The evaluation of large-scale nourishment strategies for Duval County, Florida

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The evaluation of large-scale nourishment strategies for Duval County Florida

by

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Cover: The aftermath of Hurricane Matthew at Neptune Beach, Florida. Photography by Robert Wilson.

Preface

This thesis concludes the Master of Science program in Hydraulic Engineering at the Faculty of Civil Engineering and Geosciences at the Delft University of Technology. In the past year, I have been working on this thesis at research institute Deltares, in collaboration with the Delft University of Technology and U.S. Army Corps of Engineering. Deltares provided me with an open and inspiring working environment, which made it a great place to graduate. I would like to thank all the employees and fellow students that were always willing to help with even the smallest obstacles I experienced.

This study was done in collaboration with the Delft University of Technology, Deltares and the U.S. Army Corps of Engineers, to investigate the applicability of large-scale nourishment strategies in the United States. I would like to thank my graduation committee for providing me with this interesting topic, and giving me the opportunity and freedom to investigate the aspects that I found the most interesting. Stefan, thank you for your positive attitude and enthusiasm during the meetings, and providing me with heaps of suggestions about related studies that I could look at. Arjen, as my daily supervisor you always made time for me when I encountered difficulties in my project, and provided me with great feedback and inspiration to carry on. Moreover I highly valued your guidance throughout the whole process of graduating, and being available for advice that was not necessarily always related to my project. Thank you Freek, for you guidance in the first few months of my graduation, and helping me finding the right direction. Brian, thank you for providing me with the project site of Duval County, and supplying me with lots of useful material about the nourishment history. As my supervisor from the USACE, you provided me with great insights into the coastal management strategies in the US and I enjoyed our conversations about the differences between Dutch and American culture. Even though you headed back to the States halfway, you were always enthusiastic about my results and stayed available for questions, which I appreciated very much. Thank you Matthieu for your feedback on every version of this report, and giving me thoughtful suggestions on bringing my writing to a higher level. Lastly, Joep thanks for participating in my graduation committee in the last period.

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Abstract

The coastline of the United States has been threatened by significant erosion for the past decades. A study in 2000 predicted that 25% of the houses located within 150 meters of the shoreline will be destroyed by erosion in 2060. The east coast of the US experiences an average erosion rate of roughly one meter per year. Moreover, the Atlantic coast can be classified as highly erosive as it is vulnerable to hurricanes in the summer as well as winter storm events. The erosive behavior is counteracted by the application of beach and shoreface (nearshore berm) nourishments, referred to as non-feeder nourishments.

To illustrate this problem on a local scale, a project side in the northeast of Florida is selected, Duval County. At this site numerous beach and shoreface nourishments have been applied with an average nourishment cycle of approximately 5 years. However, taking the effect of climate change and sea-level rise into account, the required nourishment volumes will increase in the future. This means that other solutions need to be investigated. In the Netherlands, the pilot experiment Sand Engine is carried out, involving a large-scale feeder nourishment. It is expected that this type of nourishment will be more beneficial as it reduces the nourishment frequency and contains a concentrated displacement area. The nourishment will spread along the adjacent coastlines in a natural fashion, reducing the impact on ecology. Lastly, large-scale nourishment can temporary lead to additional recreational and environmental area, with a potential of creating new ecological habitats. This leads to the following research question:

> 'How can a large-scale feeder nourishment be beneficial for highly erosive coastlines along the Atlantic coast of the US, and how can the effects of such nourishments be quantified on different timescales?'

In order to evaluate the effect of large-scale feeder nourishments on the coast of Duval County, an evaluation framework has been developed. This framework is based on ecosystem services, which describe the way humans are linked to and depend on nature. Three main ecosystem services have been identified, which have been divided into several sub-services indicated by quantifiable parameters. The first ecosystem service is coastal protection, which is evaluated in terms of flood protection and maintenance of the coastline position. The time-dependent indicators for these sub-services are the foreshore volume and the distance between the Coastal Construction Control Line and the Momentary Coast Line. Secondly, recreation is evaluated by the sub-services of beach leisure, swimming, kitesurfing and strolling. Beach leisure is indicated by the dry beach width, swimming by the offshore directed flow velocities around the nourishment, kitesurfing by the additional sheltered area, and strolling by the walkable beach length along the shoreline. Lastly, the ecosystem service of habitat provision is split into three sub-services, namely nursery area, turtle nesting and dune growth potential. The nursery area is quantified by mapping the existing ecotopes, turtle nesting is evaluated by the beach slope and the beach width and finally the dune growth potential is indicated by the intertidal beach width.

The researched nourishment alternatives differ from geometric shape and in nourishment frequency. Two shapes are connected to the beach and have a width to height ratio of (1:1) and (1:3), while one is detached from the beach in the form of an island. The first two shapes have been applied with a frequency of 1, 3, 5 and 10 years, and the island only for 5 and 10 years. The morphological development of the alternatives is predicted with the numerical model of Delft3D over a period of 10 years.

All nourishment alternatives have been evaluated for all the selected indicators. For coastal protection the most suitable nourishment alternative is an attached and elongated nourishment with a frequency of 10 years (the (1:3) nourishment alternative). For recreation it differs largely per sub-service, but considering all sub-services have an equal weighting, the (1:3) alternative in combination with a 1 year frequency and the offshore island alternative with a 10 year frequency perform the best. The (1:3) nourishment alternative with a 1 year frequency creates the most benefit for beach leisure and swimming, while the offshore island with a 10 year frequency does this for kitesurfing and strolling. Finally for the ecosystem service of habitat provision, the

offshore island in combination with a 10 year frequency has the most potential. The most suitable nourishment alternative cannot be selected for Duval County as a whole since the weighting between the different ecosystem services is unknown, as it depends on the stakeholders involved.

Based on the analysis of the different nourishment strategies, the following conclusions have been drawn for the application of large-scale feeder nourishments:

- Large-scale nourishments can decrease the required coastline maintenance on the long-term as long as they are placed within the dynamic wave zone. However, shore connected shapes can cause initial downdrift erosion because of their protrusion into the ocean, which requires extra nourishments at these locations. The application involves a trade-off between applying a low nourishment frequency with a large volume, and being able to place all the sediment within the dynamic zone.
- The largest temporal additional recreational and environmental area is created by emerged alternatives. Shore connected nourishments provide the largest accessible beach area, while detached nourishments provide the largest sheltered area. In this study, the increase in sheltered area was up to 5 times as large compared to the original situation.
- Nourishment alternatives that are elongated and streamlined along the coastline have a larger region of influence after the simulation period. Here, the region of influence was 10-20% larger compared to the other shapes.
- Large-scale feeder nourishments have the potential to transport sediment over the entire project area under sufficient tidal and wave forcing. It leads to a more gradual spread of sediment than small-scale nourishments, as they tend to pile up within the placement area.
- As the disturbance of large-scale feeder nourishments is less frequent and concentrated, the adjacent coastlines are fed in a natural fashion, reducing the stress on ecology.

In conclusion, large-scale feeder nourishment can be evaluated by the approach of ecosystem services. They can certainly be beneficial for highly erosive coastlines, but its optimal dimensions depend on the required wishes for the considered coastline.

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1 Introduction

Along the coast of the United States, there are several locations where significant erosion has occurred over the last decades. It is expected that before 2060, one out of four houses situated within 150 meters of the shoreline will be destroyed by erosion [The H. John Heinz III Center for Science, Economics and the Environment, 2000]. Most of the damage will take place in the low-lying areas which are also subject to the highest flooding risks.

In the states along the Atlantic coast, the average annual erosion rate is roughly one meter per year. Most of the structures within the 60-year erosion hazard area, which was mapped in 2000, are located along this coastline. The Atlantic coast can be classified as highly erosive, as it is vulnerable to hurricanes in the summer as well as winter storm events. To counteract this behavior, several beaches in the US are actively nourished to compensate the persistent erosion of the beaches. In the US, typically beach and shoreface (nearshore berm) nourishments are selected as nourishment alternatives [The H. John Heinz III Center for Science, Economics and the Environment, 2000]. These nourishment strategies are referred to as non-feeder types, since they solely influence the area where they have been applied.

To illustrate this on a local scale, a project site along the Atlantic coast has been selected. The southern half of the Duval County coastline, which lies in the north-east of Florida, is considered. At this site numerous surveys of bathymetry and dry beach area are available between 2011 and 2017. From these surveys it is evident that chronic erosion is present along the coastline as well as instantaneous erosion caused by hurricanes or tropical storms. Both these processes increase the local erosion of the beach. Non-feeder nourishments are the preferred nourishment alternative for Duval County, and the erosion has been countered by artificially nourishing the beaches with a reactive approach [U.S. Army Corps of Engineers, Jacksonville District, 1992]. This means that a new nourishment was applied once the design profile was exceeded, which lead to an interval of approximately 5 years.

However, such regular nourishments are costly and have a high impact on the environment, both on the places where the sand is mined and where it is placed. On the nourished beach sections, organisms will reestablish within 6 to 18 months after completion of the sand fill operation, while in the borrow area a succession of biological communities is reached within 3-4 years after the operation [U.S. Army Corps of Engineers, Jacksonville District, 1992]. For both locations less frequent nourishment is preferable for the ecological system. On the other hand, providing an excessive amount of sand to the coastline can lead to burying of shallow reefs, coral or oyster beds more easily [Peterson and Bishop, 2005].

Taking the effect of climate change and sea-level rise into account, it is expected that the nourishment volumes will increase in the future. Applying these volumes as traditional nourishments, further referred to as non-feeder beach nourishments, leads to significant widening of the beach which is unattractive for beach visitors as the water becomes less accessible. Localized large-scale nourishments will lead to less perturbation of the shoreline while feeding the adjacent coastal sections [Stive et al., 2013].

The pilot experiment Sand Engine in the Netherlands raised the interest for large-scale multifunctional nourishments as potential nourishment alternative for the US coast. In the Netherlands a lot of research has been carried out studying the advantages of large-scale, multifunctional nourishments instead of regular small-scale nourishments. However, the applicability of such a solution on the US coast has not been examined yet. Nourishments in the form of cross shore swash zone placements, where material is discharged directly into the swash zone of the beach until a salient is formed, have been applied but they never involved such large sediment volumes as the Sand Engine.

1.1. Problem statement

Most beaches along the US coastline have been artificially nourished by small-scale non-feeder nourishments to counteract erosion. The selected project site is located along the southern half of Duval County, Florida on the east coast of the US. The Atlantic Coast can be classified as highly erosive as both tropical storms in the summer as winter storm events lead to significant erosion. However, due to sea level rise it is expected that the required nourishments volumes along these coast will increase in the future and non-feeder beach nourishments can become very costly.

The possible application of large-scale nourishments has been investigated on the Dutch coastline between Hoek van Holland and Scheveningen. Applying these types of solutions has advantages on multiple facades. First, the nourishment frequency will be reduced to approximately every 10-20 years. Furthermore the nourishment will disrupt less length of the beach as all sediment is concentrated in one location. The nourishment causes a timely dispersion of sediment alongshore which is crucial for its success. Moreover, as it slowly expands along the adjacent coastlines, it will feed the beach in a more natural fashion than non-feeder beach nourishments. Another advantage comes from the ecological perspective as reducing the nourishment frequency has a positive effect on the existing marine life. Less frequent disruptions of the soil will reduce the ecological stress. Another advantage is that the large initial local perturbation will temporary lead to additional recreational and environmental space. It has the design potential to create new habitats for species living along the coastline [Stive et al., 2013].

The hydrodynamic conditions at the US coastlines are different than the Dutch conditions, as the Florida coastline experiences a calmer wave climate, but is more prone to large storms and hurricanes. This means that the results from the pilot experiment of the Sand Engine cannot be applied directly. The reasoning behind the pilot experiment needs to be investigated in detail to see if this can be applied for the US coasts as well. This leads to the knowledge gap of the applicability of large-scale nourishments in other wave climates. Furthermore the assessment of such solutions need to be examined in more detail, as the advantages of large-scale nourishment are broader than coastal protection alone. Both the short-term and long-term effects need to be evaluated on various aspects to make a reasonable prediction of the behavior of such a structure in the US climates.

The following knowledge gaps have been identified for the possible application of large scale nourishments on the US coastlines, and will be used as a starting point for this study:

1. Are large-scale nourishments applicable on the US coast in terms of physical feasibility?
2. How can we quantify the effects of such nourishments on spatial and temporal scale?

The relevance of the project lies in the fact that there is no knowledge on the applicability of large scale nourishments in the US and how to evaluate them. The project will thus gather as much information as possible to address the feasibility of such nourishments in the environmental conditions present along Duval County.

1.2. Objective

The main objective of this thesis will be to develop and apply an evaluation framework for large-scale nourishment strategies along an highly erosive coast in the US. However, even if large-scale nourishments can be applied based on the environmental conditions, it is not necessarily a better solution than the non-feeder beach nourishments. This leads to the following research question:

> “How can a large-scale feeder nourishment be beneficial for highly erosive coastlines along the Atlantic coast of the US, and how can the effects of such nourishments be quantified on different timescales?”

The benefits of a large-scale nourishment can be judged on multiple aspects, for example the physical, the practical and the political aspect, but not all of these can be answered by a numerical modeling approach. In this thesis the focus will be on the multi-purpose application of large-scale nourishments. On the long-term, it needs to be investigated whether the nourishment is able to settle along the adjacent coastlines as it is transported by nature. Furthermore it should be investigated whether it is physically attractive to reduce the frequency of nourishing. If large-scale nourishments prove to be applicable along the US coast, it is important to quantify the effects from different viewing points.

To solve the overarching research question, the following sub-questions need to be answered:

1. Which nourishment concepts have been applied in the US and for Duval County until now?
2. What are the environmental conditions at Duval County and how does this influence the morphological beach evolution?
3. How can large-scale nourishments be described by ecosystem services and be quantified through time-dependent indicators?
4. How can the nourishment dimensions be optimized based on the chosen function?

The first sub-question treats the history of nourishment concepts that have been applied along the US coastlines and Duval County. This question considers the application of non-feeder beach nourishments as well as the possibilities for alternative shapes and solutions. Furthermore, it considers the local morphological evolution of the current application strategy.

The second sub-question answers whether it is possible to create large-scale nourishments in terms of wave climate, tidal conditions, wind conditions, sediment composition, transport magnitudes and directions. Furthermore a short comparison will be made to the conditions in the Netherlands as large-scale nourishments have been proven to be beneficial at this location. Lastly the influence of the environmental conditions on the beach evolution is investigated.

The main goal of the large-scale nourishment solution is to counter the significant erosion and provide a more robust solution than frequent small-scale nourishments. However, the effects of large-scale nourishments can be quantified in various ways. The third sub-question considers a common method to classify the effects called ecosystem services. Multiple (sub)services will be defined to address the effects on different time-scales. Furthermore it couples the selected (sub)services to measurable indicators. These indicators will be linked to output parameters of the numerical models.

The last sub-question considers the optimal shape and size for large-scale nourishments in Duval County. With the help of the necessary annual nourishment volume, the optimal nourishment frequency can be found. By applying this sediment in different geometries, the most beneficial design for the different ecosystem services can be found.

1.3. Approach

The feasibility of large-scale nourishments will be investigated by numerical modeling. A schematic depth-averaged two-dimensional Delft 3D model will be set up for the project site of Duval County. The U.S. Army Corps of Engineers (USACE) has provided multiple beach surveys after the nourishment of 2011 which will be used for the validation and calibration of the model.

First a separate Delft3D-FLOW and Delft3D-WAVE model will be set up, which will be integrated into a larger model together. The goal of this step in the research method is to validate the model for the project site. Once the schematic model produces acceptable results for the present conditions of the project site, the best nourishment location and necessary annual nourishment volume is investigated based on the sediment transport rates found in the model and literature.

In the coupled model different nourishment designs will be evaluated. Initially these nourishments will differ in size related to the duration of the nourishment cycle, which is based on the annual necessary sediment volume. Once the most suitable nourishment frequency has been found, the focus will be on optimizing of the geometry of the applied sand volume. Each alternative will be assessed by the selected set of indicators to provide insight into the benefits of the different solutions.

2
Literature study

In order to provide the most suitable solution for large-scale nourishments along the US coastline, background information on the nourishment history in the US and the benefits of large-scale nourishments is necessary. In this chapter, the available knowledge on the problem statement is presented. It can roughly be divided into four sections.

The first section includes the existing knowledge about erosion and nourishments, and is followed by section on the applicability of large-scale nourishments. The third part treats the erosion management history along the US coastlines. Specific attention is paid to the Atlantic coast, as the selected project site is situated over here. Fourthly, the project site of Duval County in Florida is discussed. The last section contains the background information for the evaluation framework of the nourishment strategies. This framework will be based on the ecosystem services approach, which will be divided into several sub-services. For these sub-services, corresponding indicators will be selected with their output parameters from numerical models.

2.1. Coastal erosion

Coastlines all over the world are permanently changing due to the action of waves, currents and tides. Material is transported by streams and rivers to the coastlines in the form of continental material such as sand, gravel and cobble fragments. At the coast, most of the sediment is suspended in the water column and transported along the coast by currents. As the sand is deposited by the longshore current on the coastline, it is affected by the oscillating motion of the waves breaking onto and receding from the beach. The sediment is gradually moved along the beach edge by the continual onshore-offshore movement of the water [American Geosciences Institute, 2018]. Changes in the morphology of a coastal system depend on the spatial and temporal fluctuations of the sediment budget. If the incoming volume of sediment along a beach section is equal to the volume of sediment leaving the section, no shoreline change is visible. On the other hand, if the incoming sediment flux is smaller than the outgoing one, the sediment deposited at the bottom will supply the deficit leading to a lowering of the bottom. This process is called coastal erosion, and is generally divided in two types, acute erosion and chronic erosion. Often it is misinterpreted that storms are the reason for chronic erosion along coastlines, while this is caused by a gradient in the longshore sediment transport rates [Bosboom and Stive, 2011], and storms cause mainly acute erosion. In the Shoreline Management Guidelines [Mangor et al., 2017, p. 9], these two types are defined as:

> Acute coast erosion: Erosion in the coastal profile. This is taking place in the form of scouring in the foot of the cliffs or in the foot of the dunes. Acute coast erosion takes place mainly during strong winds, high waves, high tides and storm surge conditions which results in coastline retreat. Acute coast erosion is partially reversible.
> Chronic coast erosion: The process of wearing away material from the coastal profile due to imbalance in the supply and export of material from a certain section. Erosion will take place on the shoreface and on the beach if the littoral drift export is greater than the supply of material to a certain area, this means that the level of the shoreface and of the beach will decrease. Chronic erosion thus occurs when the littoral transport increases in the direction of the net transport or if there is a deficit in supply of sand to the area in question.

Erosion is not necessarily harmful for the coastal zone, as it depends on the dimensions of the coastline and the conditions of the hinterland. It is called critical erosion once there is a threat to or loss of specific interest lying in the hinterland. Examples of these interests are upland development, recreation, wildlife habitat or important cultural resources [Division of Water Resource Management, 2016]. To protect these interests, critical erosion lines have been developed along coastal zones. Generally, these lines are used as reference lines to express the coastal width that will retreat during a reference storm.

To prevent the coastline from reaching beyond the critical erosion line, coastal erosion can be countered by different types of measurements. Generally a distinction is made between 'hard' and 'soft' measures, as hard measures are more 'permanent', while soft measurements need to be applied more frequently and are generally more flexible.

Hard measures often involve coastal structures such as groins, offshore breakwaters, submerged breakwaters, and revetments or seawalls. These structures avoid the erosion of sediment by interfering in the sediment transport rates. Acute erosion is countered by structures that prevent erosion during extreme storm events (sea walls, revetment, sea dike), while chronic erosion is countered by structures that influence the rate of alongshore transport both under normal conditions and extreme conditions (groins, detached breakwaters). Soft measurements are based on compensating the eroded sand by nourishing the beach without interfering in the sediment transport rates, but adjusting the available sediment budget. This principle allows the natural erosion processes to happen, but the eroded material is frequently replaced. The deposited sand could come from maintenance dredging of nearby rivers or harbors, or from offshore borrow areas [Bosboom and Stive, 2011].

This thesis focuses on the application of soft measures to manage erosion along coastal sections. With the help of artificial nourishments, the affected beach will develop in more natural state and preserve its recreational value compared to a coastal structure. A disadvantage of nourishments is that it is an ongoing process and needs to be repeated from time to time. The interval between two successive nourishments depends on the environmental conditions at the beach and the available equipment for such a supply operation. The borrow sand used for nourishments can come both from land-based sources as marine sources. Nourishment volumes coming from land-based sources are combined with dredging operations on nearby river beds or harbors. The borrow areas for marine sediment sources need more attention. The borrow pit should be sufficiently far away to prevent additional erosion at the coastline. Furthermore a choice needs to be made between dredging a narrow, but deep borrow pit or dredging thin layers from an extensive area. Both choices have their advantages and disadvantages [Bosboom and Stive, 2011], but will not be investigated in this thesis.

2.2. Erosion management along the Dutch coastline

Large-scale nourishments have thus far only been applied along the Dutch coast, and therefore insight into the creation of this concept is needed. Furthermore the reasoning behind the chosen dimensions can give guidelines to the application in the US.

Ongoing erosion processes along the Dutch coast caused the development of the nourishment policy of 'Dynamic Preservation' in 1990 to preserve the safety against flooding. In this policy it was decided that the preservation of the coast line was preferably done by using nourishments. The existing coastline in 1990 was selected as the reference coast line. The assessment of the coast line is based on three different indicators: the residual dune strength, the basal coast line and the coastal foundation – which imply three different scales of coastal management. With this division, the larger scale levels define the boundary conditions for the smaller scales and therefore create a pro-active approach to preserve the safety against flooding [Mulder and Tonnon, 2011].

In the year 2000, the nourishment policy was extended to a larger scale and the aspect of maintaining the sand volume in the coastal foundation was included. The coastal foundation is defined as the active profile between the -20 m depth contour and the landward boundary of the dune massive. By taking the sand volume into account, the required nourishment volume increased to $12 Mm^3$, compared to the $6 Mm^3$ which was needed for maintaining the coastline. This approach has been used until 2011 and produced good results in terms of maintaining the coastline on small and medium levels. However, the results on the large scale management level were not sufficient yet. Research into the major sediment sources in the Netherlands in 2011 showed that the negative sediment balance was approximately $20Mm^3$ based on an expected sea level rise of $2mm$. The uncertainty in the upscaling of the nourishment volumes lead to an investigation onto large-scale nourishments [Mulder and Tonnon, 2011].

Simultaneously, the research program for Building with Nature had been developed in the Netherlands in 2008. The main goal of this research program is to develop ecodynamic designs, which are innovative designs that optimally use the opportunities of the natural system. One of the tasks within the research program is to extend the knowledge of morphological developments in case of large scale nourishments [Van Wesenbeeck et al., 2008]. The new insights into the sediment balance and the development of the research program of Building with Nature lead to a paradigm shift of 'fighting' against nature to using the ecological forces as an advantage for flood protection measures. Furthermore, the effects of climate change, accelerated sea-level rise due to human-induced changes and increasing river discharges were included in the program. By including climate change and sea-level rise for the next century, the required nourishment volume increases tremendously. Applying this volume as beach nourishments leads to significant widening which is not attractive as the water becomes less accessible. From this reasoning, the concept of a localized mega-nourishment was formed [Stive et al., 2013].

Due to this paradigm shift, the idea for the 'Sand Engine' emerged as a new innovative approach for coastal protection. Especially in low-lying areas across the globe this approach could provide useful elements, as it is expected that The Sand Engine will stabilize the coastline at its present position. Furthermore the Sand Engine will be able to feed the adjacent coastal sections for the next 20 years [Stive et al., 2013]. The pilot experiment of the Sand Engine involves a mega-nourishment of $20Mm^3$ to create long-term safety conditions in combination with extra space for nature and recreation [Mulder and Tonnon, 2011]. This means that on average $1Mm^3$ of sediment is transported each year.

A localized mega-nourishment such as the Sand Engine has many potential advantages. First, the maintenance frequency of the nourishments is reduced significantly. A new renourishment operation is only required every 10-20 years as opposed to the 2-5 year cycle for non-feeder beach and shoreface nourishments. Secondly a mega-nourishment will advance the shoreline over a length of 10 kilometers in a more natural fashion as it diffuses slowly over time. Thirdly, the large initial perturbation will increase the locally available space for recreation and environment on a temporary scale. Lastly, the ecological stress on the system will be reduced, since the perturbation area is only ~2.5 km^2. It does not disturb the adjacent areas during deposition, but will still strengthen them over time [Stive et al., 2013].

The third and fourth argument consider the ecological impact of large-scale nourishments in a positive matter. On the other hand, there could also be significant environmental damage from these solutions. The extra sediment in the system could cover coral or oyster beds more easily. It could also potentially close inlets and cause major long-term changes to the system as the natural sediment system is disturbed.

2.3. Erosion management history along the US coastline

Risk along the US coastline is generally expressed in the risk prone to flooding. The National Flood Insurance Program (NFIP) investigates these risks and produces flood insurance rate maps to inform homeowners of how much they are at risk. The program was established in 1968 to provide flood insurance to home owners and enforce floodplain management regulations that meet the minimum requirements described in the program. The program thus only describes the homeowners risk against flooding, but does not take the risk of erosion into account [The H. John Heinz III Center for Science, Economics and the Environment, 2000]. The Heinz Center concluded that between 1980 and 2000, the density development along several high-risk coastal areas has increased by more than 60%.

Considering erosional behavior along these high-risk coastal areas, two types of losses are distinguished. First, shoreline retreat is present, characterized by beach and bluff erosion that undermines structures. Secondly, flood damage is increased by a combination of erosional processes. However, it is not possible to separately treat these two effects since they occur simultaneously during large storms.

In 2000 the Heinz Center presented a report for the extension of the policy of the NFIP. In their research they found that approximately one in four houses situated within 150 meters of the shoreline will be destroyed by erosion before 2060. The report investigated the extension in terms of mapping erosional hazards to make sure that homeowners are correctly informed about the risk of their properties. One of these suggestion included the possibility of shoreline protection measures like nourishments, dune restoration or structural measures.

In the previous chapter it was defined that erosive coastlines can be countered by artificial nourishments. The interest in these types of solutions has increased significantly since the 1950's along the US coastlines. The increasing amount of projects involving beach nourishments reflects a change in the approach to shoreline protection within the coastal engineering community. Furthermore the harmful ecological and aesthetic impacts of these structures were recognized over time. The loss of beaches has severe economic impacts on tourism and recreation, supporting the attractiveness of beach nourishments [The H. John Heinz III Center for Science, Economics and the Environment, 2000].

In the last 60 years, a lot of research has been conducted in the field of artificial nourishing the US coastlines. Especially the environmental and economic impacts of such operations have gained a significant amount of interest. The economic benefits have proven to be significant in cases of frequently nourished beaches that have a stable coastline. However, the long-term commitment to continuous renourishment leads to a huge financial challenge due to the unpredictable weather conditions along the US coastlines. Especially the unpredictability of major storm events proves this difficulty regarding finding sponsoring agencies. Furthermore, previous experiences with the durability of beach nourishments have been highly variable. Besides the weather conditions, differences is sediment quality and grain size, scientific uncertainty about littoral currents and sediment transport conditions and inconsistency in project construction quality have played a large role the development of the projects. Additionally, the ecological effects of nourishments on the borrow areas and the disposal sites are not fully understood, contributing to the doubts about these types of solutions [The H. John Heinz III Center for Science, Economics and the Environment, 2000].

In 1972, the Coastal Zone Management Act (CZMA) had passed. In this act, the coastal states became the intermediaries between the federal agencies and local communities in terms of coastal policies. This led to increased attention towards issues of erosion, sea level rise and cumulative negative effects of receding shorelines. However, the developed management programs vary highly along the coastal states, leading to a difference in experience, institutional structure, and capacity for managing coastal erosion.

The Atlantic coast can be classified as a highly erosive coastline, since it is vulnerable to tropical storms in the summer as well as winter storm events. The Atlantic coast is partially bordered by a high amount of barrier islands. These islands are primarily composed of loose sand causing them to be very dynamic. Due to slowly increasing sea level rise, a trend of landward moving islands has been discovered [The H. John Heinz III Center for Science, Economics and the Environment, 2000].

In the previous section it was explained that erosion is only harmful for a coastline if specific interests in the hinterland are threatened. These areas are designated as critically eroded shorelines, and many have been restored through beach restoration and nourishment projects. The Florida Department of Environmental Protection (FDEP) has defined critically eroded shorelines as:

> A segment of the shoreline where natural processes or human activity have caused or contributed to erosion and recession of the beach or dune system to such a degree that upland development, recreational interests, wildlife habitat or important cultural resources are threatened or lost. Critically eroded areas may also include peripheral segments or gaps between identified critically eroded areas which, although they may be stable or slightly erosional now, their inclusion is necessary for continuity of management of the coastal system or for the design integrity of adjacent beach management projects [Division of Water Resource Management, 2016, p. 7].

Coastal erosion has large influence on people's lives since most coastal property owners only move their property the minimum distance that is required by the government to maximize their ocean view, instead of moving it as far as possible back on the lot. Many would rather repair damages than relocate their houses along the Atlantic coast. This has influence on the erosion management strategies, and makes artificial beach nourishments look the most promising [The H. John Heinz III Center for Science, Economics and the Environment, 2000].

Even though no knowledge is available on the application of large-scale nourishments along the US coast, some research has been done into alternative forms than traditional beach placements. Especially the feeder beach strategy has been applied in multiple locations. The feeder beach concept means that a nourishment is placed at the most updrift location of the littoral cell. Due to wave impact and alongshore sediment transport, the placed fill is distributed and thus 'feeding' the adjacent coastline. This strategy has been applied at Upham Beach along the west coast of Florida in 2004 for a volume of 300 000m^3 [Elko and Wang, 2007].

Another project, located at Egmont Key (west-central Florida), investigated the application of cross shore swash zone placements (CSSZ). These placements involve the discharging of material directly into the swash zone of the beach until a salient has formed. The discharge line is then extended perpendicularly offshore until a point feature has been created on the shoreline. The point feature is highly erosive and acts as a feeder beach towards the adjacent coastline. Furthermore, the natural spreading causes a well-sorted spreading of sediment and finer fraction to be washed out [Maglio et al., 2015].

The CSSZ was constructed from late 2014 to early 2015 and involved a total nourishment volume of 62 000m^3. In late June 2015, preliminary results were presented at the Dredging Summit and Expo 2015 in Houston, Texas. The potential positive environmental and economic outcomes of the CSSZ can be described in three points. The first positive outcome relates to the quality of the placed sediment. As the sediment is discharged into the relatively energetic swash zone, fines and organics are washed out of the material which leads to lightening of the sediment material color. Furthermore, placement of sediment on the active beach causes a natural sorting of the sediment into the appropriate equilibrium beach profile locations. As the CSSZ acts as a feeder beach, the affected shoreline area is much less than traditional placements. Secondly, the methodology reduces the costs of future renourishments as less manpower and less equipment is needed during construction. Lastly, the CSSZ has the potential to align with the concepts of 'strategic placement' and 'Engineering with Nature' approaches [Maglio et al., 2015].

The findings at Egmont Key give an insight into the potential benefits of applying large-scale nourishments on the US coastline. Even though the placement volume at Egmont Key is still relatively small compared to the Sand Engine, it shows the potential benefits of alternative shapes. The approach of Egmont Key can be applied more permanently if larger nourishment volumes are involved.

2.4. Duval County, Florida

Duval County, Florida is located along the east-coast of the United States and borders the Atlantic Ocean. Due to past threats to development and recreational interest, the coastline is classified as critically eroded. The considered project site is currently part of a beach restoration project, and is continually maintained. It has a length of approximately 16 kilometers (10 miles), and reaches from the south of the St. Johns River jetties all the way down to the Duval-St. Johns County line in the south, see figure 2.1 [U.S. Army Corps of Engineers, Jacksonville District, 1992].

In 1964 the original feasibility study took place, which was especially done to examine the erosion and damages along the coastline. Furthermore it proposes different alternatives to prevent erosion in the future, including included both soft and hard measures. The study concluded that artificial restoration via periodic nourishments would be the best solution to protect the coastline. Therefore, the Duval County Shore Protection Project was found in 1965. The primary purpose of the project was to prevent damages due to storm-induced erosion on the upland properties of Duval County [U.S. Army Corps of Engineers, Jacksonville District, 2012].

Initial construction of the nourishments started in 1978 and were completed in 1980. In 1984 a plan was developed for the periodic renourishments which included the recommendation of implementing sand fences and sea grasses to prevent windblown losses. In 1992 the original federal support for the shoreline protection project was coming to an end, so again a feasibility study was carried out to extend the federal support. The new feasibility study developed a plan for nourishments for 50 years from the initial beach restoration in 1978 until 2028. In this plan a specific design berm cross-section was described which should be constructed and maintained during the 50-year period. The cross-section consisted of an 18 meter wide berm at an elevation of 3.3 meters above Mean Low Water (MLW), which is equivalent to +2.6 meters above Mean Sea Level (MSL).

The Duval County Shore Protection Project is divided into four reaches based on the characteristics of each section. An overview of these four sections is given in figure 2.1. The first reach consists of Naval Station Mayport and Hanna Park. This section is the most affected by the shoals and jetties from the St. Johns River. The second reach consists of Atlantic Beach, and appears to have more critical erosion than reach 1. Furthermore, part of the second reach was originally protected by seawalls and revetments that have become exposed over the years. The third reach consists of Neptune Beach and the north of Jacksonville Beach, and is partly protected by seawalls and revetments as well, but has substantial dune in the front of these structures. Lastly, reach 4 consists of southern Jacksonville Beach until the end of the Duval-St. Johns County line. Similar to reach 2, it appears to have more critical erosion problems than reach 1 and 3 and has exposed seawalls and revetments.

The 1992 study noted the total measured absolute losses between 1978-1988 after initial construction were approximately 475 000 cubic meters. Adding the nourishment volumes as well, the total eroded volumetric loss comes down to 2 483 500 cubic meters, approximately 250 000 cubic meters per year. This is less than figure 2.2 suggest since the maintenance disposal of 1985 was not taken into account. This high annual rate is likely to be caused by severe storms and the fact that the maintenance disposal material was finer than the proposed nourishment material. This resulted in higher initial losses, since less sediment is able to settle on the shoreline. Between the years of 1978 and 1988 portions of the beach, especially Naval Station Mayport, were periodically used as disposal areas for the maintenance dredging of the St. Johns River. The 1992 study also noted if the section of the Naval site at Mayport is excluded, the volume over the previous 10 years reduces to 1 855 000 cubic meters and an annual erosion of approximately 185 000 cubic meters can be found. Due to the regular nourishments, it was not part of the initial plans.

From the surveys done in 1992, it became clear that only three areas along the coastline were smaller than the authorized project berm of 18 meters. Furthermore, it could be concluded that in most areas the elevation of the berm gained approximately 1 meter, which significantly reduced the susceptibility of the area behind the dunes to flooding and wave damage. The applied volumes in 1992 were based on placing enough sediment to restore the design beach width and to compensate for the erosion losses until the next nourishment.

The borrow area sediment that had been used for the initial shore protection project and subsequent renourishments of the coastline was generally coarser than the pre-project native beach. However, the sand placed at the beach redistributed itself back to the gradation that was present before the project took place during the period of analysis.

After the initial construction of the nourishment in 1978, several other large nourishments have taken place along the coastline in 1985, 1991, 1995, 2005 and 2011. These nourishment intervals were based on optimizing the annual costs, leading to an interval of 5 years. In between these large nourishment, smaller beach fills have taken place due to the maintenance dredging of the adjacent federal navigation project at Jacksonville Harbor. These occurred in 1980, 1985, 1990, 1993, 1995, 2002, 2003 and 2013. These small scale nourishments were mainly placed in the north, immediately down drift of the federal navigation channel [U.S. Army Corps of Engineers, Jacksonville District, 2012]. An overview of the nourishments between 1978 and 2013 is given in figure 2.2.

In each of the large nourishments, the design berm cross-section was adjusted to the erosion pattern that was observed. In the first renourishment of 1985, the design berm had a width of 30 meters along reach 2, and 40.5 meter along reaches 3 and 4. In all cases the berm was constructed at an elevation of +2.57 m MSL. The nourishment material along reach 2 came from maintenance dredging of Jacksonville Harbor, while the material along reaches 3 and 4 came from the offshore borrow area. The second renourishment took place in 1991 and was placed along Atlantic Beach and all material came from the offshore borrow area. In 1995 the third renourishment project was carried out along the southern half of Atlantic beach downwards until the Duval-St. Johns County line. The berm widths at reach 1 and the northern part of Atlantic beach were adequate during this survey. The design berm width for the 1995 nourishment was still 40.5 meter at an elevation

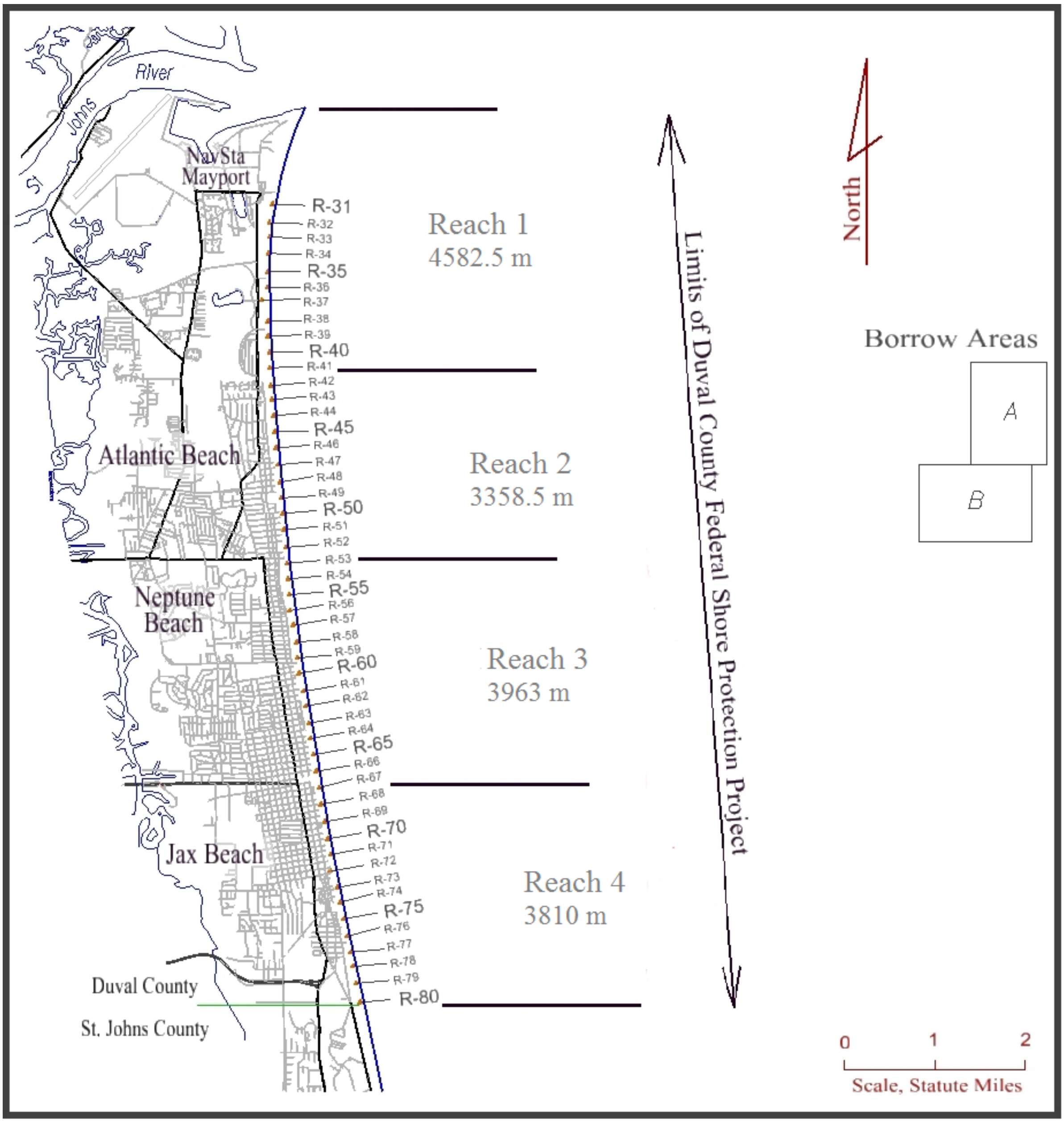


Figure 2.1: Reaches in the Duval County Shore Protection Project [U.S. Army Corps of Engineers, Jacksonville District, 2012].

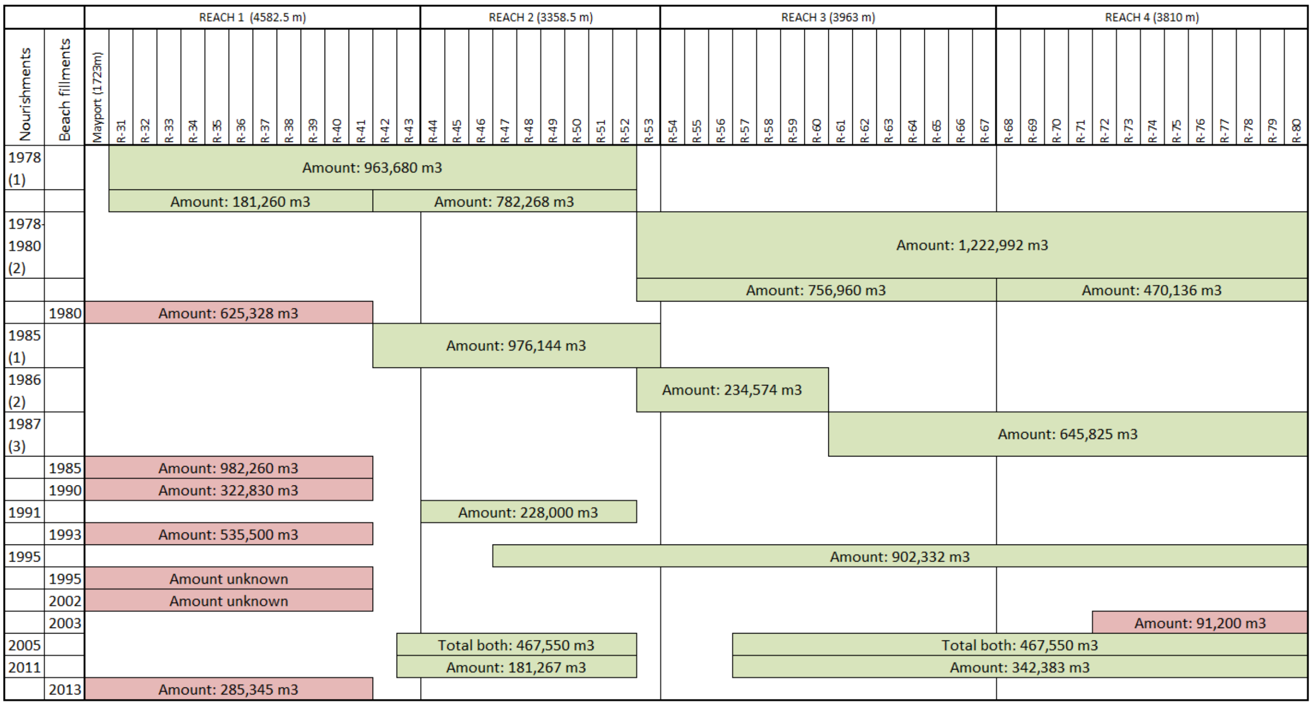


Figure 2.2: Overview nourishment history along Duval County, Florida.

of +2.57 *m* MSL, and the material came from a borrow area approximately 11 kilometers east from Atlantic Beach [U.S. Army Corps of Engineers, Jacksonville District, 2012].

In 2004, four major hurricanes impacted the shoreline of Florida, and to repair their damages the fourth renourishment took place in the summer of 2005. It was constructed along two sections, one along Atlantic Beach, and one along the southern portion of Neptune Beach and all along Jacksonville Beach. The source material for the renourishment came from the same offshore borrow area as last time. The design berm width along reach 1 and 2 increased to 42 meter, while the berm width along reach 3 and 4 remained at 40.5 meter. Both design berms had a required elevation of +2.57 *m* MSL.

Figure 2.2 shows that the most frequent renourishments took place along reach 1 and 2. This is partly in accordance with the expectations from the original feasibility report of 1964 as reach 2 was classified as a critically eroding coastline. The frequent nourishments along the southern end of reach 3 were not expected, since a substantial amount of dunes was present before the structures. Most nourishment along reach 1 were primarily based on the necessary channel depth of the St. Johns river instead of the necessary volume along the beach, which means that determining an actual erosion rate is not possible.

The fifth renourishment of the coastline took place in 2011. The pre-construction survey showed that the erosion was slightly less than the expected value of the long-term predictions. However, several areas along the coast were highly affected by erosion such that renourishment was necessary before the start of the 2011 hurricane season. The decrease in annual erosion rates can be explained by slowly onshore migrating sediment which was eroded from the deeper foreshore and offshore bar system by previous hurricanes. Profile surveys showed that the sediment volume in the offshore bar system was higher than normal, and more movement has taken place in deeper waters. The suspected onshore movement of the sediment caused the volumes for the 2011 nourishment to be based on historic standards and thus have a relatively low value. However, the new design berm cross-section had a width of 50 meters at an elevation of +2.87 *m* MSL along all reaches, leading to an increase of required nourishment volume. The new berm width was not realized along the entire coastline as places of minimal fill placement were excluded. Strengthening of the coastline eventually happened along the same sections as the 2005 renourishment including almost identical volumes.

Along the entire coast of Florida, the FDEP has placed monuments to investigate the behavior of the shoreline, the so-called DNR monuments. In Duval County, these monuments are located along most of the coastline, see figure 2.1. The monuments are shortened to R-monuments for convenience, and begin at the southern end of Mayport Naval Station (R-31) until the Duval-St. Johns County line (R-80). The 2011 nourishment was constructed along two parts of the coastline. The northern part was constructed between R-43.5 and R-53, while the southern part was constructed between R-57 and R-80 [U.S. Army Corps of Engineers, Jacksonville District, 2012].

The nourishment was constructed between 8th of July until the 16th of August of 2011. A post-construction survey took place in the end of September, and after that three annual monitoring surveys were conducted along the R-monuments. The first annual survey was conducted in beginning of July of 2012, the second one at the end of June 2013 and the third in May 2014. Appendix A gives an overview of several transects for the post-construction survey and the three annual surveys.

During the first year the process of shoreline recession dominated the coastline, but some accretion was visible in between the northern and southern segment [U.S. Army Corps of Engineers, Jacksonville District, 2012]. Approximately 67% of the placed material stayed within the surveyed profile, and 33% was lost to deeper regions. The overall average shoreline recession was −7.2 meters. In the second year, the observed shoreline recession trend persisted at a slightly increased rate. However, the sediment volumes in the surveyed profile remained almost the same, as 65% of the originally placed material was still present. This means that the shape of the beach in cross-shore direction changed significantly while keeping the same sediment volume. Visual inspection showed that very little of the beach berm remained visible, and that most beach profiles sloped steadily downward at the beginning of the toe of the dune. The third annual survey showed that the shoreline was reasonably stable, but local variations were visible. The berm had recovered substantially along both segments. It appears that sediment located beyond the survey depth has been shifting landwards reforming the eroded berm. The eroded material from the first year had thus accumulated in deeper waters, but returned to the active beach profile in the third year. The total sediment volume present in the active profile had increased back to 94%, which means that only 6% of the nourishment material was lost in the first three years.

The 2011 renourishment was not the last one at Duval County. In 2016 the sixth renourishment took place, which was mainly done to reconstruct the shoreline and dunes eroded by Hurricane Matthew [Duval County 2018 Beach Renourishment Information, 2018]. The total applied nourishment volume between 1978 and 2016 is roughly 9 333 000 cubic meters of which 37% came from navigation dredging of the St. Johns River. The remaining 63% comes from an offshore borrow area. The latest renourishment is planned for late October 2018 until January 2019, since part of the 2016 nourishment was eroded by Hurricane Irma. This renourishment will repair the erosion damage of Hurricane Irma and complete the dune repairs of both hurricanes.

2.4.1. Environmental conditions

The project site is located along the east coast of Florida, and can be classified as an amero-trailing coast [Bosboom and Stive, 2011]. From a geological perspective, these coastlines are the most mature and contain large continental shelves. The extensive shelves cause frictional damping of storm waves and experience less wave energy. On the other hand, these coasts are extremely vulnerable to storm surge as it piles up at wide shelves, and generally have a large tidal range. The coastline in northeast Florida is governed by barrier island systems [The H. John Heinz III Center for Science, Economics and the Environment, 2000], which shows that the shape of the coastline is dominated by waves.

The climate in northeast Florida can be classified as a 'Cfa' system, a humid subtropical climate, according to the Köppen-Geiger climate classification system [Peel et al., 2007]. The present weather climate is moderate, without a dry season but with a hot summer. The summer occurs from April to October, while winter conditions are present between November and March. Seasonal variations in terms of temperature, precipitation, wind direction and storminess are present. Average temperatures in the summer range from 25.1°C to 32.2°C with July as the hottest month. Average monthly precipitation ranges from 64 to 189 mm with September as the wettest month. In the winter the average monthly temperature ranges from 18.0°C to 22.8°C where January is the coldest month. The average monthly precipitation is lower and varies between 61 and 93 mm, where November is the driest month.

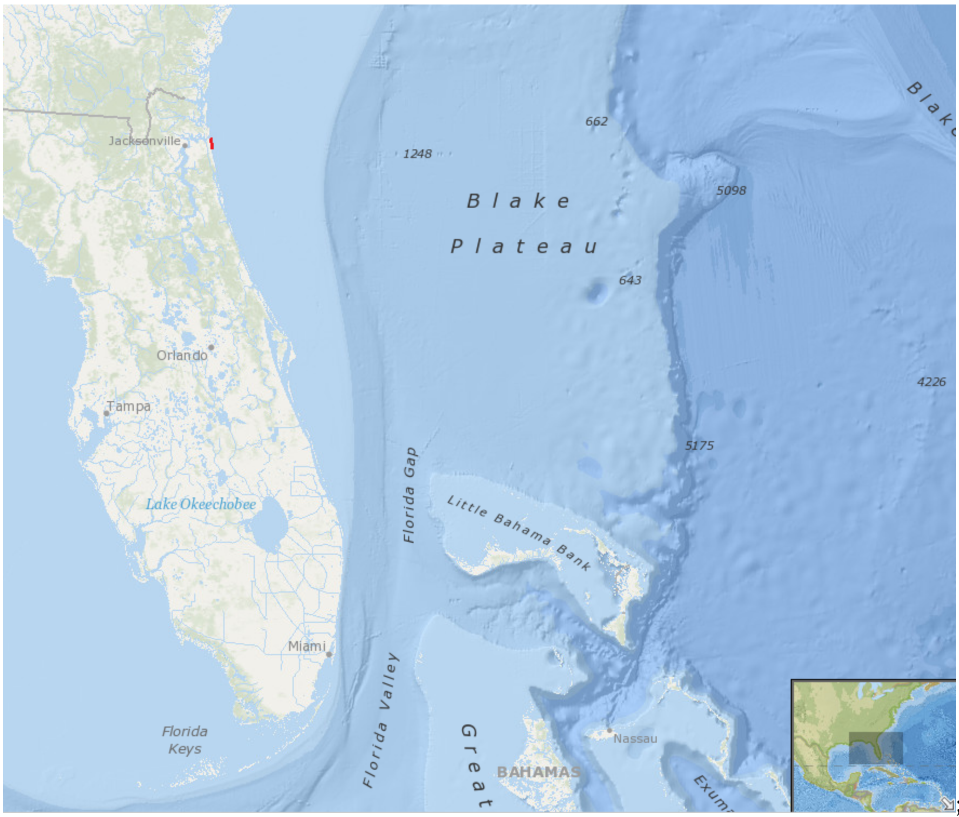


Figure 2.3: The continental shelf around Florida, [National Oceanic and Atmospheric Administration, 2018a]. The red section gives the location of the considered coastal section for Duval County.

Bathymetry

The coast of Duval County is located on a large continental shelf with a width of approximately 120 kilometers and an offshore depth of 25 meters. Beyond the continental shelf the Blake Plateau is located which goes over into the North American Basin further offshore (see figure 2.3). The coastline taken into account by the Duval County Shore Protection Project is marked in red. At this location, the USACE has performed multiple bathymetric surveys as explained previously. In appendix A some transects of these surveys can be found. The average profile steepness at the coastline is 1 : 55, which means that it is a mildly sloping beach. Furthermore it can be observed that the 2011 nourishment was placed in the form of a beach nourishment with a bar at $-2\ m$ MSL. In the following years, this bar was transported offshore. This caused the intertidal beach slope to become steeper.

Waves

In the 1992 report, the wave climate at Duval County was investigated based on 20-year hindcast data from an experiment station from the USACE close to the shore. This data showed that during summer the waves were predominantly from the south and southeast, while in the winter they approached mainly from the north and northeast. The average significant wave height for the 20-year period was 0.69 meters, and a maximum of 4.62 meter was predicted. The highest wave heights occurred during northeastern storms in the fall-winter season and the tropical storms in the summer-fall season. As the northeast storms occurred more frequently, they had a higher impact on the coastline.

A more recent data set is obtained from the ERA5 database for the years of 2011 until 2015. The closest data point (−81.3°W, 30.3°N) is located 8.5 kilometers offshore of the coastline. In figure 2.4, a wave rose is presented based on the wave climate obtained from the ERA5 data point for the years of 2011 until 2015. The dominant wave directions are still from the northeast to the southeast, with the highest waves coming from the northeast to east. However, the most frequent waves in the system come from the southeast. Moreover, it can be observed that the average wave height is 0.78 meters and has increased slightly in 20 years time, but is still relatively low.

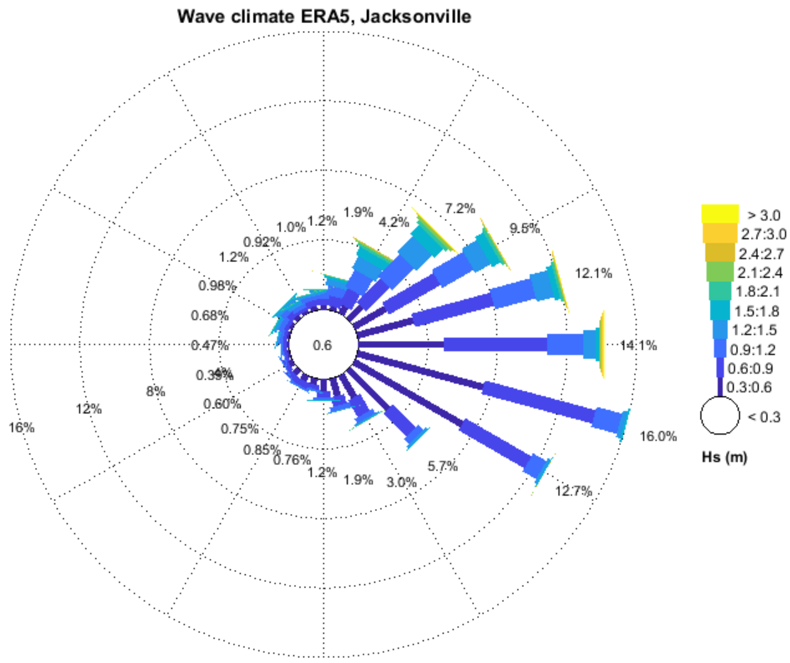


Figure 2.4: The wave climate at Jacksonville, Duval County (−81.3°W, 30.3°N) between 2011 and 2015.

Tide
The considered coastal section has a semi-diurnal climate, which means that high and low water occur twice a day. In 1992, the mean tidal range was 1.56 meter (measured between Mean High Water (MHW) and Mean Low Water (MLW)). The spring tidal range (measured between Mean Higher High Water (MHHW) and Mean Lower Low Water (MLLW)) was 1.71 meter. In 1962 a combination of wind set-up, barometric pressure set-up and tidal peak lead to a storm tide of +1.62 m MSL with a runup of 1.1 meter.

Currently, the mean tidal range at Jacksonville Beach is 1.546 meter, and the spring tidal range is equal to 1.711 meter. The tidal climate has not changed over 20 years, and is still classified as moderate. In figure 2.5 an overview is given of the most important tidal datums and their range relative to MSL.

Wind
The wind climate was not explicitly described in the 1992 report. Nevertheless the report mentioned that winds from the northeast dominate in the generation of waves due to the long uninterrupted fetch.

The present wind climate was obtained from the same ERA5 data point as the wave climate, located 8.5 kilometers offshore. In figure 2.6 the wind rose is given. It can be observed that the highest wind speeds come from the northeast to the southeast, and the average wind speed is approximately 5 m/s.

Sediment
In 1983 the last sediment survey was conducted at the native beach of Duval County [U.S. Army Corps of Engineers, Jacksonville District, 1984]. The sand present at the beach was fine-to-medium grained quartz sand with varying amounts of gravel and shell-sized material. The median grain size was 0.192 millimeter with a phi mean grain size of 2.40 and a phi sorting value of 0.85. This classifies the beach as moderately sorted, fine sand-sized material.

Between 1956 and 1975, the littoral transport along the coastline was observed. In this 20-year period, the gross northern transport was 2 065 500 cubic meters and the gross southern transport was 3 748 500 cubic meters. This comes down to a net longshore transport of 1 683 000 cubic meters, and an average of 84 500 cubic meter per year. The gross littoral transport is thus approximately 290 700 cubic meters, which is higher than the average annual sediment loss. This could be related to the fact that the littoral transport is based on the shoreline orientation.

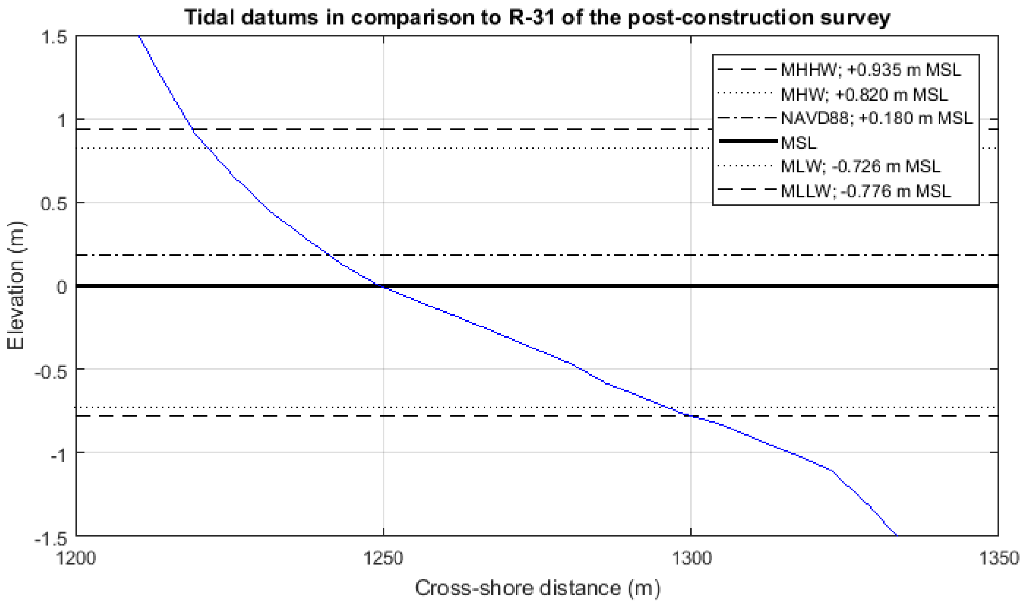


Figure 2.5: Tidal datums at Jacksonville Beach relative to MSL.

Extreme events

Due to the extensive length of the coastline of Florida, approximately 13 500 kilometers, the state is very vulnerable to storms. Tropical cyclones are generated by thunderstorms off the west-coast of Africa traveling along the equator and mixing with the warm oceanic waters, the moist air and the converging winds. The tropical cyclone generally passes through the following three stages based on the wind speed [University of North Florida, 2016]:

- Tropical depression: The maximum sustained surface wind speed (measured for an average of one minute) is 61 kilometers per hour or less.
- Tropical storm: The maximum sustained surface wind speed lies between 62 and 118 kilometers per hour (measured for an average of one minute).
- Hurricane: The maximum sustained wind speed is more than 119 kilometers per hour (measured for an average of one minute).

Once these storms reach the stage of hurricane, they are classified along the Saffir-Simpson scale ranging from category 1 to 5 based on their strength and potential for property damage. This scale can be found in table 2.1.

Table 2.1: Saffir-Simpson Hurricane Wind Scale [National Hurricane Center, 2018b].

Category	**Pressure (mb)**	**Wind speed (km/h)**	**Storm surge (m)**	**Effects**
1	> 980	119 – 153	1.0 – 1.7	Very dangerous winds will produce some damage
2	965 – 980	154 – 177	1.8 – 2.6	Extremely dangerous winds will cause extensive damage
3 (major)	945 – 965	178 – 208	2.7 – 3.8	Devastating damage will occur
4 (major)	920 – 945	209 – 251	3.9 – 5.6	Catastrophic damage will occur
5 (major)	< 920	> 252	> 5.6	Catastrophic damage will occur

In the 1992 report of the USACE, it was stated that northeastern storms are generally more damaging than hurricanes as the duration of these storms is generally longer than those of hurricanes [U.S. Army Corps of Engineers, Jacksonville District, 1992]. Currently Florida is hit more frequently by hurricanes than any other US state, and only two hurricane seasons have passed since 1851 where the state of Florida was not hit. The

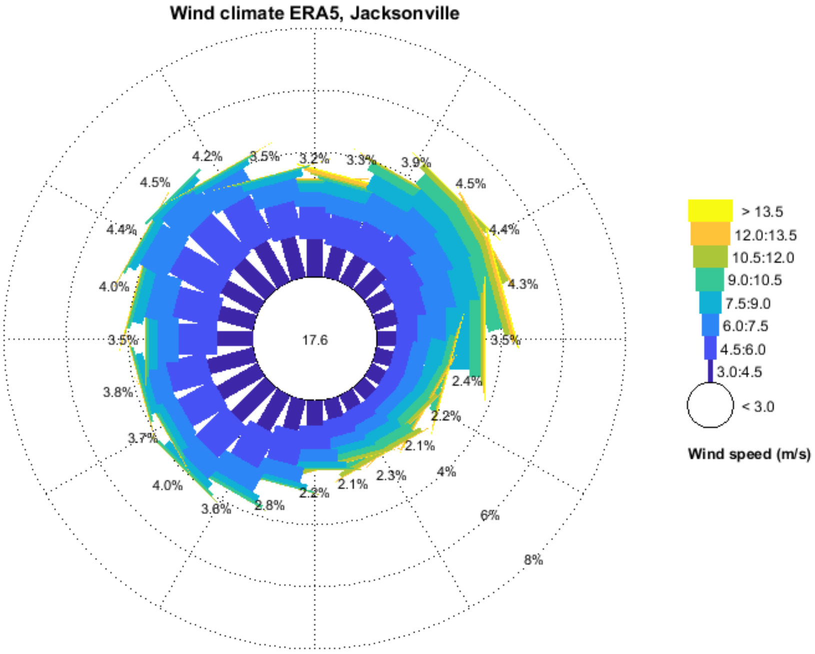


Figure 2.6: The wind climate at Jacksonville, Duval County (−81.3°W, 30.3°N) between 2010 and 2014.

hurricane season extends from the 1st of June until the 30th of November, with its peak between August and October [National Hurricane Center, 2018a]. The average return period of a hurricane, reaching the coast within 50 nautical miles and a wind speed over 119 kilometers per hour, is between 12 – 13 years for north-east Florida. For a major hurricane (wind speed over 178 kilometers per hour), it lies between 33 – 40 years [National Hurricane Center, 2018a].

For the selected coastal section, the Category 1 or 2 hurricanes are able to destroy or heavily damage buildings along the beachfront. Hurricanes from higher categories can cause massive destruction of the coastal barrier islands, and thus have a large impact on the coastal communities situated along Duval County. The destructive impact of hurricanes is mainly caused by the storm surge and not necessarily by the wind alone [University of North Florida, 2016].

2.4.2. Comparison with the Dutch climate

The wave climate along the Sand Engine is characterized by high waves in the winter (November to January) with an average height of 1.7 meter, and calmer conditions in the summer (April to August) with an average height of 1 meter. Waves with a height smaller than 1 meter originate predominantly from the northwest, while average waves (between 1.5 meter and 3.5 meter) come from both the southwest and northwest. The highest waves (> 4.5 meter) originate predominantly from the west and northwest [Luijendijk et al., 2017].

In figure 2.7 an overview is given from the wave climate obtained at the closest ERA5 data station at the Sand Engine (4.2°E, 52.2°N), which lies approximately 10 kilometer offshore. This data is largely in accordance with the description given above, since most waves come from the southwest to the northwest. Furthermore, it can be observed that the wave climate is more active than the situation in Duval County. This could be explained by the fact that the Dutch coast is classified with a storm wave environment, while the Florida coast experiences a east coast swell environment [Bosboom and Stive, 2011].

The sandy beach at the Sand Engine has an average median grain size of 0.242 millimeter, which is coarser than the sediment at Duval County. The coast is prone to chronic erosion due to relative sea level rise, reduced sediment supply, and sediment demand by adjacent tidal inlet systems. For Duval County the relative sea level rise is important as well. Duval County experiences thus a calmer wave climate, but is more prone to the influence of occasional storms and hurricanes with larger magnitudes than the Dutch coast. This calmer wave climate has an effect on the sediment transport rates as well. At Duval County, the net transport rate is

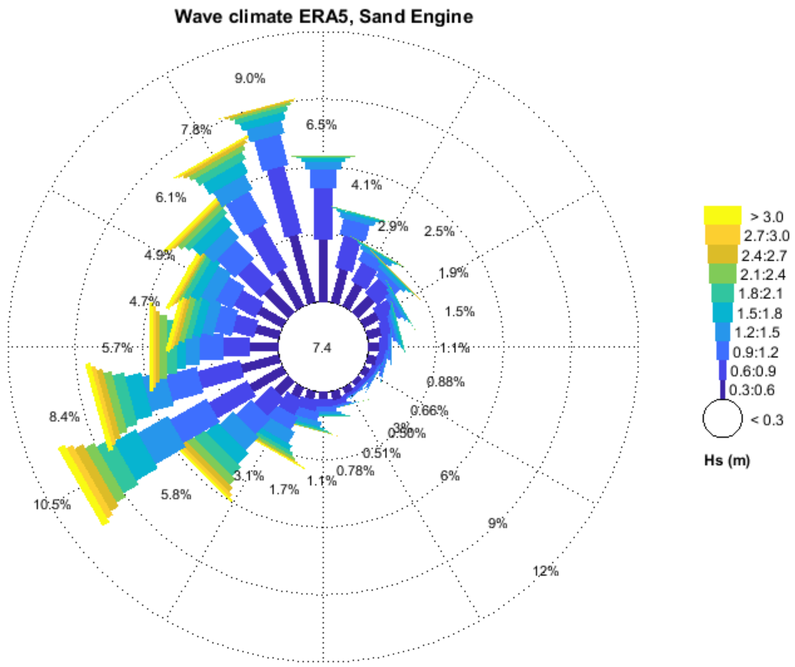


Figure 2.7: The wave climate at the Sand Engine (4.2°E, 52.2°N) between 2010 and 2016.

approximately 300 000 cubic meters per year, while the annual sediment transport rate at the Sand Engine is approximately 1 000 000 cubic meters.

2.5. Quantification of the effects

The last decades, the coast of Duval County has been renourished using non-feeder beach nourishments. To determine whether a large-scale nourishment is preferred above the traditional nourishment method, quantification of the effects is necessary on both spatial and temporal scales. The main purpose of nourishments is to enhance the coastal protection, but it has the potential to provide space for recreation and nature development as well [Van Zanten, 2016]. The experiments at Upham Beach, Egmont Key and the Sand Engine have proven to have additional benefits. Especially the last two functions are encouraged by applying other concepts than the traditional ones.

In order to incorporate the different functions of nourishments in the quantification of the effects, the ecosystem services approach will be used. This is an attractive approach since it potentially helps to describe the ways that humans are linked to and depend on nature. Ecosystem services can generally be described as the contributions of ecosystems to human well-being [Haines-Young and Potschin, 2012].

2.5.1. Ecosystem services

Ecosystem services can generally be divided into four categories: provisioning, regulating, cultural and habitat services. The first category, the provisioning services, contains goods or products obtained from ecosystems, such as food, beverages, raw materials and energy. The second category treats the contribution of ecosystems in regulating processes, also called the regulating services, such as erosion prevention, protection against hazards and climate regulation. The cultural services represent the non-material contributions of ecosystems to human well-being, such as intellectual and experiential contributions. Furthermore ecosystems are important as they provide habitats for species which are necessary for the production of other ecosystems services. These are included in the last category called habitat services [Van Zanten, 2016].

In Duval County three main ecosystem services can be identified based on the applied nourishment concept. The same ecosystem services are expected to result from the application of large-scale nourishments. Each of the ecosystem services is divided in several sub-services according to the framework of Van Der Moolen [2015].

Coastal protection
The ecosystem service of coastal protection can be divided into two sub-services. The first sub-service considers the protection of the hinterland against flooding. This sub-service can be quantified by the resistance and recoverability of the dune system after storm events. During storms the dunes erode and sediment is relocated to the surfzone. This material is not necessarily 'lost' as the next storm waves break earlier due to the shallower surfzone depth. These waves have thus less impact on the remaining dune system, and the transported sediment still adds to the safety of the total dune system.

The second sub-service is the maintenance of the position of the coastline. This position is affected by different processes on different temporal scales. On a monthly scale, the shoreline position changes due to the seasonal climate conditions, but even on a hourly scale the position is affected by tidal conditions. The position of the coastline must be able to compensate for the losses of sea-level rise and both chronic and acute erosion. It can be defined as the buffer width the beach has from reaching critical erosion.

Recreation
The second ecosystem service is recreation. In general, beach nourishments enlarge the existing beach and provide more space for recreation in different forms. The carrying capacity of the beach for beach leisure activities is thus of importance. Besides the sub-service of beach leisure which incorporates the main activities on the dry beach area, three specific activities have been selected. The second activity that occurs frequently is swimming, and the application of a nourishment should not decrease the swimmer safety at the beach. This is mainly influenced by the magnitude and direction of the flow near the shoreline, but the occurrence of rip currents can have an important effect as well. Rip currents are strong, narrow, localized currents which are directed away from the beach. Furthermore, they are hard to predict and thus impose a threat to swimmers.

If the design of the nourishment alters the wave environment at the beach, the surfing potential could be enhanced, leading to recreational benefits [Hodgens et al., 2016]. Detailed wave modeling studies showed that the surfability at Hanna Park could be enhanced, but that the costs and environmental permits are difficult obstacles. Furthermore, kitesurfing hotspots are currently located along Neptune Beach and Jacksonville Beach in the project area [Kiteforum.com, 2018], making this an interesting sub-service. Moreover, strolling is a beach activity along the shoreline which takes place all over the year. The shape of the nourishment affects the length of the shoreline, and thus the available strolling distance.

Habitat provision
The last ecosystem service considers the category of habitat provision. As beach nourishments change the physical conditions at the project site, it is expected that the existing ecosystems will be affected as well. In the report of U.S. Army Corps of Engineers, Jacksonville District [1992], it was stated that recovery of the benthic invertebrates in the borrow area takes 3 – 4 years. In the beach fill area, these invertebrates will generally not be destroyed, but can survive by upward burrowing. It is expected that the biological communities will recover within 6 – 18 months after construction of the nourishment. The effect of nourishments on the existing habitats will be predicted by using ecotopes. Ecotopes can be described as spatially defined ecological units that have the same abiotic conditions. Mapping the existing ecotopes, based on the newly formed physical conditions, can give an insight into the potential ecological value of the nourished beach. The first sub-service considers the potential capacity of the ecotopes to inhabit different types of species and provide a nursery area for their offspring. The potential is based on a combination of the physical surroundings, such as the intensity of the hydrodynamic forcing [Van Zanten, 2016].

Furthermore the Florida coast is an important nesting site for sea turtles. In 1983, almost 85% of the turtle nests in the US were located in Florida, of which the majority was situated on the East Coast [Davis et al., 1999]. Sea turtles are listed as endangered species by the U.S. Fish and Wildlife Service, therefore the second sub-service of turtle nesting is selected. The changing environmental conditions due to the nourishments may have positive or negative effects on the suitable nesting area. The primary drivers for turtle nesting are beach slope, beach width, beach elevation, dune/beach vegetation, escarpments, artificial lighting, beach compaction and sediment color [Dunkin et al., 2014].

The last sub-service of habitat provision involves the potential for dune growth. In the report of De Vries [2013], it is stated that annual dune volume growth is correlated with the beach slope, and the sediment supply comes from the intertidal beach zone. In this zone, tides cause aeolian processes to be exchanged with marine processes. A large intertidal beach width can generate large aeolian transport of sediments towards the dunes, but is also more prone to dune erosion and vice versa. This means that the dune growth potential can be related to the intertidal beach width.

Additional ecosystem services
The three presented ecosystem services and their sub-services have been selected based on their ability to be quantified in the form of output parameters from the numerical models. However, these are not the only ecosystem services that large-scale nourishments can provide. For example the pilot experiment of the Sand Engine has a large intellectual value as its hook shape provides room for research on sediment transport, flora and fauna, swimmer safety, dune development, ground water and recreational use [De Zandmotor, 2018]. Furthermore, nourishments on beach areas can have spiritual value for people as well. These additional values do not all fit in the conceptual framework of the ecosystem services [Cooper et al., 2016], and therefore will not be taken into account.

2.5.2. Indicators

Ecosystems are composed of both biotic and abiotic elements which interact constantly. The presented ecosystem services and their sub-services have been described as concepts, but cannot be measured directly from numerical models. However, the output parameters of Delft3D are abiotic elements, and should be linked to the sub-services. Therefore indicators for each sub-service have been defined which contain the necessary measurable parameters.

By predicting the development of the abiotic factors under the influence of nourishments, it might be possible to predict the behavior of the sandy beach ecosystem. Furthermore an indication can be given about the development potential of ecosystem services in the future. The relationship between the abiotic factors and the ecosystem services needs to be established to assess this [Van Zanten, 2016].

Coastal protection
The first sub-service of coastal protection considers protection of the hinterland against flooding. The indicator for this sub-service can be defined as the resistance and the recoverability of the dune system. The indicator can be quantified by the total sediment volume present on the active foreshore (including the dune system), from a reference line to the closure depth. However, keep in mind that Delft3D is only able to capture the morphological changes below MHW. The dune volume itself will not change between different nourishment alternatives, but the overall volume can.

The reference line is defined as the Coastal Construction Control Line (CCCL), which is developed by the Florida Department of Environmental Protection [2018]. In all 25 of Florida's coastal counties with sandy beaches this reference line is defined. The location is based on the landward extent of the damaging effects of a 100-year storm event and establishes the landward limit of jurisdiction of FDEP along the sandy beach. In figure 2.8 the CCCL is projected along the shoreline of Duval County. The CCCL does not include Mayport Naval Station, which means that this sub-service will only be quantified from R-31 to R-80. In theory, the CCCL would shift seaward if nourishments are applied at the coastline, due to the increase in sediment volume. However, the original location defined by FDEP is chosen as the reference line in this study.

On the seaward side, the domain is limited by the depth of closure (DOC). This theoretical depth is the offshore depth where the sediment transport is very small or non-existent [U.S. Army Corps of Engineers, 2018]. The DOC is determined with the inner limit of Hallermeier [1981] giving a depth of 10.4 meter. The inner limit gives the seaward boundary of the littoral zone where the bed experiences extreme activity due to breaking waves and their related currents.

The second sub-service considers the maintenance of the coastline position. The corresponding indicator is the variation of the coastline position over the years. This indicator can be quantified by the difference between the Momentary Coast Line (MCL) and the CCCL. Again this sub-service will only be quantified between R-31 and R-80.

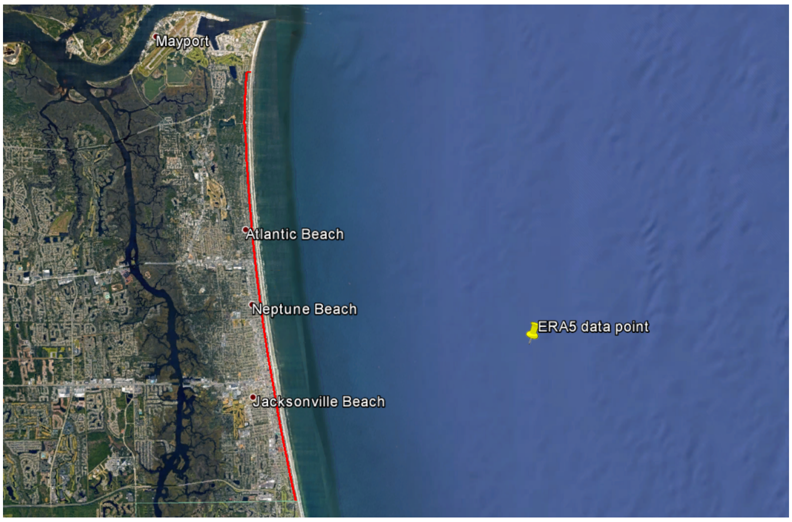


Figure 2.8: The CCCL along Duval County (Google Earth 2018), given in red. The placemark gives the location of the ERA5 datapoint.

The MCL is the representative coastline position, and is based on the wet part of the coastal profile. The landward boundary is defined as the dune foot on the most seaward side of the dune system. Even though the dune foot position varies along the considered coastal section, an uniform elevation of +3.00 m MSL is chosen for consistency. The seaward boundary of the wet part of the coastal profile is calculated by applying the same elevation range relative to MLW as the dune foot [Rijkswaterstaat - Dienst Getijdewateren, 1990]. The dune foot lies 3.726 meter above MLW, which means that the seaward boundary lies −4.452 meter below MSL. The MCL is calculated by dividing the area between these boundaries by the vertical elevation between these planes, which can be seen in figure 2.9.

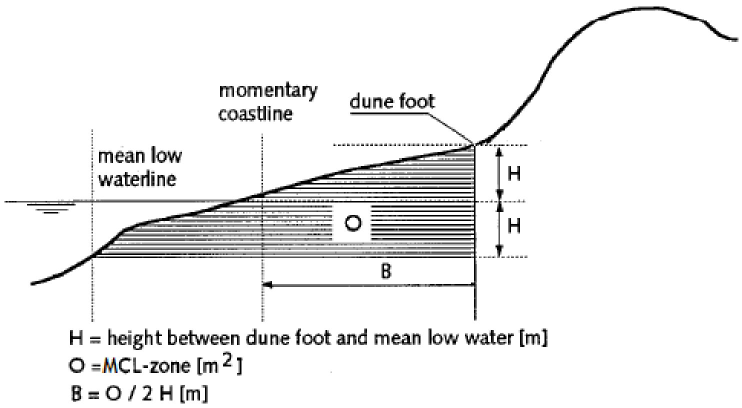


Figure 2.9: Definition of the MCL, adjusted from [Niemeyer et al., 1995].

Recreation

The sub-service of beach leisure is defined as the dry beach area available for recreation. This indicator can be quantified by multiplying the dry beach width by the beach length along the coast. The dry beach width is defined as the beach width between the dune foot and the MHW line. However, the ideal beach width for beach leisure is limited. It is estimated that for moderately intensively used beach, at least a width of 50 meters is necessary to accommodate for visiting crowds, including beach restaurants. Furthermore, the effect of lost space due to wind set-up and security services need to be taken into account [Broer et al., 2011]. On the other hand, if the beach width is too large, the walking distance to the waterline is too large, and it is assumed that beach visitors will not take the effort. Therfore, the minimal required beach width is 60 meters and the maximum beach width is 200 meters [Van Zanten, 2016].

The second indicator involves swimming safety in terms of flow direction and magnitude, and the occurrence of rip currents. An average swimmer can withstand a current of approximately half a meter per second

[Hoekstra, 2018], and therefore high velocities are not wished for. Furthermore, offshore directed currents (> 180 degrees) can transport swimmers offshore, which is even be dangerous with velocities around 0.30 m/s. In case of rip currents, both of these aspects occur simultaneously and thus decrease the swimmer safety. However, rip currents are difficult to predict with a Delft3D model and will not be included separately. Another important aspect to take into account is the likelihood of swimmers present during these conditions. During storm conditions, the chance of high offshore directed velocity currents is higher than during calm conditions, but it is less likely that people will be present in the water [Radermacher, 2018]. However, Delft3D cannot be used to quantify the presence of people, thus this aspect cannot be taken into account directly. The swimmer safety will be quantified by observing the flow velocities around the nourishment during average 'calm' conditions.

The sub-service of kitesurfing is indicated by the suitable water surface. It can be quantified as the surface area that has limited wave exposure, so only waves which are smaller than 1 meter are considered. Furthermore, a minimal depth of 0.5 meter is required. The sandy beach at Jacksonville Beach is already a popular spot for both beginners and advanced kitesurfers. However, sheltered areas, such as inside the hook of the Sand Engine, have additional value for beginners as it is easier to learn in quiet conditions.

The sub-service of strolling is indicated by the walkable dry beach length along the shoreline. In principle, a more curvy shoreline and a wider beach indicate a longer strolling length. However, if the shoreline extends more than 200 meter in the cross-shore direction, this is not beneficial anymore. In that case, a horizontal line along the 200 meter contour is taken until the beach width reduces again.

Habitat provision
The sub-service of the nursery area considers the provision of habitats for migratory species by ecotopes. A suitable reproduction habitat is necessary to protect juveniles and maintain existing fish species. Ecotopes are defined as spatial ecological units in which the abiotic factors are similar. The ecotope classification scheme provides a tool to analyze the spatial variation of species communities that are predominantly determined by the physical environment [Van Zanten, 2016]. The sub-service is indicated by ecotope mapping, which can be quantified by calculating the area of each ecotope over time and comparing this to the reference situation. In Stoll et al. [2007] it is stated that hydrodynamic stress is a crucial factor for the growth of fish within the littoral zone. Thus suitable nursery areas are governed by flat, shallow parts of the subtidal and intertidal zone with low hydrodynamic conditions. As Delft3D is only able to predict stresses and bathymetry changes in the wetted shore, a division of the supratidal zone is not taken into account. Furthermore, the influence of sediment type and grain size on the suitability of nursery areas is excluded.

In table 2.2, the ecotope division of Van Zanten [2016] is presented, which was used for the classification of the pilot experiment of the Sand Engine. The ecotopes are divided based on the bed level and the hydrodynamic conditions. In shallow areas, higher hydrodynamic stresses are found compared to the deeper habitats. An elaborate description of the different ecotopes can be found in appendix B. The most important ecotopes for nursing are 5 and 8 according to Van Zanten [2016] for the Dutch coast, as they provide sheltered area.

Table 2.2: Classification of ecotopes based on Van Zanten [2016], with theoretical depth zones for Duval County.

	Ecotope	**Water Depth**	**Hydrodynamics**
1	Surfzone	< MLW and > $2 * H_s$	Very high
2	Seaward side of the surfzone	< $2 * H_s$ and > DOC	High
3	Nearshore	< DOC and > 12 meter depth contour	Moderate
4	Far offshore	Beyond the 12 meter depth contour	Low
5	Sheltered subtidal	< MLW	Very low
6	Exposed lower intertidal	Between MLW and MSL	–
7	Exposed upper intertidal	Between MSL and MHW	–
8	Sheltered intertidal	Between MLW and MHW	Very low
9	Supratidal zone	> MHW	–

The Dutch coast is classified as highly dynamic, which means that high current speeds and significant wave impact can lead to hydrodynamic stresses over $4N/m^2$ in the surfzone, and over $0.3N/m^2$ beyond the −12 m NAP depth contour Van Zanten [2016]. For Duval County the hydrodynamic stresses are expected to be much lower, as the coastline experiences a much calmer wave climate. In table 2.3 a quantification of the ecotopes for the Duval County is given, using the local tide levels (MHW = +0.820 MSL and MLW = −0.726 MSL), and wave conditions. Furthermore, the frequency of disruption is taken into account for the sub-service of nursery area. The traditional nourishment has a nourishment cycle of approximately 5 years, thus alternatives that have a larger time span are preferred.

Table 2.3: Quantification of the ecotopes for Duval County.

	Ecotope	**Water Depth (m MSL)**	**Hydrodynamics (N/m^2)**
1	Surfzone	≤ −0.726 and > −7.5	> 1
2	Seaward side of the surfzone	≤ −7.5 and > −10.4	> 0.6 and ≤ 1
3	Shoreface (outside surfzone)	≤ −10.4 and > −12.0	> 0.3 and ≤ 0.6
4	Inner shelf (outside surfzone)	≤ −12.0	≤ 0.3
5	Sheltered surfzone	≤ −0.726	≤ 0.1
6	Exposed lower intertidal	> −0.726 and ≤ +0.00	> 0.1
7	Exposed upper intertidal	> +0.00 and ≤ +0.820	> 0.1
8	Sheltered intertidal	> −0.726 and ≤ +0.820	≤ 0.1
9	Supratidal zone	> +0.820	−

The second sub-service is specified as the potential nesting area for sea turtles. Nesting along the beaches in Florida occurs between half of April and the end of November [U.S. Fish and Wildlife Service, 2015]. Turtle nesting is influenced by different morphological, environmental, anthropogenic and habitat parameters. However, a lot of these conditions cannot be quantified by the use of numerical models. The quantifiable primary drivers for turtle nesting are beach slope and beach width because sea turtles nest more frequently on steeper slopes and prefer narrow beaches [Dunkin et al., 2014]. However, no quantitative numbers are given for these parameters, as they have been found to be site specific. Consequently, the nourishment alternatives will be compared to the reference situation without nourishments. The closer the beach profile is to the pre-construction profile, the better it performs regarding turtle nesting.

The last sub-service of habitat provision involves the potential for dune growth. The indicator for this sub-service is based upon De Vries [2013], who stated that annual dune volume growth is related to the intertidal beach between MHW and MLW. However, since no historical data on the annual dune volume at Duval County is available, the intertidal beach width for which the dune volume stays constant cannot be found. Therefore, the beach width present before nourishing is chosen as a reference beach width. If the resulting beach width is larger than the reference width the nourishment creates potential for dune growth.

2.5.3. Summary

In table 2.4 an overview is given of the selected indicators and their quantifiable parameters. Each of the nourishment alternatives will be judged on these criteria. However, not all parameters have quantifiable values, which means they can only be judged on their behavior compared to the reference situation of the traditional non-feeder nourishments.

Table 2.4: Overview of the ecosystem services, sub-services, indicators and their corresponding quantifiable parameters for Duval County.

Ecosystem service	Sub-service	Indicator	Quantifiable parameter
Coastal protection	Flood protection	Resistance and recoverability of dune systems	Foreshore volume between CCCL and DOC (m^3)
	Maintenance of the coastline position	Variation of coastline position	Distance between CCCL and MCL (m)
Recreation	Beach leisure	Suitable beach area	Beach width from dune foot to MHW times beach length (m^2)
	Swimming	'Safe' swimming area per year	Flow direction ($degrees$)
			Flow magnitude (m/s)
	Kitesurfing	Suitable water surface	Sheltered wave area (m^2) with a minimal depth of 0.5 m
	Strolling	Walkable beach length	Dry beach length along the shoreline (m)
Habitat provision	Nursery area	Ecotope mapping	Number and area of ecotopes (m^2)
			Frequency of disruption (-)
	Turtle nesting	Suitable nesting area	Beach slope relative to native beach (-)
			Beach width relative to native beach (-)
	Dune growth potential	Resulting beach width compared to reference beach width	Beach width from dune foot to MLW (m)

3
Model setup

The application of large-scale nourishment along the coast of Duval County is investigated using the process-based numerical model Delft3D. This model computes the hydrodynamics, the waves, the sediment transport and the morphological changes under the influence of tidal, wind-driven and wave-driven currents [Luijendijk et al., 2017]. The morphological feedback loop used in Delft3D is presented in figure 3.1. A more elaborate description of the model can be found in [Lesser et al., 2004].

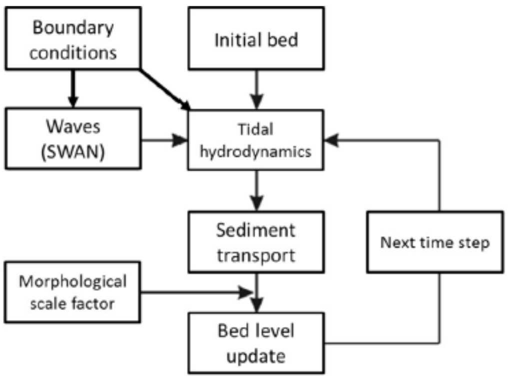


Figure 3.1: Morphodynamic feedback loop applied in Delft3D [Luijendijk et al., 2017].

In Delft3D, a depth-averaged two-dimensional model is made to recreate the conditions at Duval County. The target of the model is to reproduce the sediment transport magnitude and direction at the coastline, leading to a prediction of the sedimentation and erosion patterns. Important model parameters are validated with the available real-time information. This real-time information is limited to the annual bathymetric surveys and the computed sediment transport.

3.1. Grid and bathymetry

The computational grid is based upon the curvilinear grid used in the Sand Engine models [Luijendijk et al., 2017]. This grid is enlarged, rotated and translated to fit the coastline of Duval County. The grid is 19 kilometers long in the alongshore direction and extends 9 kilometers in the cross-shore. It consists of 262 by 163 cells and its resolution varies from 16 meters at the coastline to 405 meters on the offshore boundary.

The bathymetric surveys supplied by the USACE are given in projected State Plane Coordinates for the east of Florida (Easting, Northing). These surveys are conducted in the horizontal datum of NAD83 in feet and the applied vertical datum is NAVD88 in feet. These surveys are transformed via the Online Vertical Datum Transformation tool created by the National Oceanic and Atmospheric Administration (NOAA) into geographic coordinates (Longitude, Latitude) in the reference frame of NAD83 [National Oceanic and Atmospheric Administration, 2018b]. The resulting coordinates are similar to ones defined in the reference frame of WGS84. As Delft3D calculates the shoreline change relative to MSL, the vertical datum of the surveys is transformed into meters relative to MSL.

The provided surveys only cover part of the bathymetry which is necessary for the numerical model. The overall bathymetry is provided by the Coastal Relief Model (CRM), created by NOAA, where the reference elevation is MSL. As the surveys are adjusted to the same reference level, the data sets are merged and the portion of the CRM covered by the surveys is replaced with the more accurate survey data. The left part of figure 3.2 shows an overview of the bathymetry from the CRM. On the right the resulting grid is present. This figure shows that the entire grid is located on the wide continental shelf. The offshore depth of the grid is approximately 20 – 25 meters below MSL.

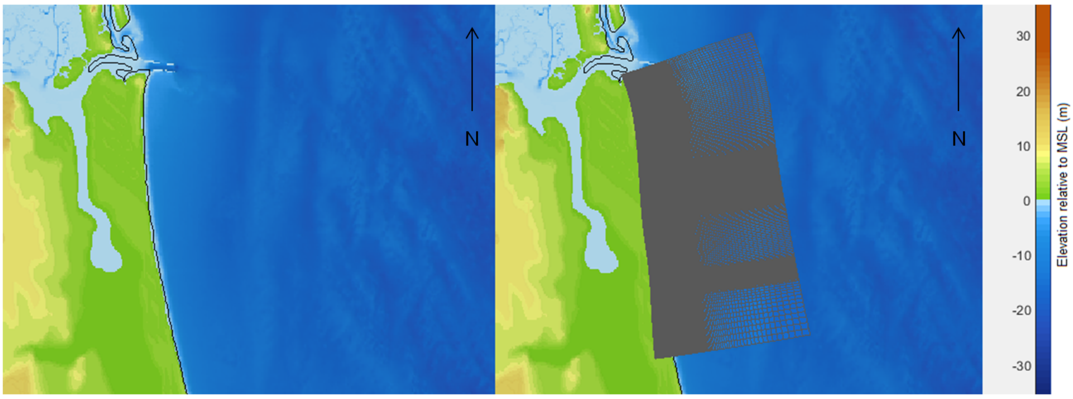


Figure 3.2: Left: the bathymetry extracted from the Coastal Relief Model (CRM), created by NOAA. Right: the same bathymetry with the location and size of the computational hydrodynamic grid.

Using the SWAN module, waves are generated on the boundaries of the computational grid. However, this can lead to model instabilities where the water depth goes to zero. In order to prevent these instabilities on the boundaries of the hydrodynamic grid, a separate wave grid is created. This grid is similar to the hydrodynamic one, but is extended for 20 grid cells in both lateral directions.

3.2. Boundary conditions

The tidal conditions at Duval County come from the TPXO8 database, which is based on fully-global models of ocean tides. The constituents are computed via a least-squares method which best-fits the Laplace Tidal Equations and altimetry data on the location of the ERA5 data point. The found amplitudes and phases are applied uniformly at the offshore boundary as astronomical water levels. The lateral boundaries are implemented as Neumann boundaries, zero-gradient water level conditions.

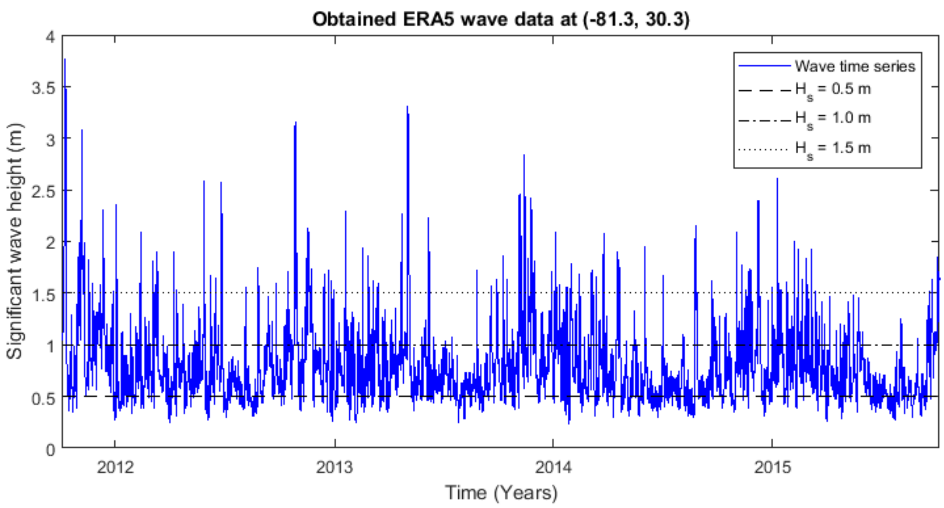


Figure 3.3: The wave time series at Duval County (-81.3, 30.3) in the period October 6th 2011 until October 6th 2015. The dashed lines indicate wave heights of 0.5, 1.0 and 1.5 meter.

The wave data is obtained from the ERA5 database located at the offshore boundary (see figure 2.8). The obtained wave time series between October 6th 2011 and October 6th 2015 is given in figure 3.3. The hourly wave and wind conditions are applied uniformly over the offshore and lateral boundaries of the wave grid.

3.3. Input reduction

The target of the model is to represent the morphological changes of the nourishment over time. However, applying the full wave climate will lead to unnecessarily long calculation times, since not all waves influence the sediment transport. First of all, offshore directed waves are eliminated, meaning only waves with a direction less than 180 degrees are considered.

Furthermore, small waves are generally not strong enough to mobilize sediment, and therefore these are excluded as well. In figure 3.4 a comparison is given of model results of a test nourishment after 1 month. The left upper figure presents the results of the full wave climate, while the remaining figures represent climates where offshore directed waves and waves lower than 0.5, 1 and 1.5 meter are eliminated. The figures are visually compared to select the most suitable input reduction. It can be seen that excluding waves lower than 1 meter will lead to approximately the same sedimentation/erosion pattern as the full climate.

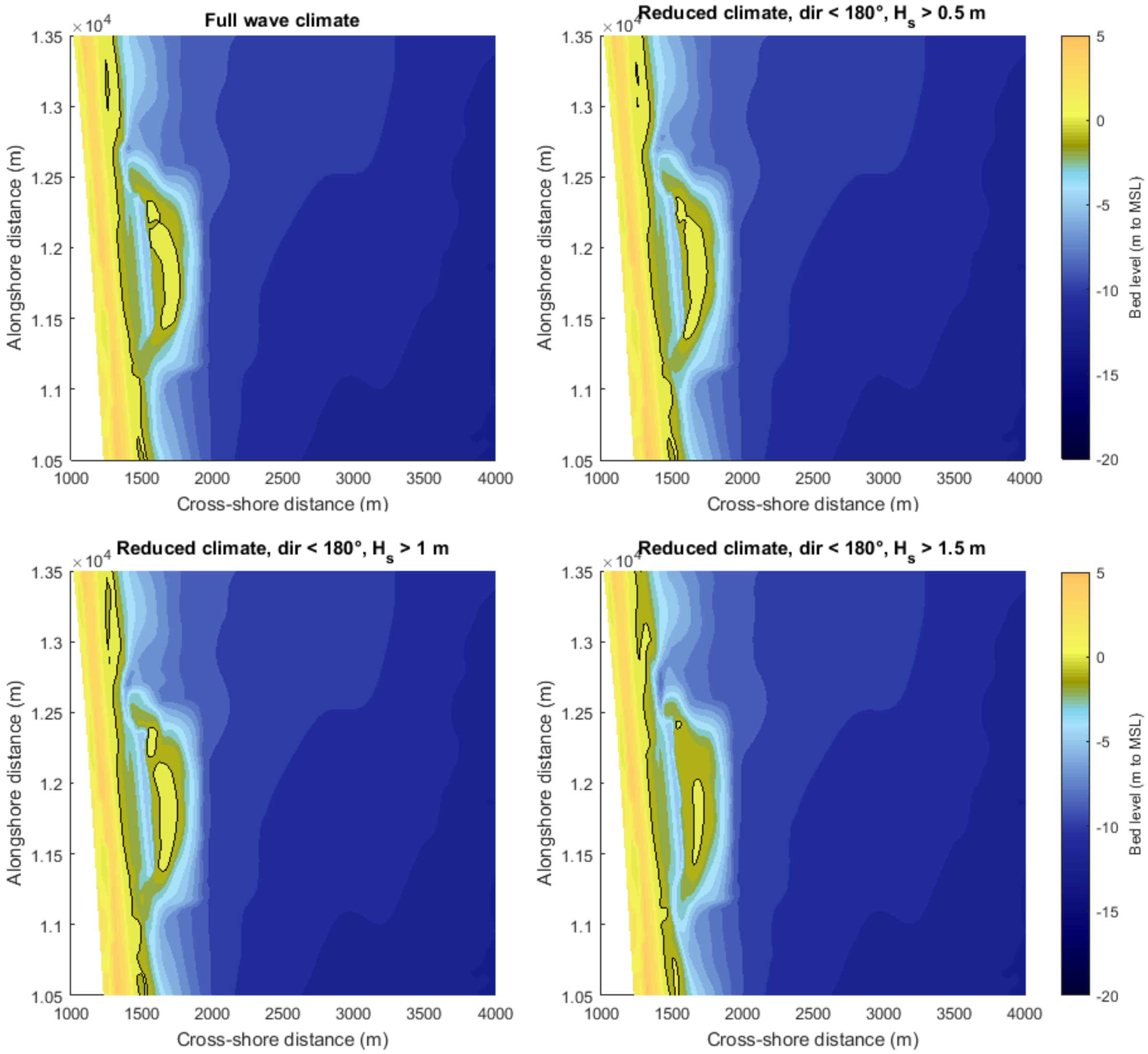


Figure 3.4: Comparison of wave climates after 1 month. Upper left: full climate, upper right: eliminated > 180 degrees and < 0.5 meter, lower left: eliminated > 180 degrees and < 1 meter, lower right: eliminated > 180 degrees and < 1.5 meter. In each figure the 0 m MSL depth contour is given.

Applying this reduction to the full climate obtained from the ERA5 database leads to a reduction of 80% of the available conditions. In figure 3.5 the remaining conditions are presented for both the wave and the wind climate. From this reduced set of conditions it is clear that the predominantly wave and wind direction is the northeast which leads to southwards sediment transport.

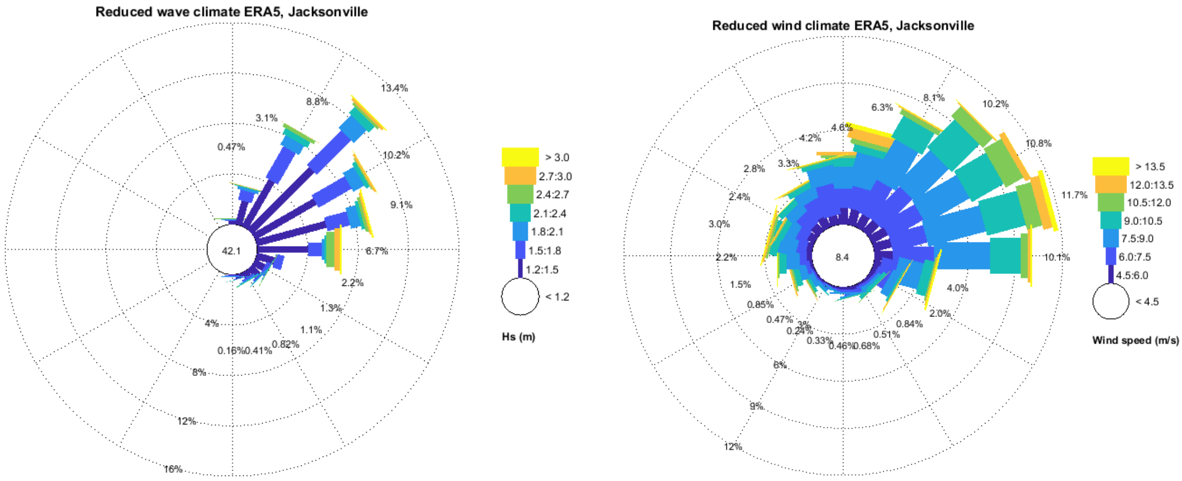


Figure 3.5: Reduced wind and wave climate for Jacksonville, Duval County between 2011 and 2015.

In order to speed up the morphological calculations, Delft3D includes an option to use a morphological acceleration factor. This option changes solely the morphological time scale while the hydrodynamic time scale stays the same. For an acceleration factor of 5, the time series of the wave and wind input should be divided by 5 to obtain realistic results. This option reduces the computational time, but needs to be calibrated as well. In figure 3.6 the model results for a test nourishment after 1 month are compared. Two different morphological acceleration factors are applied besides the default setting of 1.

Looking solely at the bed level figures, a clear distinction is not visible between the different morphological acceleration factors. However, looking at the cumulative sedimentation/erosion patterns it can be observed that factor 1 and 5 look comparable, while factor 10 exaggerates the transport volumes. Therefore, a morphological acceleration factor of 5 is applied, and new wave and wind conditions are implemented every 12 minutes.

3.4. Important parameters

To complete the calibration process, three important parameter settings are needed. These parameter settings were based on Luijendijk et al. [2017]. The parameters make the model computationally more expensive, but obtain better results than the default settings.

The zone around the MHW line is difficult to model, as this zone includes both water level variations due to multiple processes as well as unaffected 'dry' cells. Current models are not able to resolve this transitions properly, but parameterizations have been made. In Delft3D this is done by the dry cells erosion feature. This setting enables dry cells to erode as well. Computational cells that are initially above the maximum water level are activated as wet cells, so they can be gradually eroded when the bed level is lower than the water level. The total amount of erosion is distributed over the adjacent wet and dry cell. For Duval County, this factor is set to 1, which means that 100% of the erosion that occurs in the wet cell is applied to the adjacent dry cell as well. If the water level becomes higher than the bed level in the 'new' wet cell, this process is repeated. The eroded sediment is transported with the present current and/or waves to locations elsewhere in the model.

Secondly, a different sediment transport formulation is selected compared to the default options in Delft3D. In Luijendijk et al. [2017] it is discussed that the formula of Van Rijn performs the best in the deposition area where more sand is deposited higher up in the profile. This formulation is used in the model as well.

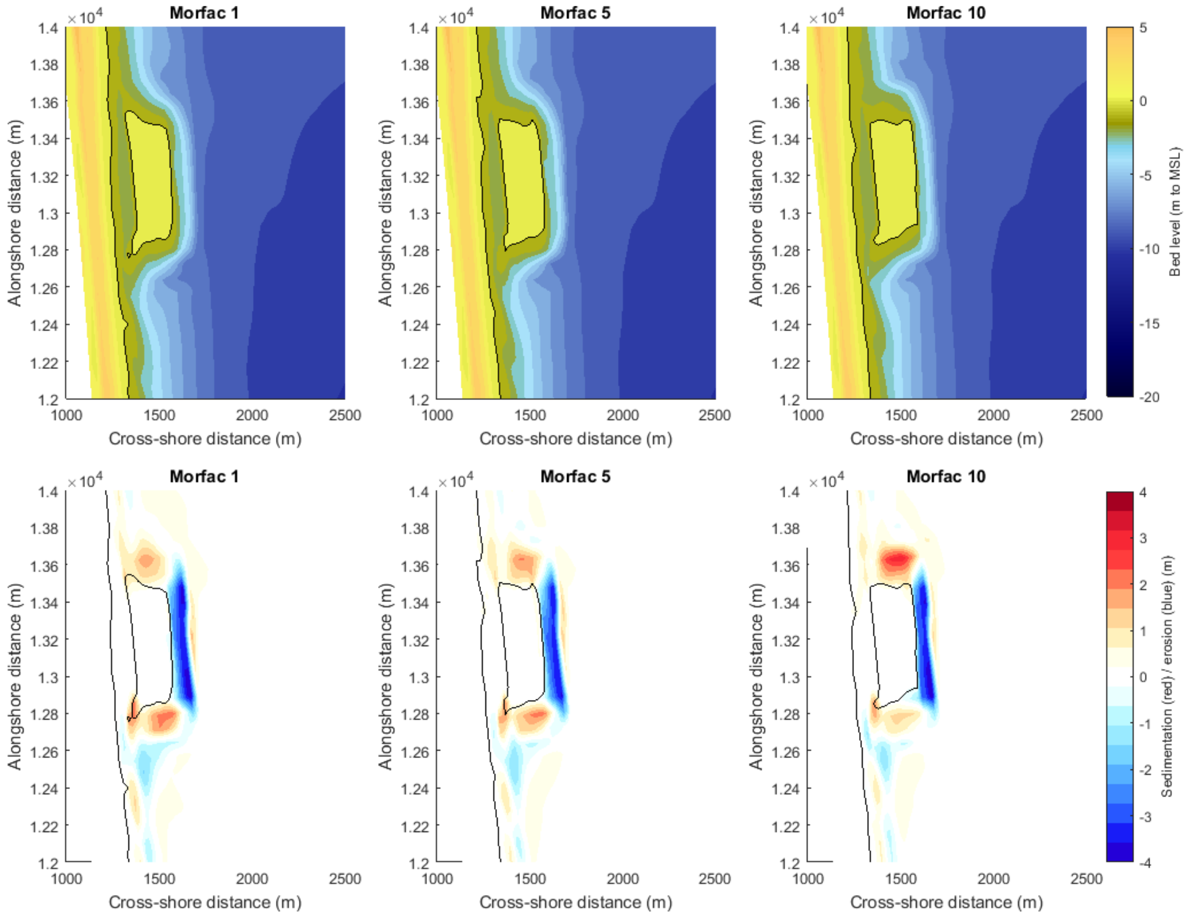


Figure 3.6: Comparison of morphological accelerations factor 1, 5 & 10 after 1 month. The upper three figures give the resulting bed level, while the lower plots represent the cumulative sedimentation/erosion pattern. In all figures the 0 m MSL depth contour is given.

Lastly, the Roller model was used [Reniers et al., 2004]. For numerical models, this means that onshore sediment transport is enhanced, and the peak of the cross-shore distribution of the longshore current is shifted.

3.5. Nourishment parameters

In order to find the most suitable nourishment alternative for the coast of Duval County, several nourishment aspects are investigated. Some of these aspects can be found in literature and are applied equally over the nourishment alternatives, while others are applied as a changing parameter.

3.5.1. Annual nourishment volume

The applied Delft3D model is calibrated based on the sediment transport found in the literature. In section 2.4.1 it was stated that in 1992 the annual net sediment transport was 290 700 cubic meters per year. The sediment volume was based on the computation of transport rates depending on shoreline orientation. However, no information is available of the shoreline orientation changes in the past decades.

In order to calibrate the created model to the historic sedimentation transport rates, a reference run is modeled with the reduced wave conditions. No sediment is added to the model, and it is run for one year. In figure 3.7, the resulting sediment transport rates are presented between R-31 and R-80. The northern and southern transport are computed separately, after which the cumulative transport is calculated. The model was calibrated on the average cumulative transport magnitude that occurs between R-31 and R-80. The computed gross transports do not comply with the values present in literature, but the calibrated model gives a good representation of the situation at Duval County.

In the north, higher sediment transport magnitudes are found than at the southern half of the shoreline. This is likely to be caused by the blockage of the jetty at the south side of the St. Johns River. On average, a net sediment transport of 300 000 cubic meters is found. This value lies close to the one found in literature, and is therefore selected as the required annual nourishment volume in the system.

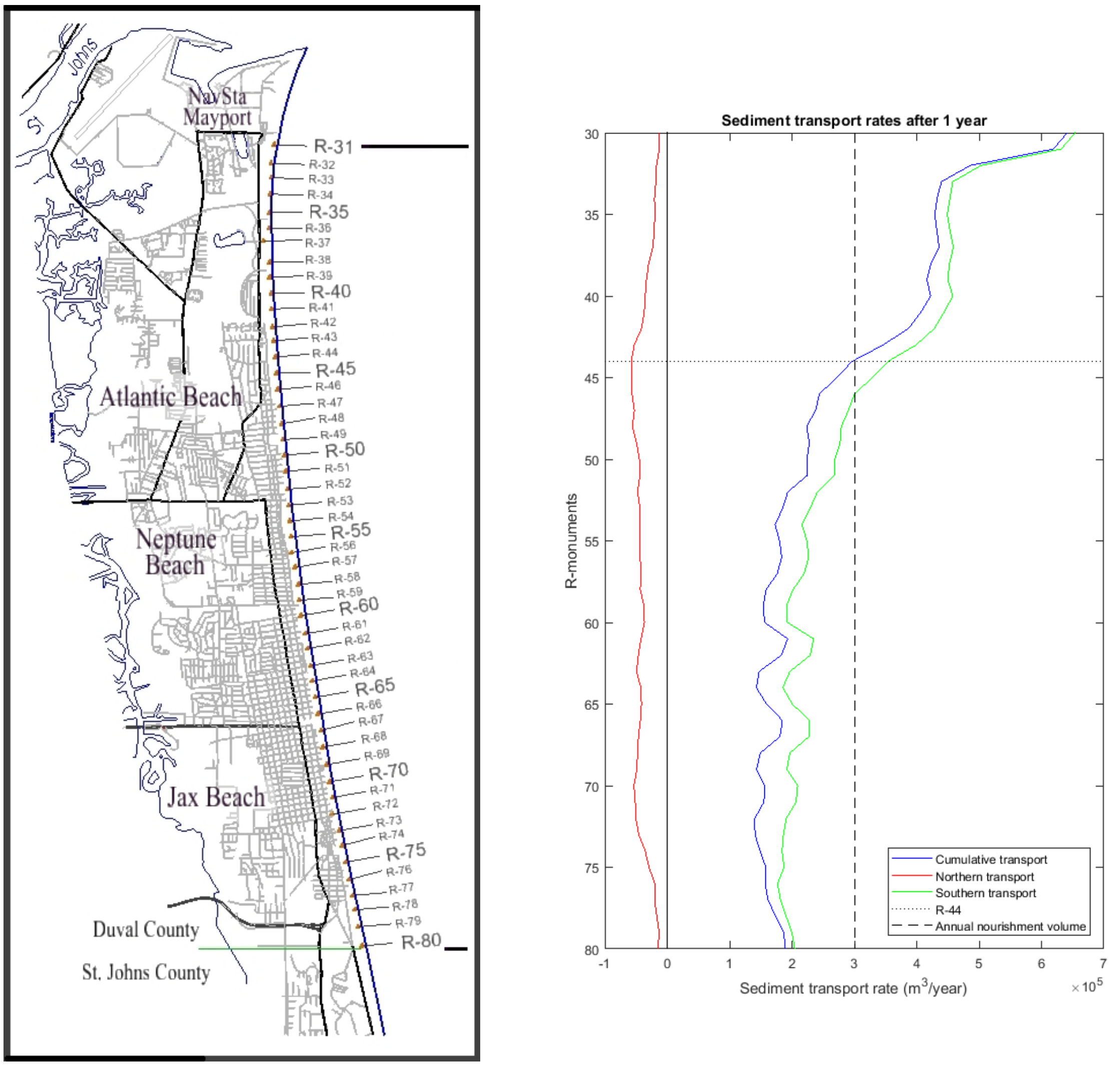


Figure 3.7: The northern, southern and cumulative sediment transport rate along Duval County after 1 year. The most suitable location is R-44, and the annual nourishment volume is 300 000 cubic meters.

3.5.2. Nourishment location

Another result from figure 3.7 is the most suitable location for the nourishment. The nourishment is expected to feed both adjacent coastlines, which means that the location should include both northern transport and southern transport. Around R-44, there is a peak in the northern transport rate while still a large southern transport rate is present. This location is selected as the applied location for the nourishments.

3.5.3. Nourishment frequency

Another aspect that is important for selecting the most suitable nourishment alternative is the frequency with which the nourishment is applied. As explained in section 2.2, large-scale nourishments can reduce the ecological stress as they disrupt the shoreline less frequently. In order to investigate the application of a large-scale nourishment for Duval County, the involved sediment volume should be larger than the volumes that have been applied until now. However, since the previous nourishments did not follow a fixed nourishment cycle (see figure 2.2), smaller volumes are applied as well.

In table 3.1 the applied nourishment frequencies are presented with their corresponding volume per cycle. All nourishment alternatives will be modeled for a simulation period of 10 years.

Table 3.1: Selected nourishment frequencies and volumes.

Nourishment frequency	**Nourishment volume**
1 year	300 000 m^3
3 year	900 000 m^3
5 year	1 500 000 m^3
10 year	3 000 000 m^3

3.5.4. Nourishment shapes

The last aspect involves the geometric shape of the nourishments, as this has an effect on the different ecosystem services as well. Three different shapes are selected, based upon their length to width (h:b) ratio and their geometric adaptability for the selected frequencies. The first nourishment alternative has a ratio of (1:1), meaning that the nourishment extends equally far in the cross-shore direction as the alongshore direction. The resulting shape will be a sharp triangular nourishment, presented on the left of figure 3.8. The second geometry, shown in the middle, has a ratio of (1:3) meaning that the nourishment is three times larger in alongshore direction than in cross-shore direction. However, some of the selected indicators will not differ much between these shapes, for example the sub-service of kitesurfing. Therefore a third geometry is selected, namely a emerged offshore island (on the right of figure 3.8). The island has a ratio of (1:4) and is thus elongated but detached from the shoreline.

The original coastline has an average profile steepness of 1:55, based on the surveys in appendix A. As the three selected shapes disturb the original shoreline, they create larger gradients. The (1:1) nourishment has the largest protrusion into the ocean, and therefore the largest elevation difference. The edges have been smoothened to reduce the cross-shore slope steepness. The (1:3) nourishment is more streamlined along the shoreline, but contains steeper slopes on the edges. The offshore island nourishment experiences a steeper slope on the ocean side due to the larger elevation difference. The north, west and south side of the nourishment experiences a more gradual slope.

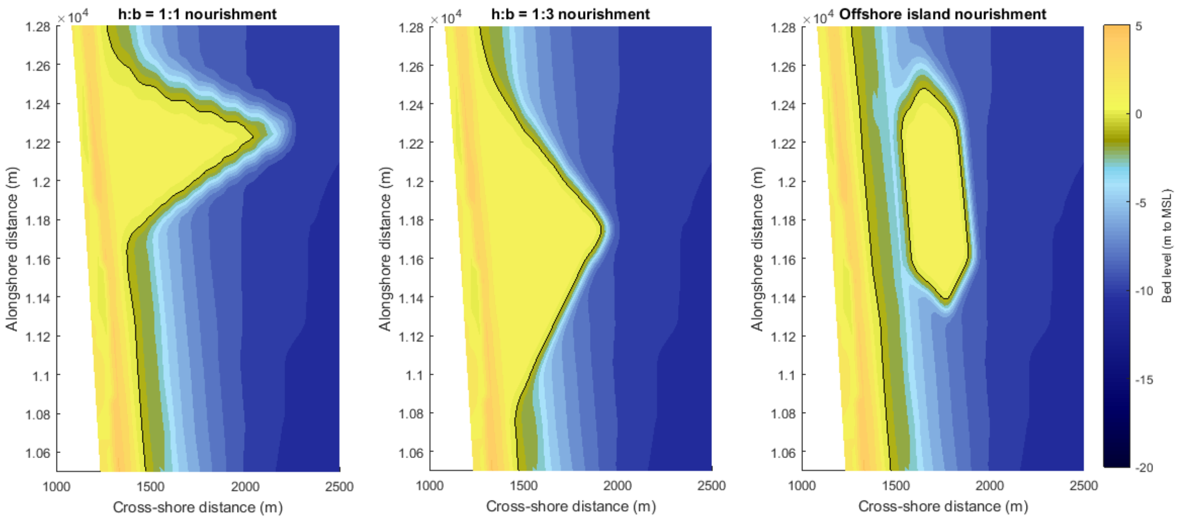


Figure 3.8: The three different nourishment geometries directly after placement. In each figure the 0 m MSL depth contour is given in black.

The first two geometries are applied for all selected nourishment frequencies. The offshore island approach is only applied for the 5 and 10 year nourishment frequency, since shorter nourishment cycles are not feasible. Constructing an offshore island with a volume of 300 000 or 900 000 cubic meters is difficult, especially if frequent renourishing is needed.

4
Modeling results

In the previous chapter the model setup has been treated in detail. This chapter presents the results from the different nourishment alternatives in terms of morphological development and the indicators mentioned in section 2.5. For each indicator corresponding quantifiable parameters have been selected, which will be elaborated upon. A most suitable nourishment alternative is selected for each ecosystem service, dependent on the results for the different sub-services. In the end, an evaluation framework is presented to summarize the results. Lastly, a comparison is made with wave climates from other locations along the Atlantic coast of the US.

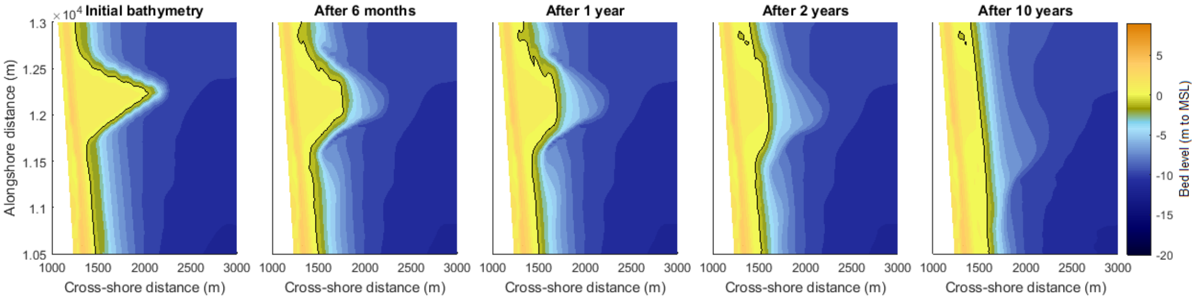
4.1. Morphological development

In figure 4.1, the morphological development of the 10 year frequency models is given. Consecutively the bathymetry of each nourishment alternative is shown at the beginning, after 6 months, 1 year, 2 years and after 10 years. Only the largest frequency models are shown, as the smaller nourishment frequencies experience a similar behavior. Even though the behavior happens on a smaller spatial and temporal scale, the morphological developments are comparable. Furthermore, the smaller temporal scale means that the behavior occurs more often within the 10 year simulation period.

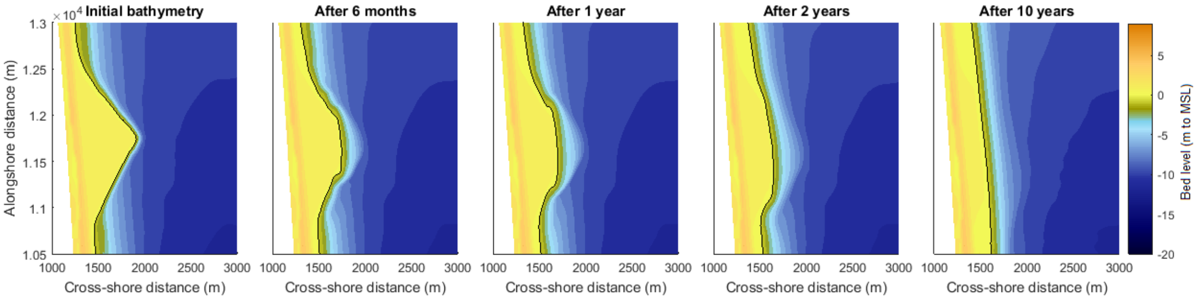
Initially, the placement of the (1:1) nourishment causes a large protrusion into the ocean with steep sloping edges. The most morphological changes occur within the first year of placement. At the end, the protrusion of the nourishment into the ocean is only half of the initial protrusion. After 2 years, a small pit below MSL appears on the north side of the nourishment. It is expected that this pit will be filled in by aeolian transport in reality, but this is not taken into account by Delft3D. Furthermore, it can be observed that the nourishment has spread along the adjacent coastlines at the end of the simulation period, and a more gentle beach slope is restored at the coastline. In deeper regions, the protrusion of the nourishment is still visible after 10 years. The sediment in deeper regions is somewhat trapped as it moves on a slower scale than the sediment placed higher in the profile. This suggest that not all sediment is placed within the dynamic wave zone.

The (1:3) nourishment alternative shows a more gradual displacement than the (1:1) nourishment. The protrusion in the initial bathymetry is less, which means that the sediment displacement occurs over a larger period of time. The northern part of the nourishment is displaced more rapidly than the southern half during the first 2 years. This is due to the predominant waves coming from the northeast, causing the southern edge to be sheltered. In the first few months the transport magnitude will reduce to almost zero, leading to a stop in sediment displacement. Once the northern edge becomes parallel to the original shoreline again, the transport at the southern edge increases again and sediment is displaced to the adjacent coastlines. At the end of the simulation period, the computed shoreline is comparable to the (1:1) nourishment situation. However, the protrusion below MSL is less striking and the shoreface has returned to its original slope, showing that all sediment is placed within the dynamic zone.

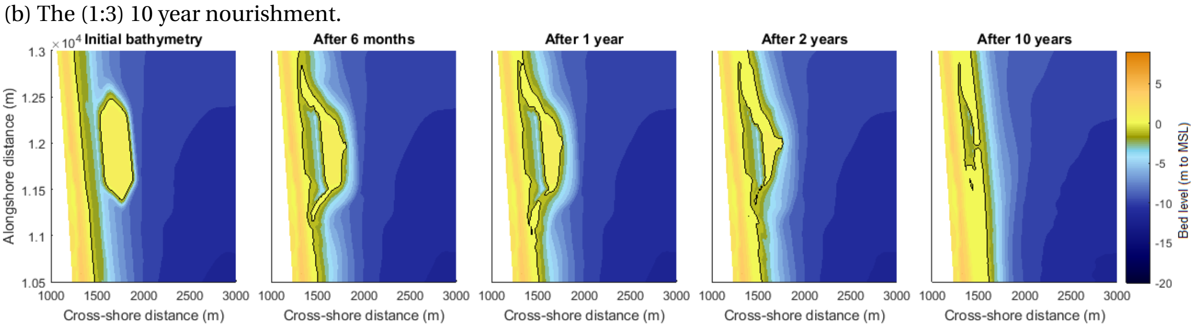
The behavior of the offshore island nourishment is different than the previous nourishment alternatives as the island is initially detached from the coastline. Furthermore, the shoreline orientation of the island is al-



(a) The (1:1) 10 year nourishment.



(b) The (1:3) 10 year nourishment.



(c) The 10 year offshore island nourishment.

Figure 4.1: The morphological development of the 3 alternatives. All have a volume equal tot the 10 year cycle (3 000 000 m^3).

ready parallel to the coastline of the unaffected regions, and thus a comparable transport is present. These large transport magnitudes cause the island to become attached to the coast within the first 6 months on both sides. This attachment disappears more rapidly on the south side, as the southern transport magnitude is higher. Simultaneously the island decreases the sediment transport from the north as the shoreline orientation just north of the island turns towards the predominant wave direction. Furthermore, it can be observed that a significant lagoon arises once the island becomes attached. In the simulation, the lagoon is only partially filled in by sediment transport due to waves, as aeolian transport is not taken into account by Delft3D. Also, the lagoon is only temporarily in contact with the ocean, as the tidal channel opens and closes frequently during the last years of the simulation.

4.2. Coastal protection

The ecosystem service of coastal protection is divided into two sub-services. The first sub-service, flood protection, gives the resistance and recoverability of the dune system for the different alternatives. Secondly, the variation of the coastline position is assessed over time. Both sub-services have been evaluated monthly to exclude tidal influences.

4.2.1. Flood protection

The sub-service of flood protection is based upon the foreshore volume located between the CCCL and the DOC. The volumes are integrated over the coastline between R-31 and R-80 is considered, which is the entire project area. The volume of the different nourishment runs is compared to a reference run without an additional nourishment, and only the additional volume is taken into account. In figure 4.2, an overview is given of the results for the different nourishment alternatives.

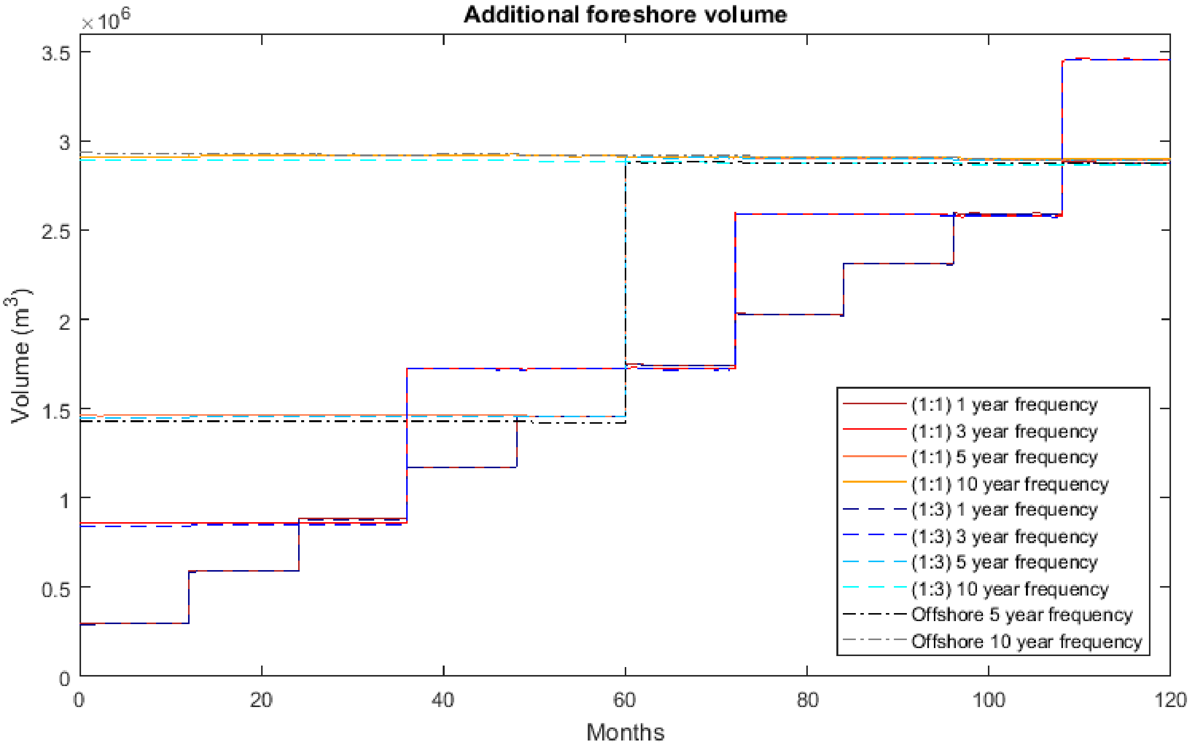


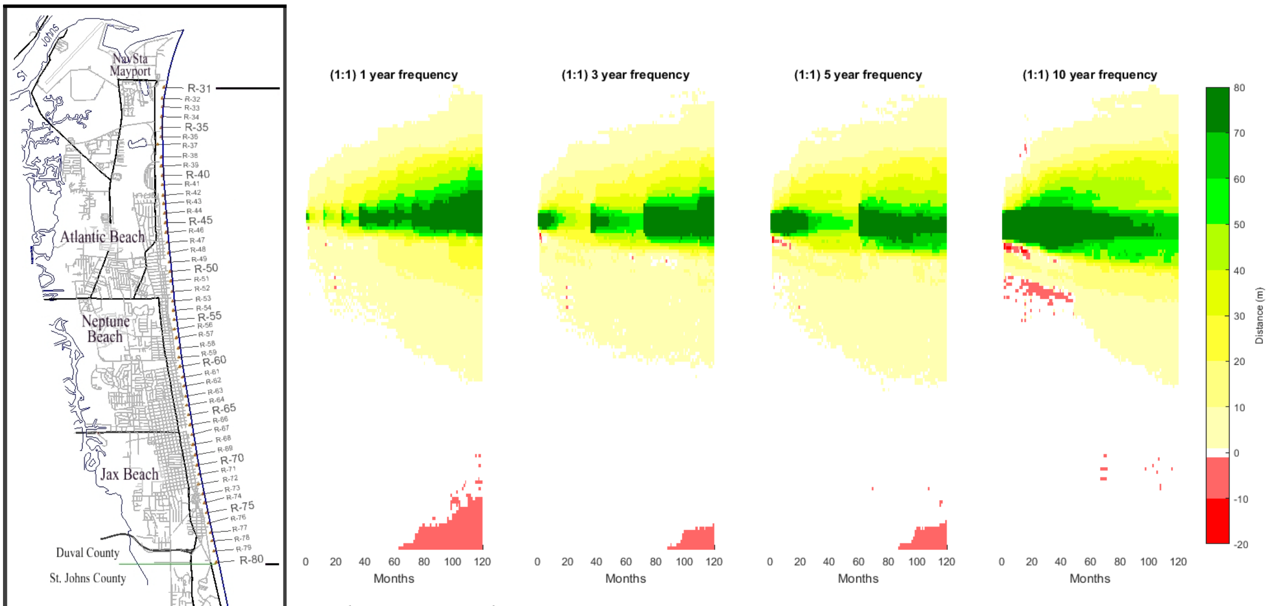
Figure 4.2: The additional foreshore volume due to the applied nourishments, integrated over the area between R-31 and R-80.

The initially placed nourishment volumes are not equal to the values mentioned in table 3.1, since smoothing of the nourishment edges leads to a small decrease of volume. However, the deviation is within 5% of the proposed values.

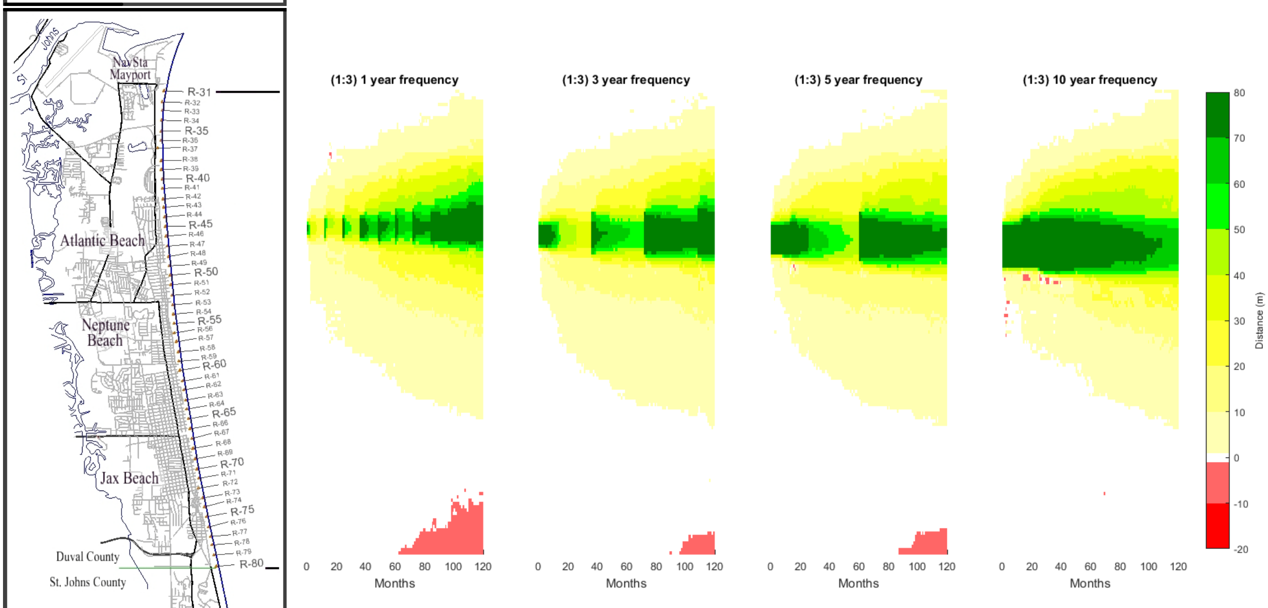
Over a period of 10 years, the additional foreshore volume is fairly constant for all nourishment runs. Jumps in the graphs only occur during renourishments at the end of a cycle. This indicates that the applied nourishments stay within the foreshore, and a minimal amount is transported offshore or in lateral direction. The only observable difference is the additional foreshore volume due to the 3 year frequency models. After 10 years, the 3 year frequency models are in the middle of a cycle, and thus cannot be compared directly to nourishment alternatives at the end of a cycle. If only one-third of the volume was applied at the beginning of year 10, it would have resulted in the same overall volume. For all nourishment alternatives, a significant portion of sediment remains within the area around the nourishment during the simulation. It slowly spreads towards adjacent coastlines, but this accumulating behavior is more apparent for the small-scale frequencies than the large-scale ones. Since the focus of this indicator is on the total volume within the foreshore, a most suitable nourishment cannot be chosen.

4.2.2. Maintenance of the coastline position

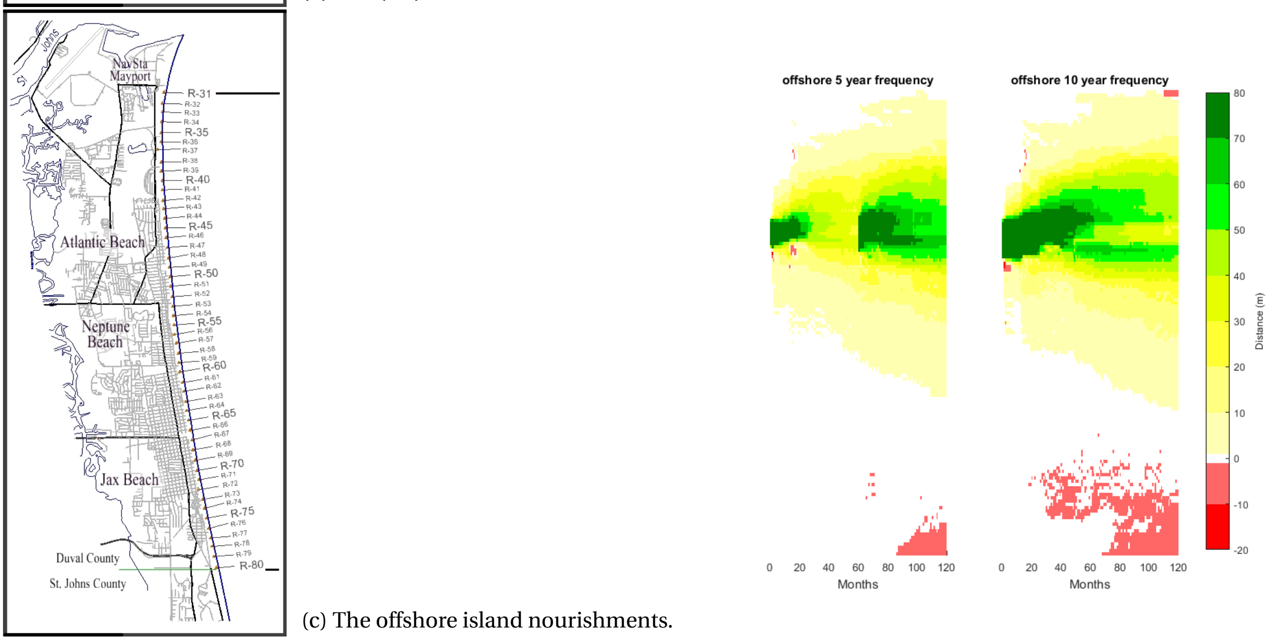
The second sub-service of coastal protection is the maintenance of the coastline position. This indicator is based on the distance between the CCCL and the MCL. This distance is calculated every month during the 10 year simulation. The effect of a reference run without a nourishment has been eliminated from the results, showing solely the impact of the applied nourishments. As the distance between the CCCL and the MCL varies both spatially and temporarily, the results are given as time-stacking plots in figure 4.3. Furthermore, they have been grouped per nourishment shape in horizontal direction, and per frequency in vertical direction.



(a) The (1:1) nourishments.



(b) The (1:3) nourishments.



(c) The offshore island nourishments.

Figure 4.3: Timestack of the distance between the CCCL and the MCL over time for all nourishment alternatives. Horizontally they are grouped per geometry, while vertically they are grouped per nourishment frequency.

Figure 4.3 shows solely the results from the project area, so between R-31 and R-80. The computational grid is larger than the project area itself, so model boundary problems are excluded from the results. The yellow and green colors indicate an increase in distance, which means that sedimentation has taken place at the coastline. On the other hand, the red colors indicate that the coastline position is retreating, and erosion is present.

For all nourishment alternatives, the yellow/green colored part extends over time, indicating that the nourishments spread and feed the adjacent coastlines. The smaller nourishment frequencies experience more renourishments, leading to a larger increase in distance around the placement area and less gradual spreading over the project area. On the other hand, large nourishment frequencies experience erosion spots in the beginning just downdrift of the placement area, indicating the formation of eddies.

The changes in the coastline position for the (1:1) and (1:3) nourishment alternatives are comparable. In the first few months, the distance seems to increase evenly on both sides of the nourishment. However, after 10-15 months the shoreline orientation becomes almost parallel to the original one, and the southward transport increases. Eventually, the placed sediment reaches a larger region on the south side of the nourishment than on the north side.

The offshore islands show a different behavior as the region where the largest increase in distance occurs seems to move northwards over time. As explained previously, this behavior is caused by the decrease in transport on the north side leading to a pile up of sediment. On the south side of the island, the transport magnitude remains the same, and thus the sediment is transported more rapidly.

For almost all alternatives, a retreating behavior can be observed southwards from R-75, which grows over time. This indicates that the particular nourishment alternatives are not successful in supplying sediment to the entire project area. More extensive figures on the variation of the coastline position over time can be found in appendix C. Consecutively the coastline position is shown after 1, 3, 5 and 10 year conform the selected frequencies.

In table 4.1, the regions of sedimentation and erosion are calculated after 10 years. From these columns it becomes clear that the (1:3) nourishment with a 10 year frequency performs the best as the nourishment has spread over 10.3 kilometers after 10 years. Furthermore, the sedimentation and erosion region are calculated over time. Looking at the performance during the nourishment period, it becomes evident that the (1:3) nourishment with a 10 year frequency also performs the best.

Table 4.1: Sedimentation/erosion of the distance between the CCCL and the MCL. Computed both during and at the end of the simulation period.

Nourishment run	**Region of sedimentation (> 1 meter)**	**Percentage over time (%)**	**Region of erosion (> 1 meter)**	**Percentage over time (%)**
(1:1) alternatives				
1 year	8 700 m	43%	1 800 m	3%
3 year	8 000 m	45%	800 m	1%
5 year	8 600 m	48%	900 m	1%
10 year	8 800 m	44%	0 m	1%
(1:3) alternatives				
1 year	9 700 m	52%	1 800 m	3%
3 year	9 700 m	53%	700 m	1%
5 year	10 100 m	54%	800 m	1%
10 year	10 300 m	53%	0 m	0%
Offshore island alternatives				
5 year	9 000 m	48%	1 000 m	2%
10 year	9 400 m	54%	2 000 m	7%

4.3. Recreation

The ecosystem service of recreation is measured on the basis of the activities that take place around the shoreline. Firstly, the suitable dry beach area is considered for activities such as sunbathing. Secondly, the main water activity is considered, namely swimming. This is indicated as the safe swimming area that is present during the swim season. Furthermore, the activity of kitesurfing is considered, as the beach in Duval County is a popular kitesurfing spot. The additional effect from the nourishments is computed as the suitable water surface that is sheltered from waves. Finally, the activity of strolling is taken into account as a sub-service. This is indicated as the walkable beach length along the shoreline.

4.3.1. Beach leisure

The sub-service of beach leisure is indicated as the suitable dry beach area. However, the beach length does not vary between the different nourishment alternatives which means the focus lies on the dry beach width. On a monthly basis, the dry beach width has been calculated between the dune foot and the MHW line. Similarly to the coastline position, the beach width varies spatially and temporarily. The results are presented in the form of time-stacking as well, and are grouped per nourishment shape horizontally and per frequency vertically.

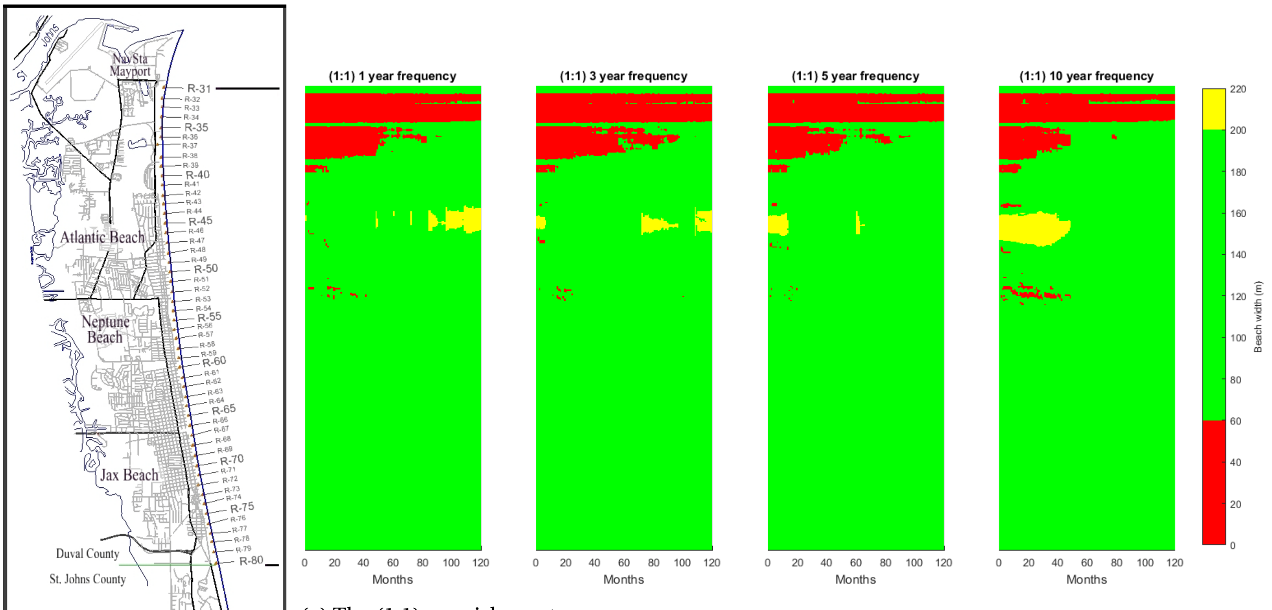
Delft3D only computes the sediment transport in the marine zone of which the upper limit is defined as the local water level. This means that the upper boundary shifts with the tide and the marine zone varies over time. This leads to computational problems around the MHW line, meaning that the location of the MHW line is not accurately described. Therefore, the computational MHW line is lowered to 0 m MSL to exclude these problems.

In figure 4.4 the time-stacking plots are given for the different nourishment alternatives. The most suitable beach width is between 60 and 200 meters and is indicated by a green color. Red colors indicate that the beach width is less than 60 meters, and this occurs mainly north of the nourishment. In this region, the initial shoreline and the CCCL lie closer together than the rest of the project area. Some sections remain too small over the entire period, while others increase in beach width over time. This indicates that the sediment transport to the north cannot counteract the too small beach widths. It can be observed that for larger frequencies the northern red areas disappear more rapidly, but occasionally some arise south of the nourishment as well.

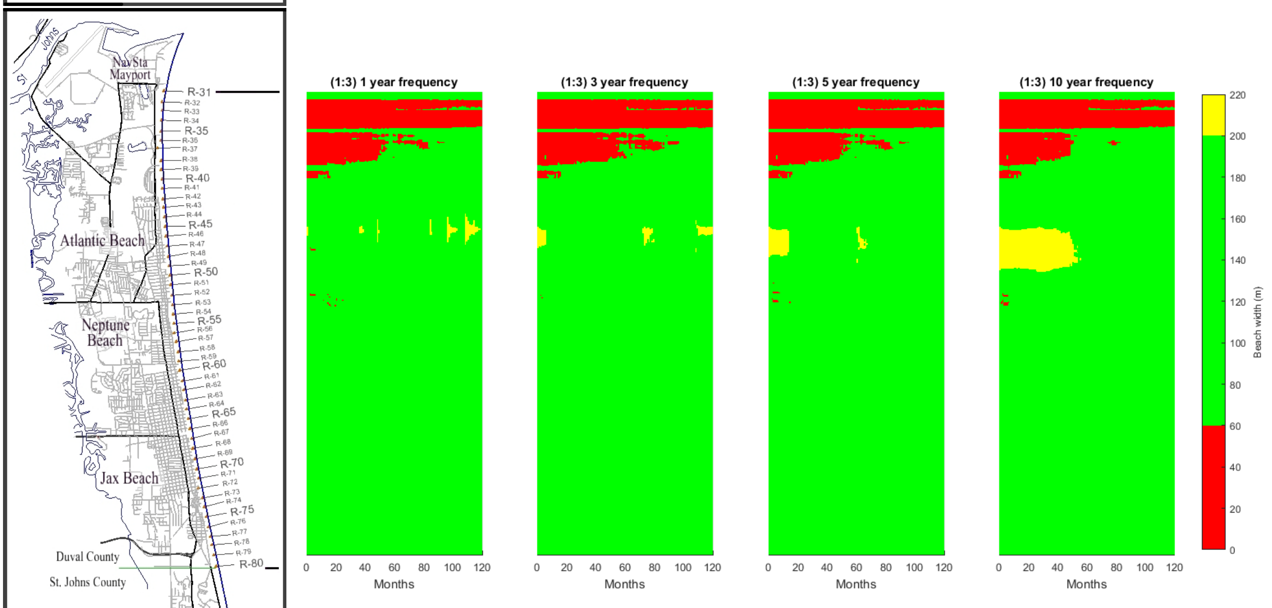
The yellow sections represent beach widths over 200 meters. Logically, they appear more often for larger frequencies since larger volumes are placed in one time. While the yellow sections in the larger frequency models disappear over time, they arise in the shorter frequency models due to the renourishments. This indicates that the large frequency nourishments spread over time, while the shorter frequencies pile up sediment at these locations. Finally it can be observed that for the offshore island nourishments, the yellow section moves to the north. This indicates that transport to the north is present beyond the 200 meter beach width. However, this does not mean that the northern transport magnitude is larger than the southern one as the red areas remain to exist.

In appendix D, the beach width is presented in more extensive figures. For every nourishment frequency a time record is made to compare the beach width for the different models in combination with the time-stacking plots.

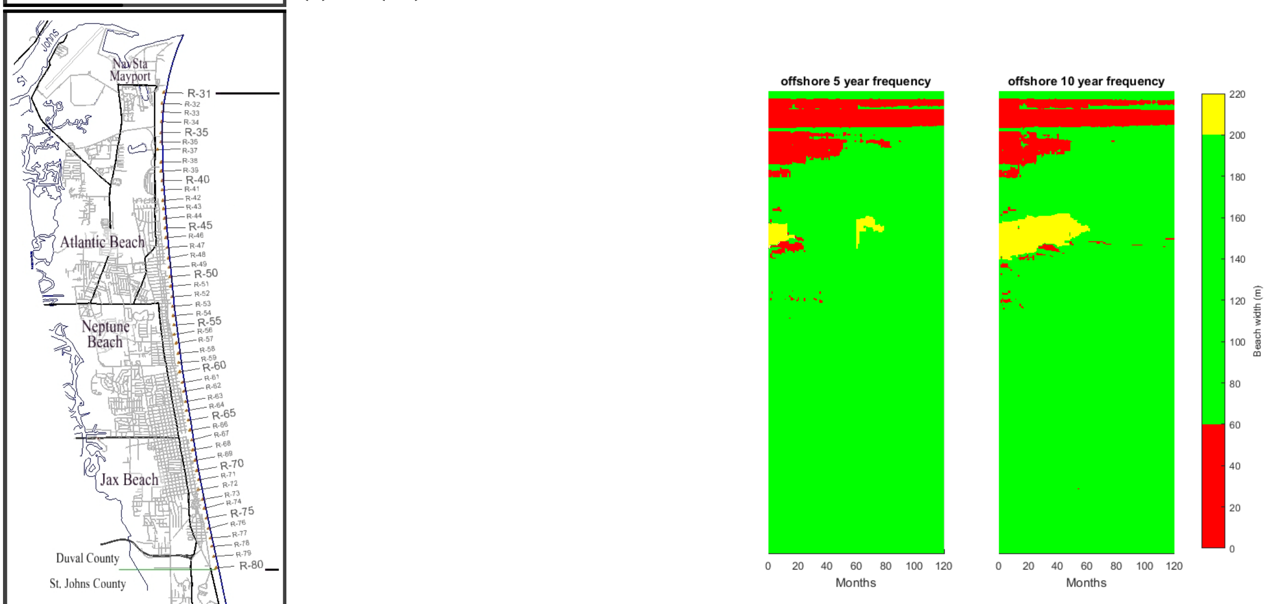
In table 4.2, the red, yellow and green sections are computed at the end of the 10 year simulation. From these values it can be seen that larger frequency models have the least red and yellow sections at the end of the simulation, indicating that the sediment is distributed more evenly across the coastline. Based on this, the most suitable solution is the offshore island with a 10 year frequency. However, looking at the overall performance, the (1:1) nourishment with a 5 year frequency scores better. The percentage of suitable beach widths over time is the highest for this nourishment alternative.



(a) The (1:1) nourishments.



(b) The (1:3) nourishments.



(c) The offshore island nourishments.

Figure 4.4: Timestack of the beach width over time for all nourishment alternatives. Horizontally they are grouped per geometry, while vertically they are grouped per nourishment frequency.

Table 4.2: Beach width, computed both during and at the end of the simulation period.

Nourishment run	Red (< 60 m)	Percentage over time (%)	Yellow (> 60 & < 200 m)	Percentage over time (%)	Green (> 200 m)	Percentage over time (%)
(1:1) alternatives						
1 year	740 *m*	9.5%	680 *m*	1.0%	12 740 *m*	89.5%
3 year	800 *m*	10.1%	680 *m*	0.9%	12 680 *m*	88.9%
5 year	780 *m*	8.6%	0 *m*	0.5%	13 380 *m*	90.6%
10 year	680 *m*	8.7%	0 *m*	2.3%	13 480 *m*	89.0%
(1:3) alternatives						
1 year	740 *m*	9.2%	0 *m*	0.3%	13 420 *m*	90.5%
3 year	800 *m*	9.8%	220 *m*	0.5%	13 140 *m*	89.8%
5 year	780 *m*	9.3%	0 *m*	0.7%	13 380 *m*	89.9%
10 year	740 *m*	8.7%	0 *m*	3.5%	13 420 *m*	87.7%
Offshore island alternatives						
5 year	720 *m*	9.1%	0 *m*	0.8%	13 440 *m*	90.2%
10 year	640 *m*	7.9%	0 *m*	3.1%	13 520 *m*	89.0%

Solely looking at the beach width variation below 60 meters and beyond 200 meter gives a quantitative description of the behavior of the different nourishment alternatives. However, it does not give insight into the absolute values of the beach width, and thus the dry beach area suitable for beach leisure. Therefore, a qualitative assessment is made as well. In figure 4.5, the suitable dry beach area over time is shown. It is computed as the sum of the suitable green area of the time-stacking plots.

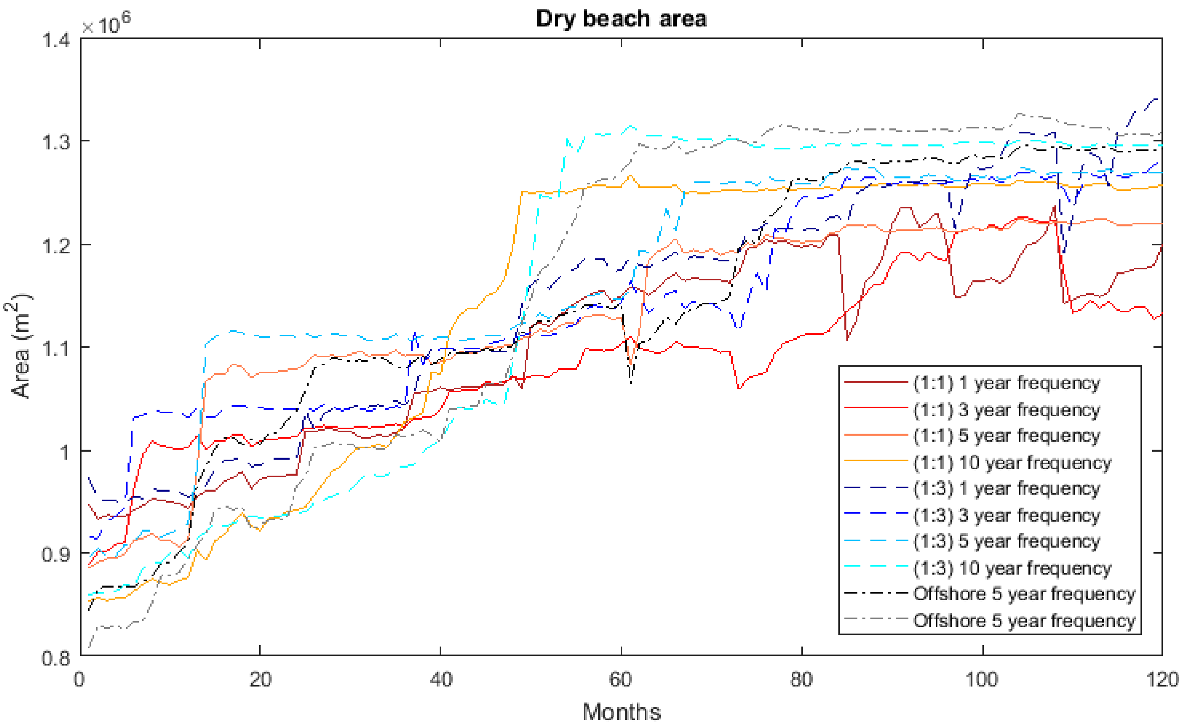


Figure 4.5: The dry beach area of the different nourishment alternatives. The area is based on the suitable beach width between 60 and 200 meters from figure 4.4.

From this figure it can be observed that the (1:3) nourishments and the offshore island nourishments perform better than the (1:1) alternatives. This is logical, as the (1:1) nourishments extends beyond the 200 meter beach width more often. After a simulation period of 10 years, the (1:3) nourishment with a 1 year frequency contains the largest suitable beach area. Even though this alternative does not have the most green sections at the end of the simulation, the beach width of the beach sections which are suitable is the widest.

Combining both results, the offshore island with a 10 year frequency performs the best at the end of the simulation period. However, the intermediate results need to be taken into account as well, and therefore the (1:3) nourishment with a 1 year frequency is chosen as the best alternative for the sub-service of beach leisure.

4.3.2. Swimming

Determination of a 'safe' swimming area is very complex and therefore difficult to capture in simple quantifiable parameters. Due to input reduction, the temporal hydrodynamic scale in the model is disturbed. This means that temporal fluctuations due to seasons and night & day cannot be taken into account. Furthermore the occurrence of rip currents is excluded as well, as they are too complex to predict accurately with the model. However, observing the change in flow velocities due to the application of the nourishment alternatives can give a preliminary insight into the unsafe situations than can arise. The sub-service of swimming is highly dependent on the presence of people in the water, which is only the case during calm conditions. As the previous presented models only consider waves with a height above 1 meter, calm conditions are not present. Therefore three new wave conditions have been selected which represent the average wave climate at Duval County, see table 4.3.

Table 4.3: Representative 'calm' conditions for swimmer safety.

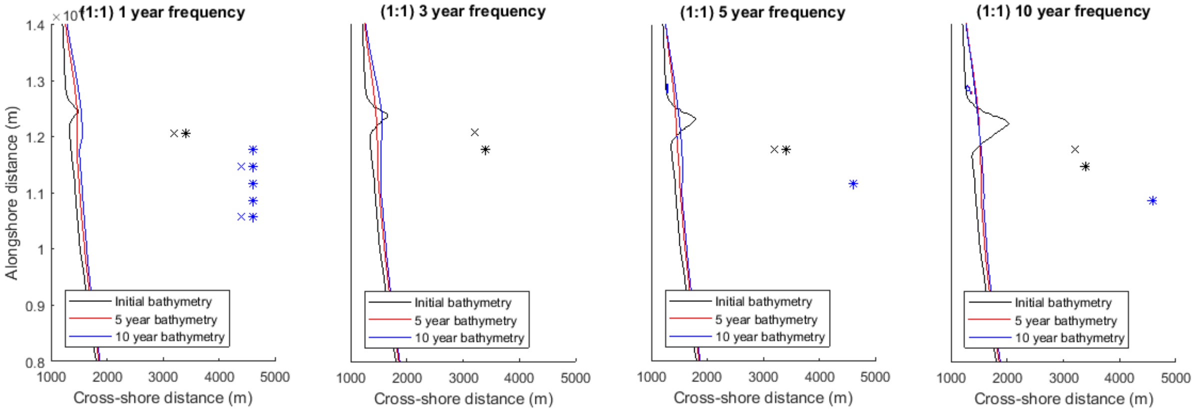
Condition	H_s **(m)**	T_p **(s)**	**Direction (degrees N)**	U_{wind} **(m/s)**	**Direction (degrees N)**
1, +	0.50	7.9	107	3.7	107
2, x	0.75	7.6	96	4.8	96
3, $*$	1.00	7.8	83	6.0	83

The suitable swimming area is limited to a water depth of -5 m MSL, as most of the time this depth contour is located between 150 and 200 meters offshore. It is assumed that no swimmers will be present beyond this depth. Furthermore, the coastline is divided into sections of 300 meters width, which correspond with the R-monuments defined in figure 2.1. For each section, the flow velocities within the defined depth region are computed during the selected wave conditions. The threshold for unsafe situations is defined as offshore going flow velocities with a magnitude higher than 0.30 m/s. If one vector within the defined region exceeds this threshold, the whole coastal section is considered unsafe.

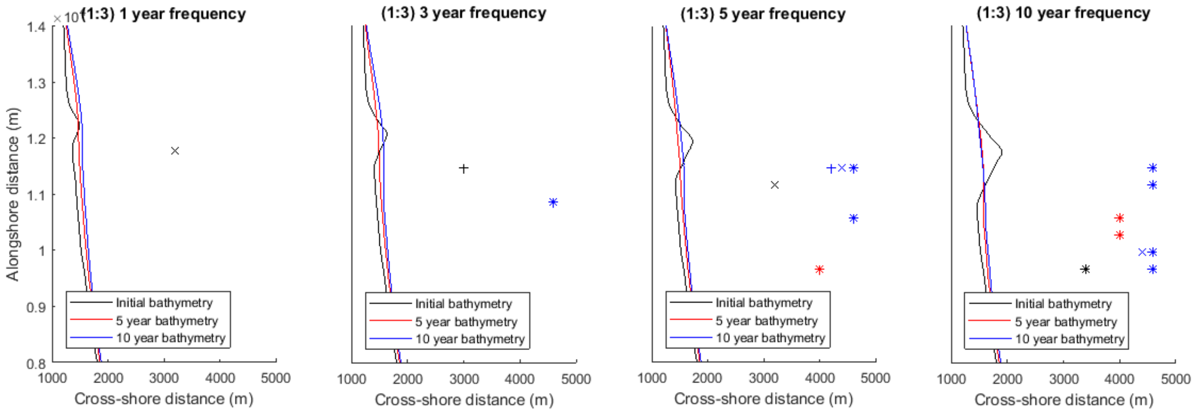
Another simplification is made with respect to the morphological developments, as each nourishment alternative is varying over time. Three bathymetry profiles have been selected for the evaluation of swimmer safety, namely the initial bathymetry, the bathymetry halfway and the bathymetry at the end of the 10 year period. In total, 9 different simulations are made per nourishment alternative.

Figure 4.6 gives the results of the different simulations. On the left side of each figure, an overview of the three different bathymetry profiles is shown. On the right side, the locations of the unsafe sections are presented. For each of the three wave conditions, a symbol is selected, which can be found in table 4.3. The colors of the symbols correspond with the applied bathymetry. If symbols or colors are lacking, it indicates that the threshold was not exceeded in any section.

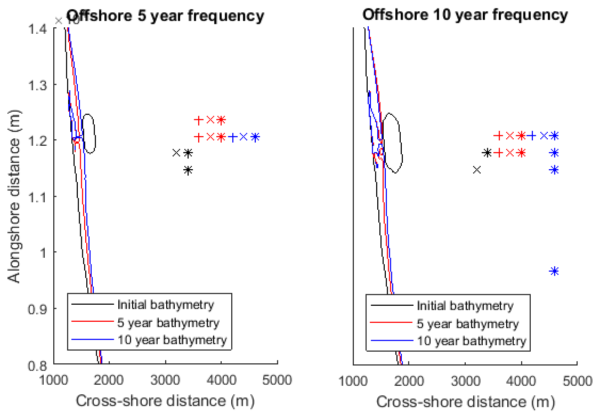
The flow velocities around the offshore island nourishment exceed the threshold the most often. Unsafe conditions arise for each of the three bathymetries, in combination with almost every wave condition. The attachment process of the island to the coastline and the temporarily opening and closing of the tidal channel create conditions with high offshore flowing velocities. The other nourishment alternatives exceed the threshold less often.



(a) The (1:1) nourishments.



(b) The (1:3) nourishments.



(c) The offshore island nourishments.

Figure 4.6: Unsafe swimming area over time. For each nourishment alternative, the three selected bathymetries of initial, 5 and 10 years are shown on the left side of the figure. On the right side, the unsafe sections are given, of which the colors correspond with the bathymetry (black = initial, red = 5 year, blue = 10 year). The symbols indicate the applied wave climates (+ = H_s 0.5 m, x = H_s 0.75 m, $*$ = H_s 1 m).

For the (1:1) alternatives, the most unsafe sections appear for the 1 year frequency during a wave height of 1 meter, in combination with the 10 year bathymetry. The unsafe sections are present on the downdrift side of the nourishment, where the bathymetry deviates the most from the original shoreline orientation and thus leads to the highest offshore velocities. For the (1:3) nourishments, this is not true as the most unsafe conditions can be found for the 10 year frequency, independent of the present bathymetry.

Keep in mind that swimmer safety is in reality way more complex than only considering the offshore directed velocity. However, by looking at the resulting flow velocities, an insight is provided into which nourishment alternative has the least influence on the velocity profile at the project site and is the most suitable alternative. The (1:3) nourishment with a frequency of 1 year only exceeds the threshold once for the initial bathymetry, and is therefore chosen as the most suitable for swimming.

4.3.3. Kitesurfing

This sub-service is described as the suitable water surface for kitesurfing. The suitable area is defined as the area between the -0.5 m MSL and -5.5 m MSL depth contours which is sheltered from waves, defined as a wave height smaller than 1 meter. The minimal depth is needed to prevent running aground, while the maximum depth is chosen based on a maximum width of 200 meters from the shoreline. As Jacksonville is already a popular kitesurfing spot, only additional area created by the nourishments is taken into account. The suitable kitesurfing area is computed as the sum of the surface area of the grid cells where these conditions hold. To exclude the effect of the tides and seasons, the area is computed monthly and averaged per year.

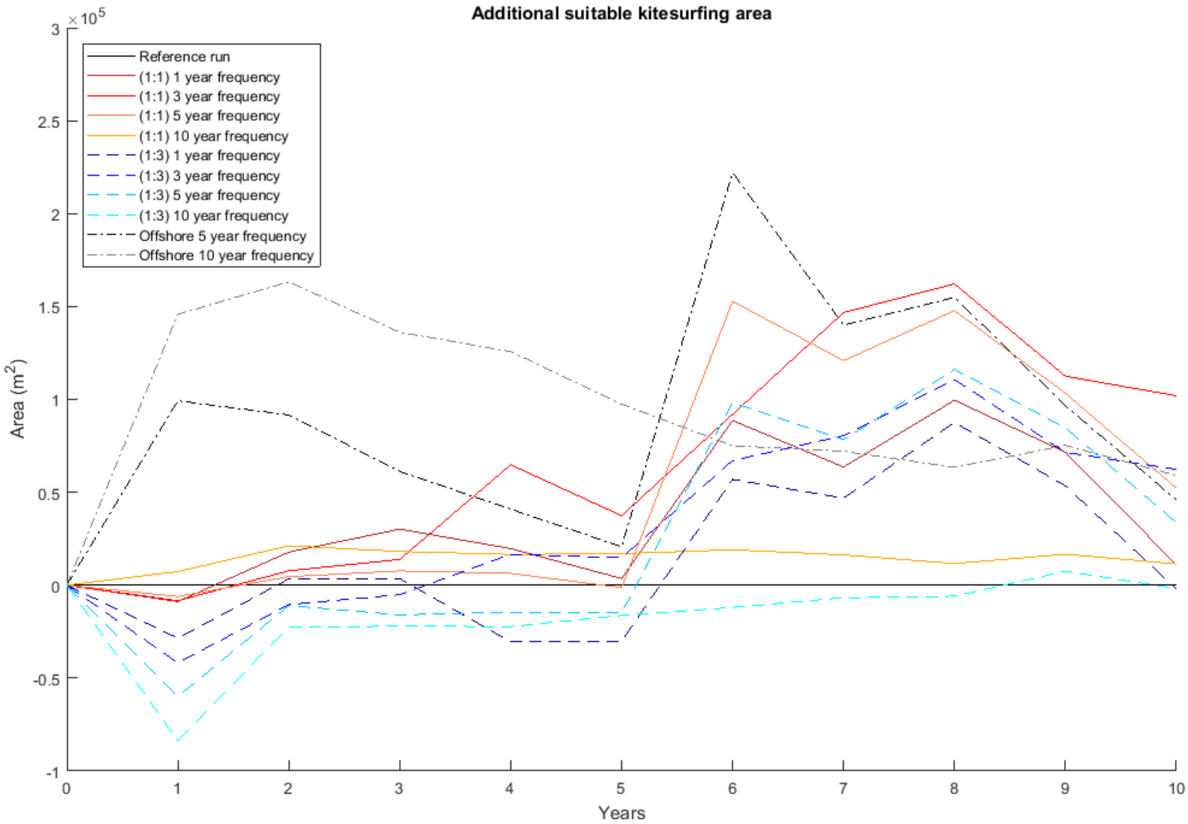


Figure 4.7: The additional kitesurfing area, temporally averaged per year.

In figure 4.7, the results for the different nourishment alternatives are shown. For the (1:1) and (1:3) nourishments, the placement of sediment has a negative effect in the beginning of the simulation. In the first year, the additional area is negative which means that less suitable kitesurfing area is available than for the reference run. The nourishments are mainly placed within the defined depth region containing steep sloping edges, reducing the inundated area. Over time, the nourishments spread and the shoreline returns to its original slope creating additional area. Especially the lower frequency runs increase in additional area over time, suggesting that frequent renourishing has a positive effect on creating sheltered kitesurfing area.

The offshore island runs show contradictory behavior compared to the other alternatives, but this is in accordance with their morphological development. In the beginning of the simulation the additional sheltered area of the islands is large due to the development of the lagoon. Over time, the lagoon gets partially filled in with sediment and therefore decreases in size. For the 5 year frequency run, the appearance and disappearance of the lagoon happens twice during the simulation period which corresponds with the 'jump' in area halfway the simulation. In reality, the decrease of the lagoon will happen even faster due to the contribution of aeolian processes which are not taken into account by Delft3D.

In the last year of the simulation, all nourishments have spread along the adjacent coastlines and the additional kitesurfing area reduces again. After 10 years, most alternatives still contain additional kitesurfing area, of which the (1:1) nourishment with a 3 year frequency contains the largest area.

Besides the sheltered area at the end of the simulation period, the average additional area per year is computed for each nourishment alternative (shown in table 4.4). For the (1:1) and (1:3) nourishment alternatives, the highest average area is given by the 3 year frequencies. This shows that large-scale nourishments do not necessarily provide more sheltered area than small-scale ones. Contrary, the offshore island nourishments show a different behavior. The average additional area is much higher than for the attached nourishments, moreover, the 10 year frequency provides the highest average additional area overall.

Table 4.4: Additional kitesurfing area per year, computed as the average during the 10 year simulation period.

Nourishment frequency	**Average area per year (m^2/py)**
(1:1) alternatives	
1 year	39 100
3 year	68 000
5 year	56 200
10 year	15 000
(1:3) alternatives	
1 year	16 200
3 year	33 500
5 year	27 800
10 year	-18 500
Offshore island alternatives	
5 year	95 000
10 year	98 400

The (1:1) nourishment with a 3 year frequency contains the largest additional sheltered area at the end of the simulation period, and performs second best for the highest average area per year. The offshore island with a 10 year frequency shows the opposite behavior, as it performs second best in figure 4.7 and the best in table 4.4. Therefore, both nourishment alternatives are selected as most suitable.

4.3.4. Strolling

The sub-service of strolling is indicated as the walkable beach length along the shoreline. The shoreline is chosen to be the 0 m MSL depth contour, but is limited by a maximum beach width. If the beach width extends beyond 200 meters, it is assumed that people will not follow the shoreline anymore, but cut off along the 200 meter line.

The strolling length is calculated only along the continuous 0 m MSL contour. Other emerged spots above this depth are not taken into account, since they are inundated half of the time and thus cannot be reached.

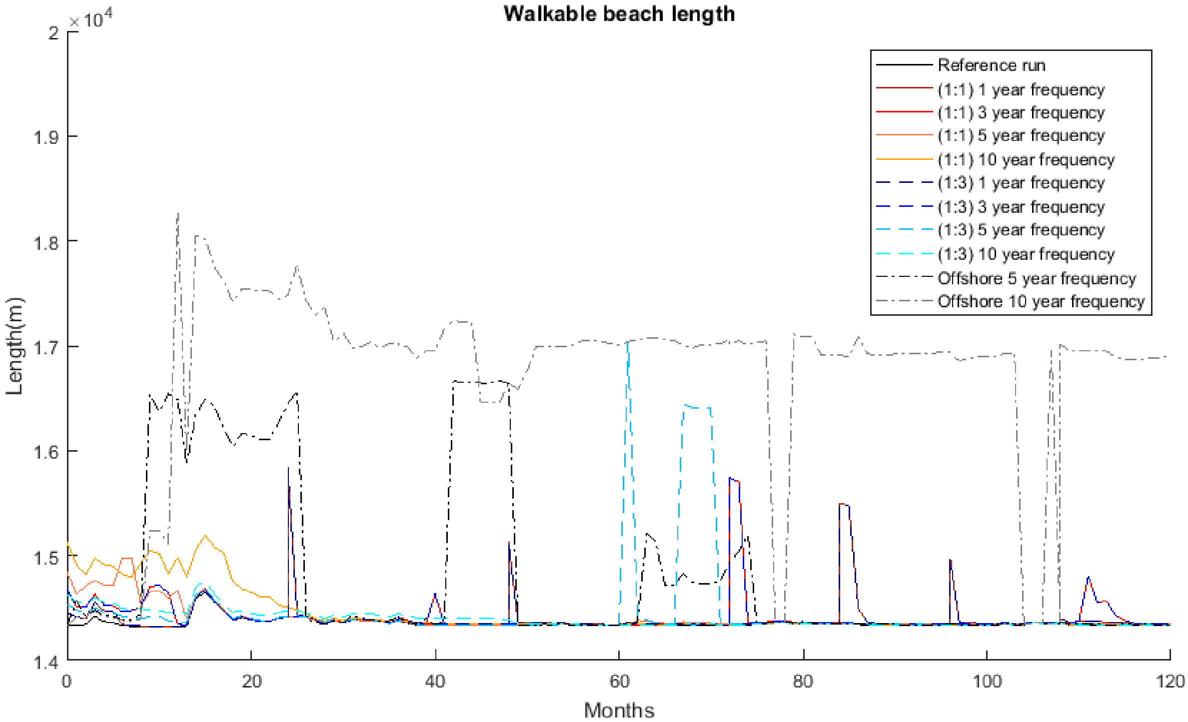


Figure 4.8: The strolling length along the 0 m MSL contour for the different nourishment alternatives, computed per month.

Figure 4.8 present the results of the different nourishment alternatives for the shoreline length over time. From this graph it becomes clear that the offshore island nourishments provide the longest walkable length. Both graphs contain jumps which are initially caused by the attachment of the (re)nourishment to the original shoreline. Later on, the jumps are caused by the temporarily opening and closing of the tidal channel.

For the (1:1) and (1:3) nourishments, these jumps mainly occur for the small-scale frequencies. The 3 year frequency runs of both these alternatives experience the jumps simultaneously, suggesting that they experience the same (re)attachment behavior of the nourishments. Furthermore, some renourishments are not directly placed attached to the shoreline, leading to a time lag between placement and attachment to the shore. Delft3D spreads the sediment uniformly over the defined renourishment region, which means that it needs to be placed seaward of the last nourishment to prevent the piling up of sediment above the MHW line. As Delft3D only considers transport within the marine zone, it is not able to transport sediment above the MHW line.

From this figure it can be observed that the largest strolling length is provided by the offshore island with a 10 year frequency, both during and at the end of the simulation period.

4.4. Habitat provision

The ecosystem service of habitat provision is divided into three sub-services. The first sub-service considers the influence of the applied nourishments on the existing habitats and is indicated with ecotope mapping. Secondly, the influence on turtle nesting is investigated. This is done by comparing the suitable nesting area for the different alternatives. Finally, the dune growth potential is compared, which is indicated by the ratio between the resulting intertidal beach width and a reference intertidal beach width. For each of these sub-services, the frequency of disturbance plays a large role.

4.4.1. Nursery area

The nursery area is indicated by ecotope mapping of the different nourishment alternatives. The classification of the different ecotopes is based on the water depth and the hydrodynamic stresses that occur below the waterline. Shallow areas usually experience more wave-induced bottom stresses than deeper habitats, indicating greater hydrodynamic stress. The amount of hydrodynamic stress is crucial for the growth of fish in the intertidal and subtidal zone [Stoll et al., 2007]. Small fishes have a greater ability to cope with hydrodynamic stresses as they seek shelter during wave events to reduce the current velocities they experience. Additional sheltered area containing low hydrodynamic stresses will thus benefit the survival of juvenile species.

As both the bed level and the hydrodynamic stresses vary over time, an ecotope map is usually a snapshot in time, as it represent the static state of the present ecosystem. In order to exclude the influence of local conditions in time, the hydrodynamic stresses are averaged over a complete tidal cycle. Furthermore, ecotope maps are computed annually to track the progress of the ecotopes during the simulation period. The situation directly after placement of the nourishments is not taken into account, as the ecotopes still need to recover from the sediment placement.

In section 2.5, it is stated that due to the calmer wave climate at Duval County, it is expected that lower hydrodynamic stresses will occur. In figure 4.9, an overview is given of the hydrodynamic stresses that occur for the different nourishment alternatives with their corresponding water depths. It can be observed that significant hydrodynamic stresses only occur between −5 and +1 m MSL, which means that the defined depth regions of Van Zanten [2016] cannot be applied directly on the coast of Duval County.

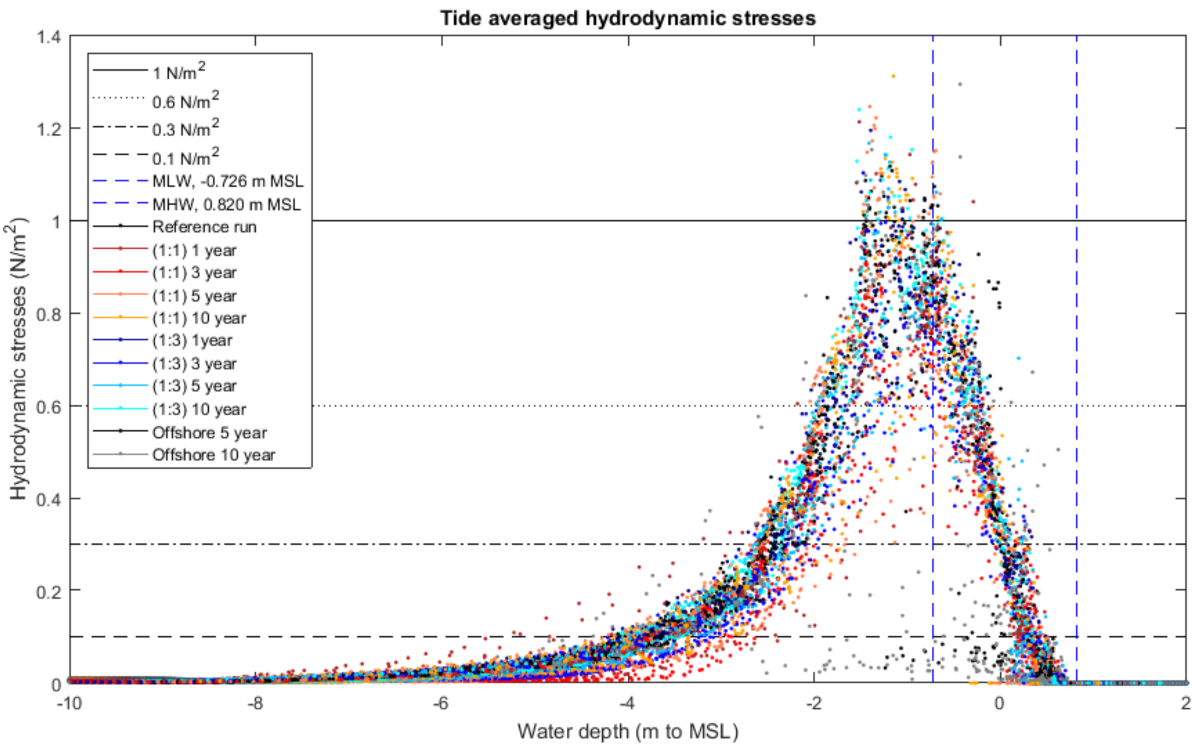


Figure 4.9: The hydrodynamic stresses versus the water depth, for the annual assessments of the nourishment alternatives.

The surfzone at Duval County is defined between the MLW line and the −7.5 m MSL depth contour. Significant hydrodynamic stresses only occur within this depth region. This means that the first three ecotopes, containing moderate to very high hydrodynamic stresses, are situated within the surfzone. The area with stresses lower than 0.3 N/m^2 is present within the surfzone and seaward of the surfzone. Therefore, it is classified as a single ecotope. The fifth ecotope is defined as the area within the surfzone where extremely low stresses are present, and is constricted between MLW and the −5 m MSL line. Within this depth zone also higher hydrodynamic stresses can occur, which means that extremely low stresses indicate sheltered areas. For Duval County only ecotope 5 and 8 are of interest for nursery area, as they provide additional sheltered area. The newly proposed depth zones are given in table 4.5.

Table 4.5: Quantification of the ecotopes for the Duval County coastline. Depth zones adjusted for figure 4.9.

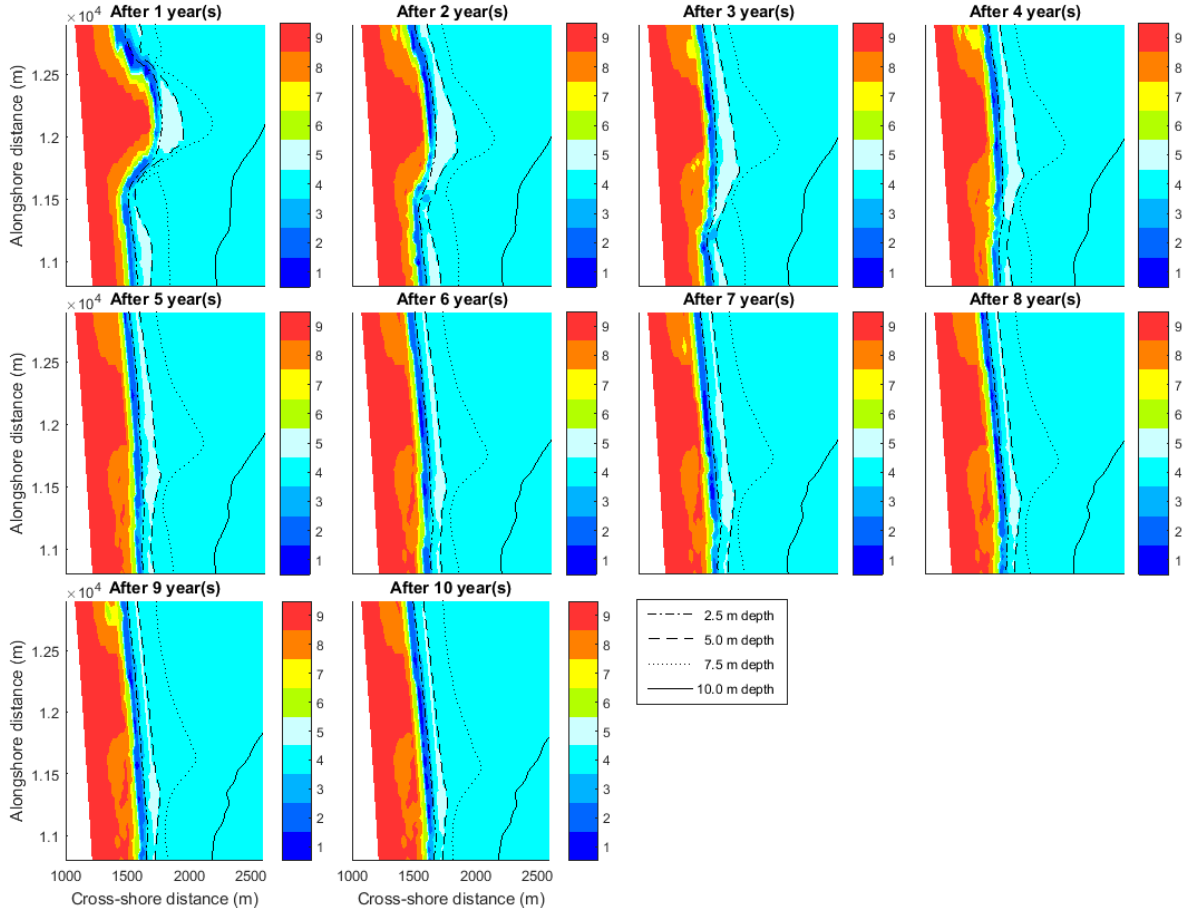
	Ecotope	Water Depth (m MSL)	Hydrodynamics (N/m^2)
1	Surfzone (very high stresses)	≤ −0.726 and > −1.5	> 1
2	Surfzone (high stresses)	≤ −0.726 and > −2.1	> 0.6 and ≤ 1
3	Surfzone (moderate stresses)	≤ −1.5 and > −2.5	> 0.3 and ≤ 0.6
4	Surfzone (low stresses) & seaward of the surfzone	≤ −2.0	≤ 0.3
5	Sheltered subtidal	≤ −0.726 and −5	≤ 0.1
6	Exposed lower intertidal	> −0.726 and ≤ +0.00	> 0.1
7	Exposed upper intertidal	> +0.00 and ≤ +0.820	> 0.1
8	Sheltered intertidal	> −0.726 and ≤ +0.820	≤ 0.1
9	Supratidal zone	> +0.820	–

In figure 4.10a, 4.10b and 4.10c the results of the 10 year frequency runs have been presented. The colors correspond with the ecotopes given in table 4.5. For all three alternatives, the largest diversity in ecotopes is found within the first three years of placement. Furthermore, ecotope 1, 2 and 3, containing the high and moderate hydrodynamic stresses, are located close to the shoreline, between MLW and the −2.5 m MSL depth contour. This indicates that the waves and currents causing these stresses are only of influence within this zone for all nourishments. The sheltered subtidal area increases after placement of the nourishments during the first half of the simulation period. In the second half of the simulation, the sheltered subtidal area decreases again to a minimum value for all three nourishment alternatives. The total intertidal area varies slightly during the 10 year period, but the interaction between the exposed and sheltered intertidal is clearly visible as the sheltered intertidal area becomes bigger over time. Finally, the supratidal area decreases over time, as the nourishment is spread along the coastline into shallower regions. At the end of the simulation time, the ecotopes present in the (1:1) and (1:3) alternatives are comparable, and the diversity has decreased. For the offshore island nourishment the lagoon is still present, increasing the diversity of ecotopes present.

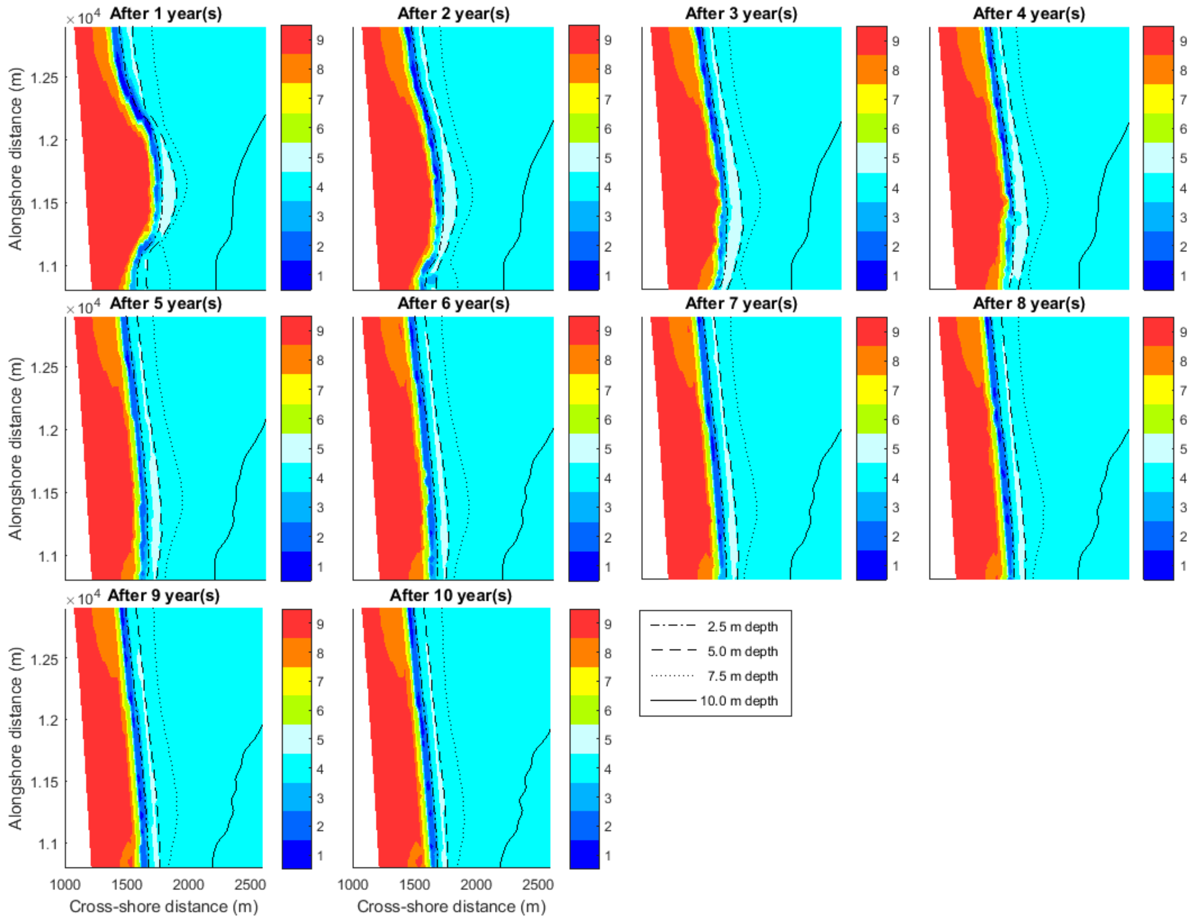
For the (1:1) nourishment it can be observed that the morphological changes, and thus the variation in ecotopes, primarily happen within the surfzone as the −7.5 m depth contour is constant after 2 years. The sheltered subtidal area, ecotope 5, is the largest after the first year. Until the fourth year the area decreases, whereafter the area remains fairly constant. Likewise, the lower intertidal area decreases over time as the (1:1) nourishment spreads along the adjacent coastlines. The sheltered intertidal area, ecotope 8, grows within the first four years, and remains constant thereafter. This suggest that as the coastline returns to its original orientation, the sheltered subtidal area is exchanged for sheltered intertidal area.

During the entire simulation, the total intertidal area for the (1:3) nourishment is much smaller than for the (1:1) nourishment. As the nourishment is elongated along the coastline and protrudes less far into the ocean, a larger portion of the nourishment is situated in the supratidal zone than in the intertidal zone. Moreover, the sheltered intertidal area is significantly less during the simulation as well. The subtidal area containing ecotopes 1, 2, and 3 is comparable to the (1:1) nourishment. On the other hand, the sheltered subtidal area is less. It increases slightly during the first four years, but reduces to a minimum after that.

The offshore island experiences a different behavior during the simulation. In the beginning a high diversity of ecotopes is visible in the entire nourishment section. Whereas on the north side, large hydrodynamic stresses are mainly present on the outer bank of the island, the south side shows significant stresses both inside and outside of the mouth. After four years, the magnitude of the hydrodynamic stresses decreases inside the mouth but remain visible after 10 years. Due to the formation of the lagoon between the island and the original shoreline, a large sheltered subtidal area is added to the ecosystem. As the island spreads along the adjacent coastlines and partially fills in the lagoon, the sheltered subtidal is transformed into sheltered intertidal area. The sheltered subtidal area outside the lagoon reduces to a minimum after 6 years, while a significant area remains within the lagoon.

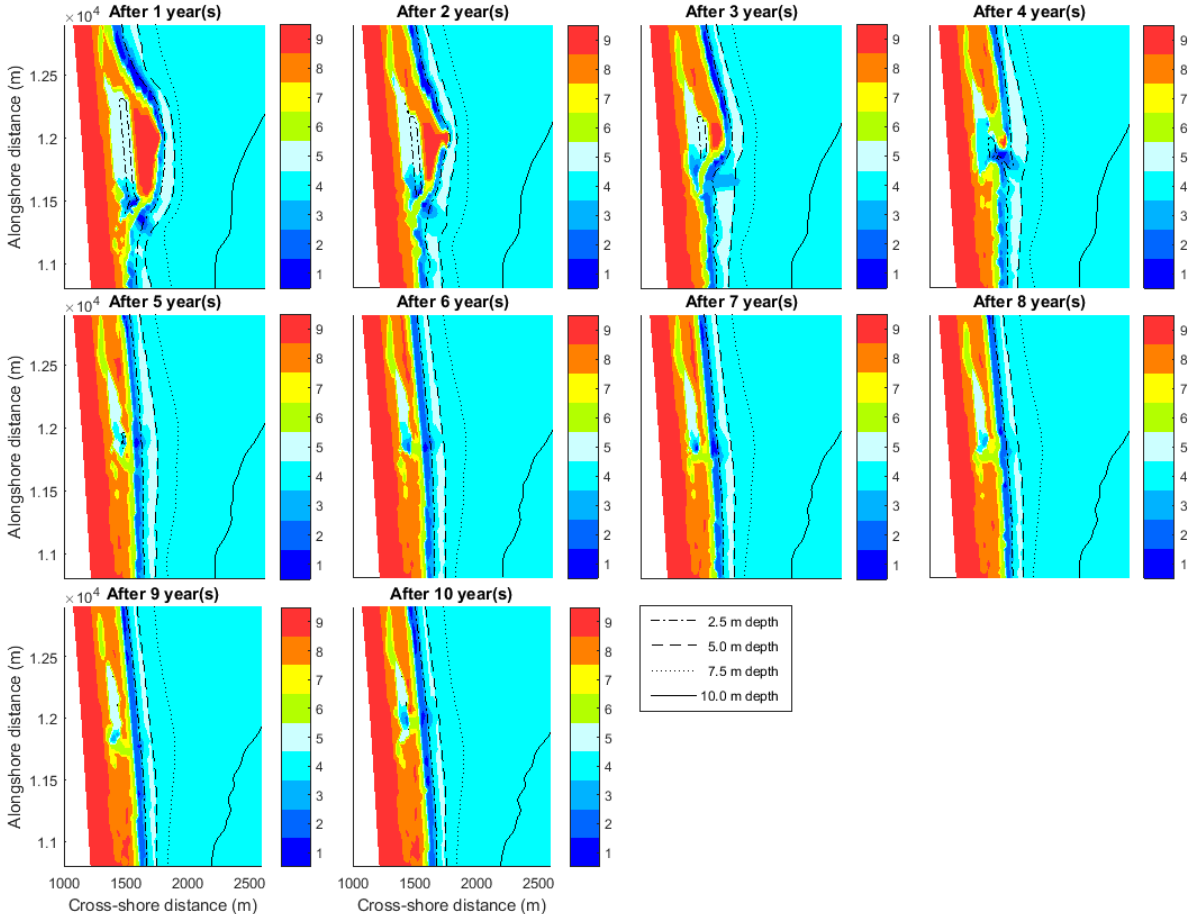


(a) The (1:1) 10 year frequency nourishment.



(b) The (1:3) 10 year frequency nourishment.

Figure 4.10: Annual ecotope maps of the 10 year frequency runs. The colorbar corresponds with the ecotopes defined in table 4.5.



(c) The offshore island 10 year frequency nourishment.

Figure 4.10: Annual ecotope maps of the 10 year frequency runs. The colorbar corresponds with the ecotopes defined in table 4.5.

In figure 4.11, an overview is given of the area of the ecotopes over the years for the reference run and the 10 year frequency runs. The area has been normalized over the entire nourishment section to simplify the comparison. The majority of the considered area is made up of ecotope 4 and 9, the subtidal area with low stresses and the supratidal area.

First, the subtidal zone is considered. For the first ecotope, it can be observed that models contain a relatively low percentage of area during the entire simulation period. This means that very high dynamic stresses only occur in a small section along the coast. During the first five years, the area of ecotope 1 decreases for the three nourishment alternatives, while they increase again in the second half. For the reference run, a slightly increasing trend can be observed. Ecotope 2 occurs more frequently than ecotope 1, but still only covers a small section and is highly variable over the years. The third ecotope, containing the moderate stresses, is fairly constant over the years. Ecotope 4 makes up the largest area of the considered coastal section, as it contains the entire seaward area of the surfzone. For the reference run, the amount varies between 74-76% of the area, slightly decreasing over time. The three nourishment alternatives contain a considerable smaller portion of ecotope 4, indicating a higher diversity of ecotopes. The percentage increases slightly over the simulation period, suggesting that the diversity becomes less over time. The sheltered subtidal area, ecotope 5, decreases for all models, of which the decrease is the largest for the offshore island alternative. However, as this alternative starts with a large portion of sheltered subtidal, due to the lagoon, the remaining area after 10 years is larger than the other alternatives and the reference run.

For the intertidal zone, ecotopes 6, 7 & 8, a different behavior is observed. The offshore island alternative contains the largest intertidal area during the entire simulation period, likely to be caused by the formation of the lagoon. For all alternatives, the change of area remains within 1-3% deviation. The sheltered intertidal area is the largest for the offshore island alternative, again due to the lagoon. Furthermore, it can be observed that all nourishment alternatives have additional sheltered intertidal area.

Lastly, the supratidal area is discussed, which is described by ecotope 9. This ecotope is the largest for the (1:3) nourishment alternative, as the largest amount of sediment is placed above the MHW line for this alternative. The offshore island contains the smallest section of supratidal area, meaning it has the largest inundated area, and is likely to have the highest diversity in ecotopes.

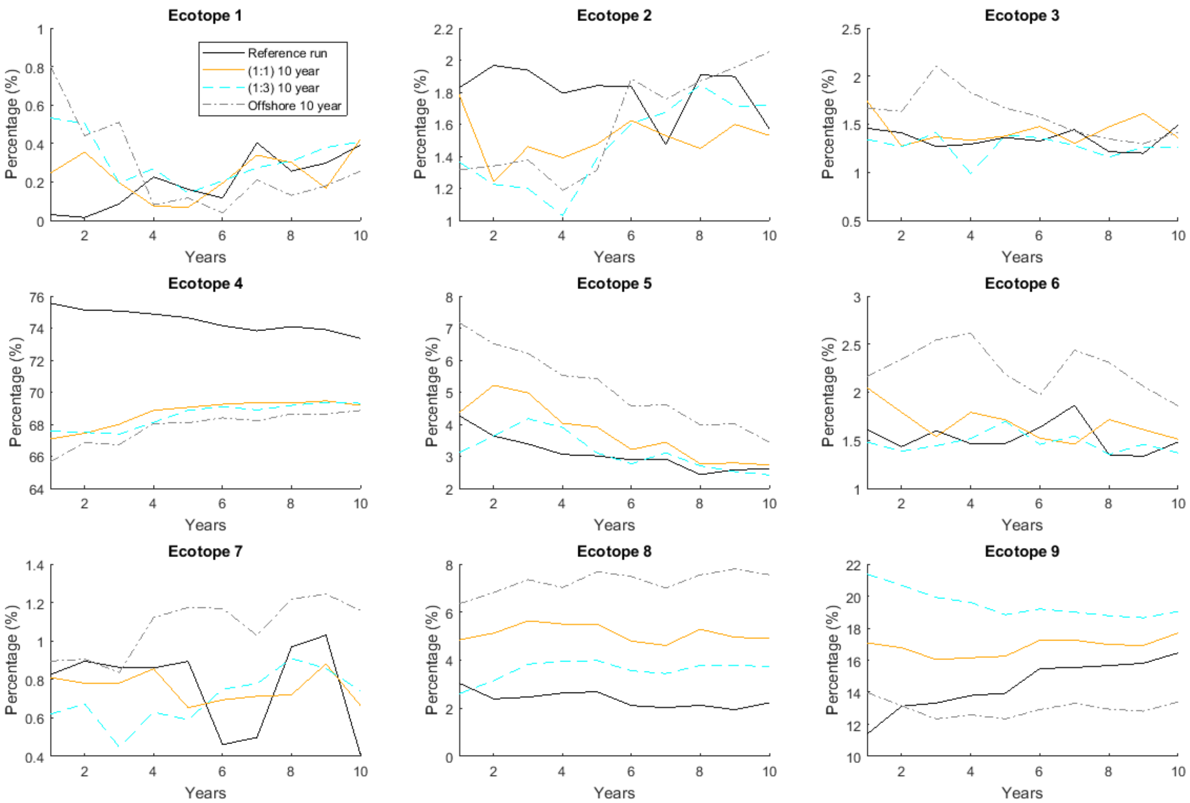


Figure 4.11: The normalized area for each of the defined ecotopes, given for the reference run and the 10 year nourishment frequencies.

The previous figures describe the differences in ecotopes for the 10 year frequency runs, but do not include information on the smaller frequencies. For nursery area, the interest is primarily focused on ecotope 5 and 8, as these provide additional sheltered area compared to the reference situation. In figure 4.12, the normalized area for ecotope 5 and 8 is shown for the frequencies of the three different nourishment shapes in combination with the reference run. In appendix E, more extensive figures can be found, including all ecotopes.

The (1:1) nourishment alternatives (left side of figure 4.12) show a variability of sheltered ecotope area over the years, especially for ecotope 5. It can be observed that the smaller frequencies have a larger sheltered area than the 10 year frequency at the end of the simulation. On the other hand, the frequency of disruption is important for nursery, which favors the large frequencies. For the (1:3) nourishments, shown in the middle, a similar behavior can be observed. The sheltered ecotope areas are variable during the simulation, and the smaller frequencies perform better at the end of the simulation time. For ecotope 5, the resulting sheltered area of the (1:3) nourishments is lower compared to the other shapes. For ecotope 8, this is true for the 10 year frequency, but the other frequencies are comparable to the (1:1) nourishments. The right side of figure 4.12 shows the offshore island alternatives. For both ecotopes, the 5 year and 10 year frequency have a comparable area after 10 years. For ecotope 5, an increase in sheltered area is observed after 5 years, which corresponds with the timing of renourishment. Furthermore, the figures show that the offshore island alternatives provide a larger sheltered area during the simulation period than the attached shapes. Taking the frequency of disruption into account, the 10 year frequency is preferred over the smaller frequencies.

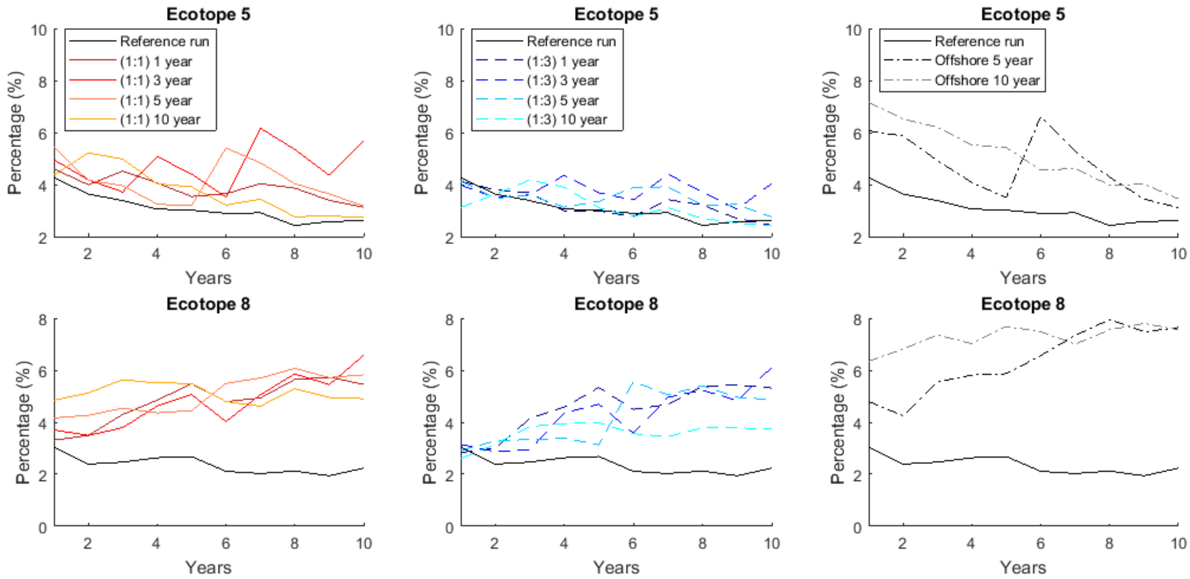


Figure 4.12: The normalized area for ecotope 5 & 8, for the reference run and the different nourishment alternatives. Left: the (1:1) nourishments, middle: the (1:3) nourishments, right: the offshore island alternatives.

Solely looking at the 10 year frequency runs, it is evident that the offshore island nourishment performs the best for the sheltered ecotopes. However, taking the smaller frequencies into account, the 10 year frequencies do not necessarily contain the largest sheltered area. On the other hand, the frequency of disruption is very important for the development and constancy of the ecotopes. For example, the 3 year frequency runs show large sheltered areas after 10 years, but they have just been renourished. It is unknown whether the ecotopes have already recovered from this. Therefore, the 10 year frequencies are preferred above the smaller frequencies. Overall, the offshore island alternative with a 10 year frequency is selected as the most suitable alternative.

4.4.2. Turtle nesting

The sub-service of turtle nesting describes the suitable nesting area that is present for each alternative. Two primary drivers have been identified that influence this, namely the beach slope and the beach width. These parameters are calculated monthly. No information is available on the ideal values of these parameters, and therefore the nourishment alternatives are compared to the reference situation.

The beach width is taken between the same elevation levels as the beach leisure indicator, meaning that the lower boundary of the beach is set to 0 m MSL. The beach slope is determined by dividing the vertical distance between these locations by their horizontal distance. Moreover, the results have been averaged spatially over every 5 R-monuments (figure 2.1).

The results for the beach width are given in figure 4.13. Each graph shows the deviation of the different alternatives with respect to the reference run. For all nourishment alternatives this happens mainly between R-36 and R-65. For the other sections, the beach width is fairly similar to the reference run. This region corresponds with the placement region of the nourishments, increasing with volume. Especially the (1:3) alternatives show larger deviation further downdrift as the nourishments are elongated along the coastline. Another observation that can be made is that for the large-scale nourishments, the beach width remains fairly constant over the simulation period. On the other hand, the influence of the renourishments is visible for the small-scale nourishments as jumps occur at the end of each cycle between R-41 and R-50. In the last figure, the results for R-76 to R-80 are shown. The beach width of the nourishment alternatives is lower than the reference, which suggests that less sediment is supplied to this part of the coastline compared to the required volume. Additionally, the 10 year frequencies show the smallest deviation, which suggest that these alternatives perform better in supplying sediment to the entire project area.

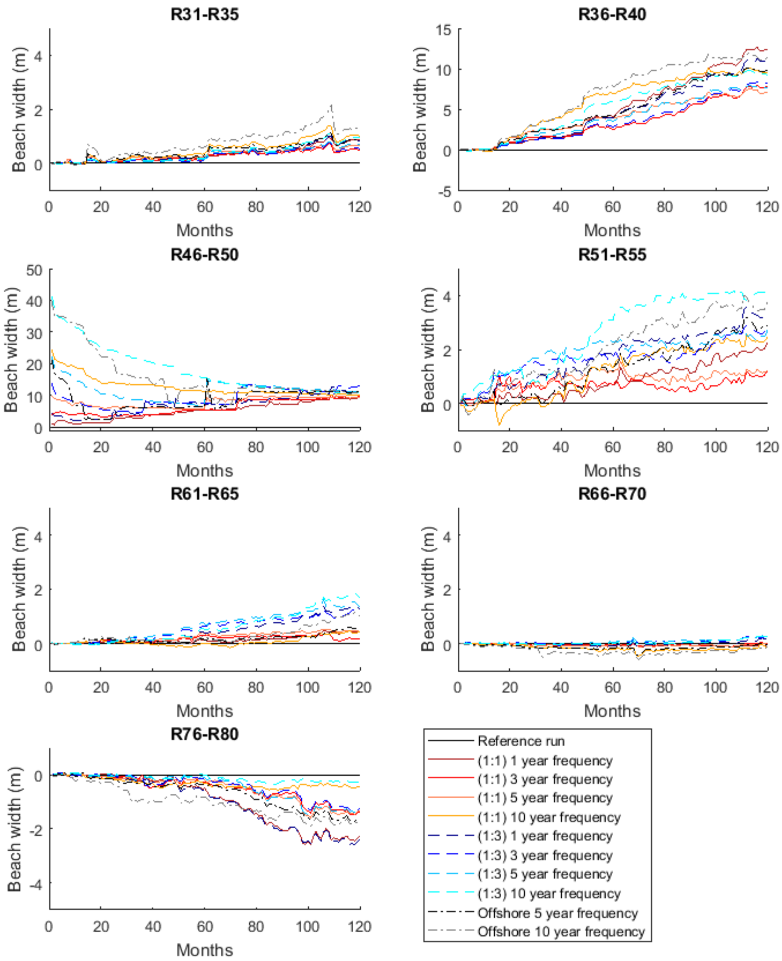


Figure 4.13: Beach width between dune foot and 0 m MSL. Temporally averaged per month, and spatially averaged per 5 R-monuments (see figure 2.1).

Figure 4.14 gives the beach slope of the different nourishment alternatives. For all alternatives, large deviations are limited between R-36 and R-65. Initially, the small-scale nourishments show a smaller deviation from the reference run than the large-scale nourishments between R-36 and R-45. Later on, the small-scale ones deviate as much as the others. This behavior correlates with the sediment volumes that are applied over time. Between R-46 and R-60 it can be observed that the (1:1) alternatives deviate less from the reference run than the other alternatives. These alternatives have a smaller deposition area than the corresponding (1:3) and offshore island alternatives, and therefore disturb less of the original shoreline. The small deviation of the nourishment alternatives compared to the reference run suggests that the adjacent coastlines are fed in a natural fashion and that the beach slope remains suitable for turtle nesting.

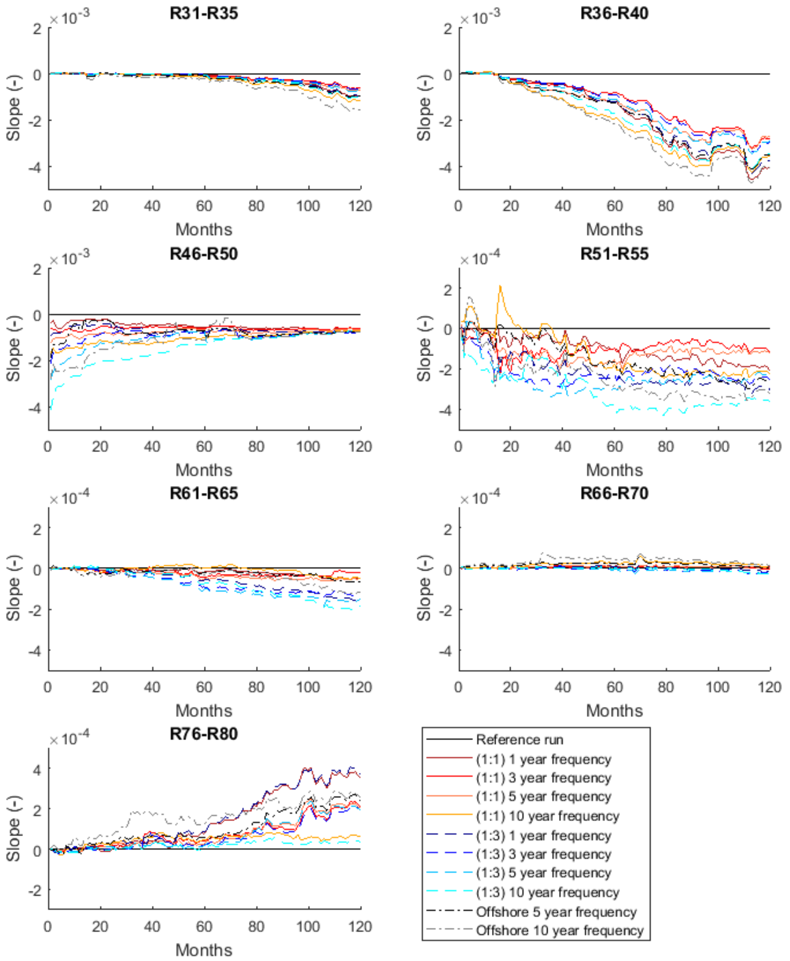


Figure 4.14: Beach slope between dune foot and 0 m MSL. Temporally averaged per month, and spatially averaged per 5 R-monuments (see figure 2.1).

Overall, the alternatives show comparable deviations from the reference run in terms of beach width and beach slope. However, taking the frequency of disturbance into account, the large-scale nourishments perform better. These alternatives have a more stable beach width and slope than the small-scale frequencies, which is preferred for turtle nesting. Between the three alternative shapes, the (1:1) nourishment with a 10 year frequency seems to be the closest to the reference situation over the entire simulation period.

4.4.3. Dune growth potential

The dune growth potential is indicated by comparing the different alternatives on the intertidal beach width. The intertidal zone is constrained between the MHW and MLW line. Similarly as the previous calculations of beach widths, the MHW line has been adjusted to exclude the model inaccuracies of Delft3D. For the intertidal beach width the upper limit has been set to 1.1 meter, just above the MHW line.

The resulting intertidal beach width is compared to the initial width from the reference run without a nourishment, since the equilibrium beach width for dune growth potential is not known. To exclude the effect of tides and local wind and wave conditions, the intertidal beach width is computed monthly but averaged over each year. If the intertidal beach width grows annually, this suggest that the dune growth potential increases over time.

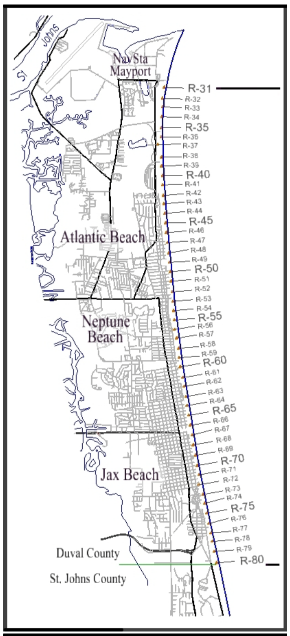
In figure 4.15, the results of the different nourishment alternatives are shown. Locally around the nourishment, the (1:1) and (1:3) alternatives show a decrease of intertidal beach width during the first year. This effect can be explained by the initial placement of the nourishment which is beyond the upper limit. The MLW line remains the same since the nourishments are applied with steep sloping edges, decreasing the intertidal area.

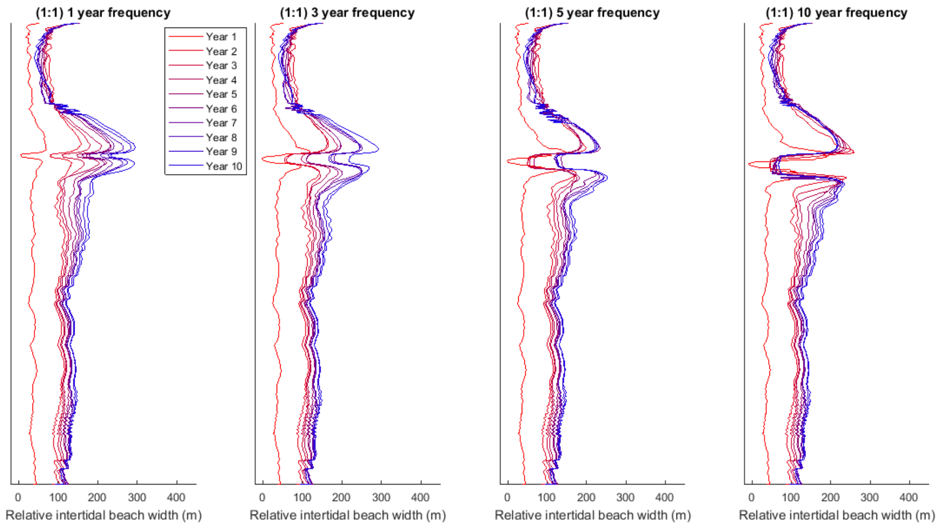
Over the years, the intertidal beach width grows along the entire project area, but the smallest increase occurs at the placement area. The coastlines adjacent to the nourishment area have the largest increase in intertidal beach width.

The offshore island alternatives have a more difficult profile for computing the intertidal beach width. In theory these alternatives contain three separate intertidal zones; the original shoreline, the landward side and the seaward side of the island. Combining these zones would lead to a large increase in dune potential, but some comments need to be made. The presence of the lagoon in between the shoreline and the island reduces the chance for sediment to reach the dune area, as it is likely to be captured by the lagoon during transportation. Therefore, only the most landward intertidal area is taken into account. Over time, the lagoon gets filled in by sediment from the waves which increases the selected intertidal zone. This increase is also shown in figure 4.15. In reality, it is expected that the lagoon will be filled by aeolian transport, which is not taken into account by Delft3D, decreasing the intertidal zone again as it raises above the MLW line.

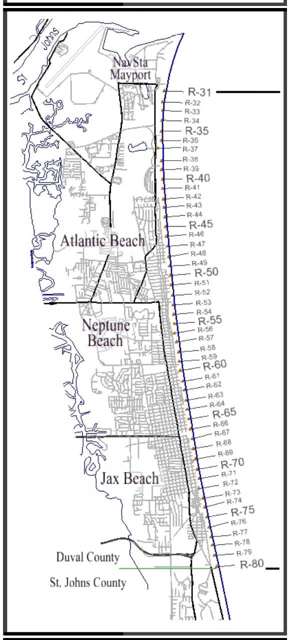
Moreover, the initial intertidal beach width of the offshore islands contains a large amount of wiggles. This is caused by the attaching behavior of the nourishments during the first few months. After the first year, the islands become permanently attached to the original shoreline, and therefore the wiggles largely disappear.

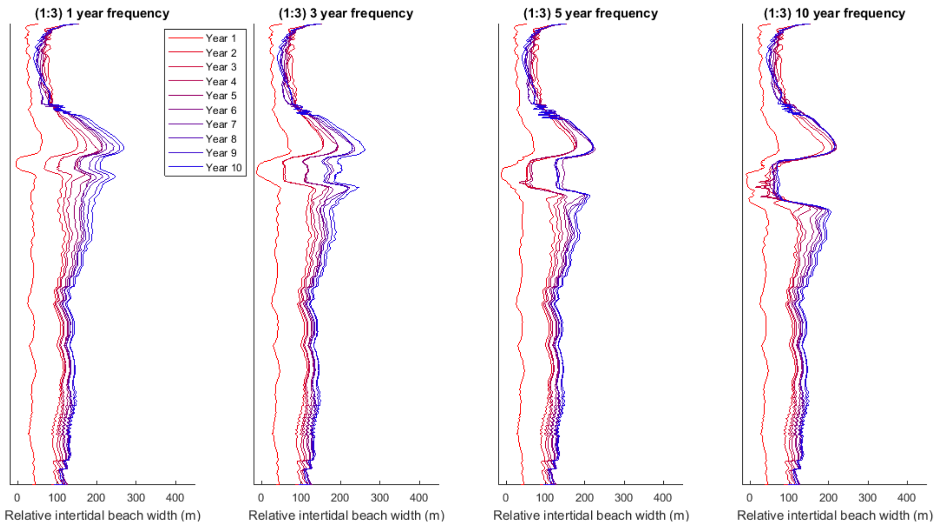
Overall the offshore island with a 10 year frequency shows the largest increase in intertidal beach width, suggesting that it adds the most potential for dune growth.



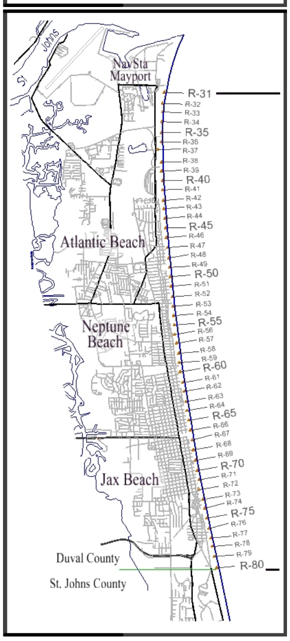


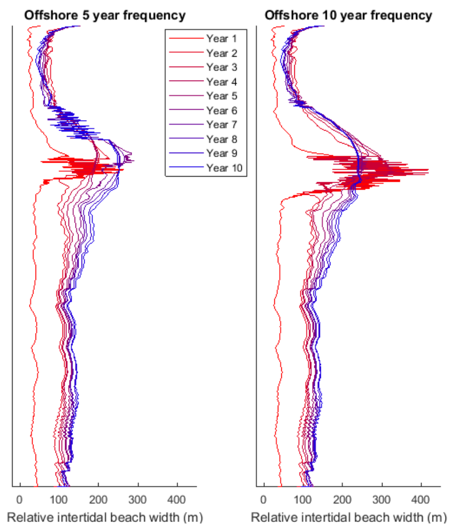
(a) The (1:1) nourishments.





(b) The (1:3) nourishments.





(c) The offshore island nourishments.

Figure 4.15: Intertidal beach width between MLW and MHW, temporally averaged per year.

4.5. Evaluation framework

During this research, three nourishment shapes have been investigated for multiple frequencies on the indicators defined in section 2.5. First the most striking results per nourishment shape is given, after which the different ecosystem services are evaluated.

The (1:1) nourishments contain the smallest deposition area per frequency, approximately 15-20% less compared to the (1:3) nourishments, and cause initially the smallest disturbance of the coastline. However, as the nourishment protrudes far into the ocean, sediment is placed in deep regions, slowing the spreading of sediment across the project area. Furthermore, this extensive protrusion causes the erosion on the downdrift side of the nourishments due to the formation of eddies. These erosion spots are mainly visible for the 5 and 10 year frequencies.

The (1:3) nourishment alternatives are more elongated along the coastline and protrude less deep into the ocean, while providing the same volume. A larger portion of the nourishment is placed within the surfzone, causing a faster and more gradual spreading of the sediment over the adjacent coastlines. After 10 years, the sediment has reached over 10 to 20% more of the project area, compared to the other alternatives. On the other hand, the sediment is placed on a wider beach section, causing a more significant impact on nature.

Initially, the offshore islands provide additional sheltered area between the island and the original coastline, which has a positive effect on the kitesurfing potential, the sheltered ecotopes and the dune growth potential. The additional sheltered area ranges from 10-60% for the ecotopes, to even six times as large for kitesurfing. However, the bathymetry around these nourishments is highly variable, causing frequent high offshore directed velocities compared to the other alternatives. As the developed lagoon gets filled in over time, the additional sheltered areas disappear, reducing the additional benefits.

The ecosystem of coastal protection is evaluated based upon the sub-service of flood protection and the maintenance of the coastline position (see table 4.6). For the flood protection, all nourishment alternatives perform equally, such that a decision for the most suitable alternative cannot be made. For the maintenance of the coastline position it can be seen that the (1:3) nourishment with a 10 year frequency performs the best. At the end of the simulation, the sediment is able to reach the entire project area and has spread evenly across the coastline. This shows that a large-scale nourishment will definitely benefit the coastal protection service.

Table 4.6: Evaluation framework for the ecosystem service of coastal protection. The colors indicate their relative performance (red = very bad, orange = bad, yellow = average, lime = good, green = very good).

Ecosystem service	**(1:1) alternatives**				**(1:3) alternatives**				**Offshore islands**	
Frequency (year)	1	3	5	10	1	3	5	10	5	10
Coastal Protection										
Flood protection	All appropriate									
Maintenance of the coastline position										

The ecosystem service of recreation is more complex, as the different sub-services involve a large variation of indicators. The performance of the different nourishment alternatives is given in table 4.7. For most nourishment alternatives, their performance is not consistent over the sub-services. Several alternatives perform the best for one indicator, but perform the worst for another. However, for both beach leisure and swimming, the (1:3) nourishment with a 1 year frequency is selected as the most suitable alternative. For the studied ecosystem, large-scale nourishments does not necessarily have additional value compared to small-scale ones. The attached (1:1) and (1:3) nourishments primarily add dry beach area to the system, while the offshore islands provide additional suitable water surface and increase the shoreline length. Initially, the large-scale nourishments provide more recreational space than the smaller frequencies, but these effects decrease over time. On the other hand, the positive influence of the small-scale nourishments increase over time leading to a more stable situation. Combining all sub-services, both the (1:3) nourishment with a frequency of 1 year and the offshore island with a frequency of 10 years perform the best.

Table 4.7: Evaluation framework for the ecosystem service of recreation. The colors indicate their relative performance (red = very bad, orange = bad, yellow = average, lime = good, green = very good).

Ecosystem service	**(1:1) alternatives**				**(1:3) alternatives**				**Offshore islands**	
Frequency (year)	1	3	5	10	1	3	5	10	5	10
Recreation										
Beach leisure										
Swimming										
Kitesurfing										
Strolling										

For the ecosystem service of habitat provision the frequency of disturbance plays a large role. The results of the indicators in combination with the investigated nourishment alternatives is given in table 4.8. The corresponding sub-services result in the preference for large-scale nourishments, as they cause the least amount of disruption during the simulation period. The sub-service of nursery area is indicated by ecotope mapping, specifically considering sheltered ecotopes. The lowest additional sheltered ecotopes can be found in the (1:3) nourishment alternatives, as these are most streamlined along the original coastline. For turtle nesting the most suitable solution is the (1:1) nourishment with a 10 year frequency as it contains the smallest deposition area and the lowest nourishment frequency. Consequently, it leaves the adjacent coastlines intact, which leads to the smallest deviations in comparison with the reference run. The dune growth potential is the highest for the island alternative with a 10 year frequency, as the intertidal beach width grows over time due to the shallowing of the lagoon. The most suitable nourishment alternative for habitat provision is the offshore island with a 10 year frequency.

Table 4.8: Evaluation framework for the ecosystem service of habitat provision. The colors indicate their relative performance (red = very bad, orange = bad, yellow = average, lime = good, green = very good).

Ecosystem service	**(1:1) alternatives**				**(1:3) alternatives**				**Offshore islands**	
Frequency (year)	1	3	5	10	1	3	5	10	5	10
Habitat Provision										
Nursery area										
Turtle nesting										
Dune growth potential										

In literature, the main advantages of large-scale nourishments are presented as the reduction of maintenance and disruption frequency, and a more natural dispersion of sediment leading to a decrease in ecological stress. Furthermore, they cause a temporal increase in recreational and environmental area without disturbing the adjacent areas during deposition. Combining this information with the results from tables 4.6, 4.7 and 4.8, most of these advantages are visible at Duval County. The large-scale nourishments do reduce the disruption frequency and decrease the ecological stress on the system, but they have not necessarily a more positive effect for recreation. The advantage of a smaller perturbation area and a more natural dispersion of sediment along the coastline are true for the project area. For each ecosystem service, an advice is given on the performance of the different nourishment alternatives. The most suitable nourishment alternative for the project area of Duval County can now be quantitatively assessed based on its desired functions.

4.6. The US east coast

To check whether the results of Duval County can be applied to other coastlines along the Atlantic coast of the US, additional locations have been selected. Each of the considered coastlines can be described as highly erosive, as they are prone to chronic erosion and contain residential and commercial buildings close to the shoreline. The prevailing sediment transport direction is southwards along all locations [Van Gaalen, 2004].

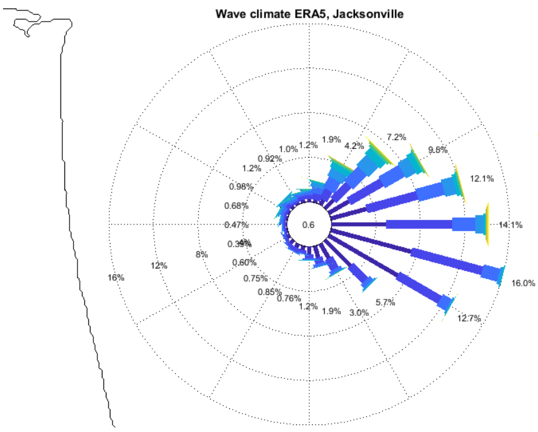
Along the coasts of New Jersey, erosion is an ongoing problem. Large sections of the shoreline are protected with seawalls, leading to extensive erosion downdrift [The H. John Heinz III Center for Science, Economics and the Environment, 2000]. Therefore, the first location is situated at Long Beach Island, New Jersey. Secondly a coastal section in Maryland is considered, Ocean City. At this location, sediment is transported southwards under the influence of currents and winds. Moreover, barrier islands are slowly moving westwards due to sea level rise, which have caused the disappearance of the natural dune system [Maryland Geological Survey, 2019]. The beach at Ocean City is currently part of a beach replenishment project by the USACE.

The third comparison site is located at Topsail Beach in North Carolina. Topsail Beach is vulnerable to erosion due to hurricanes and storms. Moreover, it is known as a family ocean resort community for outdoor recreation, which shows a high amount of residential and commercial properties U.S. Army Corps of Engineers, Wilmington District [2009]. Further south, the coast of Pawley's Island, South Carolina is selected as the shoreline experiences chronic erosion. In Dolan et al. [2015], it is given that Pawley's Island experiences high levels of beach erosion due to sea level rise and climate change. The beach has been restored by beach renourishment projects, but accelerated sea level rise threatens the island. Lastly, Miami Beach in the southeast of Florida is considered. This beach section is classified as critically eroded by the FDEP, like Duval County [Division of Water Resource Management, 2016]. The considered reach is part of a beach restoration project as threatened development and recreational interests are present behind the shoreline.

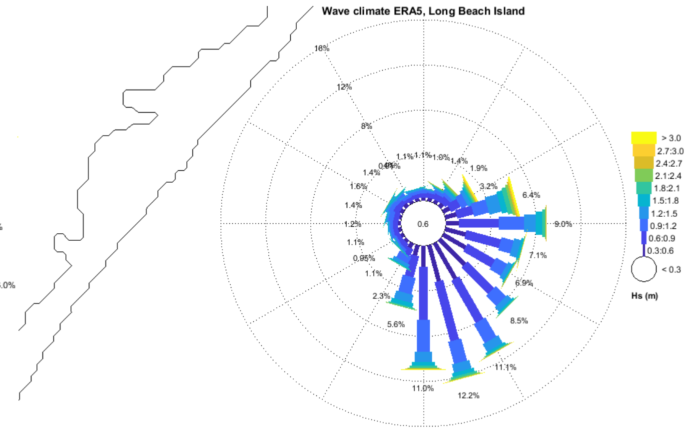
In figure 4.16 the different ERA5 climates of the locations are presented with the full wave climate of Duval County. Furthermore, the orientation of the coastline is given for each location. From this comparison the following observations arise:

- The coastline at Jacksonville has a north to south orientation, while the other locations have an orientation more tilted towards the northeast. Especially Topsail Island experiences a northeast to southeast orientation. However, the governing sediment transport directions remains southward.
- At Jacksonville, Long Beach Island, Ocean City, Pawley's Island and Miami Beach, the highest waves originate from the northeast. These waves have the largest influence on the net sediment transport, and correspond with the prevailing southern transport.
- Due to the difference in shoreline orientation at Topsail Island, the highest waves originate from the south and are rarely higher than 2 meters. Topsail Island experiences sheltering from Cape Lookout, which is located in the northeast of North Carolina. Waves originating from the north and northeast have a limited fetch, resulting in low wave heights.
- All locations experience a relatively calm wave climate, since the majority of the waves have a wave height lower than 1.5 meters.

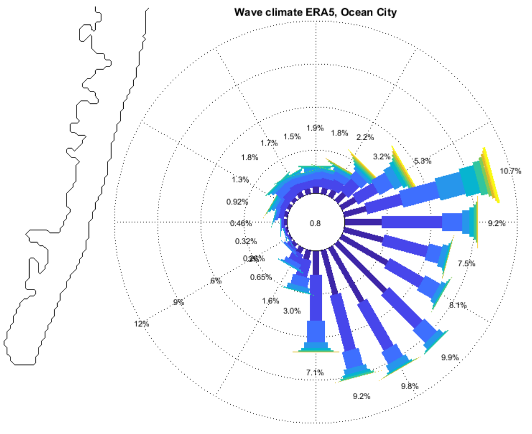
The comparison of the wave climates shows that the conditions at Duval County are largely representative for locations along the Atlantic coast of the US. This suggest that the found results can be applied at these locations as well.



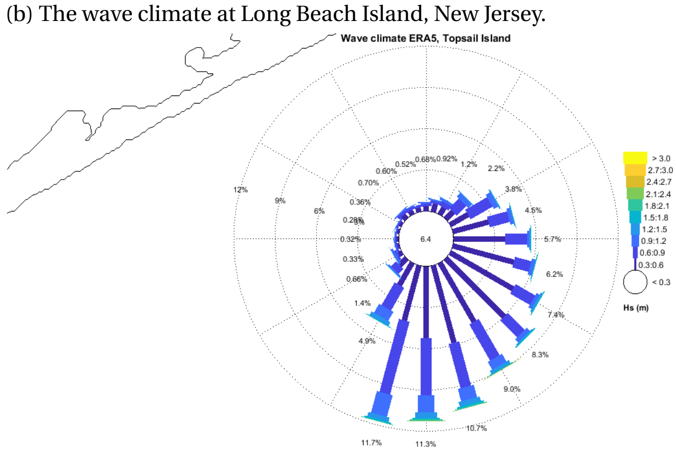
(a) The wave climate at Jacksonville, Florida.



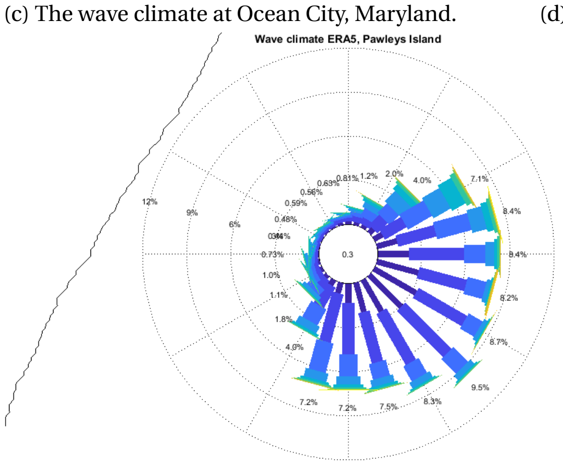
(b) The wave climate at Long Beach Island, New Jersey.



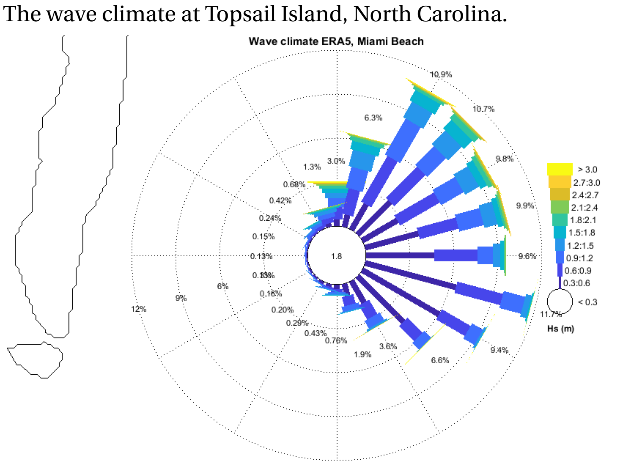
(c) The wave climate at Ocean City, Maryland.



(d) The wave climate at Topsail Island, North Carolina.



(e) The wave climate at Pawley's Island, South Carolina.



(f) The wave climate at Miami Beach, Florida.

Figure 4.16: The wave climates of several locations at the Atlantic coast of the US.

5
Discussion

In the setup of this research, several assumptions and simplifications have been made to capture the complex problem into a concise scope. The reasoning behind the choices will be explained in this chapter, in combination with the limitations that arise from them. Furthermore a reflection is given on the found results in a broader perspective.

5.1. Scope and objective

The objective of this research is to develop and apply an evaluation framework for large-scale nourishments along the Atlantic coast of the US. The research mainly treats the physical aspect of this, while other aspects need to be researched as well before this solution can be implemented in reality. Besides the physical aspect, the practical aspect and the political aspect are of importance.

The physical aspect treats the environmental conditions at Duval County, and whether the system is able to transport the potential nourishment along the adjacent coastlines. In this reasoning, it is assumed that sufficient sediment is available for the deposition of these nourishments. However, it has not been investigated in this study where this sediment should come from, and whether the available sediment is of good quality. A matching grain size between the fill and the native beach is important, especially for the benthic recovery [Wilber et al., 2009]. A good match results in a rapid recovery, while poor matching can result in slow recovery or even in defaunation. Previous nourishments at Duval County have come from borrow areas approximately 11 kilometers east from Atlantic Beach, but no knowledge is available on whether these areas can be used for future renourishments as well. These borrow areas are located within the Duval Ridge Field, extending from St. Johns County north to Nassau County, containing potential sand resources up to 7.5 billion cubic meters [U.S. Army Corps of Engineers, Jacksonville District and Bureau of Ocean Energy Management, Regulation and Enforcement, 2011].

The next aspect that needs to be taken into account is the political aspect of shore protection. The rules and regulations of shore protection projects differ per country, but can also differ per state in the US. These regulations can limit the flexibility of the possible nourishment alternatives both in terms of shape and size. Furthermore, environmental considerations are mainly expressed within political regulations. In this research, the environmental aspect has been treated in the form of applying multiple ecosystem services in the evaluation framework instead of solely looking at the coastal protection. However, specific regulations about the environmental concerns in Duval County have not been investigated in detail. The potential limitations of solutions due to political regulations have not been taken into account as it falls outside the intended scope.

The scope of this project is largely based on applying the concept of the Sand Engine in a different set of environmental conditions. In Oost et al. [2016], several learning points have been identified to address the usability of the concept. If the need for sand in the coastal system is evident and there is a need for a multi-functional design, the concept is a reasonable alternative. From a financial viewpoint, the concept is particularly valuable if the cost of dredging is low and the sediment will contribute to the coast on a long-term basis. In terms of recreational and nature values, the concept is mainly interesting if the present coastline experiences long continuous gradients and lacks sheltered areas. Considering these learning points, it is obvious that a most suitable solution cannot be selected in advance, but it highly depends on the stakeholders involved and their share in the project.

5.2. Indicators and evaluation framework

The method of ecosystem services was selected as the most suitable approach to capture the influence of nourishment alternatives on the system. This approach was selected as it links human behavior to the existing ecosystems. In order to make the ecosystem services quantifiable for engineering purposes, several assumptions have been made.

Ecosystem services generally fall within four categories: provisioning, regulating, cultural and habitat services. In this research an attempt has been made to select quantifiable indicators for the provisioning, regulating and habitat services. The cultural services are mainly linked to non-material contributions of ecosystems to human well-being and cannot be easily quantified [Cooper et al., 2016]. These services include intellectual and spiritual value of ecosystems, which are very subjective. Before these can be incorporated in the evaluation framework that has been used in this report, research needs to be conducted on which aspects of large-scale nourishments contribute to cultural services.

The indicators presented for the ecosystem service of coastal protection are relatively straightforward, as extensive research has been done on the protection services of nourishments. On the other hand, the other two ecosystem services are highly variable. For recreation, the chosen sub-services highly depend on the activities present on the considered coastal section, and therefore influence the usability of large-scale nourishments [Oost et al., 2016]. Habitat provision depends on the environmental conditions of the project area, which cannot always be described in quantifiable parameters.

For Duval County the sub-service of kitesurfing is taken into account, as the coastline is a popular kitesurfing spot [Kiteforum.com, 2018]. In this research, the results for kitesurfing have the same weighting as the other sub-services for recreation. It can be discussed whether this is adequate, as the amount of people engaging in swimming or beach leisure activities at the beach is usually higher. Another approach to scale the different sub-services is to investigate the stakeholder perspective of each target group. If the contribution of kitesurfers to the community is not as important as the other target groups, the evaluation framework can be scaled accordingly.

The presented alternatives have been evaluated on their influence on swimmer safety. In this research, this sub-service has been simplified to considering the magnitude of the offshore directed velocities. Looking solely at this aspect gives insight into the influence of the nourishment alternatives on the surrounding flow velocities. However, this activity is much more complicated. As Radermacher [2018] suggests, other phenomena as rip currents, eddies and tidal flow separation play a role. These aspects have been excluded from this research as they are complex phenomena that cannot be quantified within one or two model parameters. Moreover, the sub-service of swimming is highly affected by the likelihood of people being present in the water. This likelihood is affected by time, the day of the week, the season and other temporal factors [Radermacher, 2018]. Due to input reduction of excluding waves with a wave height smaller than 1 meter, the temporal scale is distorted which means that the temporal factors cannot be taken into account.

The sub-service of turtle nesting is quantified by taking the two primary drivers for suitable nesting area, namely the beach slope and the beach width. In reality, other aspects such as beach compaction, beach moisture content, sand color, escarpment formation and artificial lighting have consequences as well, but have not been taken into account [U.S. Fish and Wildlife Service, 2015]. The morphological development of the different nourishment alternatives was investigated with the numerical model of Delft3D, and this approach does not supply information on these aspects. A conservative approach is used in terms of comparing the resulting beach width and slope to the reference situation. No information is available on whether the current beach slope is ideal for turtle nesting or if the reference situation could be improved as well.

From literature, it becomes evident that the frequency of nourishing is important for turtle nesting. In Rumbold et al. [2001], the nesting activity of the loggerhead sea turtle was recorded in Palm Beach County, Florida.

The campaign involved daily measurements from seasons prior and following a beach renourishment, both on nourished beaches and unaffected beaches. From these results it became evident that nourishment projects decrease the nesting activity and increase the false crawl frequency significantly. This decrease is the most significant in the first season following the nourishment project, but is noticeable in the second season as well. The study conducted by Brock et al. [2009] evaluated nesting success for loggerhead and green turtles in Brevard County, Florida. Reduced nesting success was observed for both species in the first season following renourishment. It is argued that this decrease is primarily a result from the altered beach profile, and improved as the beach returned towards the original slope. These studies confirm the assumption that the nourishment frequency should be as low as possible to benefit sea turtle nesting.

The sub-service of nursery area is quantified by ecotope mapping based on the water depth and hydrodynamic stresses. In Van Zanten [2016], this approach was used as well with ecotopes based on literature on the Dutch coast. In this research the hydrodynamic limits have been adapted to the stresses that appeared in the simulations, as no literature was available on the situation of Duval County. Therefore, validation of the presented ecotopes is necessary on the site-specific conditions.

Two factors that have not been taking into account in the model, but prove to be important for benthic recovery are the nourishing season and the matching grain size distributions between the native and deposited sediment [Wilber et al., 2009]. The fastest recovery will occur if the nourishment is placed outside the peak larval recruitment period, which is the spring season for the east coast of the US. Furthermore, the recovery time is decreased if the nourished sediment is compatible to the native beach.

The evaluation framework in tables 4.6, 4.7 & 4.8, is used to discuss the results for the three ecosystem services individually, based on the evaluated sub-services. The weighting of the different (sub-)services is not necessarily equal, as it highly depends on the stakeholders involved in the project. However, to give an advice on the most suitable nourishment alternative per ecosystem service, it is assumed that all sub-services have a weighting equal to 1. By doing so, the multiple facades of a large-scale feeder nourishment are included. Furthermore, a color scale from red to green is introduced in these tables, to incorporate model sensitivity between the different nourishment alternatives. If the relation between the different stakeholders is known, the most suitable nourishment alternative can be selected accordingly.

5.3. Modeling approach

The decision of using the process-based numerical model of Delft3D to simulate the morphological development of the different nourishment alternatives has a significant effect on the results. Delft3D is suitable for long-term morphological computations in the marine zone, which leads to limitations in the results.

The first limitation that arises from the applied modeling approach is the lack of hurricanes. The Florida coastline is very vulnerable to storms coming of the west-coast of Africa, growing in magnitude as they travel across the Atlantic Ocean [University of North Florida, 2016]. In general, sediment is transported offshore during storms, which are most severe in the winter. The sediment returns to the shoreline again during calm conditions in the spring and summer. However, the summer is also the hurricane season, which means that erosion processes occur in this season as well. This reduces the chance that sediment is able to return to the shore [Jones and Mangun, 2001]. Furthermore, the natural processes along the coastline of Duval County are interfered by the jetties surrounding the St. Johns River, reducing the available sediment during storms.

During 2004 and 2005, six hurricanes hit the coast of Florida causing severe damages to human structures and property interests. Nourishments were undermined by the coastal storms, as they removed a large amount of nourished beach. To counteract the erosion processes, a flurry of nourishment activity arose. Some nourished beaches were able to withstand the impact, while others rapidly disappeared [Ruppert, 2008]. In September 2017, Hurricane Irma made landfall at Marco Island, Southwest Florida. The eye of the hurricane traveled northward over land, and lead to significant beach erosion and coastal damage along the Northeast coast of Florida [Division of Water Resource Management, 2017]. The project side in Duval County experienced moderate beach erosion and beach profile lowering, with an average vertical scarp of 2.5 meters. These reports show that the impact of tropical storms and hurricanes can have significant effect on the applied nourishments. Additionally, climate change will increase the intensity of tropical storms and hurricanes leading to even a higher impact on the coastline [Ruppert, 2008]. As the influence is excluded from this study, the results may overestimate the performance of the applied nourishment volumes.

Secondly, the Delft3D model does not take aeolian processes into account. Especially in the offshore island alternatives this process plays an important role. In these simulations, a lagoon is formed between the original coastline and the island which is partly filled in by sediment transported by waves. In reality, this filling process is expected to be more significant as aeolian processes help to fill in the lagoon by the capturing of sediment [Oost et al., 2016, Van Zanten, 2016]. This will results in a smaller lagoon area over time and even the possible disappearance of the lagoon. This has especially a negative effect on the sub-service of kitesurfing, but the capturing of sediment can also slow down the potential for dune growth as less sediment is transported to the dunes. The latter was observed at the Sand Engine during the first years [Oost et al., 2016].

Another limitation arises from the fact that Delft3D can only perform morphological calculations in the marine zone. The numerical model deposits sediment up to the high water line, which leads to an expansion of the dry beach around the MHW line. The deposited sand is not reworked by the model after initial placement, which can lead to piling up of sediment at the MHW line. This limitation plays a large role by the implementation of the renourishments after the first nourishment cycle is completed. Delft3D spreads the sediment volume of the renourishment uniformly over the selected region and does not fill up the deepest parts first. This means that the renourishment regions need to be placed seaward of the previous nourishment to prevent piling up of sediment above the MHW line. This means that the placement area of the high frequency alternatives is not constant over the simulation period, and can have effect on the results. This influence is limited as much as possible by shifting the calculation levels of the supratidal and intertidal zones accordingly.

The used survey bathymetry for Duval County, provided by the USACE, was the post-construction profile of the 2011 renourishment. This means that both the reference run and the nourishments simulations initially contained the 2011 nourishment. For some indicators, namely the distance between the CCCL and the MCL and the beach width, the effect of the 2011 nourishment has been filtered from the results. For the other indicators, this was not possible and therefore the results have been presented as the deviation from the (initial) reference situation.

In this study the hydrodynamic conditions were applied as time-series from the data recorded between 2011 and 2015, and not as an average climate. Due to the applied input reduction and the morphological acceleration factor, the magnitude and direction of two consecutive conditions can be highly variable. Especially for the sub-services of swimming and nursery area, the applied method leads to problems. The results were taken as snapshots in time, and thus significantly influenced by the local conditions. To eliminate this behavior, the models were rerun with average conditions and averaged on a larger time-scale.

5.4. Selected nourishment alternatives

In this study, three different shapes were investigated for the application of large-scale feeder nourishments. Two attached shapes were applied, varying in the ratio of the cross-shore and alongshore dimensions. Thirdly an offshore island was selected to investigate the influence of a detached nourishment. The selected shapes are primarily based on their geometric adaptability for different frequencies. The hook-shape of the realized Sand Engine was considered but not selected, as reapplying a hook-shape on an annual basis led to modeling problems with the mentioned limitations above.

The hook-shape of the Sand Engine was primarily chosen because of the wish for temporal additional area for recreation and nature. The coastal protection aspect served as a boundary condition for the applied design [Oost et al., 2016]. This shows that the design of a large-scale feeder nourishment is primarily dependent on the wishes of the involved stakeholders. The same reasoning has been applied in this study, as the annual volume was determined beforehand and served as the governing boundary conditions for the nourishment alternatives. However, as the specific wishes of the stakeholders are not known, a best alternative cannot yet be selected.

In the design of the Sand Engine multiple shapes were considered besides the hook-shape, namely a barrier along the shoreline, an attached bell-shape variant and a detached island. In the barrier alternative, the sediment was placed below the waterline, while the other alternatives were emerged. In Bruens [2007], the alternatives are compared which leads to the following conclusions:

- Temporary additional area is only created by emerged alternatives. Alternatives placed close to the shoreline develop a larger additional area with a smaller volume. On the other hand, alternatives where a larger portion is submerged are less erosive and require less maintenance.
- All alternatives decrease the amount of maintenance needed in the long-term. Not streamlined alternatives (hook-shape and bell-shape) cause erosion elsewhere as they protrude into the sea. These alternatives need additional nourishments at these location, decreasing their long-term benefit on maintenance.
- Nourishment alternatives that are spread along a large section of the coastline (barrier alternative) create more benefit for future maintenance than local alternatives.
- The most innovative alternative for nature is a double bell-shape nourishment, as it leads to a gradual expansion of the coastline in a natural fashion. Furthermore, it creates temporal additional area attached to the shoreline with relatively low maintenance.

Comparing the conclusions to the results of this study leads to some interesting observations. The (1:1) and (1:3) alternative can be compared to the bell-shape alternatives, and indeed cause erosion elsewhere on the coastline. In Bruens [2007], it is recommended to solve this problem with additional nourishments, while this research also shows that a smaller nourishment frequency can achieve the same effect. Additional nourishments will lead to higher costs, while a smaller application frequency does not. The (1:3) nourishment alternatives are placed along a longer section of the beach than the other alternatives, leading to a longer nourished section at the end of the simulation time. This is in accordance with the results for Bruens [2007]. In the present study the best alternative for habitat provision is the offshore island alternative as it creates the highest diversity in ecotopes and creates the most potential for dune growth. This is in contrast with the findings of Bruens [2007], as it presented the bell-shape alternative as the most promising for nature. In the end, the hook-shape was selected as the most promising alternative, as it is attached to the shoreline which means that the temporal additional area is easy accessible. Moreover, a lagoon is formed between the hook and the original coastline which adds sheltered areas both for recreation and nature. These positive aspects could be observed separately in this study as well, but none of the investigated alternatives contained all.

In this study, the focus was on a variation in application frequency besides a variation in shape. For the Sand Engine this aspect was not investigated in detail beforehand. In 2016, the Sand Engine was evaluated after the first 5 years [Oost et al., 2016], but no conclusion could be given of the performance compared to small-scale nourishments.

The coast of Duval County is nourished with an inconsistent return period, but on average every 5 years. In this study frequencies of 1, 3, 5, and 10 years were investigated with their corresponding volumes. In figure 5.1, the results of different indicators have been presented against the nourishment frequency.

The upper left plot in figure 5.1 shows the results for the maintenance of the coastline position. The (1:3) nourishment alternatives show a larger region of sedimentation, independent of the applied frequency. In general, the alternatives show that the region of sedimentation grows with a larger nourishment frequency. The only outliers are the 3 year frequencies, but this might be related to the fact that they did not complete a full nourishment cycle at the end of the simulation period. Additionally, it needs to be taken into account that the deposition area for the (1:3) alternatives involves a larger section of the beach, which reduces the region of sedimentation. However, the increase in deposition area of the (1:3) nourishment alternatives compared to the other nourishment shapes is smaller than the difference in sedimentation region. These findings suggest that the placement of sediment within the dynamic wave zone is important for reaching the entire project area.

The second indicator is the region of suitable beach width for the sub-service of beach leisure. In this figure it is evident again that the region for suitable beach width grows with the nourishment frequency, except for the 3 year frequencies. On the other hand, the (1:3) nourishment do not perform the best, but the offshore island alternatives perform best.

For the sub-service of kitesurfing, a different behavior can be observed. For each nourishment alternative, the average additional kitesurfing per year is computed. It can be observed that the offshore island alternatives show a growth in area for a larger nourishment frequency, while the (1:1) and (1:3) nourishment show the opposite. Initially, the average area per year increases, but beyond the 3 year frequency it decreases again. A larger nourishment frequency does not necessarily increase the kitesurfing potential.

In the lower right of figure 5.1, the nourishment frequency is plotted against the average sheltered ecotope area per year. For ecotope 5, the sheltered subtidal, an increase in area can be observed for larger nourishment frequencies for the offshore island alternatives. The (1:1) and (1:3) nourishments show the opposite as the area decreases for nourishment cycles bigger than 3 years. Ecotope 8 considers the sheltered are in the intertidal zone, and shows a different behavior than ecotope 5. For the (1:1) and offshore island alternatives, the average sheltered area grows with a larger nourishment frequency. The (1:3) nourishment alternatives show a decreasing trend. On average, the offshore island alternative provides the most sheltered area per year.

Figure 5.1 indicates that large-scale nourishments can have a positive effect in relation to small-scale nourishments, but that this is highly dependent on the processes that are considered.

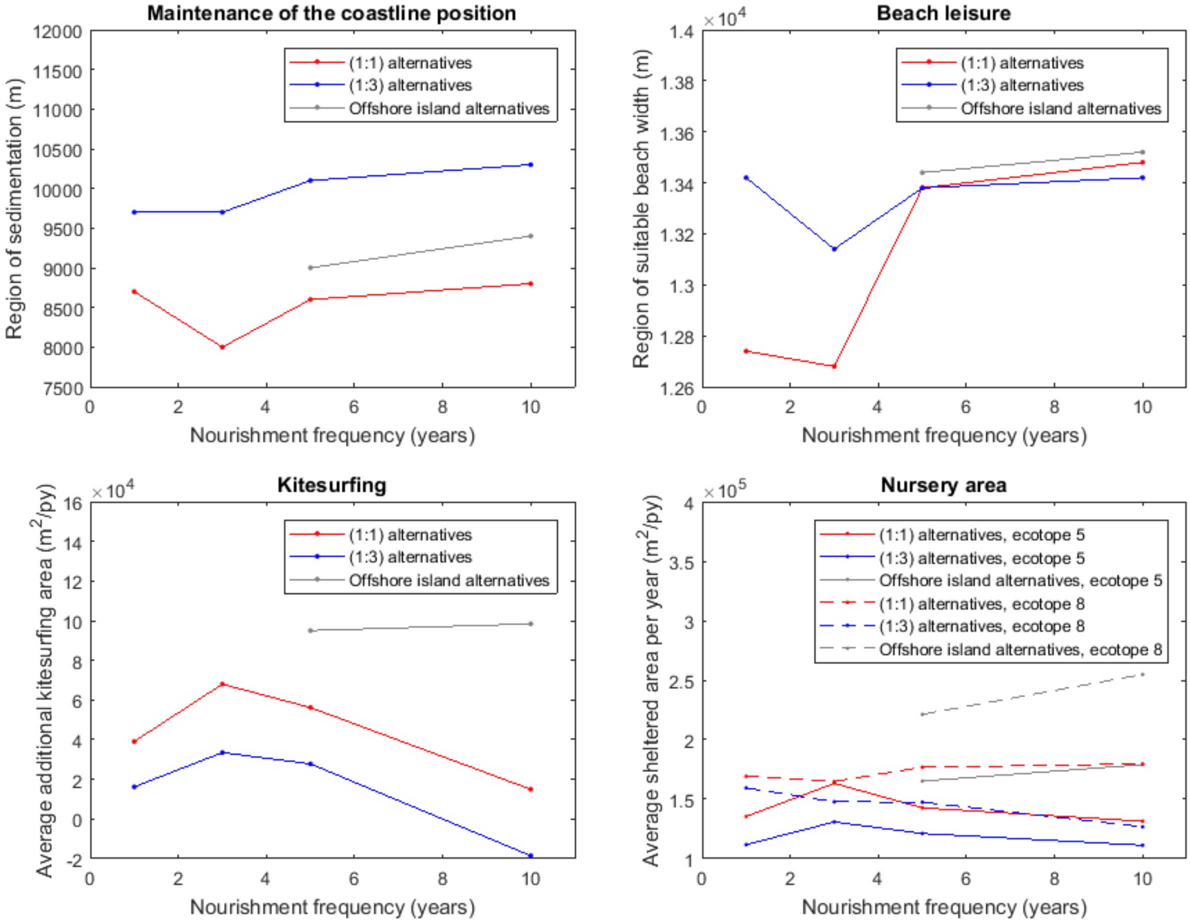


Figure 5.1: The indicators of different sub-services against the nourishment frequency. Upper left: nourishment frequency against the region of sedimentation at the end of the simulation period, upper right: nourishment frequency against the region of suitable beach width at the end of the simulation period, lower left: nourishment frequency against average additional kitesurfing area per year, lower right: nourishment frequency against average sheltered ecotope area per year.

6 Conclusions

This research investigates the application of large-scale nourishments on the coastline of northeast Florida. It has been investigated by applying morphological predictions with Delft3D up to 10 years for different nourishment strategies under representative wave conditions. The influence of extreme events such as hurricanes is not taken into account. The results of these models have been quantitatively evaluated following the approach of ecosystem services. In order to answer the full research question, several sub-questions have been developed. First the sub-questions will be answered before returning to the full research question.

1. Which nourishment concepts have been applied in the US and for Duval County until now?

On US scale, mainly non-feeder beach nourishments have been applied. Additionally, some research was conducted with feeder types, but these only involved small-scale volumes ranging between 60 000 and 200 000 cubic meters.

Locally at Duval County, only non-feeder beach nourishments have been applied. They were applied with a reactive approach, meaning that renourishment was placed once the coastline retreated beyond the reference line. The reactive approach is based upon a design berm construction profile of 18 meters wide at an elevation of +2.6 meter above Mean Sea Level (MSL).

2. What are the environmental conditions and how does this influence the morphological beach evolution?

The environmental conditions at Duval County can be described as an east coast swell climate where influence of large storms is present. The coastline is vulnerable to hurricanes and tropical storms in the summer as well as winter storm events. The dominant wave directions vary from the northeast to the southeast. The most frequent waves come from the southeast, while the highest waves originate from the northeast to the east. The net sediment transport at Duval County is southwards with a average magnitude of 300 000 cubic meters per year.

3. How can the ecosystem services be quantified through time-dependent indicators?

Three main ecosystem services have been defined for the evaluation of large-scale nourishments. First the ecosystem service of coastal protection, which is evaluated in terms of flood protection and maintenance of the coastline position. The time-dependent indicators for these sub-services are the foreshore volume and the distance between the Coastal Construction Control Line and the Momentary Coast Line. They have been computed monthly to gain insight into the spreading of the applied nourishments over time. The second ecosystem service is defined as recreation and involves four sub-services; beach leisure, swimming, kitesurfing and strolling. The indicator for beach leisure is the dry beach width and is computed monthly. Swimming is indicated by the offshore directed flow velocities around the nourishments and is computed for three representative wave conditions. The sub-service of kite-surfing is quantified by the additional sheltered area from waves that the different nourishment alternatives provide averaged for each year. Finally the sub-service of strolling is computed monthly as the walkable beach length along the 0 m MSL depth contour. The last ecosystem service is habitat provision, which considers the ecological impact on the system. It is split into three sub-services, namely nursery area, turtle nesting and dune growth potential. The nursery area has been quantified in the form of ecotope mapping of the bathymetry at the end of each year. The time-dependent indicators for turtle nesting are the beach slope and the beach width, and these are averaged for each month. Finally, the sub-service of dune growth potential is indicated by the intertidal beach width. To exclude the tidal and seasonal variations, the indicator is averaged per year. So, the ecosystem services are quantified by splitting them into multiple sub-services with corresponding parameters to capture the various aspects of the system.

4. How can the nourishment dimensions be optimized depending on the chosen function?

Based on the evaluation of the different ecosystem services, the following conclusions have been drawn for the optimization of the nourishment dimensions:

- Large-scale nourishments primarily have advantage over small-scale nourishments as they reduce the nourishment frequency and the required coastline maintenance. However, this advantage only holds if the sediment is placed within the dynamic wave zone, where the largest sediment transport magnitudes occur, such that it can be spread to the entire project area. On the other hand, large-scale nourishments involve a large initial displacement area, meaning that a large section of the shoreline is disrupted. Moreover, if the nourishment shape contains a deep protrusion into the ocean, downdrift erosion can occur, which was observed in this study. This can be counteracted by additional nourishments at these locations, but reduces the benefit over small-scale nourishments. The application of large-scale nourishments involves a trade-off between applying a low nourishment frequency with a large volume, and being able to place all the sediment within the dynamic zone. In this study, this was achieved by a nourishment with a nourishment frequency of 10 years and a length to width ratio of 1:3.
- Large-scale nourishments are applied in a concentrated location and have a low disruption frequency. These aspects are good for the environment as it reduces the stress on ecology and leaves the adjacent coastlines undisturbed. Furthermore, detached shapes create additional sheltered area between the nourishment and the original shoreline, potentially increasing the ecological diversity. In this study, the increase in sheltered water surface was up to 5 times as large compared to the original situation.
- Under sufficient tidal and wave forcing, large-scale nourishments have the potential to transport the deposited sediment over the entire project area. Small-scale nourishments tend to pile up at the deposition area, therefore decreasing its region of influence. Additionally, large-scale nourishments that are elongated and streamlined along the coast affect a larger region than narrow ones with a large protrusion into the ocean. Here, the region of influence was 10-20% larger for the elongated nourishments.
- As large-scale nourishments have a concentrated deposition area, they cause a gradual dispersion of sediment along the adjacent coastlines, feeding them in a natural fashion. This has a positive influence on the environment and recreation compared to non-feeder nourishments. They involve a limited construction area, leaving the other sections of the beach unaffected.
- Finally an advantage of large-scale nourishments is that they provide temporary additional space for recreation and habitat provision. Attached shapes provide the largest accessible beach area, primarily beneficial for recreation. Detached shapes create additional sheltered area, which is positive for ecological diversity and recreation on the water surface. The temporary area disappears over time as the sediment gets transported to adjacent locations, thus limiting the additional value.

The different ecosystem services have a different optimum in terms of size and shape of the most suitable nourishment. For coastal protection the most suitable nourishment alternative is an attached nourishment situated within the dynamic zone. This causes the most gradual spreading of sediment and has the largest region of influence. In terms of recreation, the optimal dimensions depend highly on the recreational activities that occur along the shoreline. The selected sub-services for Duval County do not necessarily perform better for large-scale nourishment compared with small-scale ones. For habitat provision the frequency of disruption is of high importance, and thus large-scale nourishments perform very well. Furthermore a detached nourishment provides a sheltered area by creating a sheltered lagoon thus improving the ecological conditions. A most promising alternative for Duval County can now be quantitatively assessed for its desired functions using the developed ecosystem services framework.

The full research question of this thesis was:

> "How can a large-scale feeder nourishment be beneficial for highly erosive coastlines along the Atlantic coast of the US, and how can the effects of such nourishments be quantified on different timescales?"

Coming back to this question, large-scale nourishments can certainly be beneficial for highly erosive coastlines. This research shows that the advantages vary over time and largely depend on the functions the nourished coastline needs to fulfill. The investigated locations along the Atlantic coast of the US experience a similar wave climate, as the highest waves primarily originate from the northeast and the majority have a wave height lower than 1.5 meters. This suggest that the found results can be applied at these locations as well. In terms of coastal protection, large-scale nourishments definitely have a positive impact as they are able to spread the sediment over the entire project area, and reduce the required maintenance. For recreation this is questionable as it largely depends on the recreational activities that occur at the beach, which can vary highly across the coastline. The ecosystem-service of habitat provision is positively affected by large-scale nourishments as the frequency of disruption is reduced, which potentially provides more stable environmental conditions at the shoreline.

7
Recommendations

This research has explored the applicability of large-scale nourishments by morphological predictions up to 10 years with different nourishment strategies. During this research several simplifications have been made which can lead to recommendations for future research. The recommendations can be split into the recommendations for the application of large-scale nourishments at Duval County, related to the modeling approach, and the optimization of the nourishment dimensions.

7.1. Scope and objective

As explained previously, this research only treats the physical aspect of the application of large-scale nourishment. It is recommended to investigate other aspects as well before implementation is possible. For the practical aspect, it is unknown whether previously used borrow areas can supply enough sediment to construct nourishments up to 3 000 000 million cubic meters. Additionally, a matching grain size distribution between the fill and the native beach is important for ecological recovery. It has been proven that a good match in grain size distribution speeds up the ecological recovery of the system [Wilber et al., 2009], and therefore it is recommended to investigate this for Duval County.

The rules and regulations of the environmental protection can differ per state, which means that the situation in Florida needs to be investigated. Before implementation of this solution at the coast of Duval County is possible, the affected stakeholders should be involved. One of the learning points of the pilot project of the Sand Engine was that incorporating the different stakeholders from the beginning led to a multi-functional design which had benefits on various aspects beside coastal protection alone. It is therefore recommended to apply the same strategy for Duval County to optimize the benefits in applying a large-scale feeder nourishment.

7.2. Modeling approach

On a sandy shoreline, both marine and aeolian processes are of importance. The choice for the numerical model of Delft3D has limited the results as it is not able to take aeolian processes into account and does not predict sediment deposition around the MHW line accurately. Coupling of the presented Delft3D model to XBeach and Aeolis could solve these problems as they include the transport mechanisms above the marine zone as well. Furthermore, this study excludes the effects due to extreme events such as hurricanes, while they prove to be important along the coast of Duval County. Coupling to XBeach gives the opportunity to incorporate the effects of storms more accurately as this model is frequently used for the computation of morphological beach changes under extreme conditions. However, first the impact of hurricanes and large storms on the sediment transport at Duval County should be investigated, as this relation is unknown for now. Furthermore the likelihood of a hurricane affecting the coast of Duval County should be known for the optimization of the nourishment frequency.

The bathymetry surveys provided by the USACE contained post-construction profiles for the 2011 renourishment and the following three years. Furthermore it was given that the next renourishment took place in 2016, which means that none of the surveys could be used as a reference bathymetry. In order to make a fair comparison between the reference run and the nourishment simulations, a survey bathymetry without any nourishment is needed. It is recommended that a similar study should be carried out with such a reference bathymetry.

In this research the placement area for the nourishments was based on the transport magnitudes along the coastline. These magnitudes were computed for the reference situation, but extensive research into the transport magnitudes that occur along the coastline could improve the location of the nourishments. Furthermore it should be researched whether a secondary placement area could benefit the coastline as well. This does not necessarily increase the affected coastal area, but increases the chance of all sediment being placed within the dynamic zone.

In order to decrease the recovery time for ecology, a matching grain size distribution is important. If the grain sizes of the possible borrowing pits are known, the influence of this parameter on the behavior of the large-scale feeder nourishments can be investigated. This aspect is not included in this study, and is therefore recommended for future studies.

7.3. Selected nourishment alternatives

In this study, three geometric designs were investigated on the coast of Duval County. Based on the analysis of these nourishment strategies, the following recommendations are given on the optimization of the nourishments:

- The sediment of the applied nourishment should be concentrated within the dynamic wave zone to benefit the largest section of the coastline.
- The nourishment should contain gradual sloping edges towards the original coastline to maintain the same beach characteristics. This is especially important for turtle nesting.
- To minimize the negative effects on ecology, the nourishments should be applied with the lowest possible frequency, while limiting the construction area to maintain the adjacent coastlines.
- Large-scale feeder nourishments can include a large protrusion into the ocean, which can cause downdrift erosion. This can be counteracted by preventive foreshore nourishments, but lead to additional nourishing. Therefore, it is recommended to create a streamlined design with respect to the original shoreline.
- Detached nourishments cause the formation of a lagoon between the nourishment and the original shoreline, which can develop an expanding tidal channel parallel to the coast. This can have a negative effect on the adjacent beaches as it influences the existing currents. To prevent this, it is not recommended to construct extensive lagoons on coastlines without groins.

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Glossary

CCCL	Coastal Construction Control Line
CRM	Coastal Relief Model
CSSZ	Cross Shore Swash Zone placement
CZMA	Coastal Zone Management Act
DOC	Depth of Closure
FDEP	Florida Department of Environmental Protection
MCL	Momentary Coast Line
MHHW	Mean Higher High Water
MHW	Mean High Water
MHWN	Mean High Water Neap
MHWS	Mean High Water Spring
MLLW	Mean Lower Low Water
MLW	Mean Low Water
MSL	Mean Sea Level
NFIP	National Flood Insurance Program
NOAA	National Oceanic and Atmospheric Administration
USACE	U.S. Army Corps of Engineers

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A

Profile surveys

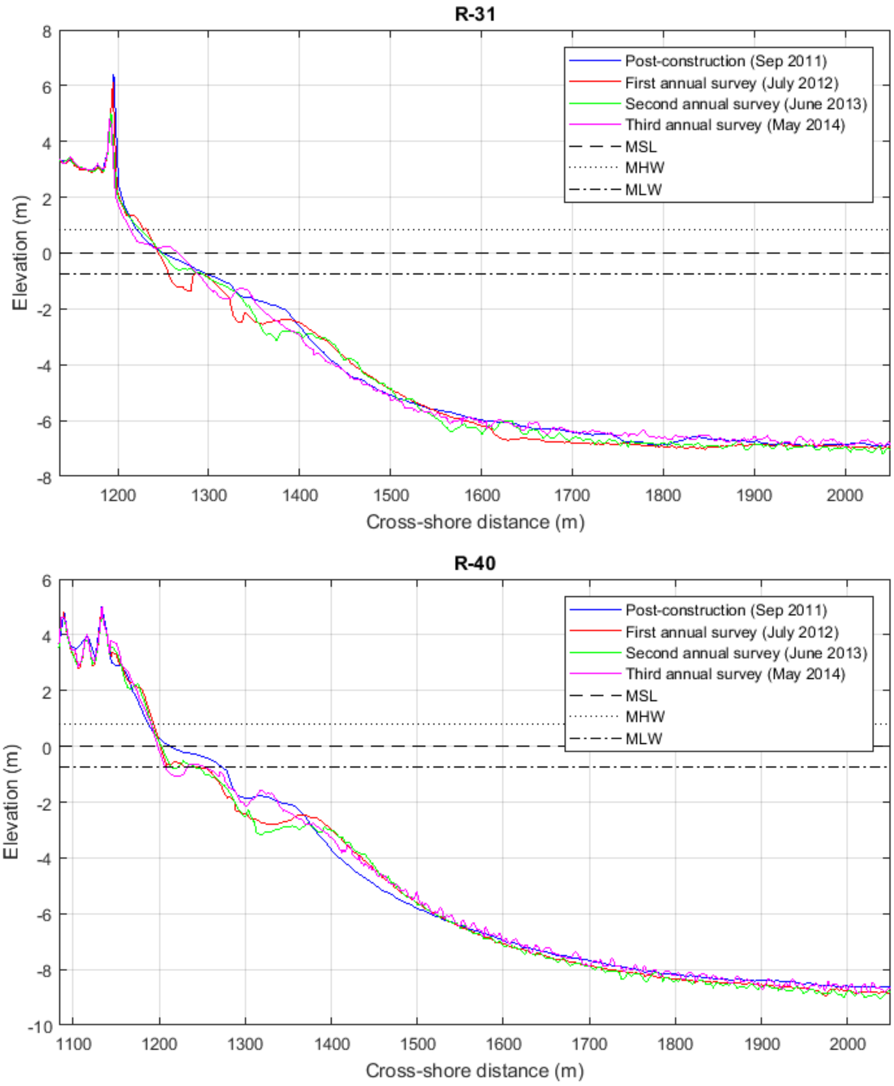


Figure A.1: Transects along Duval County, presenting the post-construction survey of the 2011 nourishment and the first three annual surveys.

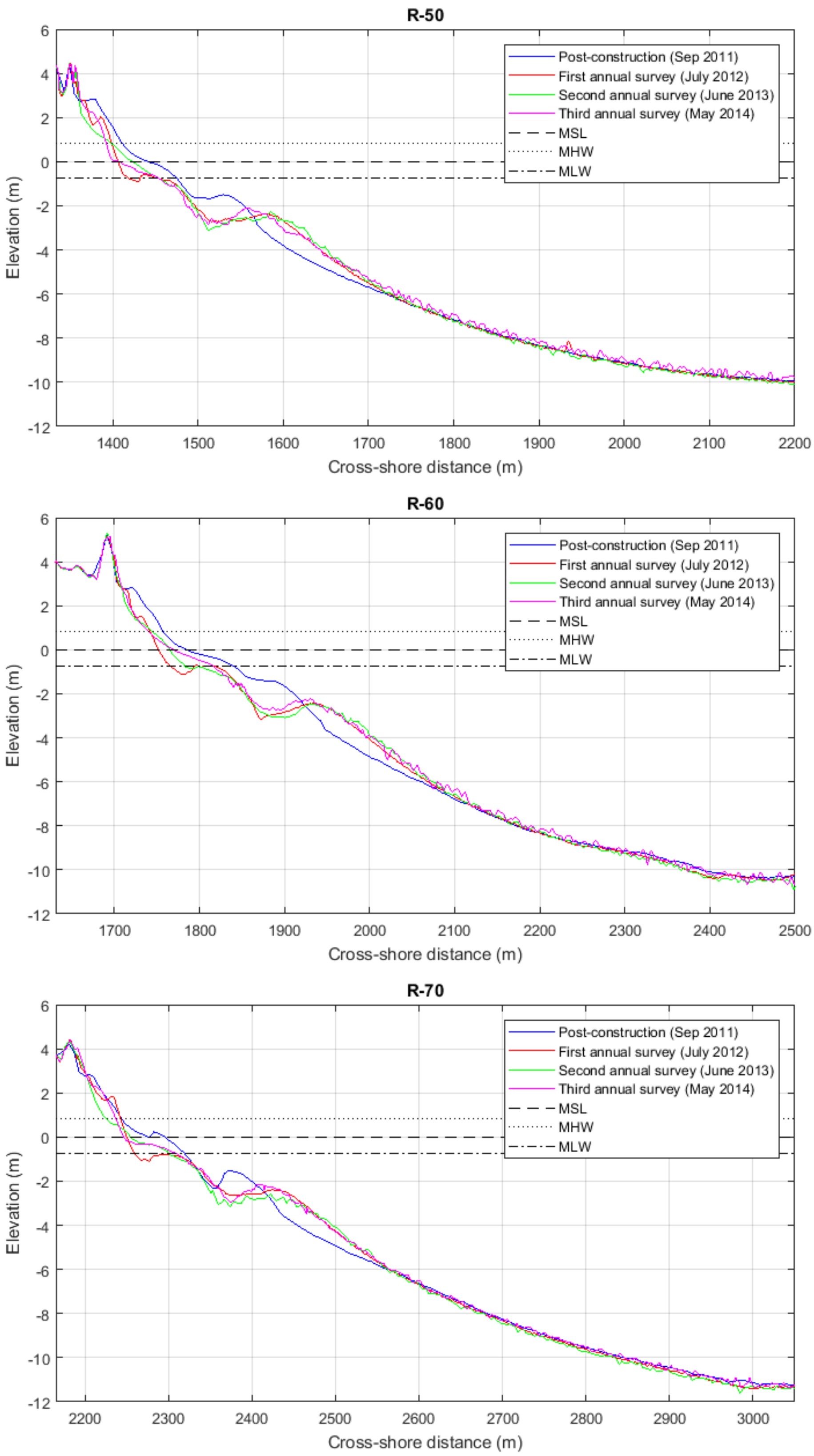


Figure A.1: Transects along Duval County, presenting the post-construction survey of the 2011 nourishment and the first three annual surveys.

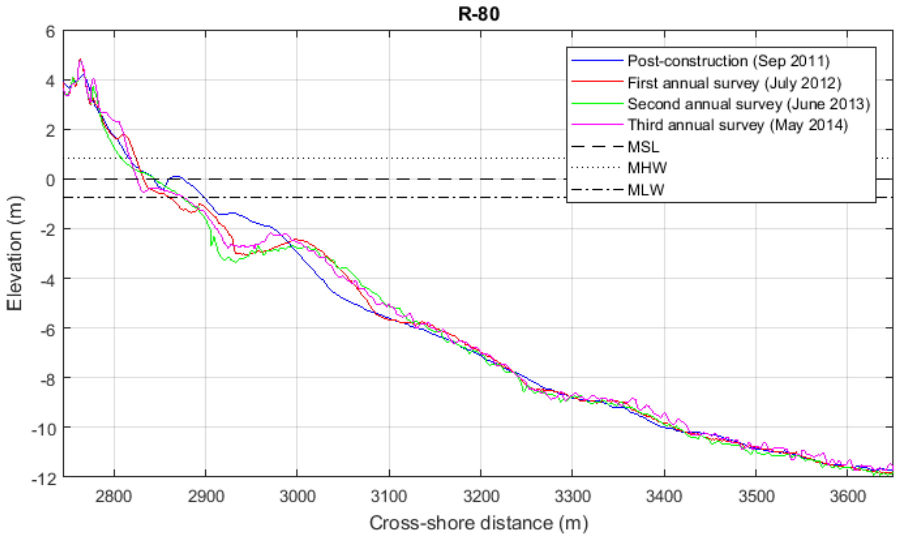


Figure A.1: Transects along Duval County, presenting the post-construction survey of the 2011 nourishment and the first three annual surveys.

B

Ecotopes

The classification of the ecotopes is based on the work of Van Zanten [2016], but has been adjusted for the Florida coastline. This coastline is described as highly erosive and has varying hydrodynamics. The occurrence of currents and wave impact influence the hydrodynamics at the bed. In Delft3D this is determined by the magnitude of the bed shear stress in the considered area.

The subtidal zone

The subtidal zone lies below the MLW line and is continuously submerged. Around −10.40 m MSL the depth of closure (DOC) is located. Landward of the closure depth, the bed is very dynamic, while seaward there is only minimal variability in bed level. In the subtidal zone birds, microphytobenthos, fishes and marine zoobenthos can be found [Speybroek et al., 2006]. Ecological knowledge of this zone is limited, as the subtidal zone is very dynamic and therefore difficult to reach with measuring equipment. It is divided into five ecotopes based on the level of hydrodynamics.

Ecotope 1: Surfzone

In the surfzone the hydrodynamic conditions are energetic due to breaking waves which cause very high bed shear stresses. Furthermore the surf zone is characterized by a low species diversity. The surfzone reaches from the MHW line to the water depth of two times the maximum wave height. At Duval County the maximum wave height is approximately 3.75 meter, thus the surfzone ranges from +0.820 m MSL to −7.50 m MSL. However, due to the division into the subtidal, the intertidal and the supratidal zone, only the depth range below MLW is considered.

Ecotope 2: Seaward side of the surf zone

The seaward side of the surf zone is characterized by still very significant bed shear stresses but relatively lower than inside the surf zone. The seaward side of the surf zone reaches from the −7.50 meter depth contour to the DOC, which is located at −10.40 m MSL.

Ecotope 3: Shoreface (outside surfzone)

The water depth increases when moving further away from the surf zone, and causes a decrease in bed shear stresses. As the conditions are milder than for ecotope 2, it is expected that the species diversity will increase. This zone is characterized by depths ranging from −10.40 meter to depths of −12.0 meter.

Ecotope 4: Inner shelf (outside surfzone)

The ecotope of the subtidal zone that is the furthest away from the shoreline is ecotope 4. It is characterized by large water depths and low bed shear stresses. This ecotope occurs below the −12.0 meter depth contour.

Ecotope 5: Sheltered surfzone

The last defined ecotope is the sheltered surfzone zone. In this zone extremely low bed shear stresses occur, leading to an increase of species diversity compared to the highly dynamic ecotopes mentioned before. Due to the sheltered conditions, this ecotope is an important nursery area for different types of species.

The intertidal zone

The intertidal zone lies between the MLW and MHW line and emerges and inundates during each tidal cycle, causing it to be highly dynamic. This zone is characterized by the presence of avifauna, microphytobenthos, marine zoobenthos and some fish species [Speybroek et al., 2006]. The most influencial abiotic factors in this zone are substrate sediment characteristics, morphology and beach type, which can all be influenced by the application of nourishments. The intertidal zone is divided into two zones based on the occurring bed shear stresses, the exposed intertidal zone and the sheltered intertidal zone. The exposed intertidal zone is again divided into two ecotopes to make a distinction between the wave impact and inundation duration that occurs in these ecotopes.

Ecotope 6: Exposed lower intertidal

The first ecotope is the exposed lower intertidal zone that ranges from the MLW to the MSL. The inundation duration is higher and the wave impact lower than for the exposed upper intertidal zone. This causes the sediment to be well-sorted along the MLW line, and have a relatively large median grain size. This is favorable for interstitial organisms as the substrate is more easily penetrable. The species number abundance and biomass is lower at the MLW line than at MSL, but still higher than at the MHW line.

Ecotope 7: Exposed upper intertidal

The exposed upper intertidal zone lies between MSL and the MHW line. At the upper boundary of this zone, the median grain size is relatively smaller and the water content lower than in the lower intertidal zone. Furthermore the sediment is more poorly sorted and less penetrable. Interstitial organisms experience more difficulty with burrowing themselves in the soil bottom in this area, and thus the abundance and biomass of species is relatively low. This ecotope is characterized by terrestrial species and drift line fauna.

Ecotope 8: Sheltered intertidal

The last intertidal ecotope is situated between the MLW and MHW line, but experiences low bed shear stresses. It can have an important nursery function for fish and crustaceans due to the low hydrodynamic conditions. The potential highest number of juvenile benthos is found near the middle of this zone, around MSL. In this ecotope the biomass and diversity of species can be large, due to the difference in wave impact and inundation duration.

The supratidal zone

The supratidal zone is defined as the area that lies above the MHW line up to the top of the dunes. The most seaward part of this zone is characterized by the wrack line, which is located between Mean High Water Spring (MHWS) and Mean High Water Neap (MHWN), and is the boundary between the intertidal zone and the supratidal zone. At the wrack line, wrack material is deposited which is an important source of organic material. The supratidal zone is characterized by the presence of avifauna, vascular plants, terrestrial arthropods, and zoobenthos and microphytobenthos at the wrack line [Speybroek et al., 2006]. As Delft3D is not able to compute hydrodynamic stresses in this zone, it is represented by a single ecotope.

Ecotope 9: Supratidal zone

This ecotope considers the entire supratidal zone, and inhabits all air-breathing terrestrial species. This includes both flora and fauna, as both are important for the ecological system.

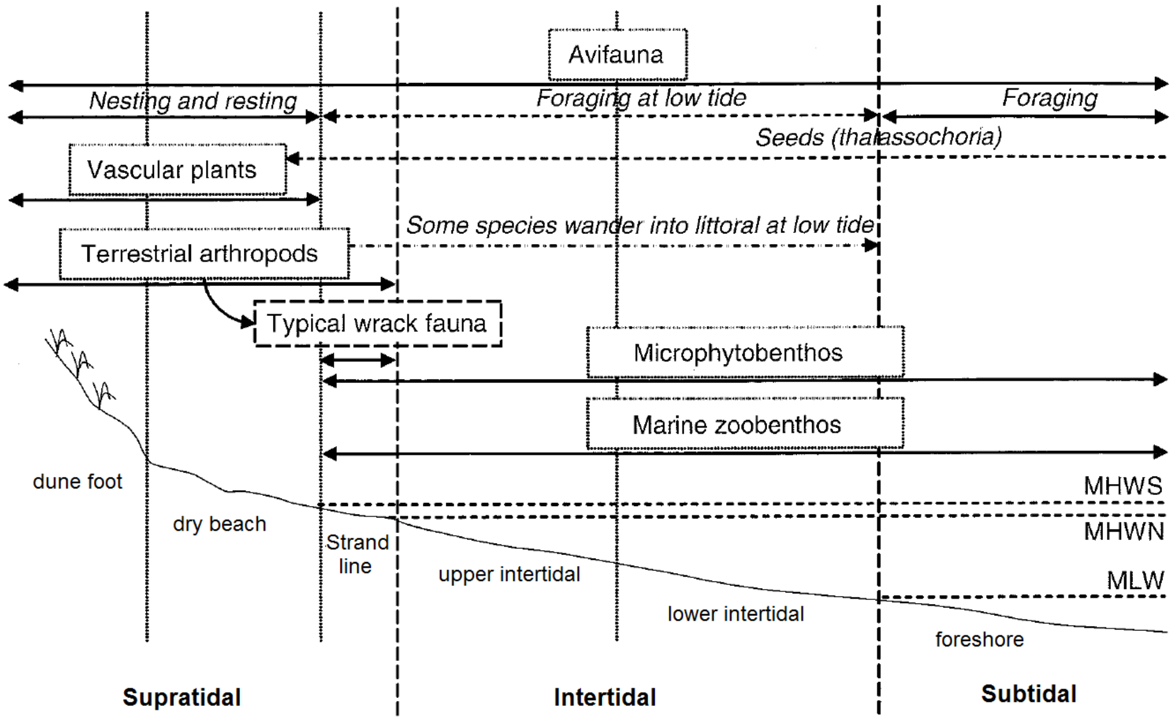
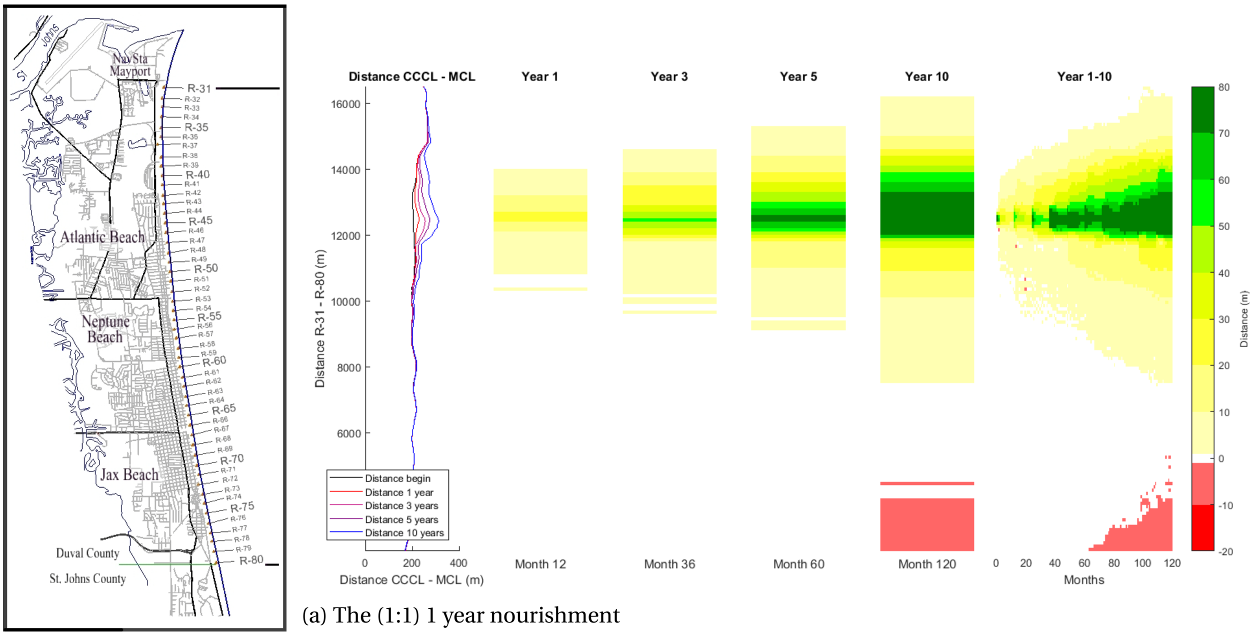


Figure B.1: A schematic overview of the sandy beach ecosystem, adjusted from Speybroek et al. [2006].

C

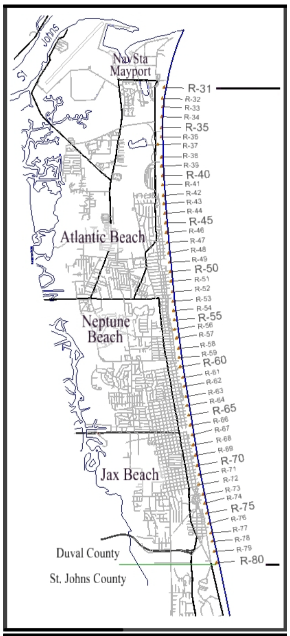
Maintenance of the coastline position

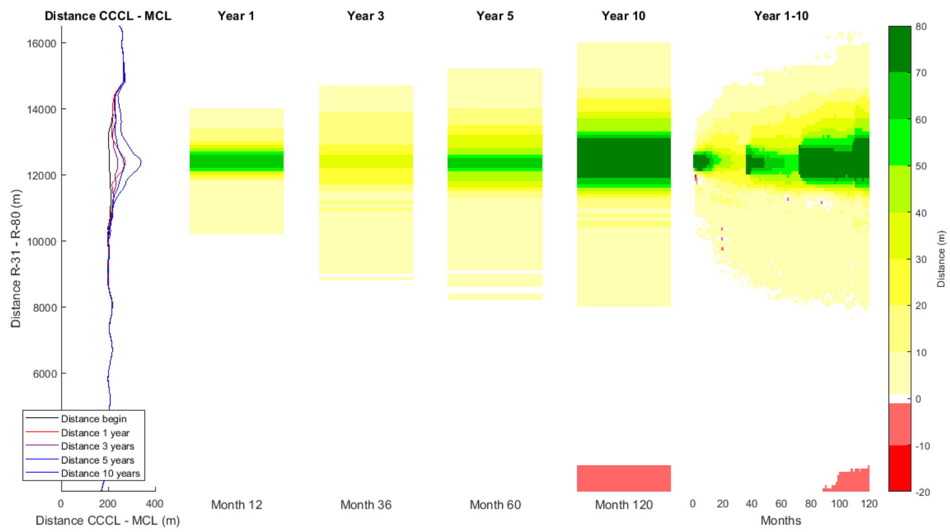
In this appendix the distance between the CCCL and MCL is shown after 1, 3, 5 and 10 years in absolute values and in color scheme. Furthermore the timestack plots are shown as well.



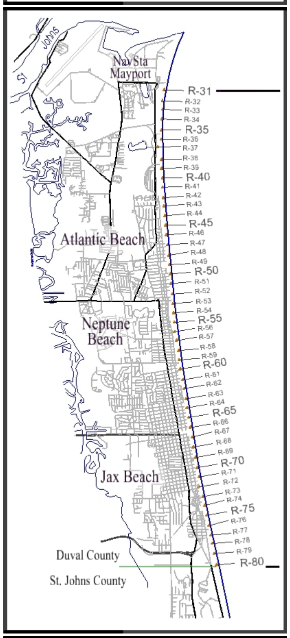
(a) The (1:1) 1 year nourishment

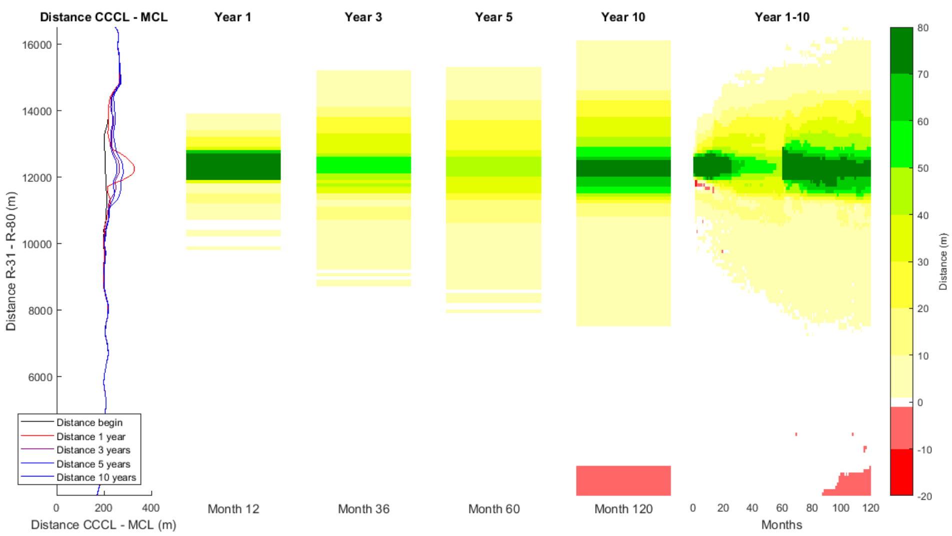
Figure C.1: The distance between the CCCL and the MCL for 1, 3, 5 and 10 years, and the timestacking plot for the different nourishment alternatives.



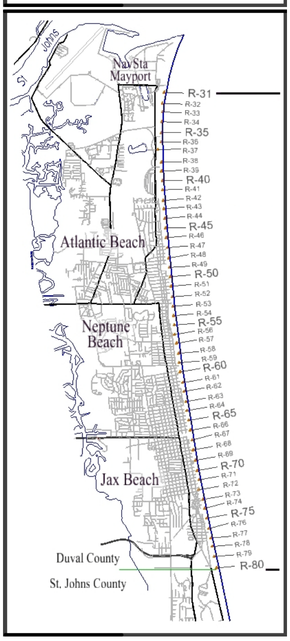


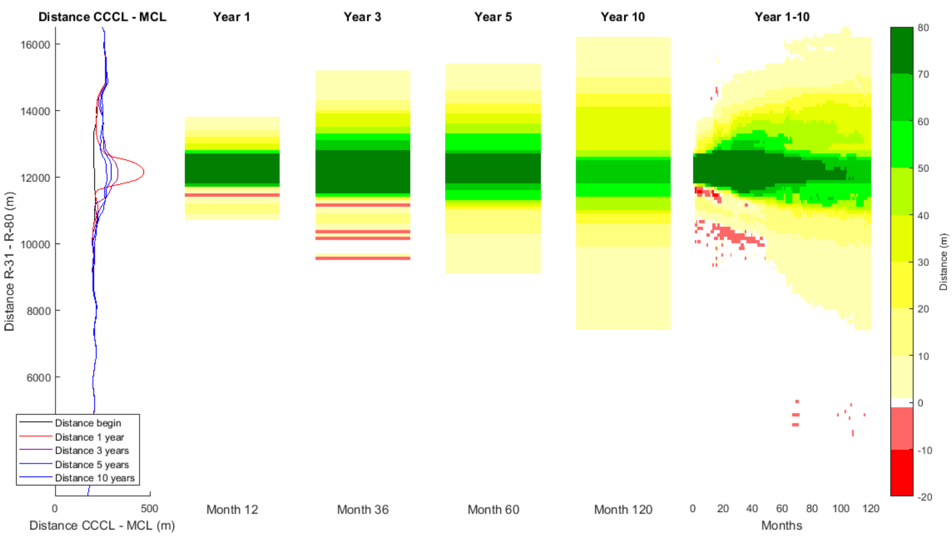
(b) The (1:1) 3 year nourishment





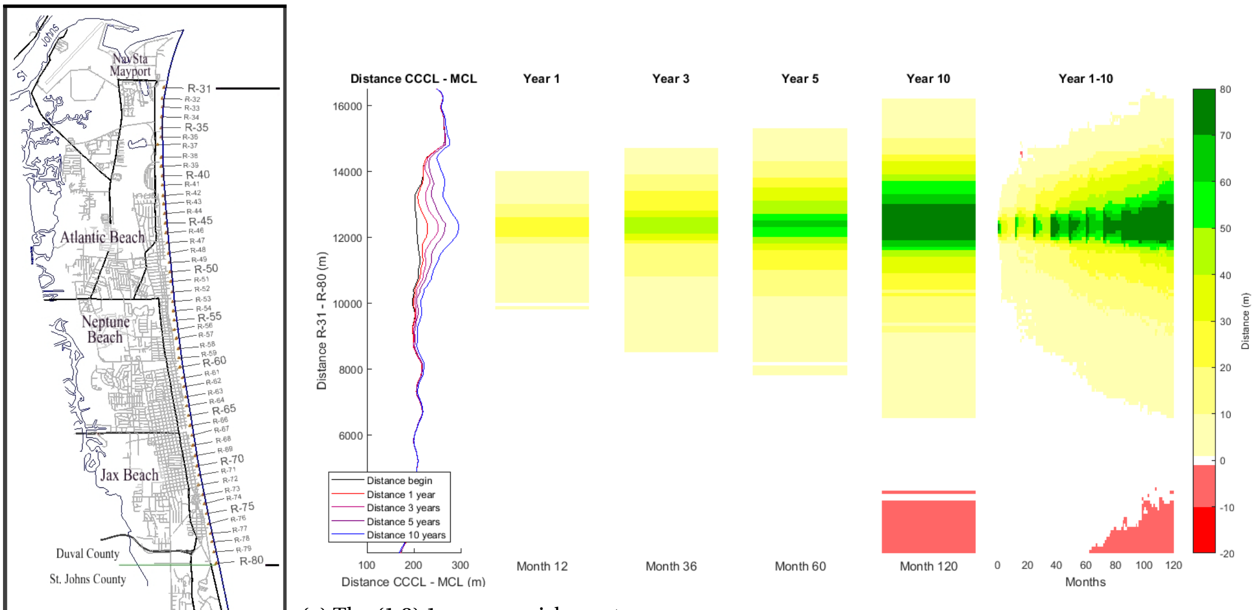
(c) The (1:1) 5 year nourishment



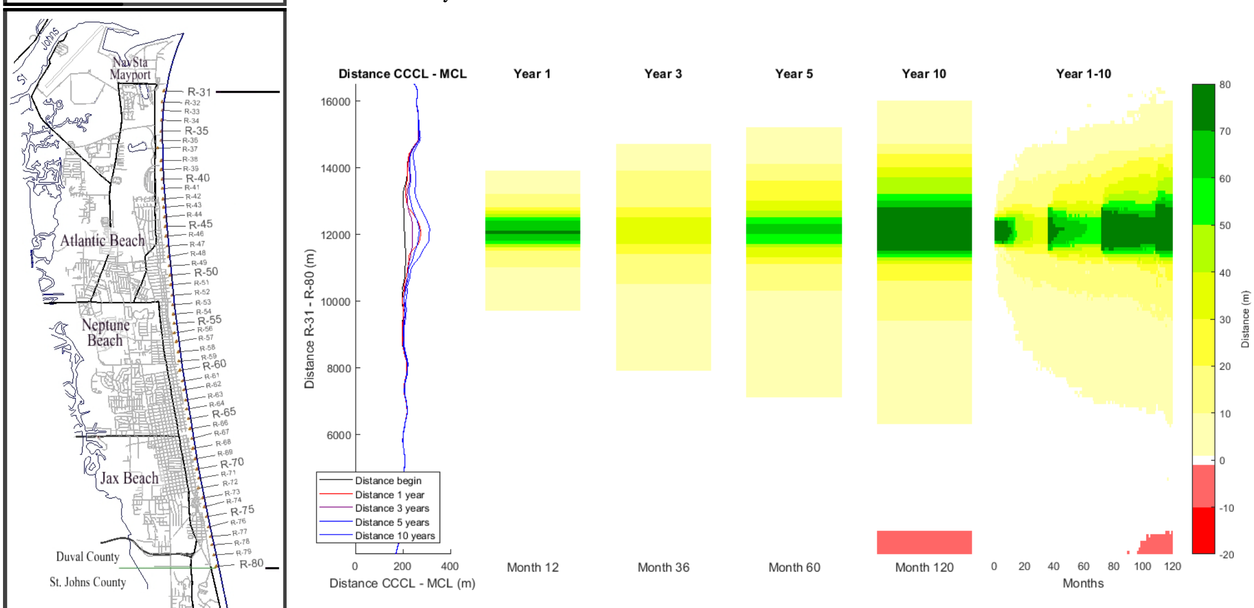


(d) The (1:1) 10 year nourishment

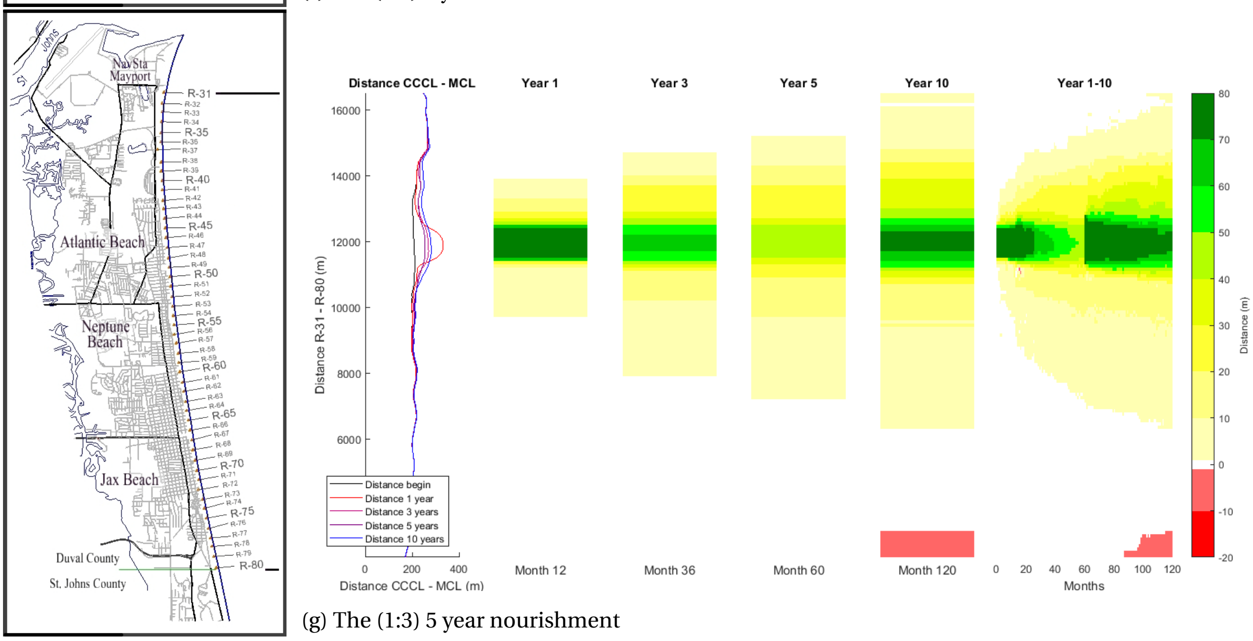
Figure C.1: The distance between the CCCL and the MCL for 1, 3, 5 and 10 years, and the timestacking plot for the different nourishment alternatives.



(e) The (1:3) 1 year nourishment

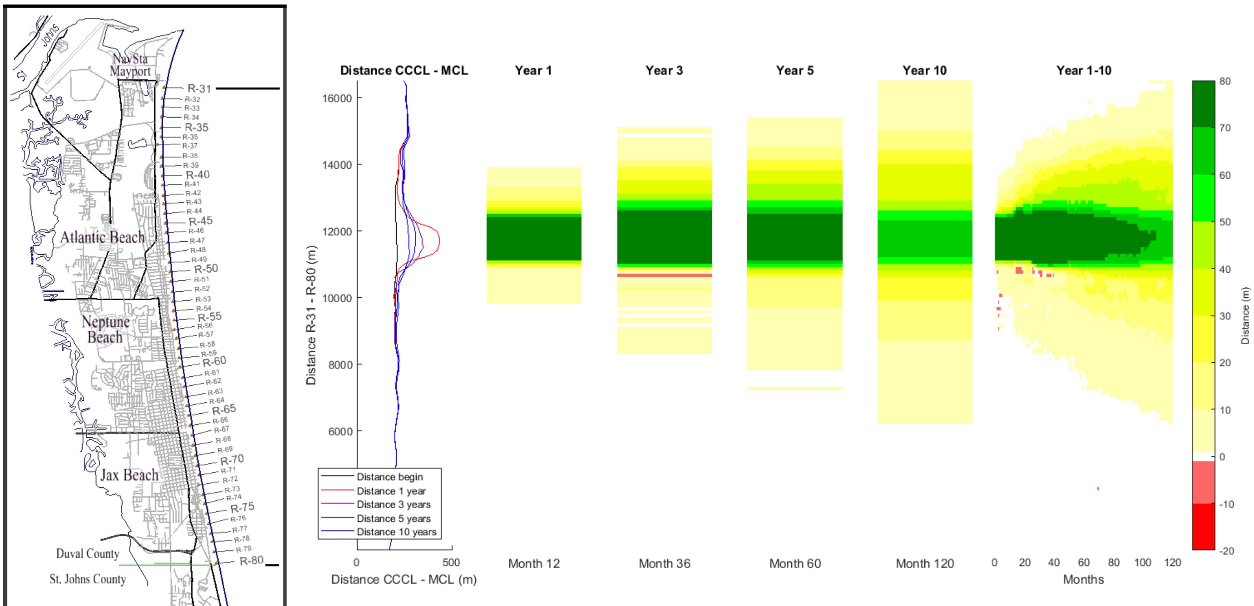


(f) The (1:3) 3 year nourishment

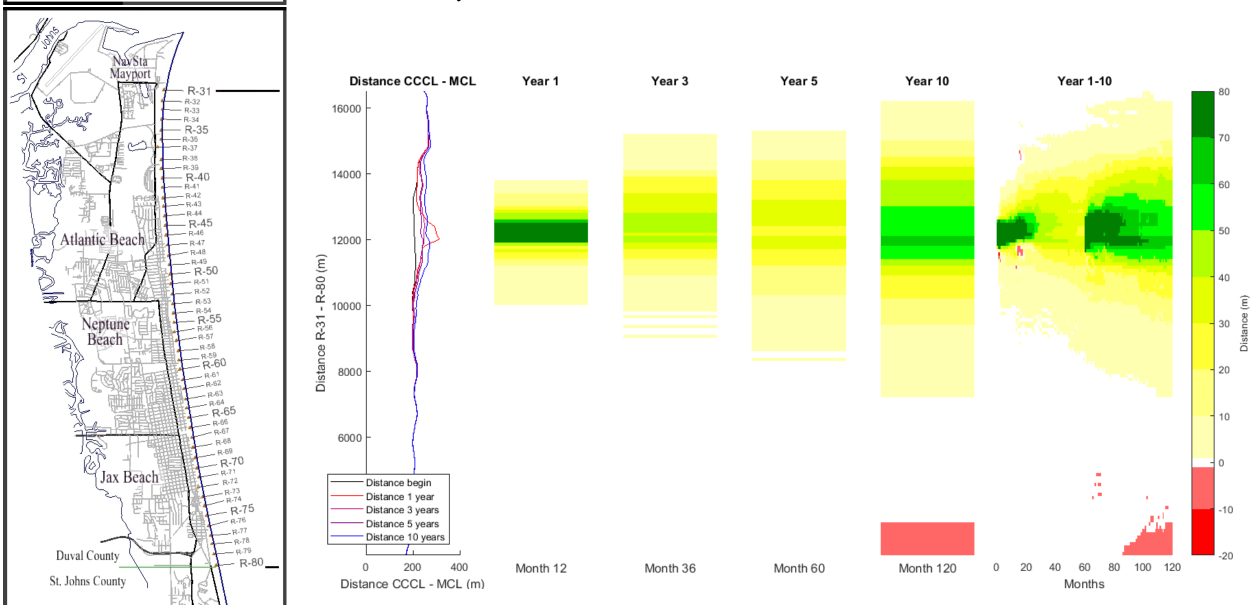


(g) The (1:3) 5 year nourishment

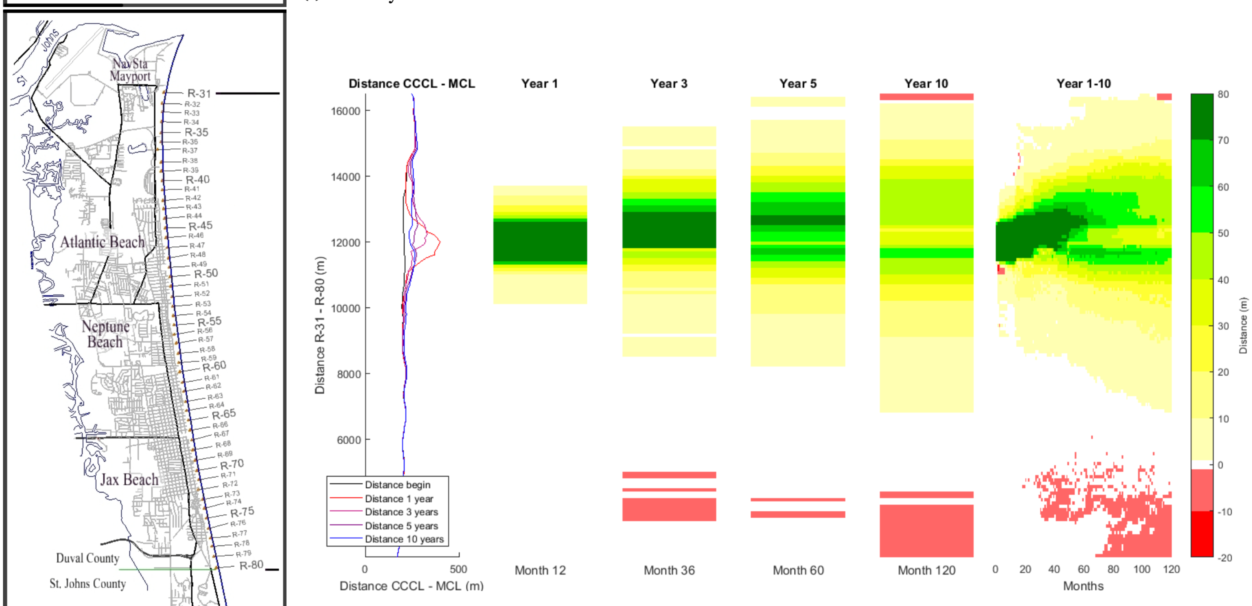
Figure C.1: The distance between the CCCL and the MCL for 1, 3, 5 and 10 years, and the timestacking plot for the different nourishment alternatives.



(h) The (1:3) 10 year nourishment



(i) The 5 year offshore island nourishment



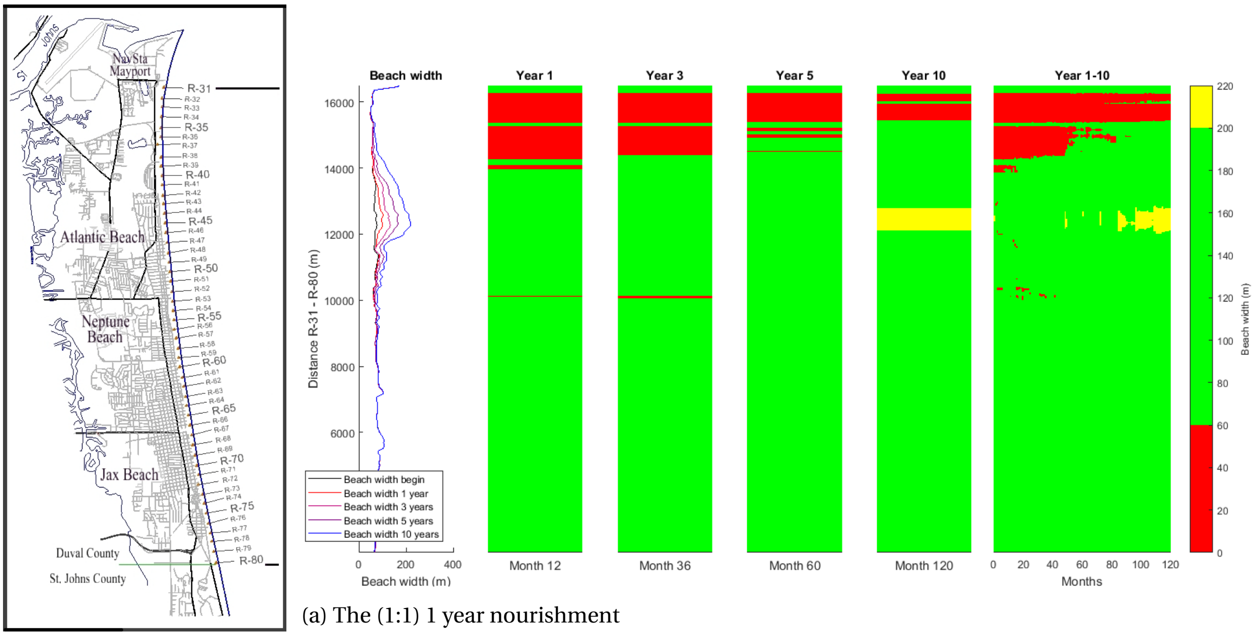
(j) The 10 year offshore island nourishment

Figure C.1: The distance between the CCCL and the MCL for 1, 3, 5 and 10 years, and the timestacking plot for the different nourishment alternatives.

D

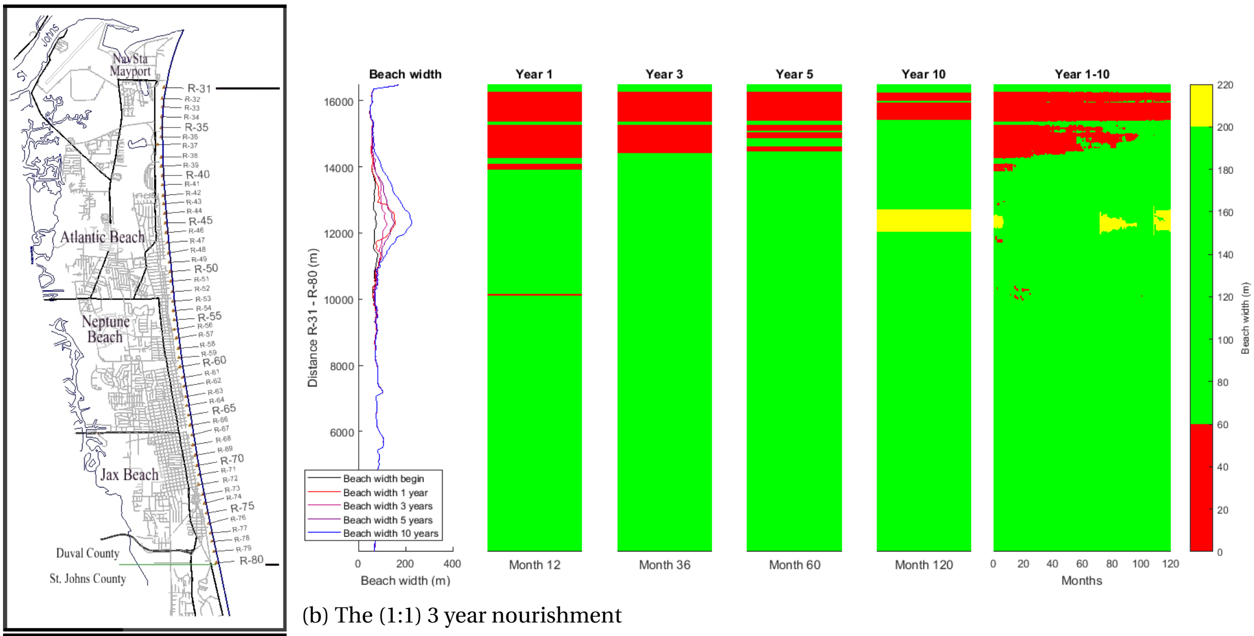
Beach leisure

In this appendix the beach width is shown after 1, 3, 5 and 10 years in absolute values and in color scheme. Furthermore the timestack plots are shown as well.

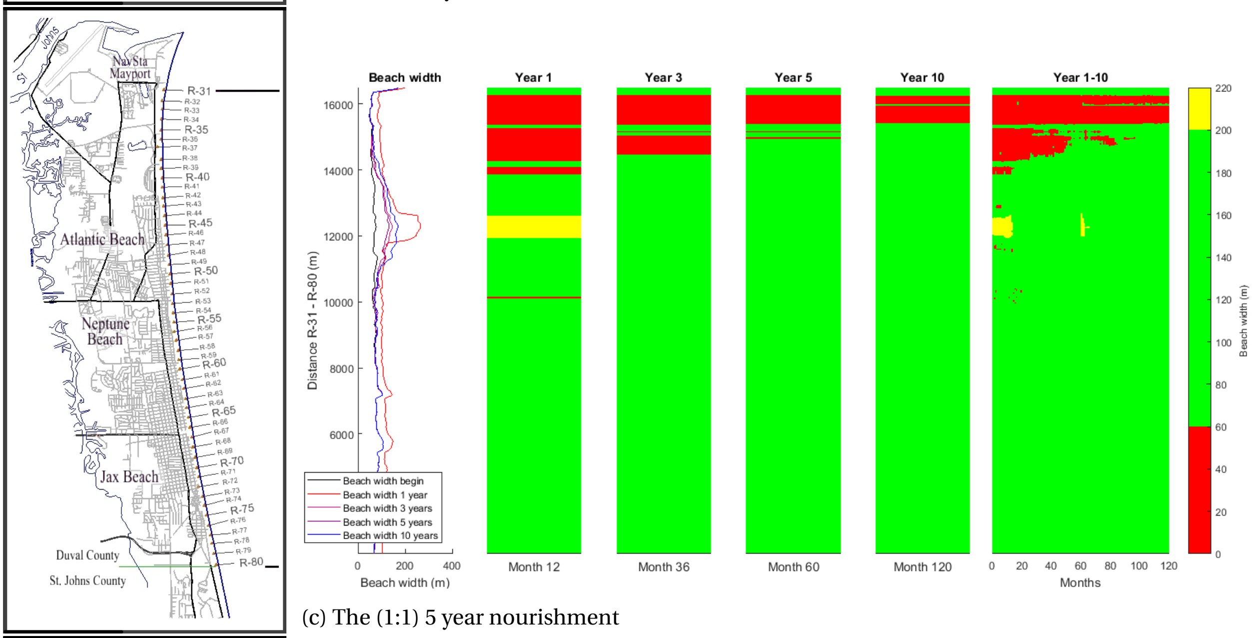


(a) The (1:1) 1 year nourishment

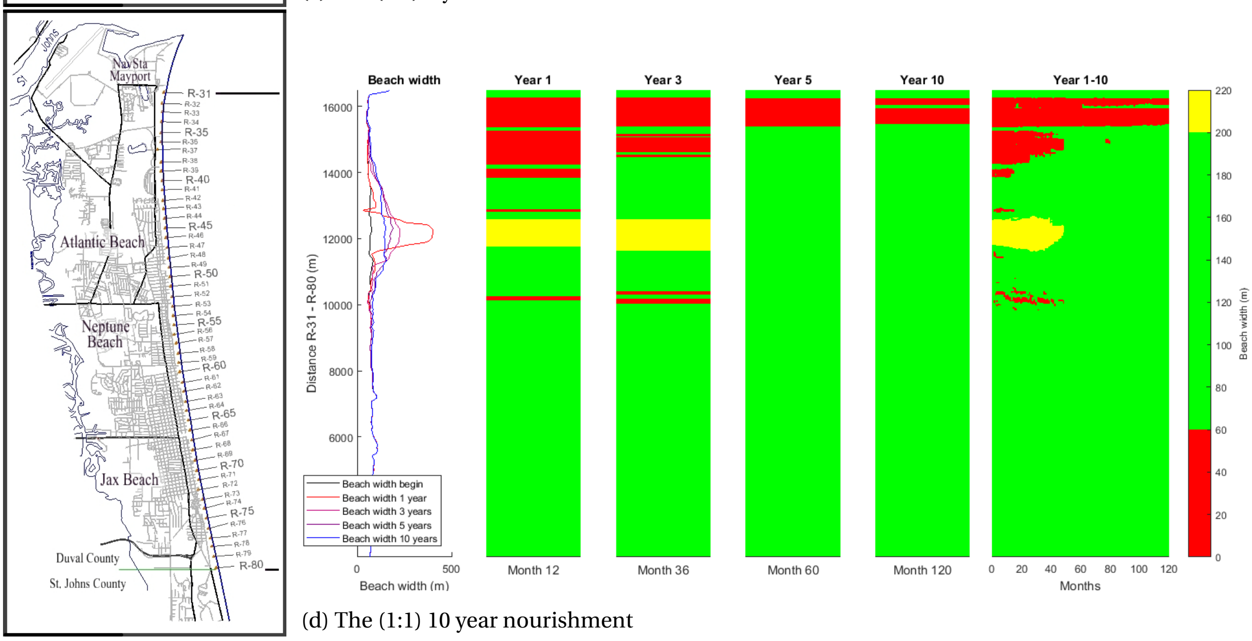
Figure D.1: The beachwidth for 1, 3, 5 and 10 years, and the timestacking plot for the different nourishment alternatives.



(b) The (1:1) 3 year nourishment

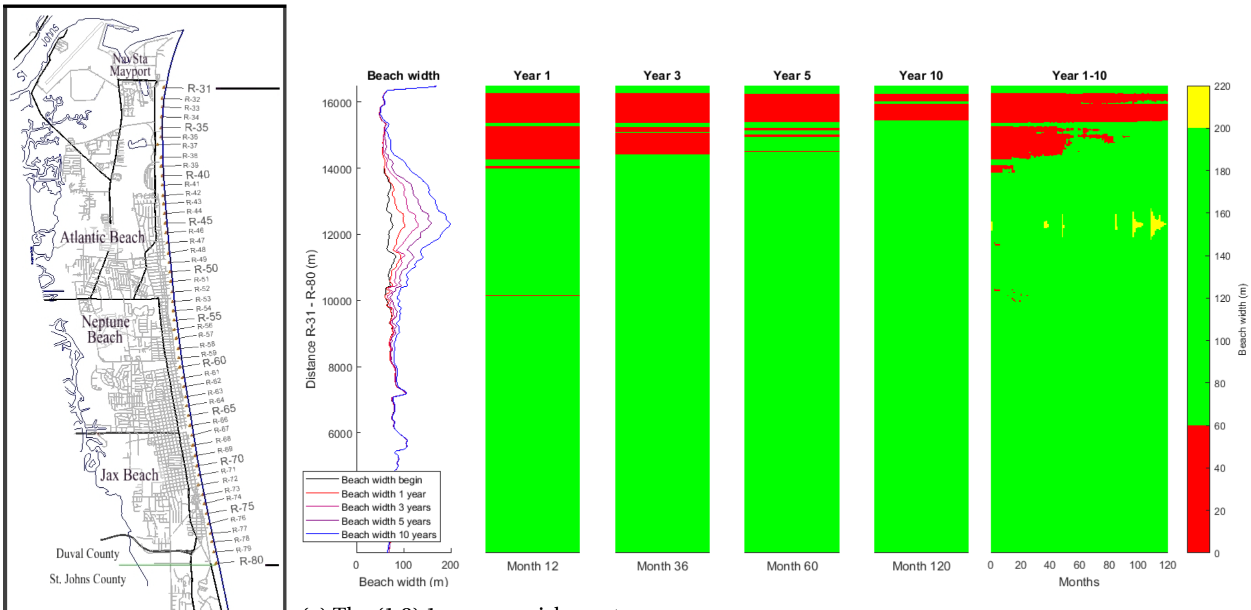


(c) The (1:1) 5 year nourishment

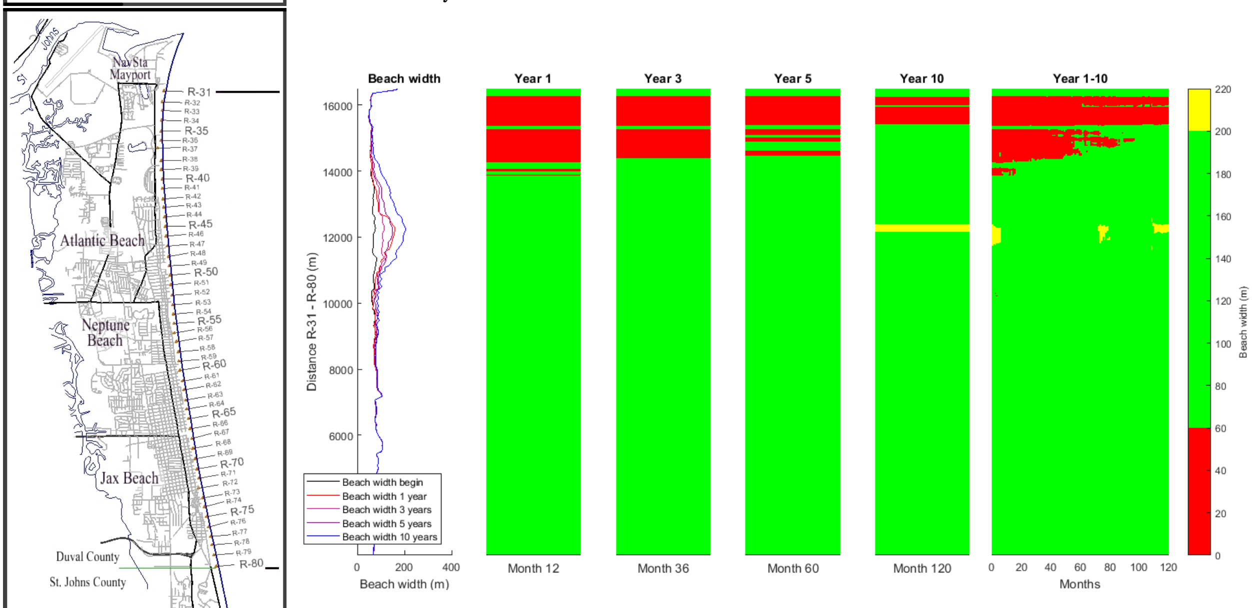


(d) The (1:1) 10 year nourishment

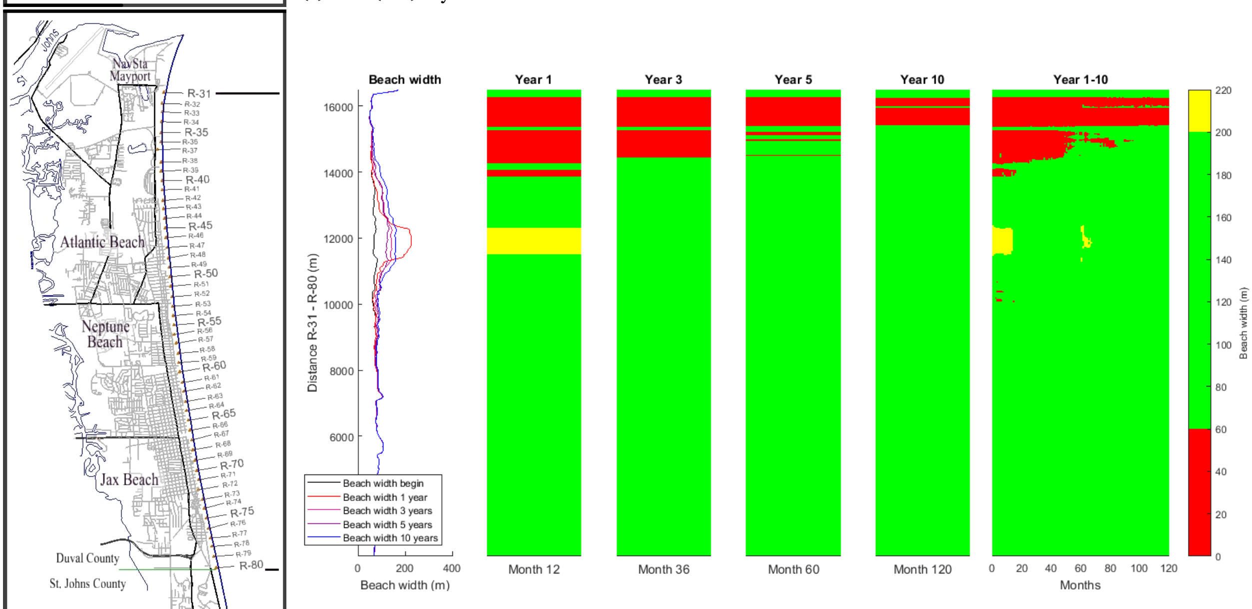
Figure D.1: The beachwidth for 1, 3, 5 and 10 years, and the timestacking plot for the different nourishment alternatives.



(e) The (1:3) 1 year nourishment

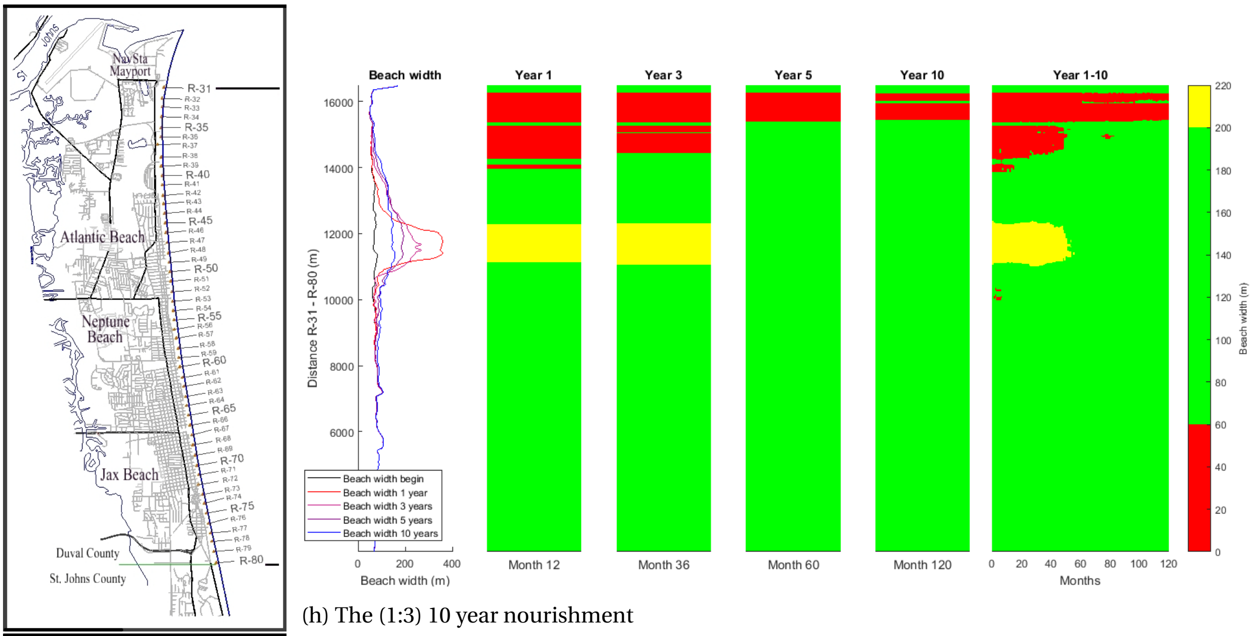


(f) The (1:3) 3 year nourishment

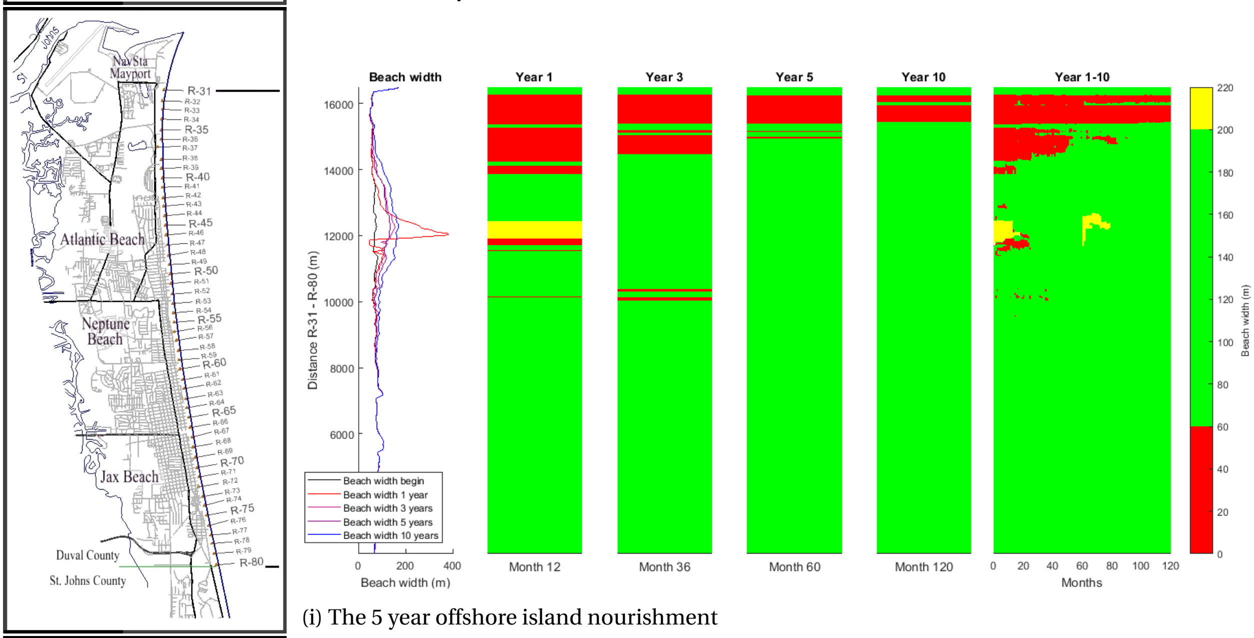


(g) The (1:3) 5 year nourishment

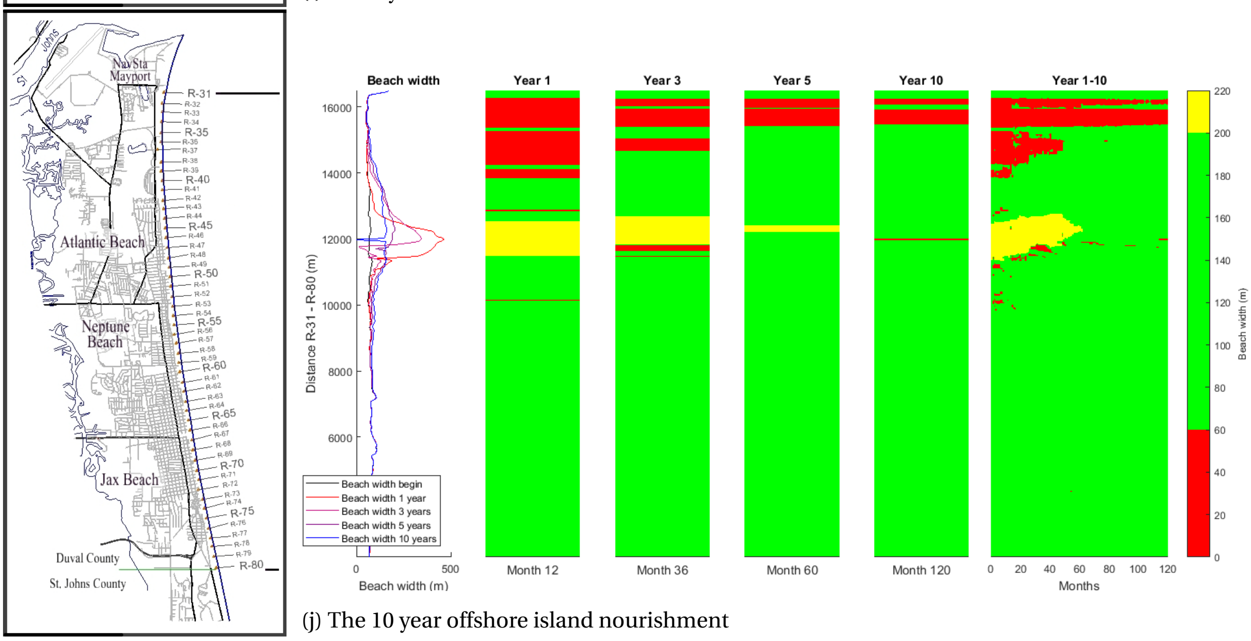
Figure D.1: The beachwidth for 1, 3, 5 and 10 years, and the timestacking plot for the different nourishment alternatives.



(h) The (1:3) 10 year nourishment



(i) The 5 year offshore island nourishment

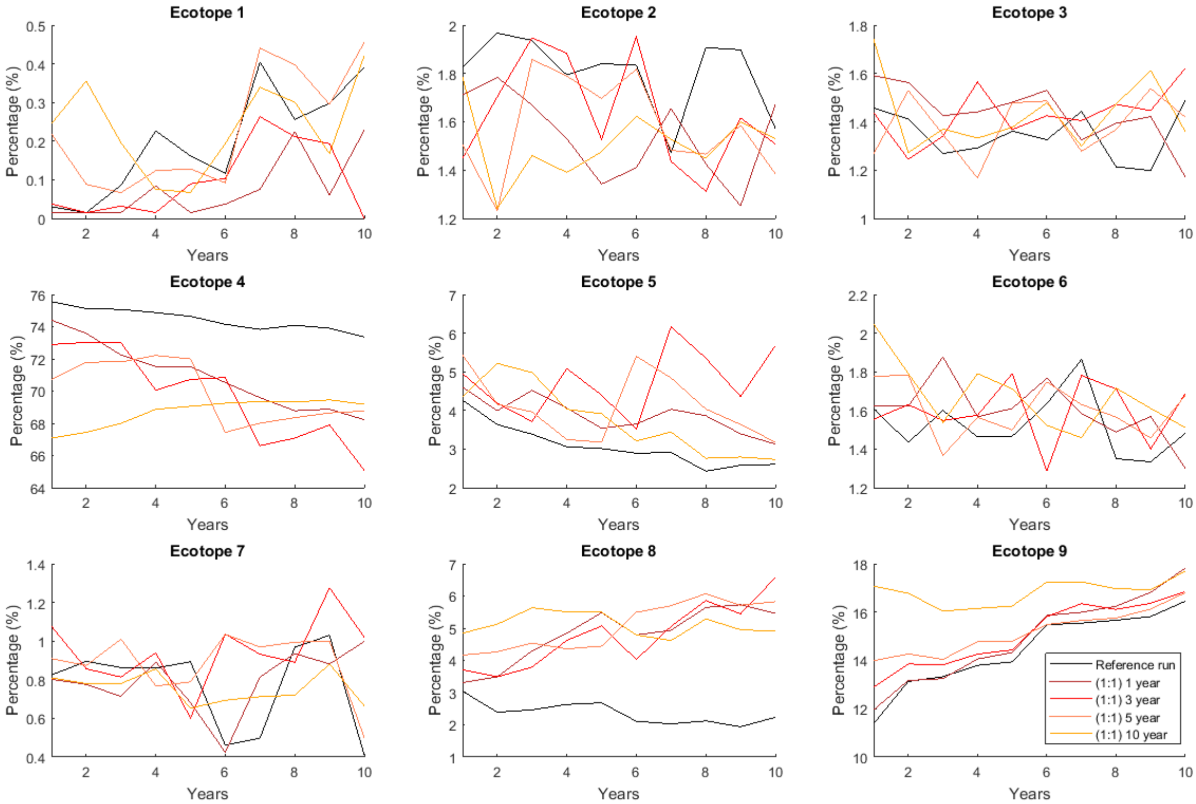


(j) The 10 year offshore island nourishment

Figure D.1: The beachwidth for 1, 3, 5 and 10 years, and the timestacking plot for the different nourishment alternatives.

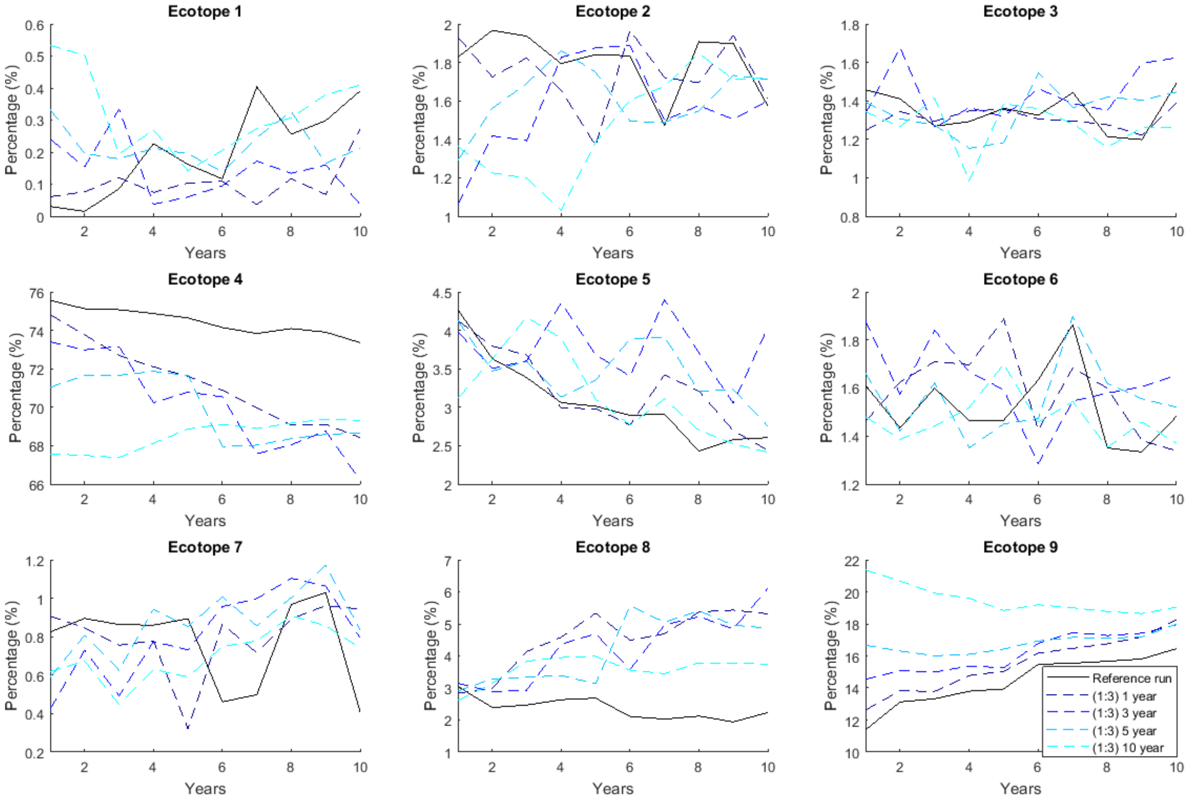
E Nursery area

In this appendix the normalized area per ecotope is shown for the different nourishment alternatives.

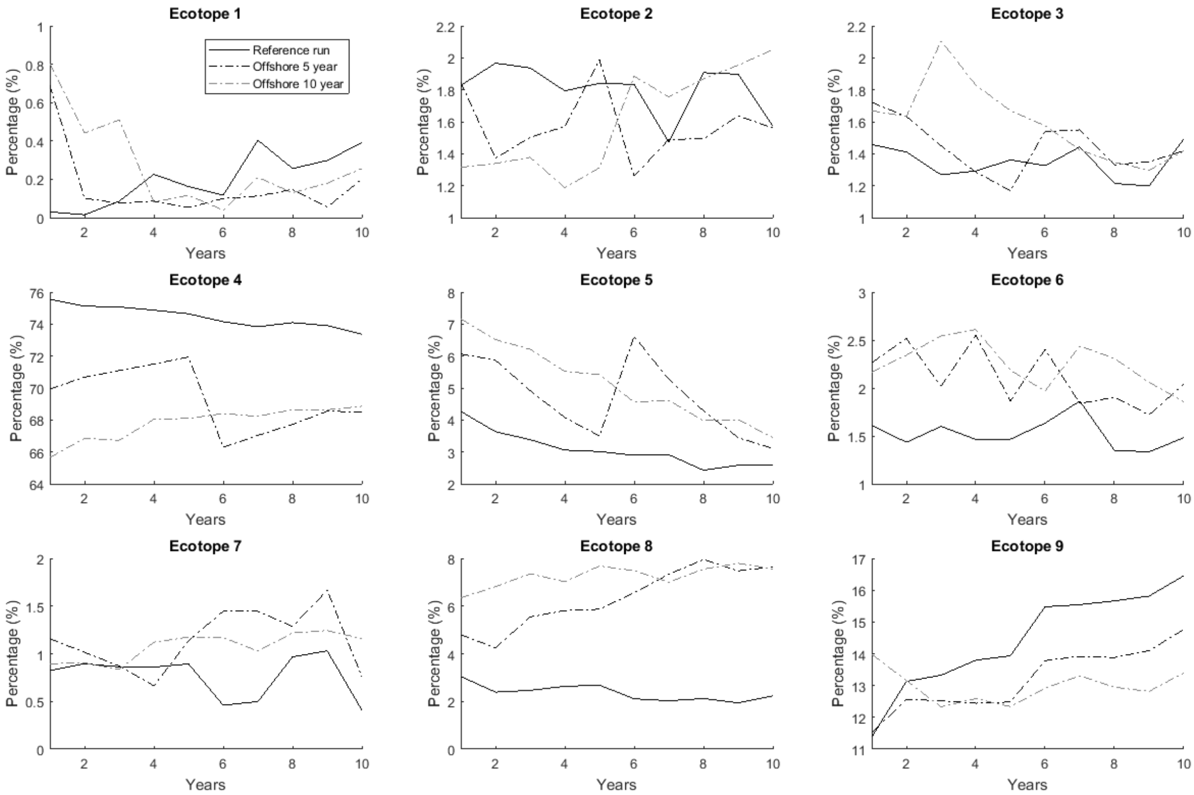


(a) The (1:1) nourishment alternatives.

Figure E.1: The normalized area for each of the defined ecotopes, for the reference run and the different nourishment alternatives.



(b) The (1:3) nourishment alternatives.



(c) The offshore island nourishment alternatives.

Figure E.1: The normalized area for each of the defined ecotopes, for the reference run and the different nourishment alternatives.