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Effect of Coastal Erosion on Storm Surge: A Case Study in the Southern Coast of Rhode Island

Alex J. Shaw

University of Rhode Island, ashaw9781@gmail.com

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EFFECT OF COASTAL EROSION ON STORM SURGE: A CASE STUDY IN
THE SOUTHERN COAST OF RHODE ISLAND

BY

ALEX J. SHAW

A THESIS SUBMITTED IN PARTIAL FULFILLMENT OF THE
REQUIREMENTS FOR THE DEGREE OF
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MASTER OF SCIENCE THESIS
OF
ALEX J. SHAW

APPROVED:

Thesis Committee:

Major Professor	Reza Hashemi
	Malcolm Spaulding
	Christopher Baxter
	Aaron Bradshaw
	Nasser H. Zawia

UNIVERSITY OF RHODE ISLAND

2016

ABSTRACT

The southern coast of Rhode Island consists of many coastal lagoons and barriers; this coast is eroding at a significant rate due to the combined effects of coastal storms and sea level rise (SLR). The propagation of waves and storm surge in the nearshore can potentially be affected by the coastal erosion and is neglected in many studies. The objective of this work was to assess the effect of shoreline retreat and dune erosion on coastal flooding in a case study located on the southern coast of Rhode Island. An ADCIRC model was developed to simulate the propagation of storm surge in the coastal ponds along the southern coast (Ninigret Pond, Trustom Pond, and Point Judith Pond). The model was validated with data that was collected in the coastal ponds from September 10th, 2010 to September 13th, 2011. Tides as well as a storm surge case of Hurricane Irene were captured in this data and were used to validate the ADCIRC model. Storm surge scenarios, such as the 100-yr storm and Hurricane Bob were then considered along with multiple beach erosion scenarios, including shoreline retreat in 25 years and the failure of dunes. A simplified methodology based on the historical trend of the shoreline retreat in this area was incorporated in the model to represent coastal erosion. Further, a geological assessment of dune erosion profiles after significant storm events was implemented to include the eroded dune profiles in the Digital Elevation Model (DEM). The results showed that for extreme storms (e.g. 100-yr event), where coastal dunes are overtopped and low-lying areas are flooded, the flooding extent is not significantly sensitive to coastal erosion. However, failure of the dunes leads to a significant increase of the flooding extent for smaller storms, which is useful for risk assessment. Substantial dampening of the storm surge elevation in coastal lagoons for moderate and small storm surges, thereby limiting the flooding extent, can be explained by using tidal inlet theory. When dunes

are overtopped or breached by surge and wave actions, the storm surge was no longer limited by the effect of inlets. It was shown that the dune erosion has a considerable impact on the flooding extent of smaller more frequent storm events, with an increase of 207%. Larger events didn't show increased flooding due to dune erosion. The shoreline change did not significantly affect the extent of flooding.

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PREFACE

The following work is a product of the authors listed. This thesis is formatted in accordance with the guidelines for a manuscript style thesis. Manuscript one is being prepared for publication in the Journal of Marine Science and Engineering.

TABLE OF CONTENTS

ABSTRACT	ii
ACKNOWLEDGMENTS	iv
PREFACE	v
TABLE OF CONTENTS	vi
MANUSCRIPT	
1 The Effect of Coastal Erosion on Storm Surge: Case Study of a Coastal Pond System in Rhode Island	1
1.1 Abstract	2
1.2 Introduction	3
1.3 Methods	9
1.3.1 NACCS	9
1.3.2 Ocean data	10
1.3.3 Data collected by Woods Hole Group	15
1.3.4 Coastal erosion	16
1.3.5 Inlet basin dynamics	19
1.3.6 Numerical model for storm surge	20
1.4 Results and discussion	24
1.4.1 Tides/Surge modeling for an idealized case	25
1.4.2 Using observed data versus USACE analytical method	27
1.4.3 Effect of signal period on damping/phase in a inlet-basin	28
1.4.4 Validation of the storm surge model for the southern coast	29

	Page
1.4.5 Effect of inlet geometry on tide/surge signals	33
1.4.6 Effect of erosion on storm surge	34
1.4.7 Effect of sea level rise	44
1.4.8 Discussion	51
1.5 Conclusions	53
List of References	54

APPENDIX

Inlet Basin Dynamics	56
List of References	60
Transects	61
Submitted Manuscript	63

LIST OF TABLES

Table		Page
1	Harmonic constituents for Newport 8452660 and Providence 8454000 NOAA water elevation stations with amplitude in me- ters and phase in degrees	21
2	Differences in flooded area near the eroded shoreline.	42
3	Wave heights and water levels for different return periods	51

LIST OF FIGURES

Figure	Page
1 Overview of the data locations in Rhode Island with save points from the North Atlantic Coast Comprehensive Study in Rhode Island (blue crosses), Woods Hole Group water level gauges (orange dots), WIS Station 63079 and NOAA water level gauges (red dots), and a red box around the study area.	5
2 Overview of the data locations in the study area with save points from the North Atlantic Coast Comprehensive Coast Study in Rhode Island (blue crosses), Woods Hole Group tidal gauges (orange dots), a blue box around the eroded area, and a red box around the study area.	6
3 Transects locations for beach profile survey during the past 30 years. [3]	7
4 The time series of storm surge for synthetic storm 457 - from NACCS - representing a 100-yr event at Newport NOAA gauge 8452660.	10
5 The Digital Elevation Model (DEM) around the study area. The study area is between Matunuck Beach and Charlestown Beach outlined by the black box(source: http://www.rigis.org/data)	11
6 Plots of the wind speed and direction for Hurricane Bob at WIS station number 63079	12
7 Plots of the wind speed and direction for Hurricane Irene at WIS station number 63079	13
8 Extremal analysis of water elevation (meters) data for Newport NOAA station 8452660; the red box shows Hurricane Bob. (tidesandcurrents.noaa.gov)	13
9 Water elevations time series during Hurricane Bob at Newport NOAA water level station 8452660. Time starts from 00:00 GMT, 8/17/91.	14
10 Water elevations time series during Hurricane Irene at Newport NOAA water level station 8452660. Time starts from 00:00 GMT, 8/25/11.	15

Figure	Page
11 Shoreline change maps for Matunuck Beach (source : www.beachsamp.org/resources/shoreline-change-maps/)	16
12 Transects made to define the coastline between Charlestown Beach and Matunuck Beach (Numbered 1-30)	17
13 The simplified method which was used to estimate the shoreline ge- ometry after erosion in future. Transect 30 (as an example), with the original shoreline (blue), 25 year shoreline (red), and intersection point (star) is shown. The vertical axis is exagger- ated for better clarity.	18
14 The simplified method which was used to estimate the erosion of the dunes. Transect 30 (as an example), with the original shoreline (blue), the shoreline with no dune (red), and an idealized 1% shoreline (black)[12]. The vertical axis is exaggerated for better clarity.	19
15 The high resolution ADvanced CIRCulation model (ADCIRC) mesh used to study storm surge propagation in southern coast of RI.	22
16 The high resolution ADCIRC mesh used to study storm surge prop- agation in southern coast of RI zoomed in over the study area.	22
17 a: Schematic of ideal mesh dimensions of the pond are 2.5 by 1 km and the inlet is 40 meters wide and 0.7 meters deep and 1000 meters long. b: Inlet profile	24
18 Comparison of water elevation from the model inside and outside the idealized coastal pond; tidal case (see Figure 17 for geometry of channel).	26
19 Effect of the idealized coastal pond on storm surge (Hurricane Bob) assuming no dune erosion (yellow) and the entire dune eroded to 1 meter MSL (red).	27
20 Impact of the Ninigret Pond inlet on the amplitude of the water elevation for different signal periods outside the pond	29
21 Comparison between modeled tide and observed tide at the NW station (see Figure 2 for location of NW station)	30
22 Comparison between the modeled tide and the observed tide at the NN station	31

Figure	Page
23 Comparison between the model prediction and the observed data at the NN station for Hurricane Irene	32
24 Comparison between the model prediction and the observed data at the NW station for Hurricane Irene	32
25 Comparison of water elevation in Ninigret Pond, Trustom Pond, and Point Judith Pond for a: Hurricane Bob b: Tides	34
26 Failure of dunes protecting Ninigret Pond after Hurricane Carol (1954); Source RI (Coastal Resources Management Council). .	34
27 Comparison of Hurricane Bob flooding extent for the current shoreline (red) and retreated shoreline in 25 years (blue dashed). . .	35
28 Comparison of Hurricane Bob flooding extent for the current shoreline (red) and retreated shoreline in 25 years (blue dashed) for Ninigret Pond	36
29 Comparison of Hurricane Bob flooding extent for the current shoreline (red) and retreated shoreline in 25 years (blue dashed) for Trustom Pond	37
30 Comparison of Hurricane Bob flooding extent for the current shoreline (red) and retreated shoreline in 25 years (blue dashed) for Point Judith Pond	38
31 Comparison of Hurricane Bob flooding extent assuming current condition (red) and current shoreline with no dune system (blue), and the 25 year retreated shoreline as well as complete dune failure (black).	39
32 Comparison of Hurricane Bob flooding extent for the current shoreline (red) the eroded dune profile and retreated shoreline in 25 years (green), and the eroded dune profile on the current shoreline (blue dashed) for Ninigret Pond	40
33 Comparison of Hurricane Bob flooding extent for the current shoreline (red) the eroded dune profile and retreated shoreline in 25 years (green), and the eroded dune profile on the current shoreline (blue dashed) for Trustom Pond	41

Figure	Page
34	Comparison of Hurricane Bob flooding extent for the current shoreline (red) the eroded dune profile and retreated shoreline in 25 years (green), and the eroded dune profile on the current shoreline (blue dashed) for Point Judith Pond 42
35	Comparison of 100-yr flooding extent assuming the current shoreline (blue), current shoreline with no dune system (green), and the 25 year retreated shoreline as well as complete dune failure (black) 43
36	Comparison of flooding extend of 100-yr storm event, assuming Sea Level Rise (SLR) (1 feet), using ADCIRC model (black) and a simple addition of SLR to Newport water elevation data (bathtub approach)(dashed blue). 44
37	Comparison of Hurricane Bob flooding extent with (blue) and without (green) 1 feet Sea Level Rise and complete failure of dunes. 44
38	Comparison of Hurricane Bob flooding extent for the retreated shoreline in 25 years with complete failure of dunes (green) and the retreated shoreline in 25 years with complete failure of dunes with one foot of SLR added on (blue dashed) for Ninigret Pond 45
39	Comparison of Hurricane Bob flooding extent for the retreated shoreline in 25 years with complete failure of dunes (green) and the retreated shoreline in 25 years with complete failure of dunes with one foot of SLR added on (blue dashed) for Trustom Pond 46
40	Comparison of Hurricane Bob flooding extent for the retreated shoreline in 25 years with complete failure of dunes (green) and the retreated shoreline in 25 years with complete failure of dunes with one foot of SLR added on (blue dashed) for Point Judith Pond 47
41	Comparison of 100-yr flooding extent with (blue) and without (black) 1 feet of Sea Level Rise and assuming complete failure of dunes and the retreated shoreline in 25 years. 48
42	Comparison of 100-yr flooding extent with (blue) and without (red) 1 feet of Sea Level Rise and assuming complete failure of dunes and the retreated shoreline in 25 years for Ninigret Pond 49

Figure	Page
43 Comparison of 100-yr flooding extent with (blue) and without (red) 1 feet of Sea Level Rise and assuming complete failure of dunes and the retreated shoreline in 25 years for Trustom Pond	49
44 Comparison of 100-yr flooding extent with (blue) and without (red) 1 feet of Sea Level Rise and assuming complete failure of dunes and the retreated shoreline in 25 years for Point Judith Pond . .	50

MANUSCRIPT 1

**The Effect of Coastal Erosion on Storm Surge: Case Study of a
Coastal Pond System in Rhode Island**

By: Alex Shaw

To be submitted to the Journal of Marine Science and Engineering

1.1 Abstract

The southern coast of Rhode Island consists of many coastal lagoons and barriers; this coast is eroding at a significant rate due to the combined effects of coastal storms and sea level rise (SLR). The propagation of waves and storm surge in the near shore can potentially be affected by the coastal erosion and is neglected in many studies. The objective of this work was to assess the effect of shoreline retreat and dune erosion on coastal flooding in a case study located on the southern coast of Rhode Island. An ADCIRC model was developed to simulate the propagation of storm surge in the coastal ponds along the southern coast (Ninigret Pond, Trustom Pond, and Point Judith Pond). The model was validated with data that was collected in the coastal ponds from September 10th, 2010 to September 13th, 2011. Tides as well as a storm surge (Hurricane Irene) were captured in this data and were used to validate the ADCIRC model. Storm surge scenarios, such as the 100-yr storm and Hurricane Bob were then considered along with multiple beach erosion scenarios, including shoreline retreat in 25 years, and the erosion of dunes. A simplified methodology based on the historical trend of the shoreline retreat in this area was incorporated in the model to represent coastal erosion. Further, a geological assessment of dune erosion profiles after significant storm events was implemented to include the eroded dune profiles in the Digital Elevation Model (DEM). The results showed that for extreme storms (e.g. 100-yr event), where coastal dunes are overtopped and low-lying areas are flooded, the flooding extent is not significantly sensitive to coastal erosion. However, failure of the dunes leads to a significant increase of the flooding extent for smaller storms. Substantial dampening of the storm surge elevation in coastal lagoons for moderate and small storm surges, thereby limiting the flooding extent, can be explained by using inlet-basin dynamic theory. When dunes are overtopped or breached by surge

and wave actions, the storm surge was no longer limited by the effect of inlets. It was shown that the dune erosion has a considerable impact on the flooding extent of smaller more frequent storm events, with an increase of around 200%. The shoreline retreat did not significantly affect the extent of flooding.

1.2 Introduction

The Rhode Island shoreline has been impacted by hurricanes in the past, most recently Hurricane Sandy in 2012. Climate change is expected to increase the strength and frequency of these events, putting more coastal areas at risk [1]. It has been estimated that sea level will rise between 0.2 and 2 meters by 2100 putting increasingly more area in the floodplain [2].

The southern shore of Rhode Island is eroding at a rapid rate. The area between Matunuck Beach and Charlestown Beach is eroding the fastest compared with the rest of the southern shore at a rate of 1.07 to 1.15 meters per year (see www.beachsamp.org/; section 1.3.4). The dunes along the southern coast of Rhode Island are also eroded during major storm events (Figure 26). Storm surge and erosion interact in two ways: (1) effect of storm surge on erosion, which is the changes of the shoreline and dunes that is caused by the storm, and (2) effect of erosion on storm surge, which is the changes in flooded propagation caused by erosion. This study will focus on the effect of coastal erosion on coastal flooding (i.e. 2). In general, there are two methods to include erosion in storm surge studies: (1) using morphodynamic models that incorporate sediment transport and bed level changes during a simulation, and (2) estimating the morphodynamic changes based on historical data. Morphodynamic models are very complex and require more computational time than other models; also, they require soil characteristics that varies along the coast. These models are also hard to validate because of limited data. The second method allows for the worst case scenario assessment

by assuming the dunes erosion scenarios, which is useful for risk assessment and planning. This study will be using the second method of representing erosion. The research will investigate the effect that shoreline retreat, as well as dune erosion on the flooding extent due to different storm events. Three ponds will be investigated in this study Ninigret Pond, Point Judith Pond, and Trustom Pond because of their different inlet geometries.

Figure 1. Overview of the data locations in Rhode Island with save points from the North Atlantic Coast Comprehensive Study in Rhode Island (blue crosses), Woods Hole Group water level gauges (orange dots), WIS Station 63079 and NOAA water level gauges (red dots), and a red box around the study area.

Figure 2. Overview of the data locations in the study area with save points from the North Atlantic Coast Comprehensive Coast Study in Rhode Island (blue crosses), Woods Hole Group tidal gauges (orange dots), a blue box around the eroded area, and a red box around the study area.

The Rhode Island coastline has been monitored for more than 30 years at 8 different transects (Figure 3). At each location the shoreline elevation was measured along the transect bi-weekly. These transects can be used to determine the erosion rate of the shoreline per year. The erosion rate at Green Hill for example, was found to be 0.95 meters per year on average [3]. The erosion of the shoreline could affect the dynamics of flooding by putting more area into the flood plain.

Figure 3. Transects locations for beach profile survey during the past 30 years. [3]

As shoreline changes the dunes change as well. Strong storms can also cause these dune systems to fail, as well as creating surge channels into the coastal ponds allowing for a higher flow rates into the pond. Based on historical evidence, dunes along the coastline are impacted by storm events and can be breached causing surge channels. Morphodynamic models such as XBeach [4] include parameters that can simulate changes in the shoreline. These channels and destroyed dunes open the coastline to further damage from a storm.

Rhode Island has many coastal ponds which can attenuate storm surges through the inlet limiting the flow into the pond. This attenuation can be characterized by simplified analytical methods [5] which treat coastal ponds as low pass filters. Changes to the barrier between the pond and the ocean during a storm

can potentially affect the characteristics of the pond. This change could negate the reduction that can occur due to the inlet limiting the flow.

In terms of previous research in this area, the effects of erosion on storm surge flooding was investigated in Hatteras Island, North Carolina [6]. This was carried out using Advanced Circulation (ADCIRC) model assuming 3 different Digital Elevation Models (DEM). The three scenarios included the current elevation of the shoreline, an eroded case with lower dunes, and a case with a surge channel in the island. This study was focused on the changes in velocity with the addition of a surge channel. In the dune breaching scenario, the velocities around the breach increased, but the peak surge decreased due to the water flow into the channel.

Storm surge in Rhode Island has been modeled in various studies. More recently, North Atlantic Coast Comprehensive Study (NACCS), conducted by the US Army Corp of Engineers (USACE), simulated 1050 tropical storm events along the Atlantic coastline [7]. The NACCS saved the data along the coastlines and inside the coastal ponds. Data was also collected in the coastal ponds by Woods Hole Group [8]. They installed water elevation stations, meteorological stations and wave stations, along the southern coastline and in the ponds. The stations were active for one year from September 2010 to 2011 (Figures 1 and 2). To best of our knowledge, no research has investigated the impact of coastal erosion on flooding in this area.

The objectives of this research were, to develop a validated high resolution model that represents tide and storm surge in coastal ponds along the southern coast of Rhode Island using observed data in the ponds, investigate the relationship of the dune erosion and coastal pond dynamics, as a limiting factor to storm surge, determine the effects of dune erosion and shoreline retreat (together and separately) on storm surge, and analyze the effect of Sea Level Rise (SLR) on storm surge and

erosion scenarios.

The results of this study were presented at Estuarine and Coastal Modeling Conference, RI in 2016, and submitted to the Journal of Marine Science and Engineering. The submitted manuscript, which includes the important results of this research, can be found in Appendix C. The following report is an expanded version of the manuscript which includes more analysis and results.

1.3 Methods

1.3.1 NACCS

The North Atlantic Coast Comprehensive Study (NACCS; [7]) used ADvanced CIRCulation (ADCIRC) [9] to model 1050 tropical and 100 extra tropical synthetic Storms on the Atlantic Coast. This model was shown to produce similar results to NOAA water level gauge stations for validation [10]. Although this model could effectively predict the storm surge at NOAA gauge stations in offshore zones, it could not resolve the inlets of the coastal ponds in Rhode Island since the mesh resolution for the southern coast was around 200 meters. The NACCS has save points where their data can be accessed for the different storm simulations (Figure 1). Some of these save points are in the coastal ponds. These save points may be inaccurate, because the mesh did not resolve the inlets or dunes along the shore well enough. This study will look at the effects that the inlets and coastal ponds have on surge by using a mesh that has a finer resolution along the coast, allowing water to be properly simulated.

For a 100-yr event, this study looked at all synthetic storms generated by NACCS [7]. Although these storms are synthetic, they have been generated using the statistical parameters of observed storms in the past. The NACCS has also computed and reported the storm surge with different return periods at many points around RI. Accordingly, a storm surge event which generated the water level

of around 100-yr storm surge at Newport (8452660) and Providence (8454000) water level station was selected. This storm had a maximum surge of 3.20 m (MSL) at Newport (Figure 4), which is close to 3.35 m (MSL) or 2.7 m (MHHW) for 100-yr event, considering 100-yr event at the upper confidence level curve (tidesandcurrents.noaa.gov). Figure 4 shows the time series of this storm. The duration of this storm is also comparable to some historical storm surges in RI for more information see [7] (see tidesandcurrents.noaa.gov).

Figure 4. The time series of storm surge for synthetic storm 457 - from NACCS - representing a 100-yr event at Newport NOAA gauge 8452660.

1.3.2 Ocean data

Depending on the purpose of the modeling different types of data are necessary such as bathymetry, water elevation, and wind data. In terms of bathymetry and topography of southern Rhode Island, a combined bathymetry and topography with a resolution of 10 meters was used. The bathymetry data were obtained from 2 sources: the NGDC Bathymetry Data Viewer (<http://maps.ngdc.noaa.gov/viewers/bathymetry/>), and the Army Corps of Engineers 2010 coastal LiDAR survey. The LiDAR survey focused on the south coast and extended about 1 km offshore. The Topography came from LiDAR techniques

as well (Figure 5; source: <http://www.rigis.org/data>).

Figure 5. The Digital Elevation Model (DEM) around the study area. The study area is between Matunuck Beach and Charlestown Beach outlined by the black box(source: <http://www.rigis.org/data>)

Wind data were extracted from the US Army Corp of Engineers Wave Information Study (WIS) hindcasts (see wis.usace.army.mil). The WIS model covers the period from 1980 to 2012. The wind data in the WIS nodes are based on a modeling system and a combination of ground and satellite wind observations. For this study, the wind fields from large storm events are of interest. For this 30 year range a large storm event, Hurricane Bob, a strong tropical storm which occurred on 8/19/1991 was chosen. Hurricane Bob gives a good representation of large storms in the area. It is the 5th largest storm in the NOAA tide gauge at Newport RI, and approximately corresponds to a 20 year event, according to the extremal analysis for the site (Figure 8). The wind field for this event extracted from the WIS is plotted in Figure 6. Hurricane Irene data from August 2011 and was also used as a validation case (Figure 7).

Figure 6. Plots of the wind speed and direction for Hurricane Bob at WIS station number 63079

Figure 7. Plots of the wind speed and direction for Hurricane Irene at WIS station number 63079

For water levels, the NOAA Newport water level station data were used (tidesandcurrents.noaa.gov). This station provides both tidal and storm surge data. The water elevation data for Hurricane Bob is plotted in Figure 9. Water elevations were also used from this station for Hurricane Irene (Figure 10).

Figure 8. Extremal analysis of water elevation (meters) data for Newport NOAA station 8452660; the red box shows Hurricane Bob. (tidesandcurrents.noaa.gov)

Figure 9. Water elevations time series during Hurricane Bob at Newport NOAA water level station 8452660. Time starts from 00:00 GMT, 8/17/91.

Figure 10. Water elevations time series during Hurricane Irene at Newport NOAA water level station 8452660. Time starts from 00:00 GMT, 8/25/11.

1.3.3 Data collected by Woods Hole Group

From 7/2010 to 9/2011, Woods Hole Group carried out an extensive data collection program [8], for the US Army Corps of Engineers New England District, entitled “Wave, Tide and Current Data Collection, Washington County, Rhode Island”. The primary purpose of this work was to collect site-specific data to support a RI Regional Sediment Management Study, and included the collection of tides, currents, wave, and meteorological data. Their study included measurement of water elevations inside the coastal ponds (Figure 1), as well as the waves and currents. For this study, the data from inside Ninigret Pond along the southern RI coastline was used for model validation. This data can be used for tidal comparisons as well as for Hurricane Irene, which impacted this area during the observation period. The water elevation can be used for understanding of the effect

of coastal ponds on water elevation. Two stations inside Ninigret pond were used for model validation. These stations are located in front of the inlet (NN) and to the far west side of the pond (NW) Figure 2).

1.3.4 Coastal erosion

The area between Charlestown Beach and Matunuck Beach on southern coasts of Rhode Island, where historical data indicates highest erosion rates (around a meter per year retreat), was chosen to be the focus of this study (Figure 2). This shoreline retreat rates were used to modify the DEM for future scenarios assuming the same rate of erosion (Figure 11). These rates were calculated using aerial photographs from 1939 to 2014. The shoreline was identified for each year, and the most seaward and landward shorelines were taken and measured between them. The distance was then divided by the number of years to create a shoreline change rate. This shoreline change rate is not perfect however. The shoreline is eroded during storm events and depending on the time of the aerial photo the shoreline could be misrepresented.

Figure 11. Shoreline change maps for Matunuck Beach (source : www.beachsamp.org/resources/shoreline-change-maps/)

To represent the effect of erosion over 25 years, a very simple method was used. A morphodynamic model could be used to represent the coastline but a simplistic approach was used. The shoreline was broken into the transects shown in Figure 12 to discretize the coastline. The selected beaches have similar morphologies which were assumed to include an offshore beach slope, a near shore beach slope, and a dune system. The offshore beach slope was extended horizontally to that corresponding to 25 years of erosion (Figure 13). At this new point where the offshore beach ends the same near shore and dune system was assumed. This method retreats the shoreline while keeping the same beach profile geometry. This method was applied to all of the transects that were created along the study area. Once the transects were modified, they were linearly interpolated to modify the bathymetry and topography (DEM) of the model. This approach only works in this area because the geology changes in different areas.

Figure 12. Transects made to define the coastline between Charlestown Beach and Matunuck Beach (Numbered 1-30)

Figure 13. The simplified method which was used to estimate the shoreline geometry after erosion in future. Transect 30 (as an example), with the original shoreline (blue), 25 year shoreline (red), and intersection point (star) is shown. The vertical axis is exaggerated for better clarity.

While shoreline change is an issue in this area the dune systems are also being eroded during storms. Very large storms result in overtopping and over-wash of the dunes. During storm conditions, the combined action of storm surge and waves erode the dune and the sediments will be carried out to sea and landward creating surge channels and wash-over fans. To study the effect of dune erosion, it was assumed that the dunes were simply cutoff at MSL (Figure 14). Although, more complex procedures (e.g. [11, 4]) such as using a morphodynamic model could be applied, given the resolution of a storm surge model around the dunes, this seemed a reasonable approximation. A similar method was outlined in [12] which removed the dune above one meter MSL. The one meter elevation was determined by looking at the wash-over fans deposited after the 1938 Hurricane, the Ash Wednesday storm, and Hurricane Sandy [12]. The elevations of the wash-over fans

were found using LiDAR techniques and were extended using a slope of $.003 \text{ cm/m}$, which is the same angle of the wash-over fans after Hurricane Sandy. Removing the dunes at one meter above MSL and MSL have a negligible difference when comparing with large storm events because the water elevations of the storms are sufficient to overtop both scenarios.

Figure 14. The simplified method which was used to estimate the erosion of the dunes. Transect 30 (as an example), with the original shoreline (blue), the shoreline with no dune (red), and an idealized 1% shoreline (black)[12]. The vertical axis is exaggerated for better clarity.

1.3.5 Inlet basin dynamics

In general, the objective of the inlet-basin analysis is to compute the water elevation range (e.g. harmonic tides) inside the basin, the maximum current in the inlet, and the phase-lag of the basin water elevation relative to ocean water elevation (θ in this research equation 1). An analytical model [5] uses simple inputs to calculate these parameters. The inputs are simple measurable parameters: the inlet cross section, surface area of the basin, the length and the frictional parame-

ters of the inlet, and the amplitude and period of water elevation outside the basin (i.e. ocean). These parameters are manipulated to create K_1 and K_2 (equations 2 and 3), which can be used with Figure A.3 and Figure A.4. For the details about these parameters see Appendix A.

$$\theta = \frac{Basin \ Amplitude}{Ocean \ Amplitude} \quad (1)$$

$$K_1 = \frac{a_o A_b F}{2LA_c} \quad (2)$$

$$K_2 = \frac{2\pi}{T} \sqrt{\frac{LA_b}{gA_c}} \quad (3)$$

Considering a 1-D approximation of the flow in the inlet, the velocity and water elevation along the inlet can be evaluated using the mass and momentum conservation

1.3.6 Numerical model for storm surge

For numerical modeling, the ADCIRC (ADvanced CIRCulation model) was used. ADCIRC is a modeling software that solves time dependent equations for water circulation, as well as transport equations over a finite element mesh in both two and three dimensions. The finite element method allows for a very customizable mesh with high resolution and lower resolution areas. This allows the computation time to be optimized (using more computations in areas of interest and less computations in areas of no interest) while still maintaining the high resolution simulations in the areas of interest. ADCIRC has been extensively used to predict storm surge flooding [9, 13]. The ADCIRC numerical model is generally forced along the open boundaries by water elevation/velocity, and wind stress/pressure over the domain. It computes the hydrodynamic field (water elevation and velocities) in the domain. ADCIRC has been coupled with SWAN (Simulating WAVes

Nearshore) and can also simulate waves and wave-surge interactions as well (e.g. [14]).

ADCIRC Model development

The first step in model development was creating a mesh that could resolve the inlets. The mesh was created in Surface water Modeling System (SMS) using a resolution of 30 meters for the coastline to accurately capture the dune changes and represent the inlet dynamics correctly. Farther onshore the resolution was increased to 150 meters. The ocean open boundary was given a resolution of 2 km to save computation time. This mesh can be seen in Figure 15. The model was run using 2D model physics with manning’s friction of 0.018 offshore while it increased to 0.06 in land areas having vegetation. The model was forced using 5 harmonic constituents for tides. The constituents that were used were M2, N2, K1, S2, and O1 [15]. These are the dominate amplitudes for this area (Table 1). The storm surge scenarios were forced with water elevation and wind drag taken from NOAA water level stations and WIS data, respectively.

1

Table 1. Harmonic constituents for Newport 8452660 and Providence 8454000 NOAA water elevation stations with amplitude in meters and phase in degrees

Harmonics	Newport Amplitude	Newport Phase	Providence Amplitude	Providence Phase
M2	0.505	2.3	0.643	9.5
S2	0.108	25	0.138	33.6
N2	0.124	345.8	0.152	354.6
K1	0.062	166.1	0.073	169.4
M4	0.057	35.8	0.103	202.2
O1	0.047	202	0.027	312.7
M6	0.0005	220.1	0.027	312.7
MK3	0.0008	19.5	0.016	39.3
S4	0.0007	5.1	0.014	23.8
MN4	0.026	347.9	0.014	12.7

¹<http://www.aquaveo.com/software/sms-surface-water-modeling-system-introduction>

Figure 15. The high resolution ADvanced CIRCulation model (ADCIRC) mesh used to study storm surge propagation in southern coast of RI.

Figure 16. The high resolution ADCIRC mesh used to study storm surge propagation in southern coast of RI zoomed in over the study area.

Tide/storm surge scenarios

Tide and three scenarios for storm surge were simulated. The simulated storms included Hurricane Irene 8/2011, Hurricane Bob 8/1991, and a synthetic storm equivalent to 100-yr event in Newport extracted from NACCS. Hurricane Irene occurred in 2011 when Woods Hole Group were collecting data. This allowed for

validation of the model for a hurricane. As mentioned before, Hurricane Bob can be considered a good representation of large storms in the area; it is the 5th largest storm in the NOAA tide gauge at Newport, and corresponds roughly to a 20 year event (Figure 8; see tidesandcurrents.noaa.gov).

Idealized model

The first scenario that was considered was an idealized beach and coastal inlet/pond system that are a scale model of Ninigret pond (Figure 17). This case was setup as a first step to evaluate the performance of numerical model and also to better understand the dynamics of the propagation of tides and storm surge in these systems. Since realistic bathymetry and topography cause many complexities in numerical models, idealized cases usually provide a more clear understanding at first stages of application. This idealized case was developed assuming a pond with dimensions of 2.5 kilometers by 1 kilometer and an inlet of 40 meters wide, 900 meters long, and 0.7 meters deep. These numbers were chosen to make the analytical models K_1 and K_2 parameters for the ideal pond and Ninigret pond to be similar. the ideal ponds K_1 and K_2 are 219 and 0.41 respectively, While Ninigret Ponds K_1 and K_2 are 237 and 0.5 which are similar.

Figure 17. a: Schematic of ideal mesh dimensions of the pond are 2.5 by 1 km and the inlet is 40 meters wide and 0.7 meters deep and 1000 meters long. b: Inlet profile

The idealized pond was modeled using astronomical tides and for Hurricane Bob to compare the analytical equations with the modeled results of the inlet dynamics. For the storm scenario, the beach was changed allowing for surge channels in the dune as well as removing the dune entirely. Removing the dunes allowed this study to explore what would happen to the coastal ponds on the south shore of Rhode Island during a real event.

1.4 Results and discussion

In the results section this study first assessed an idealized pond that modeled a simplified case and determined if the erosion of dunes would have an effect on the storm surge inside the idealized pond. Then, the impact of inlets on tide/surge dynamics in Ninigret Pond was assessed. This gives some insight to interpret model results. The model for the southern coast was then validated with the Woods Hole Group tidal/storm surge data. Consequently the shoreline/dunes were eroded to determine the effect that they would have on the 100-yr event and Hurricane Bob flooding extents. Finally, the effect of SLR was assessed in two scenarios: adding

one foot to the sea level in the model, and adding one foot of elevation to the final flooding extents. One foot was chosen to represent 25 years, the same as the shoreline erosion.

1.4.1 Tides/Surge modeling for an idealized case

The first modeled scenario is the idealized case. Using the analytical method described in Appendix A, this study computed the reduction of the amplitude of water elevation signal in the pond. The dimensions of the pond are the driving factors for the analytical method. For the geometry of the coastal pond and inlet in the idealized case, K_1 and K_2 are evaluated as 219 and 0.41 respectively. Using Figure A.3, and the K_1 and K_2 values θ was calculated to be 0.25 for a semi-diurnal tide. The ideal model should show a similar θ value.

Using ADCIRC the tidal propagation was modeled. The water elevation inside and outside of the pond are plotted in Figure 18. θ was found to equal 0.21 which is very similar to the one calculated based on the simple analytical method of 0.25. Therefore, the numerical model also shows similar impact on water elevation.

Figure 18. Comparison of water elevation from the model inside and outside the idealized coastal pond; tidal case(see Figure 17 for geometry of channel).

A storm surge (Hurricane Bob) was also considered to examine how the coastal pond affects the storm surge propagation. The open boundaries of the model were forced by water elevation which was measured at Newport RI station. The Newport Station is a good representation of the water elevation along the south shore as discussed in [16]. Here it was assumed that the dunes are not eroded during the storm. Figure 19 show the time series of water level inside and outside the coastal pond. As it can be seen, θ is about 0.33 which is more than the impact on tides but still a large effect. This shows that the coastal pond as an inlet-basin system can protect part of the land from flooding in a storm event, if the dunes are not breached. This is attributable to the fact that flows go through the existing inlet (not breaching of the barrier) and that the temporal scale for the storm is similar to that for the flood tide.

Figure 19. Effect of the idealized coastal pond on storm surge (Hurricane Bob) assuming no dune erosion (yellow) and the entire dune eroded to 1 meter MSL (red).

Different erosion scenarios were considered for the idealized case. In the first scenario surge channels were created with the same width of the inlet (40 meters) and 1 meter MSL elevation. One and two surge channels were created and tested. The first surge channel had little to no effect on θ , however the addition of a second surge channel showed a slight increase in θ . In the next scenario, the area between the pond and the ocean was lowered to 1 meter (MSL) entirely, this represents the complete failure of the dunes along the coastal pond. This had a dramatic effect on the amplitude attenuation, increasing θ to 0.65 (Figure 19). This shows that erosion can have an effect on the flooding due to storm surge.

1.4.2 Using observed data versus USACE analytical method

The data collected by Woods Hole Group was analyzed using the analytical method. For the analytical parameters Ninigret Pond's dimensions are measured

as follows: for Ninigret Pond the surface area is 7.5 km^2 , the width of the inlet is about 30 m and the length of the inlet is 1700 m, and an average depth of 1.5 m was assumed from the bathymetric data in the area. The amplitude of the tide in the area was taken to be 0.4 meters from harmonic analysis, and the period was taken at 12.42 hours for M2 tide. The remaining parameters of k_{en} , k_{ex} , and f were assumed to be 0.1, 1, 0.03 respectively using King’s method outlined in the coastal engineering manual [5]. Using these parameters, K_1 and K_2 were computed as 237 and 0.5, respectively. These values were employed in Figure A.3 and Figure A.4 to determine the difference in amplitude and phase inside and outside Ninigret Pond (θ). θ was found to be around 0.2 with a phase change of 90 degrees.

The tidal signal outside the pond was constructed using the harmonic constituents from a historical NOAA station on Weekapaug Point(Figure 1). This tidal data was compared with the data on the inside of the pond from the Woods Hole Group over the entire year. θ was found to be 0.24 for the westerly (NW) station and 0.25 for the middle station (NN) (Figure 2). This shows the analytical method has an acceptable accuracy for this pond. The phase difference that was found between the different signals was 90.5 degrees by analyzing the tides inside and outside the pond and comparing the phases of M2 which has the largest amplitude. This phase difference is very similar to the 90 degrees that the analytical model suggested.

1.4.3 Effect of signal period on damping/phase in a inlet-basin

Inlets to coastal ponds act as low pass filters. They affect a portion of shorter periods events such as tides or storm surge but have much less impact on longer periods. By computing the effect of Ninigret Pond’s inlet on various signals with different periods (Figure A.3) it was found that frequencies of 0.5, 1, 2, and 2.5 days made θ equal 0.1, 0.35, 0.62, and 0.75 respectively (Figure 20). This means

that signals with a frequency of 2.5 days or lower will not be affected by the inlet dynamics and could change the elevation of the pond over longer periods of time. The duration of Hurricane Bob was 10 hours so θ would be 0.14. The attenuation of the water elevation signal is also dependent on the geometry of the pond. Point Judith Pond experiences almost no attenuation during tides because of the width and depth of the inlet as shown later in this research.

Figure 20. Impact of the Ninigret Pond inlet on the amplitude of the water elevation for different signal periods outside the pond

1.4.4 Validation of the storm surge model for the southern coast

To validate both the tidal and storm surge cases the Woods Hole Group data were used. The observed data were compared with the model results during a spring-neap cycle and Hurricane Irene.

Tidal validation

For tides the model was run for 15 days (spring-neap cycle is about two weeks) from May 14 2011 until May 29 2011 with a one day ramping period. This was during the time that the Woods Hole Group tidal stations were active and allowed the modeled results to be compared with the observed data. Figure 21 shows the comparison between the modeled data (orange) and the observed data (blue) that occurred at Station NW. Figure 22 shows the comparison at the NN tide station that is inside the coastal pond.

Figure 21. Comparison between modeled tide and observed tide at the NW station(see Figure 2 for location of NW station)

Figure 22. Comparison between the modeled tide and the observed tide at the NN station

The modeled tide at both stations are slightly higher than the observed tide for the spring and lower during the neap cycle with an RMSE of 0.053 m and 0.051 m for NN and NW respectively. During the neap cycle the model did not allow flow into the pond. The difference could be associated with accuracy of model to resolve the inlet, which is only two nodes wide in the skinniest area. The comparison at the NW station is better than at the NN station, and this could be due to the NW station being farther away from the entrance to the Ninigret Pond.

Validation for Hurricane Irene

The storm surge case of Hurricane Irene was a category 3 event that happened in mid August in 2011. As mentioned, the collected water elevation data contained the period of Hurricane Irene. The model was forced using wind data available at WIS Station 63079 (Figure 1) and on the open boundary by recorded surge at NOAA Newport tidal gauge. Using these inputs Hurricane Irene was modeled and

is compared in Figures 23 and 24 to the observed tide at the NW and NN stations.

Figure 23. Comparison between the model prediction and the observed data at the NN station for Hurricane Irene

Figure 24. Comparison between the model prediction and the observed data at the NW station for Hurricane Irene

The comparison for both stations are good with an RMSE of 0.065 m and 0.041 m for NN and NW respectively, however the model does slightly over predict the surge. This over prediction could be due to the slightly higher surge values at Newport compared to the southern shore [16]. The NW station has better agreement because the station is farther away from the inlet.

1.4.5 Effect of inlet geometry on tide/surge signals

This research showed that coastal ponds attenuate the tides and storm surges depending on the geometry of the pond and inlet. This was proven using observed data, model simulations, and analytical approach. The study area has three coastal ponds Ninigret Pond, Trustom Pond, and Point Judith Pond with different geometries as seen in Figure 2. Point Judith Pond has a wide deep inlet with a width of 80 meters and a depth of around 7 meters below MSL. This larger inlet allows water to easily flow into the pond during a tidal cycle or a storm event causing the surrounding areas to get inundated to a greater extent. Trustom Pond is the other extreme with no connection to the ocean. It is blocked by a small barrier, that during storm events can be overtopped causing flooding behind the barrier and the pond. The water elevations in the three ponds are plotted for a tidal cycle and for a storm event (Hurricane Bob) in Figure 25. Point Judith Pond has the same tidal signal as outside the pond because of the wide inlet but the water level does attenuate slightly during the storm event with a θ of 0.93. Trustom Pond has no significant change in water elevation during tides or Hurricane Bob because the barrier isn't breached. Ninigret Pond shows a θ of 0.2 for tides and 0.32 for Hurricane Bob from the narrower inlet. For storms which do not overtop and erode the coastal dunes, the inlets of coastal ponds can significantly decrease the storm surge elevation. This is consistent with the previous theory describing the hydrodynamics of coastal ponds and inlets.

Figure 25. Comparison of water elevation in Ninigret Pond, Trustom Pond, and Point Judith Pond for a: Hurricane Bob b: Tides

1.4.6 Effect of erosion on storm surge

For erosion two scenarios were considered: shoreline change in 25 years (leading to change in beach profile and DEM), and dune erosion. The erosion of dunes is a common consequence of large Hurricanes in the study area as can be seen in Figure 26, which shows the failure of dune system of Ninigret Pond during Hurricane Carol, 1954. Several scenarios for beach erosion considering the two storm cases (100-yr and Bob) will be discussed here.

Figure 26. Failure of dunes protecting Ninigret Pond after Hurricane Carol (1954); Source RI (Coastal Resources Management Council).

Hurricane Bob

For Hurricane Bob, the flooding extents assuming eroded (retreated) shoreline and the current shoreline are shown in Figure 27. Assuming retreated shoreline DEM, the flooding extent slightly increases by 0.22 km² which is a 20% increase (Tabel 2), which is the added flooded area divided by the original flooded area. It can be argued that the shoreline retreat does not significantly increase the extent of flooding as long as the dunes are not eroded. As mentioned, for this scenario, this study assumed that the eroded beach profile does not change the dune height or shape but simply moves it landward by about 30 meters. This can be seen in the flooding extent as well.

Figure 27. Comparison of Hurricane Bob flooding extent for the current shoreline (red) and retreated shoreline in 25 years (blue dashed).

Figure 28 shows that Ninigret Ponds flooding increases slightly east of the inlet where the shoreline was moved back, but the rest of the flooding around Ninigret Pond did not change. In Trustom Pond (Figure 29) the area around the pond was unaffected by the shoreline retreat but the shoreline flooding increased slightly. Finally the area around Point Judith Pond increased in one area greatly, while the rest of the area remained the same this large area is at the end of the transects and could be a discontinuity in the DEM that was used.

Figure 28. Comparison of Hurricane Bob flooding extent for the current shoreline (red) and retreated shoreline in 25 years (blue dashed) for Ninigret Pond

Figure 29. Comparison of Hurricane Bob flooding extent for the current shoreline (red) and retreated shoreline in 25 years (blue dashed) for Trustom Pond

Figure 30. Comparison of Hurricane Bob flooding extent for the current shoreline (red) and retreated shoreline in 25 years (blue dashed) for Point Judith Pond

As expected, when the dunes are removed (assuming a failure during storm) the flooding extent increases by 2.33 km^2 , which is a 207% increase (Figure 31 Tabel 2). Since dunes no longer protect the shoreline, the water is able to flood a larger area, and the damping effect of inlet-basin systems in coastal ponds are eliminated since flows are no longer controlled by the inlet geometry. The flooding extent increased up to half a kilometer in some areas. The dunes were also removed from the 25 year shoreline. Considering shoreline erosion and dune failure leads to similar results compared with only dune failure (Figure 31). Therefore, effect of dune erosion is significant as opposed to shoreline retreat on flooding extent.

Figure 31. Comparison of Hurricane Bob flooding extent assuming current condition (red) and current shoreline with no dune system (blue), and the 25 year retreated shoreline as well as complete dune failure (black).

Figure 32 shows the increase around Ninigret Pond which is caused by the dunes not blocking the water from entering the pond. Figure 33 shows the difference in flooding around Trustom Pond which extended farther back due to the dunes not blocking the flow. Figure 34 shows that there is no difference around Point Judith Pond because the dunes in front of this area were not eroded and the flooding extent remained the same. Erosion of coastal dunes increased flooding by 207%, which is a much greater effect, compared with the retreat of shorelines increase of 20% (Tabel 2)

Figure 32. Comparison of Hurricane Bob flooding extent for the current shoreline (red) the eroded dune profile and retreated shoreline in 25 years (green), and the eroded dune profile on the current shoreline (blue dashed) for Ninigret Pond

Figure 34. Comparison of Hurricane Bob flooding extent for the current shoreline (red) the eroded dune profile and retreated shoreline in 25 years (green), and the eroded dune profile on the current shoreline (blue dashed) for Point Judith Pond

Table 2. Differences in flooded area near the eroded shoreline.

	current flooded area	changed flooded area	difference in flooded area	percentage increase
25 year shoreline	1.13 km ²	1.35 km ²	0.22 km ²	19.7%
no dune shoreline	1.13 km ²	3.50 km ²	2.33 km ²	207%

The 100-yr event

For the 100-yr event, the erosion scenarios (shoreline retreat and dune erosion) have no significant effect on the storm surge extent (Figure 35). This is because the storm surge will overtop the dunes and their effect on flooding extent is not significant. Nevertheless, it should be noted that the failure of dunes can significantly affect wave propagation as waves will break over dunes. For a very

extreme storm such as 100-yr event where coastal dunes are overtopped and all of low-lying areas are flooded, the flooding extent is not significantly changed with coastal erosion.

Figure 35. Comparison of 100-yr flooding extent assuming the current shoreline (blue), current shoreline with no dune system (green), and the 25 year retreated shoreline as well as complete dune failure (black)

1.4.7 Effect of sea level rise

SLR can potentially increase the flooding extent. There are two ways to consider the effect of SLR on flooding extent: (1) adding the magnitude of SLR to elevations predicted by model; (2) modifying the bathymetry and running the storm surge model. Consistent with 25 years shoreline change scenarios, a one foot SLR was assumed. Figure 36 shows that for extreme case scenarios such as 100-yr event the simple addition of SLR to flooding extent (bathtub approach) and hydrodynamic modeling lead to very similar results.

Figure 36. Comparison of flooding extent of 100-yr storm event, assuming Sea Level Rise (SLR) (1 feet), using ADCIRC model (black) and a simple addition of SLR to Newport water elevation data (bath-tub approach)(dashed blue).

Hurricane Bob including SLR

The effect of SLR on flooding extent in case of complete dune failure was considered for Hurricane Bob. Figure 37 shows the flooding extent from the addition of sea level rise. SLR increased the flooding between Ninigret Pond and Trustum Pond significantly but in others area not greatly. Figures 38, 39, and 40 show zoomed in areas around the ponds showing where the SLR increased the flooding.

Figure 37. Comparison of Hurricane Bob flooding extent with (blue) and without (green) 1 feet Sea Level Rise and complete failure of dunes.

Ninigret Pond shows a slight increase in flooding around the pond in specific areas of low lying topography. West of Trustom Pond the flooding extent increases greatly while other areas increase slightly or not at all. Point Judith Pond increases in two low lying areas, but stays the same everywhere else. These changes are controlled by topography in the area and the mesh resolution defining the topography.

Figure 38. Comparison of Hurricane Bob flooding extent for the retreated shoreline in 25 years with complete failure of dunes (green) and the retreated shoreline in 25 years with complete failure of dunes with one foot of SLR added on (blue dashed) for Ninigret Pond

Figure 39. Comparison of Hurricane Bob flooding extent for the retreated shoreline in 25 years with complete failure of dunes (green) and the retreated shoreline in 25 years with complete failure of dunes with one foot of SLR added on (blue dashed) for Trustom Pond

Figure 40. Comparison of Hurricane Bob flooding extent for the retreated shoreline in 25 years with complete failure of dunes (green) and the retreated shoreline in 25 years with complete failure of dunes with one foot of SLR added on (blue dashed) for Point Judith Pond

100-yr event including SLR

For the extreme case of 100-yr event, the addition of one foot of SLR did not significantly increase the flooding extent in any one area, but increased the flooding. Figures 42, 43, and 44 show zoomed in areas around the ponds showing where the SLR increased the flooding. By considering erosion and SLR, it was shown that SLR has similar impacts on the extent of inundation for both large and small storm events (e.g. 100-yr event).

Figure 41. Comparison of 100-yr flooding extent with (blue) and without (black) 1 feet of Sea Level Rise and assuming complete failure of dunes and the retreated shoreline in 25 years.

Ninigret Pond shows a slight increase in flooding around the pond. Trustum Pond increased in certain areas greatly but in others not at all. Point Judith Pond increases, and connects two fingers, but stays the same everywhere else. These changes are controlled by topography in the area and the mesh resolution defining the topography.

Figure 42. Comparison of 100-yr flooding extent with (blue) and without (red) 1 feet of Sea Level Rise and assuming complete failure of dunes and the retreated shoreline in 25 years for Ninigret Pond

Figure 43. Comparison of 100-yr flooding extent with (blue) and without (red) 1 feet of Sea Level Rise and assuming complete failure of dunes and the retreated shoreline in 25 years for Trustum Pond

Figure 44. Comparison of 100-yr flooding extent with (blue) and without (red) 1 feet of Sea Level Rise and assuming complete failure of dunes and the retreated shoreline in 25 years for Point Judith Pond

1.4.8 Discussion

The geometry of the inlets controls the reduction of the input signals, because of this relationship it is very important to get accurate bathymetry data in the inlets and the coastal ponds. The bathymetry in this research for the coastal ponds might need to be updated because LiDAR techniques can detect the surface of the water as the bottom. This could be the cause of some of the differences from the observed data in this research.

The barriers separating the coastal ponds from the ocean erode during storm events, and it was found that if these barriers erode there is an increase in the flooding along the shore. The dunes along the entire southern coast have an average

height of 3.39 meters above MSL, but a minimum of 1.1 meters. This means a storm would have to be around a 100-yr event (on upper confidence interval curve) to overtop the dunes entirely. Some areas would flood with lower storm intensities because of the dunes lower heights. However, when dunes start to erode they stop protecting the shoreline from flooding as can be seen during Hurricane Carol (Figure 26), which had a surge height of 2.1 meters at Newport RI (return period of 40 years) but caused enough erosion of dunes to breach into the coastal ponds. The limit of protection is when the dunes will start to erode. Different factors lead to the failure of dunes, including the strength of the dunes, the elevation of the dunes, and the erosion caused by wave-induced forces. The many factors affecting the dunes makes it difficult to specify the exact dune height or storm level when the dunes will fail. A way to estimate it is to add the wave heights near shore and storm surge heights from different return periods to determine the point where the combined height overtops the average dune height. Table 3 shows the different waves and water elevations, and the combined height that is higher than the average dune height of 3.39 meters is a twenty year event. The wave heights were taken from a NACCS save point 8741 off the shoreline near Ninigret Pond. Hurricane Bob was close to a 20 year event, meaning that Hurricane Bob when combined with wave effects could have eroded the dunes. This is assuming that the waves and storm surge have the same return period.

Table 3. Wave heights and water levels for different return periods

Return Period	1 year	2 year	5 year	10 year	20 year	50 year	100 year
Wave Amplitude m	1.27	1.43	1.51	1.56	1.62	1.70	1.77
Water Elevation (m,MSL)	1.04	1.24	1.44	1.64	1.94	2.24	2.54
Combined Elevation (m,MSL)	2.31	2.67	2.95	3.21	3.57	3.95	4.32

SLR was shown to have an effect on the flooding extent to both Hurricane Bob and the 100-yr event. Hurricane Bob had a localized increase in flooded area, while the 100-yr event had an increase in flooded area over the whole domain. Overall

the 100-yr event had a greater increase in flooded area compared with Hurricane Bob.

1.5 Conclusions

In this study, we explored the dynamics of tides/surge in coastal ponds in southern RI coast, and investigated the effects of dune erosion and shoreline retreat on storm surge.

1. An ADCIRC model was validated with data collected by Woods Hole Group in the coastal ponds along the coast of Rhode Island. The model prediction and the observed data were very close in both tides and storm surge case (Hurricane Irene).
2. The dynamics of tides/surge in coastal ponds were assessed using both analytical methods and a numerical model (ADCIRC). The amplitude change was found to be different depending on the different geometries of the basins and inlets. For Ninigret pond, θ (the ratio of water amplitude inside and outside of a pond) was found to range between 0.24 and 0.26, and a phase shift of 90 degrees. The attenuation was found using observed data, the analytical method, and the numerical model, which all gave similar results.
3. For storms which do not overtop and erode the coastal dunes, the inlets of coastal ponds can significantly decrease the storm surge elevation. This is consistent with the previous theory describing the hydrodynamics of coastal ponds and inlets.
4. Erosion of coastal dunes increased flooding by 207%, which is a much greater effect, compared with the retreat of shorelines increase of 20%
5. For a very extreme storm such as 100-yr event where coastal dunes are over-

topped and all of low-lying areas are flooded, the flooding extent is not significantly changed with coastal erosion.

6. Shoreline retreat did not significantly increase the flooding compared with erosion of dunes.

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APPENDIX A

Inlet Basin Dynamics

A coastal pond system consists of a basin which is connected to ocean by an inlet. Coastal ponds in general cause a reduction of water elevation and a phase-lag (delay). In this section, a basic method to estimate the effect of coastal ponds on tide/surge propagation will be presented. This analysis will further help interpret/justify model results. A detailed analysis of the hydrodynamics of coastal ponds can be found elsewhere [1], while a brief introduction and graph which can be used to estimate the reduction of the amplitude/water elevation is presented here.

Figure A.1 and A.2 show the schematic of an inlet-basin system. In general, the objective of the inlet-basin analysis is to compute the water elevation range (e.g. harmonic tides) inside the basin, the maximum current in the inlet, and the phase-lag of the basin water elevation relative to ocean water elevation. The inputs are simple measurable parameters: the inlet cross section, surface area of the basin, the length and the frictional parameters of the inlet, and the amplitude and period of water elevation outside the basin (i.e. ocean). Considering a 1-D approximation of the flow in the inlet, the velocity and water elevation along the inlet can be evaluated using the mass and momentum conservation,

$$v \frac{\partial v}{\partial x} = -g \frac{\partial h}{\partial x} - \frac{f}{8R} v |v| \quad (\text{A.1})$$

$$A_{avg} v = A_b \frac{dh_b}{dt} \quad (\text{A.2})$$

where v is the velocity in the channel, A_{avg} is the flow area in the inlet, A_b is the surface area of the basin, $\frac{dh_b}{dt}$ is the rate of change of water elevation in the

Figure A.1. Schematic diagram of an inlet-basin system [1]

Figure A.2. Time series of water elevation and velocity in a simple inlet-basin system [1]

basin, f is Darcy Weisbach coefficient, and R is the hydraulic radius. To simplify the solution, the variation of water level inside basin is neglected, and it is assumed that the inlet has a constant cross section. Using above simplified method, graphs have been generated to compute the damping effect of the inlet and the phase-lag. Referring to Fig. A.3, the reduction of the amplitude/water elevation due to a coastal pond can be computed based on two parameters: K_1 and K_2 [1]. These parameters are evaluated as follows: (1) first computing the inlet cross sectional area,

$$A_c = Bd \quad (\text{A.3})$$

where B is the width of the inlet, and d is the depth of the inlet; (2) evaluating hydraulic radius, R , and other hydraulic parameters:

$$R = \frac{A_c}{(B + 2d)} \quad (\text{A.4})$$

$$F = k_{en} + k_{ex} + \frac{fL}{4R} \quad (\text{A.5})$$

where k_{en} and k_{ex} are coefficients that describe the inlets entrance and exit losses, F is called impedance of the inlet and represents total frictional loss in the inlet, L is the length of the inlet; (3) computing K_1 and K_2 ,

$$K_1 = \frac{a_o A_b F}{2LA_c} \quad (\text{A.6})$$

$$K_2 = \frac{2\pi}{T} \sqrt{\frac{LA_b}{gA_c}} \quad (\text{A.7})$$

where $g = 9.81$, A_b is the area of the basin, T is the period of the water level signal (tide), and a_o is the amplitude. K_1 and K_2 are then used in Figure A.3 to

compute reduction of water elevation due to a coastal pond. Based on the above analysis, the important factors affecting the water elevation are as follows:

- The friction/dissipation effect of inlet: F and L
- The ratio of the area of the inlet to coastal pond: A_c/A_b
- The period and amplitude of water elevation signal

Figure A.3. Ratio of the sea to basin tidal amplitude based on K_1 and K_2 parameters [1]

Figure A.4. Phase change based on K_1 and K_2 parameters [1]

List of References

- [1] USACE, *Hydrodynamics of Tidal Inlets*, EM 1110-2-1100 ed., August 2008.

APPENDIX B

Transects

The transects that were taken along the south shore were interpolated to the bathymetry. The current bathymetry was then modified to represent the shoreline in 25 years and the shoreline after a storm event destroyed the dunes using the methods described in the text. Figure B.1 shows transects 1, 10, 20, and 30 from along the shoreline.

Figure B.1. The representation of the shoreline in 25 years (left) and the shoreline after a storm (right) for transects 1, 10, 20, and 30.

APPENDIX C
Submitted Manuscript

Article

Effect of coastal erosion on storm surge: a case study in the southern coast of Rhode Island

Alex Shaw ¹, M Reza Hashemi ^{1*}, Malcolm Spaulding ¹, Bryan Oakley ², and Chris Baxter ¹

¹ Department of Ocean Engineering, University of Rhode Island

² Environmental Earth Science Department, Eastern Connecticut State University

* Correspondence: reza_hashemi@uri.edu; Tel.: +1-(401)8746217

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Abstract: The objective of this work was to assess the effect of shoreline retreat and dune erosion on coastal flooding in a case study located on the southern coast of Rhode Island. An ADCIRC model was applied and validated - using an extensive dataset collected during 2011 - to simulate the propagation of storm surge in the coastal areas including the coastal inlets and ponds. A simplified methodology based on the geological assessment of historical trend of the shoreline retreat and dune erosion in this area was incorporated in the model to represent coastal erosion. The results showed that for extreme storms (e.g. 100-yr event), where coastal dunes are overtopped and low-lying areas are flooded, the flooding extent is not significantly sensitive to coastal erosion. However, failure of the dunes leads to a significant increase of the flooding extent for smaller storms (e.g. more than 200% for hurricane with the same strength as Hurricane Bob). Substantial dampening of the storm surge elevation in coastal ponds for moderate and small storm was associated with coastal inlets connecting to coastal ponds which are often not resolved in regional surge models. When dunes are overtopped or breached by surge and wave actions, the storm surge was no longer limited by the effect of inlets. The shoreline change did not significantly affect the extent of flooding. The accuracy of a storm surge model depends on its ability to resolve coastal inlets which is critical for reliable storm surge predictions in areas with inlet-basin systems. .

Keywords: Dune erosion; coastal ponds; storm surge; coastal flooding.

1. Introduction

The northeast of the US, including the coastal regions of Rhode Island, have been impacted by hurricanes in the past, most recently Hurricane Sandy in 2012. Climate change is expected to change the strength and frequency of these events, putting more coastal areas at risk [1]. Further, it is estimated that sea level will rise between 0.2 and 2 meters by 2100 in northeast of the US, which also magnifies the impacts of coastal flooding [2]. As coastal flooding is sensitive to changes in bathymetry and topography of a region, coastal erosion can potentially affect the storm surge propagation. Storm surge and coastal erosion interact in two ways: (1) storm surges - along with wave forces - lead to coastal erosion, (2) coastal erosion changes the propagation of storm surge and consequently alter the extent of flooding. While it is possible to examine the two way interaction processes using morphodynamic models (e.g. [3,4]), which incorporate sediment transport and bed level changes, validating morphodynamic models is very challenging, and developing those models are costly. Further, in most cases, there are not enough information and data about geotechnical properties of coastal dunes, and beaches, which can lead to poor quality predictions. Assuming worst case scenarios (complete dune erosion, shoreline retreat at specified rate, etc) is an alternative method which allows understanding the effect of coastal erosion on flooding for extreme scenarios (e.g. [5]).

Figure 1. Overview of the the study area in southern coast of Rhode Island. Other details include save points (blue crosses) from the NACCS (see Section 2.2), Woods Hole Group Inc. water level gauge locations (orange dots), and a red box around the study area. Transects in the dark blue area were used to apply erosion scenarios (Figure 8).

Our case study is located in the southern coast of Rhode Island (Fig. 1), which consists of several coastal ponds and barriers. The shorelines are retreating at a rapid rate, in some areas up to 1.15 meters per year [6]. The coastal dunes are also eroded during major storm events (Figure 2).

Figure 2. Failure of dunes protecting Ninigret Pond after Hurricane Carol (1954); source RI Coastal Resources Management Council.

The objective of this study is investigate the effects of dune erosion and shoreline retreat (together and separately) on storm surge in this area. The study was carried out using numerical modeling, and analysis of the field data.

2. Methods

Several hurricanes were considered in this study. For validation, Hurricane Irene was selected as observed data was available during this Hurricane in several locations inside the model domain. A larger storm event, Hurricane Bob, a strong tropical storm which occurred on 8/19/1991 was chosen. Hurricane Bob gives a good representation of large storms in the area, but it was not large enough to overtop the barriers. Also, two synthetic storms from NACCS study including a storm representing a 100-yr event (which is important for planning purposes) were simulated. More details are provided here.

2.1. Data

Several data sources for development of the storm surge numerical model, and interpretation of the results were used. For surge models both bathymetry and topography of the domain (a digital elevation model: DEM) is necessary due to wetting and drying during flooding. In terms of bathymetry and topography of southern Rhode Island, a combined bathymetry and topography with a resolution of 10 meters was used. The bathymetry data were obtained from 2 sources: the NGDC Bathymetry Data (maps.ngdc.noaa.gov), and the USACE 2010 coastal LiDAR survey. The LiDAR survey focused on the south coast and extended about 1 km offshore (Figure 3; www.rigis.org/data).

From 7/2010 to 9/2011, Woods Hole Group carried out an extensive data collection program [7], for the USACE New England District, entitled "Wave, Tide and Current Data Collection, Washington County, Rhode Island". The primary purpose of this work was to collect site-specific data to support a RI Regional Sediment Management Study, and included the collection of water elevation, currents, wave, and meteorological data. Their study included measurement of water elevations inside the coastal ponds (Figure 1), as well as the waves and currents offshore. This data provided a unique source for understanding the effect of inlet-pond systems on water elevation in this area. Hurricane Irene, which impacted this area during the observation period, was also used for model validation (Figure 1). Wind data were extracted from the USACE Wave Information Study (WIS) hindcasts near the domain (wis.usace.army.mil). The WIS data covers a period from 1980 to 2012. For this study, the wind fields from large storm events were of interest. It should be mentioned, as the model domain covered just the southern coast of RI, the spatial variability of wind is negligible in this small area. For this 30 year period, a large storm event, Hurricane Bob, a strong tropical storm which occurred on 8/19/1991 was chosen. Hurricane Bob gives a good representation of large storms in the area [8]. It is the 5th largest storm in the NOAA tide gauge at Newport RI, and approximately corresponds to a 20 year event, according to the extremal analysis for the site (Figure 5). Newport water elevation station is the closest station to the study area (71.33W, 41.51N) which has a long record including major hurricanes. The wind field for Hurricane Bob extracted from the WIS is plotted in Figure 4.

Figure 3. The Digital Elevation Model (DEM) around the study area.

Figure 4. Plots of the wind speed and direction for Hurricane Bob at WIS station number 63079, which is located near the region (71.22W, 41.25N).

Figure 5. Extremal analysis of water elevation meters (MHHW=MSL-0.65) for Newport NOAA station (8452660); the red box shows Hurricane Bob (tidesandcurrents.noaa.gov).

2.2. NACCS

The North Atlantic Coast Comprehensive Study (NACCS; [8,9]) used a system of numerical models including ADCIRC [10], WAM, and STWAVE [11] to model hydrodynamic and wave fields of 1050 synthetic tropical storms as well as 100 extratropical historical storms, over the Atlantic Coast. The modeling was based on a relatively high resolution unstructured mesh (30m-50m near the coast). The synthetic storms were generated based on the statistical analysis of past storms. The NACCS provides model results at the save points (Figure 1), including time series of the wind, wave and water levels for the events and return period analyses for the tropical storms. These data were used to force the model at the boundary for a synthetic storm representing a 100-yr event. It should be added, some of the save points of the NACCS are located inside the coastal ponds which may be inaccurate, as will be discussed later; For a 100-yr event, all synthetic storms simulated in NACCS were examined and a storm surge event which generated the water level of around 100-yr storm surge at Newport (8452660) and Providence (8454000) water level stations was selected. This storm had a maximum surge of 3.20 m (MSL) at Newport (Figure 6), which is close to 3.35 m (MSL) or 2.7 m (MHHW) for 100-yr event, considering 100-yr event at the upper confidence level curve (tidesandcurrents.noaa.gov).

Figure 6. The time series of storm surge for synthetic storm 457 - from NACCS - which approximately produces 100-yr storm surge at Newport NOAA water level station.

2.3. Coastal erosion

Coastal erosion was considered as two different components: shoreline retreat, and erosion during large storm events. The past shoreline retreat rates were used to modify the DEM for future

scenarios assuming the same rate of erosion (Figure 7). Although, the rate of erosion is expected to rise due to SLR, we started to examine how the coastal flooding is affected assuming the shoreline is eroded at the historical rate. The shoreline retreat rates were calculated using aerial photographs from 1939 to 2014 [6]. It should be added that the shoreline retreats in severe storms and recovers during fair weather, but there is a consistent trend of retreat over that time period.

Figure 7. A sample shoreline change map for a beach in the study area [6].

The projected shoreline retreat over the next 25 years was considered. The shoreline was divided into the crossshore profiles shown in Figure 8. In the selected area, the beach profile consists of an offshore beach slope, a near shore beach slope, and a dune system. The offshore beach slope was extended horizontally to that corresponding to the 25 years of erosion (Figure 9). The same near shore profile and dune system was then assumed at the end of each profile. This method retreats the shoreline while keeping the same beach profile geometry. Once the transects were modified, they were linearly interpolated to modify the DEM (or bathymetry and topography) of the model.

Figure 8. Crossshore transects made to implement coastal erosion between Charlestown Beach and Matunuck Beach (Numbered 1-30.)

Figure 9. The simplified method which was used to estimate the shoreline geometry after erosion in future. Transect 30 (as an example; Figure 8), with the original shoreline (blue), 25 year shoreline (red), and intersection point (star) is shown. The vertical axis is exaggerated for better clarity

Coastal erosion in large storms can lead to failure of dunes as well as retreat of the shoreline. During storm events, the combined action of storm surge and waves erode the dune and create surge channels and wash-over fans (Figure 2). To implement dune erosion in the DEM, it was assumed that the dunes were eroded or simply cutoff at an elevation (MHW) with almost a horizontal line (Figure 9). Elevation of the post storm profile was determined by examining the washover fans deposited after past hurricanes in this area including 1938 Hurricane, the Ash Wednesday storm, and Hurricane Sandy. The elevations of the washover fans were estimated using LiDAR; the slope of 0.003 cm/m was measured for washover fans after Hurricane Sandy, which can be assumed almost horizontal for the model resolution used for storm surge simulation in this study.

2.4. Numerical Model

For surge modeling, the ADCIRC (ADvanced CIRCulation model) was used. ADCIRC is based on finite element method and unstructured mesh discretization, which allows resolving areas such as coastal inlets with a reasonable computational cost. ADCIRC has been coupled with SWAN, and can simulate the wave-surge interactions [12]. ADCIRC has been extensively used to predict storm surge flooding (e.g. [10,13]).

A mesh was created, resolving coastal inlets, using Surface water Modeling System Software (www.aquaveo.com) at a resolution of 30 meters near the coastline, 150 meters farther offshore, and 2 km near the open boundaries. The mesh is plotted in Figure 10. The model was forced along the open boundaries by water elevation, and by wind stress/pressure over the domain. The model was run in 2-D mode, with Manning friction coefficient of 0.018, and up to 0.06 in land areas. For tidal case, the model was forced using 5 harmonic constituents for tides including M2, N2, K1, S2, and O1 [14]. These component represent the dominate components of tide for this area (Table 1).

Figure 10. An overview of the mesh used for surge modeling in the southern coast of RI. The model domain is larger than the study area and includes Block Island near the southern boundary. Subfigure b shows a magnified view of the rectangular area in Subfigure a around Ninigret Pond.

Table 1. Harmonic constituents at the Newport and Providence NOAA water elevation stations.

Harmonics	Newport Amplitude (m)	Newport Phase (degrees)	Providence Amplitude (m)	Providence Phase (degrees)
M2	0.505	2.3	0.643	9.5
S2	0.108	25.0	0.138	33.6
N2	0.124	345.8	0.152	354.6
K1	0.062	166.1	0.073	169.4
M4	0.057	35.8	0.103	202.2
O1	0.047	202.0	0.027	312.7
M6	0.0005	220.1	0.027	312.7
MK3	0.0008	19.5	0.016	39.3
S4	0.0007	5.1	0.014	23.8
MN4	0.026	347.9	0.014	12.7

3. Results

3.1. Model Validation

To validate the model for tides and storm surge, the Woods Hole Group Inc. data were used [7]. The observed data were compared with the model results during a spring-neap cycle (for tides), and during Hurricane Irene, for storm surge. For tides the model was run for 15 days from May 14 2011 until May 29 2011 with one day ramping period. This time period is within the duration of the Woods Hole Group data collection campaign. Figure 11 shows the comparison between the modeled results (orange) and the observed data (blue) at the two stations inside Ninigred Pond, including RMSE.

The modeled tide at both stations are slightly higher than the observed tide for the spring and lower during the neap cycle with an RMSE of 0.053 m and 0.051 m for NN and NW respectively. The model shows some issues in wetting and drying during the neap cycle. This can be associated

Figure 11. Comparison between modeled and observed tide inside Ninigret Pond (see Figure 1 for location of the stations)

Figure 12. Comparison between the model predictions and the observed data for Hurricane Irene (see Figure 1 for location of the stations)

with accuracy of the inlet bathymetry. The model skill at the NW station is better than that of the NN station, and this may be justified as the NW station is farther away from the inlet of the Ninigret Pond. For storm surge case, Hurricane Irene - which was category 3 and happened in mid-August 2011 - was simulated. The comparison of the model results and observations are depicted in Figure 12. The performance of the model for both stations are very good with an RMSE of 0.065 m and 0.041 m for NN and NW respectively, for water elevation; however, the model slightly overestimates the surge. Overall, given the magnitude of errors, the performance of the model was considered satisfactory.

3.2. Propagation of tides/storm surge in coastal ponds; effect of coastal inlets

The southern coast of RI consists of several coastal ponds, and barriers. The failure of dunes can affect this inlet-basin/pond system; therefore, it is worth to assess how a tide/surge signal is affected by coastal inlets as it propagates into coastal ponds. The analysis can be done using the previous research about the dynamics of inlet-basins, and the collected data in this area. This will help interpret modeling results. Figure 13 shows the comparison of water elevation inside and outside the Ninigret Pond using observed data for a duration of a month. A dramatic reduction of the amplitude can be observed in this figure. A coastal inlet, in general, causes a reduction of water elevation amplitude and a phase-lag or a delay inside coastal ponds relative to offshore. This is mainly associated with

the energy dissipation by high velocity currents in an inlet. Simplified analytical methods have been introduced in the literature to compute the reduction of the amplitude, and the phase lag, based on the geometry and physical characteristics of the inlet-basin system. A detailed analytical analysis of inlet-basin hydrodynamics can be found in the Coastal Engineering Manual[15]. Considering a long wave (e.g. tide or surge), with an amplitude of a_o , and a period of T , the effect of a coastal inlet on tide/surge signal as it propagates from the ocean to the pond can be written as,

$$[R, \phi_l] = f(A_i/A_b, R_h, L, T, \mathbf{F}); \quad R = 1 - a_i/a_o \quad (1)$$

where R is the reduction in the amplitude, a_i is the amplitude inside the basin/pond, ϕ_l is the phase lag, A_i is the cross sectional area of the inlet, A_b is the area of the basin or pond, R_h is the hydraulic radius of the inlet, L is the length of the inlet, and $\mathbf{F}$ represents the frictional coefficients for the entrance, exit and channel friction losses. For Ninigret Pond, $A_b = 7.5 \text{ km}^2$, $A_i = 45 \text{ m}^2$, $L = 1.7 \text{ km}$, $R_h = 1.5 \text{ m}$. Using these parameters, and assuming entrance, and exit loss coefficients of 0.1 and 1.0, respectively, leads to $R = 80\%$ and $\phi_l = 90^\circ$. The impact of inlets on tidal signal was also assessed using observed data. By performing a tidal analysis using τ_{tide} [16] inside (Wood Holes Group Station) and outside this pond ((NOAA, Weekapaug Point 71.76W, 41.33N), R for the M2 tidal component was found to be 76% for (NW) Station (Figure 1), with a phase lags of 90.5° or about 3 hours and 6 minutes; these values which are based on the observations are very close to the analytical method predictions. Considering that storm surge events have similar periods, if coastal barriers for this pond fail, this reduction of the amplitude no longer exist, which will lead to a significant increase in the flooding area.

Figure 13. Comparison of observed water elevation data inside and outside the Ninigret Pond (NW Gauge, Figure 1).

Further, the geometry of a coastal inlet has a controlling effect on the reduction of the amplitude water elevation. Considering the three coastal ponds in this area (Figure 1; Ninigret Pond, Trustum Pond, and Point Judith Pond), the effect of coastal inlet geometry can be further examined. Point Judith Pond has a wide deep inlet with a width of 80 meters and a depth of around 7 meters. Trustum Pond, on the contrary, has no permanent connection to the ocean for tides, but during large storm events part of its barrier is overtopped or breached (for example in Hurricane Sandy) causing some flooding, and Ninigret Pond has a relatively narrow inlet (35 m), protected by hard structures. The water elevations in the three ponds are plotted for a tidal cycle, and for a storm event (Hurricane Bob) in Figure 14 using the ADCIRC model. As this figure shows, the water elevation signal for tide inside

and outside of the Point Judith Pond is almost the same due to its wide inlet, but the peak of storm surge slightly attenuates during the storm event. For Trustom Pond, the barrier is not overtopped for tides or storm surge scenario, although it may breach for this storm scenario. Ninigret Pond shows a significant reduction for tides ($R = 80\%$) and for Hurricane Bob ($R = 68\%$) due to its narrower inlet. Therefore, for a storm surge like Bob which do not overtop or erode the coastal dunes, the inlets of coastal ponds can significantly decrease the storm surge in the pond.

Figure 14. Effect of coastal inlet geometry on surge inside three coastal ponds in study area; comparison of water elevation in Ninigret Pond, Trustom Pond, and Point Judith Pond for a: Hurricane Bob b: Tides

3.3. Effect of Erosion on Storm Surge

Two erosion scenarios were considered: shoreline change in 25 years (leading to change in beach profile and DEM), and dune erosion. As mentioned, the erosion of dunes is a common consequence of large Hurricanes in the study area as can be seen in Figure 2, which shows the failure of dune system of Ninigret Pond during Hurricane Carol in 1954. Several scenarios considering the two storm cases (100-yr synthetic storm and Hurricane Bob) were considered.

For Hurricane Bob, the flooding areas assuming eroded (retreated) shoreline and the current shoreline were examined first. Table 2 shows the summary of results. Considering a retreated shoreline in 25 years, the flooding extent slightly increases by 0.22 km^2 , which is 20% of the original flooded area (1.12 km^2). This increased flooding area is approximately the advance of the sea (about 30 m) due to coastal erosion; therefore, the shoreline retreat does not significantly increase the extent of flooding. However, when the dunes are eroded (assuming eroded dune profile) the flooding extent increased by 2.33 km^2 , which is 207% increase. When dunes erode, the coastal inlets of the ponds can no longer dampen the surge signal, and therefore a much larger area within coastal ponds are flooded. For this scenario, the flooding extent advanced up to 500 meters in some areas. Figure 15 shows the flooding extent for existing dunes, and eroded dune profile scenarios.

Table 2. Differences in flooded area near the eroded shoreline for Hurricane Bob assuming erosion scenarios.

	Current flooded area, km^2	Changed flooded area, km^2	Difference, km^2	percentage increase
Shoreline retreat in 25 years	1.13	1.35	0.22	19.7%
Eroded dunes	1.13	3.5	2.33	207%

Figure 15. Comparison of Hurricane Bob flooding extent assuming current condition (red) and current shoreline with no dune system (blue), and the 25 year retreated shoreline as well as complete dune failure (black).

For the 100-yr event, the erosion scenarios (shoreline retreat and dune erosion) did not lead to a significant change in flooded areas as shown in Figure 16. This is because for this event, the storm surge is large enough to overtop the dunes (the dune top elevation is about 3m, MSL in this area); therefore, even if the dunes were solid structures and could resist the erosion during storm surge, they could not protect the coastal ponds. It should be noted that the failure of dunes may significantly affect wave propagation, for 100-yr event, as waves will break over dunes, due to decreased water depth.

Figure 16. Comparison of 100-yr flooding extent assuming the current shoreline (blue), current shoreline with eroded dune system (green), and the 25 year retreated shoreline plus complete dune failure (black)

Sea level rise (SLR), in general, leads to an increase in the flooding extent [17]. A very simple way of investigating the impact of SLR on flooding is the bathtub approach or adding the magnitude of SLR to elevations predicted by a storm surge model; this method neglects the nonlinearity of the storm surge propagation. More accurate method includes changing the DEM, and simulating the storm surge assuming a SLR scenario. Consistent to our analysis which assumed a 25 years shoreline retreat, 30 cm or 1 foot SLR was assumed, corresponding to projected values by NOAA for 25 years

Figure 17. Comparison of flooding extend of 100-yr storm event, assuming 30 cm SLR, and coastal erosion.

[18]. Figure 17 shows that the extent of flooding, as expected, increases in some areas. The flooding area increased from 4.72 km² to 6.80 km², leading to 44% increase.

4. Discussion

The geometry of coastal inlets controls the storm propagation for moderate storms in areas with inlet-basin systems. Some regional modeling studies such as NACCS have not resolved these inlets, and their predictions inside coastal ponds may not be reliable beyond barriers and inside ponds. Figure 18 is an example showing the poor resolution of the NACCS mesh around Ninigret Pond inlet. In Figure 19, the prediction of storm surge for a moderate synthetic storm (220, which has a peak elevation of 1.67 m, MSL in Newport [9]), near two save points (see Figure 18b) located inside and outside Ninigret Pond, has been compared with that from our model. The surge event was channeled through the inlet, but given poor resolution of NACCS model, water levels are overestimated by NACCS model. It should be noted that NACCS results, unlike the ADCIRC model developed in this study, have not been validated inside coastal ponds and very nearshore in RI. Also, waves for this storms are not that significant inside the pond; therefore, wave-surge interaction cannot be associated with higher storm prediction in NACCS model. The results are identical at the boundary (Point A), as the ADCIRC model was forced by NACCS at the open boundary.

The dunes along the entire southern coast have an average height of 3.39 meters above MSL, but in some areas they are as low as 1.1 meters. This means that a storm with a magnitude of 100-yr (3.35 m, (MSL) considering 100-yr event at the upper confidence level curve) can potentially overtop all of the dunes (considering wave heights). A hurricane such as Carol, which had a surge height of 2.7 m, MSL at Newport RI can breach the dunes (Figure 2), and have a similar but less effect on flooding (increasing the flooding extent). Various factors are associated with the erosion of dunes [19]: the geotechnical properties of dunes, the elevation of dunes compared to surge, wave-induced forces, and wave runoff/overtopping). Therefore, it is a challenging task to specify a threshold for a storm which leads to dune failure. Morphological modeling (e.g. [4]) along with data collection during and after large storms around coastal dunes can improve our understanding of this process for this area, for future studies.

5. Conclusions

We explored the effect of dune erosion and shoreline retreat on coastal flooding in an area which consist of coastal ponds protected by dunes and connected to the ocean by narrow inlets. An storm surge model was developed/validated with a unique dataset which included water elevation

Figure 18. Effect of model resolution on the results; Subfigure a shows an example of low resolution NACCS mesh in a coastal inlet. Subfigure b shows the locations of comparison for NACCS results and those obtained in this study.

Figure 19. Comparison of NACCS results and ADCIRC model of this study for synthetic Storm 220. See Figure 18b for locations of comparison.

247 data inside coastal ponds during 2011 and included measurements during Hurricane Irene.. The
 248 conclusions are summarized as follows:

- 249 1. Shoreline retreat did not significantly increase the flooding compared with erosion of dunes.
- 250 2. For storms which do not overtop and erode the coastal dunes, the inlets of coastal ponds can
 251 significantly decrease the storm surge elevation. This can be explained using the concepts of
 252 inlet-basin hydrodynamics. For very extreme storms such as 100-yr event where coastal dunes
 253 are overtopped, and all of low-lying areas are flooded, the flooding extent did not significantly
 254 changed assuming dune failures.
- 255 3. Erosion of coastal dunes increased flooding by 207% in the study area, for scenario of Hurricane
 256 Bob.
- 257 4. Numerical surge models which do not fully resolve coastal inlets (e.g. NACCS model in RI)
 258 lead to significant error in prediction of surge in coastal ponds. Accurate bathymetric and
 259 topographic measurement of coastal inlets is essential for storm surge modeling in areas with
 260 inlet-basin systems.

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Author Contributions: Alex shaw developed the numerical models, and analysed the results. M R Hashemi initiated and led the research, and helped in discussion of the results. M. Spaulding advised the research in many aspects, including analysis of the results and development of the models. B Oakley contributed in coastal erosion and general discussions.

Conflicts of Interest: The authors declare no conflict of interest.

Abbreviations

The following abbreviations are used in this manuscript:

ADCIRC: ADvanced CIRCulation mode)
DEM: Digital Elevation Model
LiDAR: Light Imaging, Detection, And Ranging
Mean Sea Level: MSL
Mean Higher High Water: MHHW
North Atlantic Coast Comprehensive Study: NACCS
SWAN: Simulating WAVes Nearshore
SLR: Sea Level Rise
STWAVE: STeady state spectral WAVE model
USACE: US Army Corp of Engineers

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330 **Sample Availability:** Samples of the compounds are available from the authors.

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