Quantifying Storm Surge Risk of Jamaican Coastlines

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ABSTRACT

This paper describes the methodology and results of a storm surge hazard assessment for three coastal communities in Jamaica; namely, Portland Cottage in the parish of Clarendon, Morant Bay in St. Thomas, and Manchioneal in Portland.

The analyses demonstrated that while all three towns are susceptible to storm surge, Portland Cottage is the most exposed and vulnerable community, with more than 50% of the population residing within the 25-year inundation zone. The physical geography of the site, such as the bathymetry and the shape of coastline, are conducive to producing large storm surge values, and the low-lying land that characterizes the area (less than 2 – 3 metres above mean sea level) facilitates an extensive inundation zone.

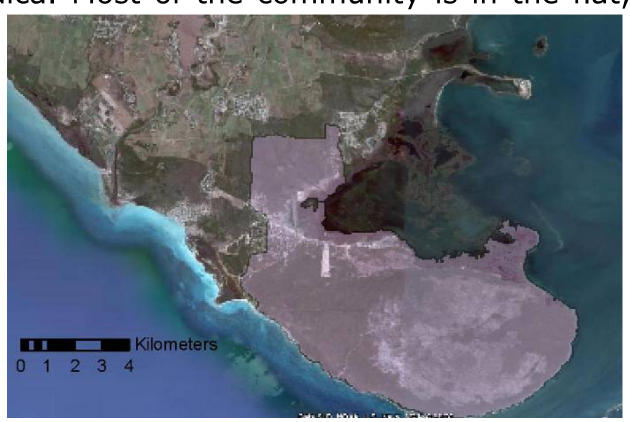
The paper also illustrates the storm surge prediction capabilities of the MIKE 21 SW/HD coupled model by comparing simulated water levels to field observation data for Hurricane Ivan (2004) at Portland Cottage and Morant Bay. The model, however, showed some limitations in simulating wave reflection and overtopping at the Manchioneal site, where the simulated storm surge levels were under-predicted along the steep rocky cliff sections of the shoreline.

Overall, the MIKE 21 SW/HD coupled model is a very useful tool for predicting storm surges and its application in the hazard mapping exercise in Jamaica will help to guide both emergency managers to identify potential evacuation zones and the planning department in regulating future development along the coastline and in determining appropriate setback distances

INTRODUCTION

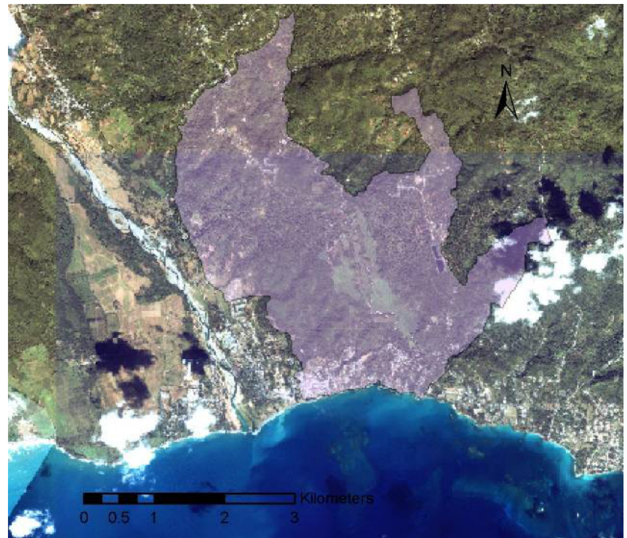
Jamaica is susceptible to a wide range of natural hazards. These include tropical storms and hurricanes, riverine flooding, landslides, seismic events, and wind. The Government of Jamaica has recognized the need to be better able to manage and reduce the impacts of coastal-related hazards. To some extent, hazard maps exist at a national level; however, there is an urgent need for these to be improved and expanded in scope, and for additional tools to be effected. Specifically, community level hazard maps are required to identify areas of high exposure and to help guide planning and disaster risk management initiatives. As a pilot project, the World Bank funded the development of hazard maps for three coastal communities in Jamaica: Portland Cottage, Morant Bay and Manchioneal. While all of the above-mentioned hazards were investigated for the three study areas (SWI, 2010), this paper will focus on the storm surge hazard assessment, using the MIKE 21 modeling suite.

Portland Cottage is a rural coastal settlement that lies on a peninsula located at the southernmost point of Jamaica. Most of the community is in the flat, low-lying lands close to the marshlands, with elevations typically less than 2-3m above sea level. Portland Cottage was devastated by Hurricanes Ivan in 2004 and Dean in 2007. Storm surge and wind hazards resulted in loss of life and extensive damage to housing and community infrastructure.



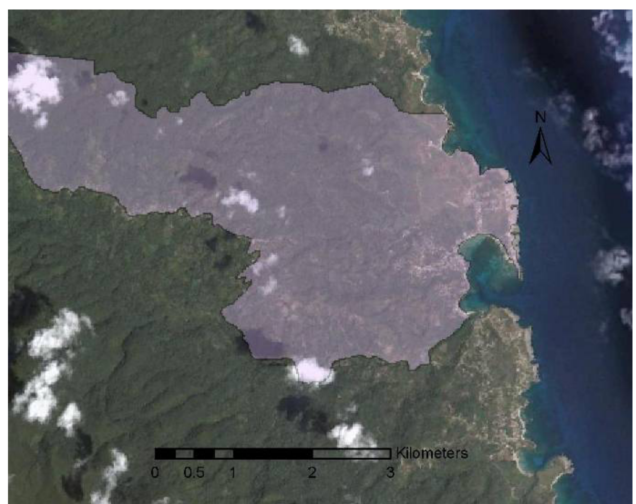
2006 Google Earth image of Portland

Morant Bay is the capital of the parish of St. Thomas and is located on the south-east coast of Jamaica. The coastline generally consists of rocky beach and low-lying cliffs, with the land rising quite steeply towards the inland area. The Morant Bay area has been impacted by storm surge and wind damage from hurricanes as well as river flooding and landslides induced by heavy rainfall. The results of the investigation demonstrate that for up to the 150-year return period event, storm surge in this area extends approximately 200-300m inland, with maximum water levels of 2.6m. There are several homes that lie within the storm surge inundation area, some of which experienced significant damage from Hurricane Ivan in 2004.



2001 IKONOS image of Morant Bay Study Area

Manchioneal is located on the south-east coast of the parish of Portland in a bay. The road providing access to the town runs along the coastline and ranges in elevation from approximately 1.5-3m above MSL. In the middle and southern sections of the bay, the land rises quite rapidly and steeply behind the coastal road. However, at the north end of the bay, the fishing beach and a few shops and residences are located along a low-lying section of the coastline. Extensive swamp lands are found at the back (north) of the fishing beach area. Historically, Manchioneal has suffered damages and loss from hurricane-related storm surge.



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METHODOLOGY

In order to predict storm surge values at each of the coastal towns and plot inundation hazard maps, the following methodology was used:

1. An in-house hurricane wave and statistical package, HURWave, was used to search the National Hurricane Center's (NHC) database of tropical storms and hurricanes, which dates from 1900-2008. All hurricane storms within a 300km radius of Jamaica were extracted from the database. A peak-over-threshold analysis was completed to filter out hurricanes that produced waves less than 5.0m (i.e. all storms with waves greater than or equal to 5.0m were included in the analysis).
2. Using the MIKE 21 coupled wave-hydrodynamic model, all identified hurricane storms were simulated, such that the nearshore conditions could be determined as the storm moved along its track. The flexible mesh model domain included the entire island of Jamaica, extending out to water depths greater than 1000m, and extending more than 100km from the coastline.
3. Pressure and wind fields were generated using the MIKE 21 Cyclone Wind Generation Tool on a 263m by 242m rectangular grid.
4. A comparison of simulated storm surge results with field observations from Hurricane Ivan for the three communities validated the model.
5. For each hurricane, the maximum computed storm surge value for the duration of the storm was extracted from the model at all of the individual sites; Portland Cottage, Morant Bay and Manchioneal.
6. For each site, the storm surge values were input to an extremal distribution, from which the various return period events were computed (25, 50, 100 and 150-year return period storm surge values).
7. Predicted global sea level rise and tide levels were added to the storm surge values to determine the predicted 25, 50, 100 and 150-year return period water levels.

Based on the local topography, the extents of inundation for the 25, 50, 100 and 150-year return period water levels were plotted and overlaid onto satellite imagery for each site. Storm surge hazard maps were prepared in GIS format for each of the coastal towns.

Data Requirements and Data Collection

The data requirements and sources of all data used for the computation of storm surge and inundation mapping are listed in Table 1.

Table 1: Data Requirements and Data Sources

Historical storm characteristics	✓ NOAA's database from 1900-2008
Historical storm surge measurements (field observations)	✓ Caribbean Coastal Area Management Foundation (C-CAM) and the Mines and Geology Division (MGD)
Satellite imagery	✓ IKONOS 2001 and Google Earth Imagery
Seabed bathymetry	✓ Existing bathymetric charts (complied in Mapsource) ☑ Bathymetric surveys completed at Portland Cottage, Morant Bay and Manchioneal
Beach Profiles	☑ Beach profiles completed at Portland Cottage, Morant Bay and Manchioneal
Topographic Mapping	✓ 1:12,500 Topographic Mapping from the Survey Department in Jamaica's National Land Agency (25 ft contour intervals)

✓ - Pre-Existing Data ☑ - Data Collected for this Study

Jamaica's Historical Hurricane Activity

Jamaica is exposed to hurricane activity each year between June and November. The National Hurricane Center (NHC) database shows that 38 hurricanes have passed within 300km of Jamaica over a 108-year period (1900 to 2008). Table 2 summarizes these storms, with hurricanes listed in chronological order. Category strength indicates the highest category the storm reached within the 300km radius.

Table 2: Hurricanes within 300 km of Jamaica from 1900-2008

Hurricane Name	Year	Within 300 km Radius of Jamaica		Point Closest to Jamaica		
		Dates	Highest Category	Category	LAT	LON G
Not Named	1903	Aug 11	Categor 3	Category 3	77.0	17.9
Not Named	1905	Oct 4-6	Categor 1	Category 1	76.1	17.4
Not Named	1906	Oct 14	Categor 1	Category 1	77.3	16.2
Not Named	1909	Aug 23-24	Categor 2	Category 2	76.6	19.0
Not Named	1909	Oct 8	Categor 1	Category 1	79.0	16.5
Not Named	1910	Sept 8-9	Categor 1	Category 1	76.8	18.6
Not Named	1912	Nov 17-19	Categor 4	Category 4	77.8	18.7
Not Named	1915	Aug 12-13	Categor 3	Category 2	76.9	18.5
Not Named	1915	Sept 25	Categor 2	Category 2	77.5	16.3

Not Named	1916	Oct 13	Categor	1	Category	1	77.4	15.7
Not Named	1916	Aug 15-16	Categor	2	Category	2	77.0	18.0
Not Named	1916	Aug 30-31	Categor	2	Category	2	77.2	16.7
Not Named	1917	Sept 23-24	Categor	3	Category	2	76.7	18.7
Not Named	1928	Aug 11	Categor	1	Category	0	75.8	20.0
Not Named	1933	Sept 20	Categor	1	Category	1	79.5	17.4
Not Named	1933	Oct 29-30	Categor	2	Category	1	77.8	17.7
Not Named	1935	Sept 27	Categor	3	Category	3	79.0	18.3
Not Named	1935	Oct 20-22	Categor	1	Category	1	75.6	18.1
Not Named	1938	Aug 12	Categor	1	Category	1	77.4	17.0
Not Named	1938	Aug 24	Categor	1	Category	1	77.7	16.2
Not Named	1942	Aug 25	Categor	1	Category	1	78.2	16.4
Not Named	1944	Oct 20-21	Categor	3	Category	3	77.0	18.1
King	1950	Oct 16	Categor	2	Category	1	78.9	19.2
Charlie	1951	Aug 17-18	Categor	2	Category	1	77.0	18.0
Hazel	1954	Oct 11-12	Categor	3	Category	3	74.8	17.1
Ella	1958	Sept 1-2	Categor	3	Category	3	75.9	19.8
Flora	1963	Oct 5-6	Categor	3	Category	2	77.7	20.3
Cleo	1964	Aug 24-25	Categor	4	Category	3	76.4	19.3
Inez	1966	Sept 30	Categor	3	Category	1	76.1	20.1
Carmen	1974	Aug 31	Categor	1	Category	1	77.9	17.2
Allen	1980	Aug 6	Categor	5	Category	4	76.7	18.7
Gilbert	1988	Sept 12-13	Categor	3	Category	3	77.0	17.9
Lenny	1999	Nov 14	Categor	1	Category	1	78.2	15.8
Iris	2001	Oct 7	Categor	1	Category	1	77.0	17.3
Ivan	2004	Sept 10-11	Categor	5	Category	4	76.9	17.6
Dennis	2005	Jul 7-8	Categor	4	Category	3	76.4	18.8
Emily	2005	Jul 16	Categor	4	Category	4	77.6	16.3
Dean	2007	Aug 19-20	Categor	4	Category	4	77.1	17.4

The temporal distribution of hurricane activity around Jamaica is shown in Figure 1. It is important to note that, while research is still ongoing, some scientists predict that climate change will result in more frequent and more intense hurricanes.

The identified hurricanes in Table 2 were further short-listed by using a minimum wave height cut-off filter (peak-over-threshold approach). The wave heights generated by a hurricane are a function of distance from the point of interest to the storm, forward speed of the storm, maximum wind speed, radius of the storm, and its central pressure. Hurricanes that produced waves less than 5.0m were filtered from the database, reducing the number of storms from 38 to 21 (all storms with wave heights greater than or equal to 5.0m were included in the analysis).

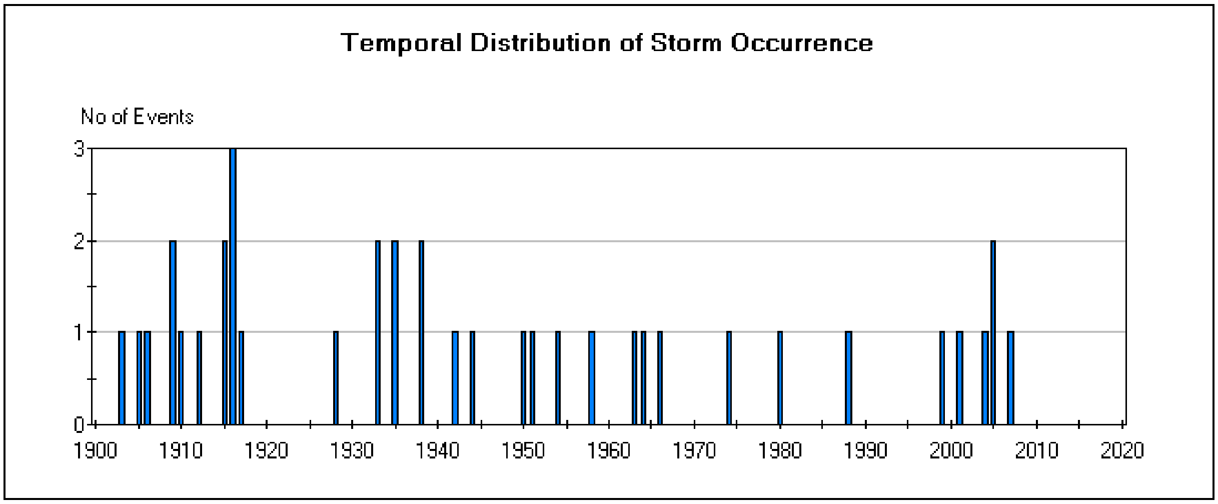

Figure 1: Temporal Distribution of Hurricane Occurrence for Jamaica (300km radius) from 1900-2008

Simulation Of Hurricane Storms Using The MIKE 21 Model

A computer model, MIKE 21, (developed by the Danish Hydraulic Institute) was used to simulate the twenty-one (21) hurricanes as they tracked across Jamaica. MIKE 21 is a professional engineering software package for the simulation of flows, waves, sediments and ecology in rivers, lakes, estuaries, bays, coastal areas and seas. MIKE 21 was used in a coupled mode to simulate the mutual interaction between waves and currents using a dynamic coupling between the Hydrodynamic Module and the Spectral Wave Module.

For each hurricane extracted from the database, the storm parameters were input to the model and the associated waves and water levels generated by the storm were calculated in a time-varying manner. Once the simulation was complete, the maximum calculated storm surge for each hurricane simulation was identified at the three sites of interest: Portland Cottage, Morant Bay and Manchioneal.

Computational Mesh

MIKE 21 uses a finite element mesh, based on linear triangular elements that represent the seabed and land elevations (bathymetry and topography of area). The finite element mesh is particularly well suited for modeling large complex areas that, at the same time, require a detailed resolution of specific features or areas. Figure 2 shows the extent of the finite element mesh used in the study. The entire island of Jamaica was represented in the model domain, extending out to water depths greater than 1000m, and extending more than 100km from the coastline. Smaller mesh elements were used in the study areas of Portland Cottage, Morant Bay and Manchioneal, to represent the bathymetry with higher resolution.

Existing bathymetric charts, relevant topographic contours and satellite imagery were digitized and geo-referenced. All existing and surveyed bathymetric and topographic data were merged and used as input to the model to define land and seabed elevations of the computational mesh elements. The computational mesh is used in the numerical transformation of the hurricane conditions to the nearshore areas.

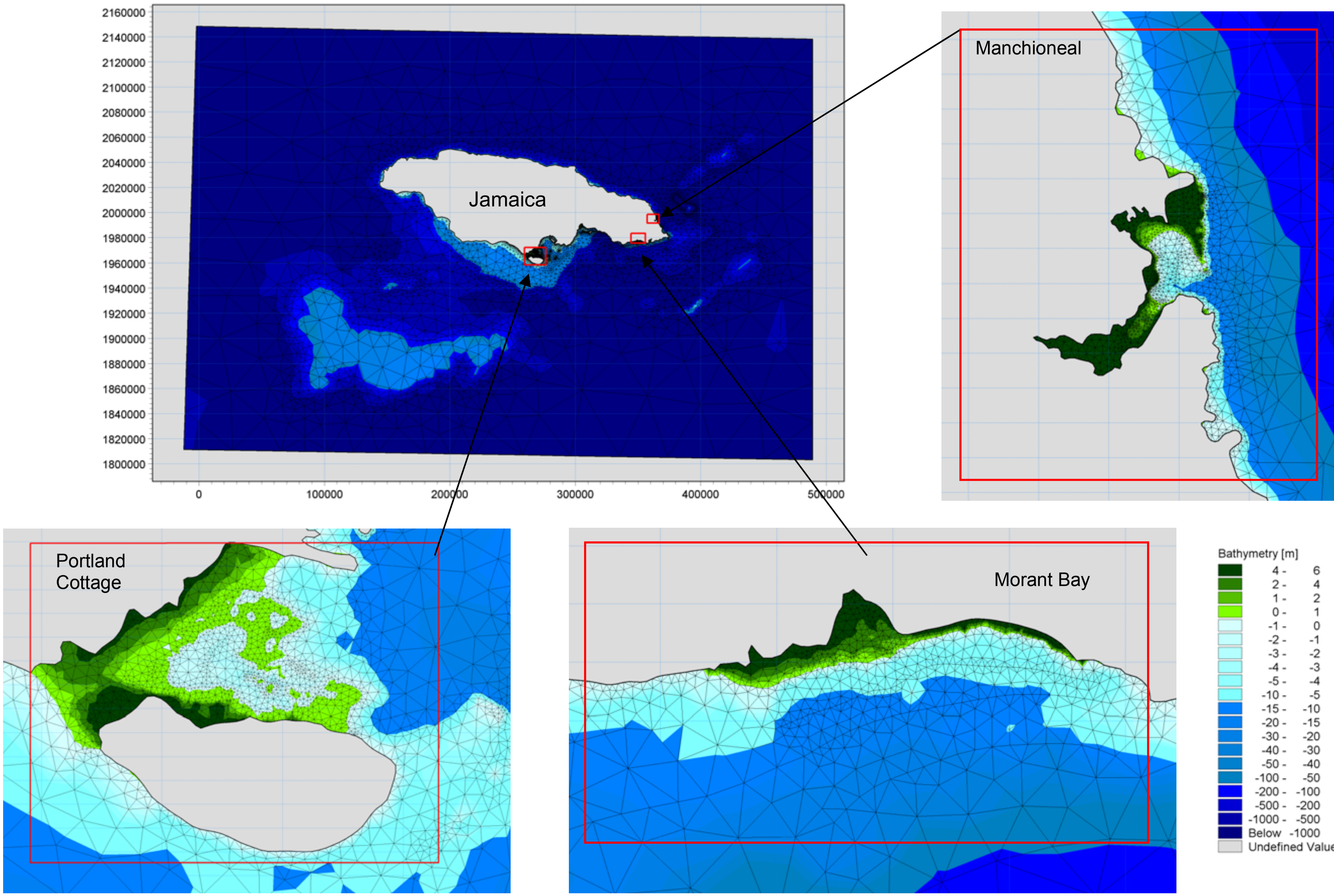

Figure 2: Finite element mesh used for the storm surge modelling

MIKE 21 Modelling Results

All of the 21 hurricanes extracted from the NOAA database were simulated with MIKE 21. The storm parameters input to the model included: time, position (latitude and longitude), maximum wind speed, radius to maximum wind speed, central pressure and ambient pressure. For each storm, wave and water level conditions were computed at hourly intervals as the hurricane tracked along its path. Table 3 summarizes the maximum storm surge value for each of the identified hurricanes.

Table 3: Storm Surge Modelling Results

Hurricane	Portland Cottage	Morant Bay	Manchioneal
NOT NAMED 2 1903	0.83	0.57	0.82
NOT NAMED 8 1906	1.15	0.45	0.37
NOT NAMED 6 1912	1.43	0.5	0.13
NOT NAMED 2 1915	0.85	0.54	0.47
NOT NAMED 5 1915	1.25	0.49	0.39
NOT NAMED 4 1916	0.75	0.58	0.92
NOT NAMED 6 1916	1.65	0.54	0.38
NOT NAMED 3 1917	0.62	0.42	0.32
NOT NAMED 19 1933	1.32	0.52	0.20
NOT NAMED 4 1935	0.21	0.05	0.02
NOT NAMED 2 1938	1.33	0.47	0.38
NOT NAMED 3 1938	1.04	0.37	0.23
NOT NAMED 2 1942	0.96	0.35	0.17
NOT NAMED 4 1944	0.90	0.65	0.97
Charlie 1951	0.55	0.46	0.80
Carmen 1974	1.46	0.49	0.39
Gilbert 1988	1.31	0.88	1.19
Iris 2001	1.76	0.50	0.61
Ivan 2004	3.33	1.35	0.96
Emily 2005	1.96	0.63	0.36
Dean 2007	3.60	1.25	1.51

Model Validation

Detailed field observations of the storm surge water levels at Portland Cottage from Hurricane Ivan were made available for this study from the

Caribbean Coastal Area Management Foundation (C-CAM) and the Mines and Geology Division. Figure 3 (developed by C-CAM), shows how Hurricane Ivan flooded the coastal town. Wave and surge inundation approached from the West Harbour (this was also the case for Dean in 2007). Storm surge affected the majority of the Portland Cottage community. The field observations and subsequent inundation mapping for Ivan was used to verify the accuracy of the model computations.

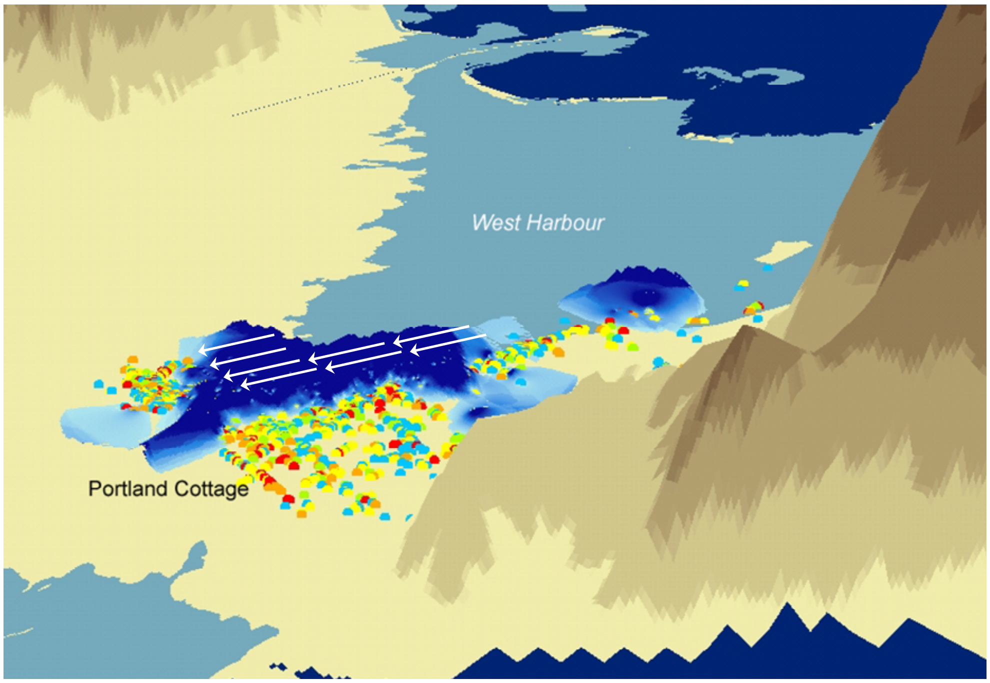

Figure 3: Graphic showing waves and water level inundation as Hurricane Ivan causes flooding in Portland Cottage (graphic created by C-CAM)

Figure 4 shows the model predicted water levels rising and then receding in Portland Cottage as Hurricane Ivan passed just south of the town. The model predicted that for a period of approximately one hour, water flooded the entire peninsula, completely isolating Portland Ridge. While this is difficult to verify with complete certainty, since residents are typically fleeing for higher ground during such an event, many local residents indicated that this did occur during Ivan. Further, the topography at the site makes this event quite plausible. Note that the water surface elevations in Figure 4 are presented in feet in order to compare the results with the C-CAM measurements and graphics.

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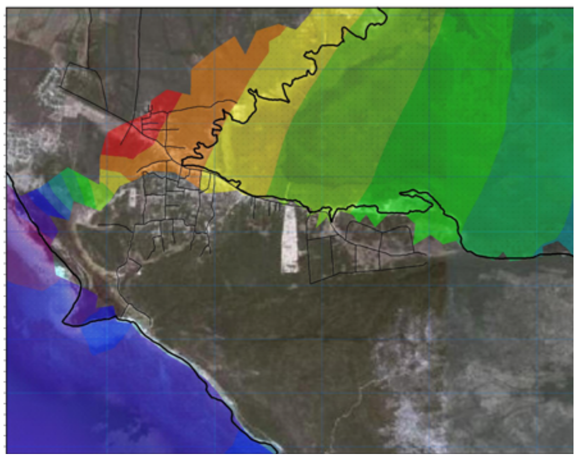

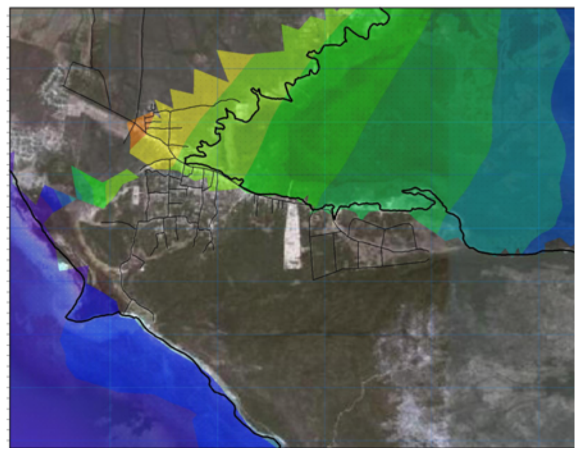

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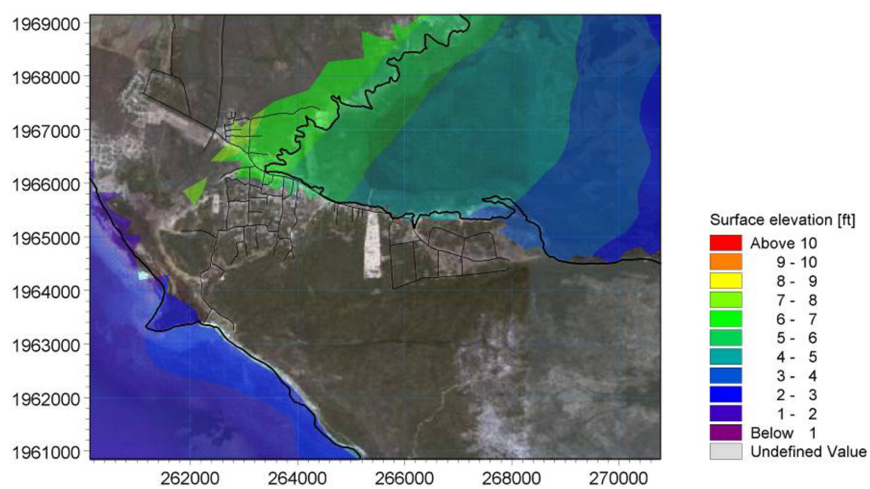


5:03:00 9/11/2004 *Time Step 30 of 54*

Figure 4: Hurricane Ivan water levels at Portland Cottage over 4-hours showing peak water levels

Figure 5 following compares the measured storm surge heights from C-CAM with the computed storm surge for Hurricane Ivan. The C-CAM data was collected and presented in a slightly different manner from how the MIKE 21 model exports storm surge inundation levels, however, a comparison of the information can still be made. The data presented by C-CAM shows the storm surge "height" that was measured during the storm, i.e., the depth of water that occurred. The model presents the storm surge as an elevation above MSL. Therefore, when making a direct comparison of the two plots, one must add the elevation of the land above MSL to the storm surge water depth from C-CAM.

The field observations from C-CAM show that the storm surge reached up to 3m (10 ft), mostly in areas where land elevations are at or close to MSL. Thus, the maximum recorded storm surge elevation above MSL was approximately 3m (10 ft). This compares very well with the maximum surge elevation from the numerical model.

The extent of inundation from the computations also compares well with the measurements. The C-CAM data shows some irregularities in the storm surge mapping along the south-eastern section of Portland Cottage. It appears that one or two recorded storm surge heights may have been entered incorrectly and, as a result, the surface that was created to represent the storm surge heights is misrepresented in these areas. Referring to the figure, the elevations in the area in question range from 10-15m and, as such, it is not likely that these areas recorded storm surge depths of 3m (10 ft). Other than this area, the extent of the inundation mapping compares very well with the model.

The Mines and Geology Division (MGD) also produced maps showing the storm surge impact on the community of Portland Cottage as a result of Hurricane Ivan (Figure 3-5). The mapping was based on field investigations and interviews with community members after the event. Similar to the C-CAM data, these measurements indicate depth of water as opposed to water elevations. Their mapping indicates that flooding crossed from one side of the island to the other, completely isolating the Portland Ridge, which coincides with the model predictions.

The MGD mapping indicates that along the eastern end of Portland Cottage, water depths along the coastline ranged from 1.5 to 2m. Referring to Figure 6, the model also computed values of storm surge for this section of coastline ranging from 1.5 to 2.4m (5 to 8 ft – the green color in the figure). Along the Freetown area, the MGD data indicates storm surge values of 3m at the coastline, which also correlates well with the modeled results of 2.4 to 2.7m (8 to 9 ft – the yellow color in the figure).

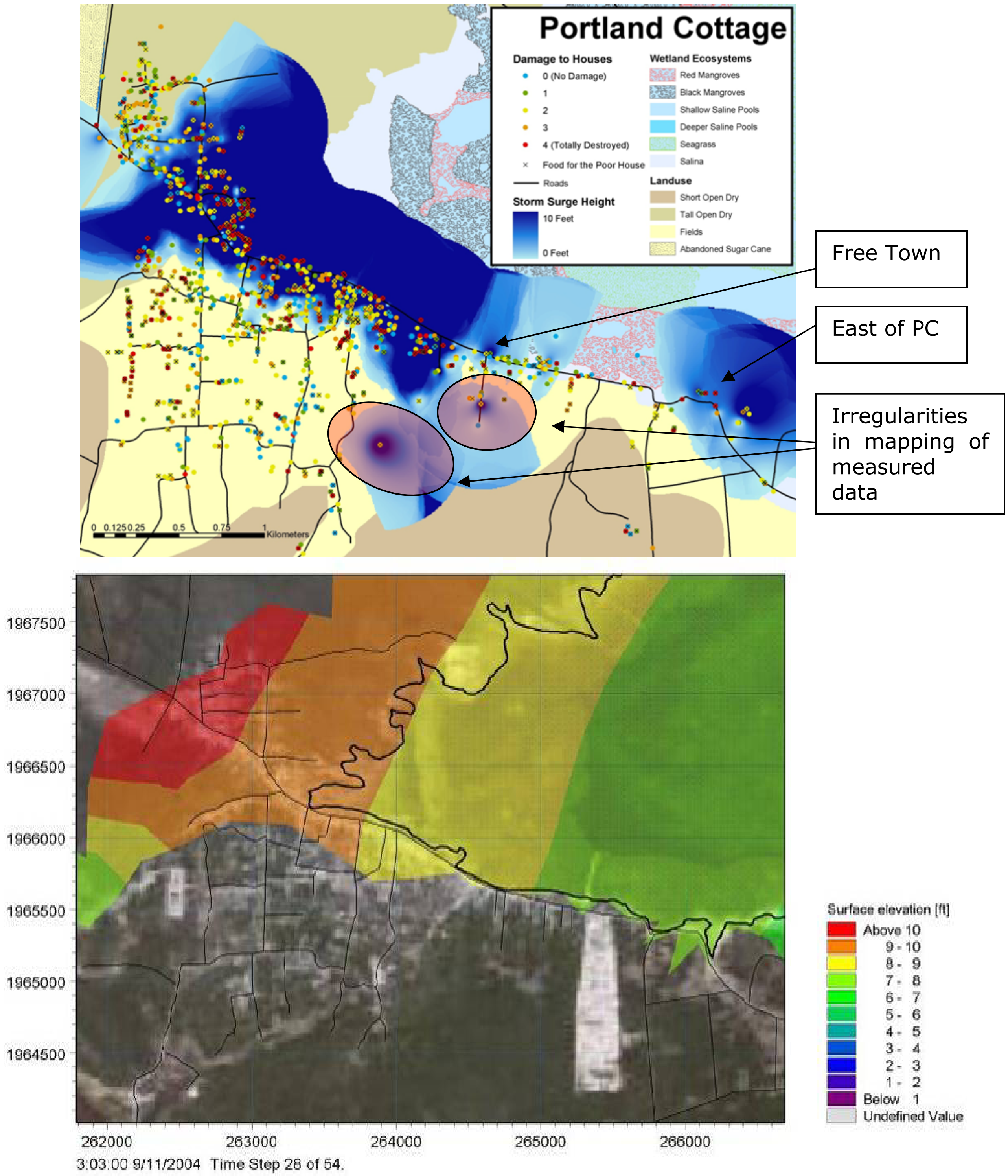


Figure 5: Measured storm surge heights compared to model predictions for Hurricane Ivan. Note that the measurements show storm surge height above land elevations, while the model results show water level relative to mean sea level

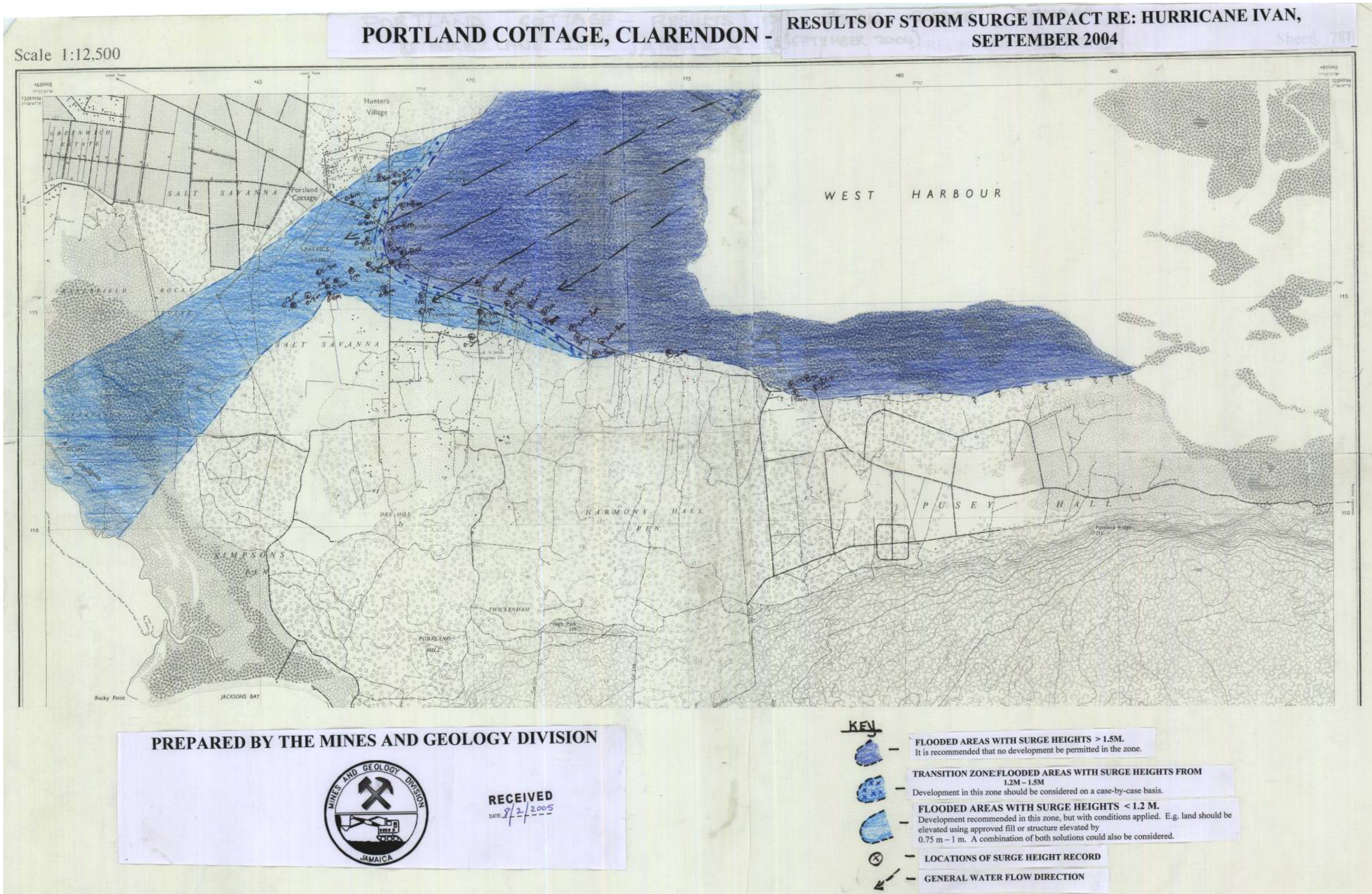


Figure 6: Mapping of storm surge impact from Hurricane Ivan on Portland Cottage from MGD (2004)

For the other communities, the model slightly under-predicted the storm surges based on field observations carried out by the MGD as shown in Figure 7 and Figure 8. These figures show storm surge values of 1.35m at Morant Bay and 0.96m at Manchioneal, which are less than what the field observations are showing especially for Manchioneal. Possible reasons for the under-prediction at Manchioneal could be the occurrence of wave reflection off the sea wall, which would not be simulated by the spectral wave model.

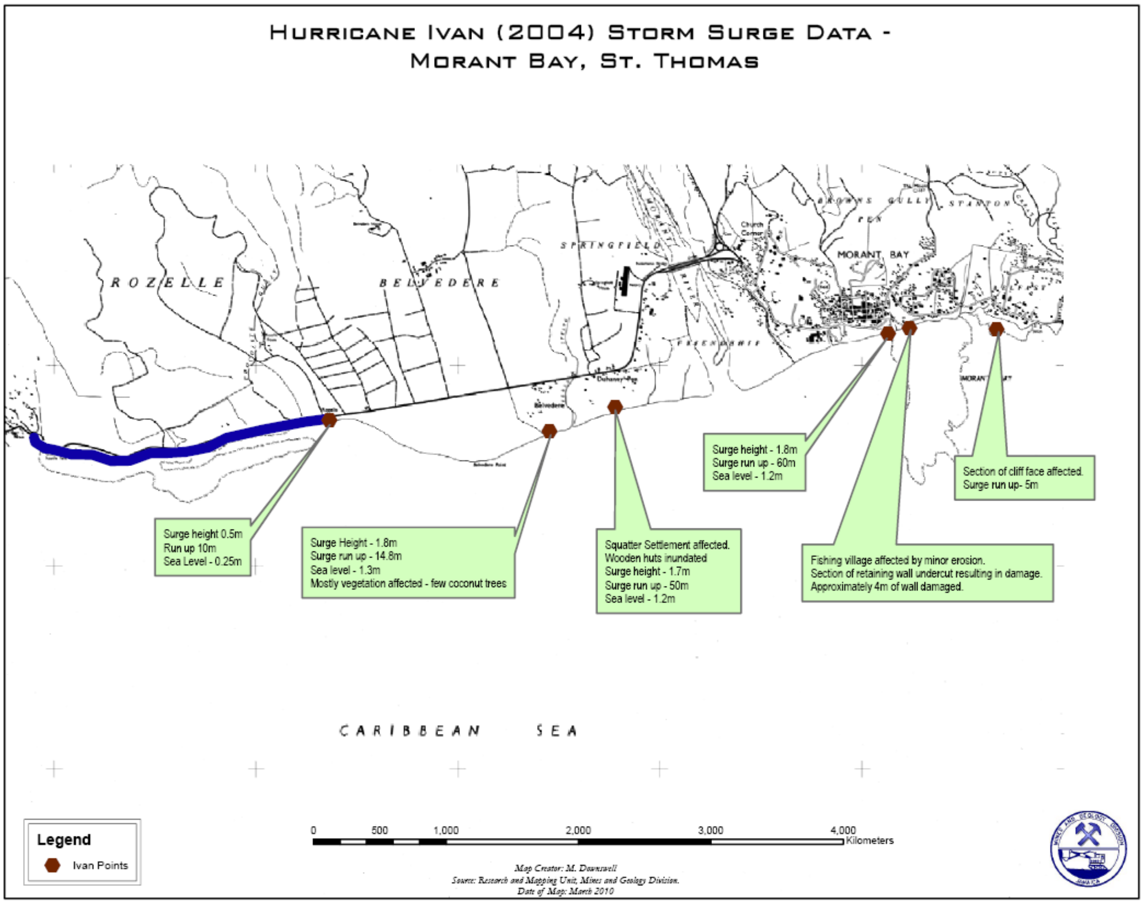


Figure 7: Hurricane Ivan (2004) Storm Surge Data at Morant Bay (Mines and Geology Division)

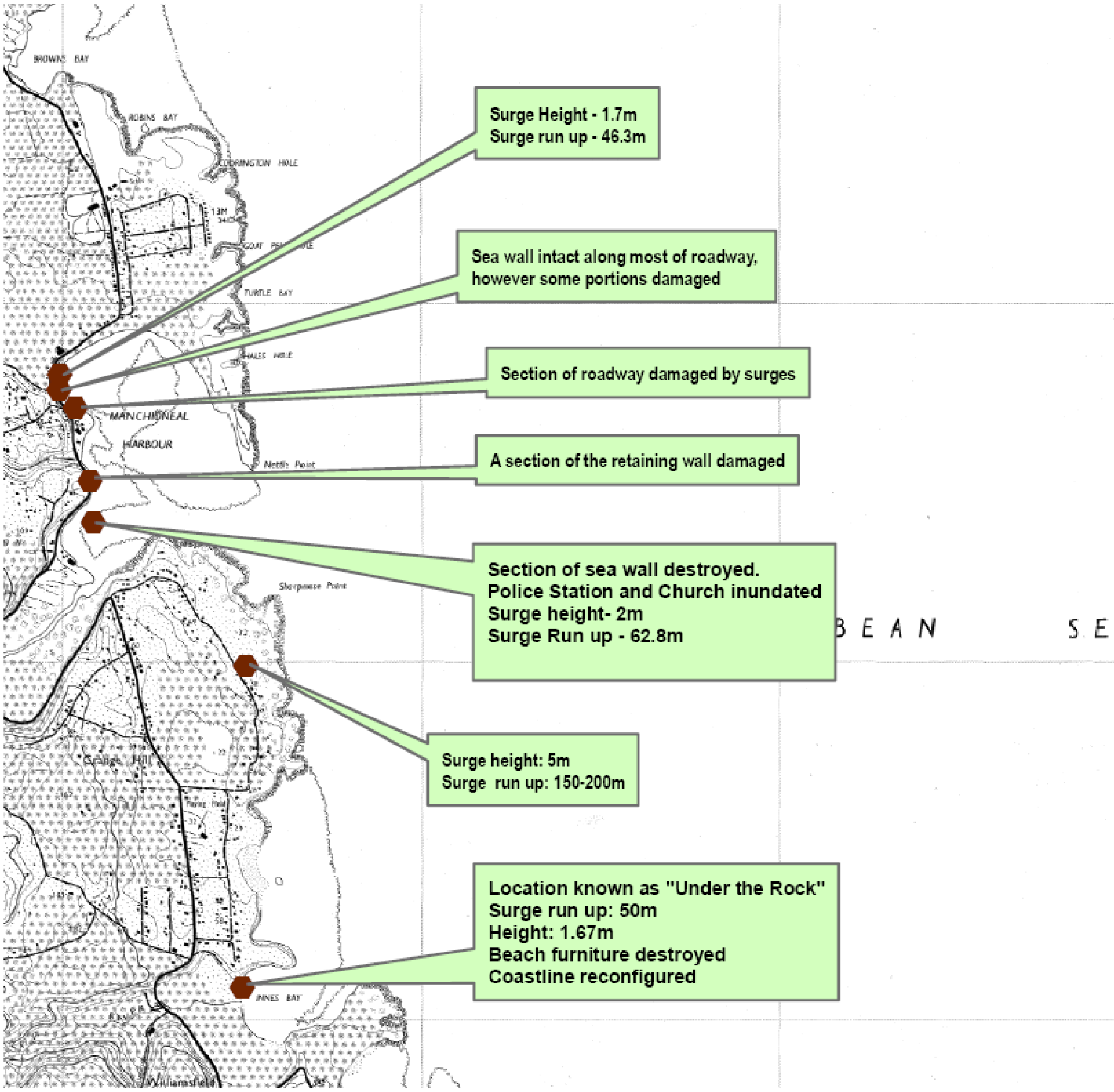


Figure 8: Hurricane Ivan (2004) Storm Surge Data at Manchioneal (Mines and Geology Division)

Table 4 summarizes the model validation results during the Hurricane Ivan simulation.

Table 4: Summary of predicted surge and field observations

Location	**Model Prediction**	**Field Observations**
Portland Cottage	Surge heights of 10 feet	Surge heights up to 10ft
East of Portland Cottage	Surge heights ranging from 5-8 ft	Surge heights of 5-8 ft
Free Town	Predicted heights of 8-9 ft	Observed 8-9 ft
Morant Bay	Predicted 1.35m	Observed 1.7-1.8m
Manchioneal	Predicted 0.96m	Observed 1.6-2.0m

EXTREMAL ANALYSIS

Analysis and Water Level Results

An extremal analysis was carried out using the calculated storm surge values from which various return period events were identified. The statistical analysis was carried out according to the method of Goda (1990). The data was fit to various statistical distributions, and the best-fit distribution was determined from the correlation as well as the goodness of the fit to the most extreme values in the distribution.

Return period values for the 25, 50, 100, and 150-year storms were computed. A flooding event with a return period of T- years is the flood that is expected to occur, on average, once every T- years. It is a statistical measurement denoting the average recurrence interval over an extended period of time.

A 95% confidence interval was applied to the extremal analysis. The application of confidence intervals helps in the estimation of the likely range of a parameter computed from a limited sample of a population. Since the population sample used was limited, these calculated storm surge values are considered to be a sample only of the total population of storm surge that would have affected each site. As such, the imposed confidence interval applied gives the likely range of storm surge values for each return period, taking into account the expected inaccuracies in the projection. The use of an upper bound 95% confidence interval means that there is 95% confidence that the predicted return period storm surge values would not be exceeded by the total population of storm surge events. This was the value for storm surge that was used in the mapping.

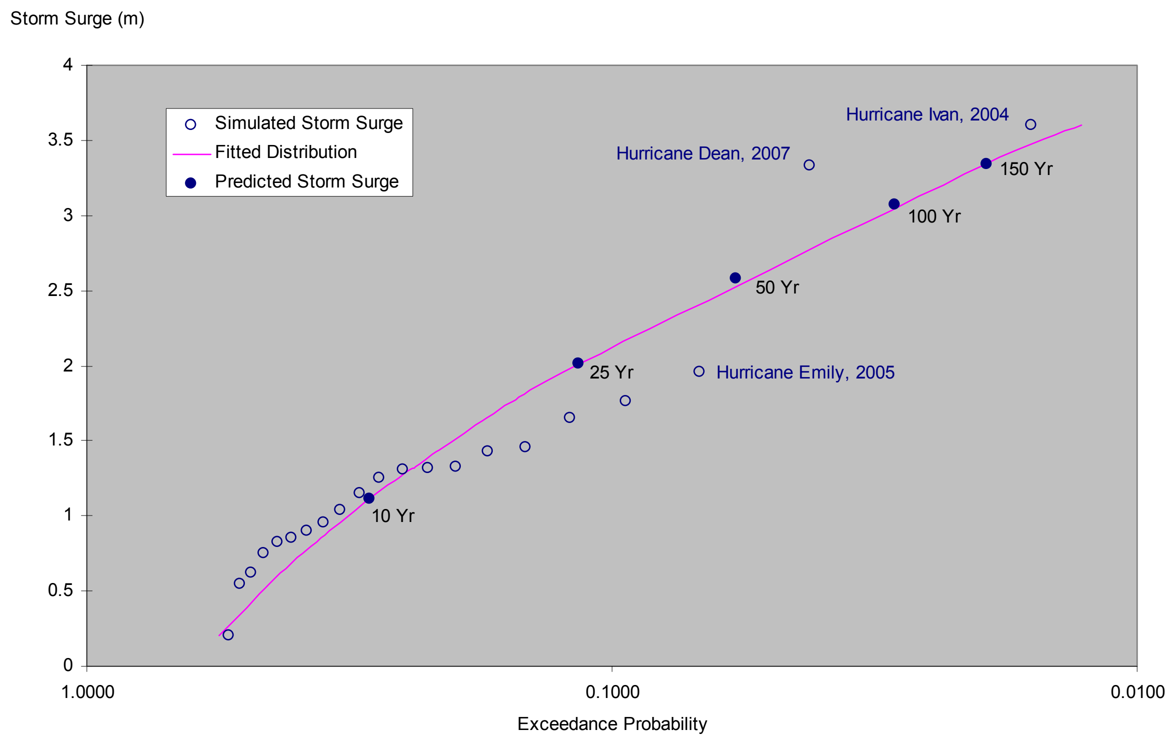
The extremal analysis determined the likelihood that a particular event will occur at a site based on historical records only. While this is a useful tool, it has some limitations. The statistical analysis did not investigate synthetic storms that could represent worst-case scenarios. Only storms that have occurred over the last 108 years have been included in the analysis, and within this record period, none of the sites were hit directly by a Category 5 hurricane. Thus, the analysis represents the storm surge values for the 25, 50, 100 and 150-year return periods based on the historical data. This does not mean that a site cannot be impacted in the future by a more severe storm than has happened over the past 108 years, which could potentially cause flooding that extends beyond the inundation areas presented in the hazard maps.

In addition to storm surge, the tidal variations and global sea level rise were taken into account to determine the final water levels. Based on tidal predictions, high tide above Mean Sea Level (MSL) was set to 0.45m. Tidal variations (high tide) were added to the storm surge predictions (mean sea level) to estimate the maximum predicted water levels (i.e., a storm occurrence at high tide as opposed to mean sea level).

Global Sea Level Rise (GSLR) has been predicted by scientists according to current rates of sea level rise and forecasting of the effects of global warming on the thermal expansion of the seas and the melting of glaciers and polar ice caps. The increase in sea level over the next century (until 2100) is estimated in the Intergovernmental Panel on Climate Change – Third Assessment Report to range between 90 and 880mm, with a central value of approximately 480mm. The Fourth Assessment report has been revised, giving a smaller range of values than the Third Report, however, the mean value for predicted sea level rise has remained the same. This corresponds to approximately 0.125m, 0.25m, 0.5m and 0.75m over the next 25, 50, 100, and 150 years, respectively.

For all three sites, Figure 9 to Figure 11 show (a) the results of the storm surge extremal analysis, with the data fitted to the best fit distribution, and (b) the predicted water levels for the various return periods, with 95% confidence interval bars.

It is of interest to note that from the extremal plots presented below, and from comparison with the actual storms, the following inferences can be made relating to the linkage between return period and hurricane category for these three sites. First, the data shows that Category 3 storms fall within the range of 50 – 75 year return period events. Second, it is seen that Category 4 storms fall within the range of 80 – 170 year return period events. This comparison shows that a lot of variability exists in doing a comparison like this, largely due to the differences in hurricane track, forward speed, and other critical hurricane parameters.



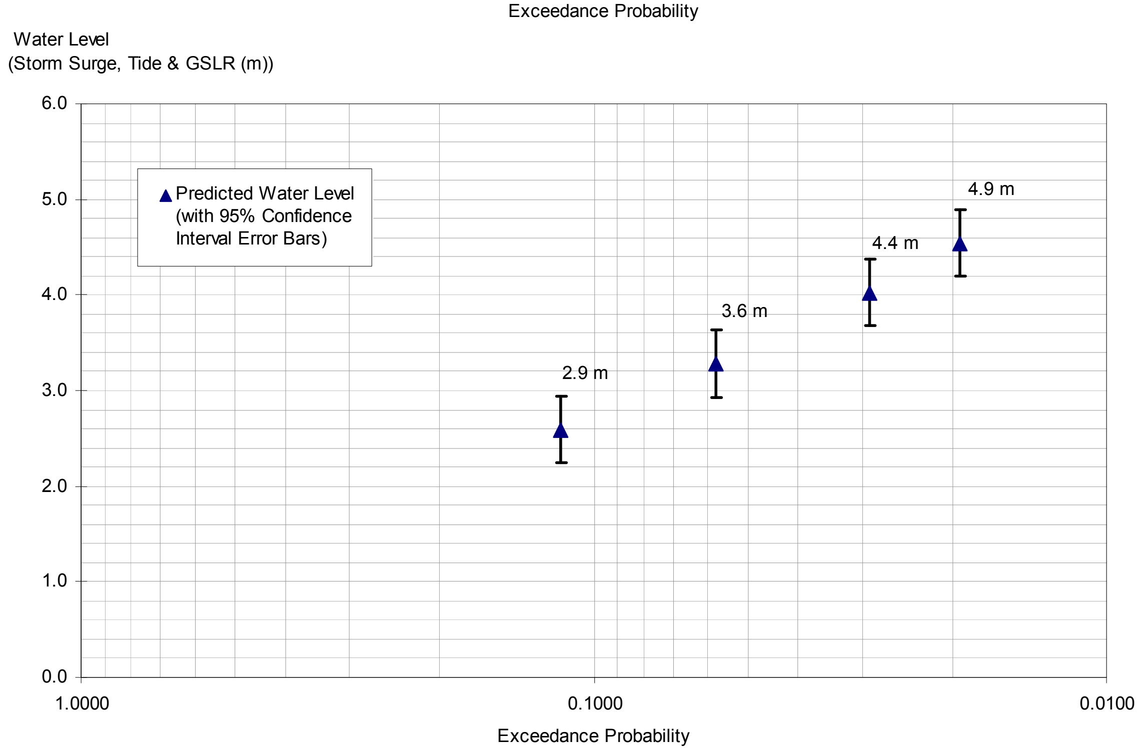


Figure 9: Storm Surge Extremal Analysis (top) and Water Levels at Portland Cottage (bottom)

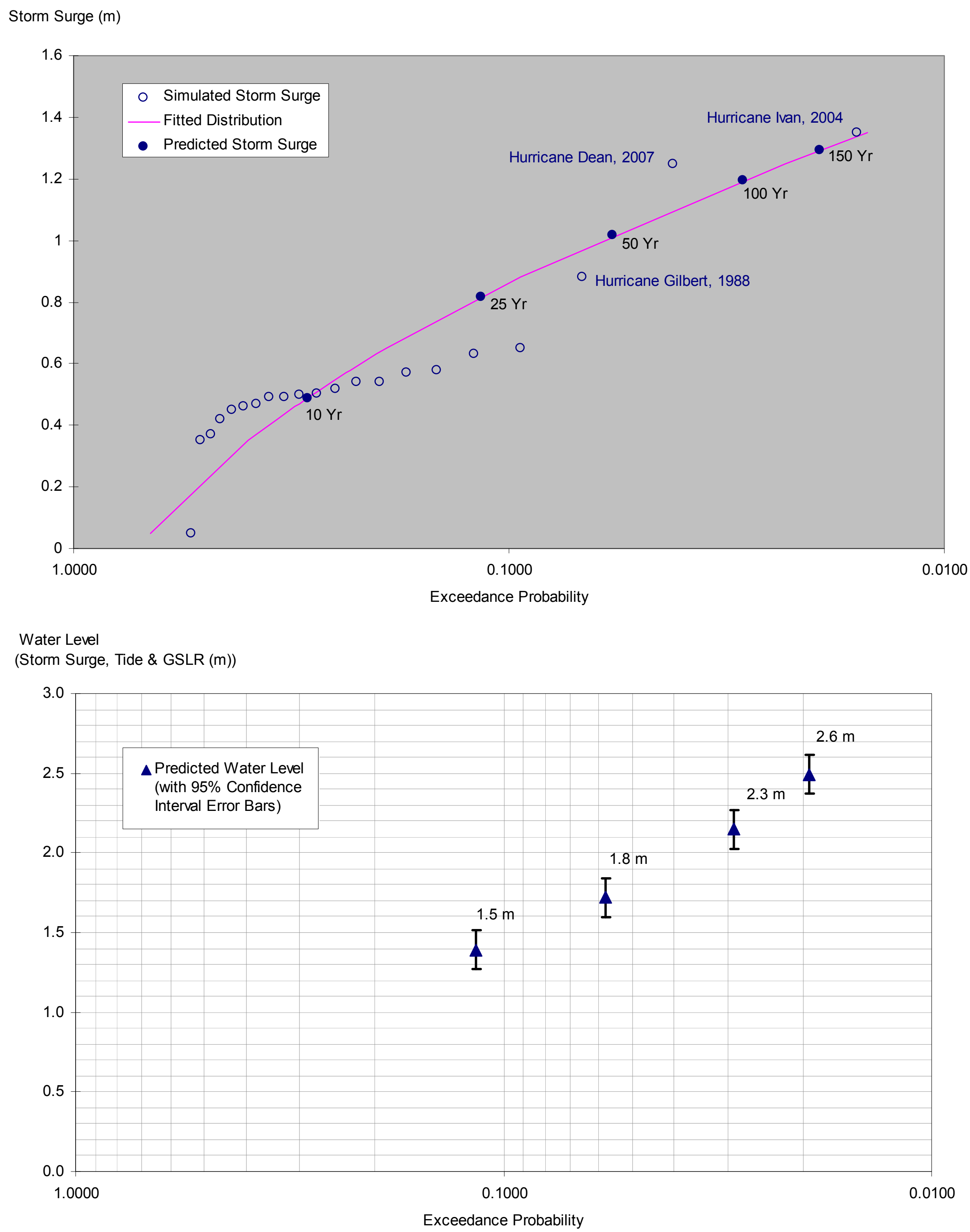
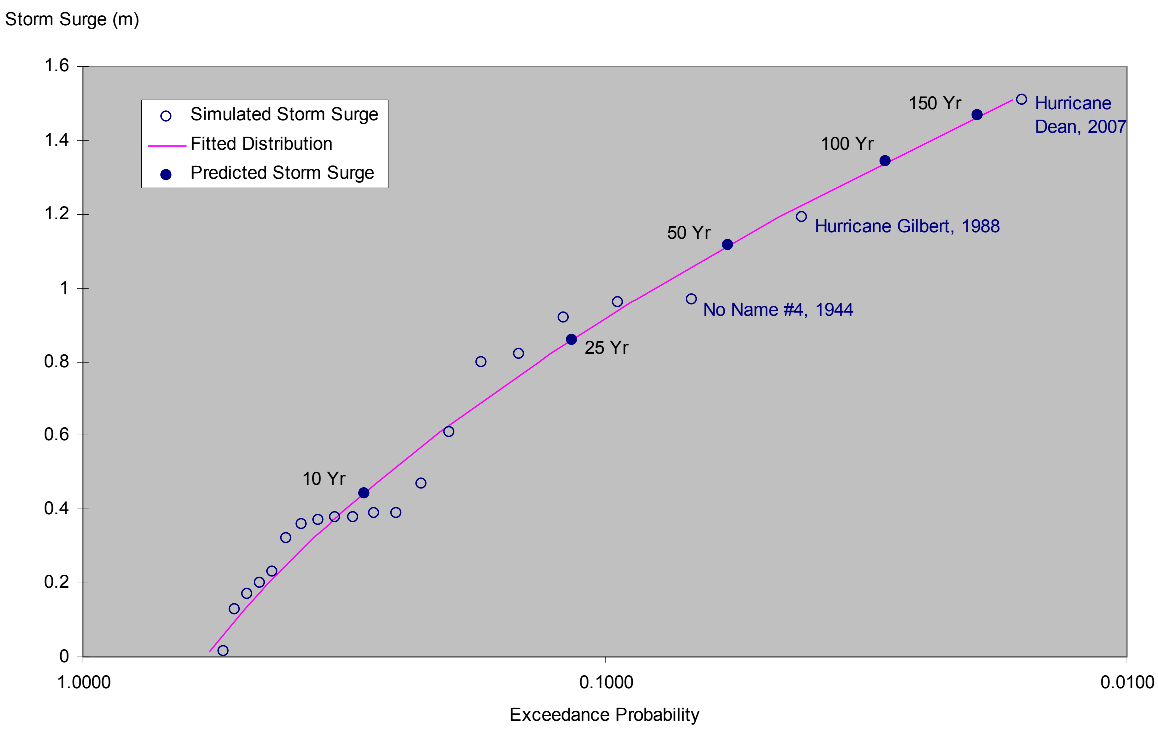


Figure 10: Storm Surge Extremal Analysis (top) and Water Levels at Morant Bay (bottom)



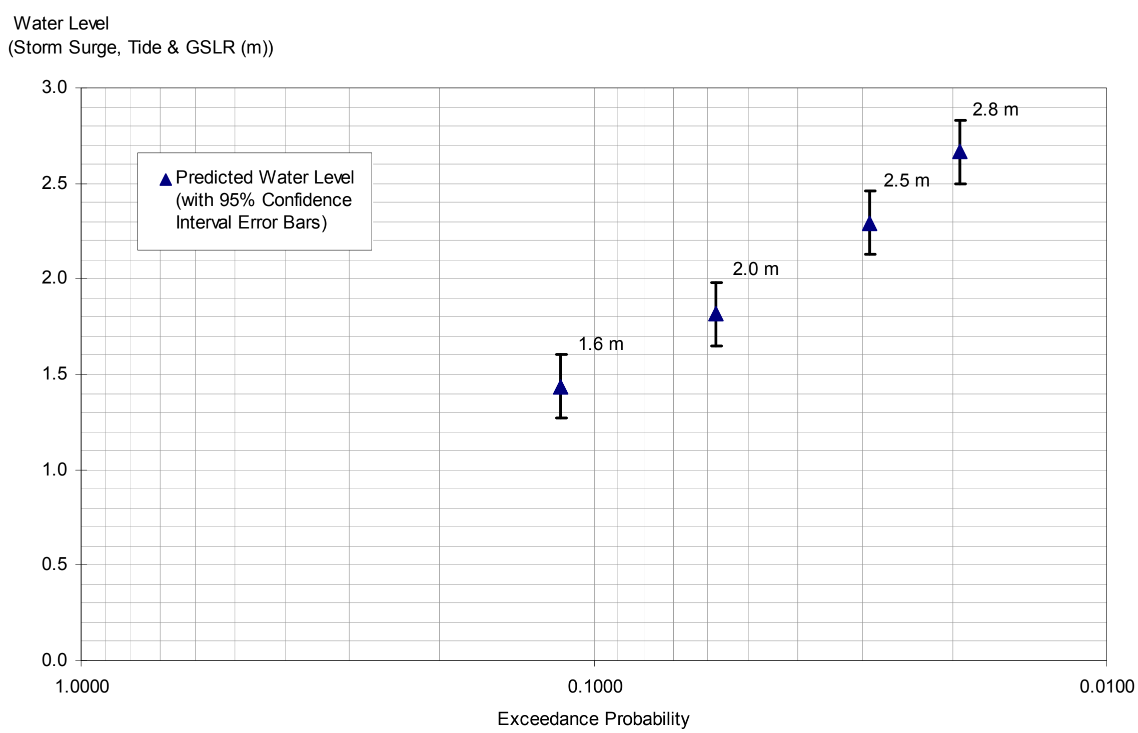


Figure 11: Storm Surge Extremal Analysis (top) and Water Levels at Manchioneal (bottom)

Storm surge hazard maps were prepared by integrating the predicted water levels and topography of the study areas in a GIS-compatible environment, overlaid on top of satellite imagery. The 25, 50, 100 and 150-year inundation zones were mapped, and the resulting hazard maps are shown in Figure 12 to Figure 14.

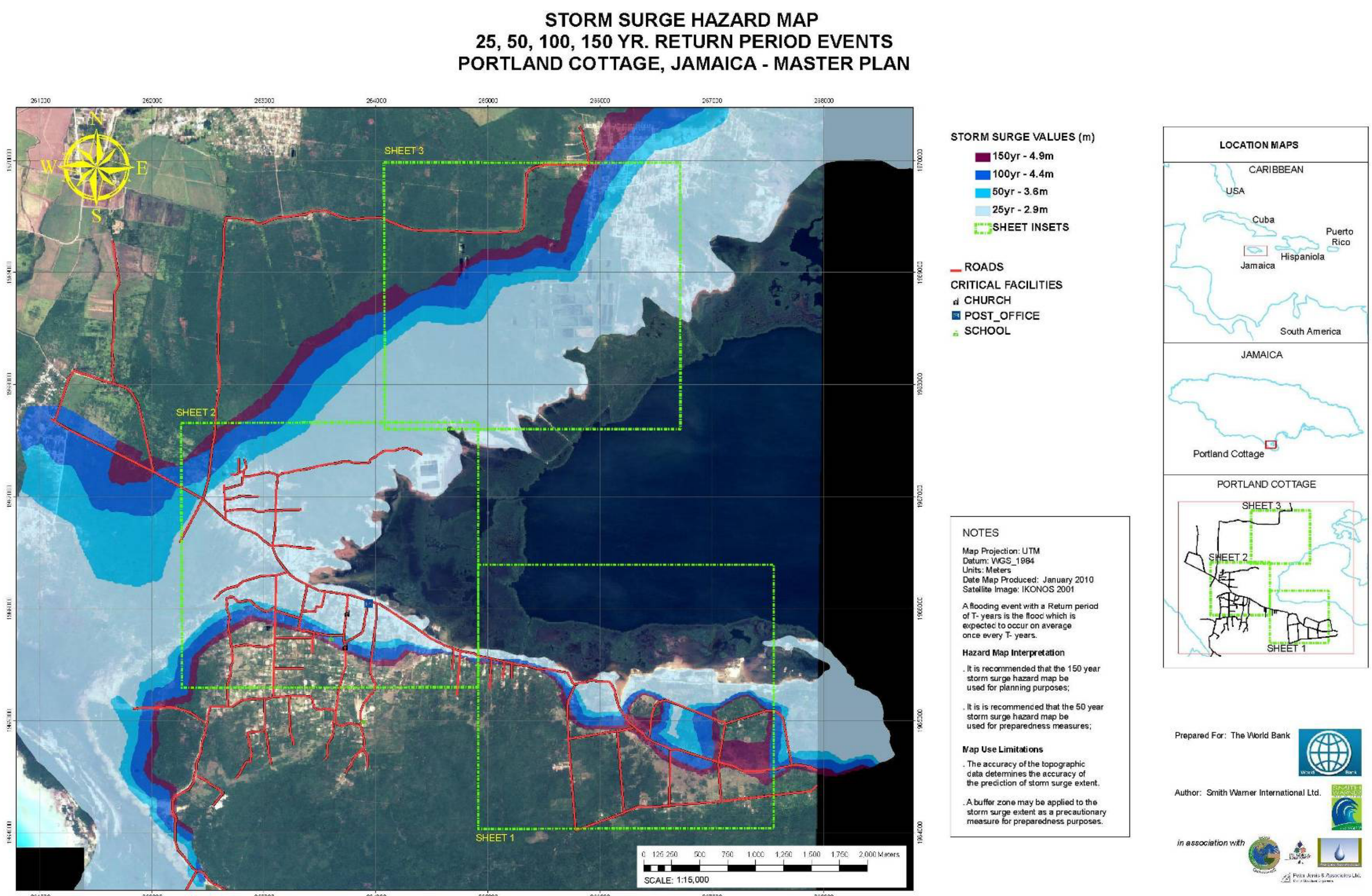


Figure 12: Storm Surge Hazard Map for Portland Cottage

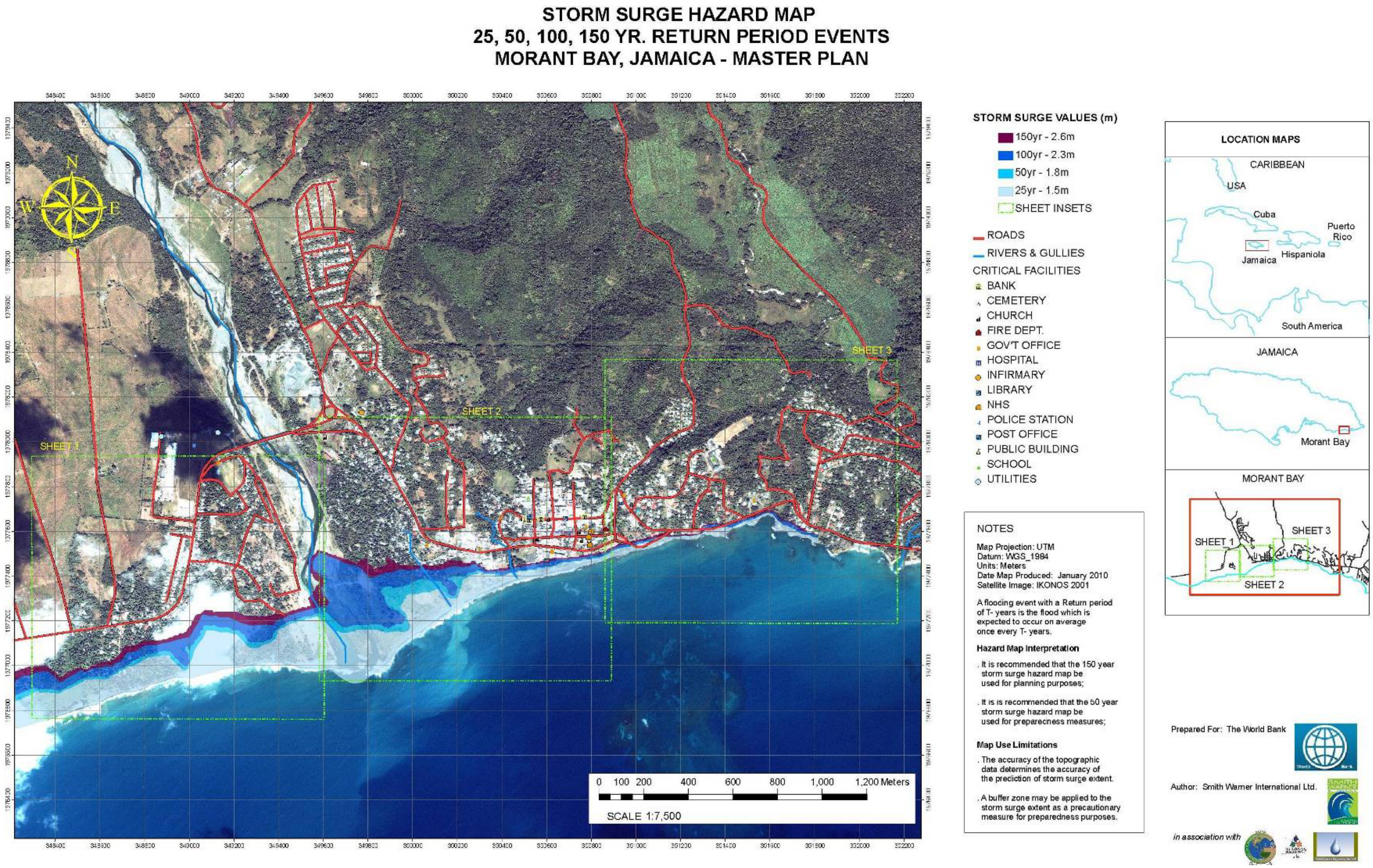


Figure 13: Storm Surge Hazard Map for Morant Bay

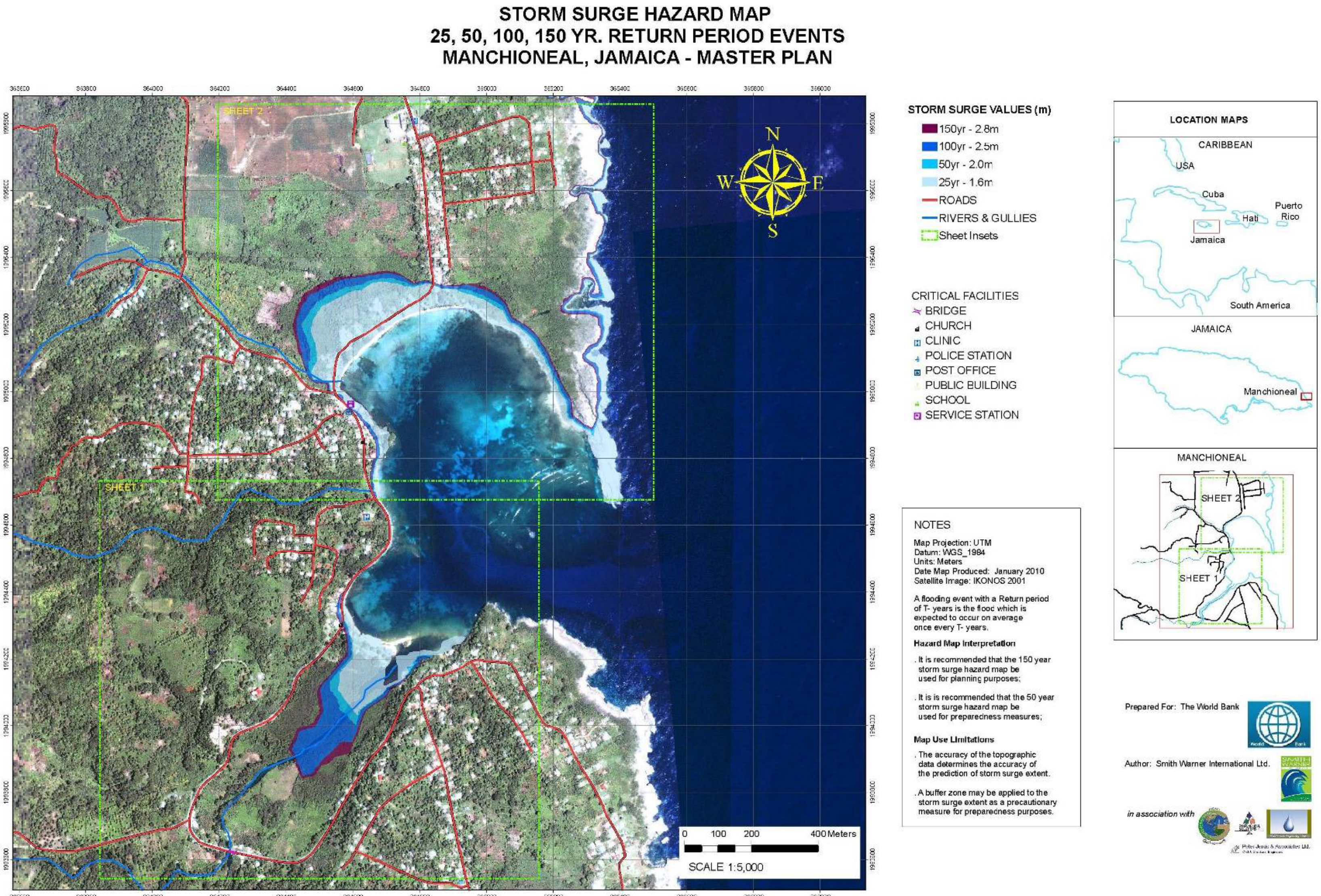


Figure 14: Storm Surge Hazard Map for Manchioneal

DISCUSSION OF RESULTS

By applying the MIKE 21 SW/HD coupled model along with the cyclone wind generation model, fairly accurate storm surge results were simulated for Hurricane Ivan (2004) for the communities of Portland Cottage, Morant Bay and Manchioneal, Jamaica. The model was then applied to a number of historical hurricane events, from which storm surge levels were extracted and an extremal analysis completed to obtain the 25, 50, 100, and 150-year return period events. These results were then included in an overall multi-hazard assessment of the communities.

The extent of the storm surge in a certain area will depend on the characteristics of the shoreline, the seabed bathymetry, the topography, the distance from the coastline to deep water, and other natural physical features, including the presence of mangroves and vegetation cover. The storm surge values for Portland Cottage are noticeably larger than those for Morant Bay and Manchioneal. This is largely due to the physical geography of the site. Specifically, the West Harbour adjacent to Portland Cottage is a large, extremely shallow water body, which is conducive to large wind set-up values.

CONCLUSION AND RECOMMENDATIONS

Overall, the coupled model provided accurate and representative results in simulating storm surge. The use of MIKE 21 enabled detailed, high-resolution storm surge hazard maps to be developed for three coastal communities, which can help guide emergency managers, planning agencies and insurance companies within Jamaica. The methodology described above could be applied to other coastal communities in Jamaica and throughout the wider Caribbean.

The model predicted accurate storm surge results at Portland Cottage, while slightly under-predicting water levels at Morant Bay and significantly under-predicting values at Manchioneal. The under-prediction at Manchioneal is likely due to the presence of vertical cliffs along the coastline and also the presence of sea walls, which would result in wave reflection that cannot be properly simulated by the coupled MIKE 21 SW/HD suite.

An extremal analysis was then carried out from which the return periods of 25, 50, 100 and 150-year storm surges were computed for each of the communities. A 95% confidence interval was also applied to the extremal analysis to account for inaccuracies in the projection. The inclusion of synthetic storms that could represent worse case scenarios was not included in the extremal analysis.

To improve the prediction capabilities of the model for future sites within Jamaica and the Caribbean, the following is recommended:

- Collect more detailed topographic data to enhance the accuracy of the inundation mapping (the process of converting the storm surge elevation to an inundation line, based on local topography would be improved). It is recommended that ground-corrected LIDAR data be collected.
- Tidal data should be collected at specific sites around Jamaica to establish a proper Mean Sea Level Datum, from which inundation could then be consistently mapped.
- Improve filtering systems when selecting hurricanes: some slow-moving, less intense storms with smaller wave heights still produce significant storm surge.
- Further develop the hurricane selection and ranking system based on the value of the IBR and the wave height. These components should be weighted and combined in the most effective way to methodically rank the storms that pass the site.
- Increase the number of storms and the potential use of synthetic storms to represent worst case scenarios (this would allow a reduction in the confidence interval).
- Inclusion of hard structures which may force the storm surge flow into localized areas thereby leading to a more realistic representation of what occurs in communities.

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