sediment that is eroded from the feeder nourishment due to wave- and tidal forcing combined. At the Sand Engine this percentage is significantly larger, where it measures 75% in the first year. The relatively low contribution of wave forcing to the total erosional volume is probably the result of the calmer wave climate at Hilton Head Island. This potentially leaves tidal forcing with a larger contribution to the total erosional volume at Hilton Head Island than at the Sand Engine, where it measure approximately 20%. Eliminating tidal forcing has no influence on the occurring sediment transport pattern. The sediment transport reversal at the centre of the island still occurs.

The integrated erosion volume of all storm events (Hmax > 3.0 m) accounts for 23% of the total eroded volume after one year. This percentage measures 60% at the Sand Engine, and that percentage only considers the 12 largest storm events. Again, this difference is most likely the result of the calmer wave climate that is present at Hilton Head Island. While 1999 is one of the stormiest years ever recorded at Hilton Head Island, it only boosts a total of 4 storm events that surpass the threshold of Hmax > 3.0 m. The wave time-series between August 2011 and August 2012 at the Sand-Engine counts more than a dozen storm events.

At Hilton Head 58% of the volumetric losses in sediment of the feeder nourishment was compensated by accretion in the adjacent control domains. This percentage is larger at the Sand Engine, where it measures 72%. The amount of sediment that accretes on the adjacent coastal sections (58%), exactly agrees with the contribution of the wave forcing to the total erosional volume (58%). This suggests that there is a link between wave forcing and accretion of sediment in the adjacent coastal sections. Or formulated differently, that there is a link between the amount of sediment that is lost from the control domains and tidal forcing. Analysis of the cumulative erosion/sedimentation plots shows that the sediment that is transported outside of the control domains does not seem to deposit anywhere else in the finer nested grid domain, or in the overall main grid. This could suggest that sediment is being transported to the tidal inlets and deposited outside the main grid. However, analysis of the cumulative erosion/sedimentation pattern does not indicate that large amount of sediments are being transported towards the inlets. Secondly, it is also possible that the 'missing' sediment is preserved in Delft3D as suspended sediment.

Finally, both at Hilton Head and the Sand Engine the feeder property is related to wave-forcing such that high energy wave events result in a larger erosional volume than low energy wave events.

5.5. Impact tidal inlets

The results of model scenario 3 show that closing of the tidal inlets and eliminating (potential) residual currents decreases the total erosional volume in the first year from the feeder nourishment by 7%. This indicates that residual tidal currents are present, and that they increase the total amount of sediment that is eroded from the nourishment. This is contrary to the formulated research hypothesis, in which was stated that it was not expected that the tidal inlets would have any influence on the feeding behaviour of the nourishment. Because of the large distance (>6 km) between the inlets and the feeder nourishment. What needs to be noted, however, is that the tidal channels and ebb-tidal delta owe their existence to the tidal inlets. Closing of the tidal inlets would also have an impact on these bathymetrical features. To let the bathymetry fit better to the new situation, it was altered compared to the previous model scenarios. The tidal channels were filled in and the ebb-tidal delta was smoothed out. Such a change in bathymetry can have a significant impact on the character of the flow pattern and/or sediment transport pattern. Therefore, one has to be careful with the interpretation of these model results. The decrease in the total erosional volume from the nourishment could also be the result of the change in the bathymetry and the associated changes in flow/sediment transport pattern. Finally, both inlets are closed off at once. Therefore, it is unknown what the separate impact of each tidal inlet is on the behaviour of the feeder nourishment. What can be said be said with certainty is that the tidal inlets have no influence on the net sediment transport pattern. Closing of the tidal inlets, and even eliminating tidal forcing as a whole, does not change the pattern. The divergence in the transport at the centre of the island still occurs. Which means that the sediment transport reversal is wave driven, probably in conjunction with the bathymetry

5.6. Potential of the feeder nourishment concept for the Atlantic southeast coast of the U.S.

The fourth research question asks: what do the results at Hilton Head Island mean for the Atlantic southeast coast of the U.S. in general? This research question is, again, answered through means of a literature study. First an assessment is made of the hydrodynamic conditions and geomorphological setting of the coastlines that make up the Atlantic southeast coast of the United States: South Carolina, North Carolina, Georgia and Florida's east coast. This provides insight into the representativeness of the conditions at Hilton Head Island compared to the remainder of the Atlantic southeast coast of U.S. Second, the morphological behaviour (erosion/accretion) of the coastlines of the different states is analysed. This gives some insight into the potential/necessity of applying a feeder nourishment at these locations.

5.6.1. Hydrodynamic conditions and geomorphological setting

The state of a shoreline is in part controlled by the hydrographic regime. The hydrographic regime is commonly expressed as the ratio of tidal energy to wave energy. Based on the hydrographic regime, coastlines can be divided into three different categories: wave-dominated coasts, tide-dominated coasts, and mixed-energy coasts. Wave-dominated coasts are often found in areas that experience a microtidal regime (tidal range less than 6 feet). Tide-dominated coasts are often found in areas that experience a macrotidal regime (tidal range greater than 12 feet). Mixed-energy coasts are often found in areas with a mesotidal regime (tidal range between 6-12 feet) [Hayes & Michel, 2008].

A nearly continuous chain of barrier islands borders the south-eastern USA states of North Carolina, South Carolina, Georgia and Florida. This area is often referred to as the Georgia Bight (Figure 42) and is the centrepiece for the longest single development of barrier islands in the world [Davis, 1994]. The barrier islands bordering the Georgia Bight show a systematic change in geomorphology. Over 50% of the shoreline of the outer edges of the Georgia Bight is composed of transgressive, long barrier islands, that are morphologically wave-dominated. At the head of the Georgia Bight, over 50% of the shoreline is composed of regressive, mixed-energy, short (drumstick shaped) barrier islands. The shorelines of the northern and southern flanks of the Georgia Bight contain abundant welded barriers, that have narrow to non-existent back barrier systems. Towards the head of the Georgia Bight tidal inlets increase in abundance as the tidal range increases. The inlets have a major influence on the morphological state (erosion/accretion) of the barrier islands as a result of their sediment storage and migratory characteristics. Throughout the Georgia Bight both transgressive and regressive barrier islands can be found, with both types sometimes occurring on opposites side of the same inlet [Davis, 1994].

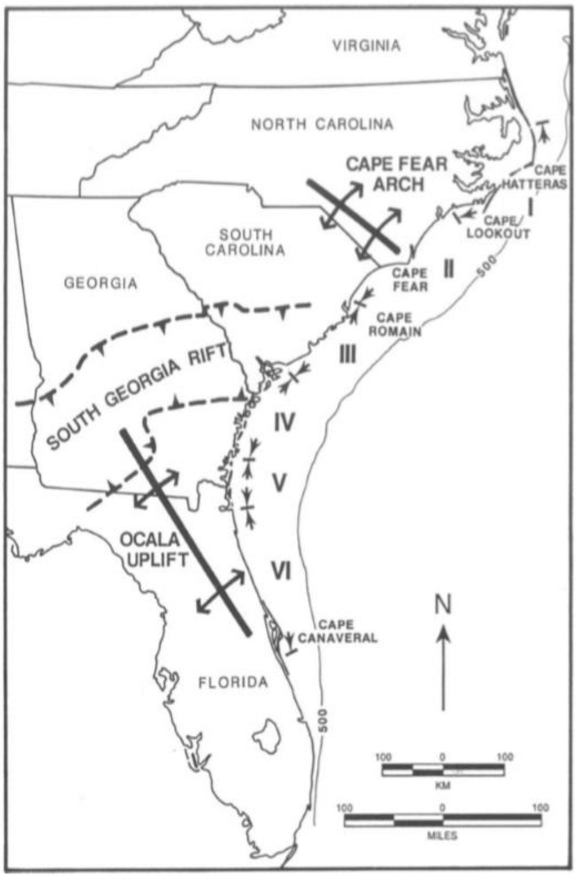


Figure 42: Coastline of the south-eastern USA. The Georgia Bight is located between Cape Hatteras (North Carolina) and Cape Canaveral (Florida).

Because the continental shelf is significantly wider off South Carolina and Georgia, the tidal range is at least twice as large as the tidal range found in Florida or North Carolina. Typical tidal ranges at South Carolina and Georgia measure 6-7 feet, compared to typical tidal ranges of 2-3 feet for Florida's east coast and North Carolina [Kana, 1988]. Florida's east coast and the outer banks of North Carolina are an example of a wave-dominated coasts. Here we find abundant long barrier islands and multiple nearshore bars offshore of the barrier island's beaches. The South Carolina and Georgia coast are classic examples of mixed-energy coasts. Which are characterized by short, drumstick-shaped barrier islands; numerous tidal flats and coastal wetlands; and complex sediment transport patterns [Kana, 1988]. More tidal energy or less wave energy allows for more inlets to form along a coast. Therefore, inlets are located much closer to one another on the coastlines of South Carolina and Georgia, compared to North Carolina's Outer Banks and/or Florida's east coast. As a result, South Carolina's and Georgia's coastlines tend to be more complex. They are broken up by numerous inlets and while one beach may face southeast, a nearby beach can face north. Florida's east coast and North Carolina's Outer Banks on the other hand are characterized by relatively straight shorelines [Kana, 1988].

The South Carolina and Georgia coastline are both comparable in hydrodynamic conditions and geomorphological setting. They are mixed-energy coasts, broken up by numerous tidal inlets, and home to short barrier islands with complex sediment transport patterns. Therefore, the remainder of this assessment into the potential of the feeder nourishment concept for the Atlantic southeast coast of the U.S. focusses solely on Georgia's and South Carolina's coastline. The wave-dominated, relative straight shorelines of North Carolina's and Florida's east coast are left out of the assessment, due to the distinct differences with the conditions found at Hilton Head Island.

5.6.2. Morphological behaviour and development of South Carolina's coastline

South Carolina's coastline is divided into four distinctly different geomorphological compartments [Figure 43, Hayes and Michel (2008)]. The first compartment is known as the Grand Strand, this curved stretch of shoreline consists of nearly continuous sand beaches. The second compartment is known as the Delta Region, home to the Santee/Pee delta region, the largest river delta on the east coast of the U.S. The third compartment is known as the Barrier Islands, this section of coastline accommodates a chain of 14 barrier islands. Finally, the fourth compartment is known as the Low Country. This complex stretch of coastline consists of two large estuarine systems. Hilton Head Island, and its accompanying tidal inlets: Port Royal Sound and Calibogue Sound, make up one of these estuarine systems [Hayes & Michel, 2008].

Figure 43: Satellite image of South Carolina. The white lines indicate the boundaries of the 4 different geomorphological compartments of the coast: Grand Strand, Delta Region, Barrier Islands and Low Country. Note that Hilton Head Island is situated in the Low Country compartment. [Source: Hayes & Michel, 2008]

Within the Barrier Islands and Low Country, tidal inlets separate the shoreline in even smaller compartments. It are these tidal inlets that essentially control the stability of the beaches and determine the evolution of the shoreline. They act as natural boundaries, partially isolating one beach from another, and allowing for differences in natural processes and development. One island for example may be sheltered from wave action due to a large ebb-tidal delta, while a neighbouring island is not. Not to mention shoal bypassing events, that can result in localized accretion and/or erosion. As a result, South Carolina’s coast tends to be complex and irregular, and there are dramatic differences in erosion problems between adjacent islands. Beach erosion is by no means a universal problem in South Carolina [Kana, 1988]. Figure 44 presents a schematic overview of South Carolina’s coastline; an overview of the beach condition changes and historic sediment transport pattern for each of the segments is given below.

Segment 1 (Grand Strand)

This segment is a densely developed 58 km arcuate strand with just one intermediate inlet (Hog Inlet). The Grand Strand is characterized by low erosion rates and low net sediment transport rates. Fifteen nourishments have occurred between 1980 and 2010. The overall condition of Grand Strand beaches was better in 2010 than 1980, with additional dune/beach area. The Aqua Monitor, a tool developed by the TU Delft and Deltares, which contains a dataset of the long-term shoreline changes (1984-2016) verifies this stable nature of the coast.

Segment 2 (Grand Strand)

This segment is a 41 km arcuate strand shoreline that includes two barrier islands: Pawleys Island and North Island. The segment is approximately 50% developed. The morphological behaviour of this segment is twofold. To the north of Debidue beach the coastline is stable, to the south there are some areas that experience high erosion rates. The transition zone from accretion to erosion splits a developed part of the beach. Various shore protection measures have been applied since 1980 (groynes, timber bulkhead) both have been rendered non-functional by now. And therefore 3 nourishment events have also occurred. A part of North Island’s coastline,

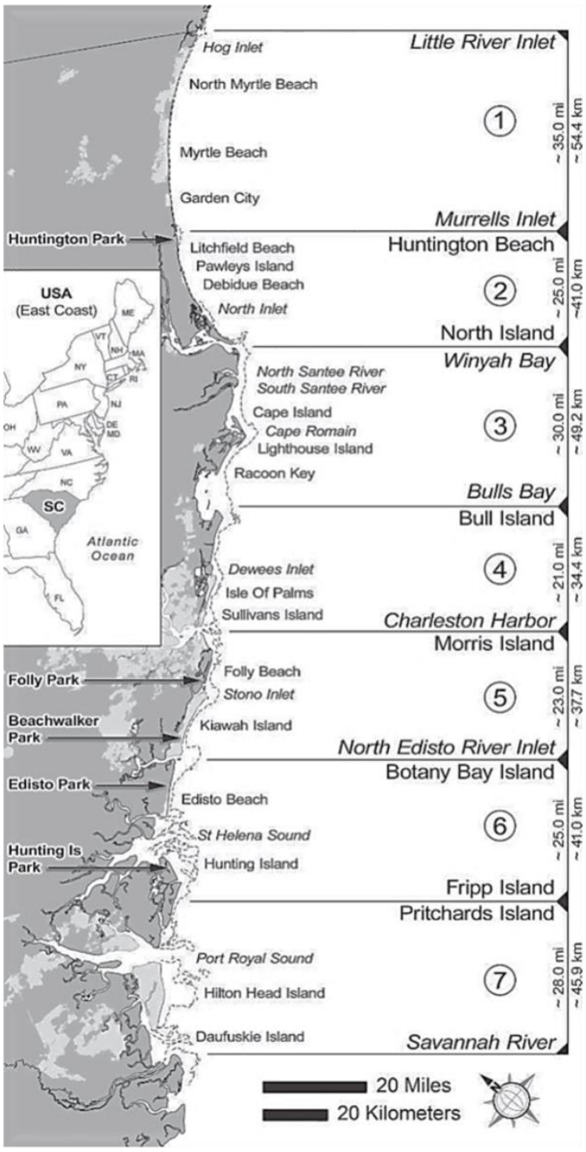


Figure 44: Schematic overview of South Carolina’s coastline. Hilton Head Island is found in segment 7, the southernmost segment . [Source: Kana et al., 2013]

downdrift from the centre of island is also subjected to erosion. The signature of erosion indicates that is the result of a diverging sediment transport pattern near the centre of the island. This part of the island's coastline is developed.

Segment 3 (The Delta Region)
This segment as a whole is undeveloped and therefore erosion mitigation measures are not necessary.

Segment 4 (The Barrier Islands)
Two barrier island in this segment experience erosion: Bull Island and Capers Island. However, both are undeveloped. Notice that, in accordance to what is mentioned above, only one inlet away the conditions can be completely different. Capers Island for example experiences erosion, while neighbouring Dewees Island is highly accretive.

Segment 5 (The Barrier Islands)
None of the barrier islands in this segment of the coast experience erosion, they either remain stable or experience accretion.

Segment 6 (The Barrier Islands)
Two barrier islands in this segment experience erosion: Edingsville Beach and Hunting Island. While Edingsville Beach is undeveloped, Hunting Island functions as a park, and is therefore classified as developed.

Segment 7 (The Low Country).
The barrier island that experience erosion in this segment are: Pritchards island, Capers Island, Hilton Head Island and Daufuskie Island. Both Pritchards island and Capers Island are undeveloped, excluding them from the assessment. Daufuskie island, while sparsely, is developed and will be part of the assessment.

The developed locations along South Carolina's coastline that require erosion mitigating measures are south Debidue beach, North Island, Hunting Island and Daufuskie Island.

5.6.3. Morphological behaviour and development of Georgia's coastline

Georgia's coastline extends approximately 160 km from the mouth of the Savannah river to St. Mary's inlet below Cumberland Island. The region contains 11 barrier islands, separated by large, stable inlets and backed by extensive salt marshes (Figure 45). Four of the barrier islands are developed: Jekyll Island, St. Simons Island, Sea Island and Tybee Island. The remaining seven barrier island are in relatively natural states with minimal development at risk from erosion [Langley et al., 2003].

Georgia is perhaps the least studied portion of the U.S. Atlantic coast in terms of shoreline change. Unlike most other states participating in the NOAA's National Coastal Zone Management Program, Georgia does not have good information on annual erosion rates [Langley et al, 2003]. Therefore, to gain insight into the morphological behaviour (erosion/accretion) of the shoreline we solely rely on the Aqua Monitor (TU Delft/Deltares. The Aqua Monitor detects changes in real-time using satellite imagery for any place on Earth. It contains a dataset of the long-term shoreline changes between 1984 and 2016. The assessment focusses on the Jekyll Island, St. Simons Island, Sea Island and Tybee Island. The only barrier islands with development that is at risk due to coastal erosion. Figure 45 provides an overview of the morphological behaviour for all four islands, according to the Aqua Monitor. The bars represent the erosion/accretion along coastlines, every 500 m, over the period 1984-2016. Green bars indicate where shoreline accretion has occurred, red bars indicate erosive shorelines, based on a linear fit through shoreline positions.

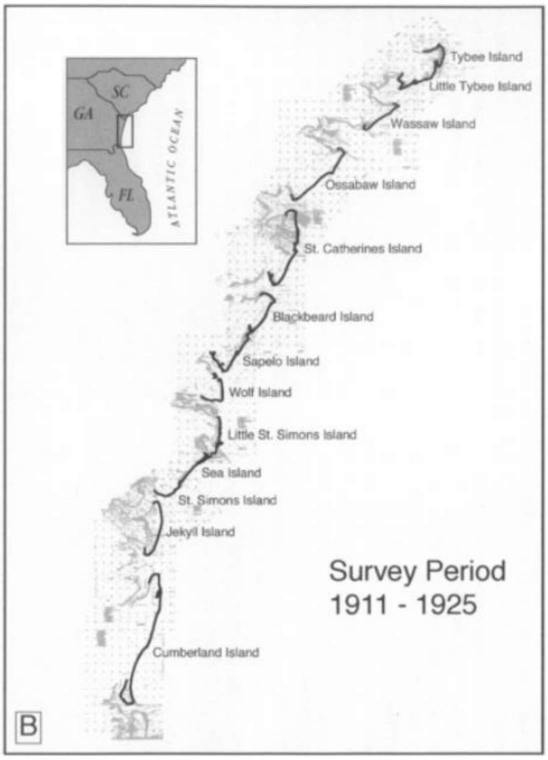


Figure 45: Schematic overview of the barrier islands that make up the barrier coast of Georgia (U.S.). [Source: Langley et al., 2013]

Jekyll Island, St. Simons Island and Tybee Island all have stable or accreting coastlines (Figure 46). The majority of Sea Island's coastline is stable and/or experiencing accretion as well. However, there are three erosion hotspots occurring along its shoreline (Figure 46). So, there is only one developed location along Georgia's coastline that requires erosion mitigation measures: Sea Island.

5.6.4. Potential of the feeder nourishment concept

The developed locations along South Carolina's coastline that require erosion mitigating measures are south Debidue beach, North Island, Hunting Island and Daufuskie Island. Along Georgia's coastline there are only some erosion hotspots along Sea Island's coastline that require erosion mitigation measures. Hunting Island has one of the highest erosion rates in South Carolina. Wave refraction/diffraction through offshore shoals, causes sediment to be spread from the middle of the island to both ends at a rapid rate [Kana et al., 2013]. Daufuskie Island lies fully in the lee of the Calibogue Sound shoals. Part of its shoreline is sheltered by Hilton Head Island, and the other part is exposed. The sediment is transported from the middle of the island, to both ends. This becomes apparent from the severe erosion at its centre, and active spit growth to the northeast and southwest [Kana et al., 2013]. The transport patterns at both Hunting Island and Daufuskie Island are thus similar to the transport pattern found at Hilton Head. A diverging pattern that transports sand from the centre to the ends of the island. At North Island, the signature of erosion indicates a diverging sediment transport pattern near the centre of the island as well [Kana et al., 2013].

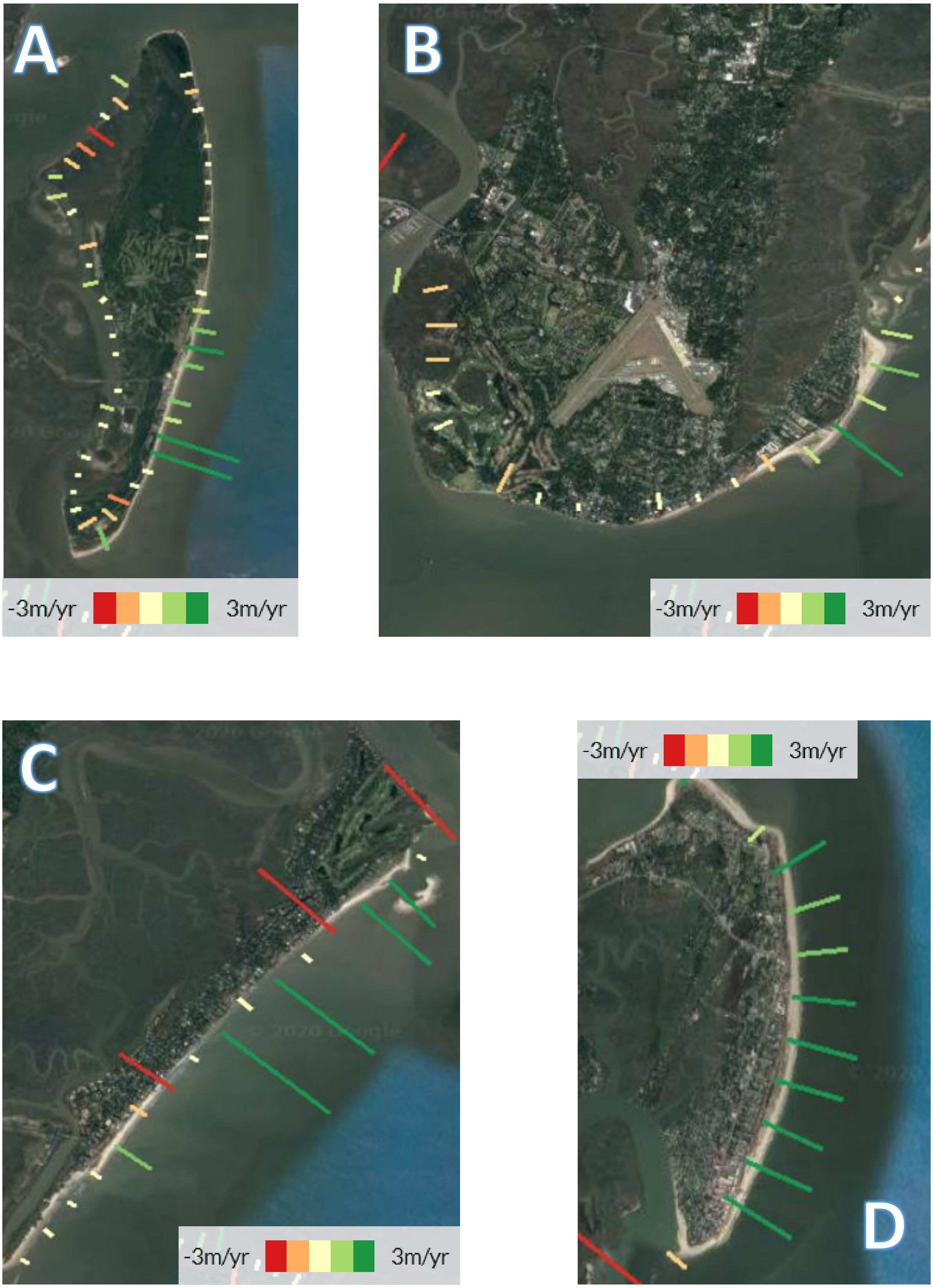


Figure 46: Screenshots taken from the Aqua Monitor app. Panel A: Jekyll Island ; Panel B: St. Simons Island ; Panel C: Sea Island ; Panel D: Tybee Island. The bars represent the erosion/accretion along coastlines, every 500 m, over the period 1984-2016. Green bars indicate where shoreline accretion has occurred, red bars indicate erosive shorelines. [Source: Aqua Monitor (TU Delft/Deltares)].

Less is known about the sediment transport pattern at both South Debidue beach and the erosion hotspots at Sea Island. The sediment transport patterns at North Island, Hunting Island and Daufuskie Island are thus similar to the transport pattern found at Hilton Head. A diverging pattern that transports sand from the centre to the ends of the island. Nothing is known about the sediment transport patterns at both south Debidue beach and Sea Island. The wave climate at all the above mentioned location is similar to Hilton Head. A southeast swell, with a narrow range of directions and an annual wave height of roughly 1,0 m. The same goes for the tidal range, with the only exception being Sea Island (Georgia), which experience a larger tidal range (2,5 m), compared to the tidal range (2,0 m) along South Carolina's coastline.

The results at Hilton Head show that erosion on adjacent coastal sections can be lessened and/or prevented by constructing a feeder nourishment. Given that these locations s are subjected to similar conditions, the results that were found at Hilton Head, could also apply to these locations. And thus, the construction of a feeder nourishment could potentially be an effective measure to prevent or lessen the occurring erosion. However, one needs to keep in mind that there are other hydrodynamic conditions besides the wave climate, tidal climate and sediment transport pattern that determine the feeding behaviour of a nourishment. For example: bathymetry, underlying erosion rate, supply rate and proximity and/or size of the tidal inlets. These conditions are not part of the assessment that is made above, and therefore the results found at Hilton Head Island cannot be readily applied to these locations.

6 Conclusions

The main objective of this thesis was to analyse the functioning of a feeder nourishment located at Hilton Head Island. To achieve these research goals, the morphological development of a feeder nourishment at Hilton Head Island was simulated with Delft3D, over the course of 1 year, for different model scenarios, with varying forcing conditions and bathymetric features. Analysis of these model results, in combination with a study of the related literature, provided the answers to the research questions which are presented below.

RQ 1: How do the conditions at Hilton Head Island differ from the Sand-Engine pilot project?
The first difference is found in the bathymetry. The Sand Engine is constructed on a straight, uninterrupted coastline. Hilton Head, however, is part of South Carolina's barrier island chain. Tidal inlets divide this coastline, separating one barrier island from another. Resulting in a complex and compartmentalized coastline. The second difference can be contributed to the wave climate. Hilton Head is exposed to a swell wave climate, while a wind sea dominated wave climate is found at the Sand-Engine. As a result, the annual wave height and annual wave period at Hilton Head are respectively lower and longer. Another important difference regarding the wave climate is the so-called storminess. The annual number of storms at Hilton Head is significantly smaller than at the Sand Engine. Of course, there is a certain degree of difference between all studied conditions for the two locations. However, the bathymetry and the wave climate clearly stand out from the rest.

RQ 2: How do the differences in conditions between the two locations impact the morphological development of a feeder nourishment?
The volume of sediment eroded from the feeder nourishment after 1 year solely due to wave forcing amounts to 58% of the total volume of sediment that is eroded from the feeder nourishment due to wave- and tidal forcing combined. At the Sand Engine this percentage is significantly larger, where it measures 75% in the first year. Second, the reduced number of storm events results in a lower contribution of storm events to the total erosional volume. At Hilton Head they account for 23% of the total eroded volume after one year, compared to 60% at the Sand Engine. And that percentage only considers the 12 largest storm events

Closing of the tidal inlets decreases the amount of sediment that is eroded from the feeder nourishment in the first year from approximately 215.000 m^3 to approximately 200.000 m^3, a difference of 7%. Closing of the tidal inlets, and even eliminating tidal forcing as a whole, does not change the occurring sediment transport pattern. The divergence in the sediment transport at the centre of the island still occurs, which means that the transport reversal is wave driven.

RQ 3: Can a feeder nourishment at Hilton Head Island supply sediment to adjacent coastal sections at a rate that is sufficient to prevent erosion?
The morphological behaviour in the two adjacent coastal sections is different. Before construction of the feeder nourishment the southern domain experienced a net sediment outflux of approximately 4000 m^3/year. After construction of the feeder nourishment, the domain experiences a net import of sediment of approximately 100.000 m^3/year. Meaning that the domain, on average, has transitioned from being slightly erosive to accreting. So, the feeding rate of the nourishment, outpaces the underlying erosion rate in this domain. Up to 500 meters away from the nourishment the cross-shore profile shows a significant seaward movement of the shoreline position (MSL = 0) compared to the original situation.

Before construction of the feeder nourishment the northern domain experienced a net sediment outflux of approximately 40.000 m^3/year. After construction of the feeder nourishment, this net outflux of sediment has decreased to approximately 25.000 m^3/year. This indicates that the feeder nourishment is feeding sediment to the domain, but at a rate that is not large enough to keep up with the underlying erosion rate. As a result, the domain, on average, still experiences a sediment outflux and stays erosive. Roughly 50 m of coastline directly north of the feeder nourishment experiences a seaward movement of the shoreline position. However, moving further away from the nourishment, the shoreline position remains erosive. And in some occasions, it recedes even more than it did in the original situation, without nourishment.

RQ 4: What do the results at Hilton Head Island mean for the Atlantic southeast coast of the United States?

The South Carolina and Georgia coastline are comparable in both hydrodynamic conditions and geomorphological setting. They are mixed-energy coasts, broken up by numerous tidal inlets, and home to short barrier islands with complex sediment transport patterns. North Carolina's and Florida's east coast are wave-dominated, with relative straight shorelines. Which is distinctly differences from the conditions found at Hilton Head Island. Therefore, the potential of the feeder nourishment concept is only analysed for South Carolina's and Georgia's coastline. The developed locations along South Carolina's coastline that require erosion mitigating measures are south Debidue beach, North Island, Hunting Island and Daufuskie Island. Along Georgia's coastline there are only some erosion hotspots along Sea Island's coastline that require erosion mitigation measures. The sediment transport patterns at North Island, Hunting Island and Daufuskie Island are similar to the transport pattern found at Hilton Head. A diverging pattern that transports sand from the centre to the ends of the island. Nothing is known about the sediment transport patterns at both south Debidue beach and Sea Island. The wave climate at all the above mentioned location is similar to Hilton Head. A southeast swell, with a narrow range of directions and an annual wave height of roughly 1,0 m. The same goes for the tidal range, with the only exception being Sea Island (Georgia), which experience a larger tidal range (2,5 m), compared to the tidal range (2,0 m) along South Carolina's coastline. The results at Hilton Head show that erosion on adjacent coastal sections can be lessened and/or prevented by constructing a feeder nourishment. Given that these locations are subjected to similar conditions, the results that were found at Hilton Head, could also apply to these locations. And thus, the construction of a feeder nourishment could potentially be an effective measure to prevent or lessen the occurring erosion

Summarized

The main differences between Hilton Head Island and the Sand Engine are the relatively calm wave climate that Hilton Head is subjected is to, and the presence of two tidal inlets. The influence of the calmer wave climate is twofold. First, the contribution of wave forcing to the total erosional volume from the feeder nourishment in the first year is smaller compared to the Sand Engine. Second, the contribution of storm events to the total erosional volume in the first year is smaller compared to the Sand Engine. Closing of the tidal inlets, and eliminating the residual currents owing to them, decreases the amount of sediment that is eroded from the feeder nourishment. However, closing of the inlets does not have an impact on the occurring sediment transport pattern, which is wave driven. The morphological behaviour in the two adjacent coastal sections is different. For the coastline to the south, which only experienced a relatively small amount of erosion to begin with, the construction of a feeder nourishment prevents erosion and transitions the domain from being erosive to accretional. For the coastline to the north, subjected to a relatively large amount of erosion, the construction of a feeder nourishment only decreases the amount of erosion. The feeding rate is not large enough to outpace the underlying erosion rate and transition the northern domain from being erosive to accretional. Finally, the coastlines of Georgia and South Carolina are home to several other locations that require erosion mitigation measures. Given that these locations are subjected to similar wave and tidal conditions, the results that were found at Hilton Head, could also apply there. And thus, the construction of a feeder nourishment could prove to potentially be an effective measure to prevent or lessen the occurring erosion at these locations as well.

7 Recommendations

7.1. Research scope

No guidelines for the allowed amount of sediment subtraction from the proposed sediment borrow areas (Barret Shoals and Baypoint Shoals) were found during the literature study. So, it is unknown if the necessary amount of 3.5 million m^3 sand can be fully subtracted from these two areas. Therefore, it is recommended to research the amount that can be subtracted from these areas. And if turns out that these amounts cannot supply the necessary amount, then identify other sustainable sediment borrow areas, that are located further away. Or as an alternative try to identify upland sand sources with compatible sediment.

The environmental impact of constructing a nourishment falls outside the scope of this research but can definitely be a decisive factor in the applicability of the concept at Hilton Head Island. Certainly, given the long list of state and federally protected species, and designated critical habitat with the potential to occur within the project area of Hilton Head Island. It is therefore recommended to do a biological assessment (BA) which evaluates the potential impact of such a nourishment on each of these protected species and designated critical habitats.

This research focusses only on the feeding ability of the nourishment. Above two other factors that determine the effectiveness/applicability of the concept are mentioned. But there are many more: financial aspects, political aspects, stakeholder opinions, etc. To get a good insight into the potential of the feeder nourishment concept at Hilton Head Island, it is recommended to perform a multi-criteria analysis (MCA) in which each of these aspects is properly addressed.

7.2. Research methodology

For further research, it is recommended to find a more recent bathymetric data source than the current one, which originates from 2006.

The second recommendation is to also include aeolian transport and surge as driving forces in the model, besides wave forcing and tidal forcing. Delft3d offers the tools to include both of them. During this research they were omitted, to reduce the computational effort. This was justified based on the results at the Sand Engine in the first year, which indicated that both only contributed less than 5% to the total erosional volume from the feeder nourishment. However, one can imagine that over time, as the nourishment is being reworked to a smoother, less protrusive form, the contribution of the tidal and wave forcing become less. And that the contribution of the aeolian transport and surge to the erosional volume will increase. Omitting them might, one larger timescales, result in less accurate model results.

The third recommendation is to model the morphological behaviour of the nourishment over the course of its entire intended lifetime, 15 years in this case. In this research, the morphological behaviour of the nourishment is only simulated over a time-period of 12 months. A longer simulation required a run-time that was too long for the timeframe of this research. However, it is therefore impossible to say whether or not all the sediment of the feeder nourishment will be dispersed to the adjacent coastal sections during its lifetime. The behaviour during the first year, is not necessarily representative for the remainder of the nourishment's lifetime. Quite the opposite possibly, as the results at the Sand Engine show that the morphological changes are most pronounced during the first year, and then become less. To achieve such a model run within a reasonable amount of time, one could either gain access to a more powerful computer or make smart model choices that reduce the run-time. One could think of changes to the grid size, or the MorFac for example.

7.3. Model calibration

For the model calibration only a limited amount of quantitative data was available. It only included the MHW shoreline change rate and the beach volume change rate in certain cross-sections. It is therefore recommended for further research to try to find other quantitative data sources as well. For example, sediment transport rates and alongshore flow velocities.

7.4. Feeder nourishment design

In this case the choice is made to give the nourishment a curved shape. This shape has already proven successful in other applications of feeder nourishments along the U.S. East Coast. And it also shows some similarity to the shape of the Sand-Engine, which has also proven its effectiveness. Regarding the geometric shape of the feeder nourishment, virtually unlimited design choices can be made curved, rectangular, triangular, etc. Different shapes could possibly have a different effect on the feeding properties. Optimization of the geometric shape could be an interesting topic for further research.

7.5. Model scenarios

Besides the model scenarios that are already part of this research, there are also some other possibly interesting model scenarios that could provide more insight into the morphological behaviour of the feeder nourishment and at Hilton Head in general. The model results show that the transport reversal is wave driven. The assumption is that the bathymetry also plays a role in creating this transport reversal. Through a process called refraction, irregularities in offshore shoals can change the direction of incoming waves and create drift reversals. An interesting model scenario would be to change the offshore bathymetry, for example remove the offshore shoals, to see if the transport reversal still occurs.

Second, in the current set-up of the model scenarios both tidal inlets are closed off. Therefore, it is impossible to determine how much of the increase in erosional volume from the nourishment due to the residual currents can be contributed to each inlet. A recommendation would be to run two separate scenarios in which in turns one of the tidal inlets is closed off, as the other remains unchanged. Allowing for an analysis of the relative impact of each inlet on the erosional behaviour.

7.6. Potential of the feeder nourishment concept along South Carolina’s coastline

Currently, the extrapolation of the results found at Hilton Head to other locations is only based on the sediment transport pattern and the wave forcing. However, one needs to keep in mind that there are other hydrodynamic conditions besides the wave climate and sediment transport pattern that determine the feeding behaviour of a nourishment. For example: bathymetry, underlying erosion rate, supply rate and proximity and/or size of the tidal inlets. These conditions are not part of the assessment that is made above, and therefore the results found at Hilton Head Island cannot be readily applied to these other two islands. Therefore, it is recommended to analyse these other conditions for the other barrier island as well.

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Glossary

WIS	Wave Information Studies
NOAA	National Oceanic and Atmospheric Administration
USACE	United States Army Corps of Engineers
DOC	Depth of Closure
DEM	Digital Elevation Model
D3D-FlOW	Delft3D FLOW module
D3D-WAVE	Delft3D WAVE module
D3D-MOR	Delft3D Morphology module
JONSWAP	Joint North Sea Wave Project
WIR	Wave Input Reduction
MorFac	Morphological Acceleration Factor
SWAN	Simulating Waves Nearshore
BED	current-related bedload transport
BEDW	wave-related bedload transport
SUS	current-related suspended transport
SUSW	wave-related suspended transport
MSL	Mean Sea Level
MHW	Mean High Water

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Appendix A

Hydrodynamic conditions

A1: Mean wave climate

The WIS data contains the monthly mean wave height and monthly mean wave period for every month from January 1980 onward. These monthly values are averaged to determine the annual mean wave values (Table 1). Averaging over a period of 35 years, results in an annual mean wave height of 0.997 m and an annual mean wave period of 8.42 s.

Table A3: Annual mean values for the significant wave height and peak period for station ID 63366

Year	**H_S [m]**	**T_P [s]**	**Year**	**H_S [m]**	**T_P [s]**
1980	0,97	8,25	1998	0,93	8,48
1981	0,95	8,42	1999	0,98	8,55
1982	1,05	8,66	2000	1,03	8,41
1983	1,02	8,26	2001	1,04	8,67
1984	1,02	8,92	2002	1,02	8,41
1985	1,00	8,18	2003	1,02	8,78
1986	0,95	8,52	2004	1,12	8,81
1987	0,97	8,21	2005	1,11	8,54
1988	0,96	8,36	2006	0,99	8,39
1989	0,98	8,85	2007	1,11	8,35
1990	0,91	8,87	2008	1,14	8,84
1991	0,92	8,29	2009	1,06	8,77
1992	0,97	8,44	2010	0,95	8,37
1993	0,97	8,23	2011	1,07	8,75
1994	1,06	8,56	2012	1,04	8,63
1995	0,99	7,91	2013	0,87	7,11
1996	1,07	8,40	2014	0,79	7,53
1997	0,85	7,99			

A2: Sediment properties

The D_{50} value at Hilton Head Island is estimated to measure approximately 0,2 mm based on Figure 1. D_{50} represents the median particle diameter, which is defined as the sediment particle diameter for which 50% by weight is finer. D_{50} is an important parameter for sediment transport characteristics.

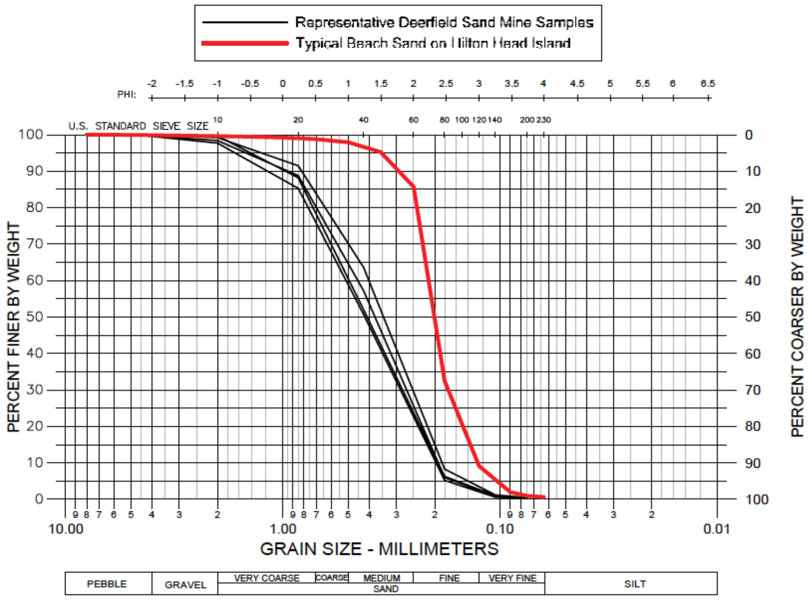

Figure A1: Grain size distributions for typical sediments from the Deerfield upland sand mine in Hardeeville (South Carolina) and at Hilton Head Island. [Source: Olsen Associates, 2015]

A3: Depth of closure

The DOC is a vital parameter for the calculation of sediment transport rates. It is the depth beyond which no significant longshore or cross-shore transports take place due to littoral transport processes. The closure depth can thus be defined as the seaward boundary of the littoral zone One way to determine the DOC, is by studying changes in the profile. By examining the profiles for a standard deviation of change that approaches zero, empirical evidence can be gathered to determine the DOC. Shown in Figure 2 are the profiles changes for Myrtle Beach and Kiawah Island over a period of several years. The standard deviation in change (STD) approaches zero at approximated depths of respectively -4.5 m NAVD and - 3.7 m NAVD.

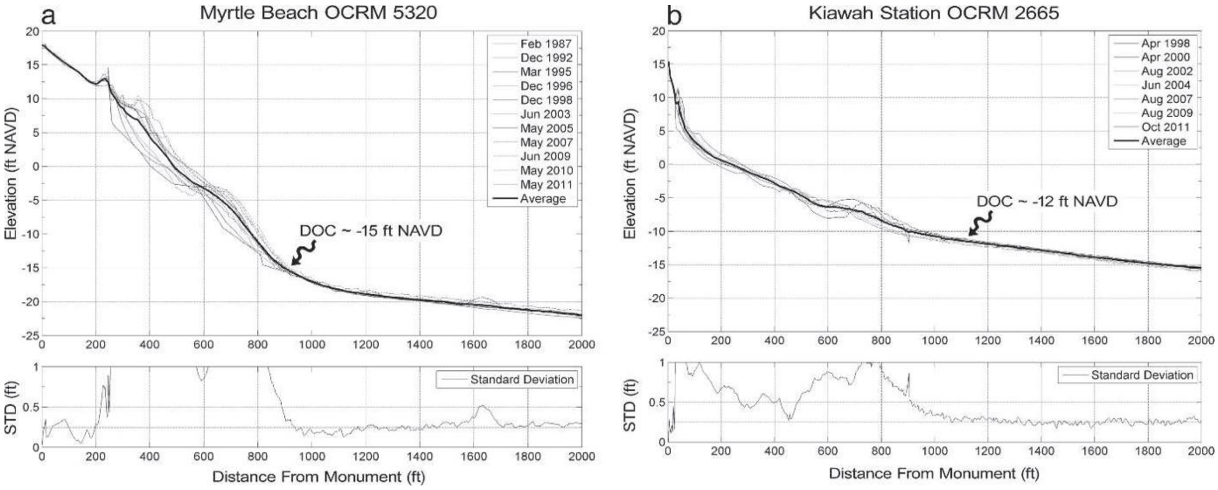

*Figure A2: **Left:** Profile changes between February 1987 and May 2011 at Myrtle Beach, accompanied by the standard deviation of change of the profile. **Right:** Profile changes between April 1998 and October 2011 at Kiawah Station, accompanied by the standard deviation of change of the profile. [Source: Kana et al, 2010]*