Hazard assessment is an essential first step of the overall risk assessment process. It involves gathering and analyzing data on meteorological, hydrological and geological hazards in terms of their nature, frequency and magnitude. Hazard assessment is characterized by triggering factors, degree of severity, spatial occurrence, duration of the event and their relationship (UNDP Myanmar et al, 2011).

The priority hazards within the scope of this project include:

1. Storm surge and Wave overtopping
2. Sea Level Rise
3. Coastal Erosion

A detailed description of the methodologies, data used and hazard maps are presented in subsequent sections.

3.1 Storm Surge Hazard Assessment

Storm surge is an uncharacteristic increase in water levels generated by a storm, which is above the predicted astronomical tides. Storm surge is caused primarily by the strong winds in a hurricane or tropical storm. This rise in water level can cause extreme flooding in coastal areas, especially when storm surge coincides with normal high tide, resulting in storm tides where the water may reach levels of up to 20 feet or above mean sea level (msl).
Methodology

Figure XXX shows the methodology for storm surge modeling for various return periods. The methodology for storm surge and sea level rise mapping has been developed using both primary and secondary data.

Data Collection

Anecdotal Storm Surge Survey

Structured questionnaires were administered to 280 persons who live and/or work in Negril. The interviews focused primarily on major storms experienced and areas with greatest impact, height of storm surge, damage and losses, width of beach erosion experienced at discrete locations, and the time to recovery of shoreline associated with different hurricane events. The locations of the interviews and observations of storm surges were referenced geospatially.

Bathymetric Survey

Storm Surge and wave heights on shore are affected by the configuration and bathymetry of the ocean bottom. Bathymetric data is required in order to facilitate the wave transformation modeling for the impact of storm surge and sea level rise in Negril. Understanding the movement of currents along the seafloor aids in the prediction of wave intensity and direction on the shoreline. Bathymetric data was acquired from the following surveys:

- Smith Warner International (SWI) - 2007
- CEA Solutions - 2013 & 2014

Topographic Survey

This survey was carried out to Mean Sea Level (MSL) datum at 30 m spacing along the road centerline. Topographic survey is required to improve the results of hazard analysis in determining the elevation at which storm surge will propagate inland from shoreline. The topographic survey involved:

1. Control survey - A control point is a point on the ground or any permanent structure whose horizontal and vertical location/position is known. The control points were set out by a Commissioned Land Surveyor using National Land Agency’s (NLA) horizontal and vertical controls.
2. Aerial Surveys - An unmanned aerial vehicle (UAV) was used to capture building footprints, road centerline, and beach dune and shoreline information. This technology was used to conduct topographic survey, provided base imagery from which detailed building footprint digitizing in ESRI ArcGIS. The survey mission was carried out to an accuracy of 5cm per pixel.
3. Finished Floor Level - Floor levels are important in order to determine susceptibility to floor inundation. The traditional survey method was used to gather the topographic data at a nominal distance of 40m along the road centerline on either side of the roadway. The elevation relative to MSL was determined and the number of storeys for the buildings recorded and incorporated into the topographic data.

Storm Surge Modeling (Numerical Modeling)

The following procedure was carried out for storm surge assessment:

1. Hurricane wave track data in the Caribbean Sea was used to determine the hurricane wind and wave conditions at a deep water location offshore Negril.
2. Extraction of storm parameters that passed within 300 km radius of Negril’s coast from National Oceanic and Atmospheric Administration (NOAA) hurricane database.
3. Application of the JONSWAP wind-wave model. A wave model was used to determine the wave conditions generated at the site due to the rotating hurricane wind field.
4. Application of extremal statistics - to estimate different return periods for waves and surge levels.
5. A bathymetric and topographic profile from deep-water to the site was then defined, respectively. This is used to calculate the wave run-up (height) based on topography of shoreline and nearshore waves.

Validation of Model

It is important to perform validation of the models. The storm surge model was validated against information collected from the anecdotal survey. The information was used to generate an estimate of actual storm surge versus the estimated values determined from the storm surge model. In addition, the observed storm surges associated with Hurricane Ivan, 2004 was also used to determine the accuracy of the model in practice and to validate its predictive capabilities. The results show that the model predictions of storm surges for Hurricane Ivan compared well with the observations of the residents.

Figure 3.2:
3.1.1 Analysis of Storm Surge Hazard Assessment

The topography of Negril is such that storm surges can penetrate well inland from the coastline as shown in Figures Maps 3.1–3.4. The predicted storm surge with run-up for the 10-100 years return period is estimated to range from 0.880m to 1.270 m above mean sea level (Refer to Table 3.1). Wave run-up occurs when a wave breaks and the water is propelled onto the beach and land. The run up values represent the likely maximum topographic elevation storm surges will propagate inland from the coastline. Projections for climate change and sea level rise is expected to increase these values relative to current Mean Sea Level (See Table 3.4).

Table 3.1: Predicted Storm Surge elevation without and with breakwater scenarios

<table>
<thead>
<tr>
<th>Storm surge Return Period</th>
<th>Without Breakwaters Storm surge predictions with run-up (m)</th>
<th>With Breakwaters Storm surge predictions with run-up (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>10</td>
<td>0.880</td>
<td>0.83</td>
</tr>
<tr>
<td>25</td>
<td>1.046</td>
<td>0.98</td>
</tr>
<tr>
<td>50</td>
<td>1.159</td>
<td>1.08</td>
</tr>
<tr>
<td>100</td>
<td>1.270</td>
<td>1.20</td>
</tr>
</tbody>
</table>

Maps 3.1–3.4 shows the areal extent of flooding with water height expected to increase in the Great Morass for all storm surge scenarios. This large area extent of flooding is likely to occur with storm surges penetrating the North and South Negril Rivers as well as the canal systems that drain to the Caribbean Sea. As such, propagation of surge through these waterway systems can reach far inland. Research has shown that storm surge penetrate approximately 10-15% more distance inland through the river systems, which is a general accepted assumption globally (Rao et al, 2007).

Recent research by Wei-Bo and Wen-Cheng (2014) also concluded that when storm surges occurred at the Tsengwen River mouth in Taiwan and meets the high water level in the river, the water cannot drain into the coastal ocean, resulting in severe flood inundation in the lowland region. They concluded that the extreme storm surge combined with high freshwater discharge increased the severity of the flooding. This conclusion can also be drawn for Negril given the results of the model.

Storm surge scenarios were further analyzed for all return periods taking into consideration installation of proposed offshore breakwaters, a structural mitigation intervention to be executed under Component I of the programme. Under this component, two (2) partially submerged breakwaters are proposed to be located approximately 1.4 km offshore Long Bay. The north breakwater is proposed to be 500 m long whilst the south breakwater is to be 400m in length. The results of the analysis has shown that storm surge with run-up are expected to be reduced ranging from 0.83m to 1.20m after mitigation compared to the storm surge values without breakwater structures (Refer to Table 3.1).
3.2 Sea Level Rise (SLR)

Sea level rise at a particular location is a combination of the global rise in sea levels and local trends. The primary contributors to sea level change are the expansion of the ocean as it warms (thermal expansion) and the transfer of water currently stored on land to ocean, particularly from land ice [glaciers and ice sheets] (Church et al, 2011). According to the International Panel on Climate Change (IPCC), observations indicate that the largest increase in the storage of heat in the climate system over recent decades has been in the oceans and thus sea level rise from ocean warming is a central part of the Earth’s response to increasing greenhouse gas (GHG) concentrations (IPCC, 2013).

The IPCC’s Fourth Assessment Report (AR4), 2007 summarized a range of SLR projections under each of its standard scenarios, for which the combined range spans 0.18 - 0.56m [Avg. 0.37m] by 2100 relative to 1980-1999 levels (CARIBSAVE Climate Change Risk Atlas – Jamaica, 2011). From estimates of observed sea level rise from 1950 to 2000, the rise in the Caribbean appears to be near the global mean (Church et al 2004).

Table 3.2: IPCC Fourth Assessment Report of SLR projections

<table>
<thead>
<tr>
<th>Scenario*</th>
<th>Global Mean Sea Level Rise by 2100 relative to 1980 – 1999</th>
<th>Caribbean Mean Sea Level Rise by 2100 relative to 1980 – 1999</th>
</tr>
</thead>
<tbody>
<tr>
<td>IPCC B1</td>
<td>0.18 – 0.38</td>
<td>0.13 – 0.43</td>
</tr>
<tr>
<td>IPCC A1B</td>
<td>0.21 – 0.48</td>
<td>0.16 – 0.53</td>
</tr>
<tr>
<td>IPCC A2</td>
<td>0.23 – 0.51</td>
<td>0.18 – 0.56</td>
</tr>
</tbody>
</table>

Source: IPCC AR4, Meehl et al, 2007a

According to IPCC it is virtually certain that global mean sea level rise will continue beyond 2100, with sea level rise due to thermal expansion to continue for many centuries. The amount of longer term sea level rise depends on future emissions (IPCC, 2013).

Methodology

For the assessment of SLR, the A2 scenario was chosen because it represents the worst case of all the emissions scenarios regarding the concentration of GHGs in the atmosphere associated with future global development patterns to the end of the century. IPCC’s projection for average SLR by the year 2100 is 0.37m.

Three scenarios were selected to represent sea level rise projections for 2025, 2050 and 2100 (See Table 3.3). The values for 2025 and 2050 were calculated using IPCC’s average rate of sea level rise per year of 0.0037m/yr. Having established rate of sea level rise per year, then a simple calculation was carried out to obtain values for 2025 and 2050.

Table 3.3: Sea Level Rise Projections

<table>
<thead>
<tr>
<th>SLR Scenarios</th>
<th>Sea Level Rise (m) Projections</th>
</tr>
</thead>
<tbody>
<tr>
<td>2025</td>
<td>0.093</td>
</tr>
<tr>
<td>2050</td>
<td>0.185</td>
</tr>
<tr>
<td>2100</td>
<td>0.370</td>
</tr>
</tbody>
</table>

*Note: At the time of preparation of this Atlas, the AR5 Report was not published and so the values for SLR could be higher.

In the calculation of future storm surges, sea level rise projections for 2025, 2050 and 2100 were added to current storm surge elevations to determine the maximum flooding and inundation levels. The following equation was used for calculation of future storm surges:

**Future storm surge = Projected SLR (e.g. [0.185m]) + current storm surge [25, 50 year RP]**

The methodology for sea level rise and determining future storm surge elevations in Negril for different storm events is shown below:

**Figure 3.4: Special Report on Emissions Scenarios (SRES)***

*To estimate future changes in climate some assumptions have to be made about what the future world might look like, especially with respect to the concentration of greenhouse gas (GHG) emissions that will be in the atmosphere. Future concentrations of GHGs will depend on multiple factors which may include changes in population, economic growth, energy use and technology. The Special Report on Emissions Scenarios (SRES) represents possible pathways for future GHG emissions premised on different storylines of change in the global development factors (Nakicenovic et al. 2000). In all there are forty different scenarios divided into four families (A1, A2, B1, B2), each with an accompanying storyline which describes the relationships between future greenhouse gas emissions levels and driving forces. The A-Family or High-Emissions Scenarios describe a future world of very rapid economic growth, global population… The B-Family describes relatively Low Emissions Scenarios.*
3.2.1 Analysis of Storm Surge and Sea Level Rise

In the analysis of future storm surges resulting from projected sea level rise, future coastal morphological changes in Negril were not factored and so estimates may be conservative.

The results of the model as illustrated in Table 3.4 shows that storm surge heights will be increased by the underlying rise in sea level moving from 0.880 to 1.270 m for current storm surge predictions for 10-100 return period to 1.25 to 1.64m by 2100. It is important to highlight that the current predicted 100 year storm surge elevation of 1.270m is almost equivalent to what future storm surge elevations is projected to be for the 10 year return period by 2100. In other words, the current 100 year storm surge return period elevation in Negril is likely to become the 10 year storm surge return period under sea level rise conditions by the end of the century.

Higher sea level provides storm surges with a higher “launch point” for the surge, which may increase both the real extent and the depth of the surge in areas already vulnerable to coastal storms (Neumann et al, 2015). And so, as storm surges increase, they will create more damaging flood conditions in Negril as the waves propagate or move further inland as depicted in Maps 3.1-3.4. In addition, the areal extent of inundation will also increase threatening larger areas than in the past. In fact, taking into account sea level rise, the potential inundation zone will increase by 29% by 2100 from current reference of the 1-in-100 year storm surge. This means that 29% more land is likely to be affected by storm surges by the end of the century.

Table 3.4: Increase in Storm Surge elevation for Baseline and SLR scenarios

<table>
<thead>
<tr>
<th>Return Period</th>
<th>Storm surge predictions (m) [Current]</th>
<th>Storm surge Predictions with SLR (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>2025</td>
<td>2050</td>
</tr>
<tr>
<td>10</td>
<td>0.880</td>
<td>0.98</td>
</tr>
<tr>
<td>25</td>
<td>1.046</td>
<td>1.14</td>
</tr>
<tr>
<td>50</td>
<td>1.153</td>
<td>1.25</td>
</tr>
<tr>
<td>100</td>
<td>1.270</td>
<td>1.36</td>
</tr>
</tbody>
</table>

Plate 3.1: Coastal vegetation in section of Long Bay
Map 3.1: Storm Surge 25 Year Return Period & Projected Sea Level Rise for the Year 2025, Negril
Map 3.3: Storm Surge 100 Year (Base Line) & Projected Storm Surge for end of century scenario
Map 3.4: Storm Surge 100 Year (Base Line) & Projected Storm Surge for end of century scenario

NOTES
Return period indicates the period in which the hazard is likely to occur based on historic records.
A flooding event with a return period of T years is the flood which is expected to occur on average once every T years.
### 3.3 Wave Overtopping Assessment

The morphological setting of West End is such that storm waves generally crash against the cliffs and are “lifted” or overtop the rocks. Wave overtopping refers to the volumetric rate at which wave run-up flows over the top or crest of a slope, be it a beach, dune or structure. Anecdotal information and technical assessments of the impact of extreme storm events on the Negril shoreline have revealed that along West End waves run up the face of the cliffs and overtop them.

#### Methodology

The Technical Advisory Committee on Flood Defense in the Netherlands has published a manual that addresses Wave Run-up and Wave Overtopping of Dikes (2002). Similarly, publication by Wallingford (1999) on "Wave Overtopping of Seawalls-Design and Assessment Manual" presents guidance on analysis and/or prediction of wave overtopping.

Due to the steeply sloped cliffs along West End, in the order of 1:1, the approach to determining overtopping discharge for plain vertical walls was used.

#### Analysis of Wave Overtopping

Overtopping analysis was undertaken for 10-100 storm surge return periods to determine the elevation at which waves can potentially impact the elements at risk on West End. To achieve this, the tolerable mean discharge had to be defined. Tolerable mean discharge is the overtopping discharge (peak volume of water) that can cause damage to buildings or infrastructure or danger to pedestrians and vehicles (Wallingford et al., 2007). In other words, it is the overtopping limit beyond which it becomes unsafe for the population and cause damage to buildings and infrastructure.

The overtopping limit used in the analysis for West End is 0.05 m³/m/s as this is the value beyond which damage will start to occur (Wallingford’s Manual, 1999). To ascertain at which elevation the overtopping limit will be reached, the cliffs on West End were subdivided into three (3) categories as follows:

1. **High cliffs** - elevation greater than 10m,
2. **Moderate cliffs** - elevation from 8 and 10m and
3. **Low cliffs** - elevation below 8m.

Overtopping estimates were determined for the 10, 25, 50 and 100 years storm surge scenarios. The results revealed that for areas classified as high cliffs, under all scenarios, the mean discharge is not sufficient to cause damage to buildings and properties as it is below the overtopping limit of 0.05 m³/m/s. The same is true for moderate cliffs under the 10 and 25 year scenarios.

For those areas classified as low cliffs, for all storm surge scenarios, the mean discharge is more than the overtopping limit (Refer to Table 3.5) and so damage to buildings and other infrastructure can be anticipated within this zone. Similarly, the population within this zone is also at risk.

Table 3.5 below shows the mean discharge for wave overtopping along West End for all storm surge scenarios.

#### Table 3.5: Mean discharge for Wave Overtopping along West End

<table>
<thead>
<tr>
<th>Storm surge scenario</th>
<th>10 years</th>
<th>25 years</th>
<th>50 years</th>
<th>100 years</th>
</tr>
</thead>
<tbody>
<tr>
<td>Low cliffs</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Hs (wave height at base of cliff)</td>
<td>5.50</td>
<td>6.00</td>
<td>6.30</td>
<td>6.60</td>
</tr>
<tr>
<td>Overtopping Calculations</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>h</td>
<td>8</td>
<td>8</td>
<td>8</td>
<td>8</td>
</tr>
<tr>
<td>h*</td>
<td>0.051</td>
<td>0.102</td>
<td>0.091</td>
<td>0.084</td>
</tr>
<tr>
<td>Freeboard (Distance of height of the crest of the cliff to still water level)</td>
<td>7.00</td>
<td>7.00</td>
<td>7.00</td>
<td>7.00</td>
</tr>
<tr>
<td>Tp (wave period)</td>
<td>12.60</td>
<td>12.60</td>
<td>13.00</td>
<td>13.20</td>
</tr>
<tr>
<td>Tm</td>
<td>12.10</td>
<td>8.19</td>
<td>8.45</td>
<td>8.58</td>
</tr>
<tr>
<td>Q</td>
<td>0.059</td>
<td>0.090</td>
<td>0.113</td>
<td>0.139</td>
</tr>
<tr>
<td>Criterion</td>
<td>0.05</td>
<td>0.05</td>
<td>0.05</td>
<td>0.05</td>
</tr>
</tbody>
</table>
3.4 Coastal Erosion Hazard Assessment

Beach erosion can be classified as either long term or short-term, depending on the time scale over which it occurs. Short term erosion refers to erosion that occurs over a period of days, rather than years, as a result of extreme weather events such as storms or hurricanes. Long term erosion on the other hand usually refers to a trend of erosion extending over several years and can be caused by a deficit in the annual sediment budget or in longshore transport rates along the beach.

Both short term and long term erosion hazard assessments were undertaken for Long Bay and Bloody but not for Orange Bay and West End due to morphology of the coastline with the former having wetlands/mangroves which protect the shoreline from erosion and the latter is a series of cliffs.

3.4.1 Short Term Erosion

Methodology
Collection of Sediment and Grain Size
It was necessary to determine the representative grain size on the shoreline in order to assess and comprehend what effects hurricane waves will have on the coastline (beach). Sand samples were collected for analysis from both the beach face and back of the beach at 6 locations along the Negril shoreline. The grain size analysis was done using the Unified Soil Classification System (USCS) which is widely used for the classification of granular material for engineering and geological applications.

Define Nearshore Wave Climate
Deepwater wave climate offers a starting point in understanding the storm surge climate of the project area, especially as waves approach the coastline. As such, wave transformation modeling simulating the movement of waves from deepwater to the nearshore was undertaken to facilitate a better understanding of how waves will behave along the shoreline. This information allows for the identification of areas along the shoreline that is vulnerable to erosion from direct wave attack, and the estimate the impact on structures in the area. At Long Bay the bathymetry changes greatly and the water depth at the shoreline approaches MSL, shoreline erosion is a common occurrence.

SBEACH (numerical model for simulating storm-induced beach change)
SBEACH modeling was carried out to estimate beach erosion due to storm waves and water levels in Long Bay and Bloody Bay. SBEACH is an empirically based numerical model for estimating beach and dune erosion due to storm waves and water levels. The magnitude of cross-shore sand transport is related to wave energy dissipation per unit water volume in the main portion of the surf zone. The direction of transport is dependent on deep water wave steepness and sediment fall speed. SBEACH is a short-term storm processes model and is intended for the estimation of beach profile response to storm events.

Wave Climate Input, Calibration and Verification
Profiles were cut from deep water to land up to a maximum elevation of approximately 2m above mean sea level, and a maximum depth of 45m spanning the entire project shoreline. This was done at three locations along Long Bay and one at Bloody Bay. The wave data corresponding to the 10, 25, 50 and 100 year storm events, Hurricane Ivan (2004) and to a swell event that took place in November 2006 were utilized in this modeling exercise. Hurricane Ivan was used to calibrate the model, and the November 2006 swell event used to verify the model results. The 10, 25, 50 and 100 year storm surge events were used to determine the beach response to the future wave climate. Table 3.5 shows the wave characteristics utilized in the model. Other input parameters included the sediment grain size on the beach face and storm duration.

Table 3.6: Input Parameters for Short-Term erosion analysis

<table>
<thead>
<tr>
<th>Storm surge RP</th>
<th>Hs (m)</th>
<th>Tp (s)</th>
<th>Wind Speed (m/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>10 year</td>
<td>5.5</td>
<td>12.1</td>
<td>25.8</td>
</tr>
<tr>
<td>25 year</td>
<td>6.0</td>
<td>12.6</td>
<td>31.0</td>
</tr>
<tr>
<td>50 year</td>
<td>6.3</td>
<td>13.0</td>
<td>34.7</td>
</tr>
<tr>
<td>100 year</td>
<td>6.6</td>
<td>13.2</td>
<td>38.4</td>
</tr>
<tr>
<td>Hurricane Ivan</td>
<td>6.0</td>
<td>10.7</td>
<td>41.1</td>
</tr>
</tbody>
</table>

3.4.1.1 Analysis of Short-term Erosion

Storm events from the west, south west and northwest were investigated in the model for the 10 to 100 year return periods. The erosion vulnerability of the shoreline for all the locations along each profile were averaged and summarized in Table 3.6 for all scenarios.

The results show that the northern section of Long Bay is most vulnerable to shoreline erosion, followed by the central section. The average distance of erosion from the shoreline inland is approximately 67m, 45m and 38m, for Long Bay's northern, central and southern sections, respectively for the 100 year storm event.

For Bloody Bay no shoreline erosion was observed for the 10 to 100 year return period scenarios. Similar results were obtained for the alongshore sediment transport analysis carried out in the following section of the report.

Coastal erosion scenarios were further analyzed taking into account the implementation of breakwaters off shore Long Bay to reduce the exposure of the shoreline and slow the rate of beach erosion. The estimated average shoreline erosion along the entire bay is 41m for all storm surge periods combined. When the breakwaters were implemented the average beach erosion was reduced by 31m for the same period. The breakwaters had the effect of considerably reducing the erosion in the central section of the bay, followed by the northern section (See Figure XXX).
### 3.4.2 Long Term Erosion

#### Methodology

Long term shoreline change was determined from 1968 to 2013 from the shoreline positions along the Long Bay Beach and compared in order to determine the spatial and temporal erosion trends. This was important in order to identify the high risk areas that are erosion hotspots and in order to verify the wave transformation modelling. The overall long-term erosion trend was estimated by assessing:

1. Estimated long-term shoreline positions from aerial photography and satellite imagery in a historical Shoreline Analysis;
2. The effects of global sea level rise on long term erosion trends that were due to chronic global trends using the Bruun rule.

#### Historical Shoreline Analysis

The observed shoreline from Satellite and aerial imagery for the years 1968, 1991, 1999 and 2005 was used for this analysis. The most recent (September 2013) shoreline position was marked manually by walking the beach and taking GPS points. The shoreline movement was analyzed by measuring and noting the displacements of the shoreline at intervals of 500 and 100m along the shoreline for Long Bay and Bloody Bay, respectively. The rates of accretion and or erosion between the time intervals were determined using the following relationships:

\[
E_j = \frac{D}{N},
\]

- \(E_j\) – the rate of erosion or accretion between two successive intervals (metres per year)
- \(D\) – the displacement between two intervals (metres)
- \(N\) – the number of years between two successive intervals (years), and

\[
E_y = \frac{D_T}{N_T},
\]

- \(E_y\) – the rate of erosion or accretion from the datum year to the final interval
- \(D_T\) – the displacement from the datum to the final interval
- \(N_T\) – the number of years from datum year to final interval

#### Bruun Model

The Bruun model (Bruun 1983 & 1988) is perhaps the best-known and most commonly used model that relates shoreline retreat to sea level rise. It is a two-dimensional model which assumes an equilibrium profile in that the volume of sediment deposited is equal to that eroded from the dunes and that the rise in the nearshore bottom as a result of the deposited sediment is equal to the rise in sea level. The model is not without criticism for its simplicity but remains the most commonly used means of estimating the impact of rising sea levels on shoreline retreat (Dubois, 1975; Cooper & Pilkey, 2004). The original Bruun model is expressed below and this mathematical relationship was the basis for estimating shoreline retreat within the study area.

\[
\Delta y = \frac{\Delta s \cdot l^*}{h^*},
\]

- \(\Delta y\) – Dune line erosion (meter s/ year)
- \(\Delta s\) – Rate of sea level rise (meter s/ year)
- \(l^*\) – Length of the offshore profile out to a supposed depth, \(h^*\), of the limit of material exchange from the beach and the offshore (meters)
- \(h^*\) – Depth at offshore limit, \(l^*\), to which near shore sediments exist (as opposed to finer-grained continental shelf sediments) (meters)

#### Analysis of Long Term Erosion

Historical shoreline analysis results show that there is a general trend of erosion occurring from 1968 to 2013 for Long Bay and Bloody Bay. For Long Bay some accretion was observed between 1999 and 2005 as well as between 2005 and 2013. An overall erosion rate between 0.2 and 1.4 m/year was observed. Over the past 45 years, approximately 62.6 meters of erosion has occurred along Long Bay based on the observation of historical aerial and satellite images of the area. These results also show that the central section of Long Bay is the most vulnerable to long term as well as short term erosion (See Maps 3.9 – 3.13). This is supported by the studies done by Smith Warner International Limited, 2007 and RIVAMP, 2010.

---

### Table 3.7: Predicted erosion for As-Is and Breakwater scenarios

<table>
<thead>
<tr>
<th>Location</th>
<th>Predicted Erosion (As-is)</th>
<th>Predicted Erosion (with Breakwater)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>10 year</td>
<td>25 year</td>
</tr>
<tr>
<td>Long Bay North</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Long Bay Central</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Long Bay South</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Bloody Bay</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

---

\[ E^y = \frac{D_T}{N_T}, \]

- \(E^y\) – the rate of erosion or accretion from the datum year to the final interval
- \(D_T\) – the displacement from the datum to the final interval
- \(N_T\) – the number of years from datum year to final interval
For Bloody Bay, an overall rate of erosion between 0.2 and 0.8 m/yr was observed for the same period. The greatest erosion took place between 2003 and 2009, following the passage of Hurricanes Ivan (2004), Wilma (2004) and Dean (2007) which eroded the Negril shoreline. Accretion was observed between 2009 and 2013, where there was a reduction in the number of extreme storms affecting the western side of the island, and in turn, the project boundary. The rate of accretion varied between 0.6 and 4.5 m/yr over the period.

Having analyzed the historical movements in the shoreline, the Bruun Model was used to estimate the projected shoreline retreat resulting from sea level rise for 2025 and 2050. The following input values were used in equation xxx above:

- Rate of sea-level rise = 3.7 mm/yr (IPCC, 2007)
- Depth to which near shore sediment exists \( (h, d_c) \) = 2.56 m

For Long Bay, the shoreline was estimated to retreat at varying rates between 0.3 and 1.1 metres per year as a result of sea level rise. The southern section of Long Bay is expected to experience the largest rate of erosion of 1.1 m/yr, whilst the central and northern profiles have erosion rates between 0.3m/yr to 0.43 m/yr. Projected shoreline retreat for Bloody Bay is estimated to retreat at 0.3 m/yr which is less than projections for Long Bay.

Further analysis of future shoreline projections was simulated using wave data for the period 2000 through 2006 for both Long Bay and Bloody Bay. The results of the simulation show that approximately 92% of the beach planform in Long Bay will be eroded with a total volumetric loss of approximately 114,000 m³ over 7 year period. The analysis further revealed that the central and northern sections of the shoreline are most vulnerable to erosion with widths of 30 and 90m, respectively. The average erosion along the shoreline is predicted to be 27m in width. The alongshore model prediction are indicative of trends in erosion that are currently being observed and likely to continue if same waves are experienced in the future.

For Bloody Bay, only 10% of the beach planform is expected to be eroded for the over the same 7 year simulation period with a total volumetric loss of approximately 501 m³. This erosion volume is quite minimal compared to Long Bay.

Having established future shoreline changes for Negril, further analysis was undertaken with the implementation of offshore breakwaters. When these breakwaters are implemented, for the said 7 years of simulation, accretion (or beach growth) and beach stability particularly in the sections of the beach most vulnerable to alongshore erosion will result. The analysis of the model shows that over 80% of the shoreline experienced accretion with the breakwaters in place (See Map 4.40). Most of the growth occurred at the northern section of Long Bay with a maximum predicted growth of 41.7m in beach width and 109,400 m³ volumetric gain.

**Limitations**

For the historical shoreline assessment, the aerial imagery obtained represent snapshots at a moment in time which cannot be manipulated to show years or times of interest (such as immediately before and after the hurricanes). As such, some of the imagery may be displaying short term shoreline configurations while others long term. The accuracy of the rates is therefore subject to the availability of limited time periods of aerial imagery.
Map 3.10: Historical shoreline for Long Bay, Negril 1968 - 2013
Map 3.11: Historical shoreline for Long Bay, Negril 1968 - 2013
Map 3.13: Historical shoreline for Long Bay, Negril 1968 - 2013