BEACH NOURISHMENT IMPACTS ON THE BEACH PROFILE

by

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TABLE OF CONTENTS

LIST OF TABLES vii
LIST OF FIGURES ix
ABSTRACT xiii

Chapter

1 INTRODUCTION 1
    1.1 Study Area 3
    1.2 Beach Nourishment Projects 5
2 DESIGN AND MONITORING OF BEACH NOURISHMENT 7
    2.1 Analytical Models 7
        2.1.1 Beach Face 7
        2.1.2 Equilibrium Beach Profiles 11
        2.1.3 Planform Model 12
    2.2 Numerical Models 16
    2.3 Monitoring 19
        2.3.1 Morphological Monitoring 19
        2.3.2 Grain Size Monitoring 21
3 DATA SOURCES 22
    3.1 Morphological Data 22
        3.1.1 Annual Delaware Coast Survey 22
        3.1.2 Beach Nourishment Monitoring Surveys 25
            3.1.2.1 Late-1990s Nourishment Project Monitoring 25
            3.1.2.2 Mid-2000s Nourishment Project Monitoring 26
        3.1.3 Profile Line for Surf-Zone Injuries Project 27
        3.1.4 Offshore Bathymetric Data 28
        3.1.5 Coordinate Systems 30
        3.1.6 Assortment of Survey Profile Lines 31
    3.2 Wave information 33
    3.3 Tidal Information 34

3.4 Sediment Information 35

3.4.1 Available Reports 35

3.4.1.1 Sieving Technique 37
3.4.1.2 Imaging Technique 38

3.4.2 Assortment of Sediment Information 40

4 PROFILE BEACH ANALYSIS 42

4.1 Beach Slopes 42

4.1.1 Beach Face Slope 46
4.1.2 Foreshore Slope 51
4.1.3 Wading Zone Slope 54
4.1.4 Beach Slope (MSL-DOC) 57
4.1.5 Beach Slope (Berm-DOC) 61

4.2 Equilibrium Beach Profile Parameter 64

5 NUMERICAL SIMULATION OF BEACH FILL 68

5.1 Model Specifications 68
5.2 Fill Design 70
5.3 Wave Model Validation 70
5.4 Storm Event 72

5.4.1 Morphology Validation 73
5.4.2 Beach Fill Scenarios 75

5.4.2.1 Different Fill Grain Size 75
5.4.2.2 Different Fill Template Slope 77
5.4.2.3 Different Fill Berm Height 79
5.4.2.4 Different Fill Volume 81
5.4.2.5 Submerged Fill 83

5.5 Moderate Storm Condition 85

5.5.1 Morphology Validation 85
5.5.2 Beach Fill Scenarios 87

5.5.2.1 Different Fill Grain Size 87
5.5.2.2 Different Fill Template Slope 88
5.5.2.3 Different Fill Berm Height and Fill Volume 90

5.6 Accretion Conditions 92

5.6.1 Morphology Validation 92
5.6.2 Beach Fill Scenarios 93

5.6.2.1 Different Fill Grain Size 93

6 CONCLUSION & RECOMMENDATION 96

REFERENCES 100

LIST OF TABLES

Table 1.1 Rehoboth-Dewey Beach 5

Table 1.2 Bethany-South Bethany Beach 6

Table 1.3 Fenwick Island 6

Table 2.1 Qualification of error ranges of process parameters (adapted from Van Rijn et al., 2003) 17

Table 3.1 Available profile surveys for the annual Delaware Coast Survey 23

Table 3.2 Corresponding profile of beach nourishment project location 25

Table 3.3: Available profile surveys for late 90s Beach nourishment projects 26

Table 3.4: Available profile surveys for mid 2000s Beach nourishment projects 27

Table 3.5: Tidal information for each profile line 34

Table 3.6 Median grain size of each beach location in mm 40

Table 3.7 Sorting of the grain sizes (standard deviation) for each beach location in mm 41

Table 4.1 Characteristic berm height for different beach locations 43

Table 4.2 Evaluation of depth of closure for different profile lines 45

Table 4.3 Statistics of beach face slope for summer 2014 and 2015 50

Table 5.1 Numerical coefficient that were modified 69

Table 5.2 Default values for numerical coefficient 69

Table 5.3 Numerical coefficient corresponding for the most accurate prediction of morphology evolution 74

Table 5.4 Predicted shoreline bathymetries 75

Table 5.5 Predicted shoreline bathymetries 78

Table 5.6 Predicted shoreline bathymetries 80

Table 5.7 Predicted shoreline bathymetries 82

Table 5.8 Predicted shoreline bathymetries...84

Table 5.9 Numerical coefficient corresponding for the most accurate prediction of morphology evolution 86

Table 5.10 Predicted shoreline bathymetries...87

Table 5.11 Predicted shoreline bathymetries...89

Table 5.12 Predicted shoreline bathymetries...90

Table 5.13 Predicted shoreline bathymetries...91

Table 5.14 Numerical coefficient corresponding for the most accurate prediction of morphology evolution 93

Table 5.15 Predicted shoreline bathymetries...94

LIST OF FIGURES

Figure 1.1 a) Map of the east coast of USA (mapsof.net), b) Zoomed map of the state of Delaware, c) Map of the Atlantic coast of Delaware (www.bing.com/maps/) ... 4

Figure 2.1 Beach face slope versus the dimensionless fall velocity (Dalrymple & Thompson, 1976)... 10

Figure 2.2 Beach face slope versus the dimensionless Sunamura (1984) parameter... 10

Figure 2.3 Evolution of rectangular beach fill as predicted from analytical solution (Work & Dean, 1995)... 14

Figure 2.4 Definition sketch for analysis of profile change between two successive years. (adapted from Figlus and Kobayashi 2008)... 15

Figure 3.1: Map of LRP profile location at Delaware Atlantic coast ... 24

Figure 3.2: Sketch of the survey area over a the nautical chart of the broader area of Delaware Atlantic coast (image is adopted from H11648 report) ... 29

Figure 3.3 User interface of the VDatum software ... 30

Figure 3.4 Survey locations of Rehoboth and Dewey Beach (Google Earth)... 31

Figure 3.5 Survey locations of Bethany and South Bethaby Beach (Google Earth)... 32

Figure 3.6 Survey locations of Fenwick Island (Google Earth)... 32

Figure 3.7 Stack of sieves that was used to obtain sediment grain size ... 37

Figure 3.8 a) the stand of the camera, b) a picture of a typical sediment sample... 39

Figure 3.9 GUI of the Matlab script to evaluate grain size distribution from a photo . 39

Figure 4.1 Example of beach profile evolution for Bethany Beach (OC 60)... 43

Figure 4.2 Example of evaluation of depth of closure ... 44

Figure 4.3 Schematic representation of different slope definitions... 45

Figure 4.4 Rehoboth Beach ... 47

Figure 4.5 Dewey Beach ... 47

Figure 4.6 Bethany Beach 48

Figure 4.7 South Bethany Beach 48

Figure 4.8 Fenwick Island 49

Figure 4.9 Beach face slope versus the dimensionless parameter $\mathrm{H}b/\mathrm{g}0.5\mathrm{D}0.5\mathrm{T}$ 51

Figure 4.10 Rehoboth Beach 52

Figure 4.11 Dewey Beach 52

Figure 4.12 Bethany Beach 53

Figure 4.13 South Bethany Beach 53

Figure 4.14 Fenwick Island 54

Figure 4.15 Rehoboth Beach 55

Figure 4.16 Dewey Beach 55

Figure 4.17 Bethany Beach 56

Figure 4.18 South Bethany Beach 56

Figure 4.19 Fenwick Island 57

Figure 4.20 Rehoboth Beach 58

Figure 4.21 Dewey Beach 59

Figure 4.22 Bethany Beach 59

Figure 4.23 South Bethany Beach 60

Figure 4.24 Fenwick Island 60

Figure 4.25 Rehoboth Beach 61

Figure 4.26 Dewey Beach 62

Figure 4.27 Bethany Beach 62

Figure 4.28 South Bethany Beach 63

Figure 4.29 Fenwick Island 63

Figure 4.30 Schematic representation of equilibrium beach profile 64

Figure 4.31 Rehoboth Beach 65

Figure 4.32 Dewey Beach 65

Figure 4.33 Bethany Beach 66

Figure 4.34 South Bethany Beach 66

Figure 4.35 Fenwick Island 67

Figure 5.1 Original template design of the beach nourishment for Bethany Beach (Source: http://www.dnrec.delaware.gov/) 70

Figure 5.2 Comparison of measured and computed wave significant height for july of 2014 71

Figure 5.3 Bathymetry of the model 72

Figure 5.4 Wave condition for Mother's day storm of 2008 73

Figure 5.5 Comparison of predicted and measured profile line after the storm. 74

Figure 5.6 Predicted bathymetries for different median grain sizes after storm 76

Figure 5.7 Predicted bathymetries for different D90 sizes after storm 77

Figure 5.8 Initial bathymetries for different template slopes. 78

Figure 5.9 Predicted bathymetries for different templates slopes after storm. 79

Figure 5.10 Initial bathymetries for different berm height. 80

Figure 5.11 Predicted bathymetries for different berm heights after storm. 81

Figure 5.12 Initial bathymetries for different fill volumes. 82

Figure 5.13 Predicted bathymetries for different fill volumes after storm. 83

Figure 5.14 Initial bathymetries for different submerged fills. 84

Figure 5.15 Predicted bathymetries for different submerged fills after storm. 85

Figure 5.16 Comparison of predicted and measured profile line after moderate erosive condition 86

Figure 5.17 Predicted bathymetries for different grain sizes after moderate erosion. . 88

Figure 5.18 Predicted bathymetries for different templates slopes after moderate erosion. 89

Figure 5.19 Predicted bathymetries for different berm heights after moderate erosion. 91

Figure 5.20 Predicted bathymetries for different fill volumes after moderate erosion. 92

Figure 5.21 Comparison of predicted and measured profile line after moderate erosive condition 93

Figure 5.22 Predicted morphology of the evolution of the eroded profile after accretion event. 95

ABSTRACT

The Delaware coast has been nourished since the early 1960s as a countermeasure for the eroding pattern that is observed on most of Delaware beaches. The beaches that were nourished are Rehoboth, Dewey, Bethany, South Bethany and Fenwick Island. Beach users have reported that nourishment projects affected the beach morphology and resulted in different surf zone characteristics. The available surveys date from the 1960s were analyzed to determine if those observations are justified from bathymetric change. The profile is divided in parts according to morphological characteristics to determine where the profile is most affected and what the consequences are. The long term evolution of the profile is evaluated from annual surveys and is compared with the variation of the profile over a summer season. The relationship of wave conditions, sediment characteristics and the resulting beach slope are investigated to explain the variability of beach profile slope over short time periods. The assessment of the impact of beach nourishment also includes the use of numerical models. Specifically, XBeach is used to simulate the morphological evolution of beach fill during storm conditions. XBeach was calibrated and validated with pre- and post-storm surveys, and different fill scenarios were simulated to determine the most appropriate nourishment practice for the Delaware coast. The fill scenarios include different fill grain size, fill template slopes, berm height, and fill volume as well as the placement of submerged fill.

Chapter 1

INTRODUCTION

The importance of coastal regions for the human civilization through history is significant and our dependence on the stability of the coastal area has been increasing. Urbanization and modification of the natural shoreline has created a tendency of erosion and retreat of the shoreline. The construction of breakwater and jetties for coastal and port protection in the 19th century created an alteration of sediment transport and led to erosive trends for adjacent areas (Bruun, 1995). The impacts of this problem are becoming more severe resulting in a growing need of counter measures

There are two main categories of beach erosion protection projects, on one hand the hard engineering projects and on the other hand the soft engineering projects. The hard engineering projects include structures as breakwaters and jetties. The use of this type of protection incorporates the risk of enhancing the erosion in adjacent beaches, especially those are located downdrift (Dean & Dalrymple, 2004). Soft engineering projects include the beach nourishment projects, where sediment is placed on the eroding beach in order to restore the shore to its initial condition. Even though beach nourishment is considered to have minimal effects on the natural coast, thorough studies of the long-term effects on the shape of the beach profile are lacking. The main focus of this thesis is to investigate if those trends in alteration of the beach profile exist, and specifically if the consecutive beach nourishment in the Atlantic Delaware coast reshaped the beaches.

Beach nourishment projects involve the transfer of sediment from a source location to a beach where supplementary sediment is needed. The main advantage of beach nourishment against hard engineering projects is that it introduces new sediment into the coastal system, whereas other types of projects alter the sediment transport patterns. Furthermore**,** the fill widens the beach and increases the available area for recreational activities without deteriorating the aesthetics of the area, hence tourism is promoted. Another advantage is the protection that the fill provides to upland properties from storm events, especially the build up of dunes, which dissipate storm waves with its erosion without losing valuable land behind it. In addition the nourished dune offers habitat to wildlife (Dean & Dalrymple, 2004). Those multiple benefits that beach nourishment offers to local communities has increased the popularity of it as an alternative for erosion management, specifically the fill material placed on the Atlantic coast of United States grew by 10 times over the 20th Century (Valverde et al, 1999)

However, if there are not additional measures in order to minimize the erosion trends, repetitive nourishment could be needed. The placed fill with sediment similar to the natural sediment has the tendency to erode faster than the natural beach and the recovery of the beach is less efficient for nourished beaches. Therefore, repetitive nourishment project are usually needed with a typical life cycle of the project of 5 years (Davison et al, 1992). Since beach nourishment has a relatively small life span, the major objective of a fill design is to increase its longevity, which can be modified with the appropriate volume of the fill, grain size and location where the fill is placed. Usually sediment similar to the natural is placed on the berm in order to extend the beach seaward. There have also been attempts to place a submerged fill in order to supply the beach through cross-shore sediment transport. Another goal of this thesis is to provide the best practices for future nourishment projects in the state of Delaware. For this reason numerical models are used in order to evaluate the performance of different fill scenarios and determine which is the most efficient, the results of which can be found in chapter 5.

1.1 Study Area

The Atlantic Ocean shore of Delaware state extends north to south from cape Henlopen to Fenwick Island and it consists of approximately 40 km of sandy beaches. The shoreline is interrupted by an opening, the Indian River Inlet which connects the Atlantic Ocean with the Indian River Bay and the Rehoboth Bay. The entirety of Delaware's Atlantic coast are located in Sussex County. The locations that have been modified by beach nourishment and therefore attract the main interest of this thesis are Rehoboth and Dewey Beach north of the inlet and Bethany, South Bethany and Fenwick Island Beach south of the inlet. The shore management began with the construction of timber groins at Rehoboth Beach in 1920s and later at Bethany Beach in 1930s. One of the major shore management projects was the stabilization of Indian River Inlet in the late 1930s with the construction of jetties, which decreased the supply of sediment downdrift creating the need of a bypass system which was eventually placed in 1990. The first beach nourishment projects for Delaware oceanic coast occurred in 1961 and numerous other projects followed later which are presented in section 1.2.

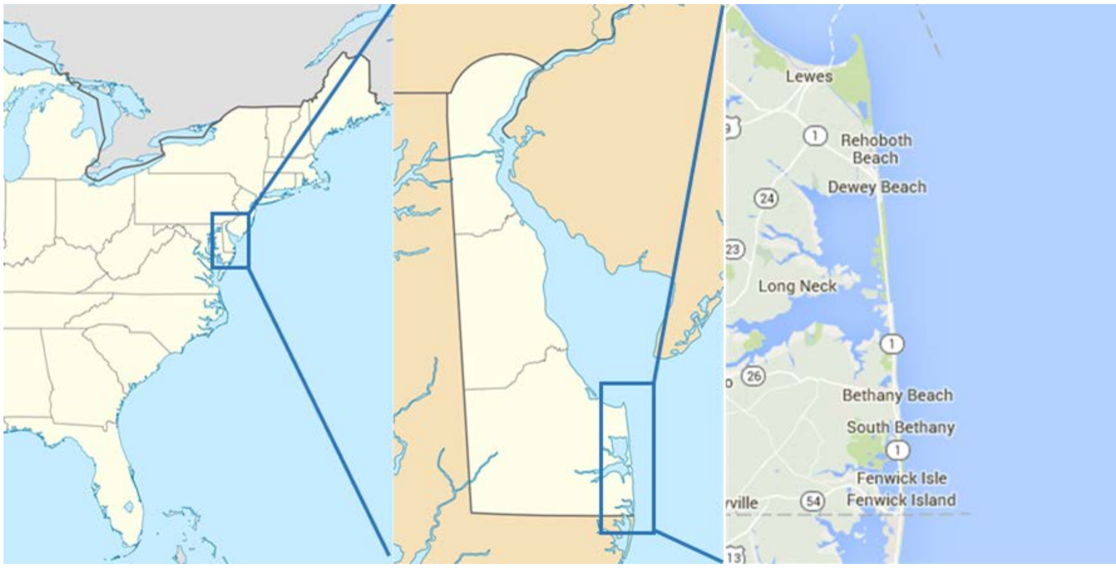


Figure 1.1 a) Map of the east coast of USA (mapsof.net), b) Zoomed map of the state of Delaware, c) Map of the Atlantic coast of Delaware (www.bing.com/maps/)

The dominant wave direction is Southwest (90^0-120^0 with respect to true North). Waves break obliquely to the shore and generate a northward alongshore current for the majority of the coastline. The net sediment transport is also directed northward for the majority of the coastline. The location where this trend is inverted (nodal point) is estimated to be in various locations, ranging from South Bethany to southern end of the border of Delaware and Maryland, with the location probably migrating with different wave conditions (Puleo, 2010). Different studies estimated the net longshore sediment transport to be around 100,000 m^3/year (Mann & Dalrymple, 1986; Chen et al,, 1983), but there have been more recent studies indicating higher transport rates ranging from 320,000 to 380,000 m^3/year depending on the location (Puleo, 2010). The sediment balance is mainly deficient with the only exception being Cape Henlopen where accretion is observed. The rest of the coast is eroding and the shoreline in the study location is retreating at a rate of 0.5-1 m/year (Galgano & Leatherman, 1999). This erosion trend creates the necessity for constant nourishing of the beaches for reintroducing sediment into the system.

1.2 Beach Nourishment Projects

This section presents the beach nourishment projects that were conducted in the location of interest (Tables 1.1-1.3). The data were acquired from the Delaware Department of Natural Resources and Environmental Control (DNREC) and are updated until 2013. Data were converted from imperial to SI units. The five nourished locations are divided into three areas, as some are adjacent beaches and share some projects. The groups of areas are Rehoboth-Dewey Beach, Bethany-South Bethany Beach, and Fenwick Island. The table with the conducted projects contain the initial projects, the designed supplementary projects and emergency projects. The early nourishment (1960s) were conducted with truck fill and the later with a hopper dredge (after 1990).

Table 1.1 Rehoboth-Dewey Beach

Year	Fill volume (m^3)	Project length (m)
1962	165393 (Rehoboth) & 62730 (Dewey)	-
1993	4403 (Dewey)	579 (Dewey)
1994	442839 (Dewey)	1829 (Dewey)
1998	209840 (Rehoboth) & 346928 (Dewey)	838 (Rehoboth) & 1858 (Dewey)
2005	1277550 (shared)	4024 (shared)
2009	237915 (Dewey)	-
2011	(Rehoboth) & 512550 (Dewey)	1499 (Rehoboth) & 1676 (Dewey)

Table 1.2 Bethany-South Bethany Beach

Year	Fill volume (m^3)	Project length (m)
1962	53289 (Bethany) & 49773 (S. Bethany)	-
1989	217515 (Bethany) & 177071 (S. Bethany)	1566 (Bethany) & 1267 (S. Bethany)
1992	167999 (Bethany) & 147367 (S. Bethany)	1566 (Bethany) & 1478 (S. Bethany)
1994	141023 (Bethany) & 75289 (S. Bethany)	1265 (Bethany) & 777 (S. Bethany)
1998	245957 (Bethany) & 129133 (S. Bethany)	1566 (Bethany) & 1036 (S. Bethany)
2008	2599487 (Shared)	4557 (Shared)
2009	152911 (Bethany)	-
2011	535188 (Bethany) & 458733 (S. Bethany)	1566(Bethany) & 1524 (S. Bethany)
2012	334110.5 (Bethany)	-

Table 1.3 Fenwick Island

Year	Fill volume (m^3)	Project length (m)
1962	51684	-
1988	254979	1829
1991	96946	488
1992	139073	1753
1994	52170	701
1998	107879	853
2004	764555	1981
2011	253832	1524

Chapter 2

DESIGN AND MONITORING OF BEACH NOURISHMENT

A reliable design and a thorough monitoring of beach nourishment projects are crucial components for the best performance of the project. The design should predict the evolution of the fill accurately and the monitoring will help improve the design of future projects as well as determining the need for supplementary nourishment. This chapter will provide theoretical background of a simple model that connects the morphology characteristics with wave climate and grain size information, aiming to explain potential modification of beach profile caused by beach nourishment and to provide reasoning for the definition of the profile parameters that are studied. In addition, there is an overview of the use of numerical models for beach nourishment design, with the main focus on XBeach software. Lastly, a review of monitoring practices is given in order to provide suggestion for improvements of the monitoring in the state of Delaware and evaluate the credibility of the conclusion made from the available data.

2.1 Analytical Models

2.1.1 Beach Face

The beach face is the part of the profile that surrounds sea level. It is typically the steepest part of the profile and one of the most energetic as swash processes are the driving forces. There are small variations of the definition of the slope of the beach face, which is also referred to as foreshore slope, definitions include the slope of mid-tidal area (Bascom, 1951) or the slope of the entire swash zone (Dubois, 1972). There are numerous studies that investigate the relationship of beach face slope and factors related to the beach. These factors are the sediment characteristics (Bagnold, 1940; Bascom, 1951), the wave characteristics (Komar, 1998), the groundwater level, the tidal range, and the longshore current intensity (King, 1953). The dominant factors that contribute to the beach face slope are the sediment characteristics, which can be parameterized with the median grain size (D) or the settling velocity (V_f) and the wave characteristics, that can be described with the offshore wave height (H_0) and the period (T). Dimensionless numbers have been implemented in order to include all above mentioned parameters and their correlation with the observed beach face slope, which were collected both in field and laboratory experiments. First there is the dimensionless sediment fall velocity parameter (Dalrymple & Thompson, 1976):

$$\Omega = H_0 / V_f T. \tag{2.1}$$

A significance of this parameter is that is an indicator for the type of profile. As a general trend there is a decrease in the slope as the dimensionless parameter increases (Figure 2.1). A similar dimensionless parameter was used by Sunamura (1984), based on the breaking wave height (H_b) and median grain size (D) as:

$$H_b / g^{0.5} D^{0.5} T, \tag{2.2}$$

and its relation with the beach face slope is shown in Figure 2.2. It is found that this parameter shares a similar trend with the previous parameter (Equation 2.1) and the relation that best described the observation from various field experiments can be expressed with the following equation:

$$tan(\xi) = \frac{0.12}{H_b / g^{0.5} D^{0.5} T^{0.5}}, \tag{2.3}$$

where tan(ξ) is the beach face slope. This study gives a more quantitative prediction and contains data points from a larger number of field measurements. The unpredictable natural parameters and local effects for each beach creates large scatter around the best fit curve. A similar relation has been developed for a laboratory experiment which is more accurate. The model predicts a steeper beach face slope for coarser sediment. This trend can be explained because larger grain sizes increase the permeability of the bed and hence enhance the uprush with respect to backwash which leads to accretion and steepening of the beach. This explanation is more appropriate for coarser sediment ($D > 1$ mm). For finer sediments ($D < 1$ mm) suspension is the dominant mechanism of sediment transport and hence grains with smaller settling velocity are more probable to be transported and form a milder sloping beach (Masselink & Puleo, 2006). Furthermore the wave steepness (and therefore also the ratio H/T) is correlated with the beach steepness. Longer waves can transport sediment onshore more easily and therefore cause accretion.

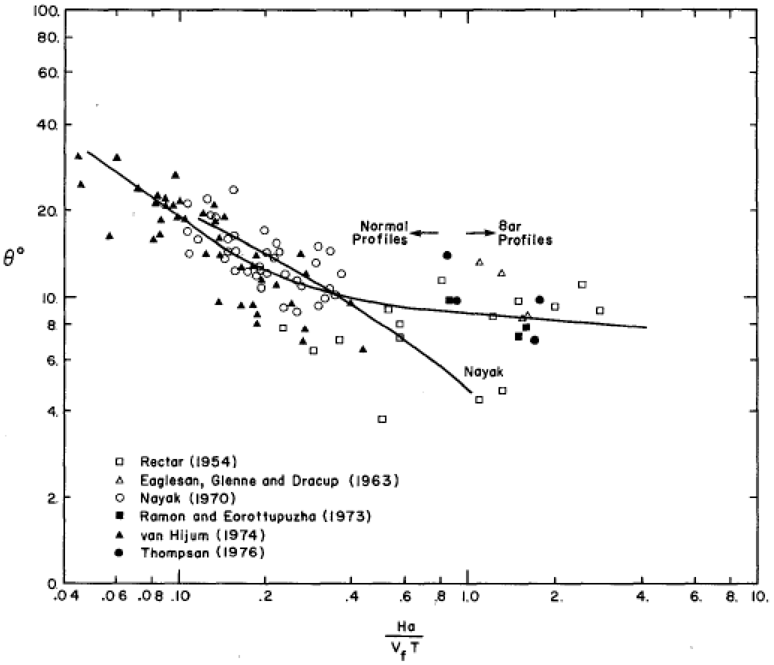


Figure 2.1 Beach face slope versus the dimensionless fall velocity (Dalrymple & Thompson, 1976)

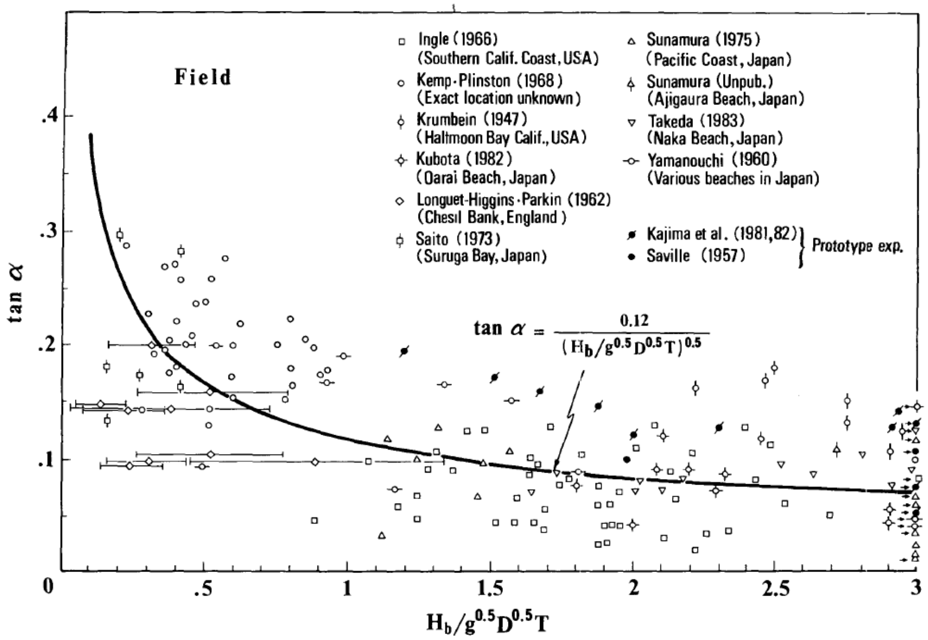


Figure 2.2 Beach face slope versus the dimensionless Sunamura (1984) parameter.

2.1.2 Equilibrium Beach Profiles

The equilibrium beach profile (EBP) concept can be used to quantify and predict the shape of the profile. This concept states that the beach profile after an exposure to a certain wave condition will respond and the profile will settle to an equilibrium. The first attempt to create an empirical model of EBP based on analyzed profile data suggested a form on a power law (Bruun, 1954):

$$h = Ax^{2/3}, \tag{2.4}$$

where h is the predicted water depth, x is the distance from the shoreline, and A is a dimensional constant of proportionality. The same result is obtained assuming the destructive force to be the wave breaking dissipation per unit volume and its uniform across the profile (Dean, 1977). The constant of proportionality is related to the sediment size and fall velocity. As a result, according to this approach, the fill material dictates the shape of the profile in a nourishment project. This method is commonly used because of its simplicity and there is only the constant of proportionality as a free parameter that can be obtained from the sediment characteristics. The main weakness of this model is the unrealistic infinite slope at the shoreline.

This shortcoming can be overcome if the gravity is considered as an additional destructive force. There have been several approaches to address this issue (Dean & Dalrymple, 2004; Komar, 1998; Kraus & Larson, 1988, 1988). The model of the former (Larson, 1988) can be written as (Özkan-Haller & Brundidge, 2007):

$$x = \frac{h}{m_{fs}} + \frac{h^{3/2}}{A^{*3/2}}, \tag{2.5}$$

where m_{fs} is the slope near the shore and A^* is dimensional constant of proportionality analogous to A. Since the slope near the shore can be easily measured, the only parameter that needs to be quantified is A^*. Although there was initially some evidence that A^* could be estimated with the parameter A of the previous EBP model, later it has been shown that the nearshore slope can affect the whole profile (Özkan-Haller & Brundidge, 2007). This suggests that the gravity factor is dominant for the whole profile, in contrast to the initial findings (Larson, 1988; Larson & Kraus, 1989). For this reason, a modified version of this model has been developed (Özkan-Haller & Brundidge, 2007):

$$x = \frac{h}{m_{fs}} e^{-\alpha h^2} + \frac{h^{3/2}}{A^{*3/2}} \tag{2.6}$$

where α is a decay coefficient. For this model similar A and A^* parameters are obtained. No significant variation in the α coefficient is found, and A^* is dependent on α.

2.1.3 Planform Model

The first planform model is a one-line model which describes only the evolution of the shore in the planform, assuming that the beach profiles respond to EBP and there is only alongshore sediment transport. The model uses conservation of sediment considering no cross-shore transport:

$$\frac{dQ}{dx} + \frac{\partial V}{\partial t} = 0, \tag{2.7}$$

where Q is the alongshore sediment transport and V is the volume of sediment per unit length of beach. Considering the Bruun rule (Bruun, 1954) for profile response the volume can be expressed in terms of the depth of closure (h_*) and the berm height (B):

$$\frac{dQ}{dx} + (h_* + B)\frac{\partial y}{\partial t} = 0. \tag{2.8}$$

Assuming linear alongshore sediment transport the shoreline evolution can be expressed as (Pelnard-Considere, 1956):

$$\frac{\partial y}{\partial t} = G\frac{\partial^2 y}{\partial x^2} \tag{2.9}$$

and,

$$G = \frac{KH_b^{5/2}\sqrt{g/k}}{8(s-1)(1-p)(h_* + B)}, \tag{2.10}$$

where G is called “longshore diffusivity”, K is the sediment transport coefficient, k is the corresponding wavenumber, g is the gravitational acceleration, s is the sediment specific gravity, and p is the sediment porosity.

This model can be used for beach nourishment assuming a rectangular fill extended from -$l/2$ to $l/2$ (Figure 2.3), where l is the length of the project, with initial width of the fill Y and the prediction of the planform will be (Dean, 2002):

$$y(x,t) = \frac{Y}{2}\left\{erf\left[\frac{l}{4\sqrt{Gt}}\left(\frac{2x}{l}+1\right)\right] - erf\left[\frac{l}{4\sqrt{Gt}}\left(\frac{2x}{l}-1\right)\right]\right\}, \tag{2.11}$$

where

$$erf(z) = \frac{2}{\sqrt{\pi}}\int_0^z e^{-r^2}dt \tag{2.12}$$

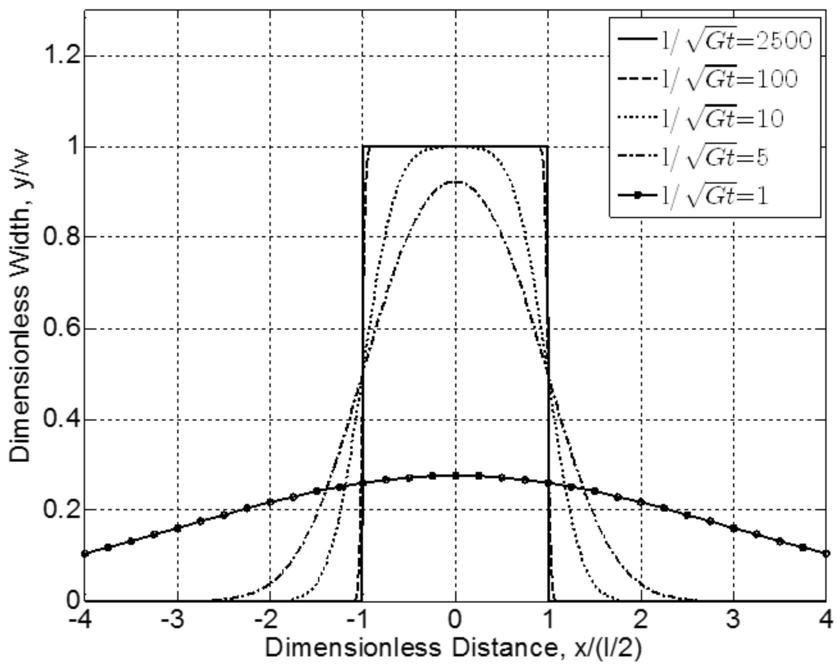


Figure 2.3 Evolution of rectangular beach fill as predicted from analytical solution (Work & Dean, 1995).

The Equation (2.11) can provide qualitative results as many assumptions have been invoked. Assumptions include the lack of spatial and temporal variation of wave climate and the insignificance of the cross shore sediment transport. The case study of Perdido Key, Florida (Work & Dean, 1995) has shown though that the analytical solution can provide a basic guideline. Therefore, the diffusion model can be still used for preliminary design.

The use of a one-line model can improve the evaluation of beach nourishment performance since the cross-shore sediment transport is incorporated in the model. In this case the landward limit (x_L) corresponds to the dune crest and the seaward limit (x_S)

corresponds to the depth of closure and no net cross-shore sediment transport is assumed at x_{S}.

The profile change of two successive years is shown in Figure 2.4, where the two profile lines are denoted as z_1 and z_2 for time t_1 and t_2, respectively. The P_1 and P_2 point are the shoreline location of the two profile lines and P3 is the intersection of the two profile lines. The elevation difference (z_2-z_1) is integrated with respect to x from x_L to P_3 to obtain the area change (A_L) in the landward zone and from P_3 to x_S to obtain the area change (A_L) in the seaward zone.

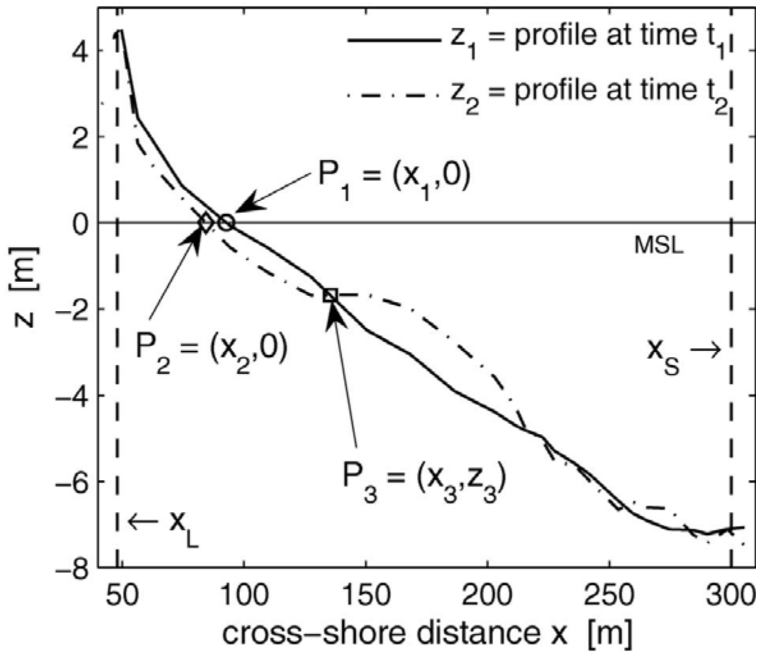


Figure 2.4 Definition sketch for analysis of profile change between two successive years. (adapted from Figlus and Kobayashi 2008)

In this case a two-line model can be used (Kobayashi & Han, 1988) for the conservation of sediment volume for the seaward and landward zone can be written as:

$$A_L = -(t_2 - t_1)(q_c - aq_l) \tag{2.13}$$

$$A_S = (t_2 - t_1)(q_c - (1 - a)q_l), \tag{2.14}$$

where q_c is the offshore sediment transport rate per unit longshore length, q_l is the net sediment transport rate, and a is the fraction of q_l occurring inside the landward section. The cross-shore distribution of the longshore sediment transport can be estimated as:

$$a = w_r^\beta\ ,\ \ w_r^\beta = \frac{\overline{x_3} - x_L}{x_S - x_L},$$

where w_r is the ratio of the landward and seaward zone and β is an empirical parameter, for β=1 the distribution of the longshore sediment transport rate is uniform.

For measured profiles the sediment transport rates can be estimated for the areas A_L and A_S (Figlus & Kobayashi, 2008):

$$q_l = \frac{A_L + A_S}{t_2 - t_1} \tag{2.15}$$

$$q_c = \frac{aA_S - (1 - a)A_L}{t_2 - t_1} \tag{2.16}$$

The two-line model can account for both the longshore and cross-shore sediment loss which a one-line model cannot account for.

2.2 Numerical Models

In addition to semi-analytical and empirical models for the prediction of the morphology response after beach nourishment, there are models that resolve the hydrodynamics and morphodynamics. This approach can predict accurately the evolution of beach morphology for known wave conditions. Evaluation and calibration are needed and there are parameters that can describe the model performance. These parameters can be the Relative Mean Absolute Error (RMAE) for hydrodynamics and Brier Skill Score (BSS) (Brier, 1950) for morphology modeling (Murphy & Epstein, 1989; Peet, Sutherland, & Soulsby, 2002) with the following definitions:

For wave height:

$$RMAE = \langle |H_c - H_m| - \Delta H_m \rangle / \langle |H_m| \rangle \tag{2.17}$$

For velocities:

$$RMAE = \langle |U_c - U_m| - \Delta U_m \rangle / \langle |U_m| \rangle \tag{2.18}$$

For morphology:

$$BSS = 1 - \left[\left(|Z_{b,c} - Z_{b,m}| - \Delta Z_{b,m} \right)^2 / \langle \left(Z_{b,0} - Z_{b,m} \right)^2 \rangle \right], \tag{2.19}$$

where Z_b the bed level and Δ the error of the measured value. The subscript *c* is the computed value, subscript *m* the measured value, and *0* the initial value. Based on these parameters, the model can be evaluated for a range of values (Table 2.1).

Table 2.1 Qualification of error ranges of process parameters (adapted from Van Rijn et al., 2003)

Qualification	Wave height	Velocity	Morphology
	RMAE	RMAE	BSS
Excellent	<0.05	<0.1	1.0-08
Good	0.05-0.1	0.1-0.3	0.8-0.6
fair	0.1-0.2	0.3-0.5	0.6-0.3
Poor	0.2-0.3	0.5-0.7	0.3-0
Bad	>0.3	>0.7	<0

Important design criteria of beach nourishment is the performance of the fill during storm events because they are vulnerable to erosion during storms and protect landward properties. An open-source program that is designed to model morphology response to storm events is XBeach (Roelvink et al., 2009), named for eXtreme Beach behaviour. The time scale of the processes that XBeach simulates is on the order of storm duration. There has been an extensive use and evaluation of this model for response of natural and nourished beaches during storm events (i.e. Bolle, et al., 2011; Bugajny et al., 2013; Faraci et al., 2014). However, the model performs better on dissipative beaches with a tendency to over predict erosion for reflective beaches. This problem can be overcome with the adjustment of numerical coefficients in order to have more accurate predictions (Vousdoukas et al, 2012).The most critical numerical coefficient is the factor for wave skewness and asymmetry that dictates the direction of the net sediment transport. In addition, even though XBeach is designed for prediction of erosion after storm events there have been studies to adjust numerical coefficients in order to reproduce accretion patterns during post-storms recovery (Pender & Karunarathna, 2013) and with the separation in calm and storm condition there can be a statistical evaluation of the morphology evolution over annual or decadal time period. The prediction of the beach response during storms can be used, except from the design, also for warning due to potential hazard of upcoming storms (Harley et al, 2011). Therefore, with the bathymetry of the current beach and the prediction of the upcoming storm there is better evaluation of the consequences and the required mitigation measures.

2.3 Monitoring

The monitoring of the beach is required for beach nourishment projects. Multiple aspects of the beach should be monitored in order to evaluate the performance of the beach nourishment as related to the environmental, geomorphological and economical aspects. This will provide a better understanding of the success or failure of the project and will provide additional information for further improvement of the design and the placement of the fill.

2.3.1 Morphological Monitoring

The monitoring of a beach nourishment project starts before the fill construction, in order to determine the pre-fill conditions as well as the location of the berm, the height of the dune, and the background erosion. After the project is completed, a post-fill survey is necessary. The post-fill survey will establish the new morphology profile of the beach. Morphological surveys should be conducted for multiple years after the project is completed in order to assess the performance of the intervention and the beach response to it.

The frequency of surveying can vary depending on the predicted response of the beach, the available funding, and the available equipment. Surveys should be conducted several times per year in order to eliminate seasonal effects. The area which is monitored should extend farther away from the area of the project and should have higher resolution at the spatial limits of the project, where larger lateral gradients are expected. In addition, for a better evaluation of the project effects monitoring should be conducted on adjacent beaches. The survey resolution, as the frequency, depends on the expected evolution of the project. Furthermore, the resolution in the longshore and the cross-shore direction should be different as the typical length scale of the corresponding features of interest are different. In the longshore a typical spacing could be 120-150 m in a beach fill with high variability (Kana and Andrassy 1994) and the volumetric error depends on the ratio of longshore spacing to the total length of the project. For a ratio equal to 0.1 the volumetric error is less than 5 % (Muñoz-Perez et al, 2011).

The most popular way of performing morphological monitoring is surveying parallel profile lines perpendicular to the shore. The dry part of the beach is surveyed by means of a Global Positioning System (GPS) device placed on manually pushed or motorized vehicles during low tide and the wet part is surveyed during high tide using a boat equipped with sonar and GPS devices. Apart from the traditional survey techniques (Seymour et al, 2005), efforts have focused on creating Digital Elevation Models (DEM) generated from Light Detection and Ranging (LIDAR) data, where three-dimensional (3D) maps are created. Both airborne (Woolard & Colby, 2002) and terrestrial (Pietro et al., 2008) LIDAR have been used. Terrestrial data are less expensive allowing a finer temporal resolution (precision of a measurement with respect to time) but with a tradeoff on the spatial coverage. Specifically, a resolution of 1 to 2 m produces fairly reliable results on volumetric changes, a resolution of up to 10 meters can provide results with some level of approximation and resolutions exceeding 10 m should not be considered as reliable (Woolard & Colby, 2002). The prominent features have a characteristic dimension of 5 m as the biggest standard deviation was calculated for the resolution of 5 m. Therefore, the spacing of 2 m can resolve those features.

Lastly, another surveying technique is quantifying the shoreline via video imagery. This technique can cover the dry part of the beach and gives anestimation of the planform but volumetric changes are difficult to estimate. Since video recording is used, the temporal resolution of this technique is high and storm events can be taken into account in estimating the evolution of beach nourishment (Elko et al, 2005)

2.3.2 Grain Size Monitoring

Evaluating the sediment grain size distribution is critical for quantifying the characteristics of the native sediment, and hence to evaluate the potential fill sediment. For this purpose sediment samples can be taken from the crest of the dune, the berm, the beach face, and the wet part of the profile exceeding the closure depth, where no significant change in the profile is occurring. The spacing of the sample location should not exceed a 1 meter elevation-depth difference. Sediment sampling after the project can help quantify the performance of the nourishment and the adaptation of the borrowed sediment to the native sediment (Dean, 2002)

Chapter 3

DATA SOURCES

Multiple data sources were used in this study in order to evaluate the effects of the beach nourishments projects on Delaware coast beaches. Data sources are divided into three main categories such as morphological data, sediment grain size and wave climate data. Since the data were not collected as part of a single project there is no spatial and temporal overlap in many cases. Hence, there is need for interpolation and generalization of the available datasets.

3.1 Morphological Data

3.1.1 Annual Delaware Coast Survey

The Delaware seashore is surveyed systematically in locations determined by the Line Reference Points (LRP), created by the Corps of Engineers. There are 37 profile lines from Cape Henlopen to Fenwick Island, with a typical spacing of profile lines at 1.1 km. The locations that were nourished as described in section 1.2 are surveyed using two to four profile lines. The corresponding profile lines for each location are presented in 3.2. Namely the locations of interest are from North to South: Rehoboth Beach, Dewey Beach, Bethany Beach, South Bethany Beach and Fenwick Island. A map of the profile lines and their locations is presented in Figure 3.1. The first survey took place in 1964, but the surveys were more systematic from 1982 with a biannual rate since then, with some sporadic gaps in between. The list of all available surveys are presented in Table 3.1 where they are divided into two regions according to their position relative to the Indian River Inlet (North and South). Since surveys were conducted during a large span of time, different instruments and datums were used. The earlier surveys were originally recorded in NAD1927 for the horizontal datum and in NGVD1929 for the vertical datum. However the dataset was updated from DNREC to a more recent datum. Therefore, the data were acquired in NAD83 and NAVD88 for horizontal and vertical datum respectively. The data from 1964 to 1998 are only available in 2 dimensional lines in LRP format, where there is information for each point of the elevation and the distance from a reference point. Later survey datasets have recorded position with 3 dimensional information, the prior format is also available for those datasets.

Table 3.1 Available profile surveys for the annual Delaware Coast Survey

Oceanic Coast of Delaware North				Oceanic Coast of Delaware South			
Year	Period	Year	Period	Year	Period	Year	Period
1964	Summer	1998	Spring, Fall	1964	Fall	1998	Spring, Fall
1982	Fall	1999	Spring, Fall	1982	Fall	1999	Spring, Fall
1984	Fall	2000	Spring, Fall	1984	Fall	2000	Spring, Fall
1985	Spring	2001	Spring, Fall	1985	Spring	2001	Spring, Fall
1986	Summer	2002	Spring, Fall	1986	Summer	2002	Spring, Fall
1987	Summer	2003	Spring, Fall	1987	Summer	2003	Spring, Fall
1988	Spring	2004	Summer	1988	Spring	2004	Summer
1990	Spring	2005	Fall	1990	Spring, Fall	2005	Fall
1991	Spring, Fall	2006	Fall	1991	Spring, Fall	2006	Fall
1992	Spring	2007	Spring, Fall	1992	Spring	2007	Spring, Fall
1993	Winter, Summer	2008	Winter	1993	Winter, Spring, Summer	2008	Winter
1994	Spring, Fall	2009	Winter	1994	Spring, Fall	2009	Winter, Fall
1995	Spring, Fall	2014	Spring, Fall	1995	Spring, Fall	2011	Spring
1996	Spring, Fall	2015	Spring	1996	Spring, Fall	2014	Spring, Fall

1997	Spring, Fall			1997	Spring, Fall	2015	Spring

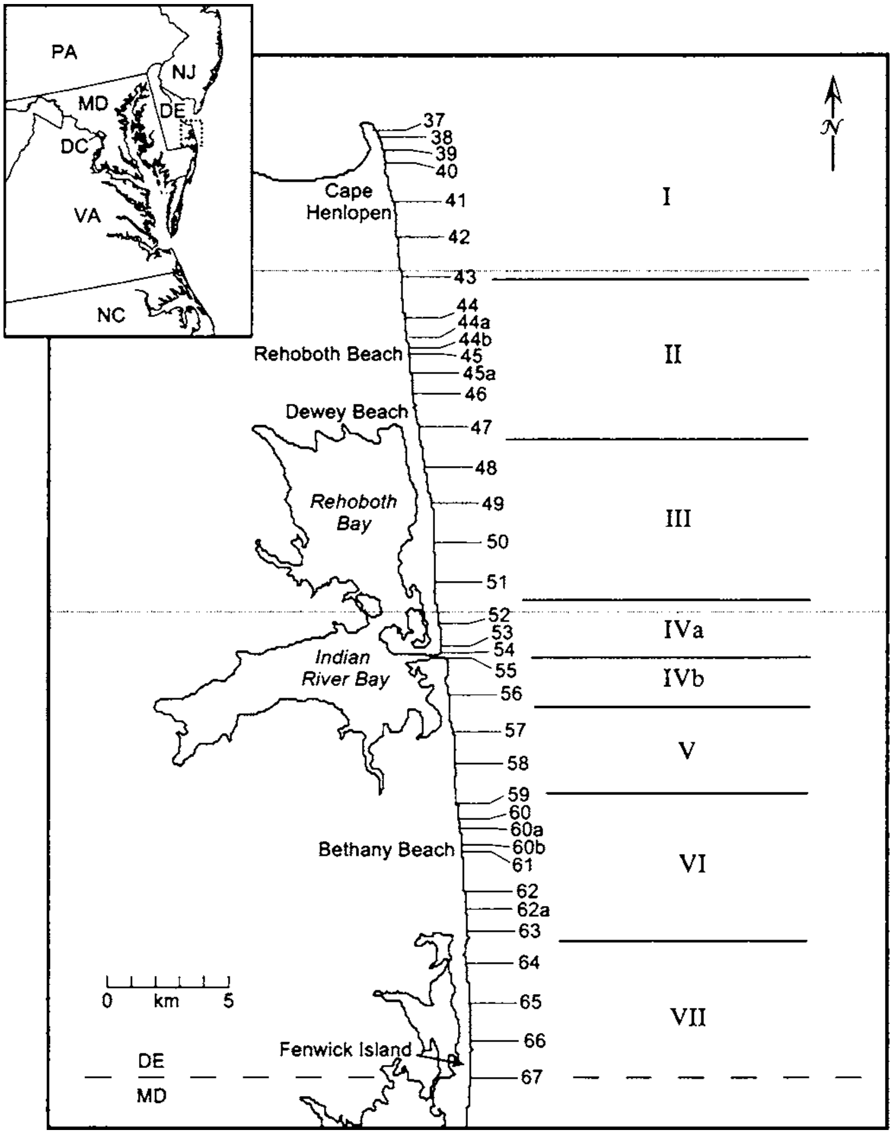


Figure 3.1: Map of LRP profile location at Delaware Atlantic coast

Table 3.2 Corresponding profile of beach nourishment project location

Beach Location	Profile Lines Surveyed
Rehoboth	OC44A, OC45, OC45A
Dewey Beach	OC46, OC47
Bethany Beach	OC60, OC60A, OC60B, OC61
South Bethany Beach	OC62, OC62A
Fenwick Island	OC66, OC67

Most of the profile lines extend from the dune crest to around 800 m offshore with a corresponding depth of 10 m. A couple of surveys covered only the onshore part of the beach with the profile extending from the dune crest to mean sea level. The cross shore resolution of the profile has increased over the year from a point for each 20 m to a point per 2 m in the onshore part and more than half the resolution for the offshore part for the more recent years.

3.1.2 Beach Nourishment Monitoring Surveys

In addition, surveys were conducted following and prior of beach nourishment for monitoring purposes. The nourishment monitoring surveys include only the project area and do not extend for the whole Delaware coast as the LRP system profile. The surveys were conducted a few months before the project commencement and continue for several years following it. The profile was surveyed biannually in order to identify the seasonal change. One survey was held in spring and the second in fall. Two different nourishments were monitored and specifically the first corresponds to the beach nourishment project of the late 90s and the second one to the beach nourishment of the mid-2000s.

3.1.2.1 Late-1990s Nourishment Project Monitoring

For the late 1990s nourishment projects the available data for the locations that are studied in the context of this thesis are bathymetric data for Rehoboth Beach and

Dewey Beach. They cover the years after the projects, from 1999 to 2003 and the available profiles are listed in Table 3.3. The profile lines are more dense in the longshore direction than the LRP profile lines, around one per 150 m and the cross shore resolution is similar, around a point per 10 m. The data are in 3D points, the horizontal coordinates are in state plane referenced in NAD83 horizontal datum and the elevation is referenced to Local Mean Sea Level (MSL).

Table 3.3: Available profile surveys for late 90s Beach nourishment projects

Rehoboth Beach		Dewey Beach	
10 Profile Lines		18 Profile Lines	
Year	Period	Year	Period
		1998	Fall
1999	Spring, Fall	1999	Spring, Fall
2000	Spring, Fall	2000	Spring, Fall
2001	Spring	2001	Spring
2002	Spring, Fall	2002	Spring, Fall
2003	Spring, Fall	2003	Spring, Fall

3.1.2.2 Mid-2000s Nourishment Project Monitoring

The projects of the mid 2000s are grouped in adjacent beaches in three groups: Rehoboth Beach - Dewey Beach. Bethany Beach - South Bethany Beach and Fenwick Island. The locations of those projects also comprise the basis of this study. The profiles were monitored from 2005 to 2013 (3.4). The monitoring surveys mostly took place during the fall months and after major storm events when the potential hazard was investigated due to potential loss of the effectiveness of the fill to protect the urban areas landward. The longshore resolution is similar to the resolution of the previous monitoring surveys with one profile line per 150 m and higher resolution of one point per 5 m. The horizontal coordinates are given in state plane referenced in NAD83 horizontal datum and the elevation is referenced to NAVD88.

Table 3.4: Available profile surveys for mid 2000s Beach nourishment projects

Rehoboth Beach - Dewey Beach		Bethany Beach - South Bethany Beach	
13 Profile Lines – 16 Profile Lines		13 Profile Lines - 11 Profile Lines	
Year	Period	Year	Period
2005	Pre Con, Pre and Post Dredge	2007	Pre Con
2008	Spring	2008	Post Con, Post Mother's Day
2009	Post Ida, Fall	2009	Spring, Fall
2010	Fall	2010	Spring
2011	Fall	2011	Spring, Fall
2012	Fall	2012	Spring, Fall
2013	Post Sandy, Fall	2013	Spring, Fall

Fenwick Island	
17 Profile Lines	
Year	Period
2005	Pre Con, Post Con
2008	Fall
2009	Post Ida, Fall
2010	Fall
2011	Fall
2012	Fall
2013	Post Sandy, Fall

3.1.3 Profile Line for Surf-Zone Injuries Project

The Center for Applied Coastal Research (CACR) of University of Delaware is currently conducting research for the investigation of potential connection of surf-zone injuries with morphological and wave characteristics (Puleo et al., 2016). The data from this study were partially used also for the purpose of this thesis. The data from the study includes surveys of profile lines from three of the studied locations, namely Rehoboth beach, Dewey beach and Bethany Beach. The data contain daily surveys of one profile line of each location during the summer (from early June to mid-August) of 2014 and 2015. The survey covers only the onshore part from the dune foot to low water, since the surveys were conducted during low tide. Since only one profile line is available no longshore features can be resolved. On the other hand the cross shore resolution is high with approximately one point per half a meter and resolves the features of the berm.

3.1.4 Offshore Bathymetric Data

The purpose of this thesis is to determine the effect of beach nourishment on beach morphology and more precisely features of beach profiles from the berm to depth of closure. Therefore, offshore bathymetric data are not relevant for this analysis. However, to increase the accuracy of numerical modeling of beach morphology evolution the offshore part is included. The bathymetric data that were used for this purpose are available in the National Oceanic and Atmospheric Administration website in the National Centers for Environmental Information (NCEI, formerly National Geophysical Data Center - NGDC) and it was used to update nautical charts. Specifically, the bathymetric data used in this thesis were acquired from the H11648 report and the area is sketched with a red box in Figure 3.2 and contains part of the continental shelf south from Indian River Inlet and northern Ocean city, MD. The survey was held from July to November of 2007 with a vessel equipped with multibeam echo sounder and GPS satellite receiver. The survey is provided as a grid with an approximate grid size resolution of 5 by 5 m. Since the bathymetry that is used from this dataset is located farther offshore from the depth of closure, it is assumed that there are not significant changes for the time period which this study is concerned. The horizontal datum is NAD83 with data provided in a geographical coordinate system and the bathymetry is evaluated from the Mean Lower Low Water (MLLW).

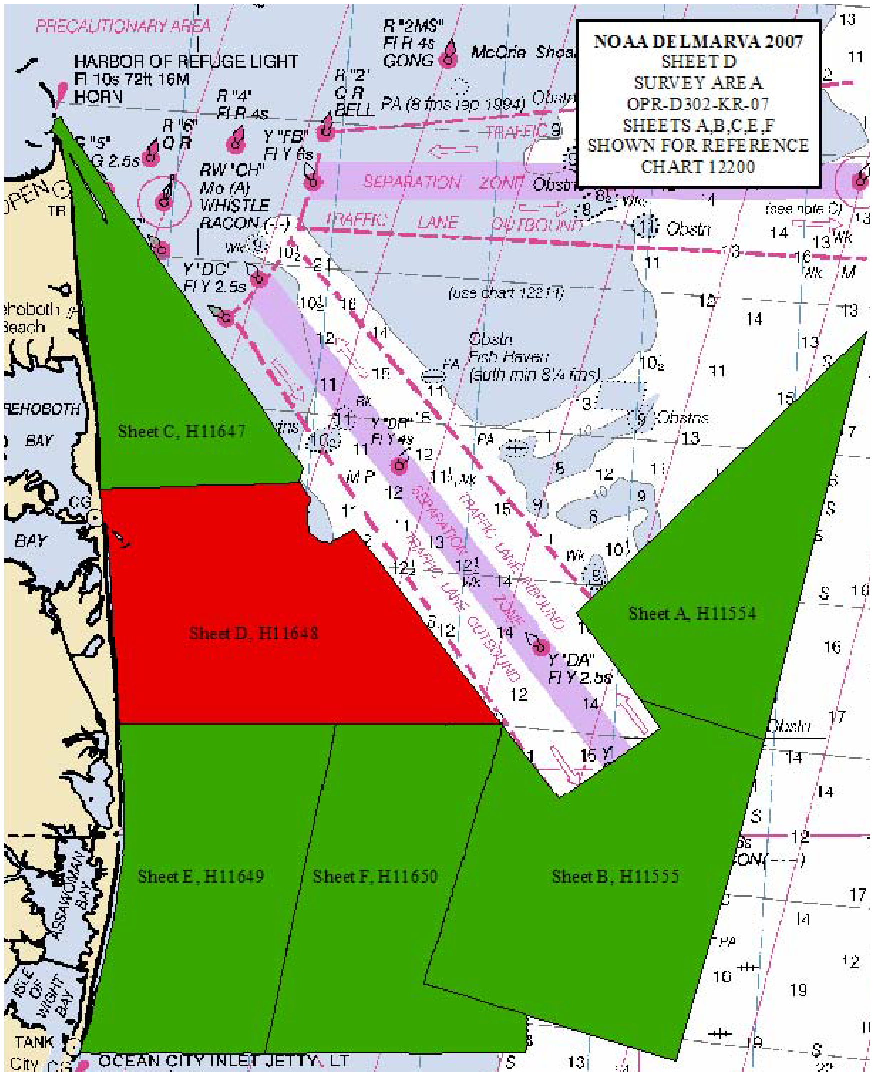
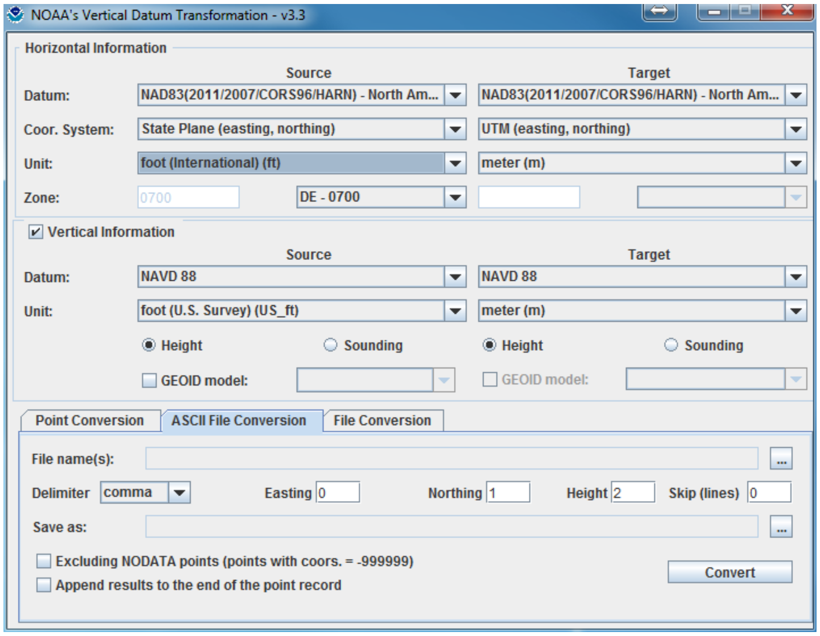


Figure 3.2: Sketch of the survey area over a the nautical chart of the broader area of Delaware Atlantic coast (image is adopted from H11648 report)

3.1.5 Coordinate Systems

The available data sets use different coordinate systems. It is crucial to transform data into a universal system. Transverse Mercator coordinate system (UTM) referenced in NAD83 horizontal datum. The vertical datum is the North American Vertical Datum (NAVD88). For this purpose NOAA's Vertical Datum Transformation (VDatum) software was used, the user interface of the software is shown in Figure 3.3.



NOAA's Vertical Datum Transformation - v3.3

Horizontal Information

	Source		Target	
Datum:	NAD83(2011/2007/CORS96/HARN) - North Am...		NAD83(2011/2007/CORS96/HARN) - North Am...	
Coor. System:	State Plane (easting, northing)		UTM (easting, northing)	
Unit:	foot (International) (ft)		meter (m)	
Zone:	0700	DE - 0700		

☑ Vertical Information

	Source		Target	
Datum:	NAVD 88		NAVD 88	
Unit:	foot (U.S. Survey) (US_ft)		meter (m)	
	● Height	○ Sounding	● Height	○ Sounding
	☐ GEOID model:		☐ GEOID model:	

File name(s):

Delimiter comma Easting 0 Northing 1 Height 2 Skip (lines) 0

Save as:

☐ Excluding NODATA points (points with coors. = -999999)

☐ Append results to the end of the point record

Figure 3.3 User interface of the VDatum software

Even though the older surveys that are used in this study date before the establishment of NAVD88 the data set was already transformed from NAD 1927 and was provided in this NAVD88. However, multiple coordinate systems were used, as Delaware State Plane Coordinate System (Zone 0700) and Geographic system. Therefore, all available bathymetric information was transformed in UTM and

NAVD88. Some of the data are using as reference point local tidal station, in order to transform those vertical information tidal statistics of the surveyed location it is used.

3.1.6 Assortment of Survey Profile Lines

A problem that was raised due to the use of different datasets is the fact that surveys had different profile lines (Figures 3.4-3.6 . For this reason the profile line of the LRP system, since this dataset covers the most part of the history of beach nourishment in Delaware coast was used as the reference profile lines. A mesh was created from the monitoring surveys and the elevation of the LRP profile lines was interpolated in order to recreate the profile line. As for the offshore data the extension of the profile line was interpolated.

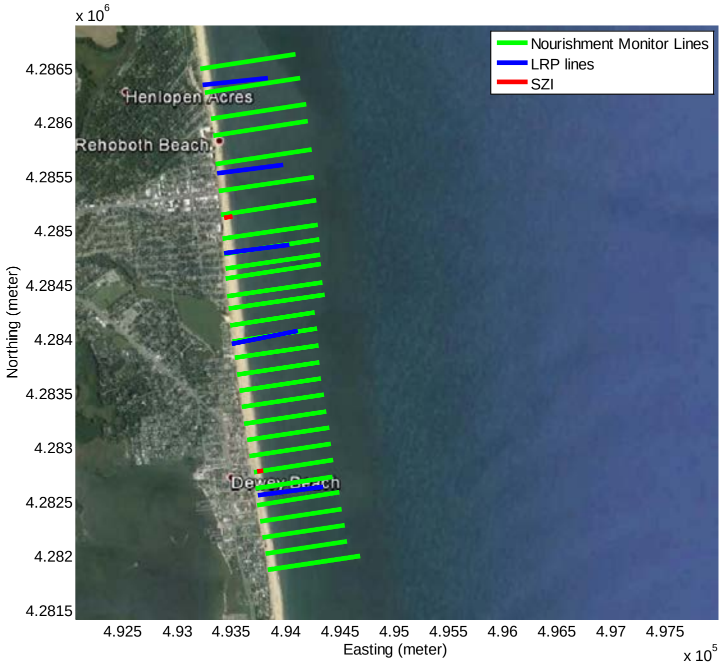


Figure 3.4 Survey locations of Rehoboth and Dewey Beach (Google Earth).

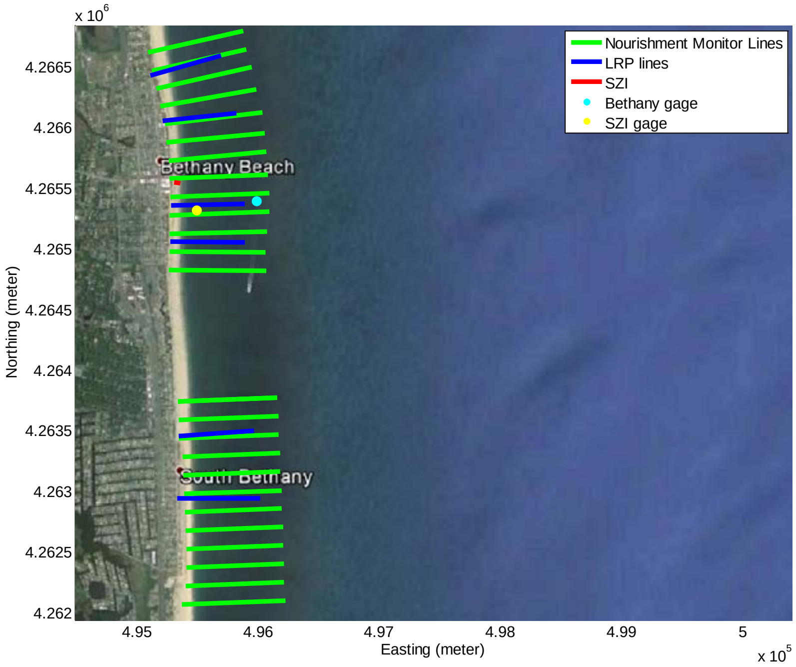


Figure 3.5 Survey locations of Bethany and South Bethaby Beach (Google Earth).

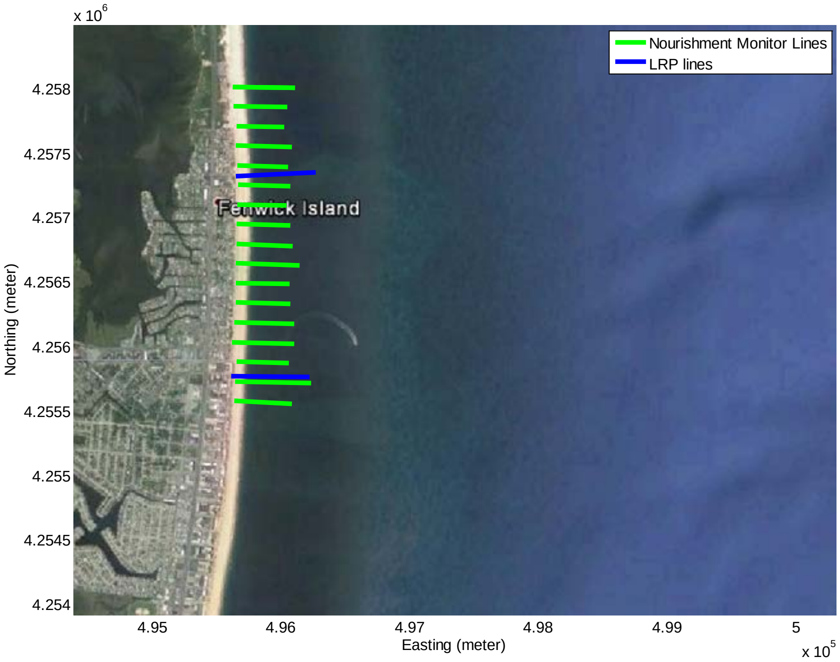


Figure 3.6 Survey locations of Fenwick Island (Google Earth).

3.2 Wave information

Wave information is needed in order to recreate the wave forcing on beach profiles for numerical modeling and also for the investigation of effectiveness of simple models to predict beach profile characteristics. For the purpose of this thesis the significant wave height, peak wave period and peak wave direction were used. The major wave dataset used was collected by the USACE at Bethany Beach at the station number DE003 which is located approximately 650 m offshore (Lat.: 38.5370N & Long.: 75.0460W) with nominal depth of 11.0 m. Hourly data are available starting in 2006 and this station is still running.

Wave information was also collected during the Surf-Zone Injury project with Acoustic Doppler Current Profilers (ADCP). Specifically, the ADCP used in this project were the Nortek Aquadopp, which were placed approximately 50 m offshore in 3 m water depth. The sensor deployment took place in the summer of 2014 and they were placed in the extension of the profile line described in section 3.1.3. The sensor collected hourly pressure and horizontal velocity for roughly 15 min from which wave parameters were calculated. The current data from this dataset were not used in this study.

For this study, wave information from the USACE DE003 was used for the analysis and it was assume to be characteristic for the whole Delaware coast. In addition, the available data contains measurement during the latest nourishment projects and the whole extent of the Surf Zone injury project, for which most part of the wave condition analysis is conducted. The wave information collected in conjunction with the surf injury project was used in order to validate the numerical model used in this study, as the wave characteristics should be predicted from wave propagation towards onshore

3.3 Tidal Information

As described in section 3.1 bathymetries are provided in different vertical reference systems and they are transformed to the NAVD88 reference system. Therefore, it is necessary to identify different tidal information in order to simulate accurately wave propagation and to evaluate different slopes of the beach profile. For each profile line the NAVD88 datum of the corresponding offshore reference point is compared with the datum of Mean Sea Level (MSL), Mean High Water, and Mean Low Water (MLW), this datum transformation is being held with the use of VDatum of NOAA. The results for each beach location are presented in 3.5. The mean sea level elevation is approximately -0.11 m NAVD88, and the tidal range decreases from north to south from 1.18 for Rehoboth Beach m to 1.05 m for Fenwick Island.

Table 3.5: Tidal information for each profile line

Location	**Profile #**	**LMSL**	**MHW**	**MLW**
Rehoboth Beach	OC44A	-0.109	0.471	-0.708
	OC45	-0.109	0.469	-0.706
	OC45A	-0.109	0.466	-0.704
Dewey Beach	OC46	-0.109	0.464	-0.702
	OC47	-0.108	0.460	-0.699
Bethany Beach	OC60	-0.111	0.419	-0.667
	OC60A	-0.111	0.418	-0.666
	OC60B	-0.112	0.417	-0.665
	OC61	-0.112	0.416	-0.665
South Bethany Beach	OC62	-0.112	0.414	-0.662
	OC62A	-0.112	0.413	-0.661
Fenwick Island	OC66	-0.115	0.401	-0.654
	OC67	-0.116	0.398	-0.652

In addition to statistical tidal information, the USACE station DE003 provides hourly water surface elevation, the water elevation is used to ameliorate the prediction of morphology change imposing it as the water elevation of the numerical model coupled with the corresponding hourly wave information.

3.4 Sediment Information

During a beach nourishment project new sediment is placed on the beach. Therefore it is crucial to determine the sediment characteristics before and after the nourishment. The natural sediment information is necessary for the design of the fill and the post-nourishment information will provide explanation for potential alteration of the beach profile and help determine the performance of the nourishment project. The main sources of beach sediment characteristics for the Delaware coast are available reports, and collected sediment from CACR.

3.4.1 Available Reports

The report that gathered all the information for the natural sediment before the nourishment project is “Beach Sand Textures from The Atlantic Coast of Delaware” (Ramsey, 1999) and is an updated version of a previous report that was conducted by the Delaware Geological Survey to identify onshore sediment resources for beach nourishment. The coast is divided in 40 segments that are aligned with the LRP lines, therefore the information of this dataset is averaged over the area of each study location. It is noteworthy that there was not a systematic sampling of each location. The period of the study comprises 55 years (1929 to 1984) prior to the major nourishment projects that altered the sediment characteristics. The part of the profile where the samples were collected varies from the mid-tide zone, the mean high water, and across the profile.

Other available reports are the USACE grain size data for Delaware coast which analyzed sediment samples collected in 1993 for the whole extent of the coast. A single sample was analyzed for each LRP line. In addition, USACE analyzed sediment samples collected in winter 1992 and summer 1993 for Dewey and Rehoboth beach. This analysis was conducted as part of the feasibility analysis of the corresponding nourishment projects. The samples were collected from 10 locations for each site. However, the part of the profile that was sampled was not mentioned. There has been an evaluation of sediment of potential sources (McKenna & Ramsey, 2002) but there is no analysis of the actual sediment that was placed during the nourishment.

In addition to grain sizes that are available from previous studies, sediment samples in the CACR repository were analyzed. The first set of sediment samples was collected in 1985 from all sites but the purpose and the part of the profile that the samples were collected was not mentioned. The second set contains sediment samples that were collected in conjunction with the SZI study during the summer of 2014 and 2015. Each SZI profile was sampled in two locations, the berm crest and the swash zone. Therefore, there are two daily sediment samples and the corresponding profile for the consecutive summers of 2014 and 2015, the total number of sediment samples is approximately 1500 since 5 sites were sampled. For the purpose of this study only the berm samples were analyzed as the sediment information of former years was similarly collected. Analysis of the sediment was conducted by two methods, the first one was by sieving of the samples which is more robust but is highly time consuming and the second one is from an imaging technique that is less reliable but more time efficient.

3.4.1.1 Sieving Technique

This is the most robust method and the result of this analysis will be also used to validate and calibrate the result of the imaging technique. Only 10 % of the berm samples were sieved (1 for each 10 days), whereas the rest of the grain size data were obtained through the imaging technique. The samples were first dried and weighed, with weights from 70-120 g. Afterwards the sediment was placed in a stack of sieves with a decreasing opening with intervals of at least 0.5 Φ, ranging from -1.0 Φ (2 mm) to 3.5 Φ (90 microns) and afterwards the sediment was separated according to its grain size using a shaker that was agitated for 12 minutes. Each sediment segment was weighed in order to calculate the relative percentage of it and checked with the total weight of sample for potential loss or contamination of the sediment from previous sediment that was stuck in the sieves.

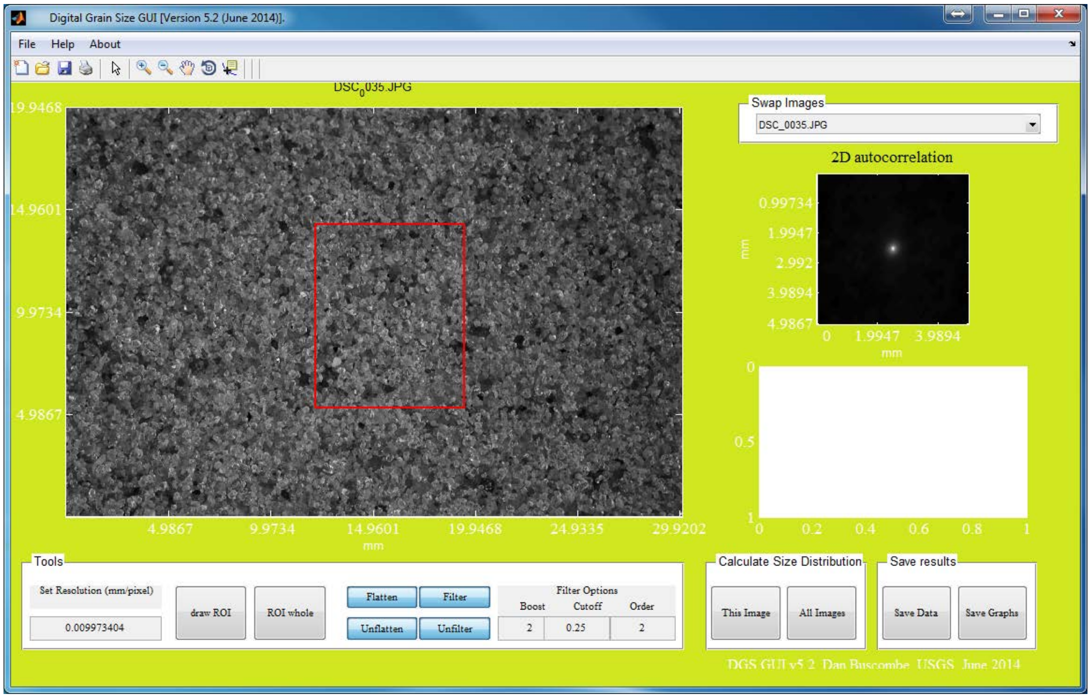
Figure 3.7 Stack of sieves that was used to obtain sediment grain size

3.4.1.2 Imaging Technique

In order to have a more complete image of the evolution of grain size over each summer, an imaging technique was used for taking photos of the sediment samples. The photos that were analyzed were taken from a stand shown in Figure 3.8 to minimize the changes in the covered area of the image and the focus, 2 light sources were attached in the stand to provide adequate and evenly distributed light over the sample to improve the image quality. The camera (Nikon D70s) was equipped with a macro lens (Sigma 50mm F2.8 DG macro) to produce a close up image shown in Figure 3.8.b. The photos of 3008 x 2000 pixels represented a length of 3 cm in reality which means that for a typical grain with diameter of 0.3 mm it would be pictured as 30 pixel diameter in the photo. In order to improve the credibility of this technique 5 images were taken for each samples and they were compared with the available sieved data. The 5 calculated grain sizes were sorted in increasing order and was weighted averaged in order to minimize the error between the estimation and the actual median grain size.

The script that was used was developed by Buscombe (2008) and uses wavelet transformation of the image in order to provide grain size distribution. A GUI of the script can be seen in Figure 3.9. The script was mainly developed for well sorted sediment and therefore only the median grain size information was taken into account. The center part of the picture (red box in Figure 3.9) was selected to be analyzed since the camera was selected to focus in the center. In addition, the box was big enough to contain enough grains to create a reasonable estimation but small enough to minimize the evaluation of unrealistic grain sizes.

Figure 3.8 a) the stand of the camera, b) a picture of a typical sediment sample



Swap Images: DSC_0035.JPG

Set Resolution (mm/pixel): 0.009973404

Filter Options

Boost	Cutoff	Order
2	0.25	2

Figure 3.9 GUI of the Matlab script to evaluate grain size distribution from a photo

3.4.2 Assortment of Sediment Information

This study uses all available aforementioned sediment information sources. Tables 3.6 and 3.7 provide all the information of the median grain size and the sorting in mm for all the years that are available. If a site was sampled in multiple locations or dates, the information was averaged in order to provide one characteristic value for each study. The presented information for the sediment samples of the SZI project is the mean value of the 10 sieved samples. The sediment information obtained from imagining technique is not included as they consist of less reliable data.

Table 3.6 Median grain size of each beach location in mm

Year	Rehoboth Beach	Dewey Beach	Bethany Beach	South Bethany Beach	Fenwick Island	Sampled Location	Source
1929					0.30	MHW	Ramsey Report
1936	0.39	0.54	0.40		0.35	MT	
1950	0.35		0.22		0.20	MHW	
1954	0.60	0.58	0.46	0.27	0.41	PFL	
1964		0.35	0.31		0.21	PFL	
1974	0.40					PFL	
1981			0.45	0.50		PFL	
1985	0.34	0.38	0.35	0.43	0.39	ND	CACR
1992	0.32	0.33				PFL	USACE
1993	0.29	0.28	0.26	0.29	0.25	PFL	
1993	0.34	0.31				PFL	
2014	0.41	0.39	0.37			BM	SZI
2015	0.39	0.37	0.33			BM	
	MHW: Mean High water PFL: Across Profile			ND: Not Mentioned BM: Berm		MT: Mid-Tide	

Table 3.7 Sorting of the grain sizes (standard deviation) for each beach location in mm

Year	Rehoboth Beach	Dewey Beach	Bethany Beach	South Bethany Beach	Fenwick Island	Sampled Location	Source
1929					0.08	MHW	Ramsey Report
1936	0.14	0.17	0.10	0.14	0.09	MT	
1950						MHW	
1954	0.20	0.17		0.08	0.11	PFL	
1964	0.12			0.07	0.06	PFL	
1974	0.24			0.21		PFL	
1981			0.21	0.16		PFL	
1985	0.11	0.09	0.10	0.14	0.10	ND	CACR
1992	0.13	0.12				PFL	USACE
1993	0.20	0.20	0.23	1.12	0.18	PFL	
1993	0.20	0.13				PFL	
2014	0.18	0.16	0.16			BM	SZI
2015	0.19	0.18	0.14			BM	

Chapter 4

PROFILE BEACH ANALYSIS

4.1 Beach Slopes

The available profile lines were analyzed in an attempt to evaluate the impact of the beach nourishment on beach morphology. The nourishment can affect the beach profile in various ways. First, the placement of the fill extends the berm offshore and makes the beach steeper. Second, the design template slope which, most of the time is steeper than the natural beach, initially can alter the morphology. However, it is reported that the profile recovers to its natural shape after few months (Komar, 1998). Furthermore, the grain size of the fill, if it is different from the natural beach, can result in a different equilibrium profile. The evolution of the morphology through the succeeding surveys as shown in Figure 4.1 cannot be determined and therefore the profile is divided into segments according to beach features. Those beach features are the berm crest, the tidal zone and the depth of closure.

The berm is the horizontal feature of the beach that is developed due to the deposit of sediment by waves and therefore is located onshore of the foreshore. The berm crest is defined as the location where the beach profile becomes horizontal and is closer to the wet portion of the beach. For the cases that there is no flat region in the dry part of the profile the location with the smallest slope was chosen. A characteristic berm height was chosen for each location presented in Table 4.1 after the evaluation of the berm height for all available surveys.

Table 4.1 Characteristic berm height for different beach locations

Location	Rehoboth Beach	Dewey Beach	Bethany Beach	S. Bethany Beach	Fenwick Island
Characteristic Berm Height (m)	1.75	1.65	1.8	1.8	1.75

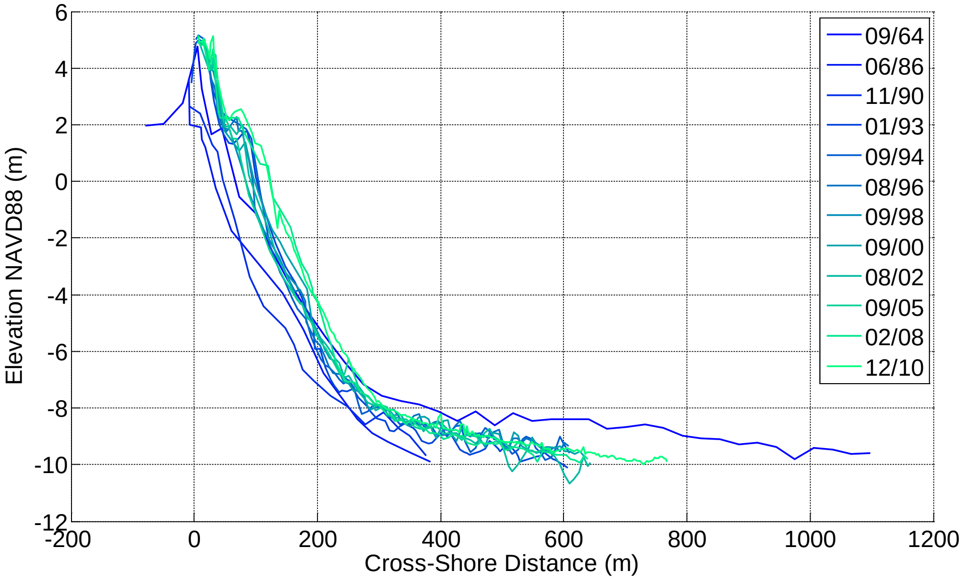


Figure 4.1 Example of beach profile evolution for Bethany Beach (OC 60)

Depth of closure (DoC) is the depth from which the profile is not subject to morphological changes, this is not a result of lack of sediment movement but rather because of the relatively small net sediment transport. The mean beach profile and the standard deviation around it is evaluated with the intent to determine the depth of closure. Example of this evaluation is depicted in Figure 4.2 where the variance is multiplied by the factor of 10 in order to be distinguishable on the same scale with the profile line. The variation in the profile is small for the dune as the dune is only subject to aeolian transport. The variation of the profile is maximum close to the mean shoreline as this part of the profile is subject to wave induced transport and fill placement. The variation gradually decreases moving offshore and reaches a plateau where it is considered to be the depth of closure. The variation can be higher offshore and is explained due to the fact that more offshore surveyed points are less reliable and tend to be noisy. Table 4.2 presents the evaluation of the depth of closure for each profile, the median of them was chosen as the characteristic depth of closure for Delaware coast as 8.2 m which is slightly larger than the estimated depth of closure from previous studies with values for depth of closure of 7.3 m (Garriga and Dalrymple, 2002) and 7 m (Figlus, 2007).

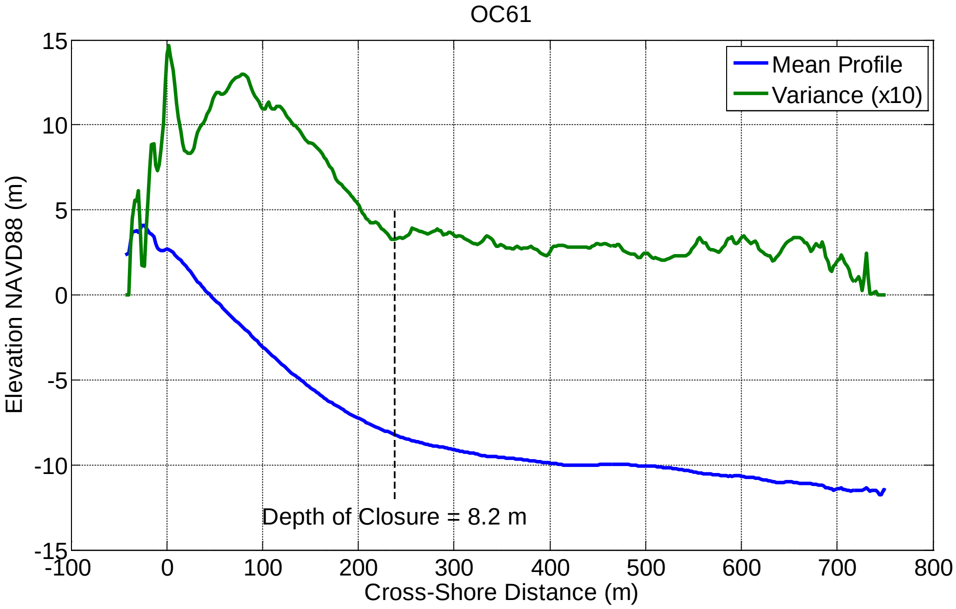


Figure 4.2 Example of evaluation of depth of closure

Table 4.2 Evaluation of depth of closure for different profile lines

Profile Line	Depth of Closure	Profile Line	Depth of Closure	Profile Line	Depth of Closure
OC44A	7.4	OC60	8.5	OC62	7.6
OC45	8.3	OC60A	7.8	OC62A	7.6
OC45A	7.6	OC60B	9	OC66	8.1
OC46	8.7	OC61	8.2	OC67	9.7
OC47	9.4				

The different definitions for beach slope that result from these distinct features are represented in Figure 4.3. Where the definitions include the slope of foreshore, beach face, wading zone, the extent of the beach from berm to DoC and the extent of the beach from MSL to DoC.

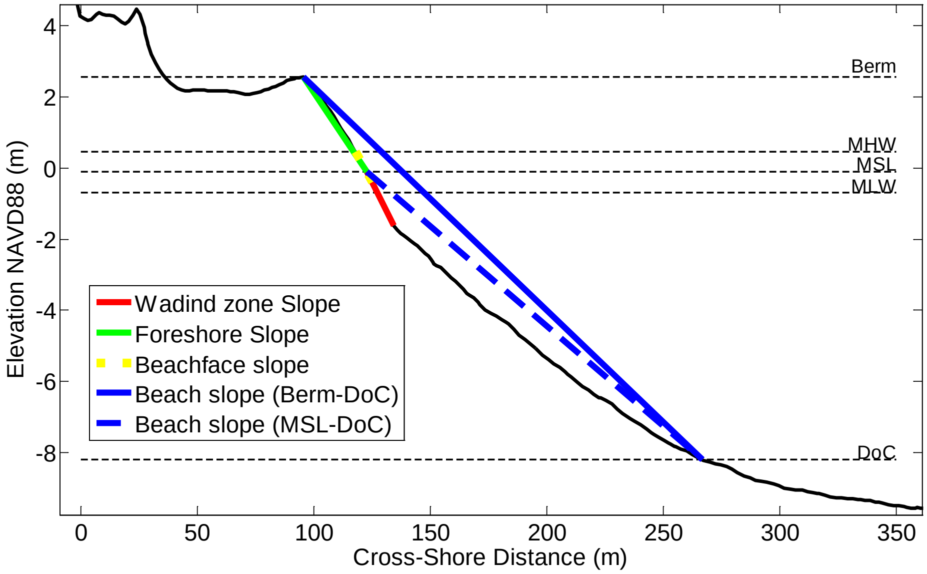


Figure 4.3 Schematic representation of different slope definitions

4.1.1 Beach Face Slope

The beach face slope is defined for the purpose of this study as the linear slope of the profile from MHW to MLW. The vertical datum information for each profile is provided in Table 3.5 and they are transformed in horizontal position with linear interpolation among the surveyed points with the closest elevations. The beach face slope is evaluated because it is the steepest part of the beach and has been used in analytical model as in the modified equilibrium profile. Figures 4.4-4.8 show the evolution for beach face slope for each location where the dot denotes the average slope and the line the range for the available profile for each location, the blue dot represents the slope evaluated from LRP surveys and green dots are slopes evaluated from monitoring surveys of nourishment projects. The left axis of the figures provides the reading of slope as ratio of 1 m depth over the horizontal length and the right axis provides the reading of the slope as a percentage. There is no clear and constant trend for beach face slopes among the different locations. For Rehoboth Beach a decrease of the slope is observed for the period after the first nourishment of 1998 until the nourishment of 2005. For Bethany Beach a gradual increase of the slope is observed.

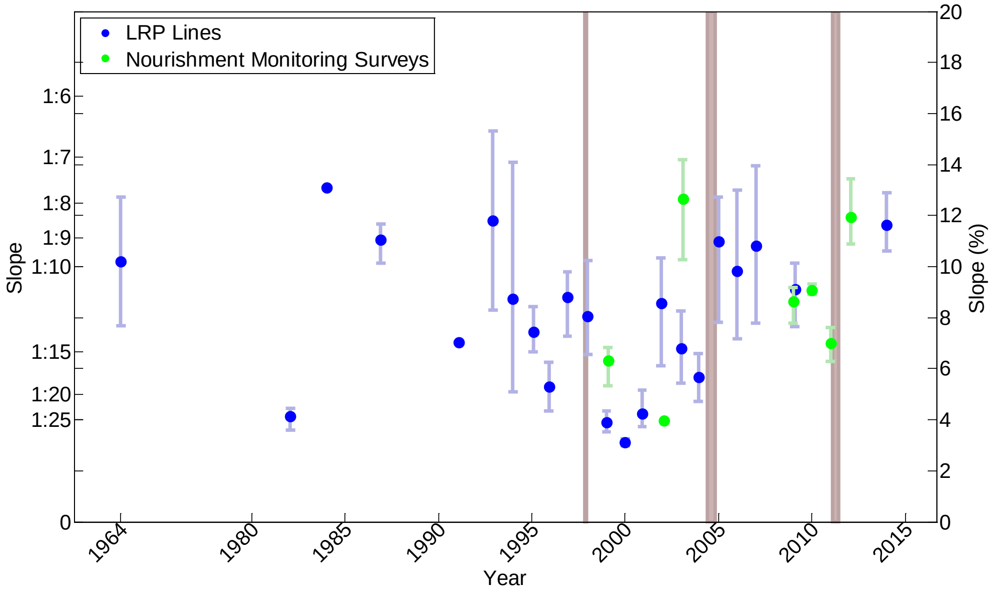


Figure 4.4 Rehoboth Beach

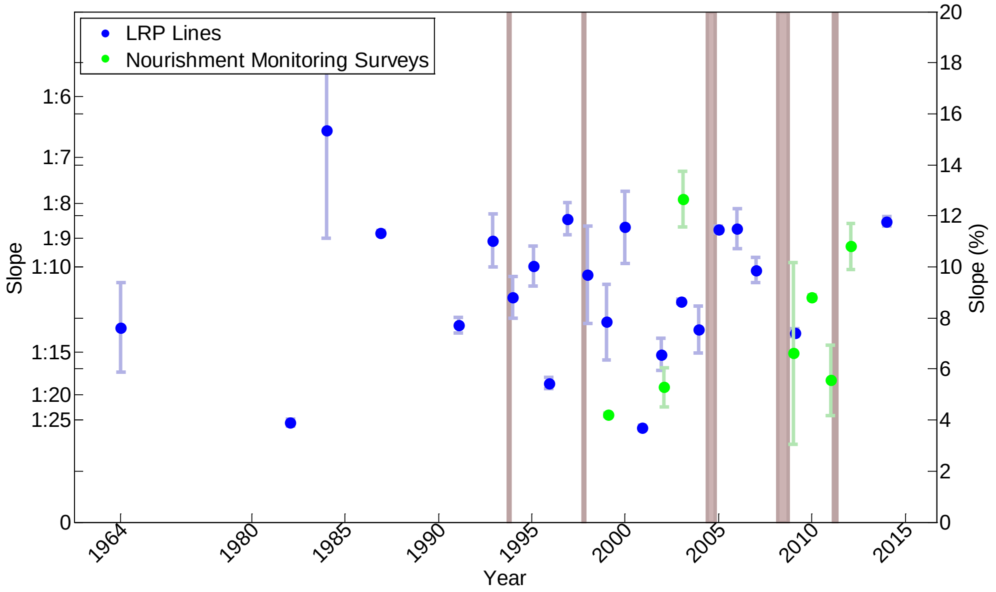


Figure 4.5 Dewey Beach

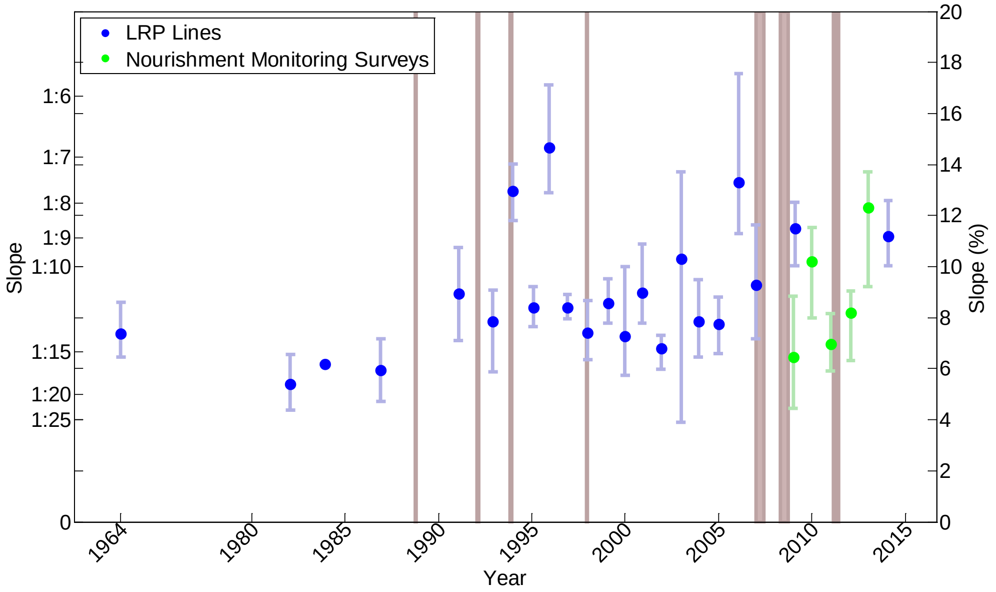


Figure 4.6 Bethany Beach

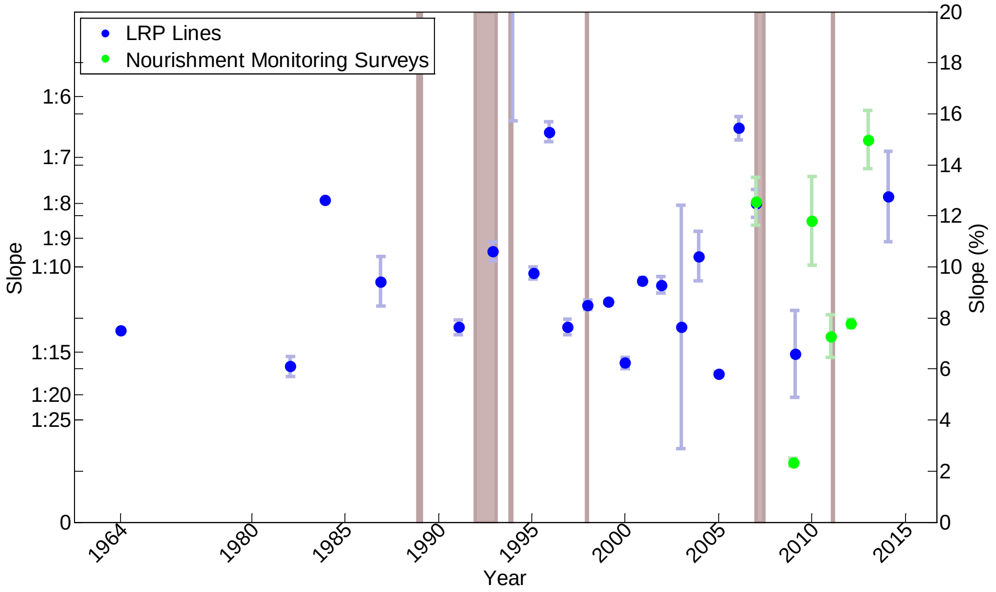


Figure 4.7 South Bethany Beach

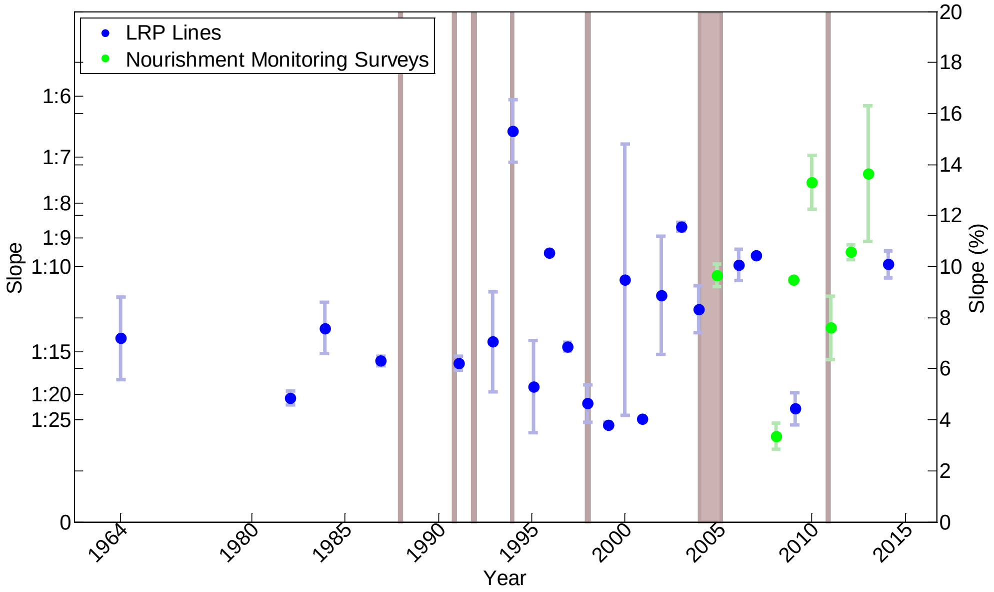


Figure 4.8 Fenwick Island

The aforementioned slopes are calculated from surveys conducted in a single day, the daily evolution of the beach face slope is evaluated for summer 2014 and 2015 where the surveys are available. The range and statistics are provided in Table 4.3. The range of slopes for extent of the time that surveys were available are similar to the range of slopes observed over a summer. Therefore, the yearly surveys are not adequate to provide a definitive conclusion for the modification of beach face slope due to beach nourishment.

Table 4.3 Statistics of beach face slope for summer 2014 and 2015

	Year	Mean (%)	Median (%)	Range (%)
Rehoboth Beach	2014	11.56	11.74	7.94-19.27
	2015	10.97	11.32	4.20-14.8
Dewey Beach	2014	12.37	12.71	7.87-15.32
	2015	10.89	11.35	4.24-15.79
Bethany Beach	2014	10.21	11.48	2.62-14.37
	2015	11.63	11.80	4.73-19.49

The range of beach face slope can be explained with variation of the wave climate over a summer. Therefore the non-dimensional parameter $\mathrm{H}_b/\mathrm{g}^{0.5}\mathrm{D}^{0.5}\mathrm{T}$ (Sunamura, 1984) was implemented to investigate this relation. Figure 4.9 shows the relation of this parameter and the beach face slope for summer 2014 and 2015. The slope can be described as inversely proportional to the square of the non-dimensional parameter, similar to previous studies. The coefficient of proportionality is equal to 0.15 instead of 0.12 that was suggested in the original work. Hence, the beach face slope is subject to change according to wave and sediment size modulations.

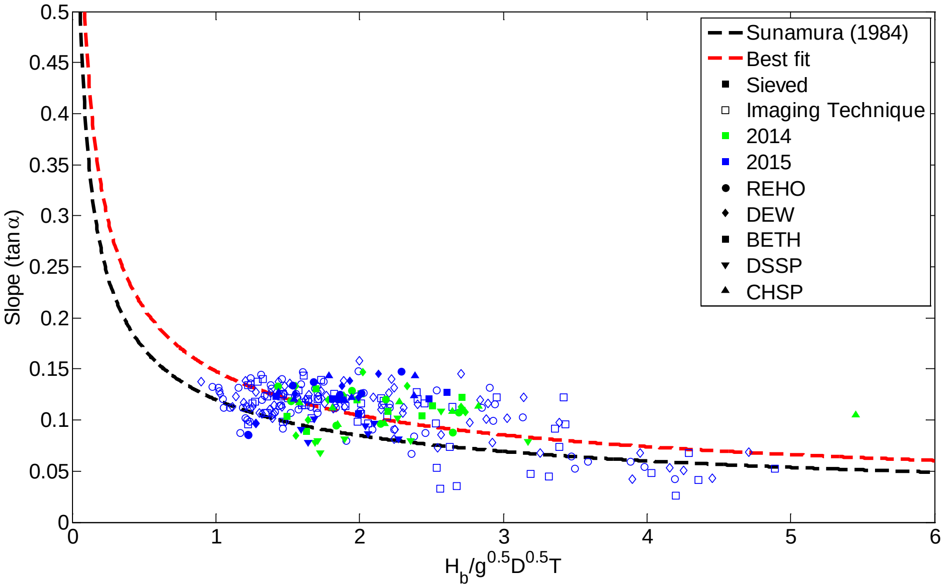


Figure 4.9 Beach face slope versus the dimensionless parameter $H_b/g^{0.5}D^{0.5}T$

4.1.2 Foreshore Slope

Foreshore slope has a similar definition as beach face slope being the linear slope between the berm and the mean sea level. The berm location was found with the characteristic berm height proposed in Table 4.1 and the mean sea level from the elevation provided in Table 3.5. The significance of this part of the profile lies on the fact that it is the slope that a beach user perceives as beach slope as the user enters in the sea. The evolution of the foreshore slope is provided in Figures 4.10-4.14 with the same figure configuration as with the beach face slope. The foreshore slope has a slightly milder slope around 1-2 %, as expected due to the fact that the foreshore region reaches the berm which is horizontal. For the foreshore slope, there is no clear and constant trend among the different locations.

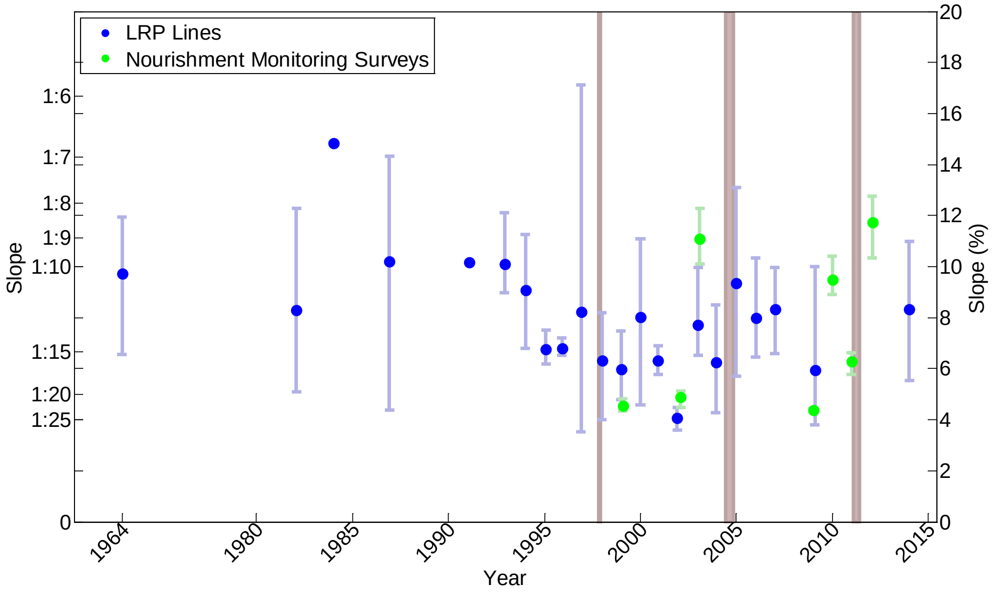


Figure 4.10 Rehoboth Beach

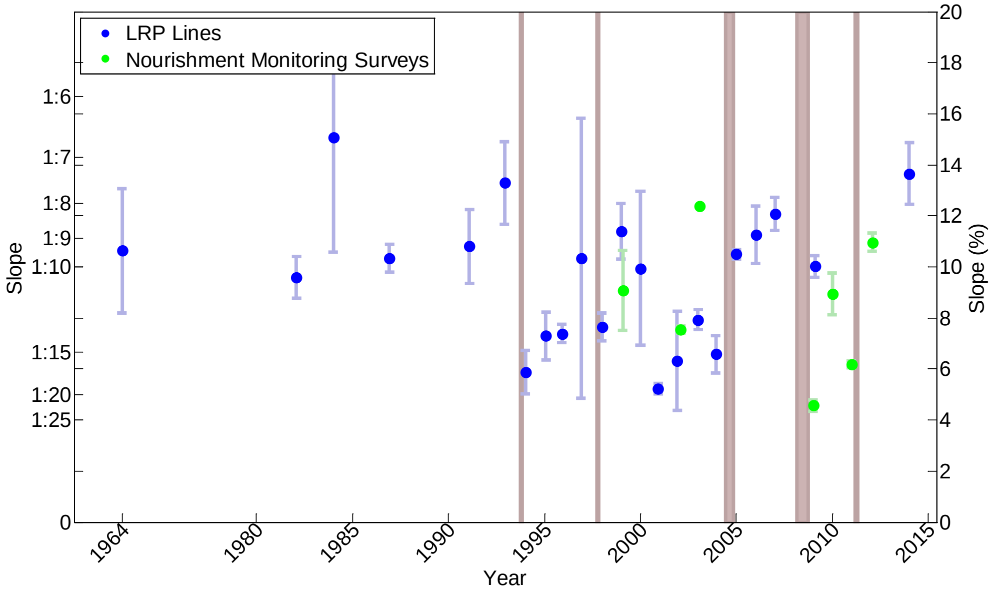


Figure 4.11 Dewey Beach

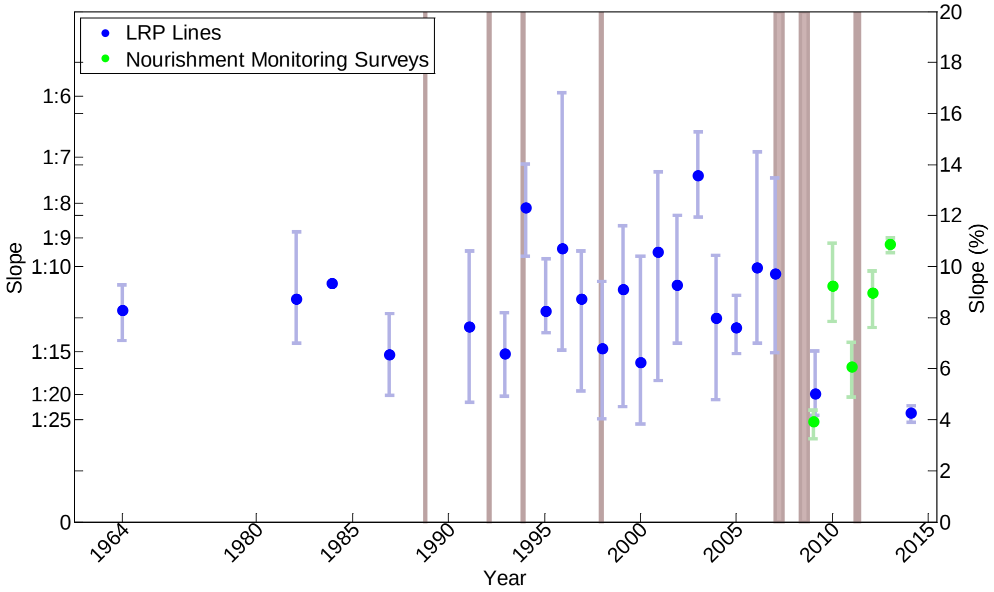


Figure 4.12 Bethany Beach

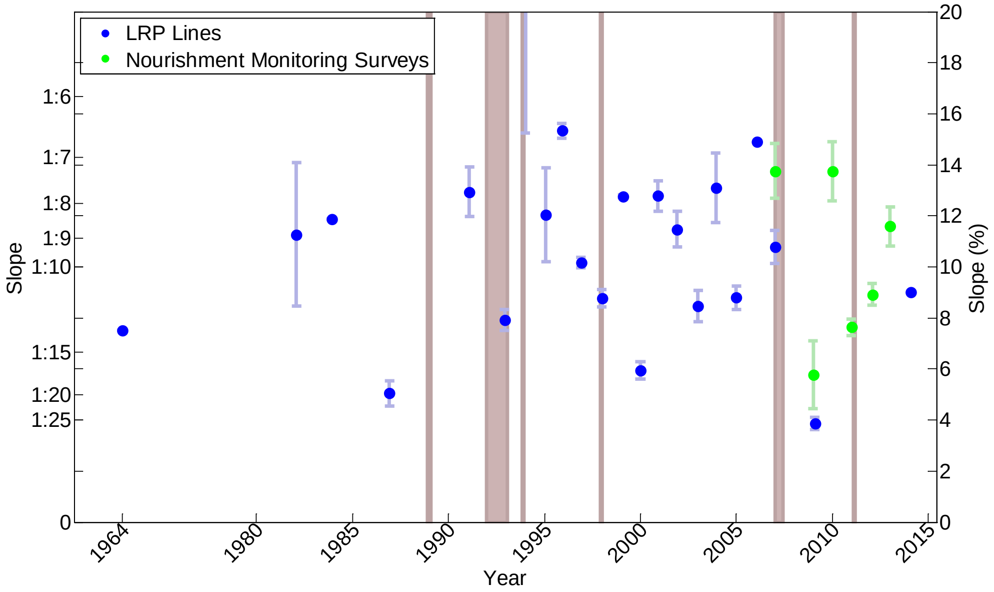


Figure 4.13 South Bethany Beach

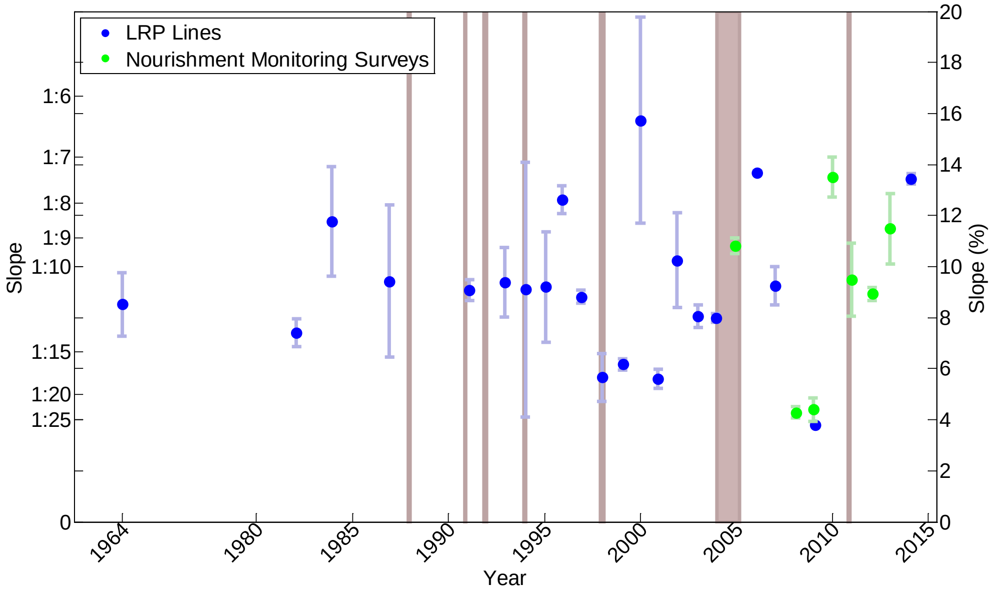


Figure 4.14 Fenwick Island

4.1.3 Wading Zone Slope

The wading zone is the part of the beach that beach users can wade, the water depth that was considered for this study is 1.5 m, as an average person could stand in that depth. The slope is defined as the linear slope between the mean sea level and the depth of 1.5 m and the evolution of the slope is provided in Figures in 4.15-4.19. The wading zone slope is milder than the previous definitions as moving from the foreshore to offshore the beach profile becomes milder sloping. This part of the profile is usually part of the inner surf zone.

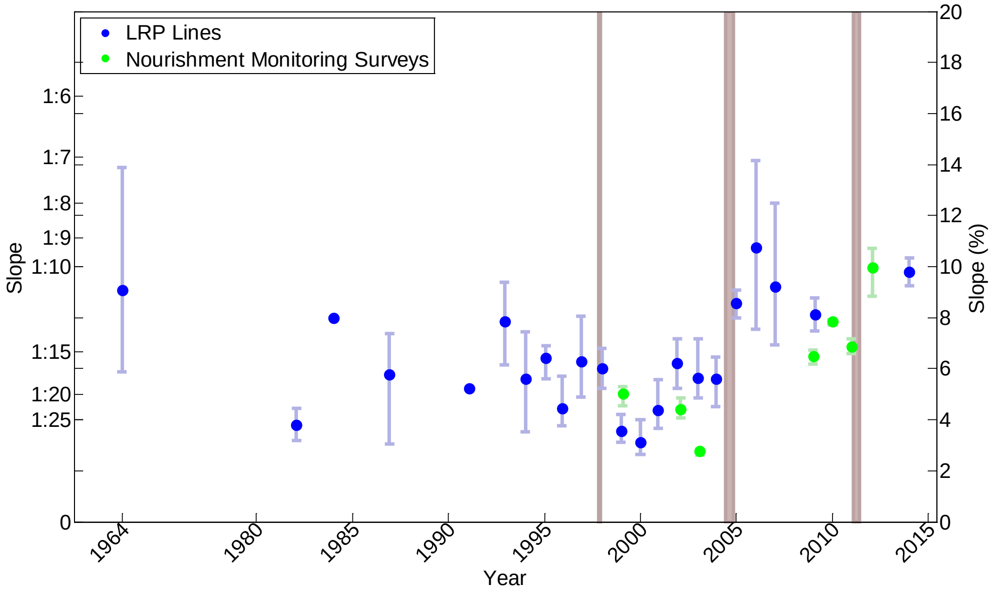


Figure 4.15 Rehoboth Beach

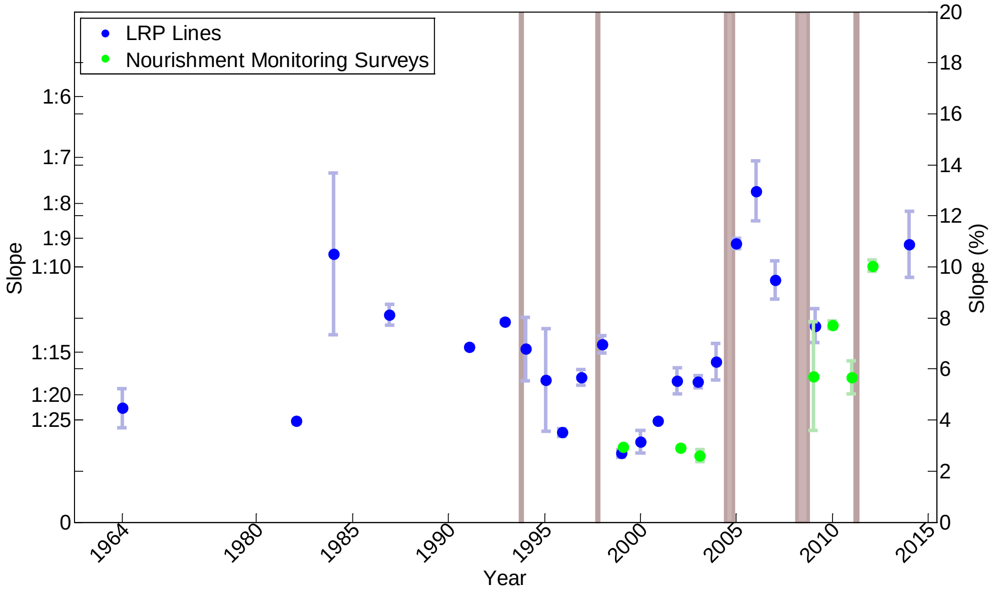


Figure 4.16 Dewey Beach

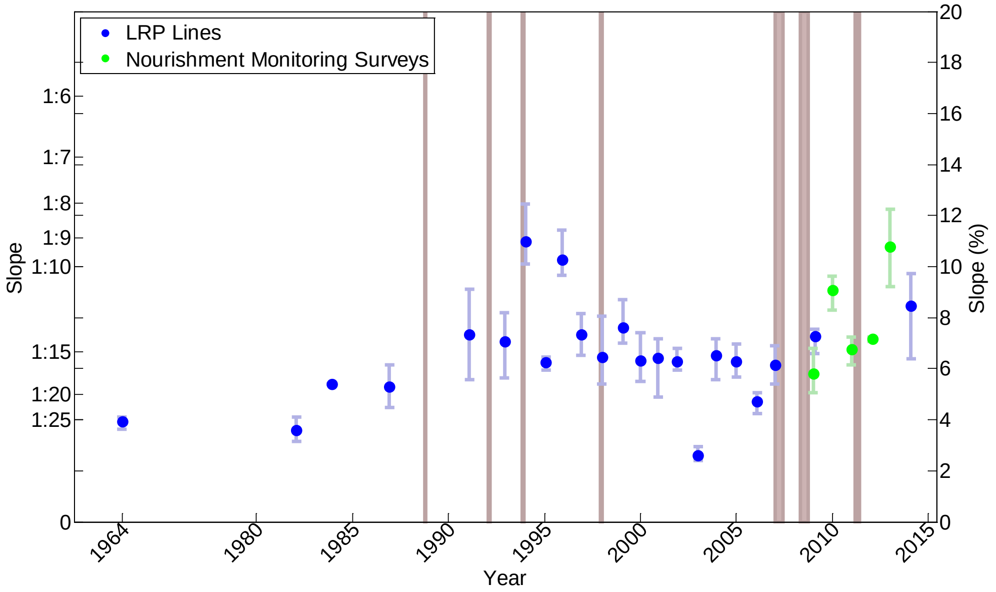


Figure 4.17 Bethany Beach

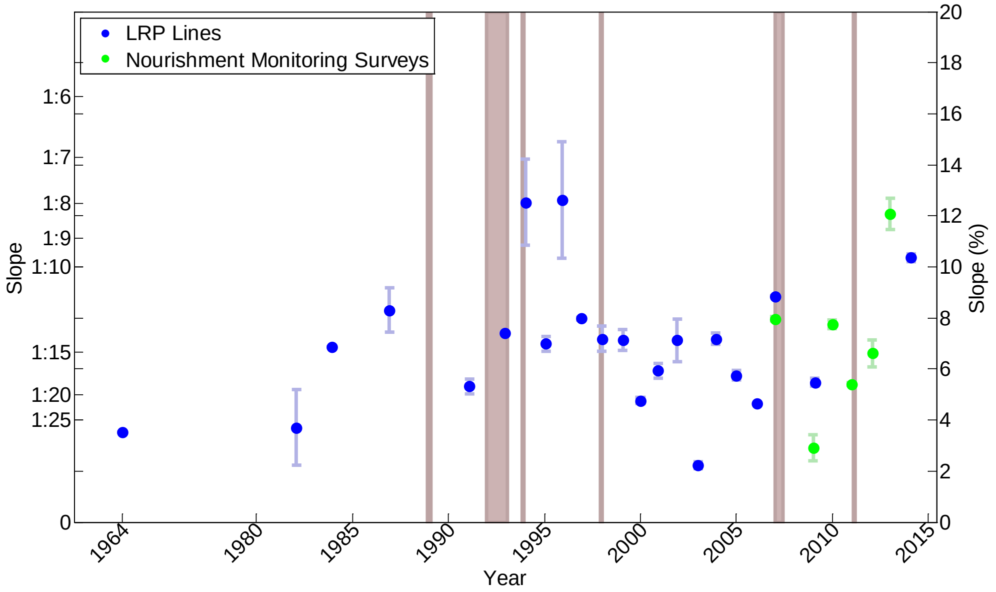


Figure 4.18 South Bethany Beach

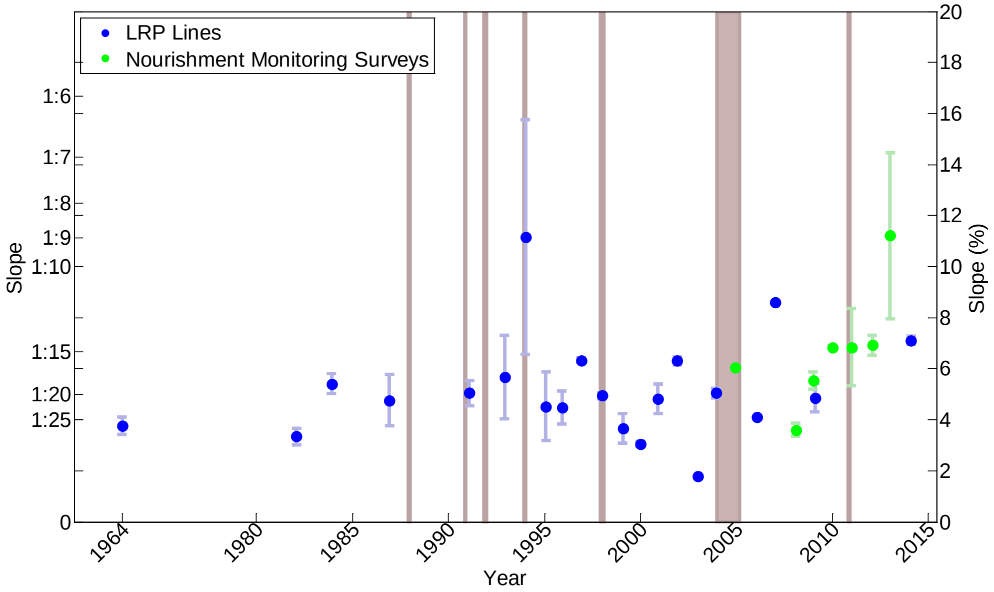


Figure 4.19 Fenwick Island

4.1.4 Beach Slope (MSL-DOC)

The previous definitions of slope include parts of the beach as the swash zone and the inner surf area, therefore they exclude any information for wave transformation. Subsequently the slope definition of the beach profile from the MSL to DoC is introduced. In this part of the profile the morphodynamic process is taking place from the definition of DoC and also affects the wave transformation from deep water to shallow water. The evaluation of this slope is provided in Figures 4.20-4.24. There is an increase of the beach slope for post nourishment measurements. The placement of the fill extends the shore and decreases its distance from DoC. These observations are more pronounced for the beach nourishment of mid 2000s when the fill volume was larger. For most cases there is a decrease of the slope between consecutive nourishments which can be explained as a result of the erosive pattern that Delaware coast has. In this case the retreat of the shore increases the length between the MSL and the DoC and therefore decreases the slope. In cases that the opposite trend is observed, a possible explanation could be a short term modification due to storm event prior of the surveys, and a recovery of the profile after the survey.

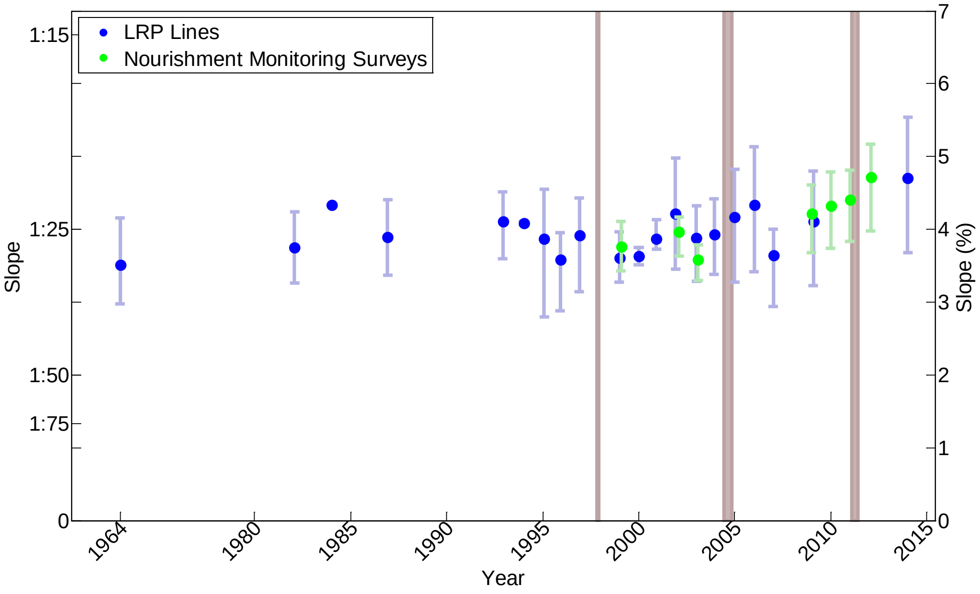


Figure 4.20 Rehoboth Beach

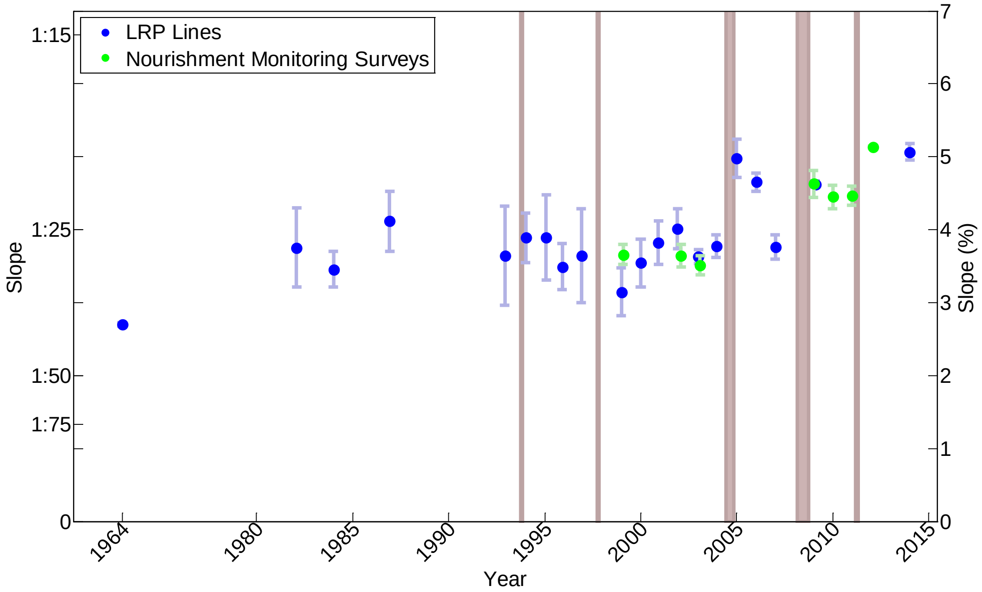


Figure 4.21 Dewey Beach

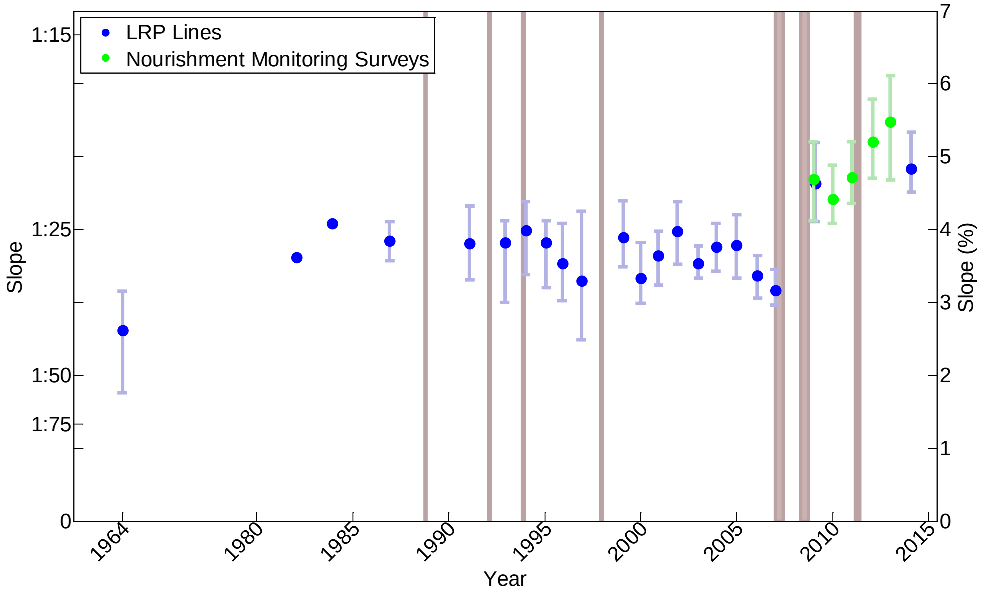


Figure 4.22 Bethany Beach

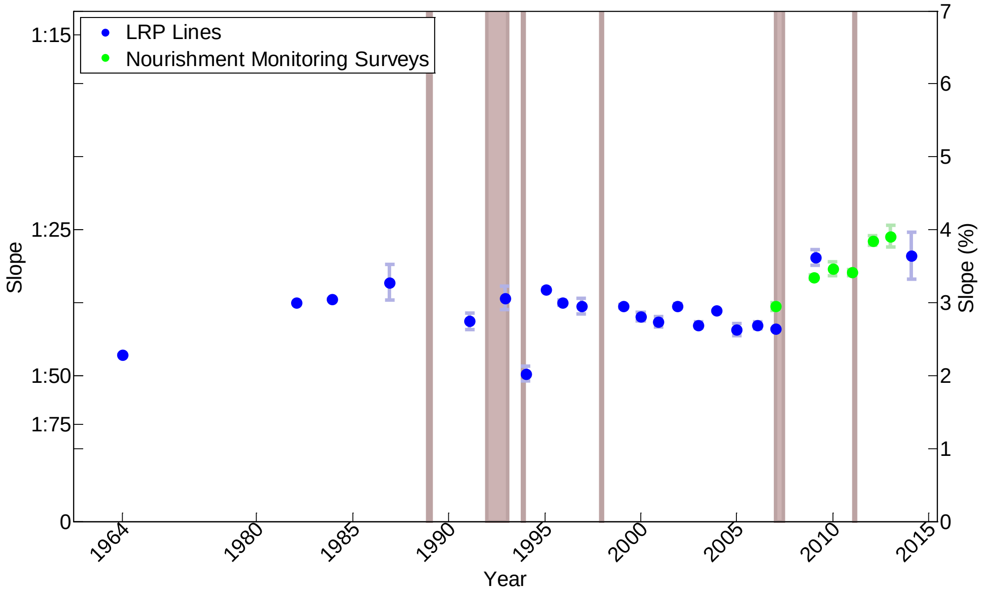


Figure 4.23 South Bethany Beach

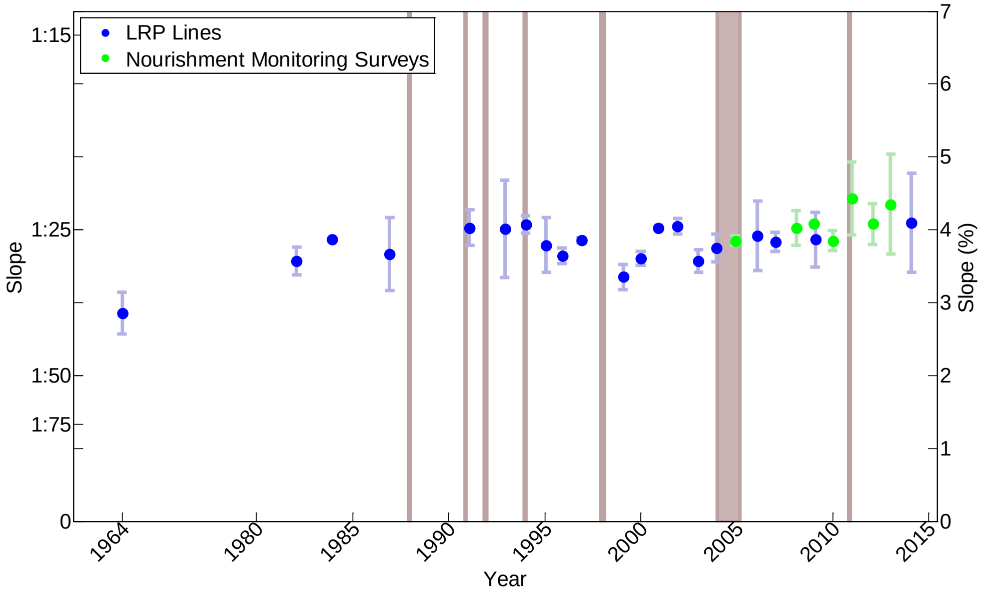


Figure 4.24 Fenwick Island

4.1.5 Beach Slope (Berm-DOC)

Similar to the previous definition is the linear slope of the beach extent from the Berm to DoC, this definition was used also in Bruun's rule as the average slope of the active profile and is significant for the beach response to the sea level change. This definition has slightly larger slopes (increased by 0.25%) than the slope of the beach extent from MSL to DoC as it contains the foreshore which is the steepest part of the beach.

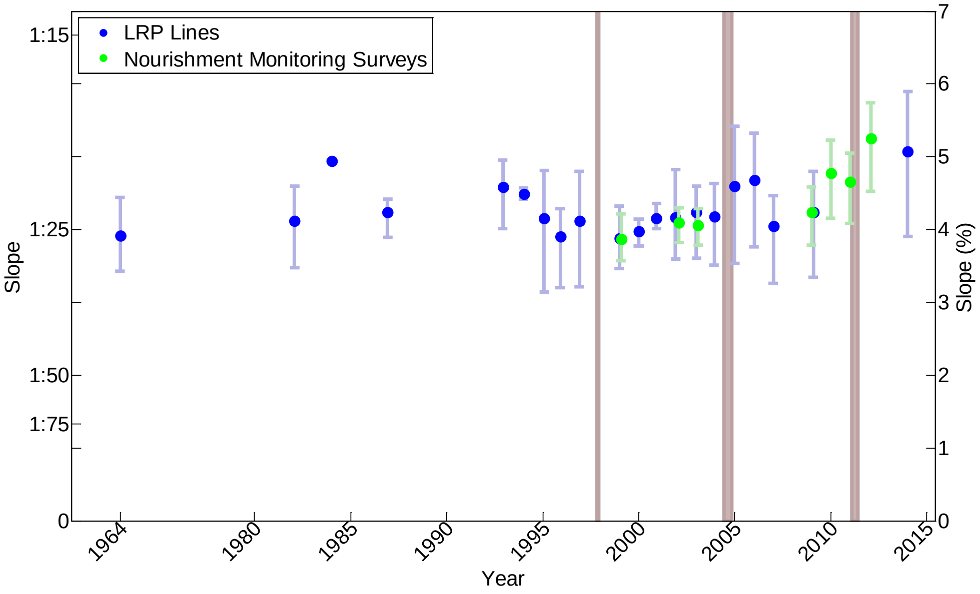


Figure 4.25 Rehoboth Beach

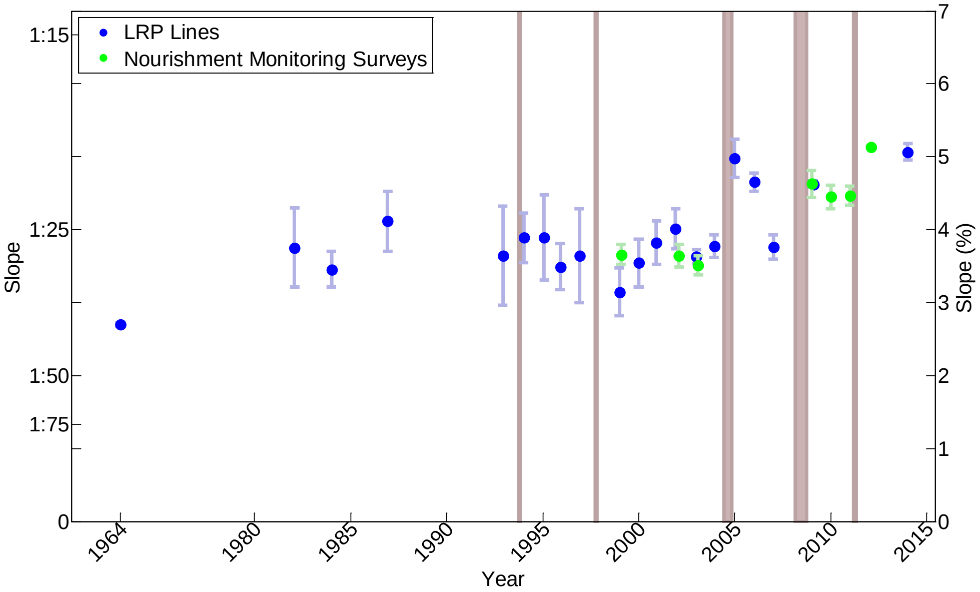


Figure 4.26 Dewey Beach

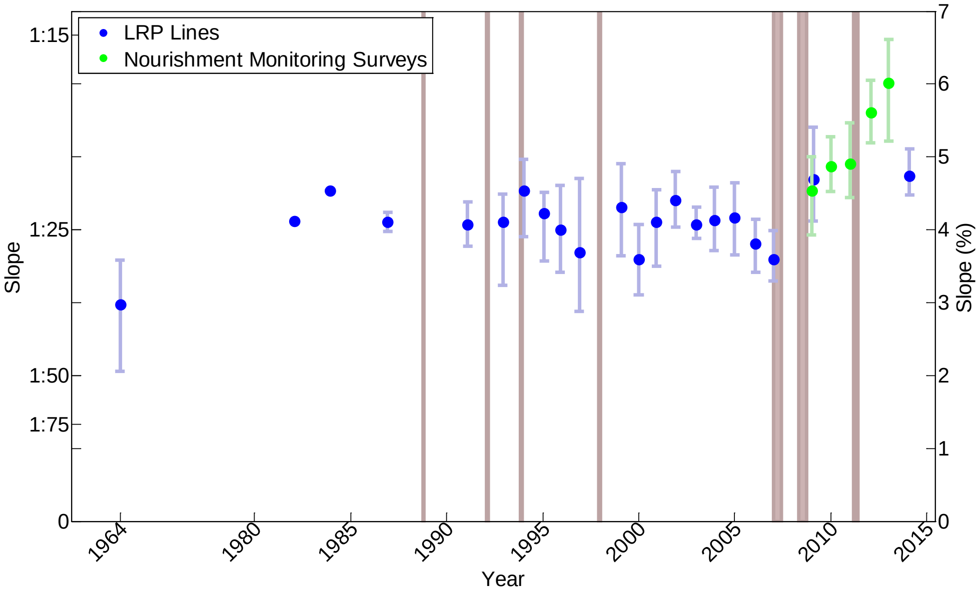


Figure 4.27 Bethany Beach

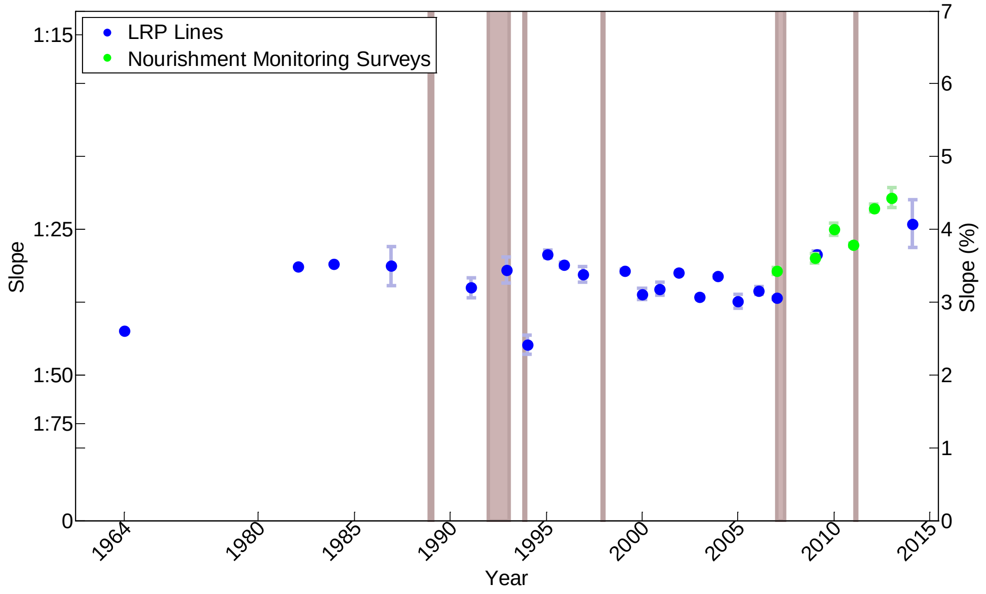


Figure 4.28 South Bethany Beach

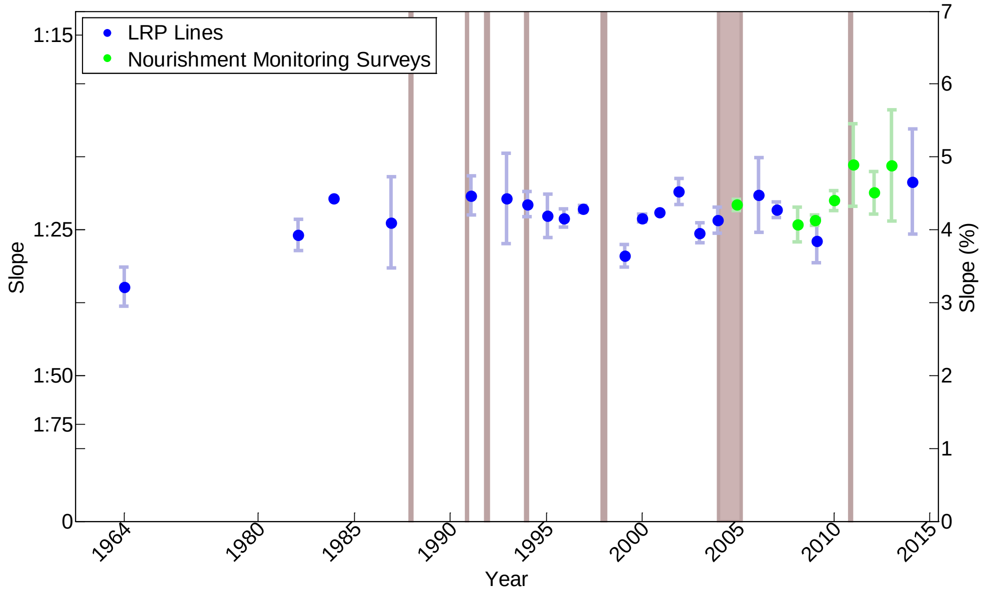


Figure 4.29 Fenwick Island

4.2 Equilibrium Beach Profile Parameter

The previous definitions considered the linear slope of different parts of the beach profile and therefore the curvature of the beach was not taken into account. The concept of the equilibrium beach profile (EBP) was used to include part of the curvature information for the evaluation of the impact of the beach nourishment to the beach profile. A higher equilibrium beach profile parameter results in steeper slopes. The EBP parameter shares similar trends with the beach slope of the segment from MSL to DoC.

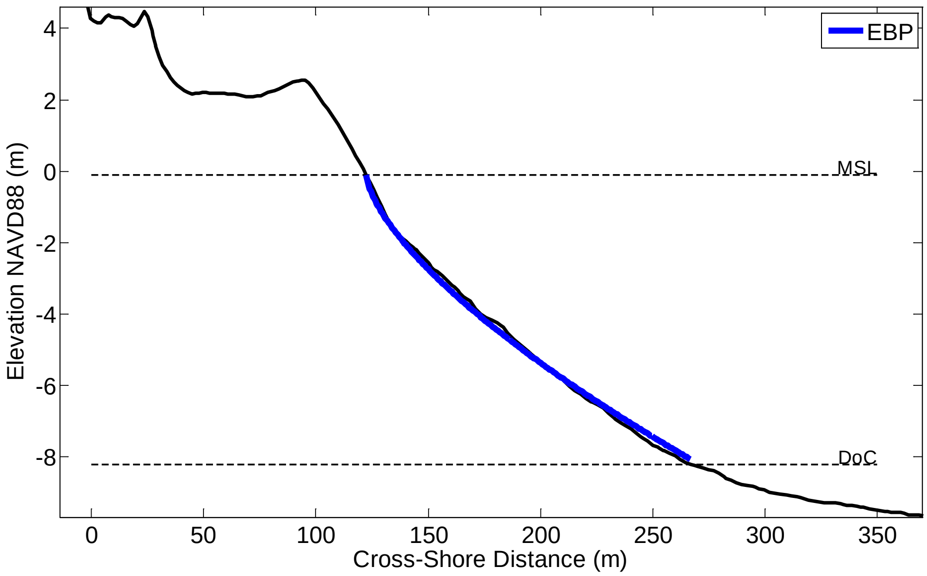


Figure 4.30 Schematic representation of equilibrium beach profile

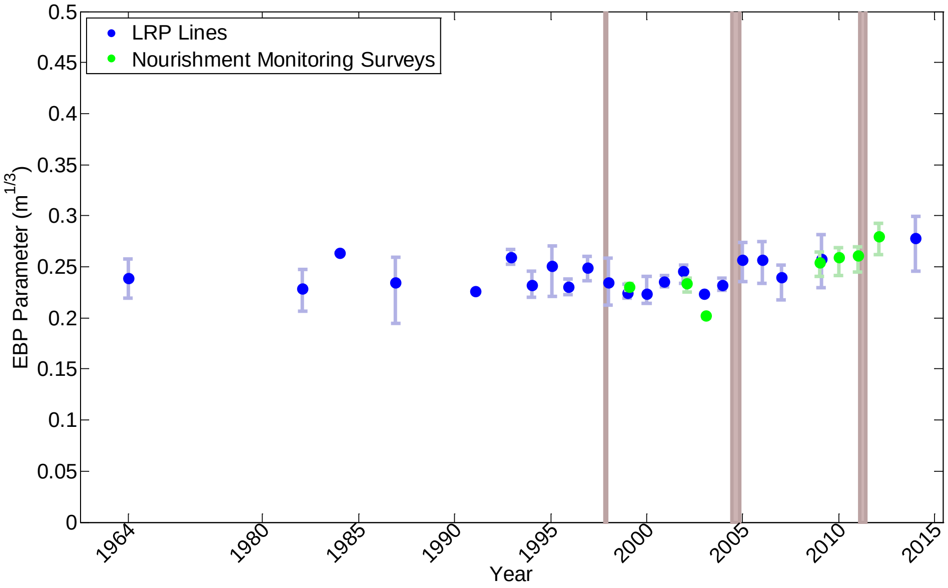


Figure 4.31 Rehoboth Beach

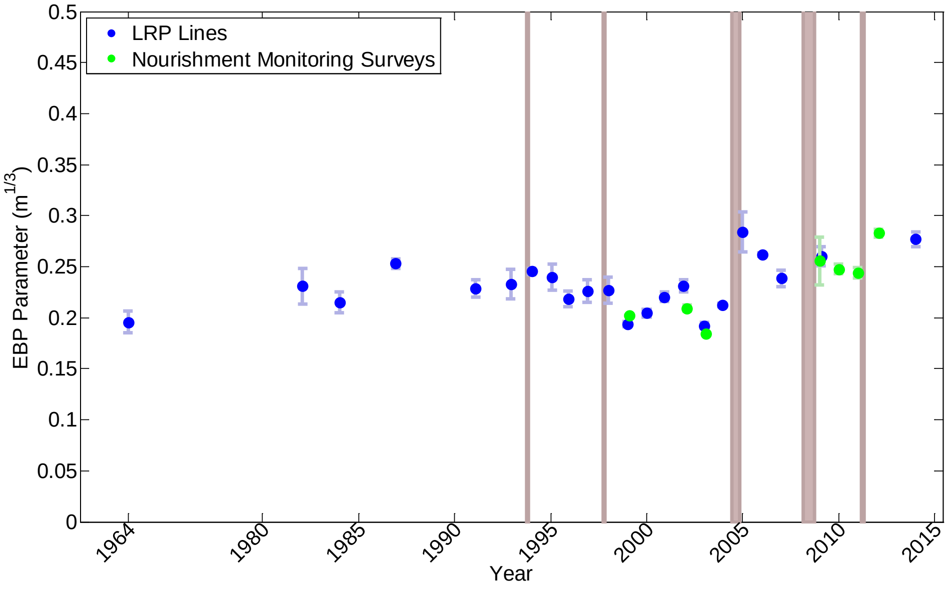


Figure 4.32 Dewey Beach

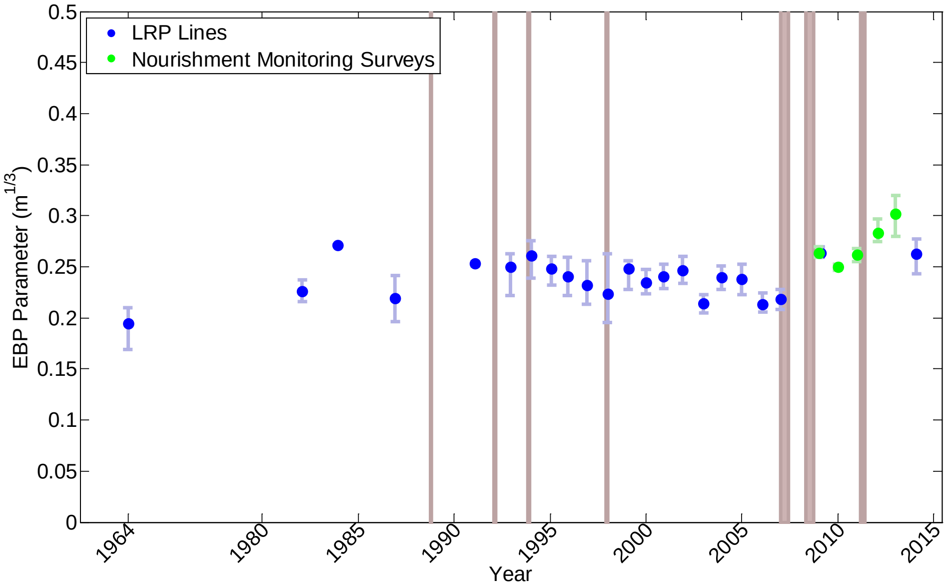


Figure 4.33 Bethany Beach

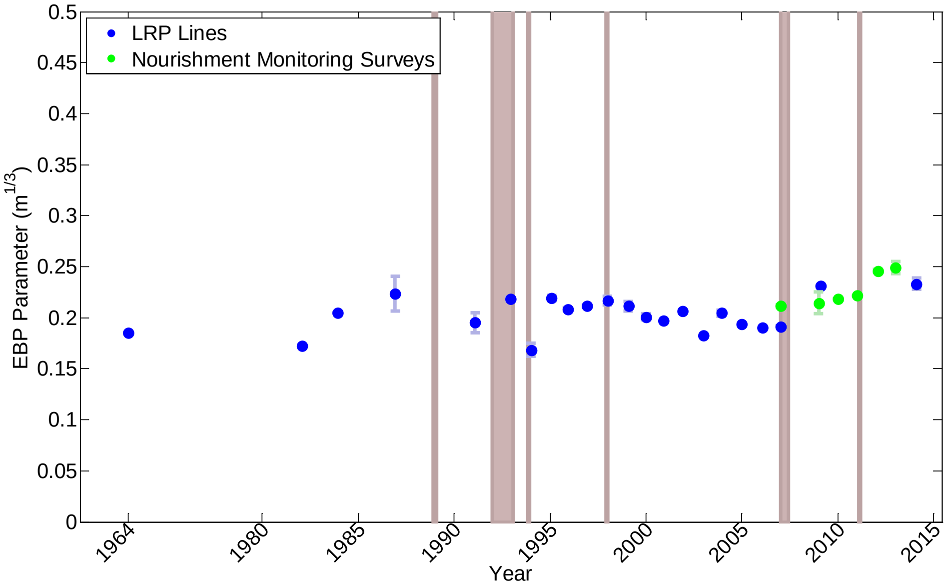


Figure 4.34 South Bethany Beach

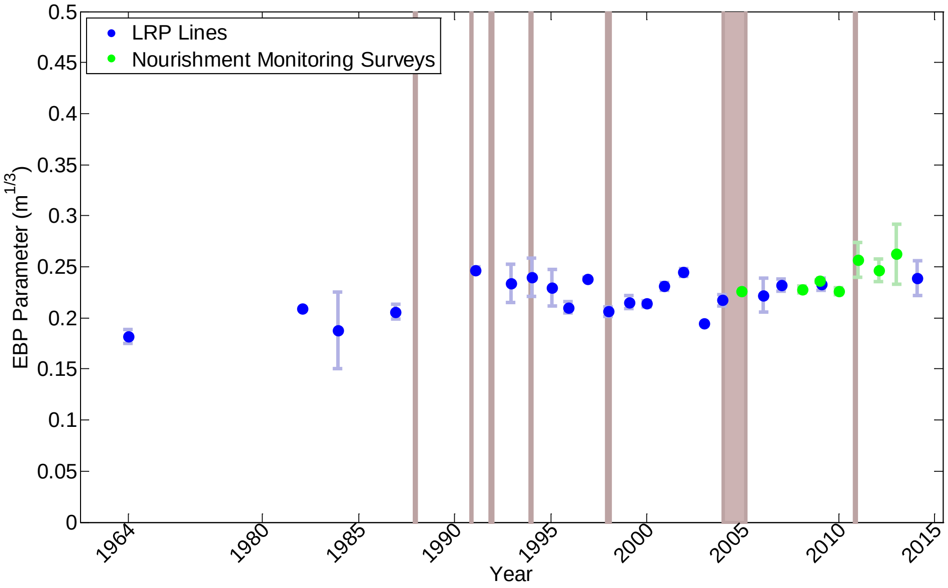


Figure 4.35 Fenwick Island

Chapter 5

NUMERICAL SIMULATION OF BEACH FILL

5.1 Model Specifications

The use of numerical models will help evaluate the best fill alternatives. Different beach nourishment scenarios are simulated and compared and the most appropriate practice for Delaware coast is discussed. XBeach was selected as the numerical model to be implemented for this cause as the model was developed for storm conditions which are a main reason of nourishment failures. The “Groundhog Day” precompiled version was used as it was the most up to date version when the analysis of the beach nourishment simulation started, a newer version has been released since then. The surf beat mode was used as it is the mode that is recommended for better evaluation of swash processes. A one dimensional (1D) cross shore domain was used in order to better quantify the various nourished profile response for different wave conditions. The 1D domain does not require a large amount of computational resources which allowed the simulation of numerous fill scenarios. The grid was generated with a Matlab toolbox of XBeach that calculates the optimal grid size for Courant condition calculated for incident short wave period of 5 sec (default) and a minimum grid size in shallow water and lad of 0.2m (1.0 m default value). The time step for wave propagation was 1 s and the morphological acceleration factor (morfac) was set to be 10 with the first available option (morfacopt=1), which means that for every 10 s the bathymetry is updated due to average sediment transport of those 10 s. The coefficient that are used as tuning coefficients or were prescribed to match the beach characteristics are presented in Table 5.1 and there default values are presented in Table 5.2. The rest of the available tuning coefficients were set to default values. It is important to clarify that gammax is not a breaking wave criterion and another wave breaking formulation is implemented (Roelvink, 1993).

Table 5.1 Numerical coefficient that were modified

Numerical coefficient	Definition	Description
D50	The median grain diameter for sediment	The most representative grain size of the sediment.
D90	The grain diameter that is coarser than 90 percent of the total sediment grain diameter	A descriptive value of the sorting of the sediment.
facSk	Calibration factor time averaged flows due to wave skewness	XBeach does not simulate the wave shape and therefore a parameterization of the shape (skewness and asymmetry) is needed, this parameter induce the onshore sediment transport.
facAs	Calibration factor time averaged flows due to wave asymmetry	
hmin	Threshold water depth above which stokes drift is included	this parameter prevents unrealistic return flows or high concentration
Gammax	Maximum ratio wave height to water depth	This parameter reduce the wave height in shallow water.
Dryslp	Critical avalanching slope above water	The largest slope that can be reach for the dry and wet part of the profile respectively
Wetslp	Critical avalanching slope under water	

Table 5.2 Default values for numerical coefficient

Numerical coefficient	D50(m)	D90(m)	facSk	facAs	hmin	gammax	dryslp	wetslp
Default values	0.00035	0.00075	0.1	0.1	0.2	2.0	1.0	0.3

5.2 Fill Design

The beach nourishment design that is considered to be the typical beach nourishment practice in Delaware for the purpose of this thesis is the beach nourishment of Bethany Beach at 2008 (09/2007-01/2008), as it is well documented and is the largest nourishment for this location. The design template is shown in Figure 5.1 and it was used to reconstruct the nourished profile, imposing the fill design over the profile line of the fall survey of 2007. The median grain size is considered to be 0.35 mm as the natural and the fill volume 565 m^3/m.

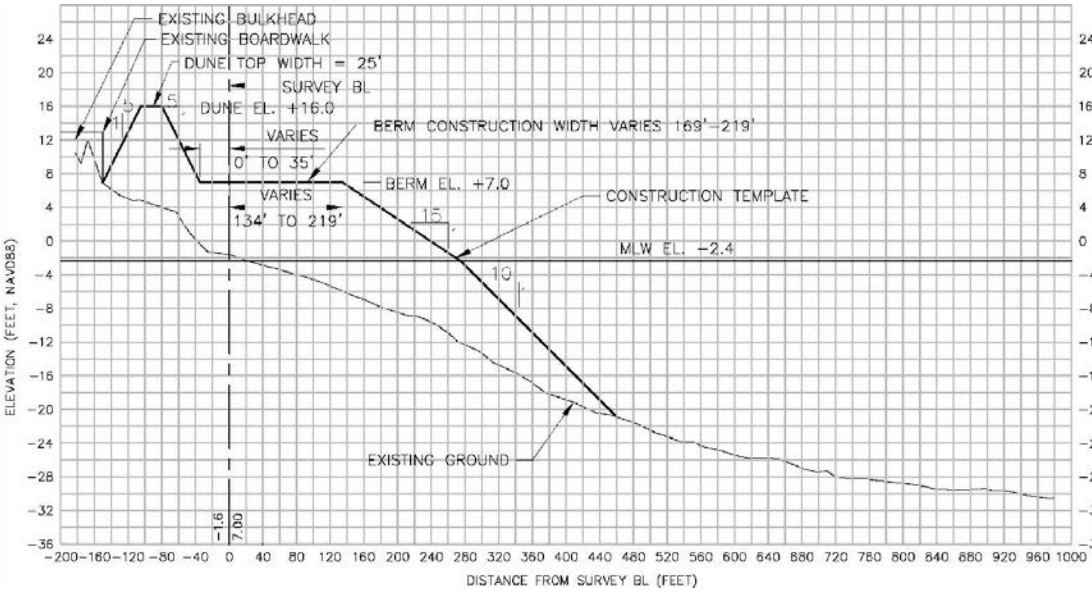


Figure 5.1 Original template design of the beach nourishment for Bethany Beach (Source: http://www.dnrec.delaware.gov/)

5.3 Wave Model Validation

The model was first validated for the wave propagation component of the model. The wave conditions that were implemented for the validation were from July of 2014. Data from the Bethany gage (DE003) was used as the forcing condition. Data from

ADCP deployment for the SZI project was used as control location. The imposed bathymetry was the OC60B profile line of October 2014, which contains the point where the ADCP was deployed. The profile line does not extend to the wave gage, and therefore the extension was created with interpolation of large scale bathymetry.

There is a reasonable performance (RMAE=0.106) of the model for wave prediction with a tendency to slightly under predict significant wave height, as it is obvious from a visual comparison of predicted and measured that is shown in Figure 5.2. The discrepancies can be explained partially to probable uncertainties of instrumentation and two dimensional effects that are not resolved.

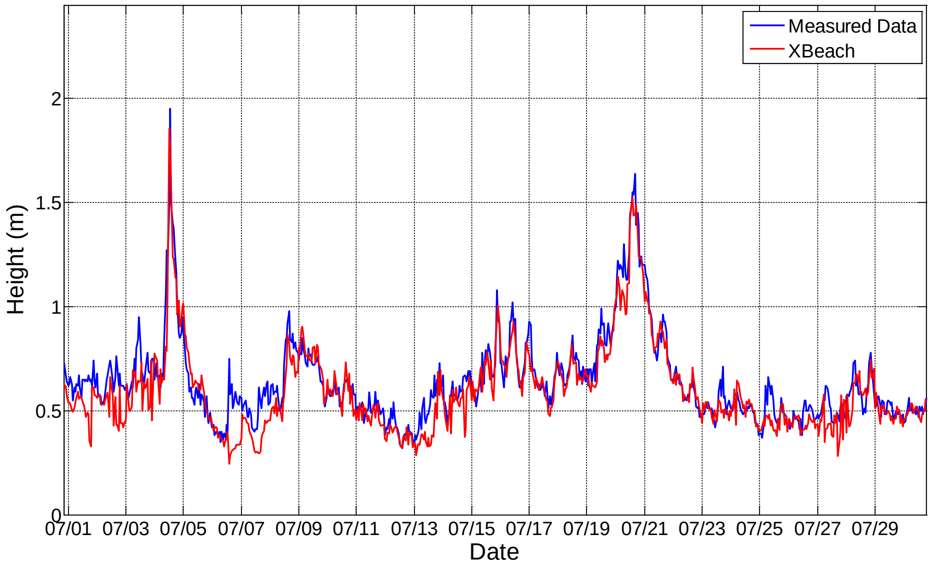


Figure 5.2 Comparison of measured and computed wave significant height for july of 2014

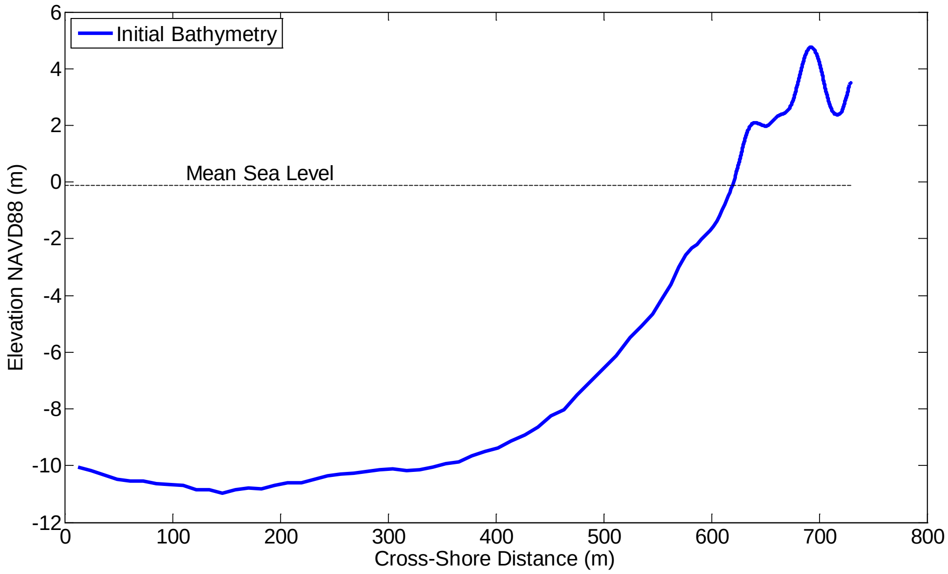


Figure 5.3 Bathymetry of the model.

5.4 Storm Event

The wave validation was held for waves during summer conditions. Therefore the storm that was contained in those dates was not as significant as a winter storm for which there are available data. The Mother’s day storm of 2008 (Figure 5.4) was chosen for simulating morphology evolution during storm conditions and to evaluate different nourishment practices. The reason for this choice is the availability of pre- and post-storm surveys that will be used to validate the model. Another advantage of the use of this storm event for evaluation for beach nourishment performance is that it occurred a few months after the nourishment project described in section 5.2. The peak wave height exceeded 3.5 m with a corresponding period around 10 s which eroded the beach to almost the dune foot.

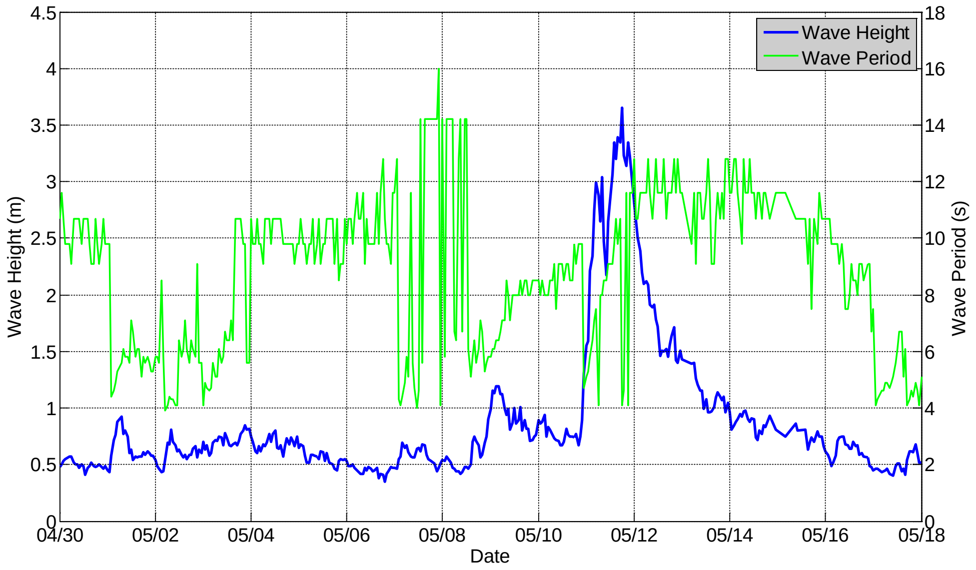


Figure 5.4 Wave condition for Mother's day storm of 2008

5.4.1 Morphology Validation

The numerical coefficients that were modified in order to improve the accuracy of the morphology prediction were the calibration factor for wave skewness and asymmetry. A range of those parameters was evaluated (0.1-0.5) and the values of the factor that achieved the best fit of observed and predicted profile was facSk=facAs=0.2. The different predicted profiles are depicted with red dotted lines in Figure 5.5 and the best fit profile is highlighted, pre and post storm profiles are depicted with blue and red solid lines respectively. Similar values (facSk= facAs=0.25) were obtained for a study of storm impacts in New Jersey shore (Nederhoff, 2014) . The proximity of the location increases the probability that wave climates share similar wave characteristics and not with Dutch beaches where the model was first validated. All the coefficients that were used for the prediction of morphology prediction are presented in Table 5.3. The discrepancy of the measured and predicted profile can be partially explained due to the fact that the model does not include longshore transport.

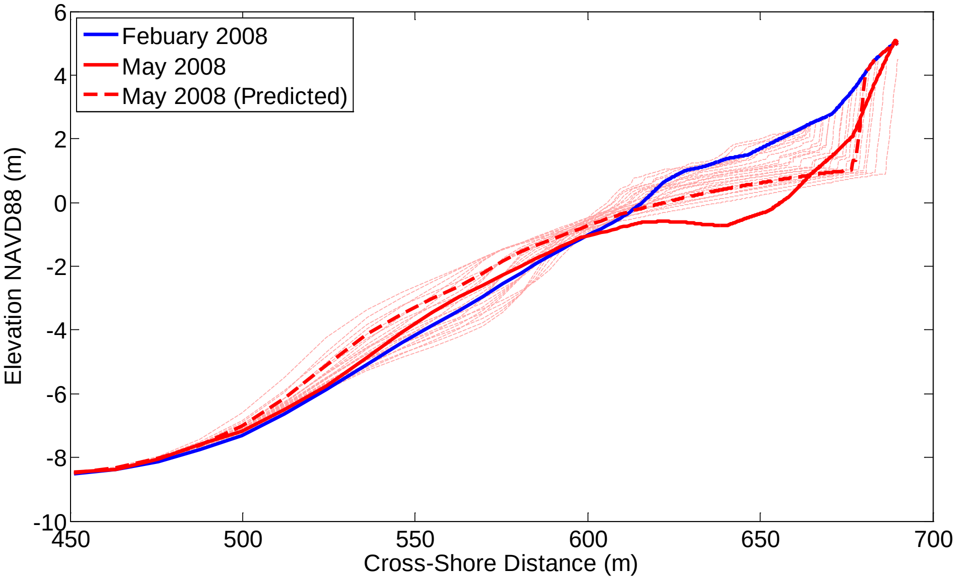


Figure 5.5 Comparison of predicted and measured profile line after the storm.

Table 5.3 Numerical coefficient corresponding for the most accurate prediction of morphology evolution

Numerical coefficient	D50(m)	D90(m)	facSk	facAs	hmin	gammax	dryslp	wetslp
Default values	0.00035	0.00075	0.2	0.2	0.2	2.0	1.0	0.3

5.4.2 Beach Fill Scenarios

5.4.2.1 Different Fill Grain Size

Compatible sediment for beach nourishment is usually considered to be sediment that shares the same grain size characteristics. The performance of the nourishment was evaluated for different grain sizes with a range of 0.2-0.55 mm. The predicted profile after the storm event (Figure 5.6) shows an increased protection for coarser sediment, as it is expected because mobilization of coarser sediment is more difficult and therefore the beach is less vulnerable to erosion. However, the shape of the predicted profile is similar especially for the part of the profile that surrounds the mean sea level. The evolution of the shoreline was evaluated to quantify the protection ability of the different fill scenarios. The results are presentenced in Table 5.4, positive and negative values denotes accretion and erosion respectively. The actual design parameter that was used for the beach nourishment of 2008 are highlighted. Sorting of the sediment is also evaluated with variation of D90 which denotes the grain diameter that is coarser than 90 percent of the total sediment grain diameter. The evaluated range of D90 was 0.65-0.8 mm, however the differentiation of the predicted profiles is almost negligible (Figure 5.7).

Table 5.4 Predicted shoreline bathymetries

Median Grain Size (mm):		0.2	0.225	0.25	0.275	0.3	0.325	0.35	0.375
Distance of predicted shoreline from:	Pre-fill shoreline (m)	49	49	50	50	51	51	51	52
	Post-fill shoreline (m)	-6	-6	-5	-5	-4	-4	-4	-3

Median Grain Size (mm):		0.4	0.425	0.45	0.475	0.5	0.525	0.55
Distance of predicted shoreline from:	Pre-fill shoreline (m)	52	52	52	53	53	53	53
	Post-fill shoreline (m)	-3	-3	-3	-3	-2	-2	-2

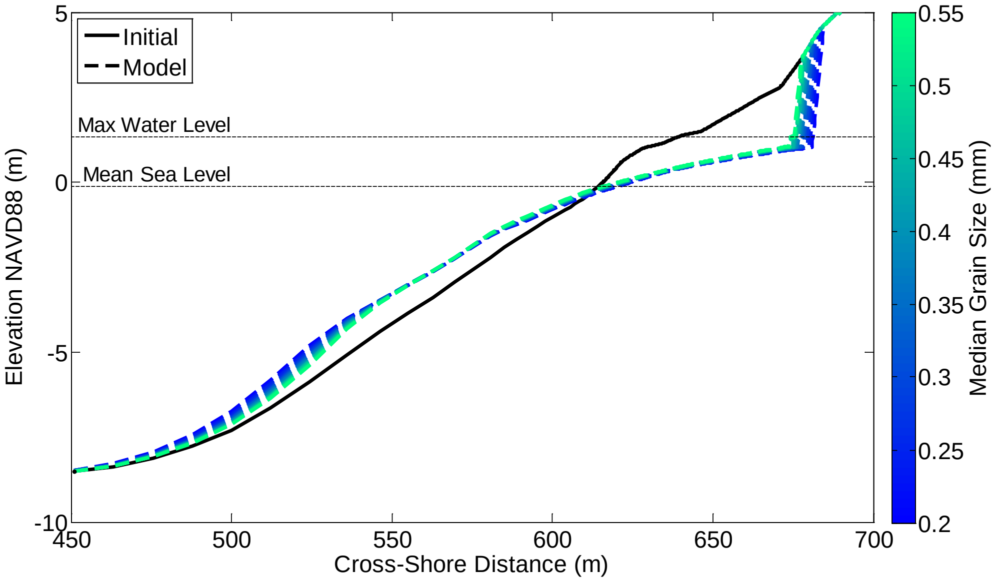


Figure 5.6 Predicted bathymetries for different median grain sizes after storm

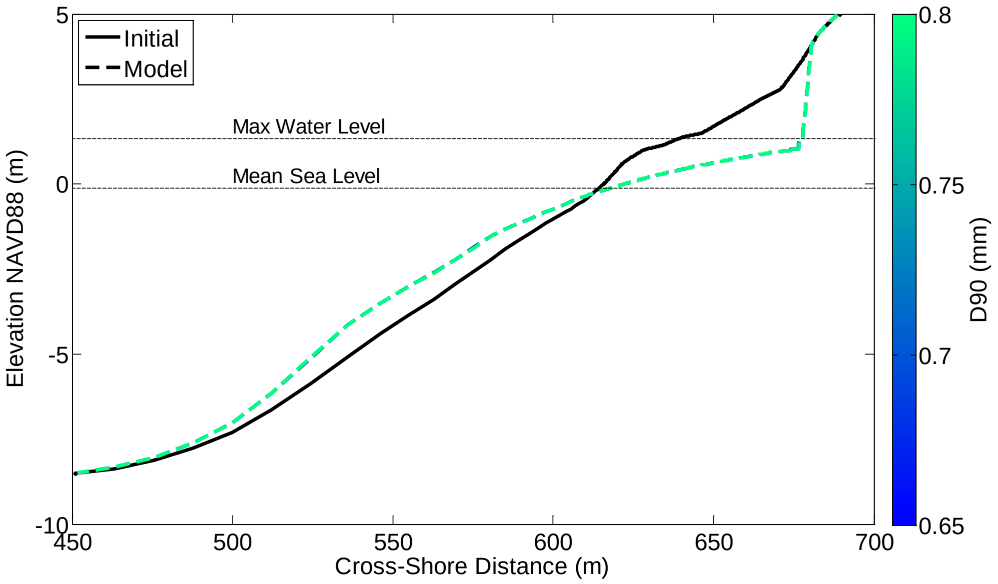


Figure 5.7 Predicted bathymetries for different D90 sizes after storm

5.4.2.2 Different Fill Template Slope

For determining the optimal fill template slope the volume of the fill is unchanged (365 m^3/m) and different slopes are imposed with a range of slope of 1:5 to 1:19 (Figure 5.8). This affects the length of the berm with steeper fill having a larger berm and milder sloping fill having a smaller berm. On the one hand the milder sloping fill is more efficient for dissipating wave energy. On the other hand the small berm decreases the available sediment for protecting the fill. This results in a slightly better performance for the steeper fill (Figure 5.9). However, in the long term this could be canceled because of the abnormal slope that is predicted for a depth larger than 5 m which will lead to a redistribution of sediment in order to obtain a profile closer to equilibrium.

Table 5.5 Predicted shoreline bathymetries

Template slope (1/):		5	6	7	8	9	10	11	12
Distance of predicted shoreline from:	Pre-fill shoreline (m)	56	56	56	56	56	56	56	55
	Post-fill shoreline (m)	-26	-25	-22	-21	-18	-16	-14	-12
Template slope (1/):		13	14	15	16	17	18	19	
Distance of predicted shoreline from:	Pre-fill shoreline (m)	55	54	54	53	52	50	49	
	Post-fill shoreline (m)	-10	-8	-6	-4	-2	-1	1	

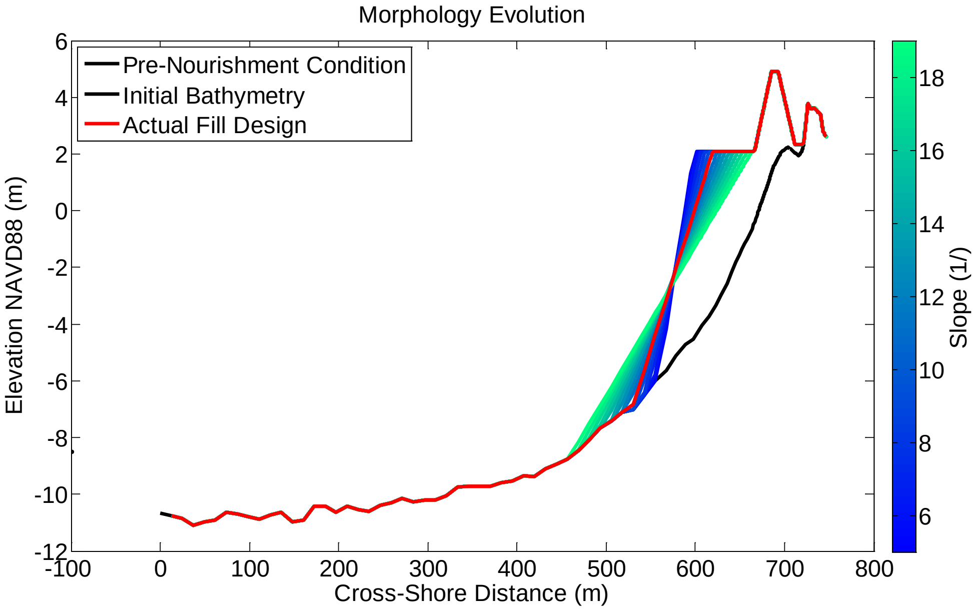


Figure 5.8 Initial bathymetries for different template slopes.

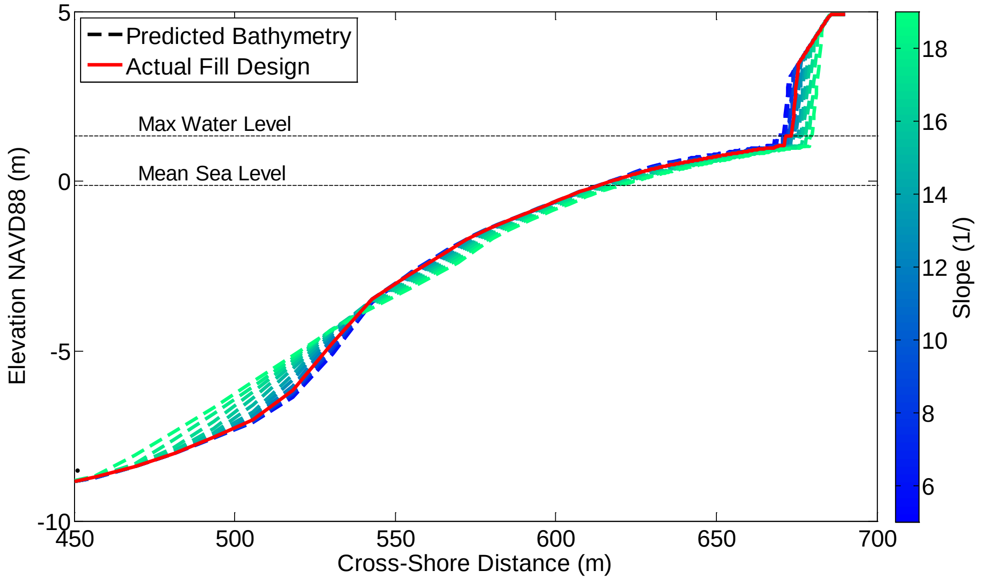


Figure 5.9 Predicted bathymetries for different templates slopes after storm.

5.4.2.3 Different Fill Berm Height

Most of the prediction of morphology evolution for different fill scenarios results in similar profile lines, a potential explanation could be the overtopping of the berm which results in erosion. For this reason, evaluation for different berm heights is conducted. The typical height is 2.1 m and a range of berm heights from 1.4 to 2.8 m is modeled. For keeping the volume unchanged the higher fill berms are also narrower. The increase of the berm height has an increase in beach protection.

Table 5.6 Predicted shoreline bathymetries

Template slope (1/):		1.4	1.5	1.6	1.7	1.8	1.9	2	2.1
Distance of predicted shoreline from:	Pre-fill shoreline (m)	55	55	55	56	56	56	56	56
	Post-fill shoreline (m)	-21	-20	-19	-18	-18	-17	-17	-16
Template slope (1/):		2.2	2.3	2.4	2.5	2.6	2.7	2.8	
Distance of predicted shoreline from:	Pre-fill shoreline (m)	56	56	56	56	56	56	56	
	Post-fill shoreline (m)	-15	-15	-14	-14	-13	-13	-12	

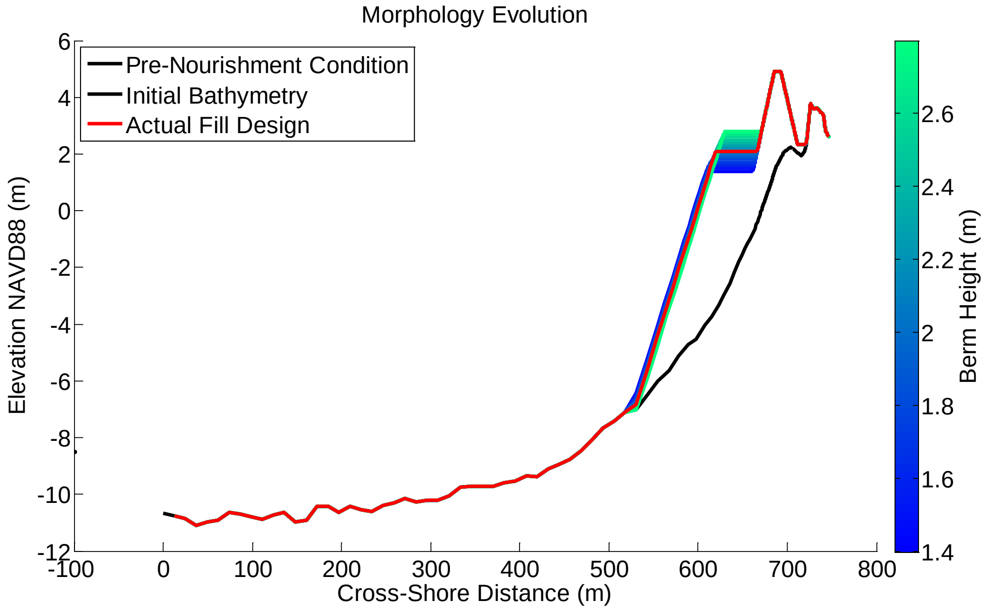


Figure 5.10 Initial bathymetries for different berm height.

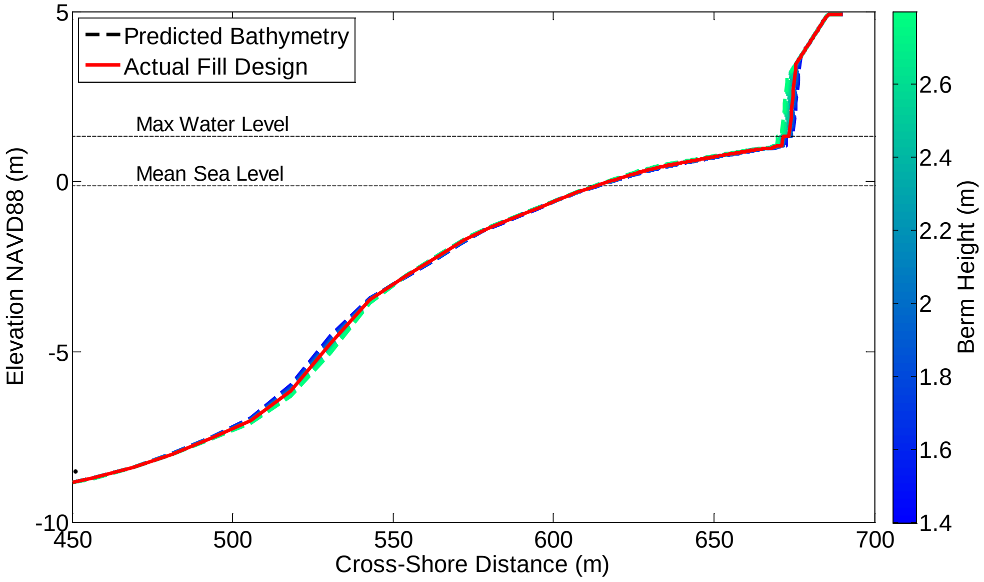


Figure 5.11 Predicted bathymetries for different berm heights after storm.

5.4.2.4 Different Fill Volume

Determining the fill volume is critical for the design for a beach nourishment project. Because on the one hand the increase of the fill volume will increase the available space for recreational activities and will improve the protection of the upland areas. On the other hand, the increase of the fill volume will affect the cost of the project. Evaluation of a range of different volumes from 315 to 1015 m^3/m with an increment of 50 m^3/m is evaluated (Figure 5.12). As was expected, larger fill volumes lead to better protection (Table 5.7), as larger volumes extend the shoreline more. Interesting is the fact even though the initial profile shape is unchanged and is only shifted seaward the shape of the eroded profile is different for the different fill volumes which could change the behavior during the reconstruction of the beach. For the lower fill volume, erosion of the dune is predicted which could put in danger the upland area.

Table 5.7 Predicted shoreline bathymetries

Fill volume (m^3/m):		315	365	415	465	515	565	615	665
Distance of predicted shoreline from:	Pre-fill shoreline (m)	33	38	42	47	51	56	61	66
	Post-fill shoreline (m)	-21	-20	-19	-18	-18	-17	-17	-16
Fill volume (m^3/m):		715	765	815	865	915	965	1015	
Distance of predicted shoreline from:	Pre-fill shoreline (m)	71	76	81	86	91	96	100	
	Post-fill shoreline (m)	-15	-15	-14	-14	-13	-13	-12	

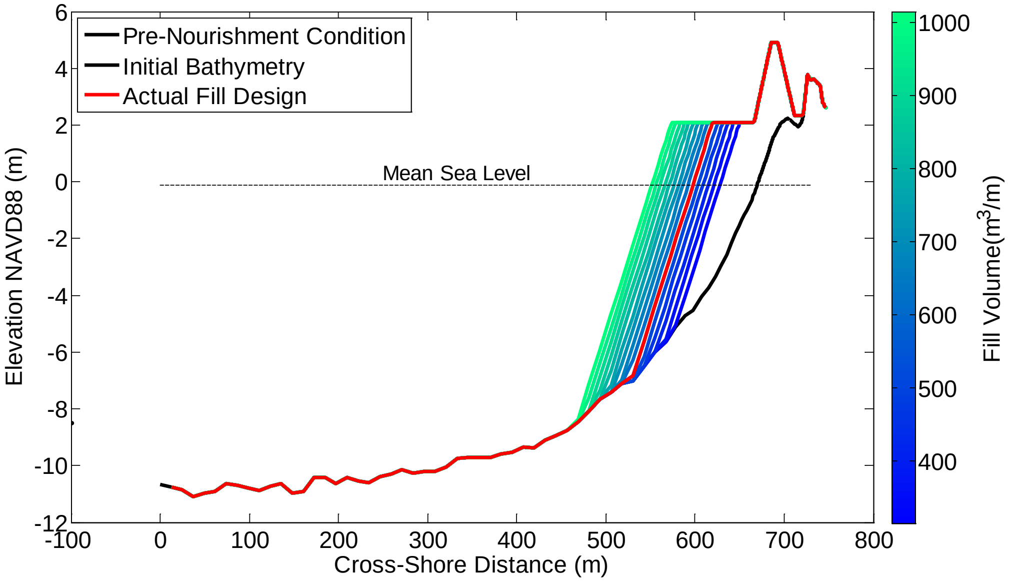


Figure 5.12 Initial bathymetries for different fill volumes.

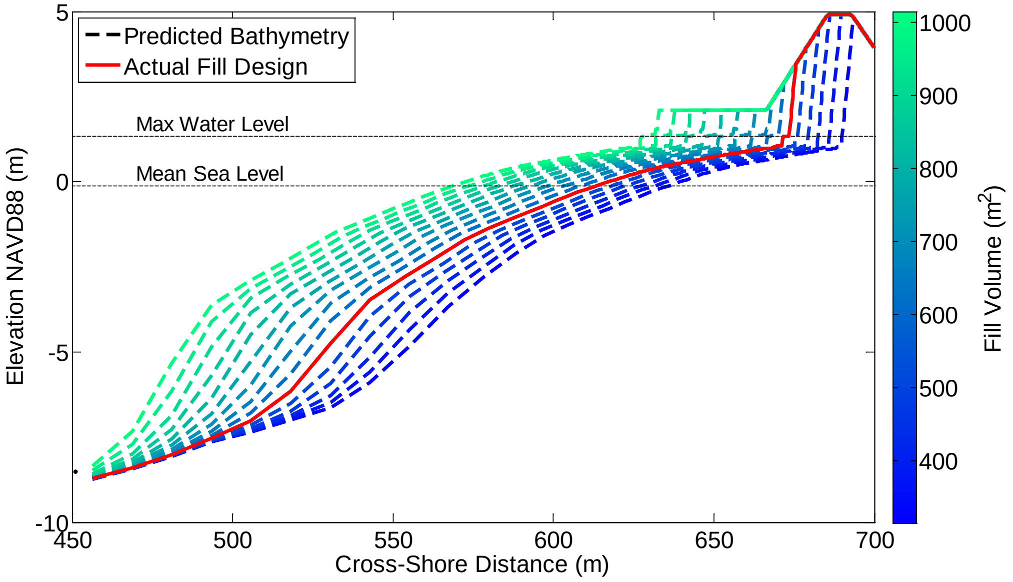


Figure 5.13 Predicted bathymetries for different fill volumes after storm.

5.4.2.5 Submerged Fill

Increase of the fill volume has significant impact in beach protection, this section evaluates the increase of the placement of the sediment with a submerged fill. A submerged fill with volume of 120 m^3/m in the shape of a trapezoid with a slope of 1:10 on both sides and flat crest of 6 m is considered. The fill is placed in a range of depths from -2.5 to -6.25 m (Figure 5.14). The submerged nourishment has limited capability of protecting the shore (Figure 5.13), since the submerged feature is smoothed and the sediment is redistributed in the profile for the shallower fills. The deeper fills are not affected from the storm and therefore do not protect the shore. The steep profiles of Delaware coast does not allow feasible options for submerged fills that will be able to dissipate wave energy. Therefore, submerged fills are not suitable practice of beach nourishment of Delaware beaches.

Table 5.8 Predicted shoreline bathymetries

Submerged fill depth (m):		2.5	2.75	3	3.25	3.5	3.75	4	4.25
Distance of predicted shoreline from:	Pre-fill shoreline (m)	65	64	64	63	62	61	60	59
	Post-fill shoreline (m)	-7	-8	-8	-9	-10	-11	-12	-13
Submerged fill depth (m):		**4.5**	**4.75**	**5**	**5.25**	**5.5**	**5.75**	**6**	
Distance of predicted shoreline from:	Pre-fill shoreline (m)	58	58	57	57	57	57	57	
	Post-fill shoreline (m)	-14	-14	-14	-15	-15	-15	-15	

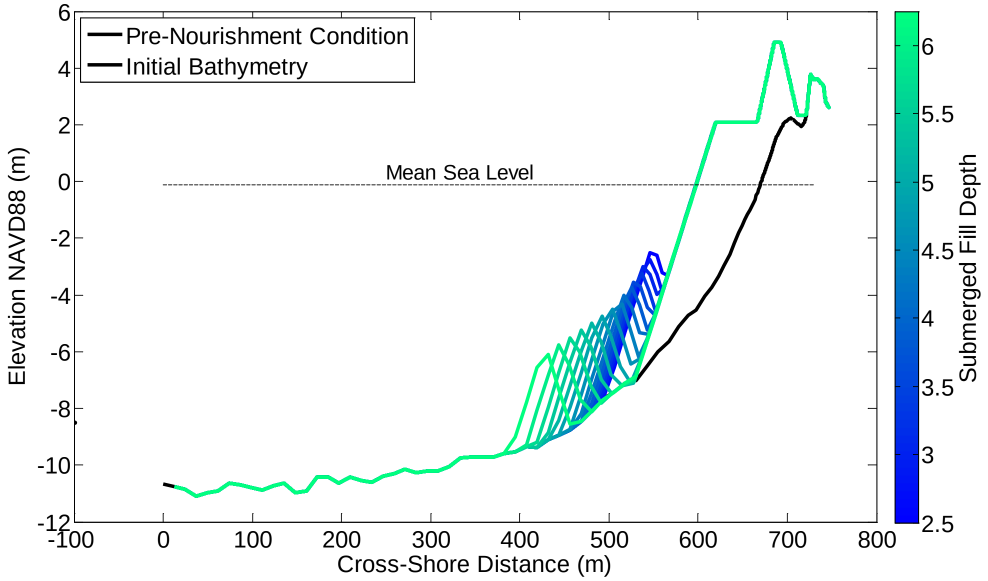


Figure 5.14 Initial bathymetries for different submerged fills.

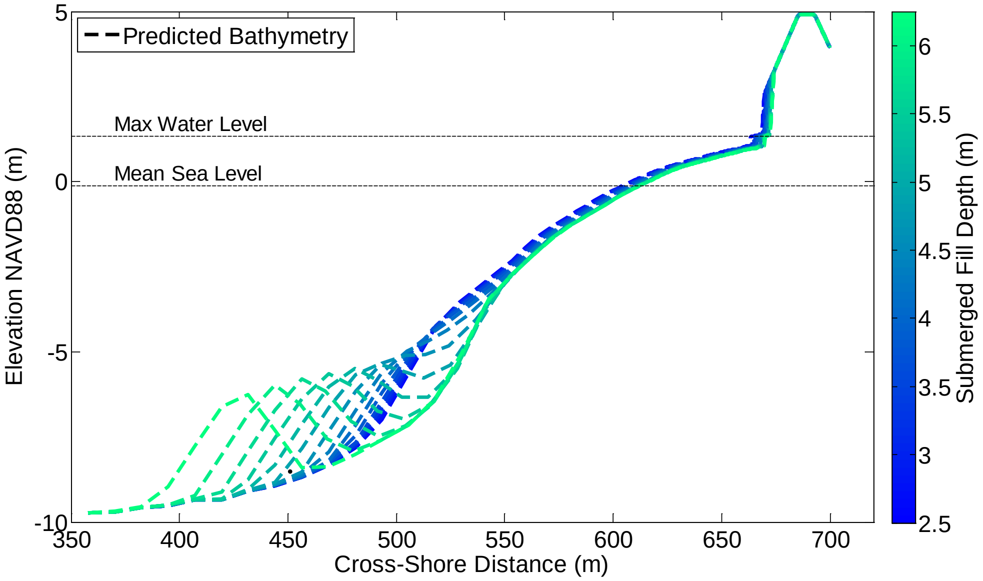


Figure 5.15 Predicted bathymetries for different submerged fills after storm.

5.5 Moderate Storm Condition

5.5.1 Morphology Validation

For winter storm conditions the differentiation in fill shape has limited effect in the resulting profile after the winter storm and therefore moderate storm conditions have to be considered to better evaluate the fill performance. For this reason the model is calibrated for the morphology evolution for the period from 3rd of July to 7th of July 2014, with the wave condition that is shown in Figure 5.2. The achieved accuracy exceeded the BSS=0.67 with the comparison of the predicted and measured profile (Figure 5.16). The corresponding numerical coefficient in Table 5.9 and they will be used for evaluation of morphology evolution for the different nourishment scenarios. The wave skewness and asymmetry factor were increased in order to further compensate the erosive forces and additional numerical factors are tuned in order to improve the morphology evolution in shallow water. The model predicts accurately the erosion of the berm but prediction near the shore is unrealistic as accretion is predicted instead of the actual erosion.

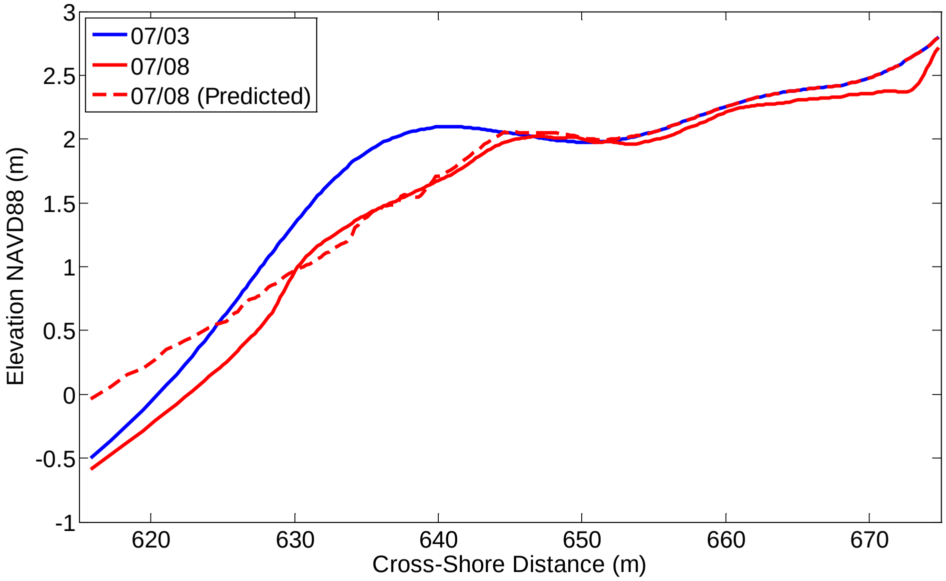


Figure 5.16 Comparison of predicted and measured profile line after moderate erosive condition

Table 5.9 Numerical coefficient corresponding for the most accurate prediction of morphology evolution

Numerical coefficient	D50(m)	D90(m)	facSk	facAs	hmin	gammax	dryslp	wetslp
Default values	0.00035	0.00075	0.45	0.6	0.01	3.8	0.3	0.2

5.5.2 Beach Fill Scenarios

5.5.2.1 Different Fill Grain Size

First the nourishment sensitivity for different grain sizes is evaluated. The beach nourishment design for the original volume design and the slope of 1:10 is used for the initial bathymetry. Different sediment grain sizes did not affected the morphological evolution for storm conditions. Similarly, for moderate wave condition the berm crest is not affected but there is an erosion above the mean sea level and accretion below.

Table 5.10 Predicted shoreline bathymetries

Median Grain Size (mm):		0.2	0.225	0.25	0.275	0.3	0.325	0.35	0.375	0.4	0.425	0.45	0.475	0.5	0.525	0.55
Distance of predicted shoreline from:	Pre-fill shoreline (m)	68	68	68	68	69	69	69	69	69	69	69	69	69	69	69
	Post-fill shoreline (m)	-13	-13	-13	-13	-13	-13	-14	-14	-14	-14	-14	-14	-14	-14	-14

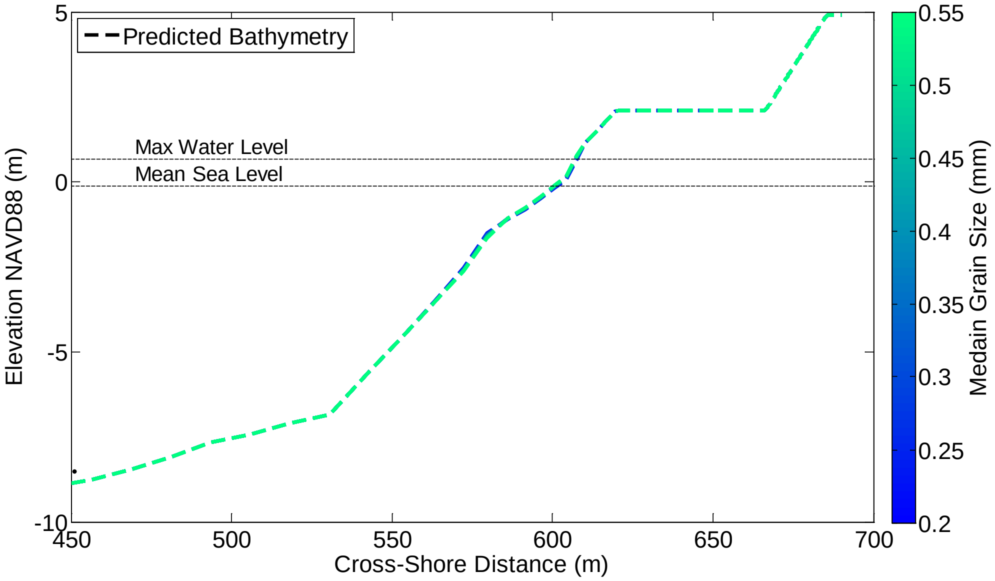


Figure 5.17 Predicted bathymetries for different grain sizes after moderate erosion.

5.5.2.2 Different Fill Template Slope

The initial morphologies of section 5.4.2.2 with different template slopes are evaluated for moderate condition. The initial slope is apparent in the predicted profiles. However, the shoreline of the steeper fills retreats since the foreshore is eroding. In contrast, there is deposition at the shoreline and berm erosion for the shallower slope fill (Table 5.11). Therefore, the predicted shoreline for the different templates slopes tends towards a single point.

Table 5.11 Predicted shoreline bathymetries

Template slope (1/):		5	6	7	8	9	10	11	12	13	14	15	16	17	18	19
Distance of predicted shoreline from:	Pre-fill shoreline (m)	74	74	72	71	69	69	70	68	66	64	64	63	59	56	53
	Post-fill shoreline (m)	-8	-6	-6	-5	-5	-3	0	0	1	2	4	6	5	5	5

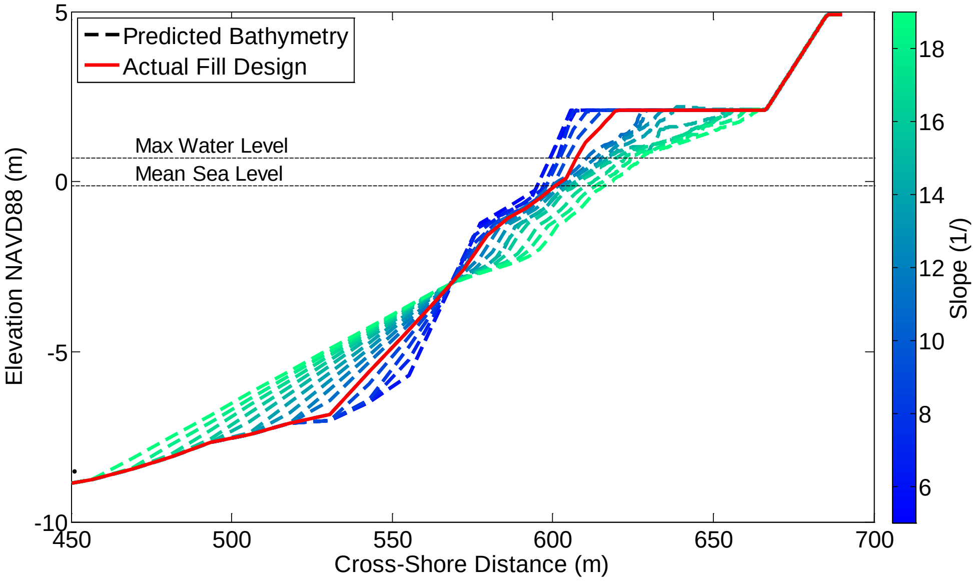


Figure 5.18 Predicted bathymetries for different templates slopes after moderate erosion.

5.5.2.3 Different Fill Berm Height and Fill Volume

The change of the berm height and fill volume is translated to an offset of the initial bathymetry. The wave condition is not energetic enough to erode the whole extent of the berm or to mobilize sediment of the offshore part. Hence, the shape of the predicted profiles are identical and are shifted according to the initial conditions.

Table 5.12 Predicted shoreline bathymetries

Template slope (1/):		1.4	1.5	1.6	1.7	1.8	1.9	2	2.1	2.2	2.3	2.4	2.5	2.6	2.7	2.8
Distance of predicted shoreline from:	Pre-fill shoreline (m)	72	71	72	71	70	70	69	69	68	68	67	67	66	66	65
	Post-fill shoreline (m)	-4	-4	-3	-3	-3	-3	-3	-3	-3	-3	-3	-3	-3	-3	-3

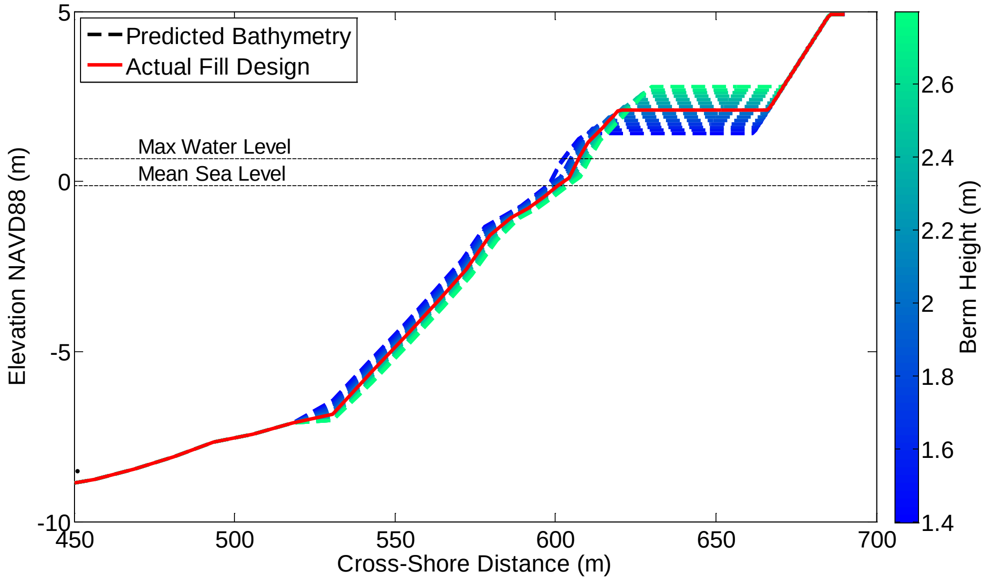


Figure 5.19 Predicted bathymetries for different berm heights after moderate erosion.

Table 5.13 Predicted shoreline bathymetries

Fill volume (m^3/m):		315	365	415	465	515	565	615	665
Distance of predicted shoreline from:	Pre-fill shoreline (m)	41	48	55	61	67	73	79	84
	Post-fill shoreline (m)	-1	0	0	0	1	1	2	2
Fill volume (m^3/m):		715	765	815	865	915	965	1015	
Distance of predicted shoreline from:	Pre-fill shoreline (m)	91	97	102	107	112	118	122	
	Post-fill shoreline (m)	3	3	3	4	3	4	4	

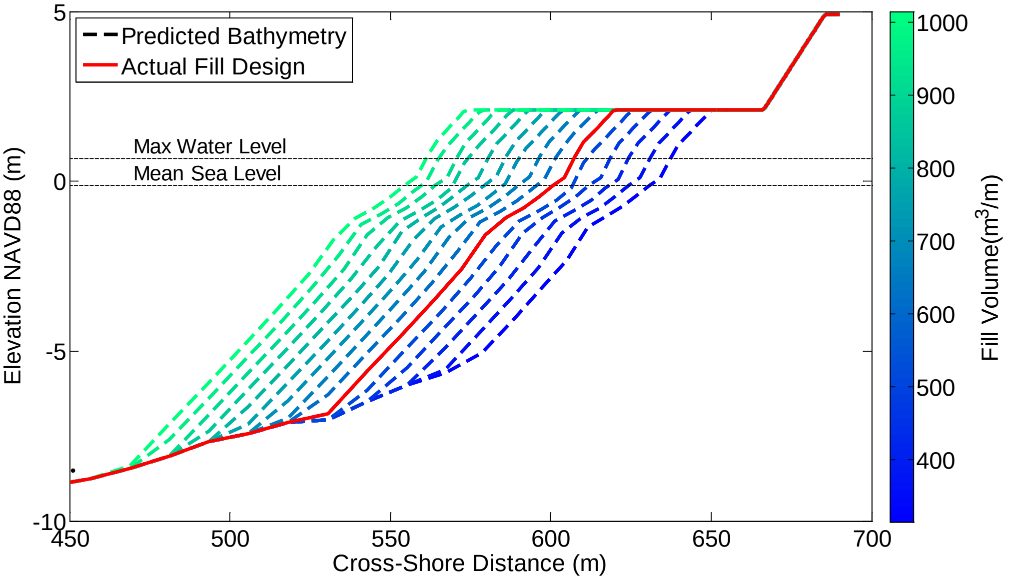


Figure 5.20 Predicted bathymetries for different fill volumes after moderate erosion.

5.6 Accretion Conditions

5.6.1 Morphology Validation

XBeach is developed for morphology erosion under storm conditions. However, the model can be tuned in order to predict accretion events. The model was validated from 21st of July to 25th of July when accretion was observed. The wave skewness and asymmetry factor are further increased and the rest of the numerical coefficient are tuned accordingly (Table 5.14). The model is capable of predicting the steepening of the beach but under predicts the accretion of the berm (Figure 5.21). Prediction of the accreting pattern is crucial for accurately modeling the recovery phase after the storm. Therefore, this condition is used to evaluate the recovery for different beach fills.

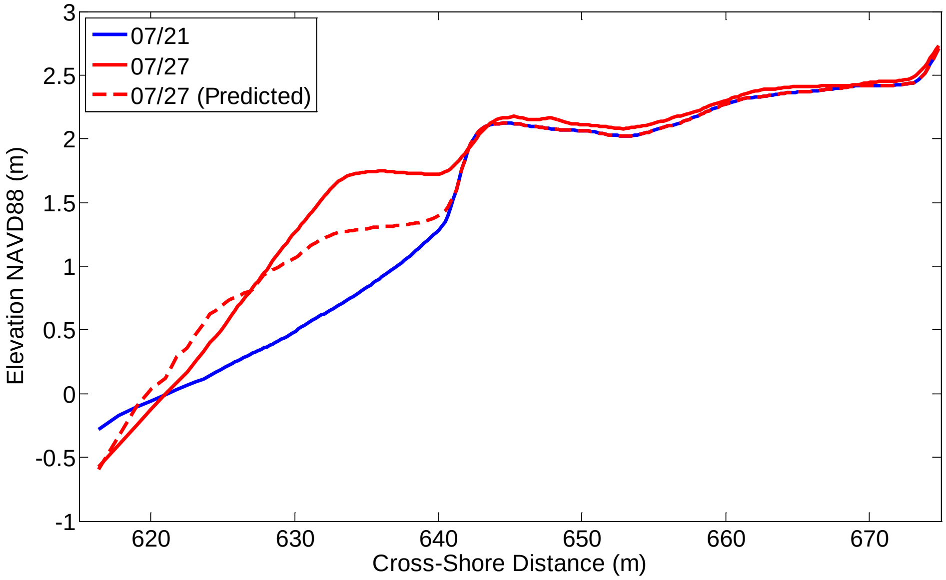


Figure 5.21 Comparison of predicted and measured profile line after moderate erosive condition

Table 5.14 Numerical coefficient corresponding for the most accurate prediction of morphology evolution

Numerical coefficient	D50(m)	D90(m)	facSk	facAs	hmin	gammax	dryslp	wetslp
Default values	0.00035	0.00075	0.7	1.0	0.01	3	0.6	0.3

5.6.2 Beach Fill Scenarios

5.6.2.1 Different Fill Grain Size

The initial shape of the fill has minimal effect on the post storm profile. Hence the grain size of the beach is the only characteristic that is evaluated. The model is assigned to evaluate accretion for 30 days with the 6 days of accreting wave condition described before of by implying the second option of morphological factor with a value of 5 (morfac=5 & morfacopt=0). The post-storm bathymetry of May 2008 is imposed for the initial condition. The models predicts recovery of the berm (Figure 5.22) and finer grain size profiles recover more easily. However, the shape and the height of the resulting berm and the shoreline is similar for the different realizations.

Table 5.15 Predicted shoreline bathymetries

Median Grain Size (mm):		0.2	0.225	0.25	0.275	0.3	0.325	0.35	0.375	0.4	0.425	0.45	0.475	0.5	0.525	0.55
Distance of predicted shoreline from:	Pre-fill shoreline (m)	44	43	40	40	38	38	38	38	38	38	37	38	37	37	37
	Post-fill shoreline (m)	29	28	25	25	23	23	23	23	23	22	22	22	22	22	22

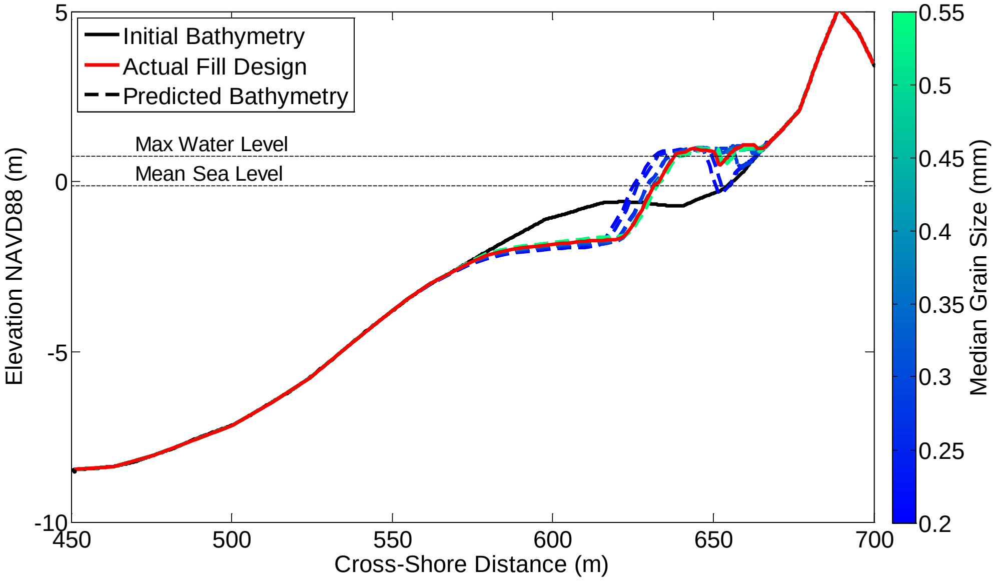


Figure 5.22 Predicted morphology of the evolution of the eroded profile after accretion event.

Chapter 6

CONCLUSION & RECOMMENDATION

Beach nourishment is a soft engineering project that is gaining popularity for the protection of shoreline from erosion. Some of its merits are the minimal modification of sediment transport patterns in the adjacent area beaches and the reintroduction of sediment in areas with a deficit sediment balance. Multiple beach nourishments have occurred along the Delaware coast in last decades. The need of further nourishment projects will remain in the future since the Delaware coast has erosive trend and nourishment projects cannot reverse these long term erosive trends. Beach nourishment modifies the beach profile in the short term, the steeper, in most cases, template slope of the fill creates a short term steepening of the beach as the beach profile has the tendency to evolve to an equilibrium state after a few months. However, the possible change in sediment characteristics can alter the equilibrium state of the natural beach to a new equilibrium for the post nourished beach. The use of coarser sediment that is used for its better performance against erosive conditions can lead to the long term steepening of the beach. Therefore, the sustainable design of the nourishment should minimize the effect on beach profile and will reassure the longevity of the project. The thorough monitoring of the project can evaluate the performance of the nourishment and provide feedback to ameliorate the design for the following nourishment projects.

The surveys that have been conducted in the past for the Delaware coast are on a semiannual base, the frequency of these is not adequate to provide definitive conclusion of the beach profile modification, as result of the consecutive beach nourishment projects. Especially for the part of the profile which is close to the shore where the morphodynamic processes modifies it according to the daily wave climate.

For instance, a storm prior to the survey can affect in short term the slope of this part which makes the surveys unreliable for estimating the slope evolution after nourishment. Nevertheless, for the Delaware coast there is not a constant and persisting trend among the locations and time periods following the nourishment project for the beach slope evolution. For the beach face slope that covers the tidal range, the variability of the slope over all the available surveys is overcome from the variability of beach face slope over a summer.

The slopes of the beach from the depth of closure to mean sea level are more reliable, since they are less likely to be affected from the short term change of wave climate. Generally, these slopes increases after the beach nourishment projects as the as the extension of the shore decrease its distance from the depth of closure. The years following the nourishment indicate that the slope decreases gradually, as a result of the erosive patterns on the Delaware coast. The shoreline retreat leads to an increase of the distance between the shore and depth of closure.

Numerical models constitute a tool for beach nourishment design and XBeach can be helpful to evaluate the nourishment performance under storm conditions. The validation of XBeach with measured hydrodynamic and morphologic conditions will further improve the accuracy of the model. XBeach can handle calm conditions with erosive and accreting patterns yet intense calibration of empirical parameters is needed. Through the utility of XBeach different beach fill scenarios were evaluated, which encompassed the change in fill grain size, template slope, fill berm height, fill volume, and the presence of a submerged fill. The result of this evaluation was that the ability of protection against beach erosion from the nourishment is regulated from the fill volume that is placed. The steep beaches of the Delaware coast do not allow a reasonable design of a submerged fill that would be able to improve the protection of the shore.

A better evaluation of the impact of beach nourishment on beach profiles calls for multiple surveys per year in an effort to calculate a mean profile which is more appropriate for this analysis. The profile part close to the shore is subject to increased morphological changes, therefore the analysis of beach face and foreshore needs an increased temporal resolution. The analysis of the daily profile performed for the surf zone injuries study was able to provide the relationship between the wave conditions and the slope with the help of a dimensionless parameter. Therefore, monitoring of beach nourishment should include daily surveys that will allow to demonstrate the evolution of the relation of the dimensionless parameter with the beach slope, and if the placement of a fill result in steeper beach for same wave conditions. The profile line is adequate to provide the slope of the beach but cannot resolve planar features which could differentiate the local slope, one being the presence of cusps could result in different slopes in the horns and the embayment. LIDAR technology can also be used to provide 3 dimensional surveys that would be able to resolve those formations and if it is performed on a regular basis the evolution could be resolved as well. In addition to the morphological information there is the need for a more thorough monitoring of sediment grain size, first it is needed for the aforementioned dimensionless parameter which allows to remove the effect of the wave condition to the beach slope. Furthermore, the evolution of the sediment grain size will allow to explain part of the erosion pattern that could be potentially a result of the finer sediment being eroded easily and leaving coarser sediment in the beach. The grain size distribution of the borrow site should be followed with the assessment of the grain size of the fill that is actually placed at the beach, since there could be a discrepancy between them as material could be dredged slightly away from the studied borrow site.

The beach nourishment monitoring is crucial for the assessment of the impacts of nourishment to beach morphology. In addition, it can provide valuable data for model validation. Monitoring the behavior of the fill during storm condition can improve the accuracy of XBeach that is developed for simulation of morphology evolution during storm condition. This will allow the improvement of the design and the determination of the required fill material that is needed to be used in order to provide adequate protection against storm conditions. Assessment of protection ability for the actual state of the beach can also be evaluated with XBeach with the updated morphology. Therefore, the necessity for additional or emergency nourishment will be decided.

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