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Working with water

North Atlantic coast of the USA - sea level change vulnerability and adaptation measures

Final report

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Executive summary

This report represents the final report of a study to assess the vulnerability of the North Atlantic Coast of the United States to sea level change and the effectiveness of various adaptation measures. The coastline of the north-eastern United States impacted by Hurricane Sandy in 2012 consists of different natural and engineered landscapes The research carried out under this project has investigated the expected response of some examples of the associated natural and engineered coastal infrastructure to sea level rise and has evaluated the added adaptation value of various response measures both in isolation or combined. The coastal types considered are barrier islands, navigational breakwaters, coastal bluffs, and marsh areas and their associated ecosystems, the spread of structure types and situations reflect the spread of the mission areas of USACE. Particular focus is given in the report to the vulnerability of barrier islands to flooding as an exemplar of the problems faced in a number of areas.

For the barrier islands, an initial simple submergence assessment was applied to bands of sea level against the elevation of three typical north east coast barrier islands to identify the area that would be lost at varying levels without levees or flood walls and assuming full hydraulic connectivity. This assessment was based on a DTM with a resolution of 2m and analysed into one foot bands of ground height and provided percentage losses of land area under the four sea level rise scenarios considered in the NACCS study. As previous studies have shown, this kind of analysis indicates significant loss of land for just 1 to 2 feet of sea level rise, with only the large dune beach systems on the Atlantic seaboard escaping much of the inundation. The analysis was completed for several barrier islands within the NACCS area and the results were broadly similar for each.

For Long Beach Island NJ a full storm inundation analysis was carried out for three increments of sea level rise (1, 3 and 6 feet) representing the range of plausible increases to be expected over the next century. That analysis suggests that the beach-dune system on the Atlantic seaboard can be maintained in a relatively robust condition even with 6 feet of sea level rise. Concerns should instead be focussed on back bay flooding. Storm surge barriers are unlikely to be viable given the expected future frequency of flooding and instead combinations of the following measures should be considered:

- New defences on the back bay shore. Maintenance of leisure access for boating will be important where quay walls already exist (with wave splashboards); here new (or raised) quay walls doubling as flood defences will be required. Stepped defences may be possible. For locations where natural beaches exist, terraced defences incorporating ecological features can be considered. In both cases paths for access and viewing are possible.
- Modifications to drainage systems. Defences will not solve all the problems because during high water events flooding can occur by water backing up the drainage systems. Flap valves or sluices will therefore need to be installed on all outfalls. Significant provision will also be required for storage of rainwater, possibly located within modified defences.
- Elevation measures. Property elevation remains a valuable tool to limit damage in the event of flooding. Elevation of the road network to improve access could be considered but will require proper drainage and rainwater storage provisions, for example located beneath any such elevated roads.

A short review was carried out of a recent study of breakwaters protecting a harbour of refuge which had concluded repair / rehabilitation of the damaged main breakwater could not be justified and that since increases in wave energy in the harbour would be modest, neither navigation activity nor coastal erosion of a shoreline protected by the breakwaters would be significantly affected The conclusions of that study were however affected by a restriction of the project evaluation period to 60 years and the assumption that

NRC curve 1 (the lowest NRC curve) was the ‘most likely’. The review emphasises the importance of the input assumptions into any analysis of resilience of navigational structures against sea level rise.

A review of available data regarding some erodible cliffs in Chesapeake Bay emphasised the vulnerability of erodible cliffs to increases in rates of erosion as a result of sea level rise. It was concluded that a sea level rise of the order of 2 ft could lead to an order of magnitude increase in the rate of erosion. Based on UK experience, mitigation measures for the erosion of coastal bluffs such as toe protection to reduce undercutting may only be justified in areas of high population density.

The study of a low lying marsh ecosystem/nature reserve in the Chesapeake Bay, which is facing major challenges as it becomes progressively submerged by rising sea levels. Drawing on UK and European experience this report identifies some additional strategies which could be considered:

- ‘trickle charging’, of sediment into the sub-tidal zone or water column at discrete discharge points and allowing natural processes to move it onshore.
- Stabilisation by flora of the recharged areas is best achieved by locating recharge points close to existing established native marsh flora to ensure propagule supply.
- Conversion of historic drainage of straight or herringbone drainage networks which are associate with rapid runoff velocities and loss of sediment to more sinuous dendritic arrangements with ponds which better mimic marsh hydrology and encourage generation of marsh habitat.

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1. Introduction

The coastline of the north-eastern United States impacted by Hurricane Sandy in 2012 consists of different natural landscapes that range from hard-rock outcrops to glacial deposits to beach and dune complexes. Superimposed on this geological foundation are urban and suburban developments, industrial complexes and harbours and ports, together with a variety of natural and nature-based features (e.g. wetlands, reefs and coastal forests) and engineered structural measures (e.g. levees, storm-surge barriers, seawalls and revetments, groynes and breakwaters) for storm damage reduction. The research carried out under this project has investigated the expected response of this natural and engineered coastal infrastructure to sea level rise (and resultant changes in wave climate) expected over the short (20 year), medium (50 year) and (100 year) long term and has evaluated the added adaptive capacity and resilience that might be achieved when individual measures are combined or integrated into a coastal defence system.

The report commences by reviewing in Chapter 2 some relevant UK research. Chapter 3 then examines the typical influences of sea level change on the four main USACE civil works mission areas across three typical coastal types: a barrier island coast, a coastal bluff and an estuarine coast. From this Chapter 4, goes on to describe how a series of exemplar sites were selected for more detailed examination to illustrate the issues. From this initial selection a review and analysis of the issues affecting each of the sites is presented in subsequent chapters. Chapter 5 presents a submergence analysis for each of the three barrier island sites. From these, a decision was made to carry out the more detailed analysis presented in Chapter 6 on an exemplar barrier island site (Long Beach Island NJ). Chapter 8 and 9 then review examples of the impact of sea level rise on navigational breakwater structures and on an erodible coastal bluff. Chapter 9 then examines some low lying ecosystems and explores the opportunity for using techniques pioneered in the UK to help meet the considerable challenges which these systems face. The final example of a coastal marginal beach in the Delaware estuary and ecosystem behind it is then briefly examined in Chapter 10. The report closes with conclusions and recommendations for further research.

2. Previous UK and European research

2.1. Introduction

Coastal research in the UK and Europe over the last 10-15 years has had a significant focus in understanding coastal forcing, geomorphic response and resulting impacts on communities and damage to infrastructure over the short, medium and long term. This has allowed the development of Shoreline Management Plans, which has encouraged thinking about adaptive management using natural and nature-based features and structural and non-structural measures and generated further development of risk analysis approaches for storm damage reduction and flood risk management initiated many years ago by USACE (1996). This has naturally led to the investigation of economic appraisal techniques, like Real Options Analysis, that are capable of evaluating mitigation measures with adaptive capacity, whilst accounting for climate change (Woodward *et al*, 2011). The primary components of a risk analysis approach to coastal risk reduction are extreme value distributions for the hydraulic loads, fragility curves to define the reliability of the structural coastal defences, and functions that relate coastal damage and flood depth to economic consequences.

These primary components have been adopted into shoreline evolution models (Stripling and Panzeri 2009) and flood risk analysis models (Gouldby *et al*, 2008) within a number of countries in Europe, including the UK, under a conceptual framework known as Source-Pathway-Receptor (see Figure 2.1 and further details at www.floodsite.net). The framework shows indicative fragility curves such as the relationship between load and the probability of the load being exceeded. The shape of the fragility curve encapsulates known (qualitative and quantitative) information about failure mechanisms, in this case for a coastal levee, and represents uncertainty in that knowledge. It means that the likelihood of failure can be considered in a probabilistic manner appropriate for risk assessment as opposed to a deterministic fashion.

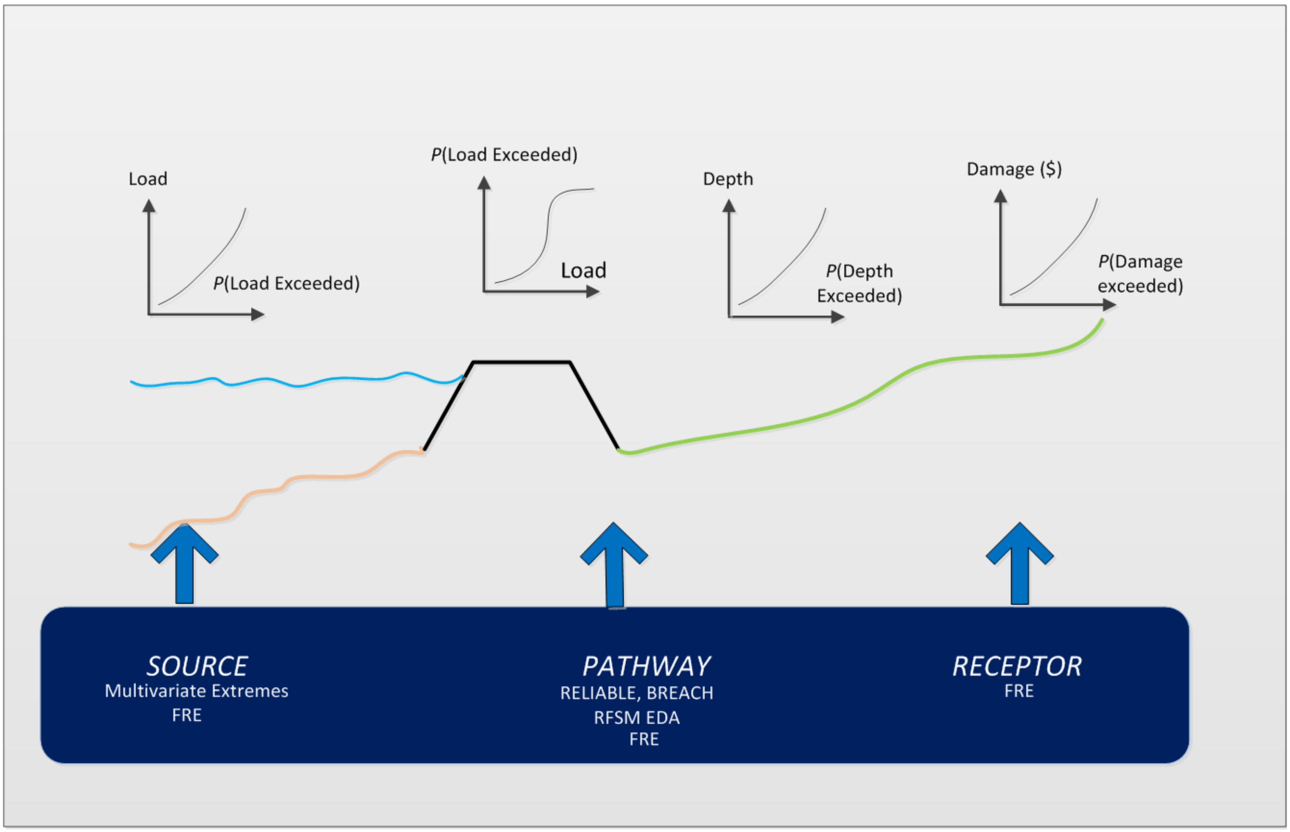

Figure 2.1: Source pathway receptor framework (referencing existing HR Wallingford models)

In this framework, the Source relates to the static and dynamic hydraulic loadings, which are not a prime focus of this research as it is understood that these are being addressed in a very comprehensive way using the hurricane and surge modelling programme being carried out by USACE and other modellers.

The Pathway relates to the coastline, and to any natural or nature-based features and structural measures located there as well as to the subsequent inundation of coastlands behind the shoreline. This would include:

- Long-term coastal geomorphic change. Impacts on geomorphology of rising sea levels, for example, in terms of shore steepening and lack of long term sustainability of current beach and barrier island systems are clearly factors which need to be taken into account. Research at HR Wallingford has addressed the impact of probabilistic shoreline variability on beach levels at the toes of defences, but development of meso-scale conceptual and empirical models to better predict large-scale, long-term changes up to 100 years are as yet immature, although there are interesting developments in the UK under the Environment Agency project SC060074 (Whitehouse *et al,* 2009) and Natural Environment Research Council iCOASST project (www.icoasst.net) (Nicholls *et al*, 2012).

- Performance of natural and nature-based features and structural measures under storm conditions. Extensive work has been carried out in the UK and Europe in this area, driven by NGO activity and legislation (e.g. Habitats Directive 1992), including research under the UK URBANE (Urban Research on Biodiversity on Artificial and Natural Coastal Environments http://urbaneproject.org) and projects such as THESEUS at the UK Tyndall Centre for Climate Change Research (see http://www.uea.ac.uk/environmental-sciences/centres-and-groups/tyndall-centre-for-climate-change-research) which have examined ecological engineering and use of nature in sea defences.
- Performance of structural measures under storm conditions. Research on structural measures in the UK has particularly focussed on the development of fragility curves (conditional probability of failure given load), a topic on which some early collaborative research has already been carried out between ERDC and HR Wallingford (Schultz *et al*, 2010). A particular facet of the UK research has been to progressively develop simplified generic fragility curves that can be used to be representative in broad scale systems analysis and hence allow useful assessment of the impact of failures in the defence system in economic terms of flood risk (Simm *et al*, 2009). This then enables the costs of maintaining and refurbishing the defences to be compared to the benefits in terms of risk reduction. Existing risk analysis approaches that have been applied to hurricanes in the North Atlantic (Lin *et al*, 2010), (Aerts et al. 2013), do not consider the performance (reliability) of flood protection systems and hence are limited in their capability to assess risk mitigation options.
- Inundation. Probabilistic systems analysis approaches have been developed, based on UK GIS databases, to allow the overall probability of inundation and resulting economic flood risk to be evaluated in terms of National Economic Development. The broad scale approach adopted in the UK using Monte-Carlo simulation of multiple potential return periods and multiple potential breach scenarios allows a realistic actuarial assessment of flood risk. Details are given in Gouldby *et al* (2008), with an update to the inundation model described by Jamieson *et al* (2012). Even though in places, data constraints may mean that the results are approximate, expressing the relative difference in risk between tracts of the coast has in our experience proved to be valuable for end-users of the research. Under a previous BAA research grant, HR Wallingford (2013) trialled the method in a fluvial context at St Paul, MN.

Finally, there is Receptor/Consequence. Whilst the FEMA HAZUS approach already provides functions to allow inundation depths to be converted into economic flood risk, questions remain about how to appropriately incorporate this within system based coastal risk analysis models and how to quantify the risk-reduction effect of non-structural measures such as land-use management, flood-proofing and building elevation and community relocation.

HR Wallingford has carried out analysis for the Adaptation Sub Committee (ASC) of the Committee on Climate Change (CCC) for England in the UK. Part of this analysis focusses on the development of indicators to monitor changes in exposure and vulnerability to flooding and the uptake of adaptation actions to manage flood risk in England (2012). A number of indicators of flood risk were developed and evaluated. These were spatially assessed through time to give an understanding of how exposure and vulnerability to the risk of flooding is changing across England. It also examined the uptake of certain measures used to mitigate flood risk.

Further analysis was carried out to develop and assess spatial indicators of climate change for the natural environment, agriculture and forestry (ECI *et al* 2013). During this further analysis phase some useful indicators (or metrics) were developed to assess the impacts of flood, coastal erosion and water related loadings to natural land and agriculture. Indicators of note included:

- The area of land that has been used for habitat creation schemes since 1991;
- The area of land under different land uses in the lee of coastal management policies of 'hold-the-line', 'no active intervention' or 'managed realignment';
- The area of land that could potentially be used for coastal habitat creation;
- The area of that is benefitting from flood protection by raised flood defences;
- The area of land that is benefitting from flood protection by natural coastal habitat;
- The area of saltmarsh that could be lost via erosion and submergence due to sea level rise.

The assessment of these indicators for the UK is described in the following section. Presently there is further work for the ASC underway at HR Wallingford to assess spatial indicators for health, energy and infrastructure related risks associated climate change which similarly include a number of metrics on flood and erosion risks.

2.2. Research carried out to quantify SLC impacts conducted for UK Adaptation Sub-Committee (ASC)

With the exception of the final sub-section on impact of beach changes on flood risk, most of this section of the report is based on conclusions presented in ECI *et al* (2013). All the analyses were carried out for the whole coastline of England (total 5,700 km).

2.2.1. Amount of UK habitat that could be lost to sea level rise and erosion

The work HR Wallingford carried out for the ASC[1] included two types of analysis of habitats lost. The first was due to submergence, the second due to erosion. These were coupled to give total amount lost due to coastal squeeze by taking the worst for any given saltmarsh area from the two types of analysis (giving a conservative perspective on the results). Figure 2.2 and Figure 2.3 provide schematics of the scenario.

Submergence losses

The assessment was undertaken for each individual area of mudflat and saltmarsh and compiled to give regional statistics. For each habitat area, a GIS based analysis was run using 2 m LiDAR data to determine how much of the habitat may be lost to submergence given sea level rise. UKCP09 SLR estimates were used for a number of different epochs and assumed the following;

1. Saltmarsh cannot survive below MSL.
2. Intertidal mudflat is lost below MLW.
3. Habitat in management policy units of 'no active intervention' and 'managed realignment' can roll back at pace with the advance of sea levels and no overall habitat is lost.

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[1] See "Assessing preparedness of England's natural resources for a changing climate: Exploring trends in vulnerability to climate change using indicators". Report prepared for the Adaptation Sub Committee of the Committee on Climate Change, available at http://www.theccc.org.uk/wp-content/uploads/2013/07/TCCC-ADAPT01-12_Final_Report_Revised_v3-without-Appendices_29July13.pdf

4. Habitat in management policy units 'hold the line' cannot rollback and habitat is lost as it falls below the lower threshold of the habitat zone (i.e. MSL or MLW).
5. No assessment of the topography or land use of the hinterland was made nor assessment of re-colonisation rates to determine whether assumed self-regulation is possible.

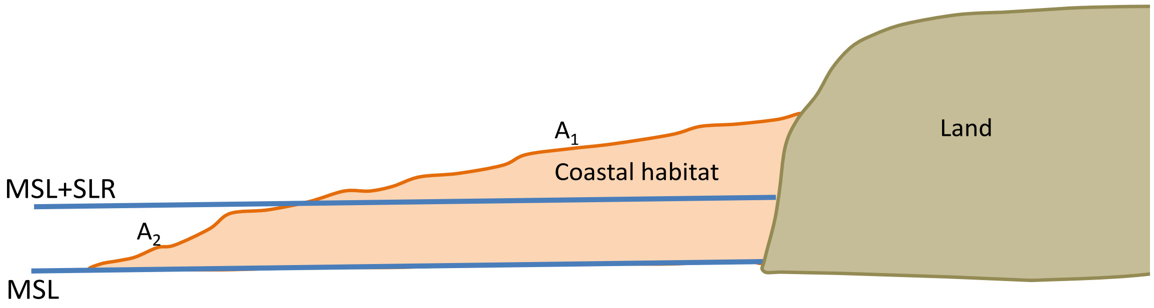

Figure 2.2: Schematic to show the approach to assessing coastal habitat loss due to submergence (for saltmarsh).

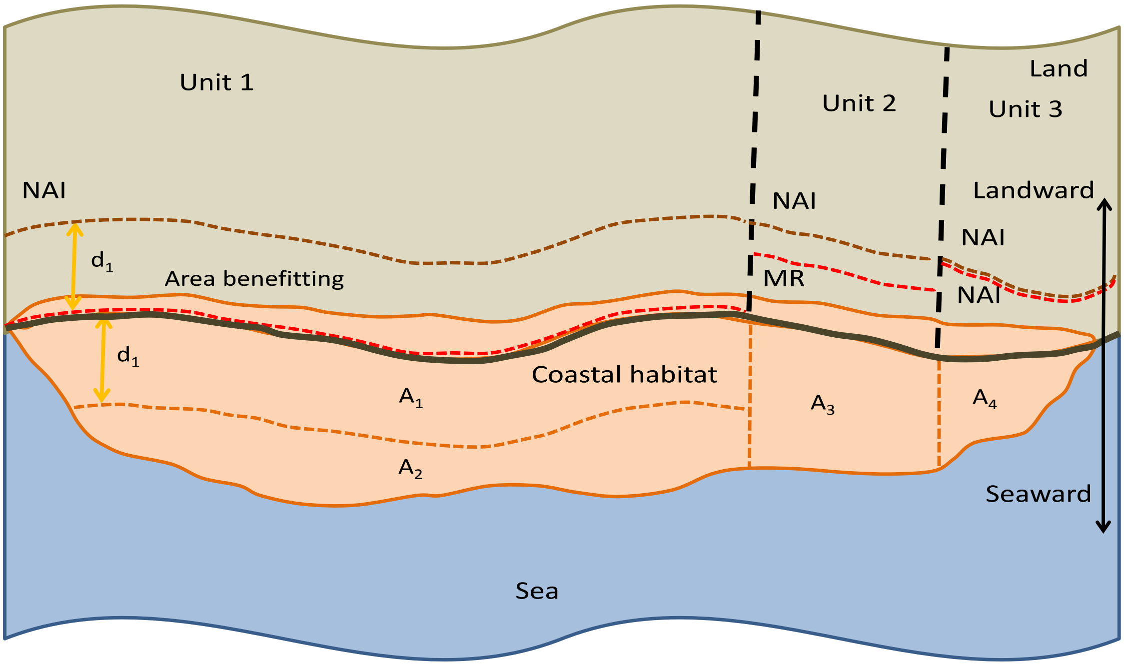

Figure 2.3: Schematic to show the approach to assessing coastal habitat loss due to coastal squeeze

A further analysis was undertaken to show the zonation of the habitats with respect to MSL and MLW for saltmarsh and mudflat respectively (Figure 2.4). The results in Figure 2.4 show the national area that may be at risk for a given amount of SLR. (so is de-coupled from the SLR estimates from UKCP09 enabling the impacts of different rates of SLR to be considered). This was presented by policy option to allow interpretation of the results enabling the assessment of the areas of land in different management policy type to be made. For example how much habitat may be lost because the policy option is HTL or how much may self-regulate due to the policy being no active intervention. In this case the results demonstrate the reduction in loss of area achieved by taking a pro-active policy to the impacts sea level change submergence.

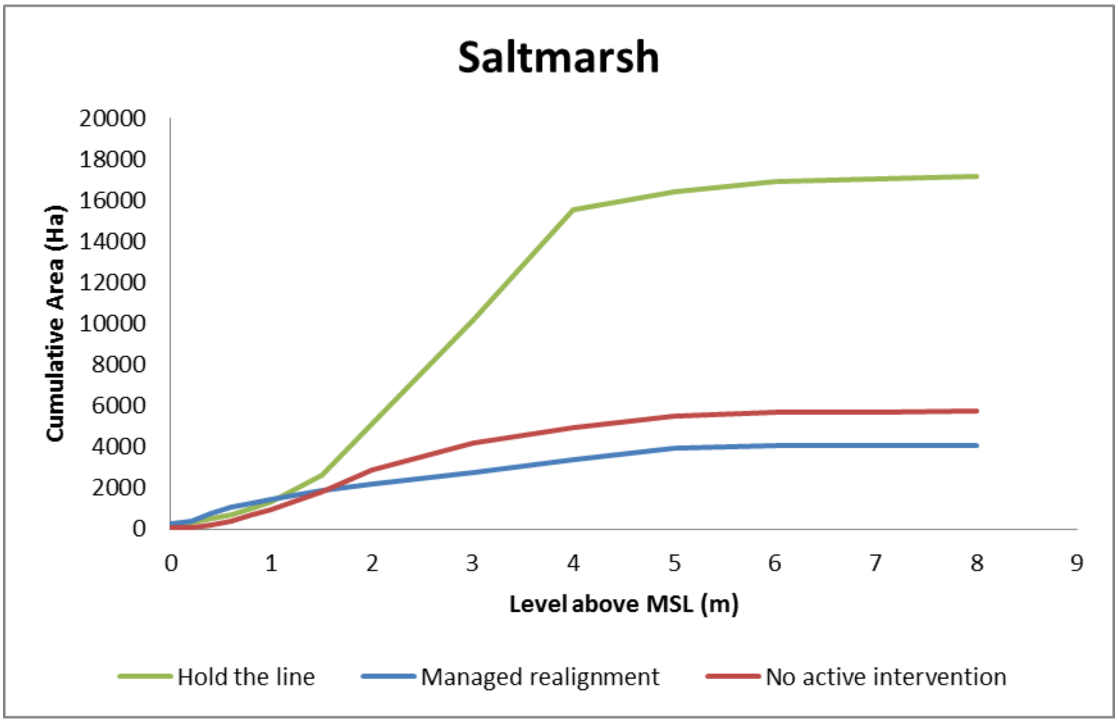

Figure 2.4: Results for saltmarsh loss in different coastal management policy areas completed by HR Wallingford (ECI *et al*, 2013)

Erosion losses

Further analysis was undertaken to assess the potential erosion of mudflat, marsh and vegetated shingle ridges (not shown here). The National Coastal Erosion Risk Mapping (NCERM) dataset was used to provide estimates of the land that may be lost to erosion for different epochs and probabilities. These data are based on Future Coast research and have been validated by the coastal local authorities. The data contain the present management policy as well as a projection of the future policies for each epoch. They give the amount of land for each stretch of coastline that is estimated to be lost under the projected policy as well as the no active intervention policy allowing the difference to be determined and hence the likely amount of habitat that may be lost due to the coastline's inability to roll back apace due to the backshore being fixed under a 'hold the line' or 'managed realignment' policy. We assessed the epochs:

- Short term (2030);
- Medium term (2055); and
- Long term (2105).

And different percentiles of exceedance confidences;

- 5th percentile;
- 50th percentile; and
- 95th percentile.

2.2.2. Area and use of coastal floodplain that potentially benefits from natural flood risk reduction due to the presence of natural habitat

In order to assess this indicator, the coastal habitat areas were used to demark reaches of coastline that were fronted by either saltmarsh, mudflat or vegetated shingle ridge and a GIS process was developed to 'backcast' up the coastal floodplain DTM in the lee of the habitats to identify the areas where the flooding may be attenuated to some degree by the presence of the habitat. The area potentially benefitting was subsequently categorised by land use and the number of commercial and residential properties assessed.

2.2.3. Area and use of coastal floodplain that potentially benefits from raised flood defences

The method used to assess this indicator was similar to that for areas benefitting from the presence of coastal habitats. Similarly, the land use and number of properties benefitting were assessed.

2.2.4. Land use at risk of coastal erosion

Assessment of the land use within the NCERM was undertaken to assess the spatial distribution of sites benefitting from coastal erosion defences. The indicator was also used to identify where designated sites are unprotected. This measure indicates current conditions, measured trends and potential for future vulnerability.

2.2.5. Land use at risk of saline intrusion

Assessment was made of the land use (particularly focused on agricultural land uses) within areas subjected to saline intrusion and as an indicator of current condition and measured trends.

2.2.6. Area of non-built up land currently protected by a 'hold the line' policy

Assessment of the area of land which would be impacted if the management policy were 'no active intervention' across the entire coast of England. The results show that numerous coastal policy units exist where the preferred management option in the long term is to hold the line, but where no further active interventions would be considered more viable in economic terms. If management is changed, but there are no active interventions, only 75 ha of non-built up land may be eroded, and 10,000 ha flooded.

2.3. Research to assess the influence of beach evolution on flood risk

A case study to explore the impact of beach evolution (specifically erosion and loss of beach volume along an eroding cliff coastline) was carried out as part of the UK Engineering and Physical Sciences Research Council project FRMRC2. The North Sea coast of Holderness was used as an example (Panzeri *et al,* 2012[2]) (Figure 2.5).

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[2] http://eprints.hrwallingford.co.uk/600/1/HRPP564-A_GIS_framework_for_probabilistic_modelling.pdf

The HR Wallingford approach to explore the influence that the neighbouring coastal zone has on flood risk was to develop a system model that sits within a GIS modelling framework which performs Monte Carlo simulation of the beach evolution model and integrates the probabilistic results of the model with a flood risk model.

The probabilistic coastal evolution model incorporated a simplified cliff erosion model which sampled cliff failure as a function of steepness due to retreat of the cliff toe. The model also considers a number of different beach nourishment processes. These include talus from the cliff erosion process, fluvial sediment load sampled from distributions and beach recharge from Coastal Management activity. As well as tracking the mean shoreline and cliff top positions, the maximum and minimum positions of the shoreline are recorded to enable the Coastal Zone Manager to discover whether the beach has been drawn down to critical levels at any times during the modelling period.

Where seawalls form a fixed line of flood defence, the coastal evolution model was linked to a backshore flood risk model. The coastal model calculates a distribution of beach level at the toe of the structures which feeds directly into a probabilistic flood risk model which samples the defence toe level along with other parameters such as defence fragility and overtopping rates in order to quantify the risk of flooding to low lying land in the lee of the defences. Flood depth versus probability curves are produced for the coastal floodplain and risk is expressed in terms of Expected Annual Damage to property as is the defence contribution to the risk.

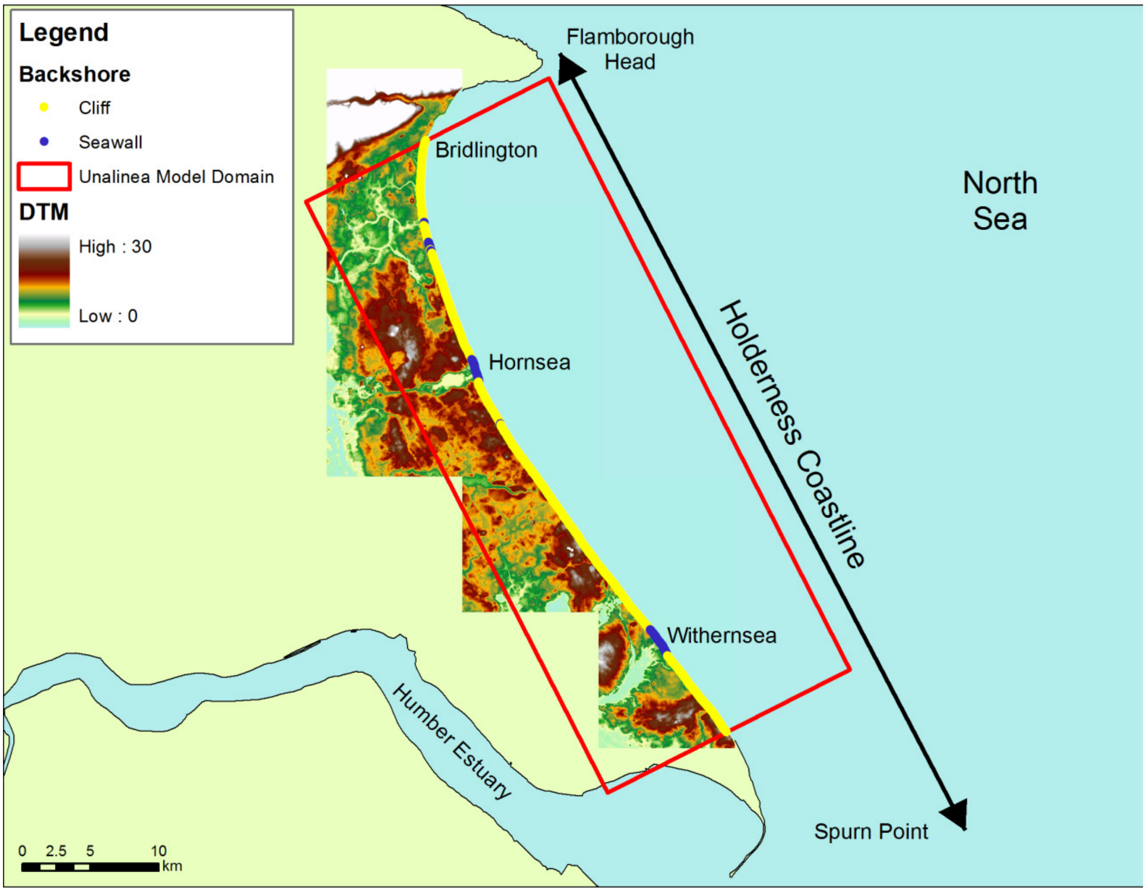

Figure 2.5: Holderness study area showing contours of hinterland

The modelling framework provides a sophisticated tool to the Coastal Zone Manager who is now able to explore variability in a number of different forcing conditions and management options and to understand the potential range and uncertainty in consequences that these may have on flooding and the evolution of the coast over regional scales (Figure 2.6). Of note, the tool allows the coastal zone manager to probabilistically explore nourishment options (Figure 2.7) and in doing so, not only assess the impact of the options on the coastal zone but also to assess the affect the options have on flood risk to any neighbouring low lying areas that are prone to coastal flooding.

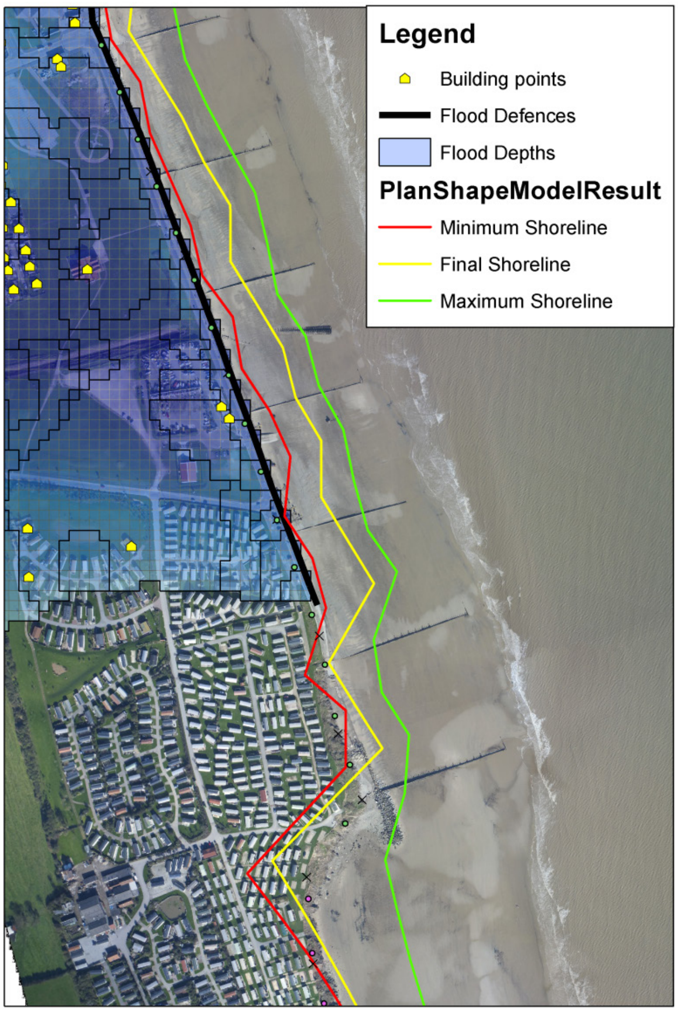

Figure 2.6: Holderness model showing results from coastal evolution model and associated mean flood depths from flood risk model run for 20 years

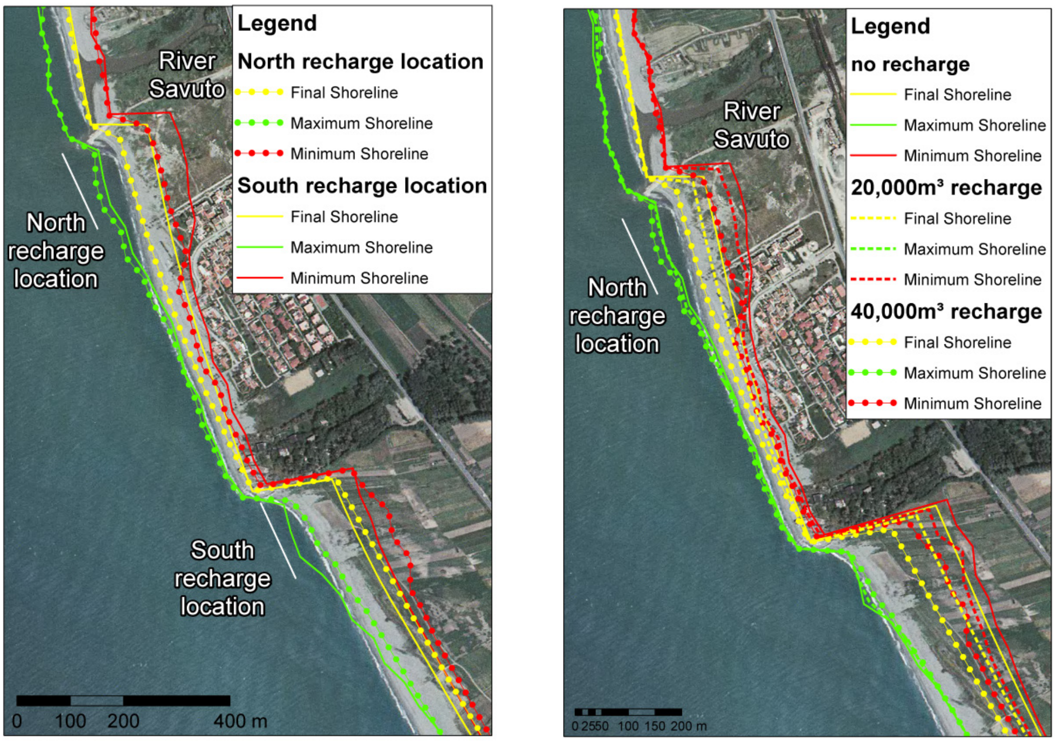

Figure 2.7: Determining where to recharge (left panel) and how much to recharge (right panel)

3. Typical influences of sea level change on USACE mission areas

The stated objective of this task was to study the different influences on the four mission areas of USACE - storm damage reduction, flood risk mitigation, ecosystems management, and navigation - resulting from changes in extreme sea levels, characterize their underlying fundamental nature, and, for some typical example cases, quantify trends and tipping points in performance over a 100 year time frame through conceptual numerical modelling. The basis of this task was that no intervention is provided to adapt for sea level change and the landform features are assumed static, i.e. no rollover of barrier beaches.

In fact, the USACE guidance on sea level change (ETL 1100-2-1) has described the kinds of influences on the four mission areas in broad terms. In order to make this assessment more concrete, this research started by focussing on the assessment of the influences on three important and contrasting coastal system types, namely:

- a barrier island coast, such as along the New Jersey coast;
- the harder coasts with rock bluffs typical of New England states; and
- and an estuarine situation typified by the Delaware or Hudson rivers.

For each of these types the likely impacts have been summarised in Table 3.1.

The quantification of these impacts is undoubtedly site specific, but is related to the envisaged magnitudes of the sea level changes. Predictions for the NOAA tide gauge locations along the North Atlantic coast have been assessed by the US NACCS team for four cases. These are the three USACE scenarios listed in the ETL on sea level change (SLC), namely low (i.e. present day rates of SLC), medium (NRC curve 1) and high (NRC curve 3) and for an extreme high scenario developed by NOAA. As an example, the USACE 'high change' scenario (NRC Scenario 3) are shown in Figure 3.1. The gauge references given in this figure relate to the map locations shown in Figure 3.2. Note that in Figure 3.1 the USACE High values for Sea Level rise for years 2018, 2068, 2100 and 2118 are plotted by gauge number progressing along the coast in a generally south to north direction, but following around each major bay. Thus the figure progresses through Chesapeake Bay in the south to Boston in the North. The plot indicates generally higher sea level increases nearer to the open coast and generally lower sea level changes the closer the gauge location to the tidal limit of the inlet. Maximum sea level changes to 2118 under this scenario are of the order of 7-8 feet (2.1 to 2.4 m).

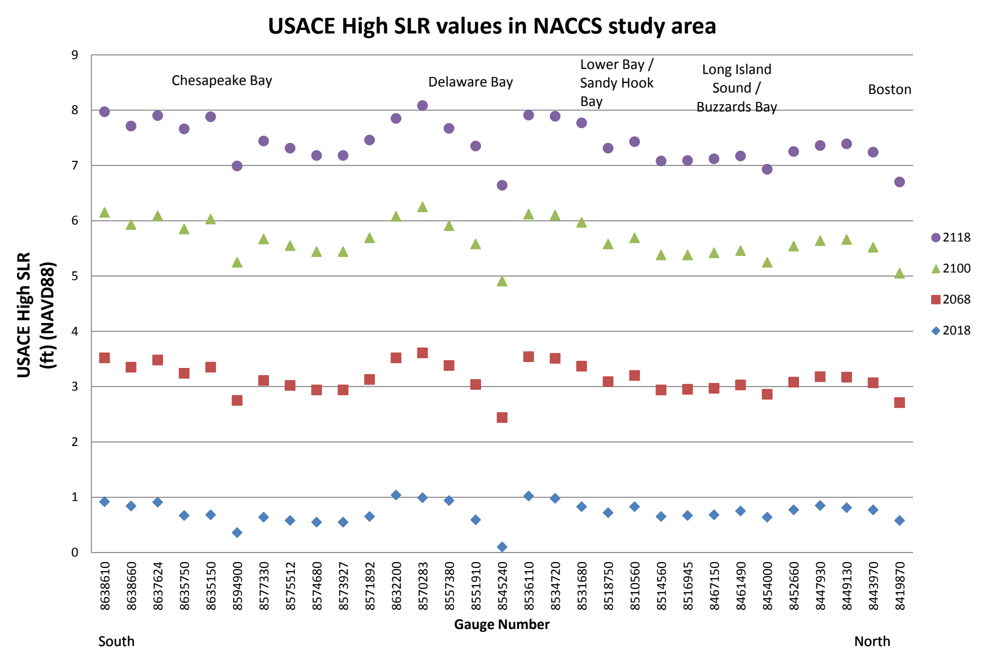

Figure 3.1: USACE High sea level rise for the NACCS Study area from Chesapeake Bay to Boston

Table 3.1: Mapping of impacts on mission area issues for the coastline types

USACE Mission area	Barrier island coast	Rock bluff with bay coast	Estuarine coast
Navigation	If lagoon area behind barrier island used for navigation **Beneficial impacts:** Increased navigation depth **Adverse impacts:** Potential loss of protection to navigation due to increased overtopping of barrier island	No direct navigation issues identified	For navigation in estuarine waters **Beneficial impacts**: Increased navigation depth **Adverse impacts:** Changed flow and sediment transport patterns cause siltation in previously navigable routes
Coastal Storm Damage Reduction	**Beneficial impacts:** None identified **Adverse impacts:** ■ Erosion of seaward face of barrier island ■ Damage of rear of barrier island by overwash ■ Increased risk of damage to property on beach and backshore	**Beneficial impacts:** None identified **Adverse impacts:** ■ Increased erosion of soft cliff headlands ■ Increased erosion of salt marsh and other low lying features between headlands ■ Increased risk of storm damage to property on low lying beach and backshore	Not applicable
Flood Risk Mitigation	**Beneficial impacts:** None identified **Adverse impacts:** ■ Increased water levels directly reduce width of barrier beach at MTL[3] ■ Increased risk of flooding during extreme events both on barrier island and bay shore ■ Drainage system loses storage capacity and has increased time periods during which the tide prevents gravity drainage	**Beneficial impacts:** None identified **Adverse impacts:** ■ Natural features such as salt marsh become less effective in reducing impacts of storm events. ■ Increased risk of flooding during extreme events to low lying properties in bay areas. ■ Reduced time availability for vehicular access across low lying areas during high water conditions	**Beneficial impacts:** None identified **Adverse impacts:** ■ Increased risk of flooding during extreme events ■ Drainage system loses storage capacity and has increased time periods during which the tide prevents gravity drainage

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[3] Mean Tide Level

USACE Mission area	Barrier island coast	Rock bluff with bay coast	Estuarine coast
Ecosystems Management	**Beneficial impacts**: ■ Increased water levels increase shallow intertidal area where invertebrates can colonise, mollusc reefs can be built up and wading birds can feed ■ Increased water levels widen lagoon area which can allow more shallow subtidal flora to establish **Adverse impacts**: ■ Increased water levels reduce terrestrial area of beach and thus vegetated area ■ Increased water level reduces beach width and therefore potential nesting sites for some seabirds ■ Increased subtidal and intertidal areas may provide potential colonisation areas for invasive species	**Beneficial impacts**: ■ Eroding soft cliffs supply more sediment to low lying beach areas between bluffs, providing some protection to marsh areas **Adverse impacts**: ■ Erosion of soft cliff headlands can smother existing low lying wetland habitat, both flora and fauna ■ Instability of cliff faces contributes to a loss of flora and fauna which exploit the cliff face ■ Reduced cliff height above water level reduces potential nesting sites for birds	**Beneficial impacts**: ■ Increased water levels increase shallow intertidal area where invertebrates can colonise and wading birds can feed ■ Increased subtidal and intertidal area for shellfish beds to expand **Adverse impacts**: ■ Marginal areas such as salt marshes and beaches are eroded, thus reducing shoreline vegetation and associated invertebrate fauna ■ Marginal areas such as salt marshes and beaches are eroded, reducing bird nesting and roosting sites ■ Saline intrusion into freshwater hinterland ecosystems
Existing natural and nature based infrastructure	**Beneficial impacts**: None identified **Adverse impacts**: ■ Lagoon area less sheltered due to reduced barrier so wave action may cause increased turbidity which reduces PAR[4] to subtidal flora ■ Loss of vegetation contributes further to loss of stability of barrier beach	**Beneficial impacts**: None identified **Adverse impacts**: ■ Loss of vertical cliff face and stability for rocky shore flora and fauna ■ Low lying habitats between bluffs liable to be more exposed and subject to extreme variations in sediment supply	**Beneficial impacts**: None identified **Adverse impacts**: ■ Erosion of marginal habitats due to increased hydrodynamic pressures ■ Instability of intertidal and subtidal sand- and mud-banks due to increased hydrodynamic pressures

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[4] Photosynthetic Active Radiation

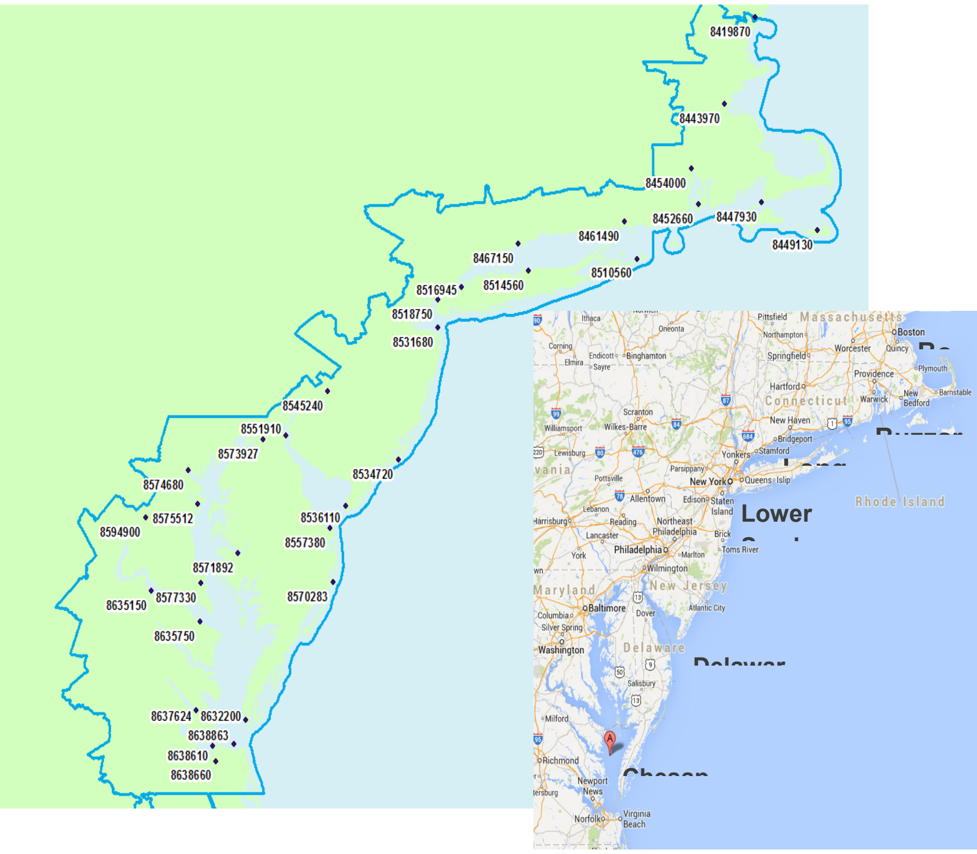

Figure 3.2: NOAA tide Gauge locations by number along the US North Atlantic coast

Quantification of these impacts highlight needs to focus on the underlying variables of interest. Review of Table 3.1 suggests that the following parameters representing adverse impact may be of interest:

- Loss of area of barrier islands to permanent or semi-permanent inundation;
- Percentage loss of non-submerged volume below +15 foot contour to permanent or semi-permanent inundation. In low lying areas this will be indicative of the loss of drainage capacity;
- Changes in Expected Annual Damages related to property subject to flooding;
- Loss of low-lying habitat areas by submergence or erosion;
- Long term net loss of beach volume;
- Miles of existing road network subject to regular inundation; and
- Changes in distribution of water depths available within estuaries for navigation.

4. Methodology for evaluating influences of sea level change on some exemplar North Atlantic coastal areas

4.1. Selection of exemplar areas

The following exemplar areas were identified at the beginning of the study as being representative of three coastal types that might be significantly affected by sea level change. The focus when selecting these sites was primarily on the mission area of flood risk reduction, but the other mission areas were also taken into account in regard to some sites:

- Barrier Island Coast:
  - Assateague Island (State and National Parks) and Ocean City (combine into one site evaluation) (barrier island coastal system type) - responsibility NAB (Baltimore District);
  - Long Beach Island, Ocean County, New Jersey (barrier island coastal system type) – responsibility NAP (Philadelphia District);
  - Long Beach, Nassau County, New York – responsibility NAN (New York District);
- Headland:
  - Cove Point, Calvert County (erodible headland in Chesapeake) - responsibility NAB (Baltimore District);
  - Point Judith, Rhode Island (erodible headland) – responsibility NAE (New England District);
- Estuarine:
  - Blackwater National Refuge (estuary in Chesapeake) – responsibility NAB (Baltimore District);
  - Delaware Bay shoreline of the lower Delaware Bay (Mispillion Inlet to Broadkill Beach) (estuarine coastal system type) – responsibility NAP (Philadelphia District).

4.2. Methodology for exemplar areas

The way in which these examples were actually analysed during the course of the study was as follows:

- The barrier island examples were primarily used to illustrate the impact of sea level rise on flood risk management:
  - **Assateague Island** is an example of a barrier island which remains nearly in a relatively natural state although it has been subject to significant beach nourishment to maintain it, at least since the barrier island inlet between the natural southern half and Ocean City to the north was maintained artificially since 1935. Assateague therefore becomes an example of a more natural state to which any interventions on the other two populated barrier islands can be compared, at least qualitatively.
  - **Long Beach Island, NJ and Long Beach NY** are both highly populated islands and after initial basic submergence analysis under sea level change scenarios and examination of availability of data, it was decided to select **Long Beach Island NJ as the example for detailed analysis**. The detailed analysis involved examining the potential for flooding from both ocean and bay shorelines under three alternative increments of sea level rise from present day (1ft, 3ft and 6ft). Long beach Island NJ is also used as the most detailed example for evaluating potential responses to sea level rise.

- The area around **Point Judith RI** is more robust to flooding and there were no particular issues of wider interest identified with regard to flooding. However, the location has an interesting example of a harbour of refuge protected by rubble mound breakwaters. The breakwaters and the harbour of refuge they protect has been the subject of a detailed USACE study, so this study merely draws out the implications for future measures for adaptation to sea level change. The site therefore provides an interesting example for the USACE **navigational mission area**.
- **Cove Point, Calvert County** is a headland area within Chesapeake Bay. Geomorphologically a ness of low lying beach material, it protects backing soft erodible cliffs (Calvert Cliffs) which prove to be the most interesting aspect of the site. The energy facility is set back a considerable distance from the top edge of the cliff and is not immediately at threat from coastal erosion, but there was sufficient data on the cliffs in the area from previous research to provide an interesting example of examining the impact of sea level rise on **storm damage reduction**.
- **Blackwater National Refuge** in Chesapeake Bay is an interesting example of an area which falls under the **ecosystems management** mission area of USACE. Set in the context of the ongoing submergence and loss of marsh areas within Chesapeake Bay, it provides a particularly acute challenge for management in the face of sea level rise. The focus of this study is not to replicate an existing comprehensive study of the area, but to explore the extent to which strategies for managing such areas which have been adopted in the United Kingdom might have some application to this type of geomorphic setting on the North Atlantic Coast.
- Finally the **Broadkill Beach** shoreline in the lower Delaware Bay is an interesting area of **mixed interest**. Here there is a small community of dwellings situated along a shoreline beach ridge in front of a salt marsh area. The area, much like an open coast barrier island, is subject to **flood risk**, not just from the bay side but also from the rear. The bay side flood risks have been mitigated by USACE in recent years using material from **navigational dredgings**, but the risks from the rear remain. Economically long-term maintenance of the community in the face of sea level rise may be more challenging than for some of the more populous open coast barrier islands. The marsh areas behind the beach also face many of the same **ecosystem management** challenges as the Chesapeake Bay marshes. Other than a overview of the site and a submergence analysis, the analysis of this mixed interest area is not taken forward in any detail.

4.3. Initial submergence assessment method

A common feature of the examination of the various sites was a GIS-based analysis of loss of area of the various sites using available US datasets (selected from those described in Appendix A). The scripts used to assess submergence of habitat areas were adapted from those used in the previous work for the UK Adaptation Sub-Committee (ASC).

An area to be analysed was identified and used to extract the DTM for that zone. The DTM available for different areas varied with some data supplied by USACE having a resolution of 2m. Where this detailed DTM was not available extracts of the National Elevation Dataset were used with a resolution of 1/3 arc second.

The extracted DTM was then classified according to a range of bands that started at zero to one metre and went up to six to seven metres. This set of values was chosen because it is appropriate for the tidal range typical for the North Atlantic Coast. The analysis was first carried out without adjusting the height values of the DTM. The heights were then adjusted to take into account mean sea level and mean high water. This produced a range of bandings that could be compared with different sea level rise scenarios.

The areas for each height band were then calculated.

As a cross-check, the results from this analysis were compared with a similar analysis carried out by NOAA for their Sea Level Rise and Coastal Flooding Impacts website (http://csc.noaa.gov/slr/viewer/). The NOAA analysis used mean higher high water (MHHW) as the baseline so the resulting areas of inundation were not as great as those found in our analysis. The NOAA method also included much more detailed local tidal variation and evaluated the inundation for hydrological connectivity.

4.4. Detailed flood risk assessment of barrier island example across a range of extreme conditions

The results of the initial submergence assessments presented for the various exemplar coastal types in Chapters 5, 7, 8, 9 and 10 suggested that a more detailed assessment of one of the barrier islands would best for extreme conditions might best illustrate the challenges facing the US North Atlantic coast. Chapter 6 sets out the detailed process of analysis.

4.5. Adaptation measures to respond to sea level rise

Given the analyses of the various exemplars of coastal types, the various chapters go on to discuss potential alternative adaptation solutions given the expected predictions of future climate change or both sea level change and superimposed storm surge. Consideration was given to typical published measures employed by USACE (2013) focussing on natural and nature-based shoreline features, and structural measures. An initial assessment of the usefulness of such measures for the different USACE mission areas has already been presented in the ETL on sea level change (see Table 4.1) and so the focus of this work was on the specifics of the particular situations examined. The examination of adaptation measures was mainly focused on storm damage reduction and flood risk mitigation. Some qualitative consideration was given to measures associated with ecosystems management and navigation interventions (piers, jetties, etc.). Quantitative evaluation of measures was restricted to the evaluation of the reduction of flood inundation for the case of the barrier island example.

Table 4.1: Potential adaptation approaches by project type. (Source: USACE ETL 1100-2-1 on SLC)

Project Type	Protect	Accommodate	Retreat
Navigation	Upgrade and strengthen existing primary structures Expand design footprint and cross section of existing structures Add secondary structures Add structures to protect backshore Improve resilience of backshore facilities	Upgrade drainage systems Increase maintenance and dredging Adjust channel location and dimensions Modify operational windows Flood proof interior infrastructure Add sediment to shoreline or underwater morphology	Relocation of interior harbor infrastructure Abandonment of harbor/port Re-purpose project area
Coastal Storm Damage Reduction	Upgrade and strengthen existing structures Expand design footprint and cross section of existing structures Add secondary structures Dune/beach construction	Increase maintenance of shoreline protection features Sediment management Beach nourishment/ vegetation Upgrade drainage systems Upgrade and modify infrastructure Flood proof buildings Implement building setbacks Modify building codes	Relocate buildings and infrastructure Land-use planning and hazard mapping Modify land use
Flood Risk Reduction	Upgrade and strengthen existing structures Expand design footprint and cross section of existing structures Construct levees or polders Add secondary structures Dune/beach construction	Increase maintenance of flood risk protection features Upgrade and modify infrastructure Improve natural shoreline resilience (vegetation) Flood proof buildings Implement building setbacks	Relocate buildings and infrastructure Land-use planning and hazard mapping Modify land use
Ecosystems	Construct drainage systems Construct shoreline protection structures, dikes or cells Construct tidal gates, install salt water intrusion barriers	Accept changes to ecosystems Sediment management Change water extraction Freshwater injection /diversion Modify land use Migrate landward	Allow/facilitate habitat conversion Forbid hard defenses Abandon ecosystem

5. Barrier islands - general

5.1. Introduction

Barrier islands are naturally migrating structures, which move in response to sediment supply, prevailing wind conditions, tidal currents and severe storm actions (e.g. Stripling *et al*, 2008). This natural migration ability is their strongest defence against sea level rise, as they can naturally reshape in response to the coastal process changes. Thus, adding permanent infrastructure to these islands and expecting that infrastructure to be defended is counter-productive when considering the resilience of coastline communities as a whole. However, a number of the barrier islands along the North Atlantic coasts have been subject to considerable development and now contain a great deal of human infrastructure, including residences, business premises, roads and other community structures. It is impractical to expect these islands to be abandoned to allow the resilience that naturally migrating barrier islands would display. In recent decades USACE has invested considerable funds in defending the Atlantic seaboard of many of the barrier islands, generally by nourishment of the natural beach-dune systems with additional sandy material. During Hurricane Sandy the better nourished of these beach-dune systems was effective in mitigating damage to properties and infrastructure on the barrier islands. However, the islands remain very low lying and it is instructive to examine the extent of submergence of the islands that would occur due to water entering from the bay side of the island either under extreme events or as a result of mean sea level rise.

Three segments of barrier islands were identified:

1. Long Beach, Nassau County, New York.
2. Long Beach Island, Ocean County, New Jersey.
3. Assateague Island (State and National Parks) and Ocean City.

As described in Section 4.3, an initial simple submergence assessment was applied to increments of sea level rise against the elevation of each of these islands to identify the area that would be lost at varying levels without levees or flood walls and assuming full hydraulic connectivity. This assessment was based on a DTM with a resolution of 2m and analysed into one foot bands of ground height. The figures in each of the following sub-sections of this chapter show the resulting percentage loss in land area compared with the four sea level rise scenarios considered in the NACCS study.

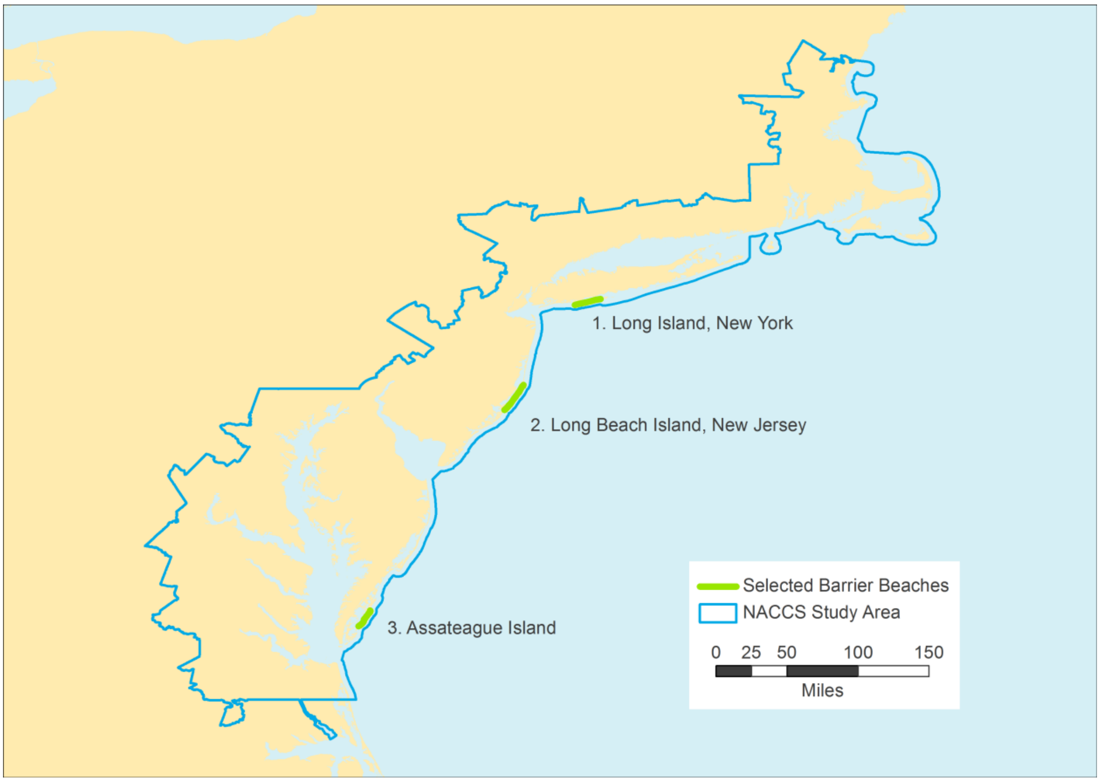

Figure 5.1: Selected barrier beach sites

5.2. Natural vegetated barrier islands: Assateague

Assateague Island (see Figure 5.2) consists of two halves, as a breach channel in front of Ocean City was formed during a 1933 hurricane event. The breach channel has been maintained by the construction of jetties and subsequent dredging, in order to provide navigational access to Ocean City. From previous map records, it can be seen that the migration of north and south parts of Assateague have been very different and the longshore sediment drift which is the background coastal process during normal weather conditions has been considerably disrupted.

The strategy of beach replenishment on the seaward face of barrier islands, manipulating the sediment supply through bypassing the anthropogenic structures in the case of Assateague, remains a highly effective means of maintaining these islands as coastal defences. Encouraging the natural vegetation to continue to act as dune or marsh stabilisation is also a priority method of maintenance. Further details of the geomorphology of Assateague Island are given in Appendix B.1.

Results of the submergence analysis are given in Figure 5.3 and Figure 5.4.

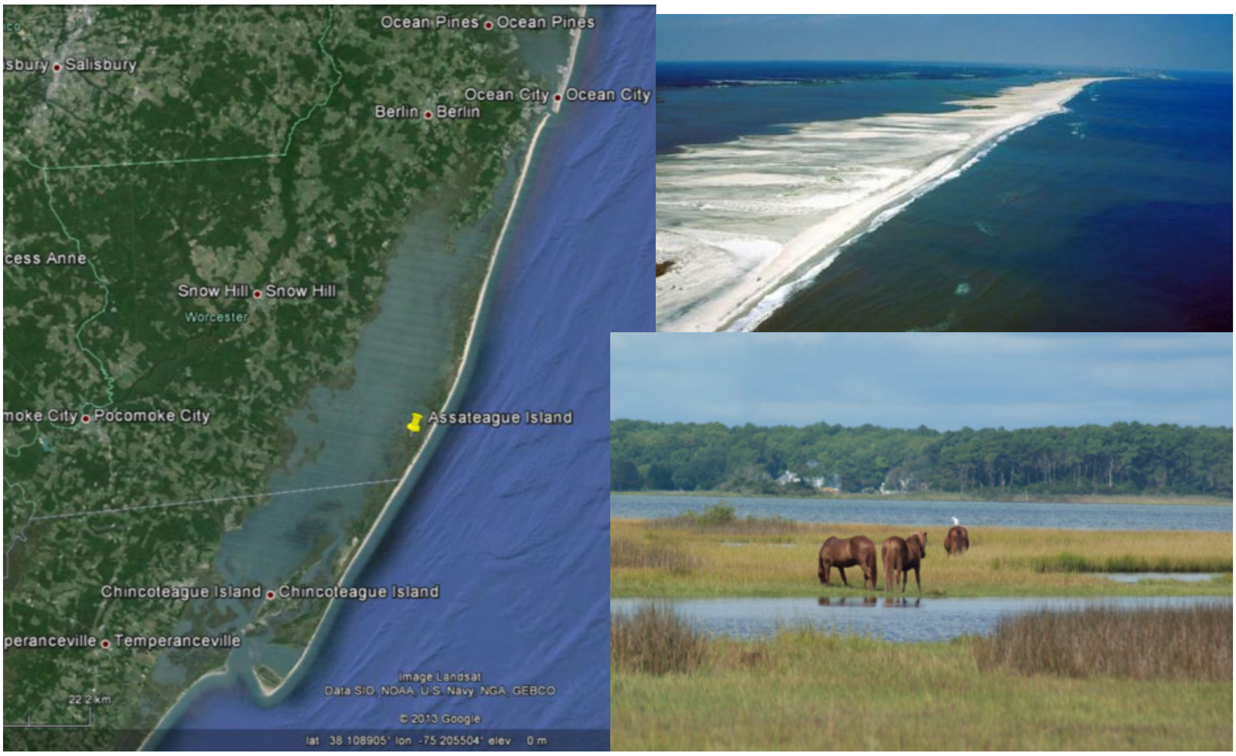

Figure 5.2: Perspectives of Assateague Island

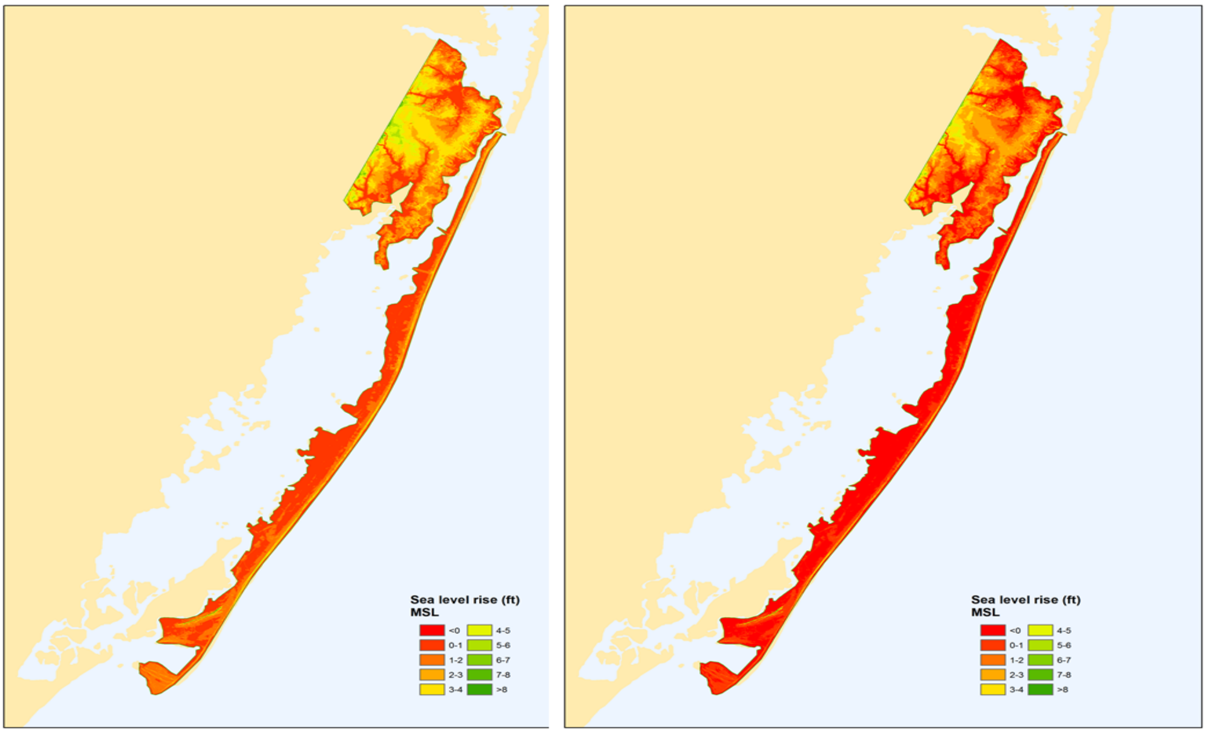

Figure 5.3: Amounts of sea level rise required to submerge Assateague Island during mean sea level (left) and mean high water level (right) conditions

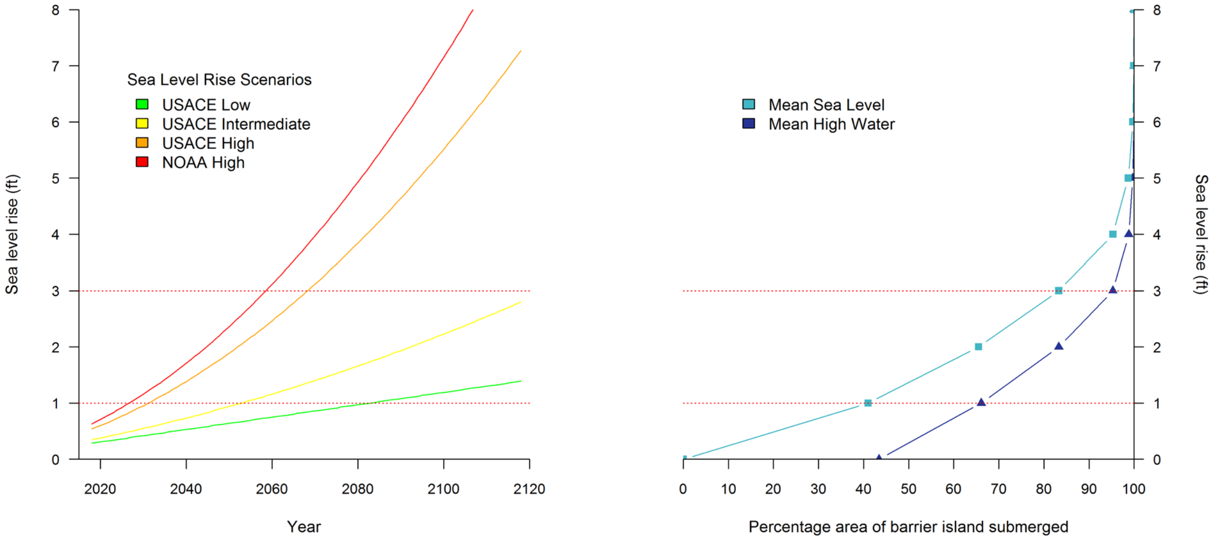

Figure 5.4: Submergence of Assateague Island as a result of sea level rise compared with sea level rise scenarios

5.3. Developed barrier islands (1): Long Beach NY

Long Beach NY provides a sharp contrast with Assateague Island. The island has been heavily developed for residential and leisure purposes (see Figure 5.5) but is as vulnerable to modest sea level rise as Assateague Island (see Figure 5.6 and Figure 5.7.

Figure 5.5: Perspectives of Long Beach, NY

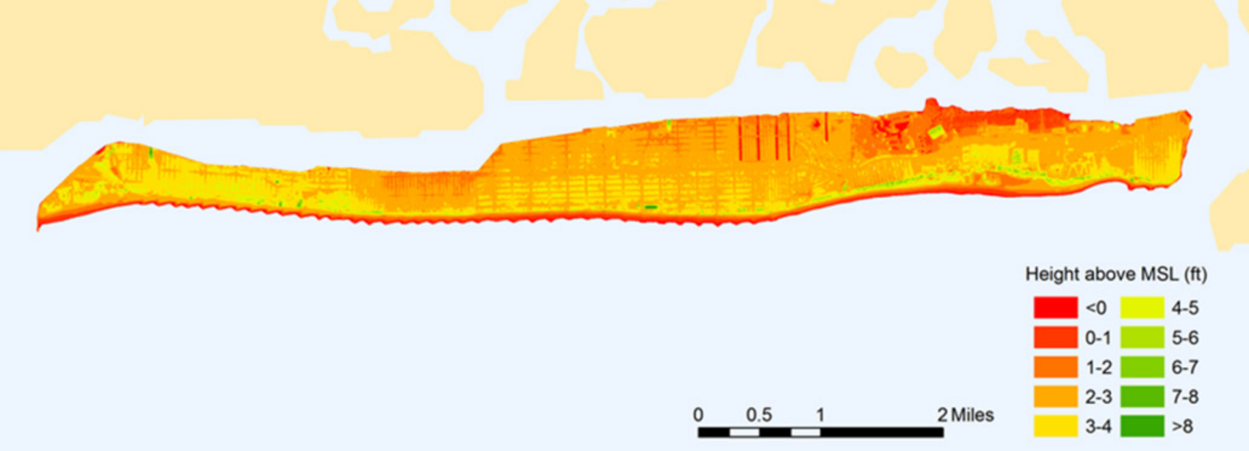

Figure 5.6: Amounts of sea level rise required to submerge Long Beach Island, NY during mean sea level conditions

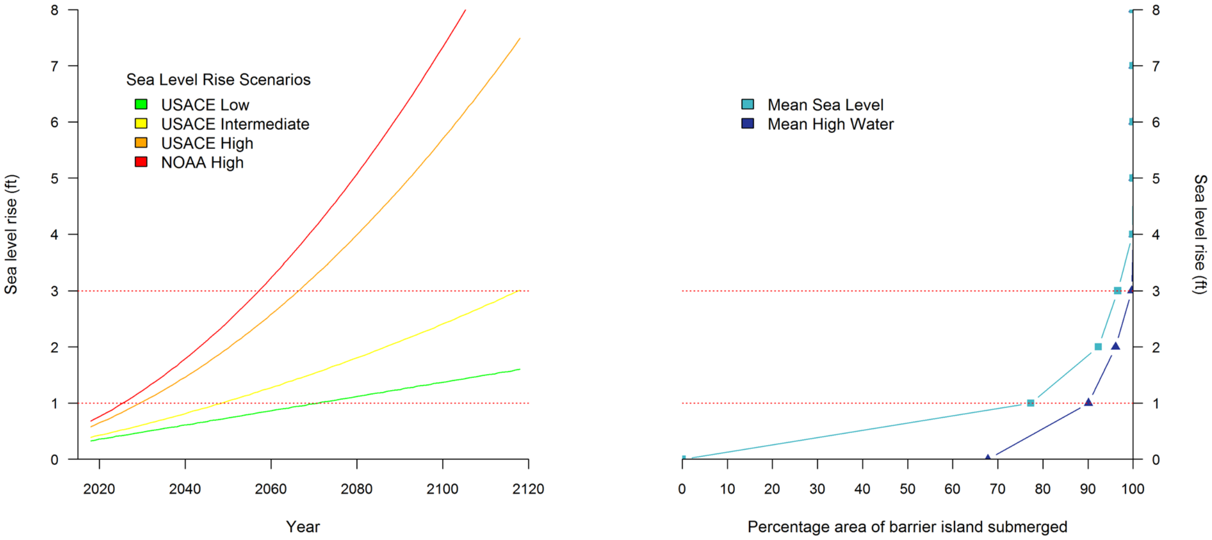

Figure 5.7: Submergence of Long Beach NY as a result of sea level rise compared with sea level rise scenarios

5.4. Developed barrier islands (2): Long Beach, NJ

Long Beach NY is similar to Long Beach island , NY in that it has been heavily developed for residential and leisure purposes (see Figure 5.8) and is similarly vulnerable to modest sea level rise The vulnerability is emphasised by low lying land shown in the cross sectional profiles (Figure 5.9) available from, the Stockton Institute (Stockton, 2012). The resulting vulnerability to sea level rise is shown in Figure 5.10 and Figure 5.11.

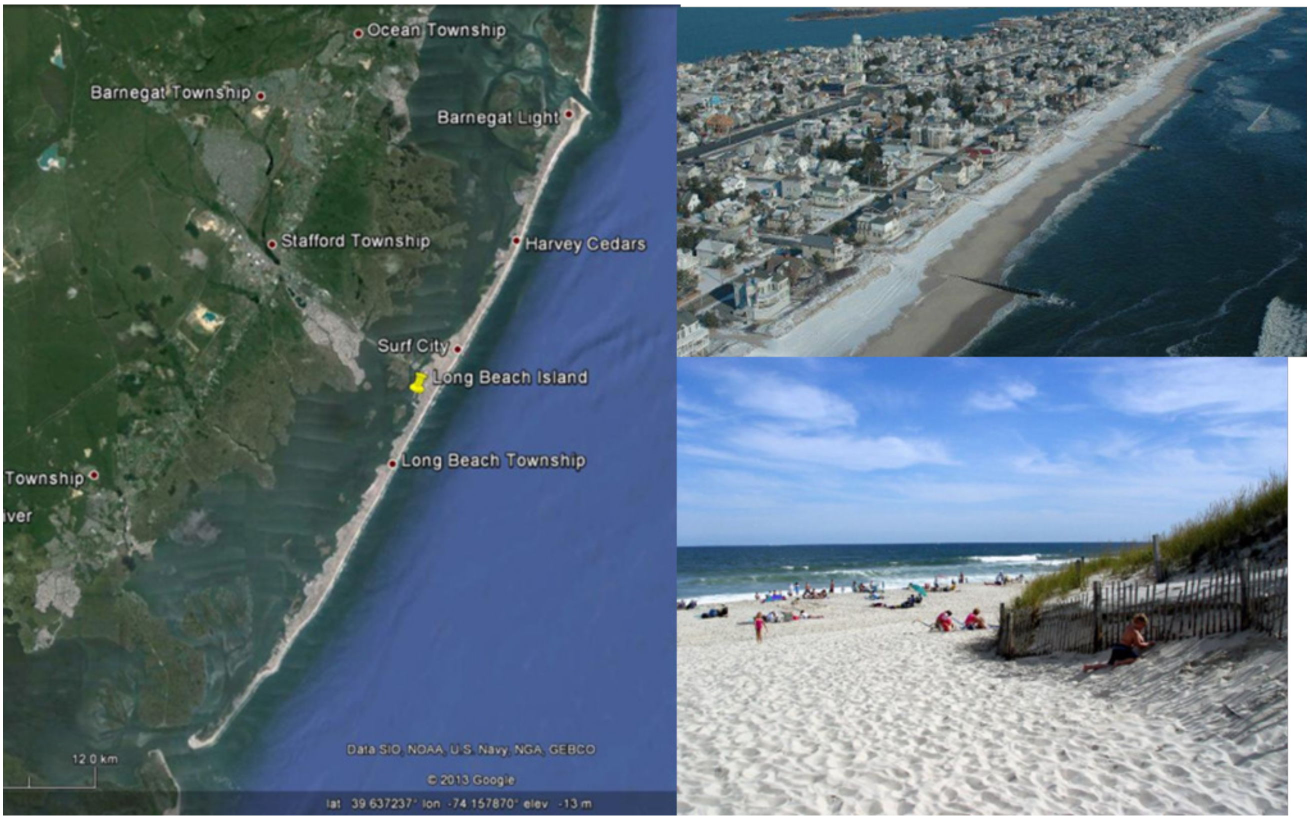

Figure 5.8: Perspectives of Long Beach Island, NJ

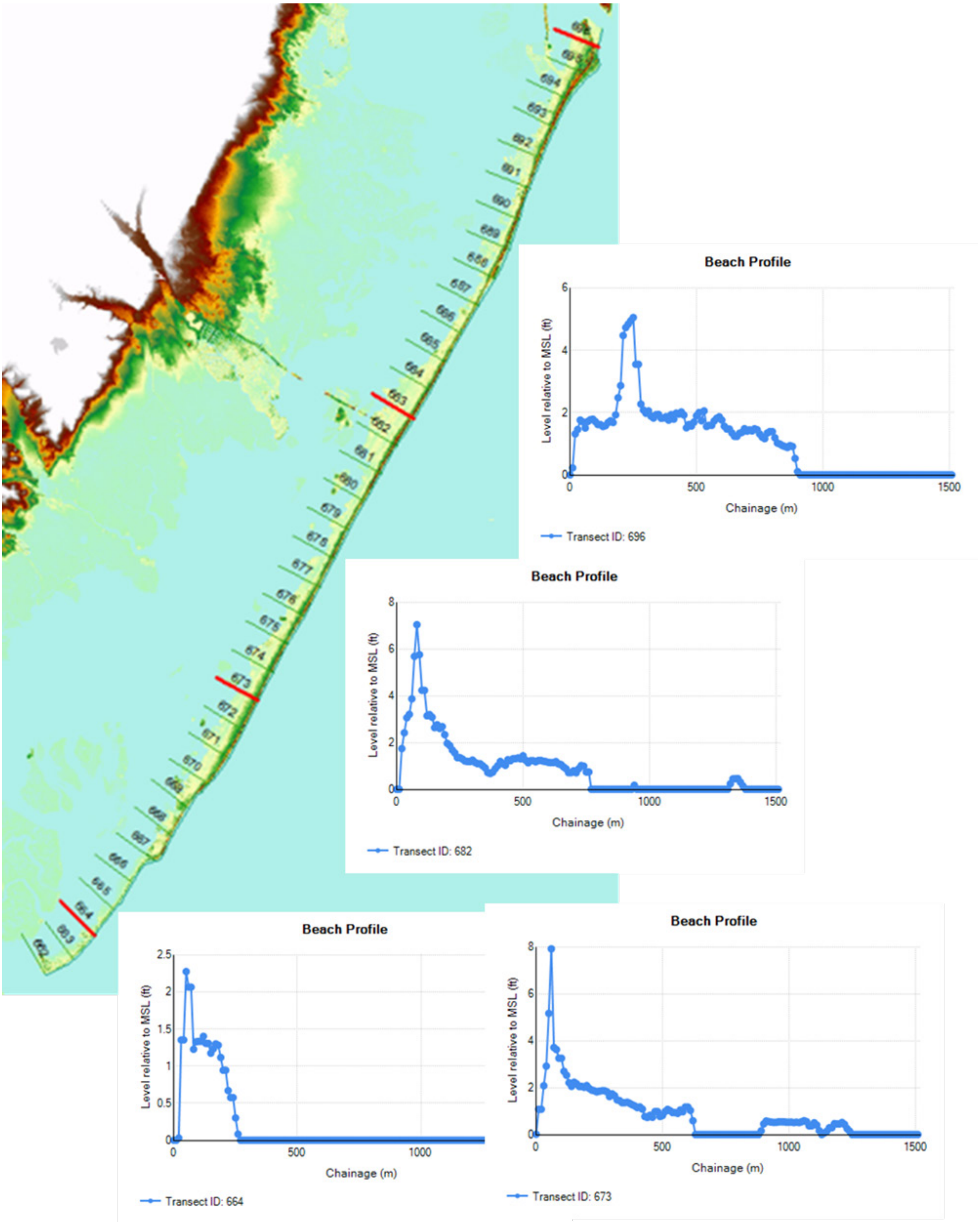

Figure 5.9: Sections through Long Beach Island, NJ

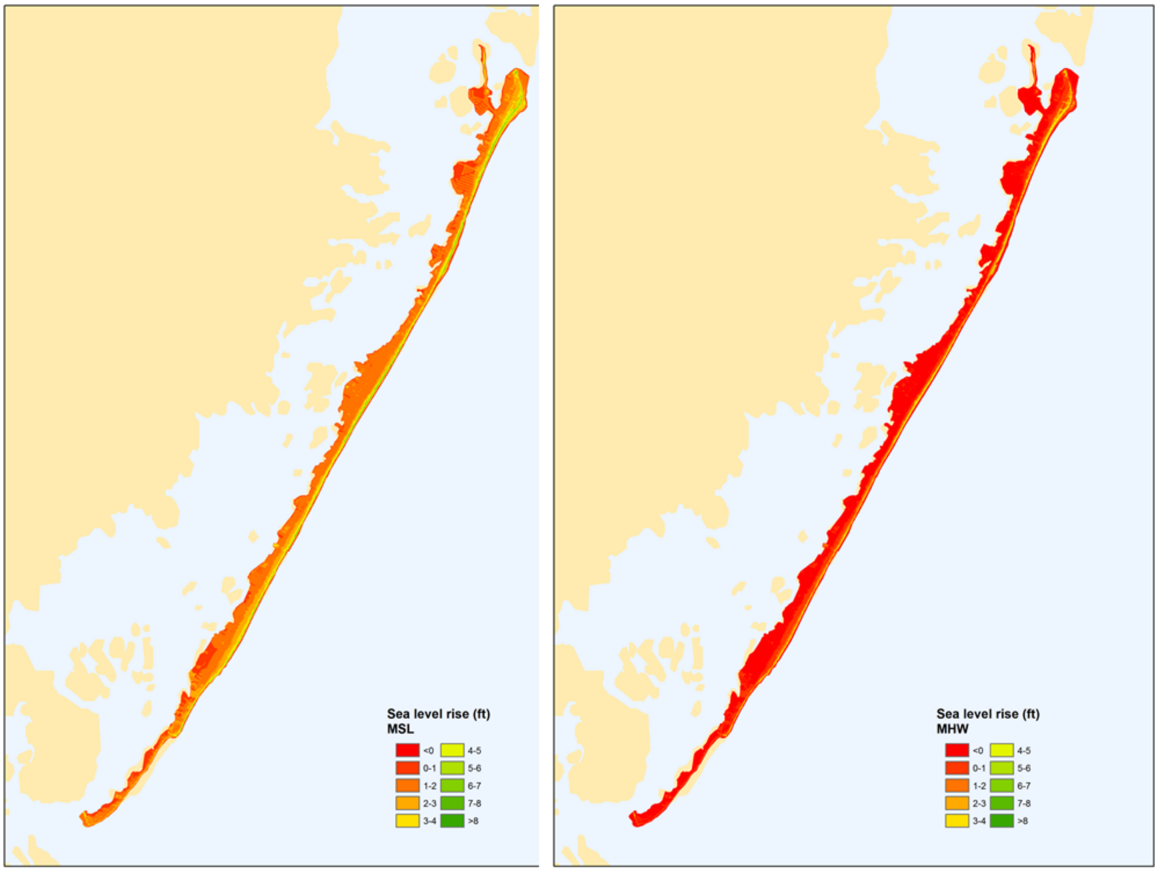

Figure 5.10: Amounts of sea level rise required to submerge Long Beach Island, NJ during mean sea level (left) and mean high water level (right) conditions

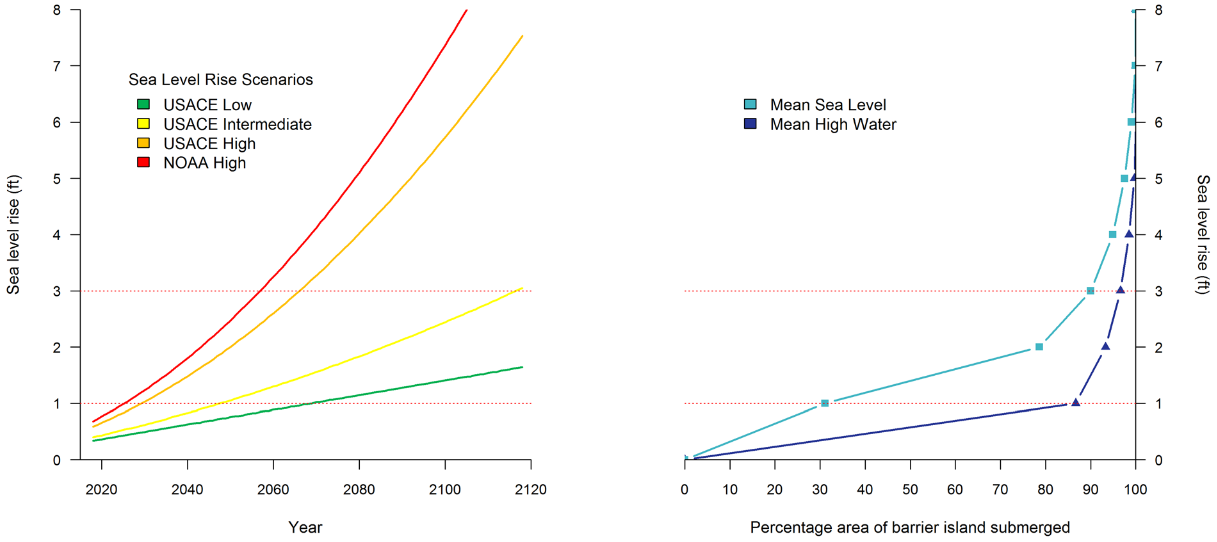

Figure 5.11: Submergence of Long Beach Island NJ as a result of sea level rise compared with sea level rise scenarios

5.5. Conclusions of submergence assessment

As previous studies have shown, this kind of analysis indicates significant loss of land for just 1 to 2 feet of sea level rise, with only the large dune beach systems on the Atlantic seaboard escaping much of the inundation. The assumption of complete hydraulic connectivity across the island does of course exaggerate the results to some extent, but given the very flat nature of the island and the embedded drainage systems which will enhance connectivity it is probably reasonably close to reality. The full flood risk analysis in the next chapter for the Long Beach Island NJ example reinforces these conclusions and the need for action.

6. Barrier island example – Long Beach Island, NJ

Long Beach Island NJ was selected as an exemplar barrier island site for a full flood inundation and risk analysis. The rationale of the more detailed analysis was to test the robustness of a significant coastal population to sea level rise and to take the simple submergence analysis in the previous chapter onto another level of detail.

6.1. Offshore wave conditions

Offshore waves for the site were obtained by recorded data collected by the National Data Buoy Center for the nearest available offshore location to the site (see Figure 6.1). This site, located at 38°27'40"N 74°42'9"W and shown in Figure 6.2 has hourly records available since 1984. It includes information on the wave height, period and direction, as well as the wind speed and direction. Excluding dates where data was not available, this gave a record length of 24.9 years.

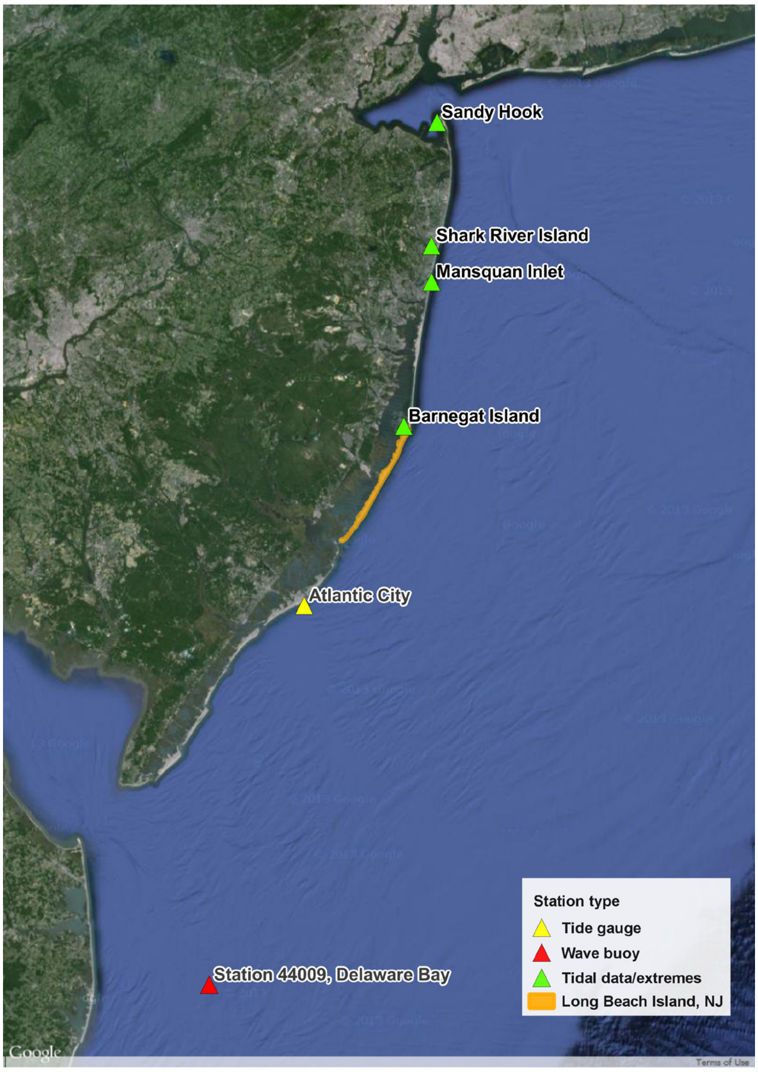

Figure 6.1: Location of offshore recorded wave data and sea level data

These records were scanned to identify individual storms, or events where the significant wave height exceeded 4m at least once during that event, with the wave height assessed in this analysis based on the largest wave height recorded in that event. This is shown for October and November 2012 for example, where two events were identified in this period, including Hurricane Sandy. Based on this assessment, 139 events were identified over the record length.

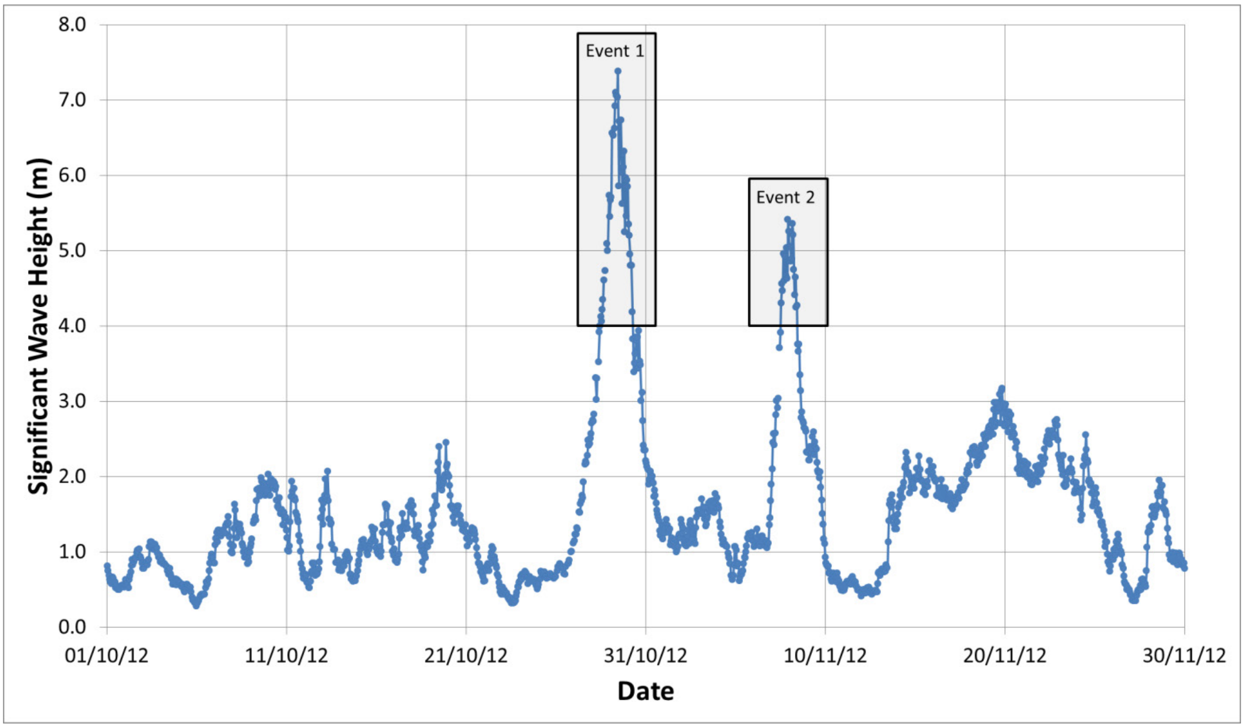

Figure 6.2: Example of wave height event selection over October and November 2012

6.2. Extreme water levels

Extreme water levels have been based on published extreme water levels for Atlantic City and Sandy Hook given in USACE (2013) and published standard tide levels for Atlantic City, Mansquan Inlet, Shark River Inlet and Sandy Hook given in UKHO (2014). Atlantic City is approximately 12 miles south of the southern-most limit of the site with Mansquan Inlet, Shark River Inlet and Sandy Hook to the north of the site (see Figure 6.1).

Extremes for the site are shown in Table 6.1 relative to chart datum[5]. These have been interpolated based on published extremes at Atlantic City and Sandy Hook and published standard tides.

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[5] 0m chart datum is approximately Mean Lower Low Water.

Table 6.1: Estimated standard tides and extreme water levels (return periods) at the site (to Chart Datum).

Tide level	Location		
	southern limit	centre of site	northern limit
MLLW	-0.02	-0.02	-0.02
MSL	0.67	0.69	0.71
MHHW	1.41	1.44	1.47
Highest astronomic tide	1.83	1.86	1.88
1 year	2.02	2.05	2.08
10 year	2.36	2.39	2.42
30 year	2.53	2.56	2.58
100 year	2.70	2.73	2.76
1000 year	3.05	3.08	3.10

6.3. Extreme nearshore wave heights

6.3.1. Set-up of input files

To determine wave heights nearshore, extreme wave heights needed to be transformed inshore based on the offshore wave height records identified from Section 6.1., together with the corresponding recorded water level. Coincident water level data was based on recorded sea level data obtained from the National Data Buoy Center for Atlantic City, translated to the site as in Section 6.2.

A data set of coincident offshore water levels and wave data from 1996 to 2014 was used as the basis for the present day offshore conditions, a Monte Carlo simulation being used used to provide pseudo water level and wave direction data for missing dates. This accounted for the distribution of water level and wave direction data for large significant wave heights, maintaining the distributions of wave heights, water levels and wave directions anticipated. The results of this analysis are shown in Figure 6.3. This indicates that larger wave heights tend to occur at higher water levels, with the largest wave heights typically from the north-east.

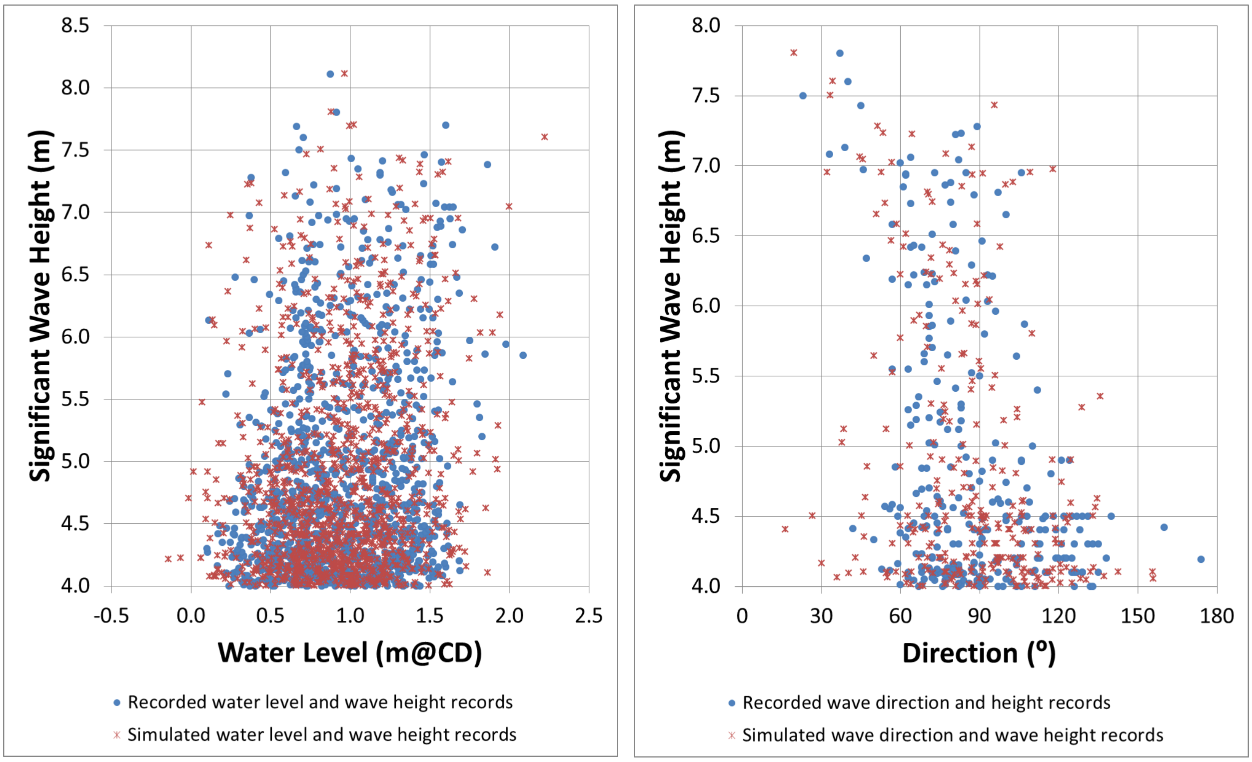


Figure 6.3: Simulated water levels (left) and wave directions (right) for dates when records are missing

6.3.2. Transformation nearshore

Wave heights were transformed to beach toes based on a wave profile model (see Section 6.7), with waves refracted based on Snell's law. Wave breaking was based on the formulation due to Goda (2010) with shoaling coefficients determined based on the methodology presented in Shuto (1974).

The results of this transformation for a typical nearshore profile is shown in Figure 6.4. This prediction point is approximately 1km offshore, about 10m below mean sea level.

These wave height records were then fitted to a univariate extreme-value non-homogeneous Poisson process to obtain extreme estimates of wave heights, see Coles (2001). The results for the representative profile are shown in Figure 6.5, together with the 95% confidence limits for this fit.

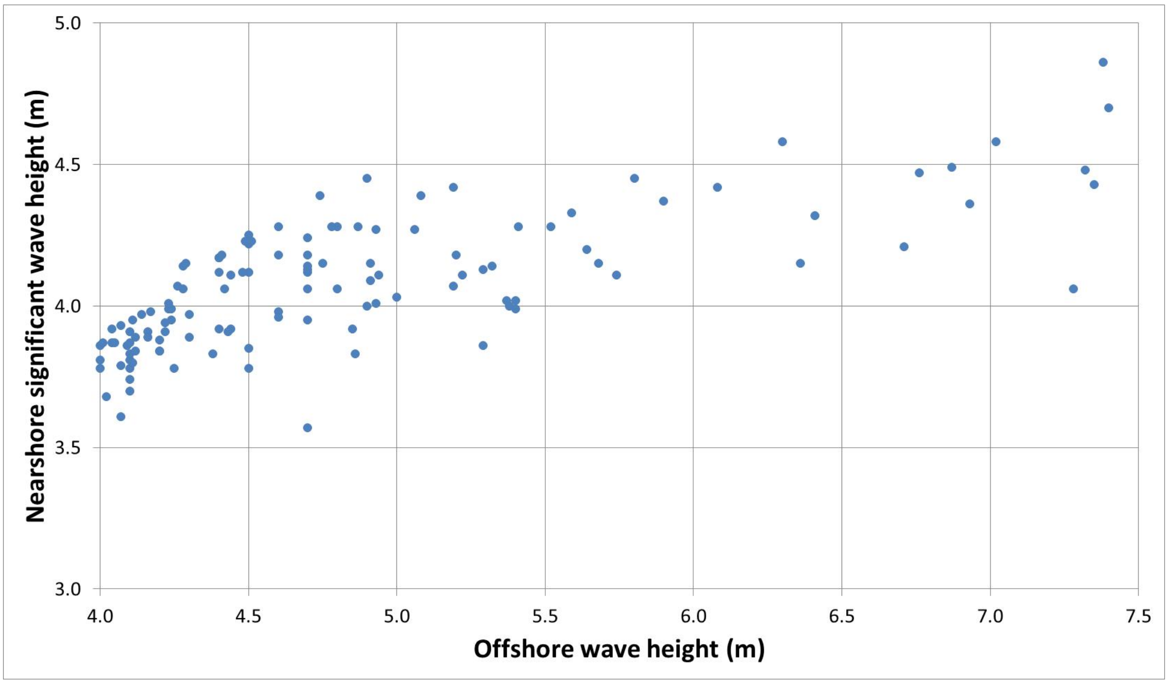


Figure 6.4: Transformed wave height records from offshore to nearshore conditions for a typical nearshore profile (at approximately the -10m seabed contour)

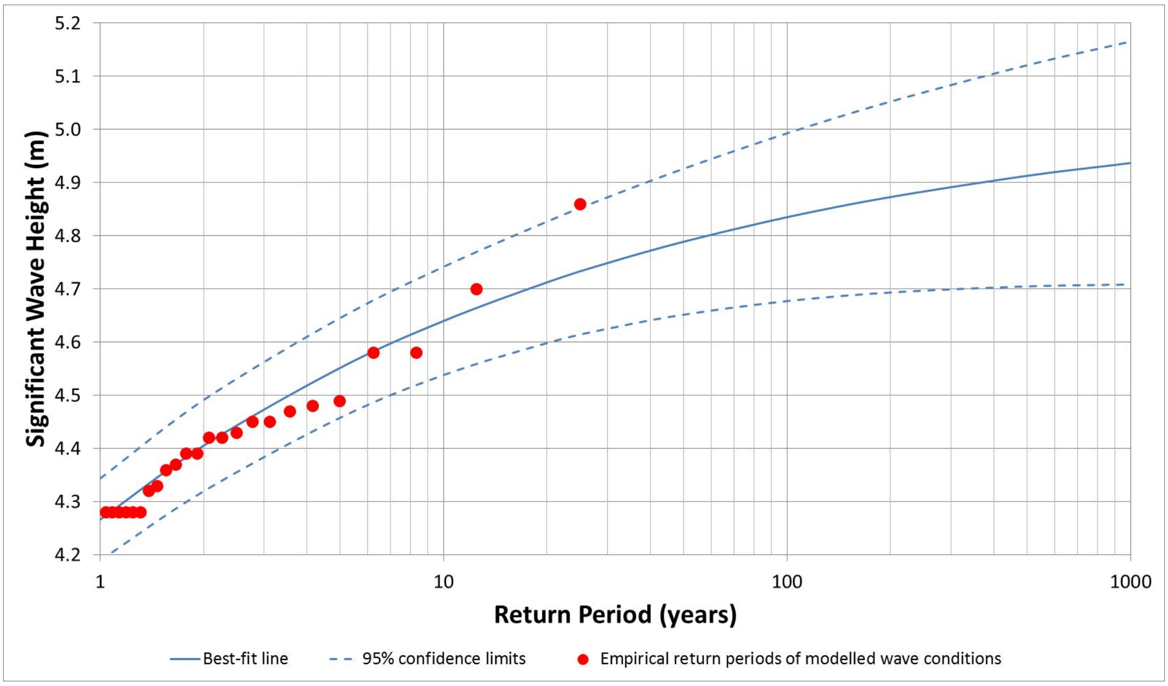


Figure 6.5: Extreme value estimates of wave heights for profile given in Figure 6.4, approximately 1km offshore (at approximately the -10m seabed contour)

6.4. Joint probability of waves and water levels

Water levels at the site are a combination of both an astronomic and meteorological component, with predicted tides based on the astronomic component only. During periods of low pressure, or strong onshore winds, these predicted tides can be increased, sometimes in excess of 1m or more, which is known as a storm surge, or a residual. This is something that occurred during Hurricane Sandy, with a storm surge in excess of 1m at Atlantic City. This can also be seen in the scatter plot in Figure 6.3, where there is a tendency for the largest waves to occur at the largest water levels.

For this study, with the relatively low tidal range and strong correlation of hurricane waves with significant storm surges, the main waves of interest occur close to the most extreme water levels. A joint probability assessment of waves and water levels is therefore not considered crucial. An assumption has therefore been made that waves and water levels are perfectly correlated, with a wave height of a given return period occurring at the same time as the water level of the same return period.

6.5. Sea level change

6.5.1. Scenario Assumptions

The scenario assumptions to test the sensitivity of Long Beach Island NJ to flooding under extreme events were based on the projected rates of sea level rise (see Figure 5.11) determined by the tidal gauge analysis carried out as part of the NACCS engineering studies. It was recognised that flooding (unlike say ecosystem response) would be sensitive to the magnitude but not the rate of sea level rise. For this reason, it was decided that the best way to span the range of scenarios was to examine some discrete magnitudes of sea level change and to this end sea level rise amounts of 1 ft, 3 ft and 6 ft were selected.

6.5.2. Impact on present day waves and water levels

In deep water, waves show little response to offshore bathymetry. As a result, waves are little changed as a result of rises in sea levels, particularly for the less extreme waves. For the profile considered in Section 6.3.2 at the -10m seabed contour for example, the effect on extreme wave heights is generally minimal for low return periods (Figure 6.5). However, for return periods greater than about 10 years, wave heights at this location can increase by approximately 15% for a rise in sea levels up to about 6ft. This is as a result of reduced interaction of these larger waves with the seabed bottom, and as a consequence, reduced levels of refraction and potential wave breaking.

However, on moving into shallower depths of water, wave breaking becomes a dominant factor and in extreme storm conditions maximum significant wave heights are typically limited to about 55% of the available water depth. If sea levels rise the available water depth increases and hence nearshore significant wave heights will also increase. (For example, whilst a wave height of 6.0m offshore might break down to 2.0m nearshore under present-day sea levels, if there were a 6ft (2.0m) increase in sea levels the resulting broken significant wave height would be expected to increase to 3.0m.) Extreme value estimates of nearshore wave heights can therefore be considered to be increased by up to 55% of the increase in sea levels.[6]

6.6. Overview of geomorphology of barrier islands

> Barrier beaches often form a natural flood defence to low-lying land behind them. However, man's chosen land-use, e.g. for residential and business properties, can often mean that the natural standard of defence afforded by the barrier is inadequate. Barrier beaches are often overtopped by large waves, they leak, can roll-back landward, and ultimately may breach. All of these events can give rise to unacceptably high flood-risks, and are likely to become more frequent as sea levels rise further. These flood-risks can justify intervention to improve the standard of protection that barrier beaches provide, but the natural heritage interests of such barrier beaches can constrain what type of intervention is acceptable.
>
> *Understanding Barrier Beaches. Stripling et al (2008)*

Barrier beaches such as Long Beach Island, NJ, are subject to rapid and large-scale changes in morphology during episodic extreme storm events, where overtopping and overwashing may occur resulting in large scale flooding. Due to the natural protection that barrier beaches provide to the extensive wetlands in the backshore, a large scale rollback of the barrier as a result of a single storm event could cause instantaneous loss of environmentally important intertidal areas. If the barrier island is developed the impact on such developments and built infrastructure could be major and even incur loss of life. A number of management techniques are generally used, such as recharge, recycling, beach scraping and hard structures.

Barrier islands are subject to both longshore and cross-shore processes and while the development of a barrier beach is linked to sea level rise, it is usually short term events that bring about change. Morphodynamic changes in barrier beaches are a result of wave and tidal conditions and associated sediment transport. By understanding these changes, an assessment of their performance as flood defences can then be carried out.

There are various factors influencing barrier morphology (Stripling *et al*, 2008): initial beach slope, berm formation, sediment characteristics, through flow (especially in gravel or mixed barriers), crest level, foreshore level, overstepping, overtopping, overwashing, breaching and inlet closure. However, according to Nicholls (1985), it is the crest level of a shingle barrier beach which is the most critical parameter in defining its stability and this crest level is dependent upon wave run-up and sediment availability. The crest level of the barrier islands under study is defined by the sand dunes at the back which are about 20 feet high.

Historically, the methods of study of barrier islands have consisted of a mix between aerial imagery, physical modelling studies, field investigations and numerical modelling. The Coastal Engineering Manual, Part III, presents a discussion of the application of a modified 'Bruun Rule' for barrier island migration in response to sea level rise (Dean and Maurmeyer, 1983). The Bruun rule has been widely adopted over the years (since Bruun, 1954) to predict the response of a beach profile to rising sea level. It states that as sea level rises, the shoreline retreats uniformly so as to maintain a constant equilibrium slope. The simplicity of the rule and its

---

[6] This assumption ignores any geomorphic response of the foreshore to long-term sea level rise. According to the Bruun Rule the foreshore would be expected to rise in concert with sea level. Consequently, the 55% increase in nearshore wave heights represents a worst case scenario.

assumptions has attracted many criticisms over the years (for example Cooper and Pilkey (2004)) but also many modifications to the rule, some of which are summarised in Table 6.2.

Table 6.2: Modifications to the Bruun rule

Author	Modification
Everts (1985)	Presented a sediment balance approach in order to quantify the effect of the re-adjustment of the profile to a new equilibrium one and separate the role of SLR from other causes of shore retreat. This was applied in Smith Island, Virginia, showing that the SLR accounts for about 53 per cent of the total retreat of 5.5 m/yr measured. In the barrier island south of Oregon Inlet, North Carolina, it accounted for about 88 percent of the measured 1.7 m/yr retreat. However, the method needs to be improved, testing the equilibrium shoreface assumption on progradational and uplifted shores.
Pilkey and Davis (1987)	Tested the simple recession models using the North Carolina barrier island shoreline as the test area. The models they tested were the Bruun, the Edelman and the Generalised Bruun rule, concluding that better models are needed, especially for shorelines where recession is part of the barrier island migration process.
Zhang et al (2004)	Presented a mathematical derivation of the Bruun model and applied the model to the U.S.. East Coast (as there is data on shorelines and sea level rise for over a hundred years). The coast is divided into five different compartments and shoreline segments influenced by inlets identified and removed as well as shoreline segments influenced by coastal engineering projects and lateral spits. The shoreline change and SLR for each compartment are then presented, finding that the ratio of shoreline change to the rate of SLR varies from about 50 to 150. Although the variability of the results among compartments is large and they recognised it needs addressing, they considered that the Bruun rule has been validated.
Coastal Impact Module (CIM) of SimCLIM (CLIMsystems, 2007)	A computer-based tool that can simulate the behaviour of the shoreline in response to particular scenarios of sea-level change in an stochastic manner. Although it addresses several of the concerns about the Bruun rule, these approaches address shore profiles and are not tools designed to yield specific geographical information about the pattern of shoreline response (Abuodha and Woodroffe, 2010).

Source: HR Wallingford

Ranasinghe and Stive (2009) questioned the use of the Bruun rule for predictions of future coastal recessions, arguing that the main assumption that all transport occurs perpendicular to the shore makes it inapplicable in most places (using Zhang et al (2004) as an example where 70 per cent of the study area, the US East coast, was excluded due to the influence of inlets and engineering structures). They advocated a robust solution to the problem by relying on comprehensive bottom-up (small scale, process-based) and top-down (large scale, behaviour-based) numerical models, comprehensively validated by field data.

For this study, a mixture between a very good source of field data provided by the NJBPN programme (Stockton, 2012) and a simple dune empirical model has been considered the most appropriate approach to the prediction of the morphology of the system, as explained in Section 6.7.

6.7. Beach/Dune profile modelling

The response of the beach and dune profile to the sea level and wave conditions Section 6.3 has been carried out by using a simple empirical model adapted from the DUROS+ model (van Rijn, 2013). DUROS+ predicts the eroded dune profile based on Vellinga’s (1986) model and later improved by others (Deltares, 2007); all of them based on several experiments carried out in the large-scale Deltaflume of Delft Hydraulics over the years. The adaptation of the empirical model to the case of Long Beach Island, NJ, has been carried out based on the measured dune profiles before and after Sandy measured by the Richard Stockton College of NJ Coastal Research Centre (CRC) (Stockton, 2012) as part of their 24 year old New Jersey Beach Profile Network (NJBPN) monitoring programme. The empirical model has been chosen due to its simplicity and relatively good fit to the available data. The adaptation of DUROS+ is justified as the experiments carried out in the Deltaflume were designed for dune profiles along the Dutch North Sea Coast and the forcing conditions were such that erosion was maximised. The background of the empirical model, the adaptation of the model to Long Beach, NJ and its validation are shown in Appendix C.

In essence, the dune erosion profile as calculated by the adapted empirical model has three parts:

- From the limit of the run up upwards: the erosion profile adopts a slope of 1V:3H until it meets the original profile; and
- From the limit of the run up downwards up until the maximum reach: the profile adopts an exponential form, where the wave height, wave period, as well as the sediment size have an influence on the shape of this curve and the storm surge level determines the position of it.
- From the maximum reach downwards until the intersection with the original profile, the erosion profile adopts a 1V:12.5H slope.

The validation of this methodology was carried out with profiles that had received a renourishment and not before Sandy occurred and with both failed and non-failed profiles, as described in Appendix C. However, for the predictive phase, only one profile, considered as representative of a replenished profile was used. The decision of only doing one profile along the site was further reinforced by the sensitivity analysis on the overtopping rates of different profile geometry parameters (see Section 6.7.1). This analysis shows the change in overtopping rates along Long Beach Island, NJ for the 1:100 year conditions, using different values of crest height, toe level, beach slope and nearshore wave height.

A uniform sediment size of 0.152 mm was assumed along the profile, this value being considered as representative of the conditions along Long Beach Island. The input hydrodynamic conditions were taken from the extreme water levels and nearshore waves described in Sections 6.2 and 6.3. The predicted run-up (exceeded by 33 per cent of the waves) necessary for the empirical model was calculated following van Rijn (2008), as described in Appendix C. The values for each of the return periods considered are given in the Table 6.3 below.

Table 6.3: Calculated run-up levels under different return-period conditions

Return period	Run up level (m)
1:1	1.98
1:10	2.38
1:30	2.49
1:100	2.56
1:1000	2.64

Source: HR Wallingford

Two different scenarios were modelled:

- Nourishment to keep pace with sea level rise; and,
- No additional nourishment.

Scenario 1: Nourishment to keep pace with sea level rise

For this scenario, the initial profile remained effectively unchanged to the Mean Sea Level (MSL) at the time, assuming that the renourishment will be such that the profile will be maintained. Although this assumes that the submerged part of the profile is also renourished and in general assumes a bigger nourishment than that needed in reality, it is preferable as no further assumptions on the volume and placement of the renourishment need to be made.

The response of the profile to the five different return periods was carried out. As the profile has been maintained to MSL , the profile response to three different sea-level rise scenarios is the same. Figure 6.6 below shows the predicted profile under the 1:1000 yr condition. The modelled dune cuts back but not to a level in which the crest can be considered to fail.

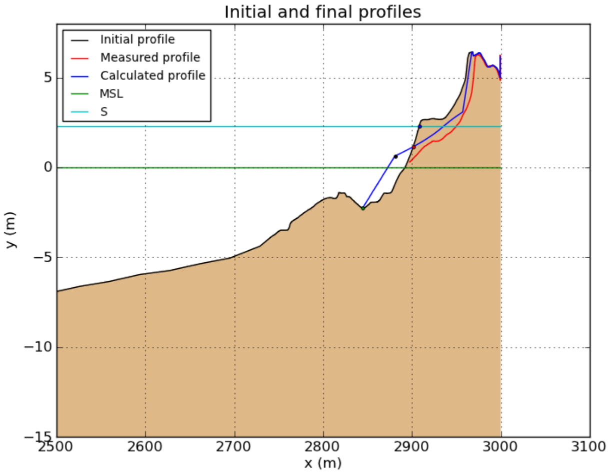


Figure 6.6: Modelled profile response to a RP1:1000 event

Source: Note that the measured profile in the figure is the post-Sandy measured profile and shown only for comparison purposes.

The modelled profile responses were then used as an input to the overtopping discharges Section (6.8).

Scenario 2: No nourishment

For this scenario, the initial profile gets submerged by the sea level rise assumed under the three different scenarios described in Section 6.4.1. The five different return period combinations of surge level and wave conditions have been modelled in the same way as in the assumption of nourishment to keep pace with sea level rise. The results of profile response are shown in Figure 6.7 to Figure 6.9.

For the SLR = 1 ft, the behaviour of the profile response is quite clear: as the event gets more extreme, the dune cuts back more, with the foreshore of the dune also moving landwards. This displacement marks the behaviour of the overall crest which will be at the position where the initial profile is intersected. As erosion in the top part of the profile increases, the accretion at the bottom part increases in order to maintain a mass balance.

Some of this behaviour is maintained within the response of the profile to the SLR = 3 ft scenario. However, the DUROS empirical model seems to include or generate a threshold behind which the foreshore of the dune cannot go back anymore; this seems to happen at a RP of 1:10. Therefore, for more extreme conditions, only the erosion of the exponential profile changes and therefore so does the consequent accretion at the submerged part of the profile. This “threshold” or constraint on dune recession is unexpected and is to some extent questionable.

In the case of the highest SLR scenario (SLR = 6 ft), all the profiles seem to have reached this threshold and therefore the foreshore of the dune does not change much.

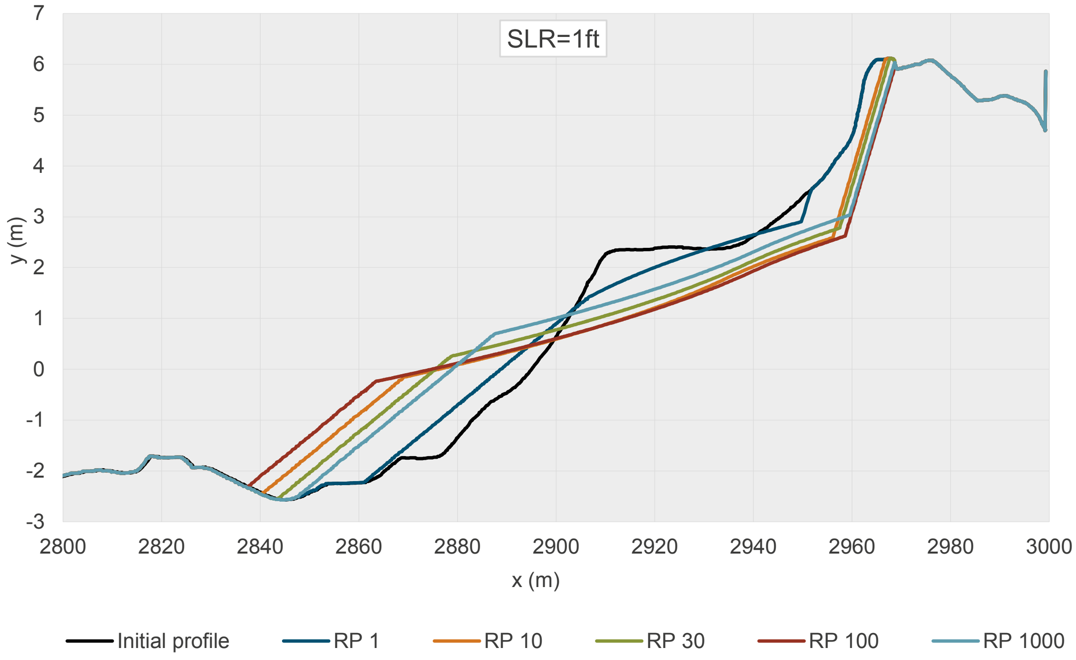


Figure 6.7: Modelled profile response to a range of RP events. SLR = 1 ft scenario

Source: HR Wallingford

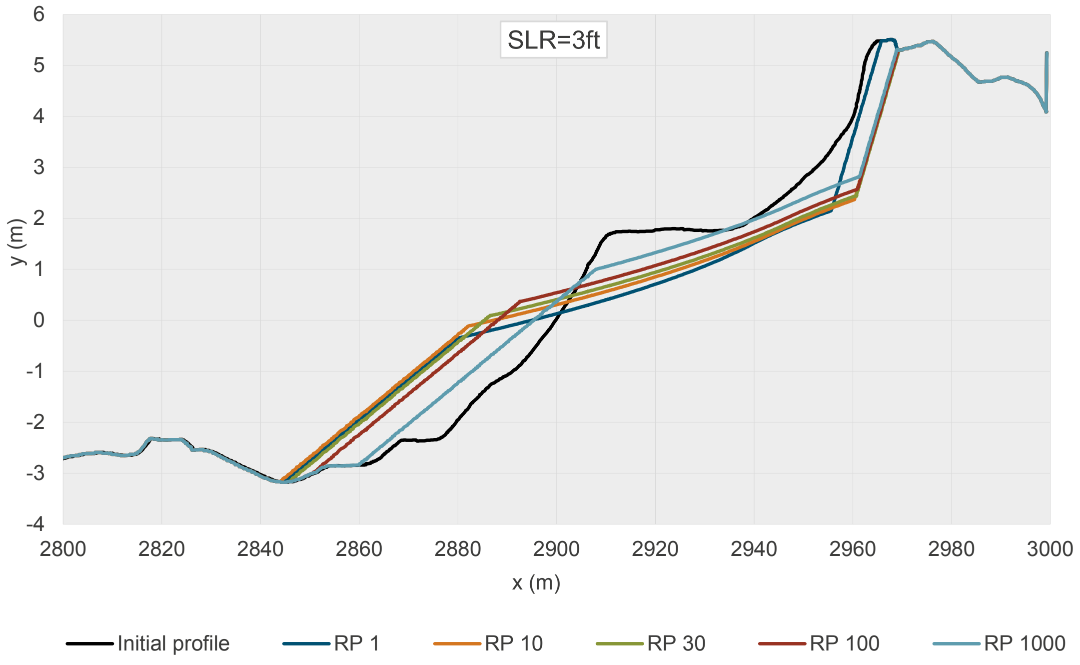


Figure 6.8: Modelled profile response to a range of RP events. SLR = 3 ft scenario

Source: HR Wallingford

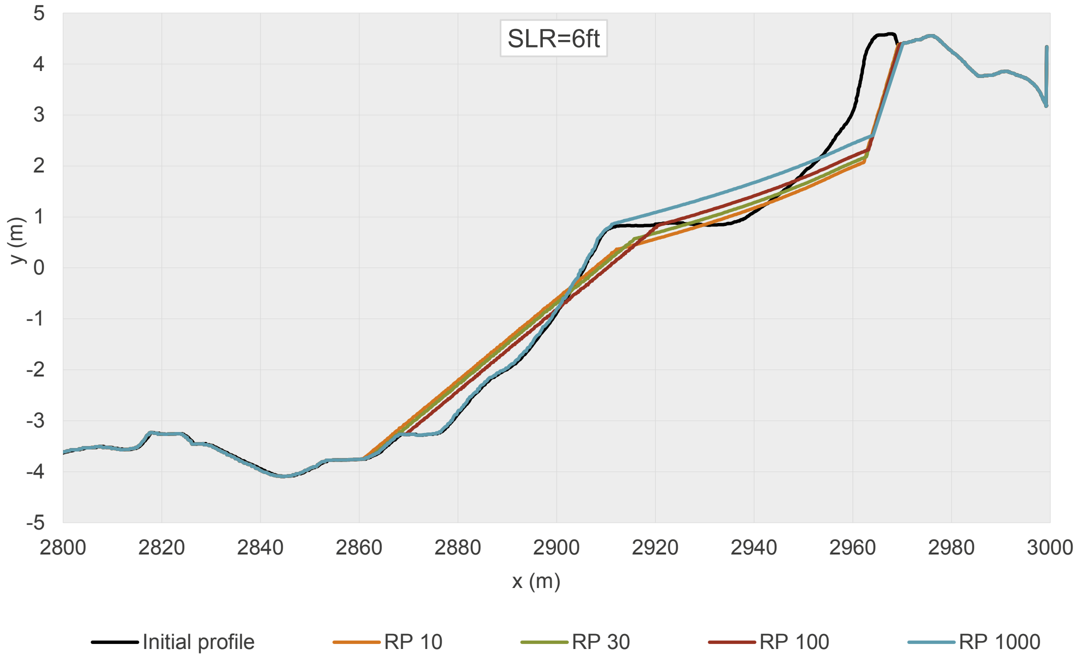


Figure 6.9: Modelled profile response to a range of RP events. SLR = 6 ft scenario

Source: HR Wallingford

6.8. Overtopping discharges (Atlantic seaboard)

During periods of significant wave action, significant overtopping of coastal defences can occur. This is most pronounced when they occur at the same time as the largest, most extreme water levels, particularly around the time of high water. As it is not possible to calculate overtopping rates based on coastline characteristics, they are therefore determined from empirical formula, primarily as a result of model experiments. With an infinite range of defence configurations, these are therefore presented for idealised defence sections, with overtopping rates interpolated from these results.

Based on data and published guidance from a number of countries, Pullen *et al.*, (2007) gives guidance of overtopping rates for a range of idealised defence sections. This guidance, commonly known as the EurOtop manual, has therefore been used in this report to assess overtopping rates. These have been estimated based on the modelled profile responses to the different storm return period events and sea level rise scenarios outlined in Section 6.5. This has been carried out for a representative replenished profile only as outlined in Section 6.7.

Figure 6.10 and Figure 6.11 show sample idealised sections for this profile for a 1 in 100 year storm event with 0 ft rise in mean sea levels (present day) and for a 6 ft rise in mean sea levels (see Section 6.7). These sections have been idealised as a simple sloping defence as defined in the EurOtop manual, with defence parameters defined based on the crest height, toe level and the beach and structure slope.

Overtopping of the defences are based on the wave height at the structure toe, with waves assumed to break and shoal using the same methodologies as outlined in Section 6.3.2.

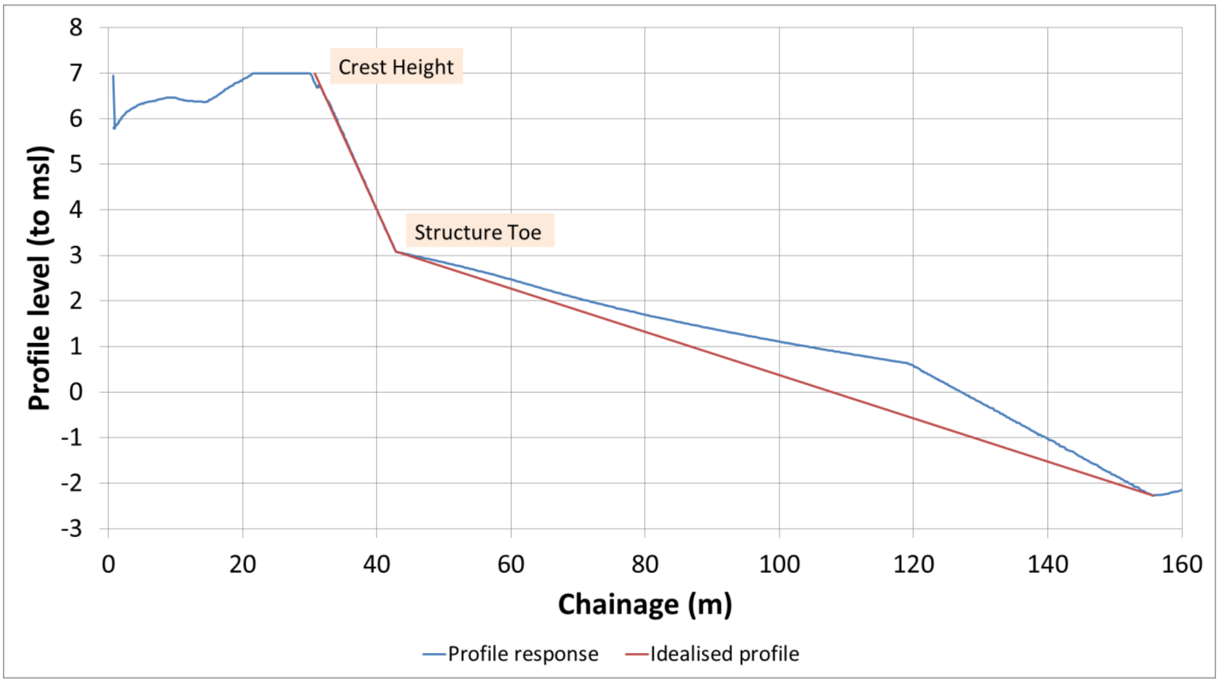


Figure 6.10: Idealised section for representative replenished profile for 100 year return period event with 0ft of sea level rise

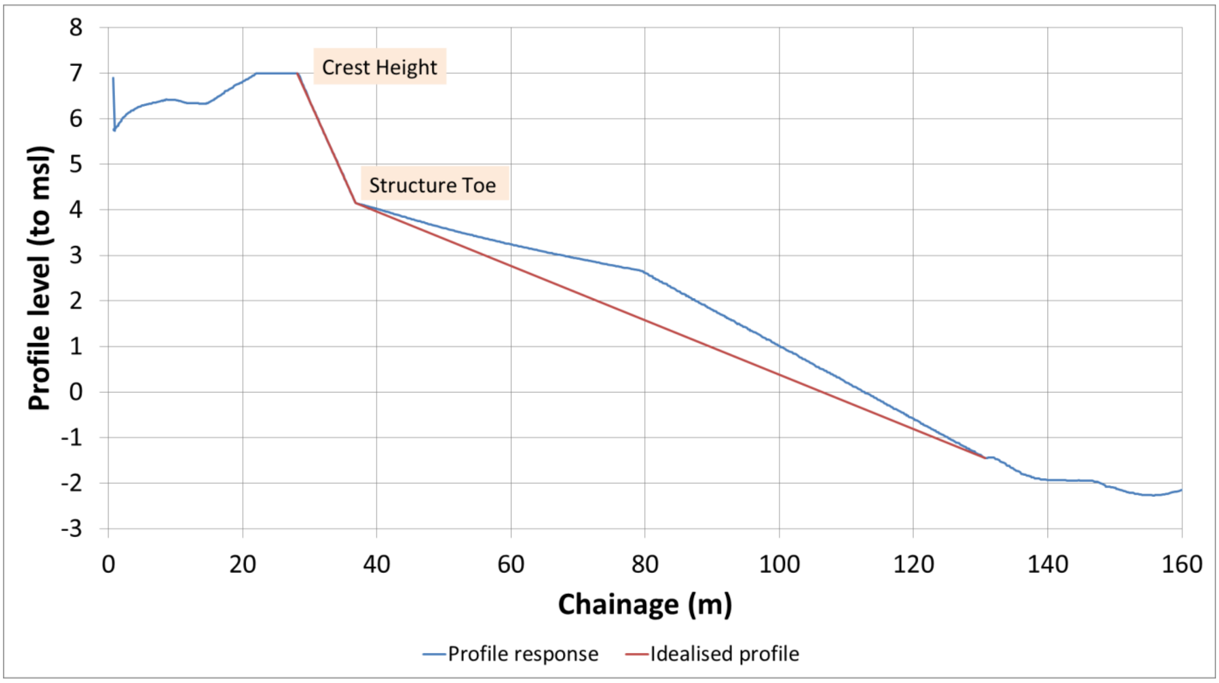


Figure 6.11: Idealised section for representative replenished profile for 100 year return period event with 6ft of sea level rise

Table 6.4 shows the results for a representative replenished profile for the different return periods and sea level rise scenarios. These are for the peak overtopping rates, corresponding to high water conditions. However, large overtopping rates can be maintained over a large part of the tidal cycle. Figure 6.12 therefore shows the overtopping rate over a full tidal cycle for this profile for the 1 in 100 year event for the different sea level rise scenarios considered. This is based on the sea level profile observed for Hurricane Sandy, which maintained a relatively constant high water for the two hours prior to high tide, with little change in water levels over a five hour period around high water. This figure highlights the significant levels of overtopping that takes place during periods of large wave action. At low water, overtopping rates are typically still 15-35% of peak overtopping rates for the preceding low water, and up to 20% for the succeeding low water. This suggests that significant levels of wave overtopping would be anticipated for the duration of any storm event, probably three or four days.

Table 6.4: Peak overtopping rates for representative profile for different return periods and sea level rise scenarios.

Return Period	Sea level rise scenario			
	0 ft	1 ft	3 ft	6 ft
1	0.001 m^3/s/m	0.008 m^3/s/m	0.181 m^3/s/m	0.871 m^3/s/m
10	0.059 m^3/s/m	0.196 m^3/s/m	0.403 m^3/s/m	0.958 m^3/s/m
30	0.189 m^3/s/m	0.271 m^3/s/m	0.505 m^3/s/m	1.155 m^3/s/m
100	0.247 m^3/s/m	0.303 m^3/s/m	0.656 m^3/s/m	1.286 m^3/s/m
1000	0.382 m^3/s/m	0.549 m^3/s/m	0.964 m^3/s/m	1.523 m^3/s/m

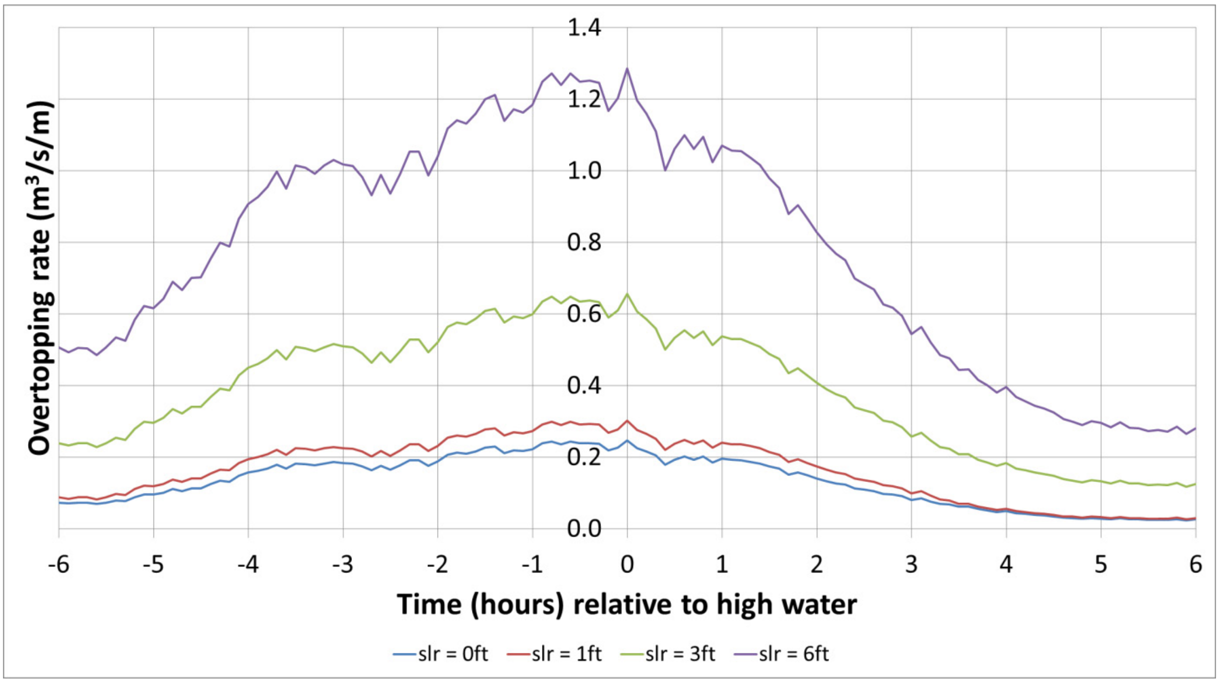


Figure 6.12: Overtopping time series over a tidal cycle for a 1 in 100 year return period event for different sea level rise (slr) scenarios

6.8.1. Sensitivity assessment on structure and design conditions

As noted in Section 6.8, overtopping rates have only been determined for a representative replenished profile which has been used for setting the boundary conditions in the inundation modelling (Section 6.9). In order to evaluate the impact of this simplification, a sensitivity analysis has therefore been carried out by considering the effect of changing different parameters. The parameters considered are outlined below, together with the changes considered.

Crest height	up to 0.5m;
Toe level	up to 0.5m;
Nearshore wave height	up to 50% (keeping wave steepness constant);
Beach slope	from 1 in 10.

These changes have been considered for the 1 in 100 year event only, considering current day events only (i.e. no sea level rise).

Table 6.5 shows the variation in peak overtopping rates for a change in crest and toe level of up to ±0.5m. These results indicate that in general, the change in toe level has the greater effect on reducing overtopping rates. This reflects the relatively high toes of these profiles, which means that waves approach the toe of the dunes in relatively shallow water. This results in wave energy lost to wave breaking before impacting the dunes. This effect is more pronounced for higher toe levels, although as toe levels reduce by more than about 0.5m from the representative profile, the change in the crest level starts to have a greater effect.

Increasing the wave height by 50%, and keeping the wave steepness constant was noted to approximately double peak overtopping rates for no change in toe level, although this was noticeably greater for higher toe levels. This was noted to be a result of the waves starting to swamp the defences, even with a high toe, resulting in the defences having less effect on the wave processes at these significant overtopping rates. The same effect was noted for beach slopes less than the current estimate of 1 in 21 beach slope used for the representative replenished profile, with overtopping rates again approximately doubling for a 1 in 10 beach slope.

Overall, the large wave heights and corresponding water levels relative to dune toe levels mean that the structure toe is the main factor that has the most significant effect on overtopping rates. With dune toe levels in the region of between 2.5m to 3.5m above msl, the dunes will always be exposed to significant wave action under design conditions. However, a higher toe level with would be expected to result in significant amounts of wave energy lost before the waves impact the dunes, even with a relatively steep beach. Considering an increase in toe level to 2m therefore would result in minimal overtopping rates regardless of any significant change in any other parameter considered (i.e. crest height, beach slope or wave height). In these cases, nearly all the wave energy would be lost on the beach as the wave approaches the dunes, and the defences, as they are currently, would not get swamped.

Table 6.5: Variation in peak overtopping rates for different structure crest heights and toe levels (based on 1 in 100 year event, for no sea level rise).

Toe level (to msl)	Crest height (to msl)				
	6.5m	6.8m	7.0m	7.2m	7.5m
2.58m	0.449 m^3/s/m	0.374 m^3/s/m	0.330 m^3/s/m	0.292 m^3/s/m	0.243 m^3/s/m
2.88m	0.407 m^3/s/m	0.335 m^3/s/m	0.294 m^3/s/m	0.259 m^3/s/m	0.213 m^3/s/m
3.08m	0.348 m^3/s/m	0.283 m^3/s/m	0.247 m^3/s/m	0.216 m^3/s/m	0.176 m^3/s/m
3.28m	0.292 m^3/s/m	0.235 m^3/s/m	0.203 m^3/s/m	0.176 m^3/s/m	0.142 m^3/s/m
3.58m	0.215 m^3/s/m	0.169 m^3/s/m	0.144 m^3/s/m	0.123 m^3/s/m	0.097 m^3/s/m

6.9. Inundation modelling

6.9.1. Calculation of the inflow hydrographs

The overtopping rates have been calculated as part of a separate task for one beach profile (profile 141). This has been done for 5 Return Periods (1y, 10y, 30y, 100y, 1000y) and 4 Sea Level Rise (SLR) scenarios (no SLR, 1 ft SLR, 3 ft SLR, 6 ft SLR).

Various assumptions about overtopping duration could have been made as part of this conceptual modelling. In this particular case, it was assumed that the sand dune cut-back occurs at the peak of the event and that prior to cut-back the greater volume and width of the existing dune and its flatter seaward profile would absorbed the majority of the wave energy without overtopping. We therefore only consider the 24 hour time frame that follows the peak of the event for the purposes of the inundation modelling (bold red line in Figure 6.13. The hydrograph is transformed into a simplified shape (6 points per wave period) to simplify the model setup (green line in Figure 6.13).

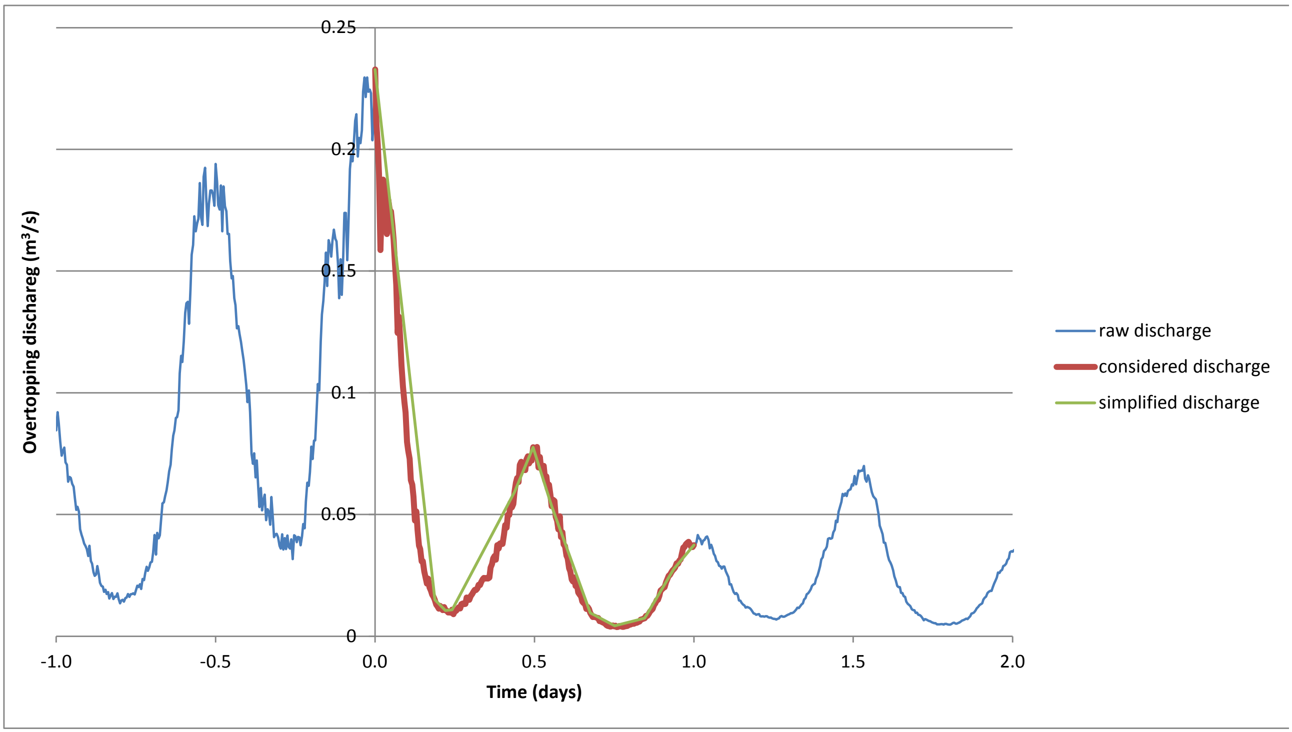


Figure 6.13: Example overtopping hydrograph, use of the 24 h period after the peak of the event .

6.9.2. Setup of the model mesh

The computational mesh to be used for the inundation simulation is generated by the pre-processing tool AccData (revision 26637).

AccData identifies the key topographic features in the input digital terrain model (DTM) and uses those to create the computational mesh for RFSM-EDA (see Jamieson *et al.* 2012a-b). The mesh is made of irregular polygons called the Impact Zones (IZs). AccData also calculates the characteristics of the IZs (neighbours, interfaces, storage).

The DTM available for this project has a 10 m horizontal resolution and is a filtered DTM (the buildings have been removed from the grid).

Although Long Beach Island has overall a large surface, it is a narrow piece of land (between 300 to 1,000 m wide approximately), and this requires to have relatively small IZs so that the inundation spreading can be captured appropriately, in particular along the direction perpendicular to the shore.

In this analysis, AccData was configured to create a relatively fine mesh (Table 6.6 and Figure 6.14).

Table 6.6: Parameters for AccData pre-processing

Parameter name	Parameter value
IZMinDepth (m)	0.0
IZMinSize (m^2)	1,000.0
IZMaxSize (m^2)	2,500.0

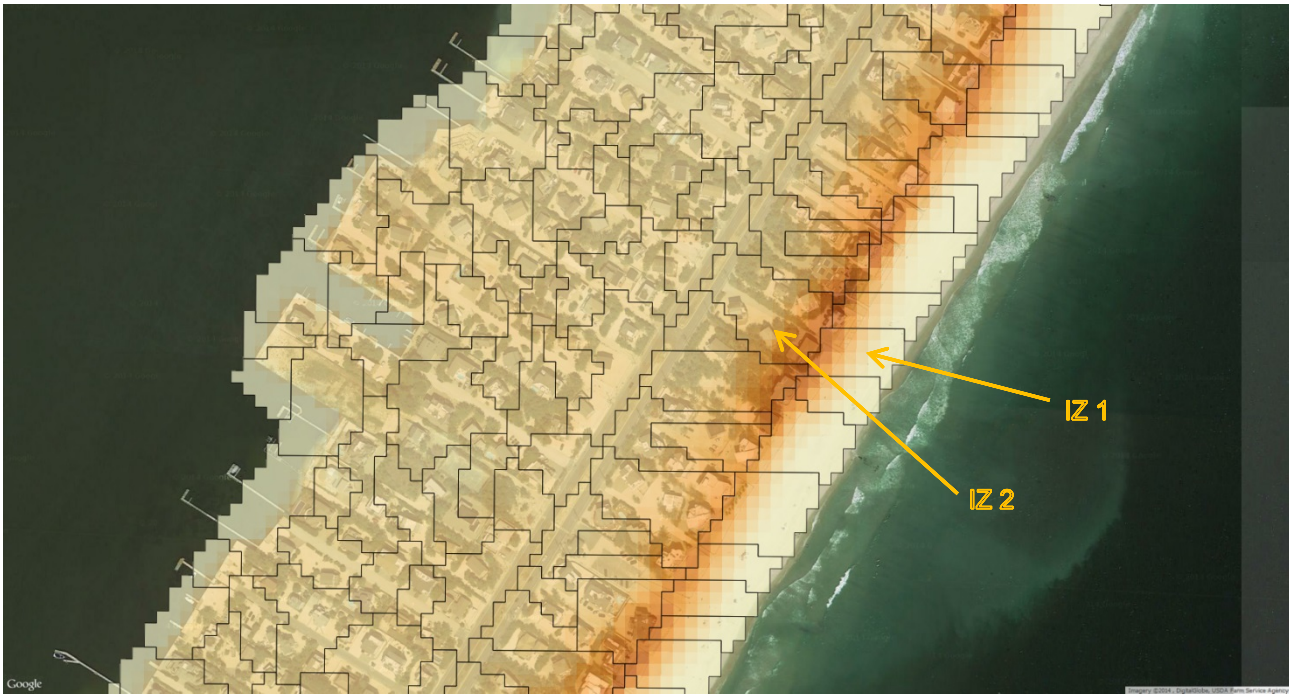


Figure 6.14: View of the computational elements (IZs, black polygon lines) generated by AccData

6.9.3. Configuration of the Boundary and Initial Conditions

The overtopping hydrographs are treated as discharge boundary conditions and these are applied to the IZs behind the crest of the sand dune (for example IZ 2 instead of IZ 1 in Figure 6.14). This is because the row of IZs along the Atlantic shore actually represent the beach areas, the dune and beach were already taken into account in the erosion and overtopping calculations.

As the simulation starts from the peak of the event, the initial discharge is a high value (in most scenarios, cf. Section 6.9.1) and this is not satisfactory from the point of view of model stability. It is necessary to have a "warming up" period at the start of the simulation before reaching the discharge boundary condition described in Section 6.9.1. Therefore the hydrographs are shifted by a duration of 200 s and start at a value of 0.0 m^3/s to minimize computational errors (Figure 6.15).

A level boundary condition is applied to the backshore of Long Beach Island to represent floodwaters spreading across the island and then spilling into the lagoon. In this study, a constant value is applied along the whole backshore for the whole duration of an event. This constant level value is calculated as the average sea level over the 24 h that follow the peak of the event (similar to Section 6.9.1) for each scenario (combination of RP and SLR). The sea levels used for this averaging are the same as those from Barnegat Inlet with an adjustment of 0.3m to reflect local conditions. Similarly to what is described above for the discharge boundary conditions, a "warming up" period of 200 s is used for the level boundary conditions along the backshore.

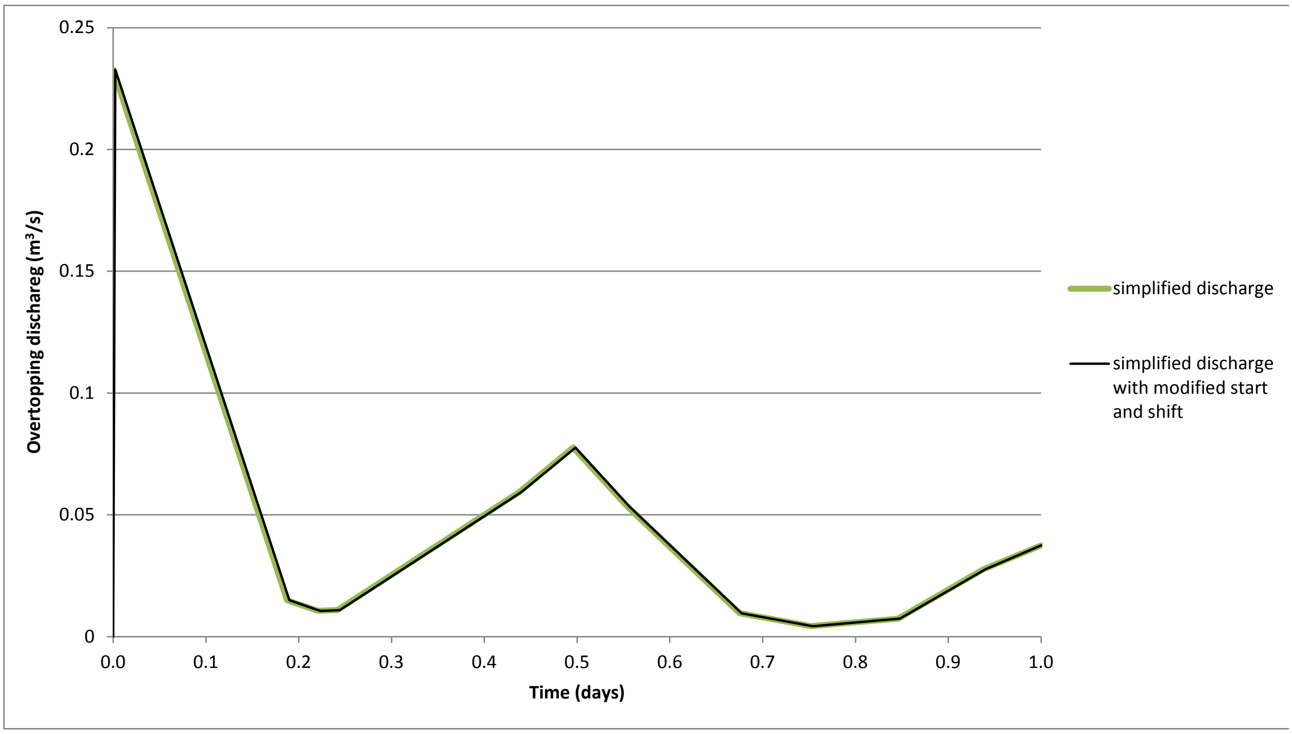


Figure 6.15: Modified Boundary Conditions to avoid model instabilities

6.9.4. Inundation model runs

The inundation model used in this study is the RFSM-EDA (revision 28103) developed at HR Wallingford. RFSM-EDA is a computational engine for the simulation of inundations, described in Jamieson *et al.* (2012a-b). It is designed to run efficiently at all scales, providing depth and velocity outputs with short runtimes. Its algorithm allows to account for the key topographic features (crests, low points, storage) derived from a fine resolution DTM while using relatively large computational elements, hence allowing fast runtimes with a good accuracy.

The algorithm in the RFSM-EDA is based on the ‘inertial’ equations (Bates *et al.*, 2010), i.e. the shallow water equations are used in a simplified form with the advection term removed. This is implemented as an explicit scheme with adaptive time-stepping (based on the Courant condition). The algorithm described in Bates *et al.* (2010) have been modified to account for the non-linear relationships between water level, cell volume and wetted interface conditions (Jamieson *et al.* 2012a-b). The RFSM-EDA has been compared to a range of 2D models as part of the Environment Agency (UK) “2D Benchmark” and has been shown to produce predictions of water levels and inundation dynamics (velocities) comparable with those of the full SWE models at least in situations characterised by low momentum and/or slowly varying flow conditions (Environment Agency 2013). In other words the RFSM-EDA can be used reliably for most flooding situations except for dam-break type flows.

The model setup is stored in a SQL database and is made of:

- The files generated by AccData that describe the mesh of IZs (cf. Section 6.9.2);
- The input files entered by the modeller for the definition of BCs and ICs (cf. Section 6.9.3).

A XML file contains the definition of the computational parameters (algorithm options and time-step management) and the outputs selection and frequency. A summary of the parameters used in this study is shown in Table 6.7.

Table 6.7: Computational and temporal parameters used for the RFSM-EDA runs

Parameter name	Parameter description	Parameter value
StartTime (h)	Simulation start time	0
EndTime (h)	Simulation end time	24
SaveTimeStep (min)	Time interval between outputs writing	15
TimeStep (s)	Initial time step	0.2
MaxTimeStep (s)	Maximum time step	5
MinTimeStep (s)	Minimum time step	0.01
ManningGlobalValue	Friction value used on the whole domain	0.0167
MinDepth (m)	Minimum depth at interfaces for flux calculation	0.0005

6.9.5. Model outputs and post-processing

The output data from each simulation is stored on a SQL server (same database as the input data). Water level, water depth, velocity magnitude and direction are produced by the RFSM-EDA. The output data can be extracted and converted into a GIS-ready format by a dedicated post-processing tool (revision 28211). An example of the maximum flood depth map is shown in Figure 6.16.

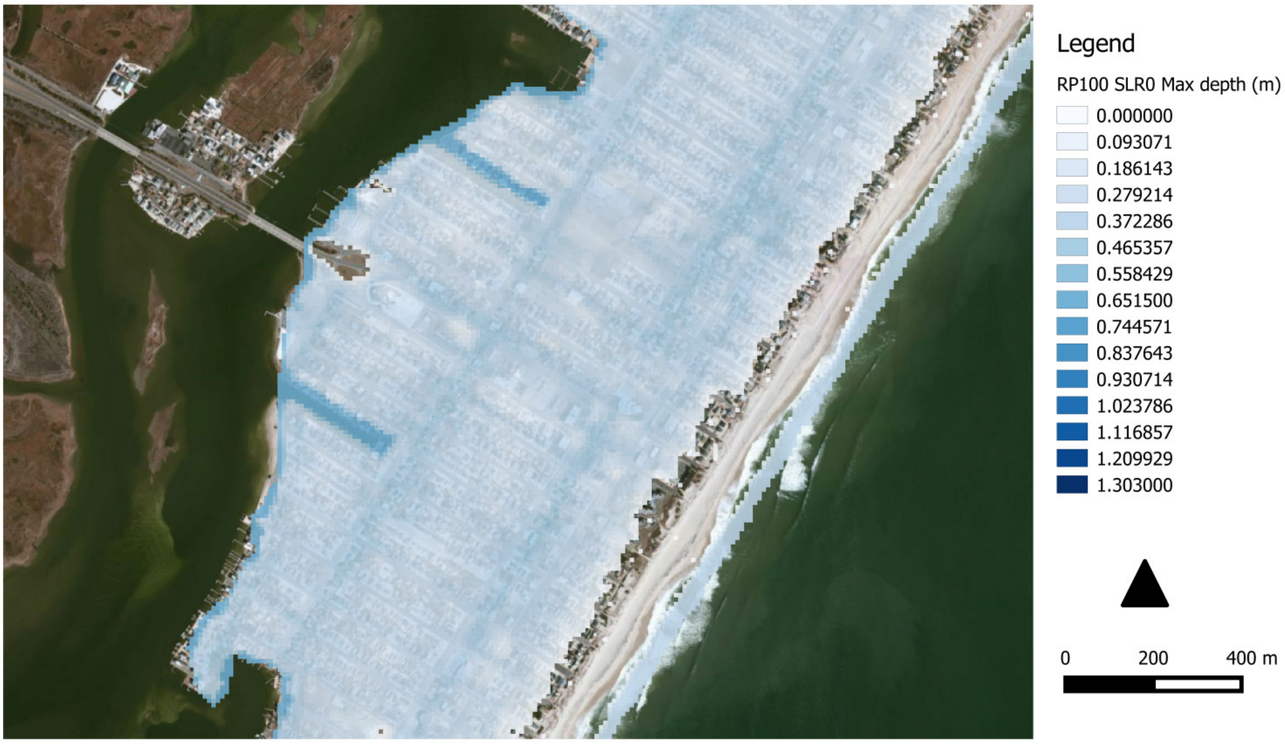


Figure 6.16: Map of the maximum flood depth for the scenario RP 100 y, SLR 0 ft

6.10. Inundated area as a function of depth for different sea level rise scenarios

The inundation outputs (maximum flooded depth) have been processed to generate plots of the inundated area as a function of depth for different sea level rise scenarios. These plots indicate the proportion of the island area that is underwater for different values of flood depth (Figures 6.17, 6.19, 6.21 and 6.23). The same analysis has been done looking only at the flooded depths on the road network (Figures 6.18, 6.20, 6.22 and 6.24). This can be useful to look at emergency access during the event. The differences between the plots for the whole island and the plots for the road network appears to be minimal.

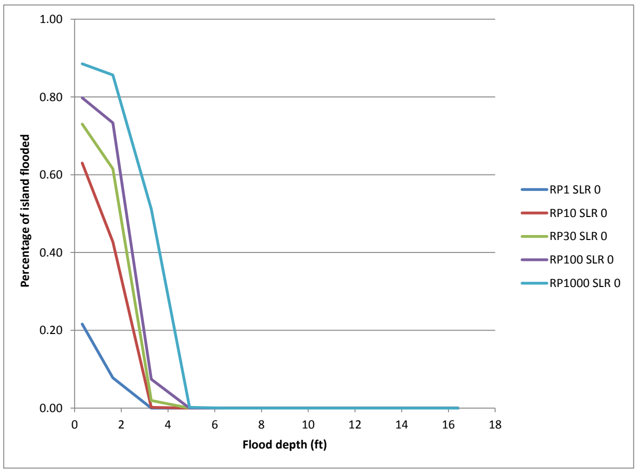


Figure 6.17: Inundated area as a function of depth for the whole island (SLR 0 ft)

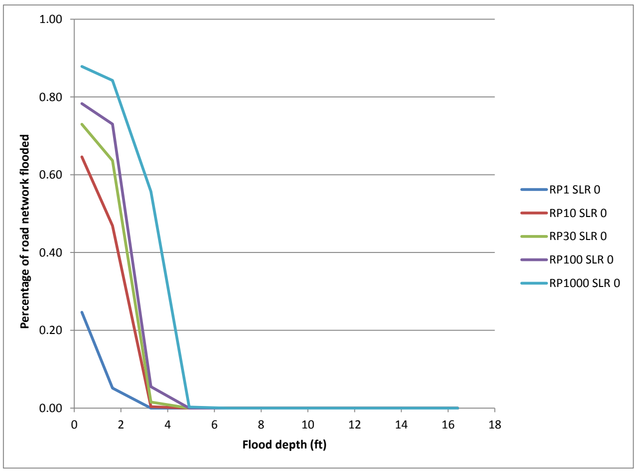


Figure 6.18: Inundated area as a function of depth for the road network (SLR 0 ft)

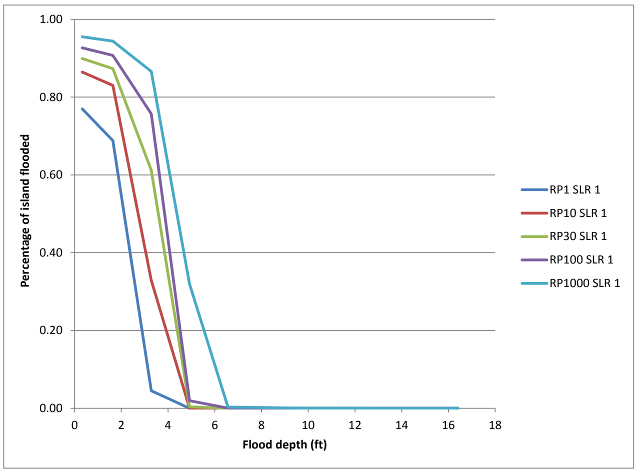


Figure 6.19: Inundated area as a function of depth for the whole island (SLR 1 ft)

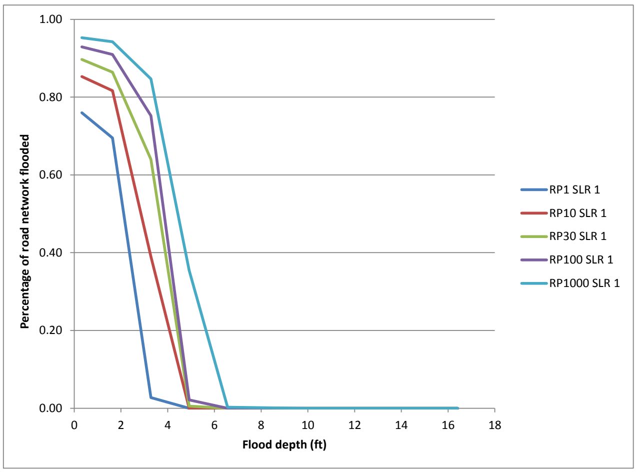
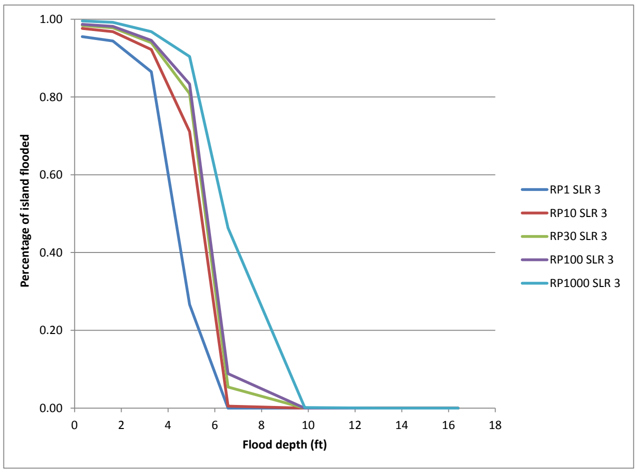


Figure 6.20: Inundated area as a function of depth for the road network (SLR 1 ft)



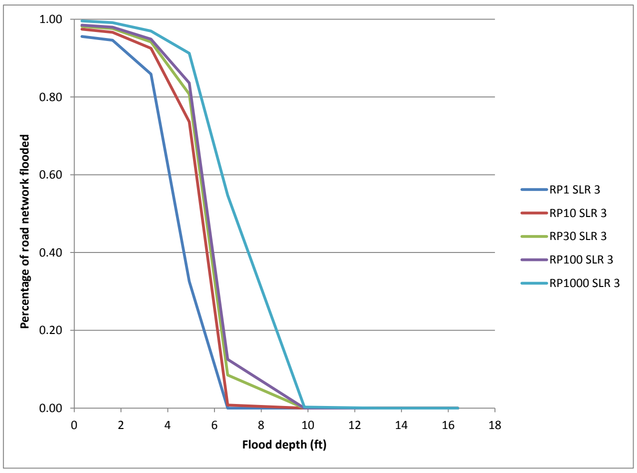
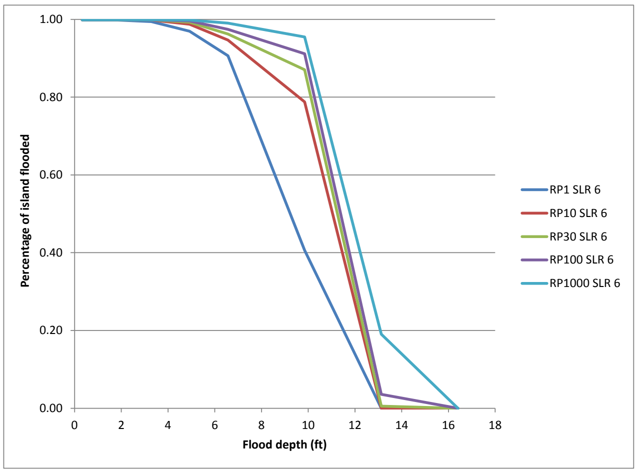


Figure 6.21: Inundated area as a function of depth for the whole island (SLR 3 ft)

Figure 6.22: Inundated area as a function of depth for the road network (SLR 3 ft)



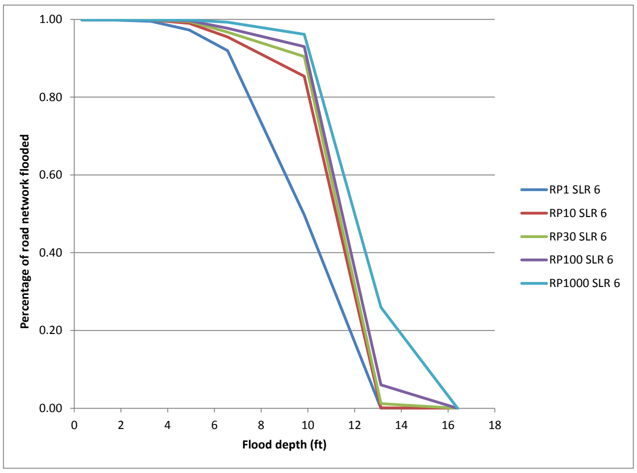


Figure 6.23: Inundated area as a function of depth for the whole island (SLR 6 ft)

Figure 6.24: Inundated area as a function of depth for the road network (SLR 6 ft)

The vulnerability of the island road network to back bay flooding even during relatively modest storms (1 year return period) is apparent from this analysis. Whilst less than 20% of the road network are flooded on such annual storms at the moment and only to an average depth of about a foot, just a foot of sea level rise increases this to about 70% with some roads flooded up to 4 feet. At a sea level rise of 3 feet the road network becomes unusable.

6.11.Risk calculations

6.11.1. Method description

The damage calculation has been done on Long Beach Island using a tool developed at HR Wallingford for the estimation of the impact of flooding. The tool can also do a simple calculation of potential loss of life but this has not been done here.

The damage calculation is based on the use of depth-damage functions associated with buildings. For each scenario (return period, sea level rise), the map of maximum depth is combined with the depth-damage function in each grid cell to calculate a damage value. Individual cell damages are summed to give a total damage on the island.

For simplification all buildings on the island have been treated as residential properties (type RES1-1SNB Residential 1 storey no basement as used by USACE). On a more detailed study, properties would be classified according to the full range of property types (i.e. the 40 types defined by USACE and used in HEC-FIA).

6.11.2. Data source and processing

There was no GIS layer of the buildings readily available for Long Beach Island (for example OpenStreetMap has only a handful of buildings digitised on the island). Instead a vector layer of the parcels has been used (downloaded from http://geoportal.njtpa.org:8080/geoportal/) to estimate the location and number of properties on the island (Figure 6.25). In total 20,117 parcels have been considered.

The depth-damage function used here for type RES1-1SNB has been extracted from HEC-FIA (Figure 6.26) and is expressed as a percentage of the total value of the property. A rapid estimation of the property values on Long Beach Island has been done using a real estate website (http://ganderson.com/lbi/ga.nsf/site/long-beach-island-properties-for-sale). This has led to the delineation of 5 zones on the island where the property values are relatively homogeneous in each zone (Figure 6.27 and Table 6.8). Therefore 5 depth damage functions have been used in the damage calculation by combining the damage as a percentage of the property values with the estimated average property value on the island.

Figure 6.25: View of the parcel polygons (bright green lines) superimposed on an aerial photography

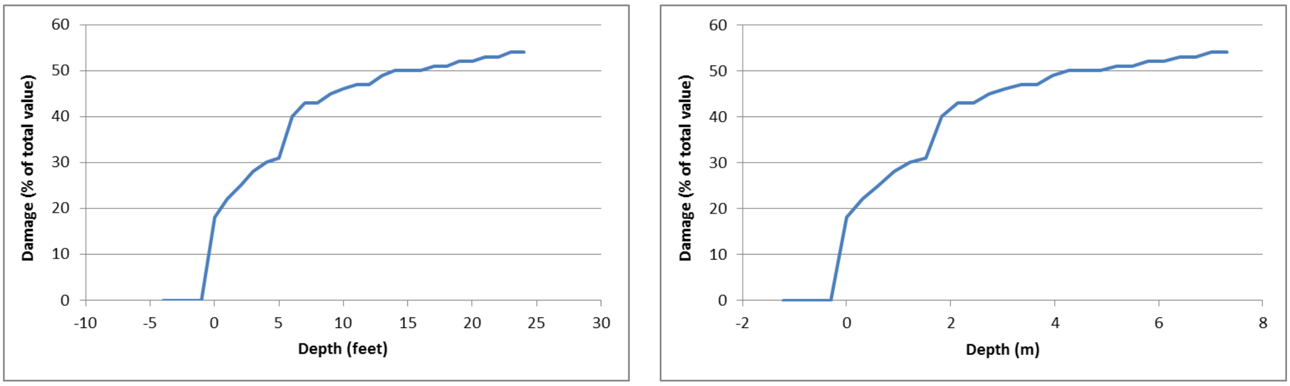


Figure 6.26: Damage expressed as a percentage of the total value of the property (RES1-1SNB)

Figure 6.27: View of the 5 different zones for the average property valuation

Table 6.8: Average market value and number of properties for the 5 zones considered

Zone name	Average Property value ($)	Number of properties
Bay front	1,496,000	2,065
Bay side	796,000	7,219
Ocean side	840,000	7,396
Ocean front	1,200,000	1,143
Ocean block	898,000	2,294

6.11.3. Damage calculation outputs

For each scenario, the grid of maximum computed flood depths have been extracted from the inundation modelling results and these are used to calculate the damages. The damage values have been aggregated per zone for reporting purposes, but they are available per parcel. Table 6.9 shows the damage values for each return period for the case of no SLR. Table 6.10 shows the damage values for each SLR scenario for the case of RP 100 year. Other combinations of RP and SLR are not shown in this report but have been calculated, as they are also needed for the EAD calculation (Section 6.11.4).

It should be noted that the damage values initially estimated were very high considering the number of properties. This is due to the fact that the property values have been estimated based on market value rather than on (re-) construction cost or depreciated replacement cost as used by the USACE for planning studies. Long Beach Island is a desirable location and the market value of properties is high. To adjust for this effect, a reduction factor has been applied to the calculated damage values. Considering a representative construction cost of $ 80 per square foot, and building sizes in the region of 1600 to 2000 square feet, it seems appropriate to use a reduction factor of 0.1 as a first approximation. For a more detailed study, the cost of (re-) construction of properties would require more accurate estimation.

Figure 6.28 shows the spatial variation of the calculated damage for the RP 100 y scenario with no SLR.

Table 6.9: Damages (m$) per zone and per return period (for SLR 0 ft)

Zone	RP 1	RP 10	RP 30	RP 100	RP 1000
Bay front	24.1	42.7	46.3	49.2	54.3
Bay side	26.0	99.2	113.1	121.9	135.5
Ocean side	2.7	33.6	58.4	85.2	124.3
Ocean front	0.0	1.0	1.8	2.6	8.1
Ocean block	3.2	37.8	42.1	44.9	49.9
TOTAL	**56.1**	**214.3**	**261.7**	**303.7**	**372.1**

Table 6.10: Damages (m$) per zone and per SLR scenario (for RP 100 year)

Zone	SLR 0	SLR 1	SLR 3	SLR 6
Bay front	49.2	57.4	66.4	93.3
Bay side	121.9	144.5	168.6	242.7
Ocean side	85.2	141.6	177.4	263.3
Ocean front	2.6	14.8	30.5	49.6
Ocean block	44.9	53.7	62.9	91.6
TOTAL	**303.7**	**412.0**	**505.8**	**740.6**

Figure 6.28: View of the calculated damage for RP 100 (SLR 0 ft). Note that the damage value is each grid cell is the damage in the corresponding parcel, not the damage per cell

6.11.4. Estimated Annual Damage outputs

The Estimated Annual Damage (EAD) is calculated for each SLR scenario as the sum of the product of the damage and a coefficient called RP factor for all RPs. The RP factors used here are shown in Table 6.11. The calculated EADs are shown in Table 6.12 and are then converted to proportions of the total present-day EAD as shown in Table 6.13.

Table 6.11: Return Period factors used for the EAD calculation

Return Period	RP factor
1	0.900
10	0.067
30	0.023
100	0.009
1000	0.001

Table 6.12: EAD (m$) for each SLR scenario

Zone	SLR 0	SLR 1	SLR 3	SLR 6
Bay front	26.1	48.6	61.5	88.4
Bay side	34.9	121.2	158.3	231.5
Ocean side	7.9	79.8	160.0	241.8
Ocean front	0.2	2.7	22.0	42.9
Ocean block	7.2	44.7	59.3	87.8
TOTAL	**76.3**	**297.0**	**461.1**	**692.4**

Table 6.13: Multipliers on EAD ($) for each SLR scenario based on total EAD for no sea level rise = 1.0

Zone	SLR 0	SLR 1	SLR 3	SLR 6
Bay front	0.34	0.64	0.80	1.16
Bay side	0.46	1.59	2.07	3.03
Ocean side	0.10	1.05	2.09	3.17
Ocean front	0.00	0.03	0.29	0.56
Ocean block	0.10	0.58	0.78	1.15
TOTAL	**1.00**	**3.89**	**6.03**	**9.07**

The vulnerability of property to increased damage as sea levels rise is very apparent from this analysis. In fact Table 6.13, which sets out the future expected annual damages as a fraction of total present day (SLR 0 ft) damages, shows that there is a quadrupling of average annual damages for just 1 foot of sea level rise.

6.12.Adaptation measures

Given the value of real estate involved on the developed barrier islands and because the barrier islands also provide protection to the mainland, it is unrealistic to expect these islands to be abandoned to the forces of nature. Other measures therefore have to be considered in order to provide medium term resilience to the communities of these barrier islands.

6.12.1. Ocean defences

Based on the analysis in Sections 6.6.and 6.7 above it appears to be realistic to maintain the existing beach-dune system. The dune systems seem to be relatively robust for various SLR scenarios; even though overtopping rates will increase under severe events, the modelling did not suggest entire dune wash-out even with 6 feet of sea level rise. However, series of capital dredging and renourishment projects will be required to provide the necessary additional sand to sustain the profiles. The main question remaining therefore relates to the affordability of the associated beach nourishment activities, including the need for potentially increasingly more active dune management as sea levels rise. Some expansion, ideally roll-back, of the foot print of the dunes may be required in order to sustain the necessary peak performance beach profile which optimally reduces the energy impacting the shore. However, where there is lack of space for the dune systems to spread or retreat to accommodate this rise, backing vertical hard defences may be required in order to contain the overall dune profile.

In terms of considering incorporation of natural and nature-based features, as with the naturally vegetated barrier islands, native flora which act as stabilisation to the dunes should be encouraged, which may require some deliberate planting initially. For dune regeneration to be successful through time, the dune systems need space to evolve and move inland if sea levels rise and climatic conditions change – thus a strategy to reduce development on the seaward edge of barrier islands should ideally be included in the mix of measures, if necessary combined with a programme of measures to extend the barrier islands on the bayside.

6.12.2. Bay defences

As the analysis suggests that the beach-dune system can be maintained in a relatively robust condition even with 6 feet of sea level rise, more immediate efforts should instead be focussed on back bay flooding.

One potentially attractive but expensive option might be the installation of a storm surge barrier at the mouth of the inlets to the barrier islands – perhaps similar to that employed at Venice (Figure 6.29). Whilst this would have additional attractions in terms of also protecting the shore of the mainland, there would be significant issues to be considered in connection with this solution. One particular issue is that such barrier are not normally designed to operate on a regular (e.g. weekly basis) whereas the expected increasing frequency of higher water events would require increasingly regular operation.

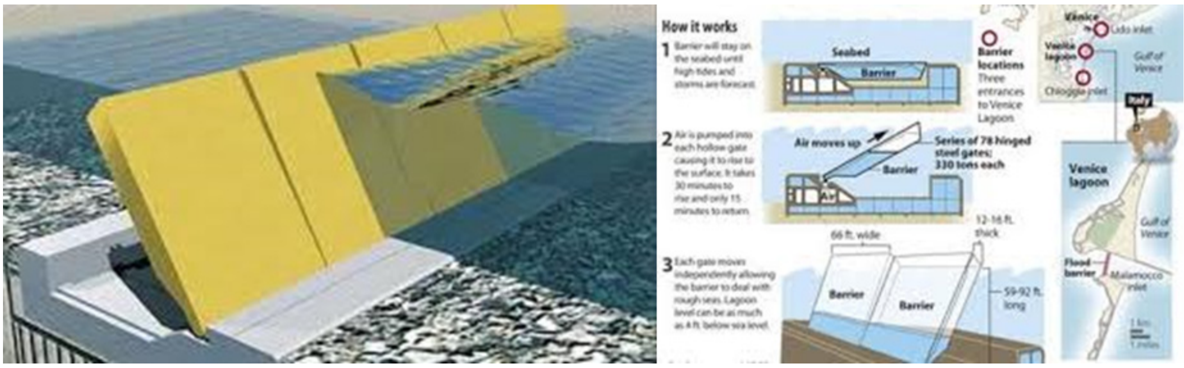


Figure 6.29: Concept of Venice storm surge barrier

It is therefore thought to be more practical to consider **flood defence measures** along the bay shore along with further measures as discussed in the subsequent sections. However, the nature of the existing bay shore (see montage of photos in Figure 6.30) indicates that the installation of defences will need to take account of the need to maintain access and ways of viewing the bay.

A key element of leisure access will be for boating, especially where mooring structures and quay walls (with low wave splashboards) already exist. Here new (or raised) quay walls doubling as flood defences will be required. Stepped defences may be possible and for locations where natural beaches exist, terraced defences incorporating natural or nature based features see below) can be considered.

Figure 6.30: Bay shore of Long Beach Island NJ – typical views

Improving and raising existing vertical quay walls is likely to involve expanding their footprint and cross-section. It will be necessary to consider the need for walkways on the defences (there are already some basic timber boardwalks). Variety could be introduced, with differences between defences for which navigational access is required and those for which a stepped defence or dike might be possible.

Not all of this would need to be done immediately. An adaptive approach might include laying foundations for full defence raising to say 6 feet, but only implementing the superstructure for the part that is required say for the next 20 years.

Incorporating natural and nature-based features

The problem of highly developed shorelines, where natural features had been either lost or seriously diminished, was considered in the European Union THESEUS project. Reinstating natural ecosystem components can contribute to providing coastal defence resilience. The components probably of most use for defence of the bay coast of a developed barrier island such as Long Beach Island NJ would include:

- Salt marsh systems;
- Biogenic (e.g. oyster) reefs; and
- Submerged aquatic vegetation (e.g. sea grass meadows).

Salt marsh development will require a suitable soft sediment supply, which can often be supplied from maintenance dredging campaigns, although some engineering techniques such as geotextile tubes, berms or gabions may be required to retain sediment to the intertidal levels required. Additionally, the plant propagule supply will need to be carefully considered, as deliberate planting in addition to sediment importation may demand too much resource for required cost benefit ratios to be realised. Some developed barrier islands already have marsh areas which are degrading due to lack of sediment supply – these can potentially be addressed with ‘trickle charging’ (Further details of this approach are given in Chapter 9 in connection with the discussion of adaptation measures for the Blackwater NWR.) Biogenic reefs such as oysters require careful placement in order to mitigate flood effects, but oysters are amenable to cage placement, which facilitates such alignment. Likewise, sea grasses are very tolerant to transplantation and the formation of meadows. Both can provide fishery benefit – direct in the case of oysters, but as nursery areas for various species in the case of the sea grass meadows.

Additionally, modifying ‘hard’ engineering structures in order to make it a more attractive habitat for colonising organisms can be useful to provide ecosystem benefits. Various techniques were considered in the THESEUS project, including:

- adding texture to concrete blocks which provided sheltered crevices;
- utilising gabions filled with mixed sizes of stones;
- manipulating the fucoid and kelp communities by transplantation and shelter; and
- timing works to minimise opportunistic macroalgae growth.

Where back shores have flood defence walls, beginning to soften the vertical faces by including gabion terraces planted with reed flora can attenuate surges which might begin to erode the walls. Gabion planting around vertical faces was done with great success on the Greenwich peninsula, on the banks of the tidal River Thames, in London (see Figure 6.31). An advantage of this technique is that the terraces can be narrow in constrained areas (such as this highly urbanised stretch of the River Thames) or more expansive where less constraints apply. This area was built with public money, along with a freshwater restoration area, which is now the Greenwich Peninsular Ecology Park, maintained and promoted by The Conservation Volunteers charity, under their Urban Ecology programme.

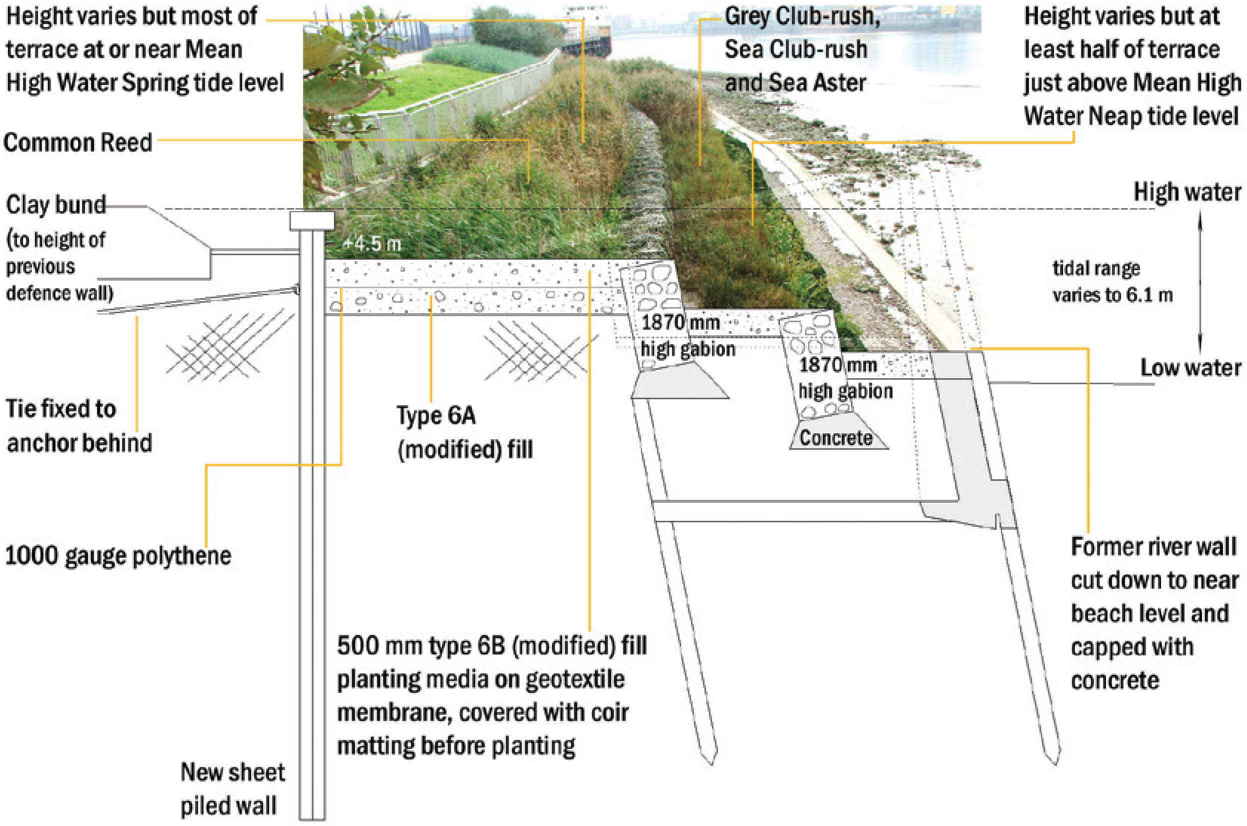


Figure 6.31: Eastern wall, Greenwich Peninsula, London: Site 3 from east, six years after implementation (autumn)

Source: Environment Agency 2008. Estuary Edges: Ecological Design Advice.

An advantage of reinstating natural ecosystem components is that they can provide both landscape and amenity value to the developed area. Experiences in Europe have been that if these areas are developed in conjunction with local communities, considerable positive benefit can be generated. Likewise, if non-governmental organisations are involved, there are opportunities for partnership funding and future proofing, with the NGO assuming responsibility for maintaining the nature-based features, whilst promoting its amenity value to the community. A good example of this is the UK Wallasea Island Wild Coast project, supported by the Department for Environment, Food and Rural Affairs and the Environment Agency, but promoted and cared for by the Royal Society for the Protection of Birds.

6.12.3. Other measures

Modifications to drainage systems

Bay shore flood defences will not solve all the flooding problems (including ‘nuisance flooding’) because with sea level rise during regular high water events flooding can occur by water backing up the drainage systems. Flap valves or sluices will therefore need to be installed on all outfalls. Significant provision will also be required for storage of rainwater, possibly located within modified defences.

Property and road protection measures

Flood proofing of properties would allow reduction of damages, although the increasing operational frequency with which resistance measures would need to be used will tend to become progressively less practical as sea levels continue to rise. Direct property elevation and other material resilience measures will remain a valuable tool to limit damage in the event of flooding. However, it is important to note that the analysis presented in Section 6.10 indicates that the road network is as vulnerable as the rest of the island and the resultant submergence of access to properties will become an increasing issue. Elevation of the road network to improve access could be considered but will require proper drainage and rainwater storage provisions, for example located beneath any such elevated roads.

Flood warning and evacuation procedures

Flood warning and evacuation will remain an important element of the flood risk management strategy for the most extreme events.

Community relocation / roll-back

Complete community relocation seems very unlikely given the real estate interests on the island. However it is possible to envisage elements of land reclamation on the bay shore which could be formed to compensate property that might need to be sacrificed in the long term on the Atlantic seaboard to accommodate dune roll-back. Such an approach would require very careful land use planning and full community engagement in order for it to be successful.

6.12.4. Timing of interventions

The timing of interventions would be a matter for discussion. However the following factors would have to be taken into account:

- The relatively urgent need to start to provide defences on the bay shore, since just 1 foot of sea level rise will already generate regular nuisance flooding of 70% of the island on high tides (see Section 5.4). The range of SLR scenarios suggests this will be required to be completed between 2030 and 2070 depending on the rate of SLR.
- As explained in Section 6.10, a foot of sea level rise will mean that the proportion of the road network are flooded on annual storms will increase to 70% of with some roads flooded up to 4 feet. This implies that work on raising the lower parts of road network and improving the associated drainage will also need to be completed between 2030 and 2070 depending on the rate of SLR.
- Property elevation works should also be programmed to be completed by about the same date on the lower parts of the island or where threshold elevations at property entrances are close to ground elevations.
- All the above measures would need to be revisited should sea level rise measures look as if they were approaching 3 feet. In this respect, it will be important to design the first phase of civil engineering works so that they can readily be adapted to accommodate further sea level rise.

7. Navigational breakwater structures – Pt. Judith, RI

As mentioned in Chapter 4, there were no particular points of interest which emerged from the submergence analysis of the Point Judith area (see Figure 7.1).

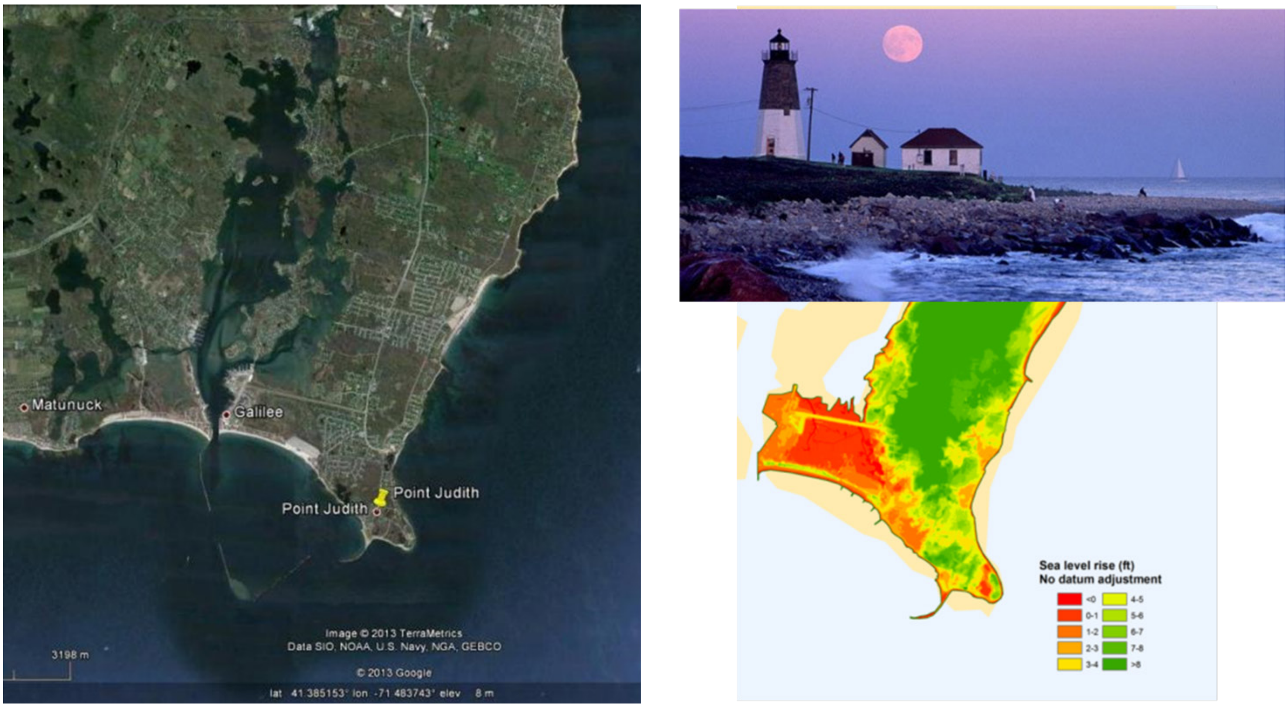


Figure 7.1: Point Judith showing harbour of refuge breakwaters to the south and flood submergence map

A short review was therefore carried out of the navigation breakwaters based on the study conducted by Melby et al (2014). As described by Melby et al (2014) three breakwater structures were built between 1891 and 1914 to provide shelter for refuge, search and rescue operations, for a commercial harbour, and a sandy recreational shoreline. Although the main breakwater was repaired in 1984, it is presently in a severely damaged state. Melby et al (2014) examined the implications of future sea level rise for structure performance and the harbour itself. Based on detailed wave modelling, a full life cycle analysis for the period 2014 to 2070 was conducted of the main (southern) design and performance, examining several rehabilitation alternatives and the implications of sea level rise over this period of time. It was concluded that repair / rehabilitation of the main breakwater could not be justified by the relatively modest increase in the damage to the breakwater armour resulting from sea level rise. It was also concluded that, even with sea level rise, most wave energy would continue to enter the harbour through the gaps between the breakwaters rather than by overtopping. For this reason increases in wave energy in the harbour would be modest and hence:

- the Harbour of Refuge function and to navigation transiting to and from Galilee Harbour would not be impacted by sea level rise. Specifically, there would not be significantly increased limitations to navigation directly arising from the wave conditions nor increased sediment deposition in the navigation channels;

- the increase storm-induced erosion of the beach on the northern back shore would be minimal, even if the breakwater is was repaired.

However, on review, these conclusions should not be taken to be indicative of the a broader trend suggesting there should not be concern about existing navigation breakwaters as a result of sea level rise. In particular the conclusions of the Point Judith study are somewhat limited by the decision to restrict the project evaluation period to the 60 year period up to 2070. A 60 year evaluation period is consistent with the normal USAE project evaluation period of 50 years, but was not able to follow the most recent guidance which suggests that the sensitivity of conclusions should be examined by looking at changes to a longer time horizon of 100 years (USACE, 2013). Thus it was not possible to identify any ‘tipping points’ that may have been identified over the longer time horizon. Other issues that should be noted are as follows:

- As Melby et al (2014) note, the original armour design appears to have been rather conservative. Hence impact of SLR is relatively small in terms of further damage to the breakwaters. However if a full 100 years sea level rise had been considered, Figure 7.2 suggests that for the higher rates of sea level rise and the more distant time epochs, significant changes can emerge in terms of future required stable stone weights for main breakwater armour (and hence in damage for a fixed stone weight). In this case, of course, this effect may have been counteracted by the crest of the breakwater becoming progressively submerged especially during the storm surges associated with the hurricanes bringing the most severe waves.
- The evaluation was somewhat coloured by the assumption that NRC curve 1 (the lowest NRC curve) was the ‘most likely’. This appears consistent with USACE (2013) which selects NRC1 curve as ‘intermediate’ between a low SLR scenario of business as usual and a high SLR scenario of NRC3. However USACE (2013) avoids suggesting that the intermediate NRC1 scenario is somehow more likely and indicates that sensitivity analysis should consider all scenarios with equal weight.

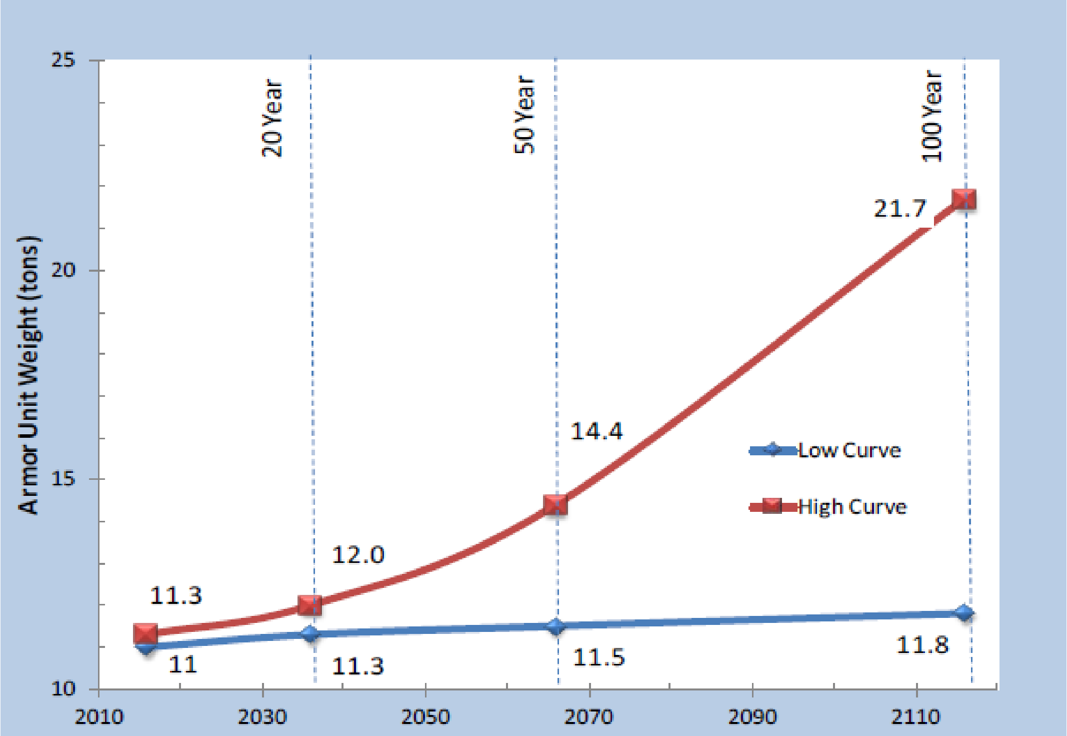


Figure 7.2: Required stable stone weight for seaward face protection of breakwaters under different SLR scenarios (USACE 2013)

8. Erodible coastal bluff – Calvert Cliffs near Cove Point, Chesapeake Bay

8.1. Analysis

As mentioned in Chapter 4, the soft erodible bluffs along the Chesapeake Bay shoreline of **Calvert County** are an interesting example for examining the impact of sea level rise.

The most recent existing study of this area which was available for review was that of Wilcock et al (1998) who discovered that the susceptibility of the bluffs to erosion were a function of an empirical parameter T/S where T= wave pressure, and S= cohesive strength of the clay material of which the bluffs are comprised.

Wilcock et al (1998) assessed these two parameters at a series of locations along the cliffs and although they did not examine sea level rise as such, the implications of sea level rise can be inferred from their work. Their work is summarised in Figure 8.1.

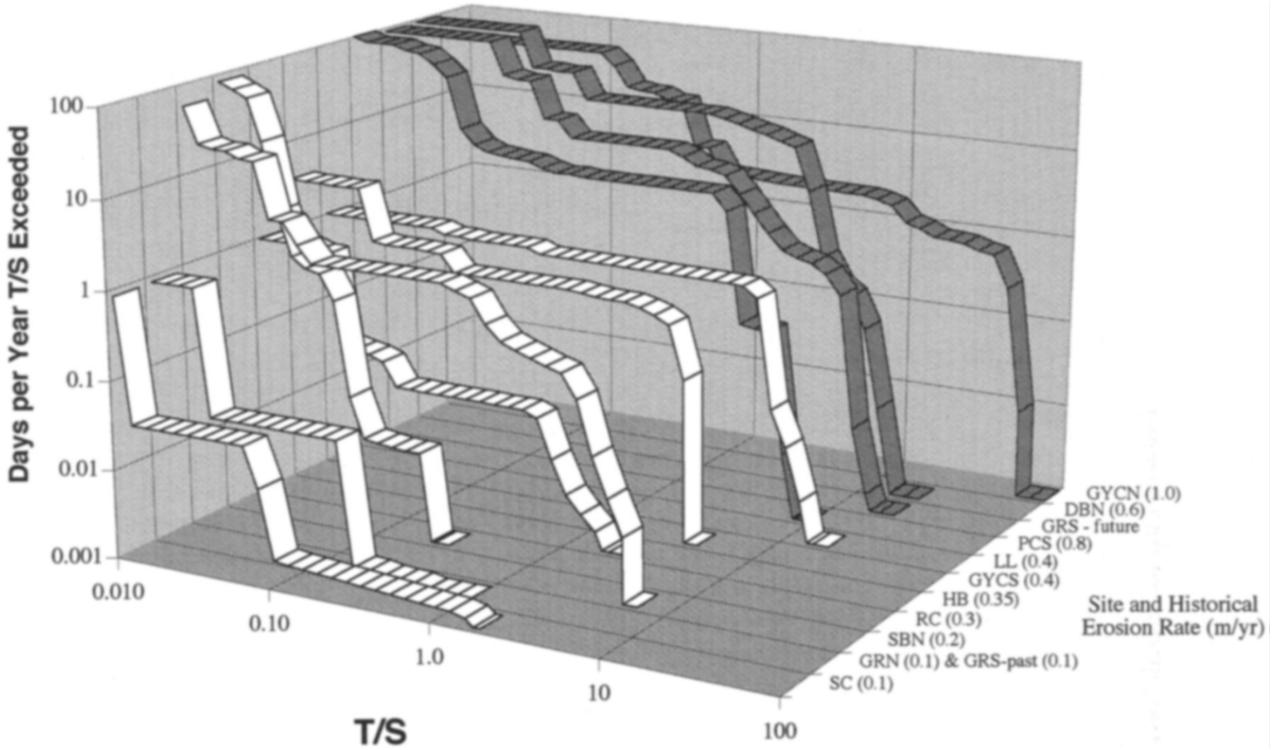


Figure 8.1: Variation of erosion parameter T/S affecting recession of Calvert Cliffs (Wilcock et al, 1998)

Note: Individual sites are separated by historical erosion rate. Undercut slopes shown with grey strips; no-undercut slopes shown with white strips. Site initials and historical recession rate (m/yr) shown as labels on right. Actively undercut slopes recede at larger rates than those that recede through slope erosion and wave removal of toe debris. Cumulative frequency of T/S distinguishes between undercut and non-undercut slopes and between moderate and high rates of slope recession.

Attention within Figure 8.1 should be addressed to the lines GRN & GRS past, PCS, GRS- future and DBN. As Wilcock et al (1998, p..265), point out:

> A special case is Governor Run South (GRS). This site has a small historical erosion rate and is presumed to have been protected by a beach over most or all of the historical erosion rate period. The beach eroded during the course of the study, presumably as a result of decreased alongshore sand supply due to trapping by an up-drift groin field. As a result, the toe elevation of the site decreased by 0.7 m, which causes the frequency of T/S to increase. With a larger toe elevation, the cumulative T/S frequency for GRS is comparable to that of GRN …. At the lower elevation, the cumulative T/S frequency for GRS is comparable to that of the directly undercut slopes (e.g. PCS and DBN). This suggests that the site will now erode by direct undercutting and that slope recession will proceed at a rate much greater than the historical value of 0.1 m/yr. This is supported by field observations of an incipient undercut notch at the site
>
> *Wilcock, P.R., Miller, D.S.,. Shea, R.H. and Kerkin. R.T. (1998) Frequency of Effective Wave Activity and the Recession of Coastal Bluffs: Calvert Cliffs,Maryland. Journal of Coastal Research, Vol. 14, No. 1 (Winter, 1998), pp. 256-268*

In the case of cross-section GRN which Wilcock examined, the change in state of the cross section (with a lower toe elevation at the foot of the bluff) had arisen because of morphological changes in beach levels. However, the implications for sea level rise are clear. Increases in sea level will accelerate undercutting of the toe of the bluff and accelerate the resulting rate of erosion. In fact the specific evidence of this location is that the rate of erosion will increase by an order of magnitude (from 0.1 m/yr to 1.0 m/yr) for a sea level rise of just 0.7m (2 ft 4 inches). Predictions of sea level change in the Chesapeake Bay at this location suggest that such an amount of sea level rise (and the resulting increase in erosion rates by an order of magnitude) could occur in as little as 30 years (NOAA high scenario) or by 2100 under the USACE intermediate scenario (NRC1).

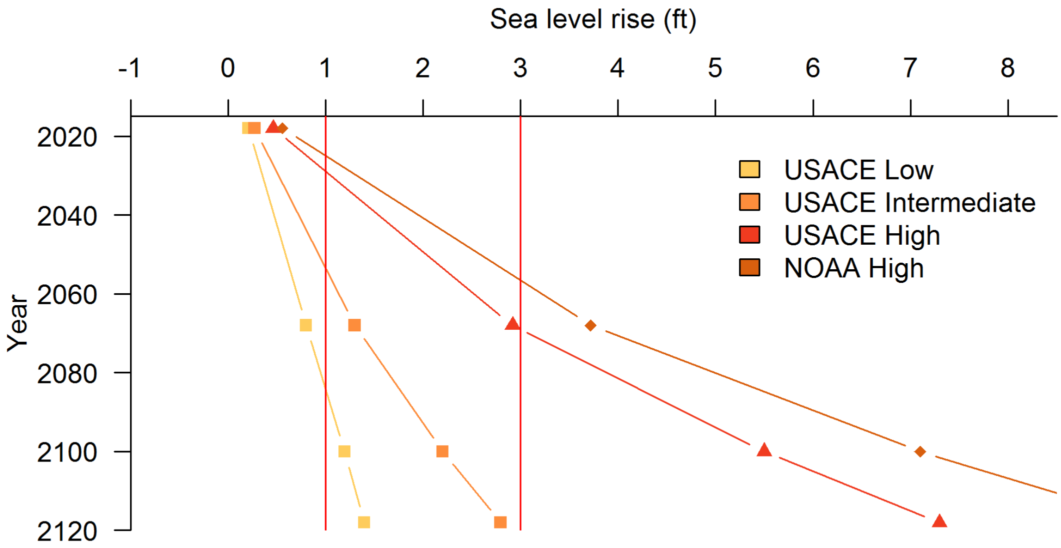


Figure 8.2: Sea level rise predictions near Calvert Cliffs, Chesapeake Bay

8.2. Coastal bluff protection measures - discussion

For a coastal bluff situation with sparse populations on top of the cliff, it may be perfectly acceptable to adapt to sea level rise and increased erosion by simply allowing the cliffs to continue to erode even if at a faster pace. It is worth bearing in mind that the erosion of the cliffs may release material into the coastal morphological system which may replenish the foreshore and thereby reduce rates of erosion in the long term. Even in the densely populated United Kingdom from which the authors of this report originate, hard decisions have had to be made to progressively abandon small coastal communities (see e.g. Figure 8.3) in order to permit a consistent approach to management of coastal geomorphological cells.

Figure 8.3: Progressive coastal erosion of bluffs at Happisburgh, village, east coast of United Kingdom comparing situation in 1981 (top) with 2008 (bottom)

Source: Photo courtesy BBC

Where there is a justification for holding the line, measures might include beach recharge to protect the toe of the cliff from erosion and undercutting. This is particularly applicable for example if there is scope for beneficial use of navigational dredgings from within Chesapeake Bay. Such an approach might also be used as an interim measure to ‘buy’ time to allow communities on the top of the bluff to relocate.

Equally it would be possible to place a rock armour or other structural protection at the toe of the bluff to prevent erosion and undercutting. If such a structure is intended to have a long life, then its design will have to accommodate increasing wave heights during its life time as sea levels rise and its crest located at such a level that it will continue to provide protection over say 100 years.

9. Low-lying ecosystem - Blackwater National Nature Reserve in Chesapeake Bay

9.1. Introduction

Salt marshes and mud flats are natural resources that are of value to both nature conservation and coastal defence interests. The Blackwater NWR, situated in Chesapeake Bay, is a Ramsar wetlands site and Important Bird Area of global significance, a vital part of the Chesapeake Bay's wildlife network and the largest complex of conservation land in Maryland. The marshes of this NWR are part of a much wider area of salt marshes which have been eroding and gradually deepening over time (see Figure 9.1).

Figure 9.1: The wider environment around Blackwater NWR in Chesapeake Bay

Source: Google Maps

All of these marginal areas are low lying and are liable to be extensively inundated with very little increase in sea level (Figure 9.2). Over the long-term, the most practical effective strategy is likely to be to allow these wetlands to migrate – although some short-term measures may be effective in slowing the erosion and assisting the marshes to adjust gradually.

Salt marshes are adapted to survive in a particular part of the tidal prism. Their characteristic vegetation consists of a limited number of halophytic (salt tolerant) species adapted to regular immersion by the tides. A natural salt marsh system shows a clear zonation according to the frequency of inundation. At the lowest

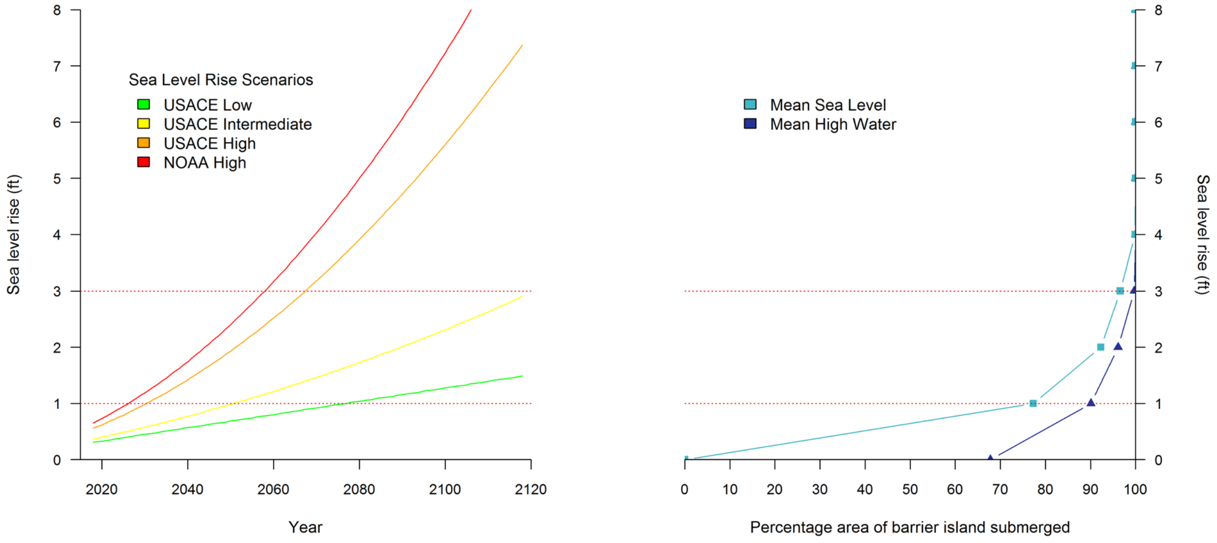


Figure 9.2: Submergence analysis for Blackwater NNR

level some flora can withstand immersion by as many as 600 tides per year, while transitional species of the upper marsh can only withstand occasional inundation. However, areas that are rarely exposed (generally below mean low water spring tide mark) are unsuitable for salt marsh to survive. Sea level rise will therefore alter the areas where salt marsh flora are able to survive, unless:

- there is sufficient sediment supply that the salt marsh level can raise at a similar rate to the water level; and
- the rate of change is slow enough that the vegetation growth rate can keep pace.

If existing marshes are to be retained, it is therefore important to consider whether sediment supply is available. Identifying whether barriers to sediment supply, such as coastal structures interrupting natural sediment processes, can be removed is an important part of retaining the marsh elevation. Otherwise, some type of sediment feeding strategy needs to be developed.

The marshes of the Blackwater NWR have also undergone extensive anthropogenic modification in the past, with straight-cut channels for increased drainage (see Figure 9.3) which was introduced by early American farmers to promote the growth of meadow cordgrass, and greatly expanded in the early twentieth century to control mosquito populations (Crain et al, 2009). These straight-cut channels have unfortunately exacerbated erosion, present a barrier to marsh migration and encouraged subsidence.

Figure 9.3: Area of Blackwater NWR showing extensive straight cut ditch network

Source: Google Maps

9.2. Ecosystems management - low lying natural marsh areas

A major study has been carried out to consider long-term management of the Blackwater NNR in the face of sea level change (Conservation Fund and Audubon Maryland-DC, undated). This study is a comprehensive and thorough evaluation. However, there are some management options which have been utilised in European marsh areas which may be worth considering in addition to the considerable number of options already documented and evaluated.

9.2.1. Sediment considerations

The Blackwater NNR report considers (see Strategy 4.2.1) sediment enhancement and considers several options for dredged material placement. However, there is the potential to consider a beneficial use technique for those sediments with an acceptably low level of contamination. This technique, called 'trickle charging', has been used in areas of the United Kingdom (UK) for over 15 years. It involves the placement of material in the sub-tidal zone (for coarser material such as sands and gravels) or released into the water column at discrete discharge points (for finer material such as silts and clays) and allowing natural processes to move it onshore. The ability of the water column to carry significant quantities of material in suspension without impacting on the seabed depends on the energy within the water column (tidal currents and turbulence). An alternative to the water column discharge is placement in a naturally dispersive subtidal location within the marsh system, if such a location can be identified. This technique has also been employed in the UK.

A disadvantage of the water column recharge technique is that sediment application may not end up in a particular desired location due to differential settling and dispersion within the water column, thereby increasing the requirement for multiple applications to achieve the desired effect. The recharge process is, therefore, slow when compared to direct pumping. However, there is the advantage of working with natural processes and rather than attempting to anticipate which area to recharge, sediment will naturally settle where it can find most stability, thus reducing erosion and potentially restoring equilibrium with rising water levels. Another advantage of this is that even small dredging campaign arisings can be usefully deployed in this manner; there is no need to await a large dredging event with sufficient material to cover a predetermined area.

When adding fine-grained sediment to the intertidal the timing of the application is of paramount importance. If the sediment is added too quickly, the density between the added sediment-water mixture and the ambient water will be too large, causing the sediment to descend quickly to the sea bed in a dense plume. Fine muddy sediment settles relatively slowly. Therefore, if the flow cannot carry the sediment, it will take some time to settle to the bed and may still be transported a reasonable distance before depositing.

If sediment from the Bay is taken and re-introduced to specific areas, that sediment: (a) has a greater chance of reaching and settling onto intertidal areas; and (b) increases the background sediment fluxes by a much larger degree than had it been re-introduced in the vicinity of the main flowing area of the Bay. This enhancement of the effectiveness of the sediment replacement is referred to as the "value-added" concept.

This practice has been ongoing within the Stour and Orwell Estuaries on the east coast of England for fifteen years (Figure 9.4). Regular monitoring of the marsh extent has taken place.

The east coast of England is vulnerable not only to sea level change through climate change, but also sinking of the land area subsequent to the retreat of the past Ice Age. The marshes in this area are also mostly constrained by engineered armoured sea defences which provide flood protection to the adjacent communities and infrastructure. Marshes throughout the wider area of the Greater Thames Estuary have been observed to be eroding and extent being lost, through coastal squeeze, where the marsh is unable to migrate in response to water level change. Trickle charging was therefore put in place at the Orwell and Stour to try to reduce some of the loss of saltmarsh, which could be exacerbated by sediment removal from Harwich and Felixstowe ports, at the mouth of the estuary, due to their navigational dredging requirements. Sediments from the navigational dredging are therefore utilised for the trickle charging.

Adjustments to the trickle charging methodology have been made during the years of activity, to 'tune' the trickle charging to the location, to reduce siltation in undesirable areas and to optimise the flow of sediment by reducing the speed of discharge into the water column. The marsh extent monitoring has generally shown few areas of erosion through time, with more accretion areas throughout the monitoring area, so it can be cautiously postulated that the trickle charging has been useful, although firm conclusions cannot be expressed.

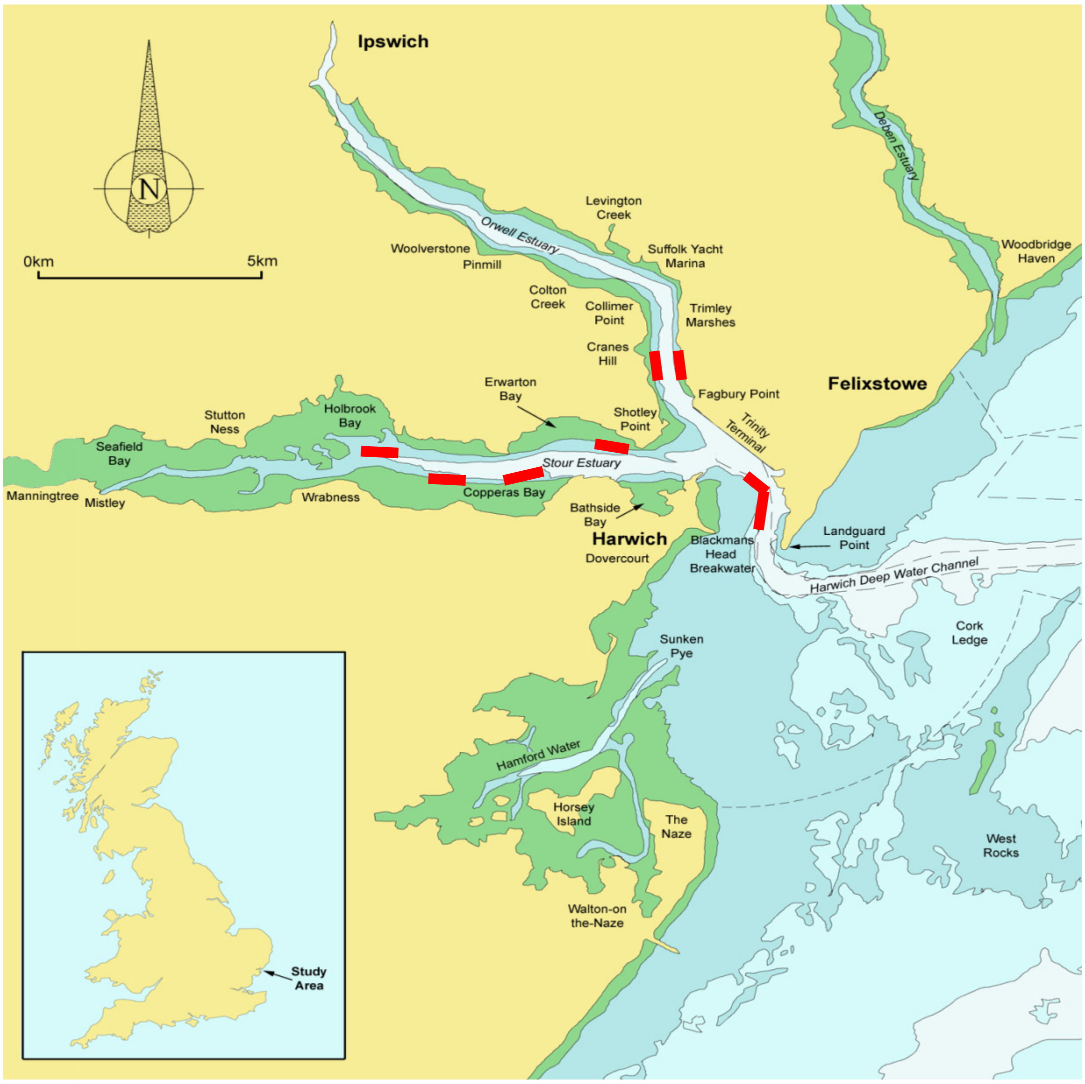


Figure 9.4: Water column recharge locations (in red) within the Stour and Orwell Estuaries, United Kingdom

Source: HR Wallingford

9.2.2. Flora considerations

Deliberate planting of sediment recharged areas is generally too labour intensive to provide value in the conditions. However, growth of plants is essential for stabilisation and further sediment entrapment in these marsh areas, as well as providing future humus during natural decay cycles. It is therefore sensible to ensure that the recharging is done in areas where existing established native marsh flora are in adjacent areas, connected by the natural water current flows. This ensures propagule supply, such as seeds or rhizome portions, to the new raised areas of settled sediments. Propagules are likely to germinate and sprout quickly as soon as conditions are favourable, harnessing the natural succession processes to assist with stabilisation without excessive resource management requirements. In European realignment schemes, where large quantities and depths of sediment have been utilised to encourage saltmarsh formation, colonisation of the placed sediments was more rapid than initially anticipated, with pioneer species being observed during the first active growing season following sediment placement. These were initially sparse, but diversity and coverage gradually increased through time, with fully functional low, mid and high marsh vegetation assemblages establishing within a decade. If existing established native marsh fauna are not available, then deliberate planting of these species can be considered, if there is an overriding requirement to create marshland.

Photograph 1: Salt marsh pioneer species developing in a sediment recharge area in River Crouch, Essex, England, United Kingdom.

Source: Marie Pendle

The results of these realignment activities provides evidence as to how marshes establish in new areas, thus extrapolation suggests how marshes will respond to climate change scenarios in adjusting their extent and if anthropogenic assistance is given for the adaptation. In European realignment schemes, invertebrate assemblages (mainly polychaetes and molluscs with some crustacea) established in a similar manner to the flora, with sparse pioneer species initially, moving toward increasing diversity though time. Vertebrates such as fish and birds are highly mobile and were observed utilising the new intertidal and subtidal areas extensively within one year of inundation by the estuarine waters. The newly created areas were of particular importance as nursery areas for various fish species.

9.2.3. Hydrological considerations

The Blackwater NNR report considers (see Strategy 4.2.3) remedies to hydrological problems. Ditch plugging is considered, but there is no consideration of partial modification to encourage these ditches to work in a more natural manner with the marsh drainage. The straight line form of the ditching encourages very fast drainage of water, which allows erosion velocities to be exceeded. These flows can be reduced by two strategies – providing brushwood dams, which allow the passage of water at a reduced rate, but can retain sediments, allowing natural siltation to reduce the depths, without the compaction that can lead to reduced oxygen levels or waterlogging remaining, as the water still drains above. The other strategy is to encourage the curves of a natural dendritic system to form, by cutting new areas and filling old areas. As the ditches sinuosity increases, the water velocities gradually decrease, also decreasing the erosive potential.

In some of the UK managed realignments, where previously reclaimed agricultural lands were being returned to marshland, a series of dendritic engineered channels and ponding areas were put in place prior to inundation taking place, when the existing concrete armoured earth bund seawalls were deliberately breached. This can be seen in Figure 9.5, which is a satellite view of Abbots Hall Farm, Essex, England. This encourages the tidal inundation to mimic a natural marsh inundation and likewise drain, without the speeds that can cause erosion problems.

Figure 9.5: Abbots Hall Farm wetland creation scheme (outlined in red). Existing degraded marsh can be seen peripherally

Source: Google Maps

10. Combined system – Broadkill Beach, Delaware River

Broadkill Beach on the southern shores of the estuary which forms the outer part of the Delaware River is an interesting mixed location. The beach comprises of a very narrow strip of beach material on which a single line of properties is located. The beach has been nourished from time to time by USACE by employing beneficial use of dredge material from navigation channels in the Delaware River. However the strip of properties remains vulnerable to sea level rise from the rear of the beach by inundation over low lying marsh land and to being cut off from the rest of the mainland by breaching In this regard the issues are similar to those discussed for barrier islands in Chapters 5 and 6. In this case the width of the strip of land is significantly smaller and makes the location more fragile.

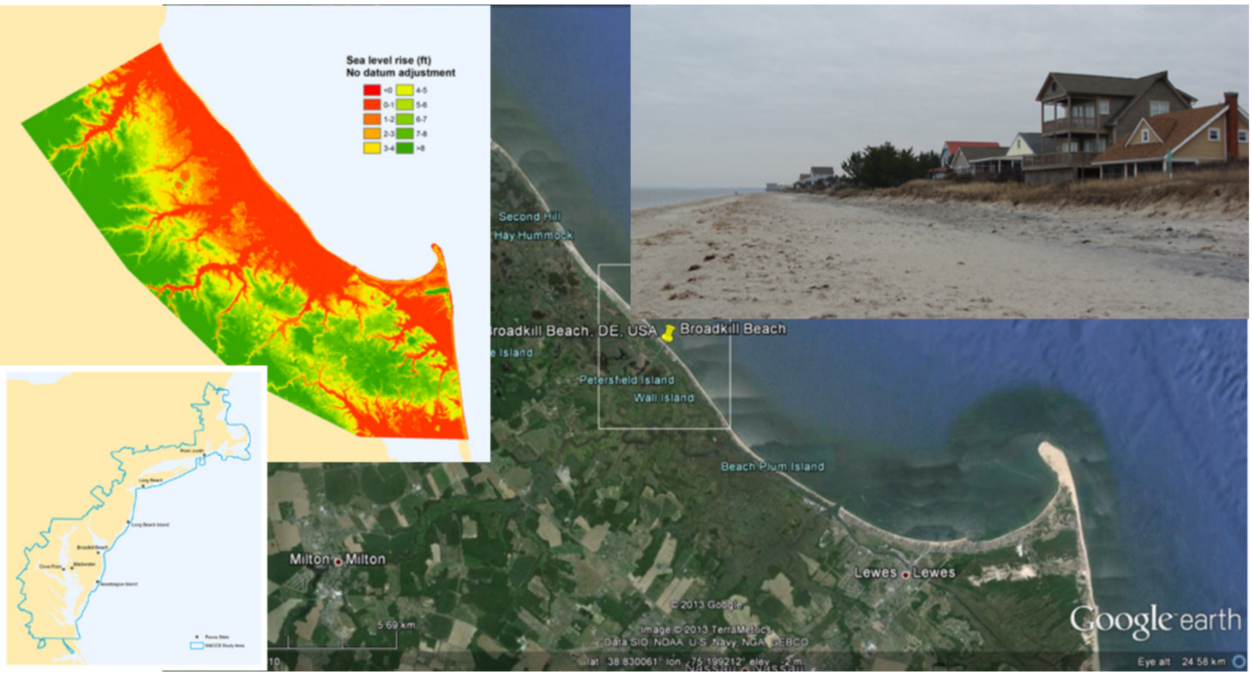


Figure 10.1: Perspectives of Broadkill Beach on southern shore of outer Delaware River

The exposure to the rear of Broadkill Beach has been exacerbated by the drainage of the marshes in a similar way to those in Chesapeake Bay discussed in the previous chapter. Management options discussed in Section 9.2 would also be suitable for consideration for the marsh areas lying behind the beach. However structural measures to defend the rear of the beach similar to those discussed in Section 6.12 are likely to be needed if the beach community is to be sustained in the face of sea level rise.

11. Conclusions

11.1. Barrier Islands

An initial simple submergence assessment was applied to increments of sea level rise against the elevation of three typical north east coast barrier islands to identify the area that would be lost at varying levels without levees or flood walls and assuming full hydraulic connectivity. This assessment was based on a DTM with a resolution of 2m and analysed into one foot bands of ground height and provided percentage losses of land area under the four sea level rise scenarios considered in the NACCS study. As previous studies have shown, this kind of analysis indicates significant loss of land for just 1 to 2 feet of sea level rise, with only the large dune beach systems on the Atlantic seaboard escaping much of the inundation. The analysis was completed for several barrier islands within the NACCS area and the results were broadly similar for each.

For Long Beach Island NJ a full storm inundation analysis was carried out. This can be summarised as containing six elements:

- *Scenario assumptions*. As the issues with barrier islands are mainly associated with the amount rather than the rate of sea level rise, it was decided to examine future scenarios following 1ft, 3ft and 6ft sea level rise rather than selecting a specific sea level rise scenario. The increased water levels also affect the wave heights, both to a limited extent in conditions offshore (e.g. in 30 feet of water) but more significantly in the near-shore conditions where the wave breaking occurs. Here wave heights become strongly dependent on available water depth and thus, in the absence of geomorphic adjustment, extreme significant wave heights will increase by about 55% of the increase in sea levels. For each scenario, extreme wave and water level conditions were examined for the 1,10, 30 100 and 1000 year return period events. Calculations were also carried out for two response scenarios: one where defences and dune systems were raised in line with sea level and the other where no such improvements were included.
- *Extreme waves and water levels.* Offshore waves were based on data from the National Data Buoy Center at the nearest available offshore location. A record length of 24.9 years was available which included 139 events (including Hurricane Sandy) where the significant wave height exceeded 13 feet. Equivalent coincident water levels were based on recorded sea level data, using Monte Carlo simulation to fill any data gaps and a joint probability distribution of waves and water levels obtained. Wave heights were transformed to the nearshore taking account of wave refraction and breaking and then analysed to obtain estimates of extreme wave heights. It should be noted that as there is a relatively low tidal range on the North Atlantic coast, a strong correlation exists between the most extreme waves and hurricane or other significant storm surges.
- *Beach/Dune Profile response.* A DUROS+ empirical dune model (van Rijn, 2013) validated by good field data obtained before and after Hurricane Sandy (Stockton, 2012) was used to predict beach-dune profile response, using a representative uniform sediment size of 0.152 mm. The predicted run-up (exceeded by 33 per cent of the waves) necessary for the empirical model was calculated using van Rijn (2008) with results ranging from 6.5 feet for the 1 year event to 8.7 feet for the 1000 year event. In the sea level rise scenarios with nourishment, these results hardly changed. In the sea level rise scenarios without nourishment, greater cut-back of the dunes occurs. (Perhaps surprisingly, as sea levels continue to rise, the DUROS+ model suggests that cut back of the dune crest reaches a threshold beyond which further erosion does not occur and under extreme conditions, further erosion is focussed on the submerged part of the beach profile. This empirical conclusion seems to warrant further exploration.)

- *Dune overtopping calculations.* The EurOtop manual (Pullen et al, 2007), was used to assess overtopping rates based on the modelled beach-dune profile and wave heights at the toe of the beach and taking account of the crest height, toe level and a simplified structure slope. Resulting peak overtopping rates are evaluated for the different return periods and peak water levels under the different sea level rise scenarios. Large overtopping rates can be maintained over a large part of the tidal cycle and hence overtopping rates were calculated over a full tidal cycle. Because of the significant variation in beach-dune profiles, sensitivity analysis was conducted and found several orders of magnitude difference in overtopping rates depending on which beach-dune profile was selected. This issue could have been explored further, but in practice the inundation of the island was dominated by inflows from the back bay.
- *Inundation modelling (ocean & bay shorelines).* The computational mesh for the flood spreading model RFSM-EDA (Jamieson et al. 2012a-b) was made up of relatively small irregular polygons Impact Zones (IZs) to capture the inundation spreading across the narrow barrier island. Discharge boundary conditions were applied using the dune overtopping rates on the ocean shore and a water level on the bayshore which represented the average sea level over the 24 h that follow the peak of the event. Plots for different sea level rise scenarios were created indicating the proportions of the whole island and also just for the road network which would be inundated by different flood depths. The proportions of inundation are slightly higher for the case of the road network reflecting lower ground elevations for the roads than for the property parcels.
- *Flood risk analysis.* The total impact of flooding was calculated for each scenario (return period, sea level rise), by combining the maximum flood depths with a depth-damage function in each grid cell based on those used in HAZUS/ HEC-FIA. Property values were based on average real-estate prices for different zones across the width of the island.

The analysis suggests that the beach-dune system can be maintained in a relatively robust condition even with 6 feet of sea level rise. Concerns should instead be focussed on back bay flooding. Storm surge barrier are unlikely to be viable given the expected future frequency of flooding and instead combinations of the following measures should be considered:

- *New defences on the back bay shore*. Maintenance of leisure access for boating will be important where quay walls already exist (with wave splashboards); here new (or raised) quay walls doubling as flood defences will be required. stepped defences may be possible. For locations where natural beaches exist, terraced defences incorporating ecological features can be considered. In both cases paths for access and viewing are possible.
- *Modifications to drainage systems*. Defences will not solve all the problems because during high water events flooding can occur by water backing up the drainage systems. Flap valves or sluices will therefore need to be installed on all outfalls. Significant provision will also be required for storage of rainwater, possibly located within modified defences.
- *Elevation measures*. Property elevation remains a valuable tool to limit damage in the event of flooding. Elevation of the road network to improve access could be considered but will require proper drainage and rainwater storage provisions, for example located beneath any such elevated roads.

11.2.Navigational breakwater structures

A review was carried out of a study by Melby et al (2014) of breakwaters protecting a harbour of refuge at Judith Point RI. That study concluded repair / rehabilitation of the damaged main breakwater could not be justified by the relatively modest increase in the damage to the breakwater armour resulting from sea level rise. It also concluded that, with sea level rise, increases in wave energy in the harbour would be modest and hence neither navigation activity nor coastal erosion of a shoreline protected by the breakwaters would be significantly affected The conclusions of that study were however affected by a restriction of the project evaluation period to 60 years. If a full 100 years sea level rise had been considered, increases in the height of the breakwater and weight of the main breakwater armour might have been justified. The evaluation was also coloured by the assumption that NRC curve 1 (the lowest NRC curve) was the 'most likely'. The review emphasises the importance of the input assumptions into any analysis of resilience of navigational structures against sea level rise.

11.3. Erodible coastal bluff

A review of available data regarding Calvert Cliffs near Cove Point, Chesapeake Bay emphasised the vulnerability of erodible cliffs to increases in rates of erosion as a result of sea level rise. In this case erosion is precipitated by an undercutting mechanism and present day evidence demonstrates the lower the beach/foreshore system in front of the cliff the more rapid the rate of erosion. From a comparison of the performance of cliffs at various sections, it was concluded that a sea level rise of about 2ft could lead to an order of magnitude increase in the rate of erosion.

Based on UK experience, mitigation measures for the erosion of coastal bluffs may only be justified in locations where the people or property density is sufficient to justify that intervention. Interventions, where required, should investigate the beneficial use of dredged material or hard solutions (rock armour) as appropriate to raise beach toe levels at the foot of the bluff and reduce undercutting and bluff destabilisation.

11.4. Low lying ecosystems in tidal estuaries

The study of these type of systems focussed on the Blackwater National Nature Reserve in the Chesapeake Bay, which is facing major challenges as the nature reserve becomes progressively submerged by rising sea levels. Drawing on UK and European experience this report identifies three strategies which could be considered in addition to the many options already investigated to address this problem:

- In order to raise land and bed levels, rather than formally placing sediment directly in managed locations, UK experience over the last 15 years suggests that a technique, called 'trickle charging', could be used. This technique involves either placing sediment in the sub-tidal zone (for coarser material such as sands and gravels) or releasing it into the water column at discrete discharge points (for finer material such as silts and clays) and allowing natural processes to move it onshore.
- Stabilisation by flora of the recharged areas is best done by locating these reasonably close to existing established native marsh flora and where they are connected by the natural water current flows. This ensures propagule supply, such as seeds or rhizome portions, to the new raised areas of settled sediments. UK experience of projects suggests that initial establishment of flora in the nourished areas can occur rapidly, with noticeable colonisation even in the first growing season.
- Historic drainage of marsh lands in the USA using straight or herringbone networks may well have helped to alleviate mosquito infestation but also generates rapid velocities in the drainage canals and associated loss of sediment. Sinuous dendritic arrangements with ponds are therefore now sometimes deliberately engineered as part of coastal realignment schemes in the UK and this seems to better mimic marsh hydrology and encourage (re)generation of marsh habitat.

12.Recommendations for further research

The rehabilitation of the coastal areas affected by Hurricane Sandy is now well advanced. However, the necessary speed of the required interventions in order to allow communities to recover has meant that it has not been possible to resolve all key underlying research questions. The future aim should be to provide a sounder basis for USACE in execution of coastal engineering projects that will reduce the risks of the Sandy-impacted areas to future coastal storm-related flood risk damage for future interventions. In particular this study has identified the following:

1. *Beach dune profile analysis*. Whilst the beach dune profile analysis conducted for the barrier island flood risk analysis example was a reasonable approach, it is suggested that further development could be carried out. The DUROS + method adopted was developed from experimental tests with very smooth and rectilinear beach and dune profiles, but ideally would need to be improved to account for a mechanism for the failure of dunes.
2. *Dune dataset*. The dune dataset provided by the NJBPN monitoring programme (Stockton, 2012) constitutes a unique dataset for the understanding of the morphology of barrier beaches in response to extreme events. Although the submerged part of the profiles after Sandy was not surveyed (due to time constraints), it is recognised that the data available is quite unique and provides a very good starting point for the validation of numerical models. Morphological development data is scarce and any dataset available is very important. Efforts to survey the dunes, beaches and submerged profile immediately before and after an extreme event has happened should be encouraged and data published. In parallel, information on the beach sediment and water level and wave conditions before and throughout the event should be collected.
3. *Adaptive bay shore defence solutions and Real Options*. Whilst improvements to the analysis approach for the beach-dune system are desirable, it should be borne in mind that we have concluded that the greater threat to the barrier islands comes not from the dune frontage on the Atlantic seaboard, but from flooding over from the bay shore, which at present is largely undefended. Detailed proposals for adaptive defence measures for the bay shore are now required (as discussed in Conclusion 11.1). Whatever solutions are adopted by the local communities, the mitigation options will need to be inherently flexible and adaptable to take account of the uncertainty associated with sea level rise and climate change more generally. Inclusion of the necessary adaptability may, however, incur an additional cost when compared to more traditional fixed engineering solutions. To justify the costs of building in such flexibility or delaying decisions until more information is available, Real Options analysis techniques can be applied. These techniques enable the costs of adaptive solutions to be valued with respect to benefits by taking accounting of future uncertainties. Adaptive options can be modified to perform well in the future and hence they can often be seen to outperform more rigid solutions. It is suggested that HR Wallingford could support USACE by undertaking research into assessing the cost-effectiveness of potential adaptive mitigation options using real options analysis techniques, perhaps initially at a suitable pilot site.
4. *Adaptive solutions for bluff protection and navigational structures*. The recommendation for adaptive measures optimised using Real Options analysis also applies to the protection of coastal bluffs and navigational structures.
5. *Natural and Nature Based Features (NNBF)*. Our investigations have confirmed that there is considerable scope for the use of NNBF as part of the portfolio of intervention measures that should be considered. In particular:

a. Techniques that have been used in the UK to trickle charge sediment to marsh areas subject to depletion due to sea level rise could be trialled and monitored, along with ensuring propagule supply and creation of dendritic drainage networks.
b. More robust engineering guidance should be developed to facilitate the practical use of a number of NNBF techniques. In our experience, lack of such guidance is the greatest barrier (after policy and governance considerations) to the practical implementation of these methods. Guidance is currently being planned in the United Kingdom by the Environment Agency on this topic and there may therefore be scope for collaboration with USACE on this issue.

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Appendices

A. Initial assessment of USACE GIS Data sources

This appendix summarises the results of an initial appraisal of GIS data sources. It is incomplete but is included for completeness for reference purposes.

A.1. Summary of data sources

At the beginning of this exercise data was supplied to HR Wallingford by USACE that covered the area of interest. The data supplied came from a variety of data sources and these included:

- National Weather Service;
- U.S. Fish and Wildlife;
- Northwest Atlantic Marine Ecoregional Assessment.

We have supplemented this data with a number of datasets that we have sourced ourselves. These are the sources from which we sourced external data:

- USGS;
- The National Atlas.

A.2. Bathymetry

A.2.1. Review of data provided

USACE supplied bathymetry data as 10m contours that covers the northern part of the NACCS study area, from New Hampshire to New Jersey. The data supplied only covers the northern part of the study area and comes in contour form.

We sourced gridded bathymetry data for the analysis of Long Beach Island, New Jersey from the State of New Jersey http://www.state.nj.us/dep/njgs/geodata/dgs07-3.htm.

A.3. Elevation

A.3.1. Review of data provided

Elevation data was supplied by USACE that covered large parts of the study area. This was in the form of a composite dataset that had been compiled from several sources of LiDAR data. Other datasets were also supplied that covered more areas. Where LiDAR data was not available National Elevation Data (NED) was downloaded from the National Atlas.

A.4. Coastal

A.4.1. Review of data provided

A number of SLOSH datasets have been provided. This information includes Hurricane Surge Inundation areas for category 1 through 4 hurricanes striking the coast of Connecticut with a peak hurricane surge arriving at high mean water. The hurricane surge elevation data used to define these areas were calculated by the National Hurricane Center using the Sea Lake and Overland Surge from Hurricanes (SLOSH) Model. The SLOSH model hurricane surge elevations have an accuracy of +/- 20 percent. The hurricane surge inundation areas depict the inundation that can be expected to result from a worst case combination of hurricane landfall location, forward speed, and direction for each hurricane category (ref: http://www.cteco.uconn.edu/guides/Hurricane_Surge_Inundation.htm). More information including a detailed description of the categories can be found at http://www.cteco.uconn.edu/guides/resource/CT_ECO_Resource_Guide_Hurricane_Surge_Inundation.pdf

Coastal Barrier Resources System dataset show a system of protected coastal areas that includes ocean-front land, the Great Lakes and Other Protected Areas.

"The Coastal Barrier Resources Act (CBRA) of 1982 restricted development on the CBRS, in an effort to protect the barrier system and prevent future flood damage. If you live in a CBRS area, you are eligible for federally regulated flood insurance only if your property was built before 1982 and your community participates in the NFIP." http://www.floodsmart.gov/floodsmart/pages/faqs/what-is-the-coastal-barrier-resources-system.jsp

More here: http://www.fema.gov/national-flood-insurance-program/coastal-barrier-resources-system

Coastal Habitats dataset has been extracted from the National Wetland Inventory and was created as a part of the Northwest Atlantic Marine Ecoregional Assessment. Attribute data includes the Intertidal habitat class.

Key to attribute codes here http://kgs.uky.edu/kgsweb/olops/pub/kgs/nwl%20index.pdf.

Information on attributes here http://deli.dnr.state.mn.us/metadata/wetl_nwipy3.html.

This dataset only has the intertidal NWI polygons that were coded as rocky shore, unconsolidated shore, emergent marsh, scrub/shrub, or forested, for coastal wetlands.

The original full NWI dataset represents the extent of wetlands and deepwater habitats that can be determined with the use of remotely sensed data and within the timeframe for which the maps were produced. Wetlands are shown in all of the conterminous 48 states and the District of Columbia. The accuracy of image interpretation depends on the quality of the imagery, the experience of the image analysts, the amount and quality of the collateral data, and the amount of ground truth verification work conducted.

There is a margin error inherent in the use of imagery, thus detailed on-the-ground inspection of any particular site, may result in revision of the wetland boundaries or classification, established through image analysis.

Wetlands or other mapped features may have changed since the date or the imagery and/or field work. There may be occasional differences in polygon boundaries or classifications between the information depicted on the map and the actual conditions on site.

Coastal Vulnerability Index The coastal vulnerability index (CVI) provides insight into the relative potential of coastal change due to future sea-level rise. The maps and data presented here can be viewed in at least two ways: * as a base for developing a more complete inventory of variables influencing the coastal vulnerability to future sea-level rise to which other elements can be added as they become available; and * as an example of the potential for assessing coastal vulnerability to future sea-level rise using objective criteria. As ranked in this study, coastal geomorphology is the most important variable in determining the CVI. Coastal slope, wave height, relative sea-level rise, and tide range provide large-scale variability to the coastal vulnerability index. Erosion and accretion rates contribute the greatest variability to the CVI at short (~3 km) spatial scales. The rates of shoreline change, however, are the most complex and poorly documented variable in this data set. The rates used here are based on a dated, low-resolution data set and thus far corrections have been made only on a preliminary level. To best understand where physical changes may occur, large-scale variables must be clearly and accurately mapped, and small-scale variables must be understood on a scale that takes into account their geologic, environmental, and anthropogenic influences. It forms part of the Northwest Atlantic Marine Ecoregional Assessment. For more information see http://nature.org/namera.

Coastal Vulnerability to Sea Level Rise seems to contain the same spatial information as the Coastal Vulnerability Index but with fewer attributes.

Shoreline Type These datasets comprise the Environmental Sensitivity Index (ESI) maps for the shoreline of New Hampshire, Massachusetts, Rhode Island, and Connecticut. ESI data characterize marine and estuarine environments and wildlife by their sensitivity to spilled oil. The ESI data include information for three main components: shoreline habitats; sensitive biological resources; and human-use resources. This dataset shows classified shorelines habitats and was derived from three separate ESI polygon feature datasets for the region. A coded domain identifies the shoreline types for the ESI classification values. Shoreline types include exposed rocky cliffs, exposed man-made solid structures, exposed wave cut platforms in bedrock, exposed scarps and slopes in clay, fine-medium grain sand beaches, scarps and steep slopes in sand, coarse grained sand beaches, mixed sand and gravel beaches, gravel beaches, riprap, exposed tidal flats, sheltered rocky shores, sheltered solid man-made structures, sheltered riprap, vegetated steeply sloping bluffs, sheltered tidal flats, vegetated low banks, salt and brackish water marsh, freshwater marshes, freshwater swamp, and scrub-shrub wetlands.

Full Metadata Record http://response.restoration.noaa.gov/book_shelf/855_MASS.pdf.

Please note that there are different attributes for different shoreline datasets.

A.5. Hydrography

A.5.1. Review of data provided

Chesapeake Bay Wetland Vulnerability These digital data files are derived from records of wetlands location and classification as defined by the U.S. Fish & Wildlife Service's National Wetlands Inventory (NWI) program. The classification is not shown in these datasets with only a yes or no as to whether it is a wetland and the level of wet risk.

Coastal Estuarine Watersheds contains classified land use information. More information may be here https://www.google.co.uk/url?sa=t&rct=j&q=&esrc=s&source=web&cd=2&cad=rja&ved=0CDgQFjAB&url=http%3A%2F%2Fcoastalsocioeconomics.noaa.gov%2Fcoastalgeospatial%2Fdocumentation%2Fcaf_full_metadata_d.html&ei=Zj5dUrDRGuGBiwLs-4HoBg&usg=AFQjCNHPNQtaVLbXEQ0SVDFpQtiyCf4WbQ but the website is not available because of the shutdown. Most land is shown as not estuarine with only around 5% (by number of polygons) listed as being ‘Bays and Estuaries’.

Lakes shows lakes over the whole study area. Attribute information contains the estuarine drainage area, the lake and river name.

Rivers RF1 show rivers for the whole study area with a large amount of attribute information that ties into the estuarine drainage area.

Upstream Fluvial Watersheds fits with the Coastal Estuarine Watersheds but shows fluvial watersheds instead. It has the same land use classification.

USFS Wetlands This data set represents the extent, approximate location and type of wetlands and deepwater habitats in the study area. These data delineate the areal extent of wetlands and surface waters as defined by Cowardin et al. (1979). Certain wetland habitats are excluded from the National mapping program because of the limitations of aerial imagery as the primary data source used to detect wetlands. These habitats include seagrasses or submerged aquatic vegetation that are found in the intertidal and subtidal zones of estuaries and near shore coastal waters. Some deepwater reef communities (coral or tuberficid worm reefs) have also been excluded from the inventory. These habitats, because of their depth, go undetected by aerial imagery. By policy, the Service also excludes certain types of "farmed wetlands" as may be defined by the Food Security Act or that do not coincide with the Cowardin et al. definition.

A.6. Benthic

A.6.1. Review of data provided

Sediment Sample Archive Data USGS From the metadata spreadsheet “This data layer is a point coverage of sediment samples collected by the U.S. Geological Survey Woods Hole Science Center's (WHSC) field operations. A geographical view of the samples in the WHSC's collections, and where they were collected along with images and hyperlinks to useful resources.”

Sediment Sample Calculated From the metadata spreadsheet “This data layer is a point coverage of known sediment samplings, inspections and probings from the usSEABED data collection and integrated using the software system dbSEABED. This data layer represents the calculated (CLC) output of the dbSEABED mining software. It contains results from calculating variables using empirical functions working on the results of extraction or parsing. The CLC data is the most derivative and certainly the least accurate; however, many clients appreciate that it extends the coverage of map areas with attributes, especially physical properties attributes.”

Sediment Sample Component Data Layer From the metadata spreadsheet “This component data layer (_CMP.txt) file gives information about selected components (minerals, rock type, microfossils, benthic biota) and seafloor features (bioturbation, structure, ripples) at a given site.”

Sediment Samples Extracted From the metadata spreadsheet “This data layer is a point coverage of known sediment samplings, inspections and probings from the usSEABED data collection and integrated using the software system dbSEABED. This data layer represents the extracted (EXT) output of the dbSEABED mining software. It contains data items which were simply extracted from the data resources through data mining. The EXT data is usually based on instrumental analyses (probe or laboratory) but may apply to just a subsample of the sediment (eg. no large shells).”

Sediment Sample Facies Data From the metadata spreadsheet “The facies data layer (_FAC.txt) is a point coverage of known sediment samplings, inspections, and probings from the usSEABED data collection and integrated using the software system dbSEABED. The facies data layer (_FAC.txt)represents concatenated information about components (minerals and rock type), genesis (igneous, metamorphic, carbonate, terrigenous), and other appropriate groupings of information about the seafloor. The facies data are parsed from written descriptions from cores, grabs, photographs, and videos, and may apply only to a subsample as denoted by the Top, Bottom, and SamplePhase fields. Lack of values in a defined facies field does not necessarily imply lack of the components defining that field, but may imply a lack of data for that field.”

Sediment Sample Parsed From the metadata spreadsheet “This data layer is a point coverage of known sediment samplings, inspections and probings from the usSEABED data collection and integrated using the software system dbSEABED. This data layer represents the parsed (PRS) output of the dbSEABED mining software. It contains the results of parsing descriptions in the data resources. The PRS data is less precise because it comes from word-based descriptions, but will include information on outsized elements, consolidation that are not usually in EXT data.”

Sediment Samples USGS From the metadata spreadsheet “This shapefile contains the locations of marine sediment samples collected and analyzed by the U.S. Geological Survey, Woods Hole Coastal and Marine Science Center starting in 1955 thru January 2011.”

Sediment Type As above?

Coastal Massachusetts Submerged Aquatic Beds

Delaware Bay Benthic Habitats

Massachusetts Sub-aquatic Vegetation

Salinity Zones for whole study area defined a mixing zones, seawater zones and tidal fresh zone.

Seagrass areas for whole study area. Additional yearly data available for download from http://web.vims.edu/bio/sav/gis_data.html.

Sediment Grain Size From the metadata spreadsheet “The sediment map of the Continental Margin Mapping Program (CONMAP) series is a compilation of grain-size data produced in the sedimentation laboratory of the Woods Hole Science Center (WHSC) of the Coastal and Marine Geology Program (CMGP) of the U.S. Geological Survey (USGS) and from both published and unpublished studies. Sediment was classified using the Wentworth (1929) grain-size scale and the Shepard (1954) scheme of sediment classification.”

Delaware Bay Sediment Distribution Grid of sediment distribution for Delaware Bay.

A.7. Boundaries

A.7.1. Review of data provided

The Coastal Shoreline Units dataset provides information on embayments although this is at a relatively coarse scale and these definitions are unlikely to be suitable for analysis purposes. As such embayments should otherwise be identified.

Boundaries	Type / Source	Description
NACCS Study Area		An outline of the study area.
Coastal Shoreline Units	Polyline	The coast of the study area divided up into shoreline units for management and analysis. Attribute information contains information on embayments and lagoons although this is shown as polylines.
Ecoregion Boundaries Line	Polyline	Part of the Northwest Atlantic Marine Ecoregional Assessment for the Northwest Atlantic Marine region. The attributes for boundary type for this dataset are all the same.
District boundaries	Polygon	Overall and divided into individual areas
NACCS Planning Reach Polygons	Polygon	NACCS planning reaches. Also supplied for August 2013
Coastal Assessment Framework	Polygon	Full metadata for this dataset available at http://geodata.lib.ncsu.edu/fedgov/noaa/estuary_bath/Pamlico%20Sound/caf_water.html
BOEM Baseline Tangents	Line	“This data set contains baseline tangent lines in ArcGIS shapefile format for the BOEMRE Atlantic Region. Baseline tangent lines are typically bay or river closing lines used by the BOEMRE to calculate the Submerged Lands Act (SLA) boundary, the Limit of '8(g) Zone', and other offshore boundary lines.”
County Laterals	Polyline	County Laterals
State Laterals	Polyline	State Laterals
Limit of OCSLA 8g zone	Polyline	“This data set contains the Limit of '8(g) Zone' line in ESRI shapefile format for the BOEMRE Atlantic Region. The '8(g) Zone' lies between the Submerged Lands Act (SLA) boundary line and a line projected 3 nautical

Boundaries	Type / Source	Description
		miles seaward of the SLA boundary line. Within this zone, revenues are shared with the coastal state(s)."
Official Protraction Diagram Outlines	Polygon	"This data set contains Official Protraction Diagram (OPD) outlines in ESRI shapefile format. Atlantic Region OPDs are approximately 2 degrees wide by one degree high."
Submerged Lands Act	Polyline	"This data set contains the Submerged Lands Act (SLA) boundary line (also known as State Seaward Boundary (SSB), or Fed State Boundary) in ESRI shapefile formats for the BOEMRE Atlantic Region. The SLA boundary defines the seaward limit of a state's submerged lands and the landward boundary of federally managed OCS lands. In the BOEMRE Atlantic Region it is projected 3 nautical miles offshore from the baseline."

A.8. Census

A.8.1. Review of data provided

Environmental HTRW	Type / Source	Description
2010 Census	Polygon	Census data at varying levels of spatial resolution - by tracts, counties and states
Population Growth Estimates for states	Polygon	Estimates in population growth provided individually by state.

A.9. Economic

A.9.1. Review of data provided

Economic	Type / Source	Description
Chesapeake Bay Transportation Risk Lines	Polyline	Risk lines for Chesapeake Bay transportation
Chesapeake Bay Socioeconomic Risk Areas	Polygon	Socioeconomic risk areas for Chesapeake Bay
NACCS Social Vulnerability Index	Polygon	NACCS Social Vulnerability Index

A.10. Environmental HTRW

A.10.1. Review of data provided

Environmental HTRW	Type / Source	Description
EPA Regulated Facilities	Point	EPA Regulated Facilities
National Water Information System Stations	Point	National Water Information System Stations
NERACOOS Buoys	Point	Northeastern Regional Association of Coastal and Ocean Observing Systems
Chesapeake Bay Cumulative Ecological Resources	Polygon	Chesapeake Bay Cumulative Ecological Resources
NACCS Environmental Risk Index	Polygon	NACCS Environmental Risk Index

A.11. Green Infrastructure

A.11.1. Review of data provided

Green Infrastructure	Type / Source	Description
Coastal Energy Generation Facilities	Point	Facilities classified by fuel, capacity, input and generation.
Permitted Cape Cod Wind Power Sites	Point	Location of sites
Tidal Hydrokinetic Energy Generation Sites	Point	Sites classed by status, capacity, production, licensee and waterway
Wave Hydrokinetic Energy Generation Sites	Point	Empty dataset

A.12. Marine Animals

A.12.1. Review of data provided

Marine Animals	Type / Source	Description
Chesapeake Bay Aqua Culture Sites	Point	Named aquaculture locations
Chesapeake Bay Aquacuture Sites	Point	Seems to be a duplicate of Chesapeake Bay Aqua Culture Sites
NE Bird Nesting Sites	Point	Locations of bird species with months of the year
Sea Turtle Nest Locations	Point	Includes name, nest numbers and date information.
Maryland Darter Critical Habitat	Line	One record, a multi-part feature.
Adult Clearnose Skate	Polygon	One record, a multi-part feature
Adult Little Skate	Polygon	One record, a multi-part feature
Adult Thorny Skate	Polygon	One record, a multi-part feature
Adult Winter Skate	Polygon	One record, a multi-part feature
American Plaice	Polygon	One record for each age stage
Atlantic Cod	Polygon	One record for each age stage
Atlantic Halibut	Polygon	One record
Atlantic Herring	Polygon	One record for each age stage
Chesapeake Bay Private Oyster Lease Sites	Polygon	Location and extent of private lease sites
Green Sea Turtle Nesting Areas	Polygon	Months of the year and other nesting information
Haddock	Polygon	One record for each age stage
Juvenile Clearnose Skate	Polygon	One record, a multi-part feature
Juvenile Little Skate	Polygon	One record, a multi-part feature
Juvenile Smooth Skate	Polygon	One record, a multi-part feature
Juvenile Thorny Skate	Polygon	One record, a multi-part feature
Juvenile Winter Skate	Polygon	One record, a multi-part feature
Large Pelagic Fish	Polygon	Attributes describe presence of various species in grid squares
Leatherback Turtle Nesting Areas	Polygon	Months of the year and other nesting information
Loggerhead Turtle Nesting Areas	Polygon	Months of the year and other nesting information

Marine Animals	Type / Source	Description
Monkfish	Polygon	One record for each age stage
NE Bird Habitat	Polygon	Multiple species and locations. Includes months
NE Cetacean Habitat	Polygon	Multiple species and locations. Includes months
NE Multispecies Essential Fish Habitat Protected Areas	Polygon	Single record
NE Shellfish Habitat	Polygon	Multiple species
North Atlantic Right Whale Critical Habitat	Polygon	Single record
Ocean Pout	Polygon	One record for each age stage
Plymouth Red Bellied Turtle Critical Habitat	Polygon	Single record
Pollock	Polygon	One record for each age stage
Red Hake	Polygon	One record for each age stage
Redfish	Polygon	Single record, multipart feature
Sea Scallop	Polygon	Single record
Shellfish Classified Areas	Polygon	Restrictions or prohibitions
Shellfish Growing Areas	Polygon	Records of growing areas and types of shellfish
Silver Hake	Polygon	One record for each age stage
White Hake	Polygon	One record for each age stage
Window Pane Flounder	Polygon	One record for each age stage
Winter Flounder	Polygon	One record for each age stage
Witch Flounder	Polygon	One record for each age stage
Yellowtail Flounder	Polygon	One record for each age stage
Zooplankton 1970 Fall	Polygon	Multiple records with counts
Zooplankton 1970 Spring	Polygon	Multiple records with counts
Zooplankton 1970 Summer	Polygon	Multiple records with counts
Zooplankton 1970 Winter	Polygon	Multiple records with counts
Zooplankton 1980 Fall	Polygon	Multiple records with counts
Zooplankton 1980 Spring	Polygon	Multiple records with counts
Zooplankton 1980 Summer	Polygon	Multiple records with counts
Zooplankton 1980 Winter	Polygon	Multiple records with counts
Zooplankton 1990 Fall	Polygon	Multiple records with counts
Zooplankton 1990 Spring	Polygon	Multiple records with counts
Zooplankton 1990 Summer	Polygon	Multiple records with counts

Marine Animals	Type / Source	Description
Zooplankton 1990 Winter	Polygon	Multiple records with counts
Zooplankton 2000 Fall	Polygon	Multiple records with counts
Zooplankton 2000 Spring	Polygon	Multiple records with counts
Zooplankton 2000 Summer	Polygon	Multiple records with counts
Zooplankton 2000 Winter	Polygon	Multiple records with counts

- A duplicate feature class (Chesapeake Bay Aquacuture Sites).
- Some of the feature classes have only one record which is a multi-part feature.

A.13. NACCS Problem Areas

A.13.1. Review of data provided

NACCS Problem Areas	Type / Source	Description
NACCS Problem Area Points	Point	Points identified as problem areas

A.14. Sandy Storm Impact data

A.14.1. Review of data provided

Civil Air Patrol Damage Assessment Photo Locations shows point locations of photographs taken to assess the damage done by Sandy. The data contains a http link to the photos and these links work. Most of the points are located in the middle and north of the study area but there are a few to the south.

FEMA Inundated Schools Depth metadata indicates that this all schools but the spatial extent suggests that this is not the case and that it shows only those inundated as a result of Sandy. The units for the depth of inundation are not specified. This information http://fema-services2.esri.com/arcgis/rest/services/2012_Sandy/InundatedSchools_StormSurge/MapServer/0 suggests that feet have been used.

FEMA County Storm Impact Analysis is a composite surge / precipitation / wind map.

“A composite of surge, wind, precipitation and snow impacts are used to assess impacts for each County. Surge is the primary driver of the severe impacts as a result of Hurricane Sandy and the relative impact assessment is summarized as follows:

Class	Description
Very High (Purple):	Greater Than 10,000 of County Population Exposed to Surge
High (Red):	500 - 10,000 of County Population Exposed to Surge, or Modelled Wind Damages > $100M, or High Precipitation (>8”)
Moderate (Yellow):	100 - 500 of County Population Exposed to Surge, or Modelled Wind Damages $10 - $100M, or Medium Precipitation (4” to 8”)
Low (Green):	No Surge Impacts, or Modelled Wind Damages < $10M, or Low Precipitation (<4”)

Population and Household Exposure values are derived by area weighting using the interim high resolution field-verified surge extents for New Jersey, New York, Connecticut, and Rhode Island and 2010 census blocks. All other coastal state exposure numbers are based off of the interim low resolution surge extent and 2010 census blocks.” http://www.arcgis.com/home/item.html?id=307dd522499d4a44a33d7296a5da5ea0

FEMA Sandy Storm Surge Maximum Extent shows the maximum extent of the storm surge

A.15. Sea Level Change

A.15.1. Review of data provided

The sea level rise datasets cover the same gauges but have different values in the same attribute columns for the gauges. These values match those for the years 2018, 2068, 2100 and 2118.

Vessel Navigation	Type / Source	Description
SLR Gages 1, 2, 3, 4	Point	Sea level rise values for various scenarios

A.16. Vessel Navigation

A.16.1. Review of data provided

Vessel Navigation	Type / Source	Description
Artificial Reefs	Point	Shows artificial reefs as points but there is an error when the trying to view the attribute information.
Deepwater Ports	Point	contains no points
NE Wrecks and Obstructions	Point	Shows wrecks and obstructions for the northern part of the study area.
Principal Ports	Point	Show principal ports as point data with information about tonnage and commodities.
UXO Location	Point	Shows point data of unexploded ordnance in MA.

B. Geomorphological characterisations

B.1. Assateague Island and Ocean City

SITE	Assateague Island and Ocean City
AUTHORITIES	Maryland (northern two thirds), Virginia (southern third)
GENERAL	The coastline along Assateague Island, at the south of the Ocean City Inlet, extends approximately 37 miles. The principal towns are Ocean City and Chincoteague on the Barrier Island. The closest towns inshore of the island are Berlin, Snow Hill and Temperanceville. The long and linear barrier island is indicative of a wave-dominated regime. Development in this region ranges from none to urban.
PROTECTION AREAS	The Maryland section contains the majority of Assateague Island National Seashore and Assateague State Park. The Virginia section contains Chincoteague National Wildlife Refuge and a small part of the national seashore.
STUDY UNIT	The study unit (shown in Figure 1) considers the whole of the barrier island together with the hinterland behind. Offshore it goes beyond the depth of closure, which although quite variable in the area it has an average value of -6m (OCTI, 2010).
BEACHES	Sandy beaches composing the barrier island shoreline with dune ridges separated by washover-dominated low areas. With the exception of the inlet jetties and some small groynes at ocean city, there are no shore-perpendicular structures in this area.
BACKSHORE	There are some hardened backshores, including seawalls and revetments protecting houses and tourist infrastructure.
TRANSPORT RATES	The subaerial vs subaqueous volume analysis carried out by OCTI, 2010 showed that for Assateague Island longshore processes are more important than cross-shore ones (the opposite applies north of the Ocean City Inlet). The natural and artificial bypass add sand while erosion and overwash remove sand. Net longshore transport is to the South and the sediment volume is estimated at 153,000 m3/yr (Leatherman et al 1987). The ebb-tidal delta captured an estimated 6,000,000m3 of sediment (Galgano (2007)), thus depriving the downdrift beaches of sand. OCTI, 2010 predicts a natural bypassing rate at Ocean City Inlet of 95,000m3/yr up until 1996 and 80,400yd3/yr for the 1995-2008 epoch.

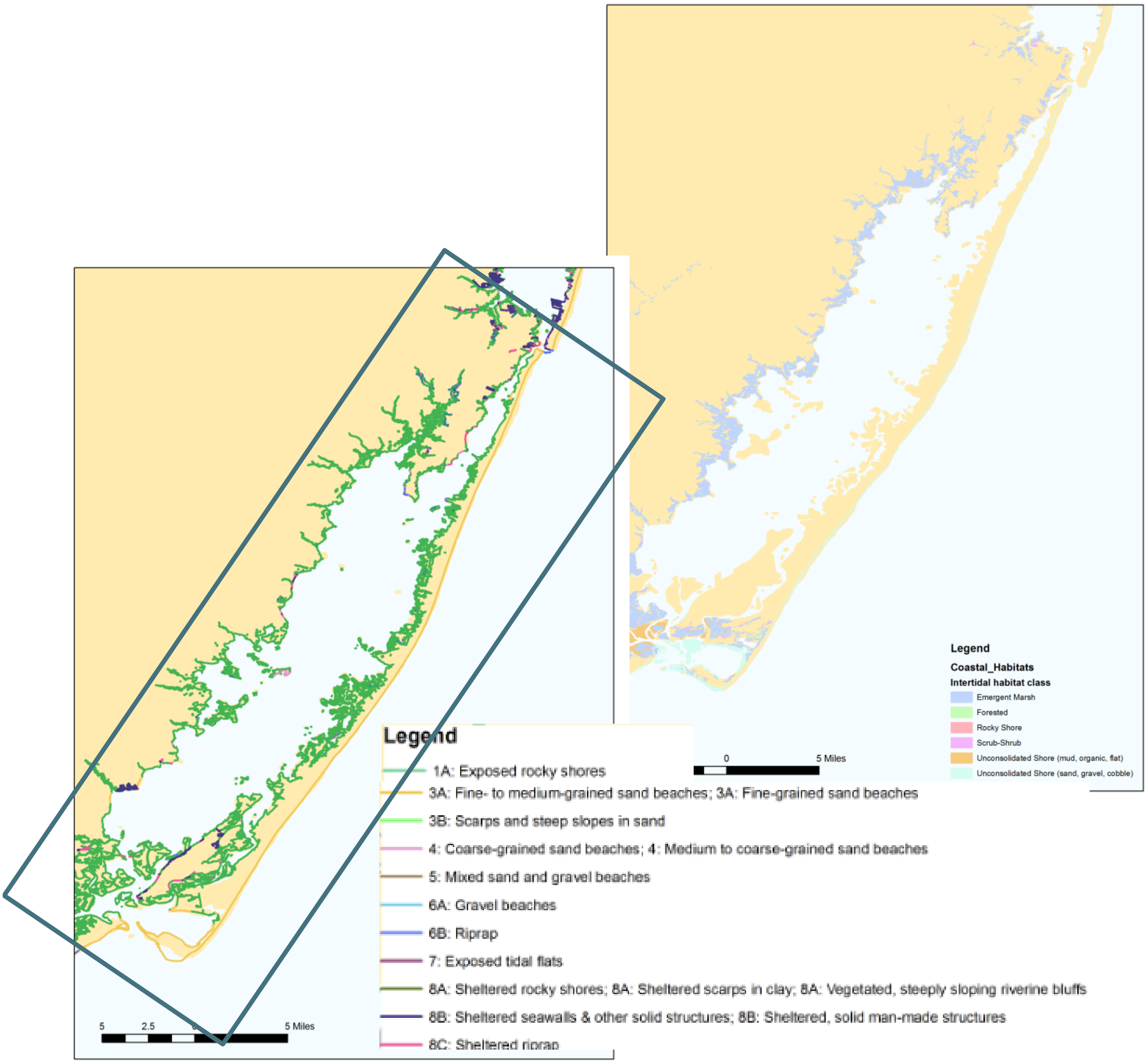
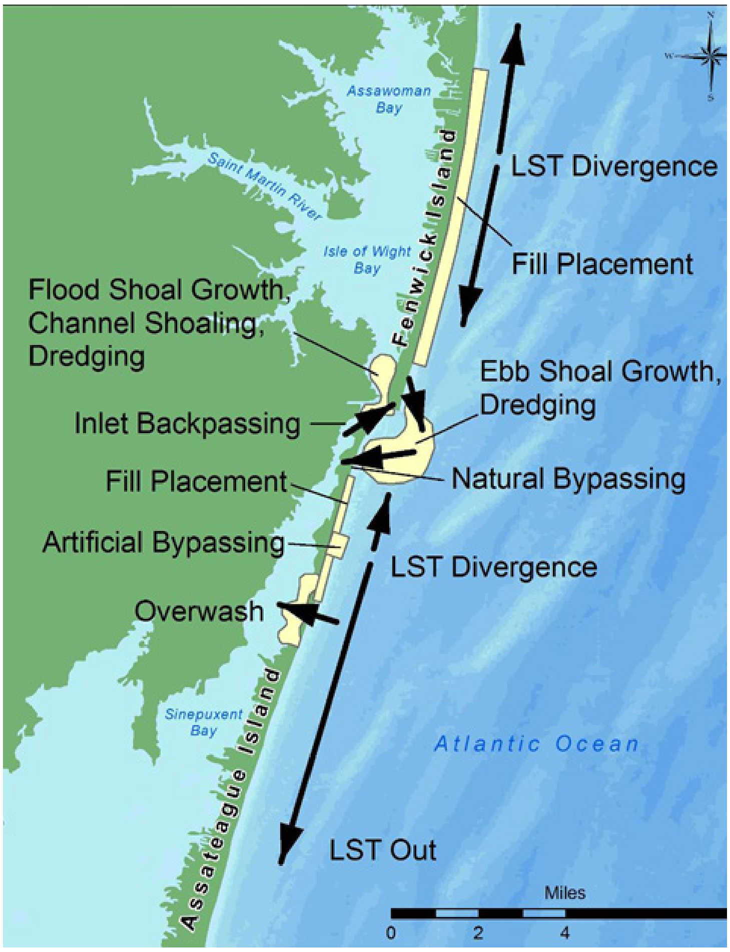


Figure B.1: Shoreline types and Coastal habitats for Assateague Island and Ocean City

Source: HR Wallingford

SITE	Assateague Island and Ocean City (Continuation)
EROSION	Long term rates of change were calculated by USGS(2010) as an average of -0.5m/yr for the whole of the Delmarva North region. They also reported a maximum erosion rate of -6.2m/yr about 1.5m south of Ocean City inlet. Downdrift erosion has been severe south of the inlet as reported by Galgano (2007) as extending for 16km: • Previous to the existence of the inlet, the historic background trend was -0.6m/yr (or -1.5m/yr according to Schupp (2007). • After stabilising the inlet, the rate of erosion accelerated to -9.3m/yr along the beach just S of the inlet. This has made the northern segment of Assateague island to displace ladward by nearly three barrier island widths. (or -3.7m/yr according to Schupp (2007). Letherman et al, 1987 states that if left unchecked, the erosion of northern Assateague Island may cause it to merge with the main shoreline within the next 10-15yrs.
LITTORAL PROCESSES	Since the jetties were built in 1935, unnatural erosion and accelerated shoreline migration has been occurring on the northern Assateague Island
SEDIMENT BUDGET	

SITE	Assateague Island and Ocean City (Continuation)
AREAS OF FLOOD RISK	According to National Hurricane centre (http://www.baltimoresun.com/news/maryland/eastern-shore/bal-hurricane2003,0,7880742.story) Ocean City town could survive a Category 1 (sustained winds of 74mph to 95 mph) or even a Category 2 (96 mph to 110 mph). Anything stronger and it would be inundated.
ENGINEERING WORKS, BYPASSING AND RENOURISHMENTS	Assateague Island was connected to the lowest point of Fenwick Island until a hurricane in 1933 created an inlet separating two landforms. A permanent system of artificial jetties was then constructed, hindering the natural siltation that would have closed the inlet. Other engineering works include: • the rehabilitation of Ocean City inlet jetty in 2002 (mainly by placing quarry stone and raising the crest elevation); • sand by-passing from the ebb/shoal to Assateague Island . Since 2004, there is a periodical bypassing of 138,000m3/yr to northern Assateague Island. The borrow area is the ebb shoal, supplemented by the flood shoal and an offshore site. The sand is placed nearshore at 3 to 4.5 m depth. • berm reconstruction (mainly spot fixes, in 1998 and 2002 to lower the potential for breaching and in 2003 to protect park infrastructure); and • periodic maintenance of the navigation channels.

B.2. Long Beach Island, NJ

SITE	Long Beach Island, NJ
AUTHORITIES	New Jersey
GENERAL	Long Beach Island is located in the southern portion of the barrier islands of New Jersey, just south of where the general shoreline orientation changes from north-northeast to northeast direction. The 32 km long barrier island separates the Atlantic Ocean from three shallow bays extending along the western side of the island (Barnegat, Manahawkin and Little Egg Harbor Bays from N to S). The oceanfront along Long Beach island is developed entirely for residential use. The bay side of the island has residential development, commercial marinas and numerous boat ramps (USACE, 2000). The main towns and townships are Barnegat light, Borough of Beach Haven, Harvey Cedars, long Beach Township, Ship Bottom and Surf City.
PROTECTION AREAS	Barnegat Lighthouse State park at the N of the island and the Forsythe national Wildlife Refuge at the S.
STUDY UNIT	Long Beach Island boundaries are: at the North Barnegat Inlet and on the South by Little Egg Inlet. The average width of the island is approximately 2100 feet. The bay edges are frequently guarded by tidal wetlands. Landward of the barrier beaches and inlets there are tidal bays which range from 3 to 5 miles in width. Natural processes have filled these bays until much of the area is covered by tidal marshes.
BEACHES	The beach strand is comprised of quartz sand with a d_{50} of roughly 0.35mm. The intratidal and swash zone has a slope of about 1:11. The widths of the beach berm along the length of the island are highly variable over time, due to the presence of groynes which compartment the beach along the entire developed ocean frontage. The beaches of Long Beach Island are typically narrower and steeper than the beaches on the barrier islands at the south
OFFSHORE	The offshore bathymetry includes a finger-like shoal features which extend out from the shoreline in a northeasterly direction.
TRANSPORT RATES	A generally accepted estimate of net sediment transport along long Beach Island is approximately 75,000-150,000m3/year towards the south (USACE, 2000). However, estimates range from 40,000 to 4,000,000 m3/year (USA Engineer District, Philadelphia, 1999). There is a local area of reversal near Barnegat inlet. It is worth noting that most beaches North of Long Beach Island, beyond the influence of Barnegat inlet, experience a net littoral drift to the North.

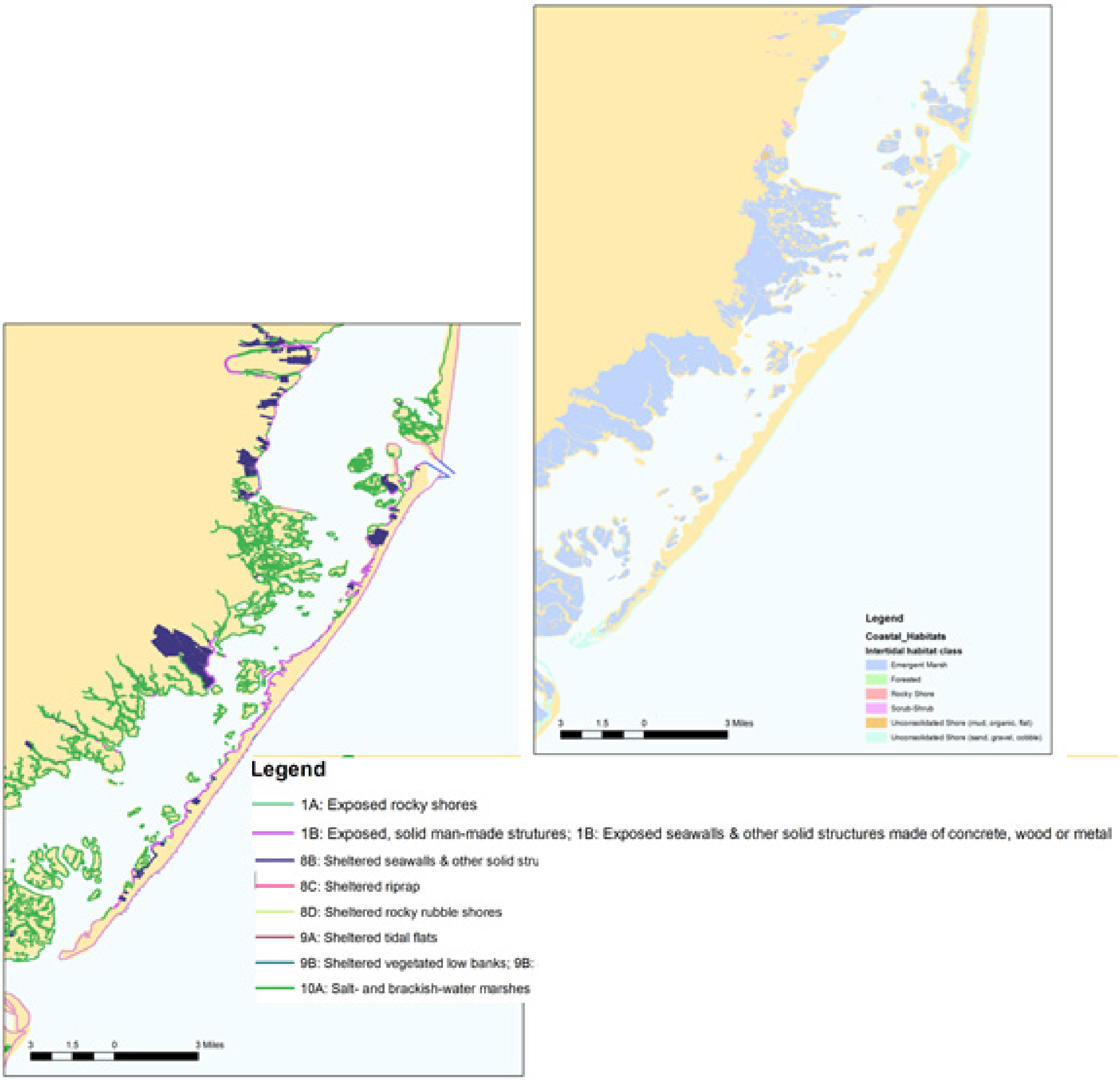


Figure B.2: Shoreline types and Coastal habitats for Long Beach Island, NJ

Source: HR Wallingford

SITE	Long Beach Island, NJ (Continuation)
ENGINEERING WORKS, BYPASSING AND RENOURISNMENTS	Barnegat Inlet has been a federally maintained inlet since 1940 with the completion of rock jetties both sides. A new south jetty was completed in 1991 to overcome design deficiencies of the first one and the shoaling and channel instability. Both jetties are nearly parallel and aligned in a roughly NW-SE orientation. Since the early '70s there have been a total of 101 groyne structures placed at intervals between 750 to 1000 feet. At various time during the year certain groynes are covered by sand. Their lengths range from 250 to 420 feet, and are constructed of timber or stone and in some cases a combination of both.
HISTORICAL DATA	USACE (2000) analysis of the area (1839-1997) indicates a relatively stable shoreline, with brief periods of erosion which are followed by a quick recovery.
RESPONSE TO EXTREME STORMS	The NJ coastline, including Long Beach Island has a long history of severe erosion subjecting the shoreline to storm damage from wave attack and coastal inundation (USACE, 2000). The March storm of 1962 created several overwash inlets on Long Beach Island, the largest of which was in Harvey Cedars. Emergency dune work and beach replenishment was carried out for nearly the entire length of Long Island Beach. Most of the groynes were also constructed in response to this storm, as the timber bulkhead and gravel-filled dike were destroyed by the storm. Beach berm restoration and dune replenishment took place in August 1978 following a coastal storm in 1978. The coastal storm of December 1992 produced overwashes in Beach Haven, Brant Beach and Harvey Cedars.

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C. Empirical coastal dune erosion model

This appendix describes the dune erosion model used in this study, its background and its validation in the area with Hurricane Sandy data.

C.1. Dune erosion modelling background

Dune erosion processes during major storm events with relatively high surge levels have been the focus of several experiments carried out in the large-scale Deltaflume of Delft Hydraulics over the years (Delft Hydraulics, 2004, 2006a,b, van Gent et al, 2008) since the initial experiments by Vellinga (1986). The experimental data typically represent beach and dune erosion conditions along the Dutch North Sea coast during a very severe storm. The results from the experiments have formed the basis of the development of several dune erosion models with different degrees of complexity:

- DUROS+: Vellinga's (1986) empirical model for the eroded bed profile, which was later improved by others (Deltares, 2007);
- CROSMOR2007 model: as a wave by wave process based profile model, based on the TRANSPOR2004 sand transport formulations; and,
- DUNERULE-model: the results of a sensitivity study based on the CROSMOR model runs have been used to develop a simplified erosion rule.

On the other hand, in the USA a couple of models have been developed in order to represent the dune response processes under storms:

- The Storm-induced BEAch CHange model (SBEACH) is a numerical simulation model of cross-shore beach, berm, and dune erosion produced by storm waves and water levels (Larson and Kraus, 1989); and
- Larson et al (2004) presented a simple analytical model to describe the erosion and recession of coastal dunes impacted by high waves and water levels during severe storms in order to overcome the input data requirements for numerical modelling.

C.2. Modelling approach

For the present conceptual numerical model, an empirical model for dune erosion has been adopted (DUROS+) and adapted to the case of Long Beach Island, NJ, based on the measured dune profiles before and after Sandy (Stockton, 2012). The empirical model has been chosen due to its simplicity and relatively good fit to the available data. The adaptation of DUROS+ is justified as the experiments carried out in the Deltaflume were designed for dune profiles along the Dutch North Sea Coast and the forcing conditions were such that erosion was maximised.

Description of the dune erosion profile

The dune erosion profile as calculated by the adapted empirical model has three parts:

- From the limit of the run up upwards: the erosion profile adopts a slope of 1V:3H until it meets the original profile; and
- From the limit of the run up downwards up until the maximum reach: the profile adopts an exponential form, as given by the DUROS+ empirical formula:

$$y = 0.4714\left(\frac{H_{s,o}}{7.6}\right)\left(\left(\frac{7.6}{H_{s,o}}\right)^{1.28}\left(\frac{12}{T_p}\right)^{0.45}\left(\frac{w_s}{0.0268}\right)^{0.56} x + 18\right)^{0.5} - 2$$

where:

x is the distance from new dune foot origin,

y is the depth below the storm surge level,

$H_{s,o}$ is the significant wave height at deep water,

T_p is peak wave period, and

w_s is the fall velocity of sand in seawater.

The origin (x=0, y=0) is defined as the intersection of this equation and the storm surge level.

- From the maximum reach downwards until the intersection with the original profile, the erosion profile adopts a 1V:12.5H slope.

The two intersection points of the calculated profile are defined by:

- Run-up limit: as used in CROSMOR2007 formulation and given by van Rijn (2008), the run-up level associated with significant waves is estimated by:

$$R_s = 0.4H_{s,o}\tanh(3.4\xi_o)$$

where

R_s is run-up level exceeded by 33% of the waves,

$H_{s,o}$ is the significant wave height in deep water, and

ξ_o is the Iribarren number as defined by ξ_o=($H_{s,o}$/ $L_{s,o}$)$^{-0.5}$ tanb, where b is the beach slope and $L_{s,o}$ is the wave length in deep water.

- The maximum reach of the profile is firstly calculated by DUROS+ formulation and then optimised do that the areas of erosion and accretion match.

C.3. Validation of the adapted dune erosion profile

The adapted dune erosion profile was validated with measured profiles before and after Sandy from the Richard Stockton College of NJ Coastal Research Centre (CRC) (Stockton, 2012). The data collected includes profile surveys during the fall of 2012 and post-storm surveys carried out on the 1st and 2nd of November 2012. These profiles were supplemented with offshore bathymetric data (see Appendix A).

Profile monitoring sites

The New Jersey beach Profile Network (NJBPN) monitoring sites comprise of 14 beach profile locations covering the municipal beaches from Barnegat Light to the entrance of the Holgate Forsythe National Wildlife Refuge (including the three constructed USACE engineered beaches in Harvey Cedars, Surf City and Brant Beach). Figure C.1 below shows a map with the location of each profile.

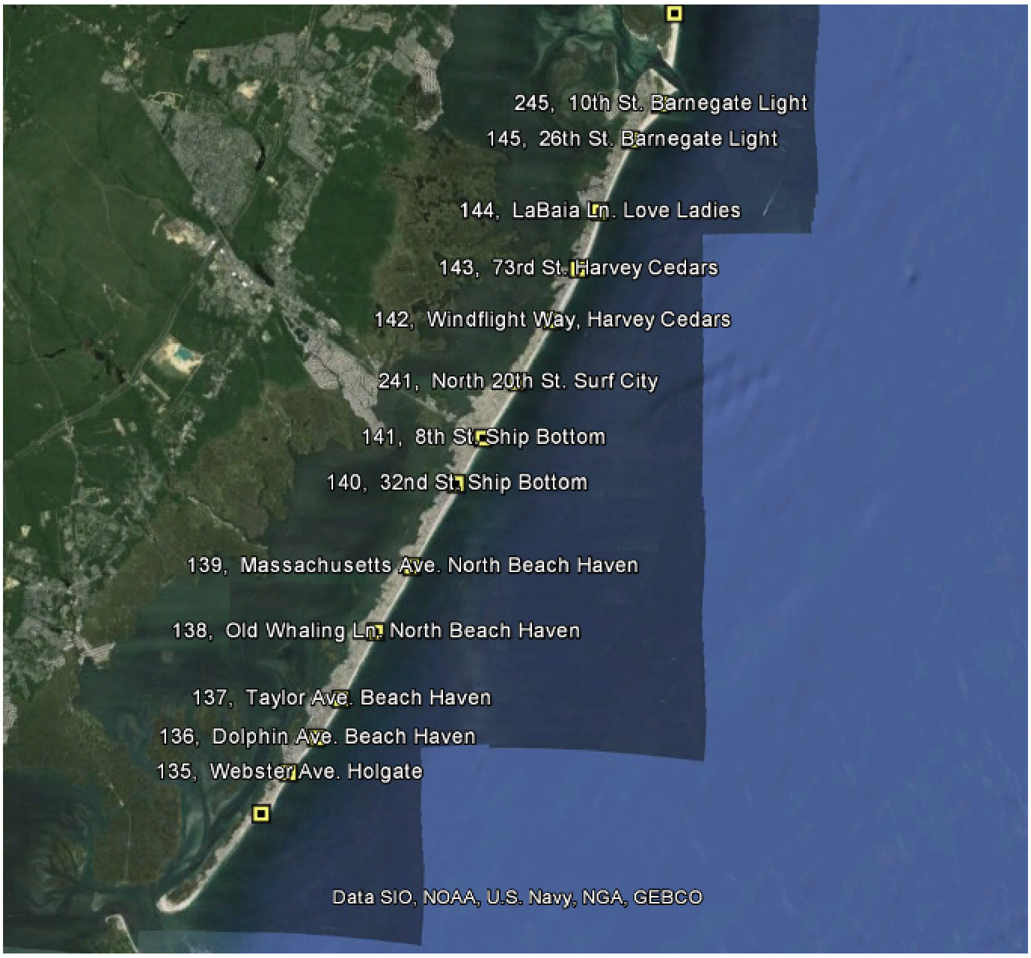

Figure C.1: The New Jersey beach Profile Network (NJBPN) monitoring sites

Source: Google Earth with information from Richard Stockton College of NJ Coastal Research Centre (CRC) (Stockton, 2012)

Some of these profiles have been surveyed for 24 years, but for this study only the surveys pre and post Hurricane Sandy have been considered. The post- Sandy surveys only covered the dry part of the beach, whereas the pre-Sandy ones extend to a depth of about 15 to 20 feet. In general terms, Stockton (2012) data shows that beach erosion due to Hurricane Sandy was significantly worse on the North side of the barrier island.

Six profiles of the 14 monitored by the CRC have been considered in this study; the selection covering both profiles which had been replenished and profiles which had not been (Table C.1 below). Two of these profiles that had not been replenished failed (in terms of dune failure such as breaching, overwash and severe erosion), whereas another two remained unfailed (with considerable erosion of the dune which lowers in elevation and a flattened beach, but no overwash).

Table C.1: NJBPN Profiles considered in this study

Profile number	Dune failure after Hurricane Sandy	Recent beach fill
245	N	N
142	N	Y
241	N	Y
141	N	N
139	Y	N
137	Y	N

Source: Stockton, 2012

Although the NJBPN survey database is a very good set of data , the fact that the profiles post-Sandy only cover the sub-aerial part of the profile means that assumptions on where the eroded sand is deposited have had to be made without validation data.

Validation of the empirical dune erosion model

The empirical dune erosion profile requires very simple inputs in terms of wave conditions and storm surge level, so that only single values and not time series are needed. The additional variable apart from wave conditions and storm surge needed is the fall velocity of sand in water, which can be calculated from the sediment size. Although it is recognised that such values would have varied along the coast, for the validation of this simple model, constant values have been used. Sensitivity analysis on the effect of the input conditions was also carried out in order to ascertain the influence of the input variables and its variability to the predicted profile.

The input values used for the validation of the dune erosion model for all six profiles are specified in Table C.2 below. The initial beach and dune profile in each case would have been the pre-Sandy measured profile (complemented with additional bathymetry information).

Table C.2: Input values for validation case

Variable	Value
Wave height	7.4m
Wave period	14.0s
Storm surge	1.68m
Fall velocity of sand in water (Calculated from a sediment size of)	0.0125m/s (0.152mm)

Source: Wave height and wave period: maximum recorded wave heights and periods during Hurricane Sandy by the Coastal Data Information Program (CDIP) and the National Data Buoy Center (NDBC), as reported for example by USACE 2013. Sediment size from an analysis of the data presented in Appendix A

Post-Sandy measured profiles were then compared with calculated ones by the empirical model and a series of modifications were done on the original formulation in order to improve the methodology. These improvements are justified as the original DUROS+ methodology was derived from physical models in the Deltaflume designed for dunes characteristic of the Dutch North Sea Coast combined with forcing conditions such that erosion was maximised.

The main differences between the original DUROS+ methodology and the adapted method used here are:

- The starting point of the exponential shape of the developed profile starts at the storm surge level for both cases, but in the adapted methodology the exponential profile extends upwards to the run-up limit;
- The developed dune front is assumed to have a slope of 1V:3H rather than the 1V:1H slope of the original method; and
- The extent of the exponential profile is not calculated by the original formulation, but just initialised to that value and then optimised by the matching of the eroded and accreted areas.

The results with the adapted methodology for the Hurricane Sandy conditions for the six profiles used within this study are shown in Figure C.2 to Figure C.7 below. For the non-failed cases (Profiles 245, 142, 241 and 141) the results (except for profile 245) are reasonable, predicting the position of the cutback of the dune reasonably well, the forefront of the dune reasonably well and the start of the exponential shape of the profile reasonably well. The calculated accretion for the submerged part of the profile cannot be validated as the measured data does not include this part. For the failed cases (profiles 139 and 137) the adapted model does not predict the failure because is not designed to do so (due to the fact that the experiments the methodology is based on did not fail). However, the shape of the developed profile in these cases follows the measured profile quite well up to the limit of the run-up. The methodology would need to be improved to account for failure of dunes mechanism. One simple way of doing this would be by calculating the eroded profile as is presently done and introducing a threshold of dune volume, so that if the calculated dune foreshore volume is bigger than the threshold, the dune is not expected to fail and if smaller than such threshold the dune will fail. This threshold of dune volume could be based on the FEMA dune failure criterion (OCTI, 2010) which establishes the volume of the frontal dune reservoir, defined as the volume of material above the 1 per cent annual chance stillwater elevation to the dune crest (or landward dune shoulder). If the frontal dune reservoir is less than 20 yd^3/ft (540 ft^2), the dune is failed and removed from profile for overland wave propagation modelling. If the frontal dune reservoir is greater than 20 yd^3/ft, the dune “survives” and the profile and dune are eroded, referred to as a “retreat case”.

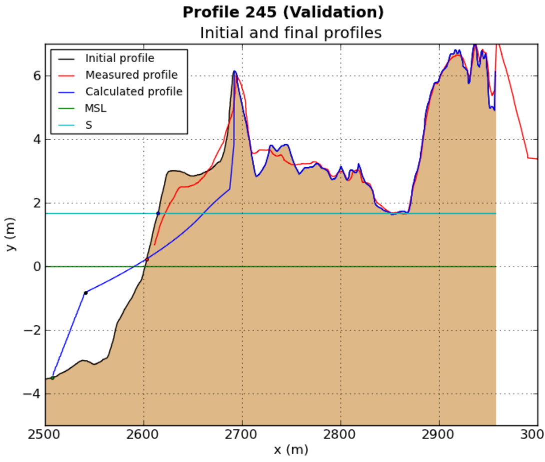

Figure C.2: Profile 245 validation results

Source: HR Wallingford calculated results with Stockton (2012) measured data

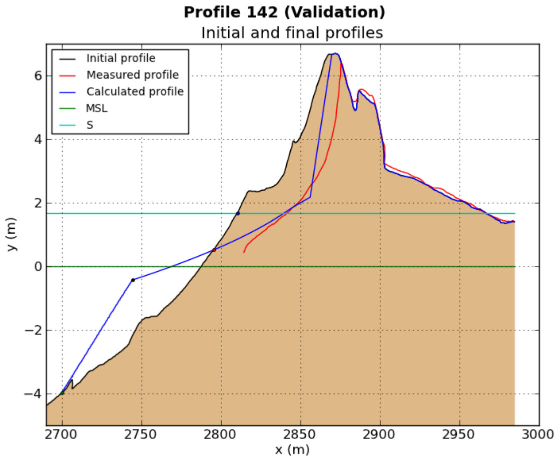

Figure C.3: Profile 142 validation results

Source: HR Wallingford calculated results with Stockton (2012) measured data

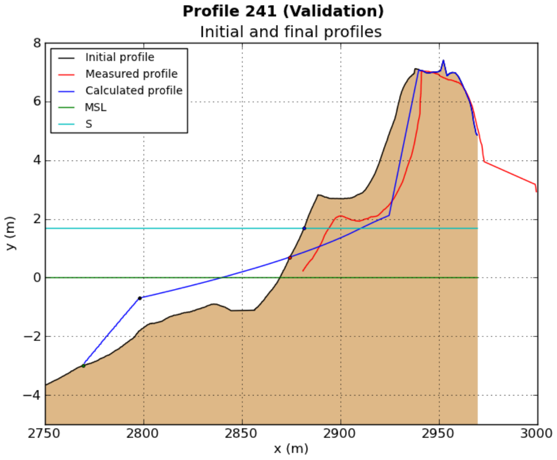

Figure C.4: Profile 241 validation results

Source: *HR Wallingford calculated results with Stockton (2012) measured data*

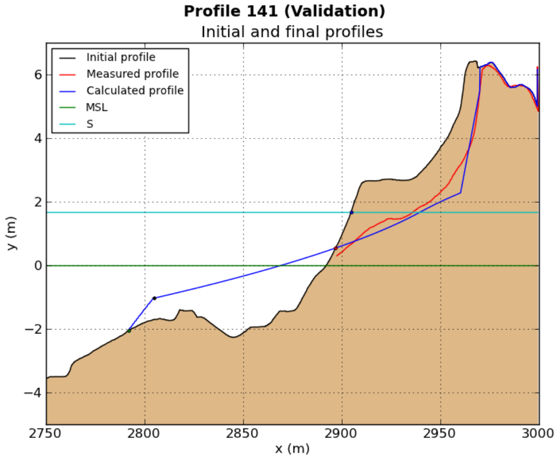

Figure C.5: Profile 141 validation results

Source: *HR Wallingford calculated results with Stockton (2012) measured data*

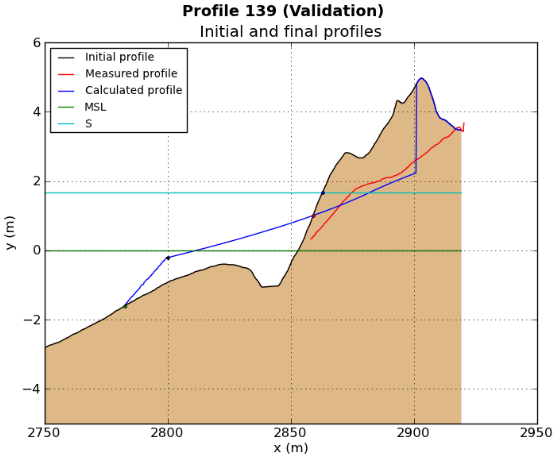

Figure C.6: Profile 139 validation results

Source: *HR Wallingford calculated results with Stockton (2012) measured data*

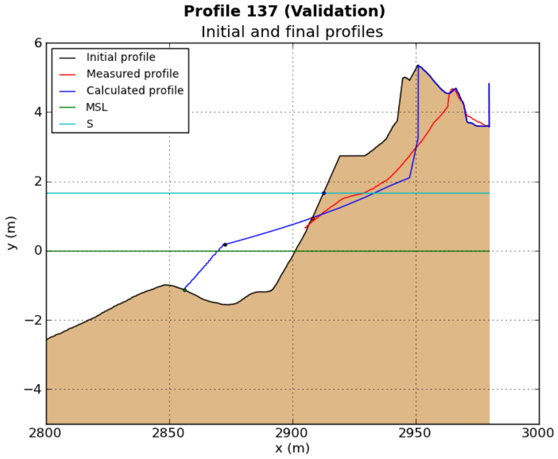

Figure C.7: Profile 137 validation results

Source: *HR Wallingford calculated results with Stockton (2012) measured data*

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