A Classification of the Protection Provided by Coral Reef Systems in Jamaica - Utilizing GIS and Oceanographic Methods of Analysis

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1. Acknowledgements

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2. Project Background

This study is part of the World Resources Institute's (WRI) Coastal Capital project in the Caribbean. The project was launched in 2005, and aims to provide decision-makers with information and tools that link the health of coastal ecosystems with the attainment of economic and social goals. WRI and its local partners have conducted economic valuation studies of coral reefs at national and sub-national levels in five countries: Trinidad and Tobago, St. Lucia, Belize, the Dominican Republic and, most recently, in Jamaica. WRI and its partners are using the results to identify and build support for policies that help to ensure healthy coastal ecosystems and sustainable economies. Additional information about WRI's Coastal Capital series is available online at http://www.wri.org/coastal-capital.

In Jamaica, WRI and its partners developed economic valuations of coral reef-associated fisheries, beach tourism and evaluated the role of reefs in shoreline protection. In particular, this paper focuses on what would happen to shoreline protection as a reef degrades, loses live coral cover and erodes. With WRI, the Mona GeoInformatics Institute (MGI) and the Marine Geology Unit (MGU) of the University of the West Indies (UWI), Mona Campus, and Texas A&M University, applied a hydrodynamic model to three pilot sites in Jamaica (Negril, Discovery Bay and Port Royal Cays) to evaluate how changes in reef condition would influence wave height (inside the reef) and coastal inundation for a range of storm events. MGI collaborated with WRI and MGU to develop a reef typology, which was based on morphological and spatial characteristics of the reef form. MGI then incorporated this into a wider coastal typology based on a combination of the reef and shoreline characteristics. This coastal typology was extrapolated from the three pilot sites to the national coastline. This allowed MGI to produce coastal typology maps, highlighting sections of the country that were afforded the greatest protection by reef, and estimate changes in inundation along different segments of coastline due to coral degradation.

The objective of the project is to identify vulnerable areas; provide information to refine policy, management plans and investment strategies that make the case for solutions to increase sustainable investment; and increase the capacity for valuing the coastal environment.

3. Overview of Analysis

Coral reefs play an important role in protecting shorelines by mitigating wave energy. This is made apparent where waves are seen breaking on the edge of a coral reef and much calmer water is found inside the reef. Coral reefs can mitigate over 75% of wave energy[1]. Coral reefs play an important role in reducing wave energy both during normal conditions and during storms. By reducing wave energy, coral reefs lessen coastal erosion and reduce inundation during storms. Coral reefs are, however, less effective attenuating the big waves and storm surges associated with very large storm events.

The effectiveness of a coral reef in reducing wave energy varies with the type of the reef (continuous or patch; emergent or submerged; fringing or barrier); distance from shore, depth below the surface, and complexity (roughness) of the live coral structure on the reef, as well as the wave height and angle of approach. Fringing, patch and barrier reefs surround just over 50% of Jamaica's shoreline within 50m from shore. The degree of protection varies with the factors mentioned above. This study is intended to help quantify the degree of protection provided by coral reefs along different segments of Jamaica's coast and estimate the extent of coastal inundation for different storm events (1 year and 25 year).

It was not possible to implement a detailed hydrodynamic modeling of wave attenuation for the entire shoreline of Jamaica, as the data input and computational requirements for each reef are great. Instead, we selected three representative sections of coastline and implemented a detailed hydrodynamic modelling for these three "pilot sites" (Negril, Discovery Bay, and Kingston / Port Royal Cays). At the three pilot locations, we estimated wave heights and coastal inundation both with the current coral reef condition and with a severely eroded coral reef for both a one-year and a 25-year storm event. We could then look at the inundated area and the property and infrastructure included in each scenario (such as the one-year storm event and an eroded reef).

The second component of the analysis allowed extrapolation of these three pilot sites to a national level analysis. A "reef protection typology" was derived from two other primary typologies, namely the reef and coastland typologies. The reef typology characteristics include reef type, slope and orientation, distance from shore, complexity of the reef shape, and the portion of the bathymetric segment occupied by its reef. Characteristics of the coastland typology were based primarily on slope and complexity of the landward segment that may be prone to inundation. Protection typology was therefore developed by combining characteristics of the coast and reef structure, allowing each segment of the Jamaican shoreline to be classified according to the pilot site it most closely matches. Each segment was therefore given a rating - low, medium or high - for the relative protection its reef allows.

Drawing on this classification scheme, it was possible to use the modeling results from the three pilot sites to estimate the height of waves reaching the shore and likely areas inundated for each storm scenario for the entire coastline. The number of buildings and infrastructure in areas likely to be inundated were mapped for coastal communities identified as having a relatively high degree of coastal protection provided by coral reefs (and the greatest wave attenuation by reefs).

4. Study Area

Three pilot sites were chosen, as agreed upon by MGI, MGU and WRI researchers, for initial modelling based on availability of data, economic importance and local knowledge of the areas. These were Negril, Discovery Bay and Kingston. Profiles (see Figures 1, 2 and 3) were created of all the sites to compare their 2D form for contribution to the bathymetric complexity criteria. Results from inundation models of the three pilot sites were the basis for extrapolation to the entire Jamaican coastline.

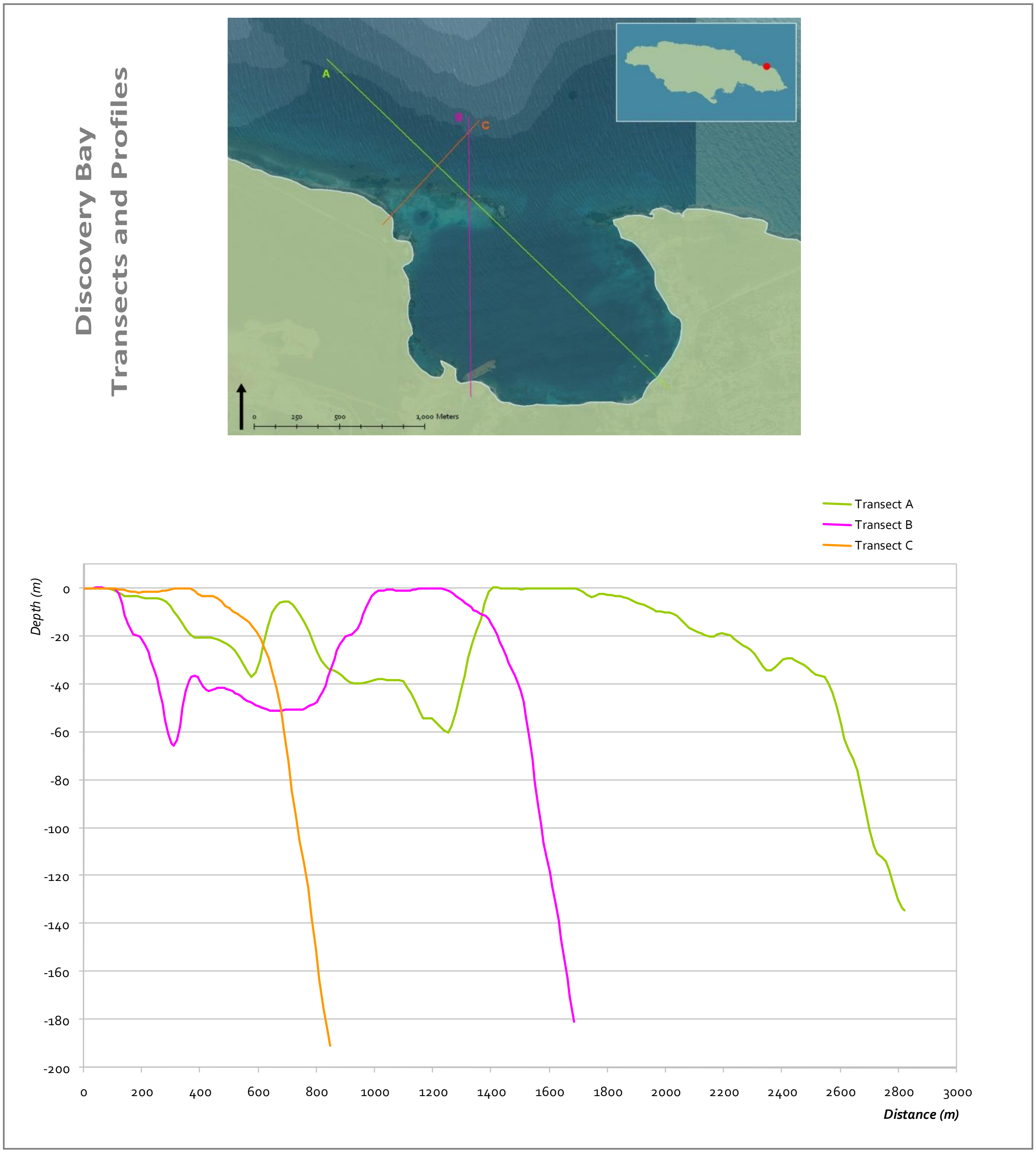

Figure 1. Reef transects and bathymetric profiles of the Discovery Bay Pilot Site

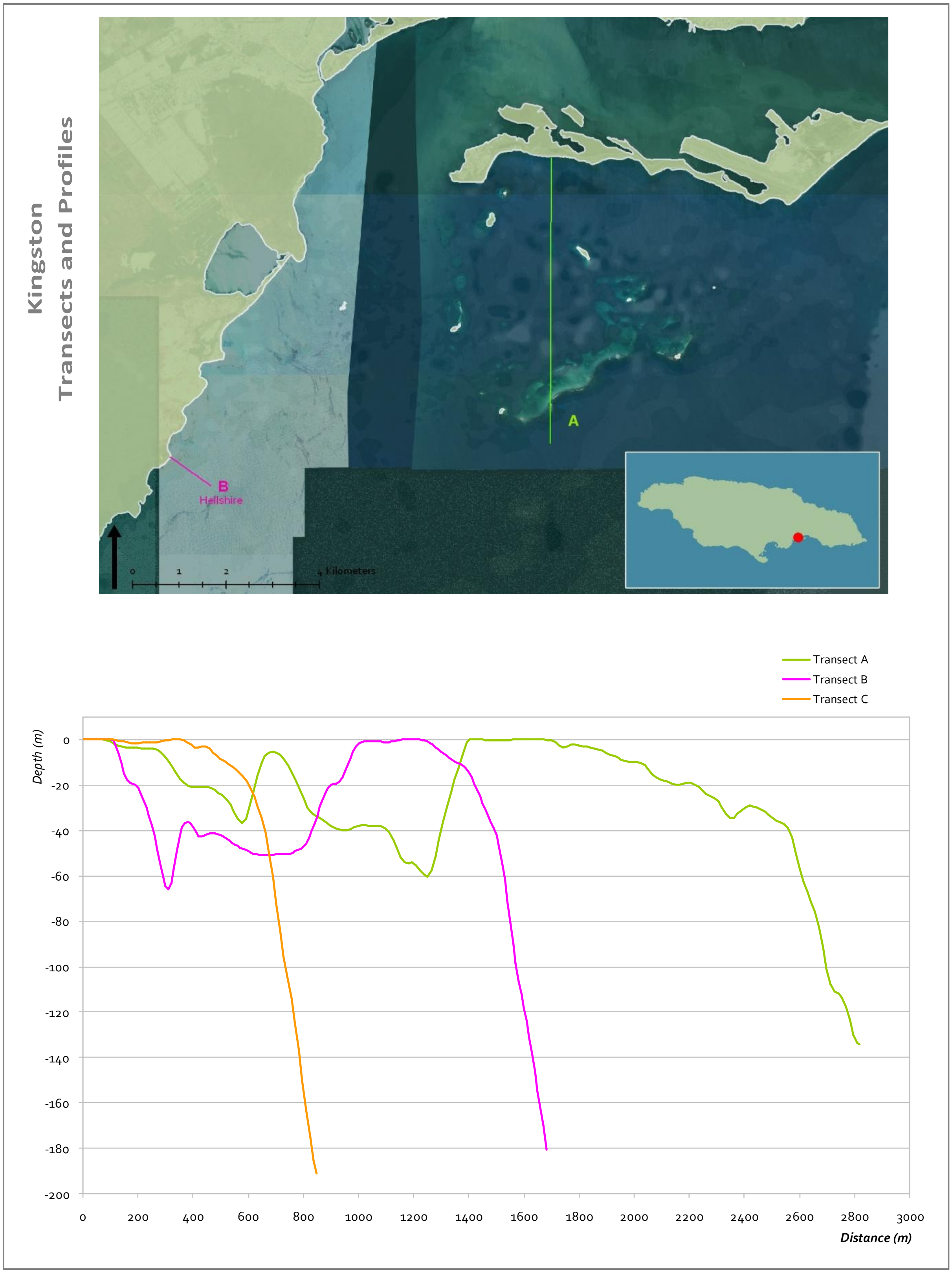

Figure 2. Reef transects and bathymetric profiles of the Kingston Pilot Site

Negril
Transects and Profiles

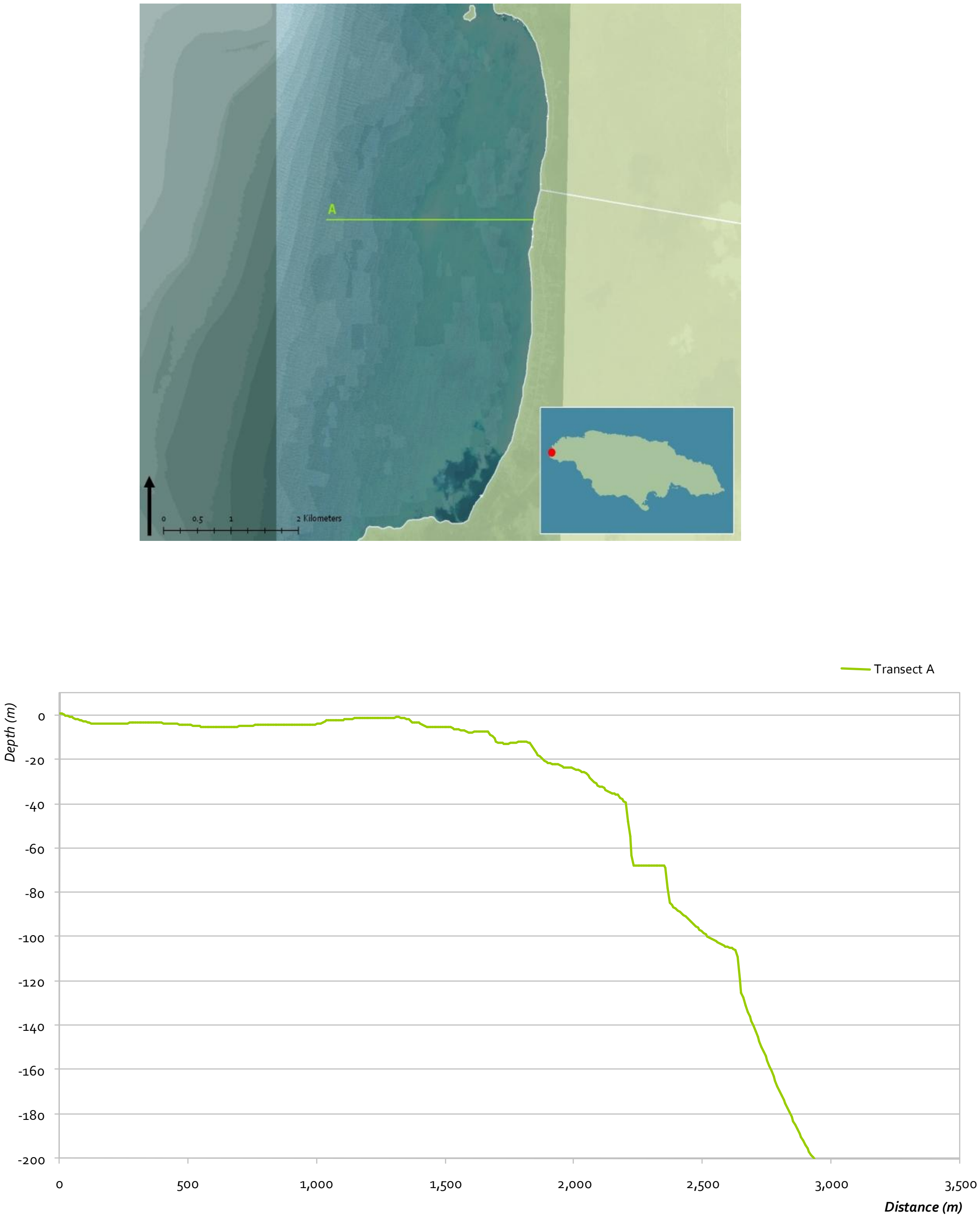

Figure 3. Reef transects and bathymetric profiles of the Negril Pilot Site.

5. Methodology

5.1. Wave Attenuation Analysis

Using inputs provided by MGI and MGU, Texas A&M University applied the MiKE-21 hydrodynamic model, developed by the Danish Hydrologic Institute (DHI), to simulate two-dimensional (2-D) wave attenuation and run-up for the three pilot sites in Jamaica using a range of wind, wave and coral condition scenarios. The application was focused on evaluating how changes in reef condition and height would influence wave height and run-up at the shoreline.

The variables for this model were:

- Water Level (m)
- Wind Speed (m/s)
- Offshore Wave Height (m)
- Offshore Wave Period (s)
- Reef Height (m)

5.1.1. Run-up Model Scenarios

1. Return Period Storms

Texas A&M applied the MIKE-21 model in 2-D mode for a range of storms – from an annual storm event through a 100 year storm (See Table 1.) The analysis of wave attenuation and run-up for the pilot sites concluded that reef degradation has a greater impact on wave attenuation and run-up for storms with a return period of 25 years or less. As such, to capture both ends of this range, the wave attenuation and inundation modelling and analysis would consider two storm scenarios, specifically the 1-yr and 25-yr return period scenarios.

Table 1. Storm scenarios used in the analysis

	1 Year	**5 Year**	**10 Year**	**25 Year**	**50 Year**	**100 Year**
Water Level (m)	0.60	0.78	0.95	1.70	2.30	3.03
Wind Speed (m s^{-1})	24.56	27.05	29.25	39.25	46.50	53.25
Wave Height (m)	3.11	3.41	3.65	4.88	5.68	6.45

Note: For the 10, 25, 50 and 100 year storms, the data on wind speed and wave height are based on the *Caribbean Disaster Mitigation Project* (*CDMP) Storm Hazard Atlas for Jamaica*[2]. The annual and 5 year return periods were estimated based on a regression analysis of the available years (10, 25, 50 and 100). All data is calculated as the average for Montego Bay, Kingston, Port Esquivel, and Rocky Point. Bathymetric data and profiles provided by MGI.

2. “With” and “Without” Reef Scenarios

Two types of reef scenarios, specifically “with reef” and “without reef”, were considered for each pilot site. It should be noted that “without reef” does not signify the complete loss of reef, but a significant loss in reef height. The “without reef” scenarios assume a loss of all live coral cover, followed by erosion (loss of height) of 4 m for Negril and 5 m at Discovery Bay and Kingston/ Port Royal.

5.1.2. Pilot Shoreline Water Levels

Water level models were run for both storm scenarios (1-yr and 25-yr return period) and reef scenarios (“with reef” and “without reef”) for each pilot site. In the case of the “without reef” scenario for Negril, reef height was modelled at 5 m depth, and for Discovery Bay and Kingston, 6 m depth. Run-up (m) and resulting water level (m) estimates at the shoreline were produced.

5.2. Reefal Coastal Protection Classification

Geomorphological and spatial statistical methods were integrated into a geographic information system (GIS) to derive a spatial analysis of shoreline protection provided by coral reef structures. A Reef-Terrain-scape classification was created to qualitatively compare the relative protection provided by different reef types from inundation due to storm-induced surge. This classification was first applied to pilot sites in Discovery Bay, Negril and Kingston, and then to the rest of the Jamaican shoreline. The coastline was segmented according to population centers, each segment was assigned reef and coastland typology classes, followed by the final protection typology classification.

5.2.1. Coastal Segmentation

The coastal unit used in this assessment was derived from a GIS polygon shapefile of communities for the entire island. Communities were grouped around town centres where it was assumed that towns were areas of relatively dense population, and merged to create larger segments around the entire coast. In all, 31 segments were created from 144 coastal communities; each segment taking the name of the most populated community. These segments were first created for terrestrial areas, and then extended to the sea. The area of coastal land between 0 and 15 m in elevation was identified and termed “Coastland”, while an area with a depth between 0 and 50 m was designated as the delimiter of the Reef Zone.

5.2.2. Reef Typology – Assigning Parameters

Reef typology was constructed in the GIS based upon the following parameters (in order of importance in shoreline protection):

1. Reef type;

2. Shape Index (SI);
3. Distance from shore; and
4. Absolute Degree Difference (between reef and shoreline orientation)

1. Reef Type

Reef Type was a description tagged to each reef feature and a value *R* assigned to determine the relative protection offered by the various types of reef systems found around the island. Spatial geometry and definitions for each reef type were provided by the Millennium Coral Reef Mapping Project[3], Mona GeoInformatics Institute and the UWI Marine Geology Unit. The derived reef for the shoreline is illustrated in Figure 4. Reef types used in this analysis were primarily Barrier, Fringing, Patch, and Pseudo Atoll. Table 2 describes the Reef Types and their combinations as listed in order of most protective (Barrier) to least (Patch) [4,5].

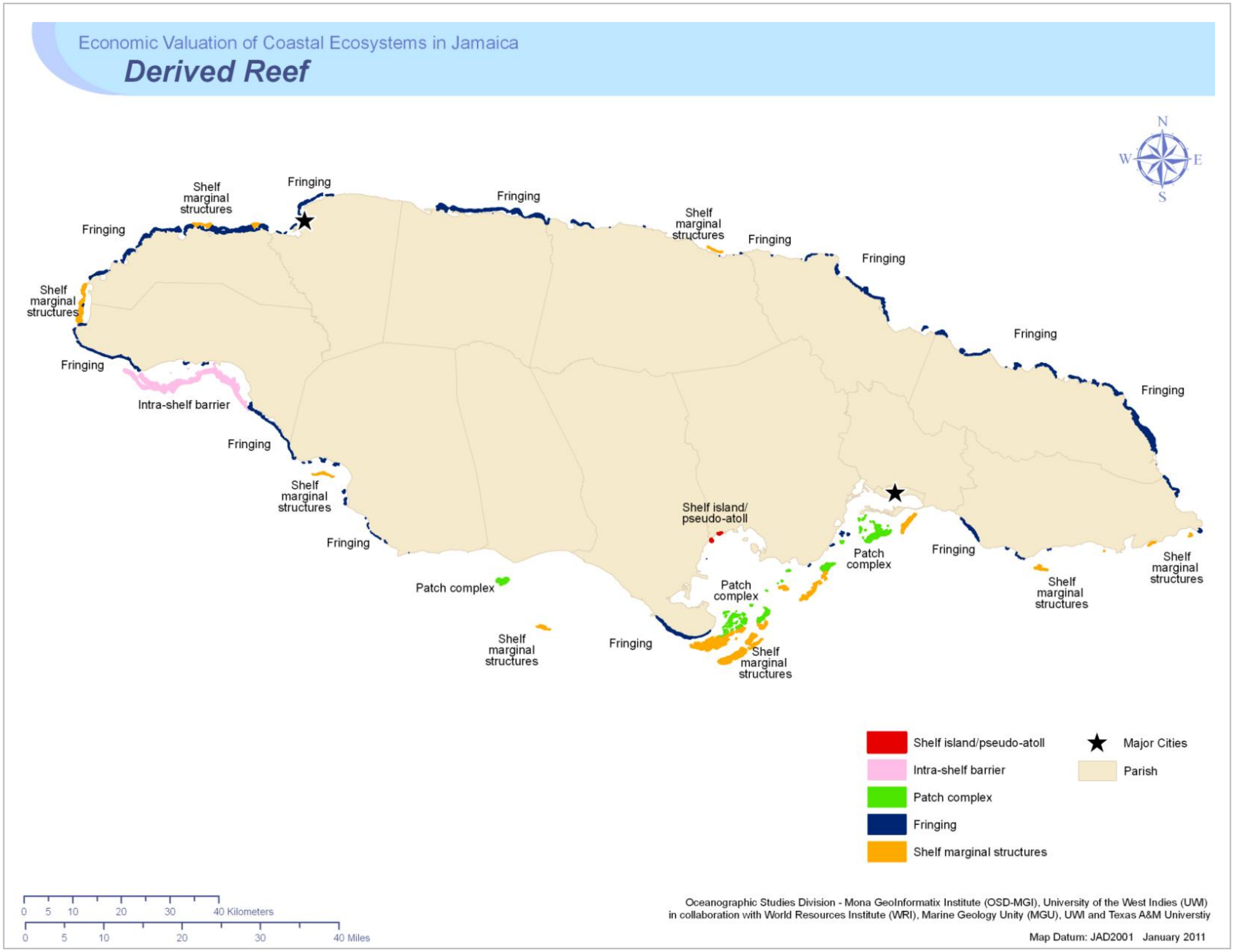

Figure 4. Derived reef dataset used for analysis of reef protection

Table 2. Definitions used for assigning type to reef polygons

Reef Type		Description	Spatial / Geometric
1	Barrier (*most protective*)	Similar to fringing system except that barrier reefs are separated from land by a lagoon.	Low density reefs away from shoreline, and not barrier-patch complex
2	Fringing	Reefs that grow along continental land or an island	Less than 1 km from shore and not patch associated with cay
3	Patch Barrier Complex	Combination of patch and barrier reef.	More than 2 reefs within 100 m proximity of each other
4	Shelf island/Psuedo-Atoll	May apply to crescent shaped reefs in areas with cays/islands (atoll: ring shaped reefs from which a few low islands extend above the sea surface).	Manually identified from patch associated with cays
5	Patch/Shelf marginal (*least protective*)	Patches that are large enough to be considered a complex with another reef type	Dense patch sets

2. SI (Shape Index)

Generally accepted theory holds that the more spatially complex a reef structure, the more likely it is to be effective at protecting the shoreline[6,7]. This complexity was calculated as the Shape Index of the reef, SI_R. Shape Index (SI) is a function of area, since SI is a calculation of perimeter:area ratio[8,9]. This method of calculating 2D complexity was done by comparing the size of the reef and a perfect circle with the same area.

$$\text{Shape Index of Reef Polygon, } SI_R = \frac{B_i}{A_i}$$

Where A_i = area of individual reef polygon
B_i = area of a circle with perimeter L_i
L_i = perimeter length of reef polygon

3. Distance from Shoreline

The closer a reef is located to a shoreline, the greater it's protective capacity to buffer it from wave energy[10,11]. The distance of the reef from the shoreline was calculated by first associating the individual reef with a section of coastline, and then by determining the distance using zonal calculations.

Individual reefs were tagged to coastline segments. The entire coastline of Jamaica was broken into over 28,000 individual segments with simple coastlines having fewer vertices (and longer uninterrupted segments) than more complex and curvy coastlines. Each segment was tagged with the coastal zone ID in which it existed. In order to isolate specific stretches of the coastline an individual reef would influence, 1km buffers were created around each reef, and where these buffers intercepted the coastline, that particular stretch of coastline was tagged by the respective reef ID. In cases where multiple reef buffers intercepted the coastline, the nearest reef was used to tag the associated coastline. Coastlines with reefs further than 1 km away, or had no reefs nearby, were not tagged.

As such, numerous coastlines were created, which could be individually characterized and then paired with an associated reef. A general coastline was created from the vertices of the extreme edges of the shoreline for each zone. However, this simplified and irregular coastline, does not explain variations in reef-coastline relationships within each coastal zone.

The distance of each reef to the shoreline (D) was computed using raster distances from the shoreline, and using zonal statistics of the reef from this grid to determine the maximum, minimum and mean distance of any part of the reef from the shore; from any direction.

$$\text{Reef Shoreline Distance, } D = \frac{\sum(X_{MIN}, X_{MAX})}{2}$$

where X_{MIN} = minimum distance of any part of the reef from the shore
X_{MAX} = maximum distance of any part of the reef from the shore

4. Absolute Degree Difference

The relationship of individual reefs to nearby coastlines was determined. The closer the reef is to the shoreline, the more effective a parallel reef will be at blocking waves coming from any direction[12]. This was quantified as the Absolute Degree Difference (θ_A).

$$\text{Absolute Degree Difference, } \theta_A = |\theta_R - \theta_S|$$

where θ_R = long-axis orientation inside individual reefs (0-180°)
θ_S = long-axis orientation inside individual shorelines (0-180°)

5.2.3. Reef Typology – Quantifying Parameter Values

Each reef polygon in the 0 to -50 m zone was assigned a parameter class value (See Table 3). Each bathymetric segment (area between shoreline and 50-m depth) was then given an overall class value for each parameter based on the dominant class. The dominant class for each parameter was determined by calculating the Percent Reef Area. The Percent Reef Area was calculated as the percent of the total reef in a bathymetric segment zone that is occupied by each individual reef polygon.

$$\text{Percent Reef Area, } A_R = \frac{\Sigma A_{i,k} \times 100}{\Sigma A_k}$$

where $A_{i,k}$ = area of individual reefs for specific reef type (e.g. barrier or patch)
A_k = area of all reef polygons in bathymetric segment

The majority of segments had a Class 3 Reef Type (Fringing or Patch-Barrier). Class 1 (1.0-2.0) and Class 3 (3.1-4.0) SI were equally dominant, while most bathymetric segments fell under Class 4 (0-0.5km). Similarly Class 4 (0-30°) was the most dominant class for Absolute Degree Difference.

Table 3. Parameters Classified for Typology

PARAMETER	Class 4	Class 3	Class 2	Class 1
Reef Type (R)	Barrier	Fringing or Patch-Barrier	Shelf island/ Psuedo-Atoll	Patch Complex
Shape Index for reef (SI_R)	>4.0	3.1 – 4.0	2.1 – 3.0	1.0 – 2.0
Distance from Shore (D), km	0 – 0.5	0.6 – 1.5	1.6 – 3.5	> 3.5
Absolute Degree Difference (θ_A), °	0 – 30	31 – 45	46 – 60	>60
Shape Index for Coastland (SI_C)	>8.0	6.1 – 8.0	4.1 – 6.0	0 – 4.0

A weight was given to each parameter according to how influential it would be at protecting the shoreline. The following factors were applied and then summed to create the weighted composite:

- Reef type: x2 ;
- SI: x1.5 ;
- Distance from Shore : x1; and
- Absolute Degree Difference : x1.

$$\text{Weighted class bathymetric segment score, } B_W = (2C_R+1.5C_{SIr}+C_D+C_{\theta A})$$

where C_R = overall class value assigned for Reef Type (R) for that bathymetric segment
C_{Sir} = overall class value assigned for reef Shape Index (SI_R) for that bathymetric segment

C_D = overall class value assigned for Distance from Shore (D) for that bathymetric segment
$C_{\theta A}$ = overall class value assigned for Absolute Degree Difference (θ_A) for that bathymetric segment

The weighted composite was then multiplied by the total percent of the zone to create the adjusted classification. This was done in order to classify the entire bathymetry zone rather than for just the reef.

The Percent Zone Area was calculated as the percent of each bathymetric segment zone that is occupied by coral reef, and was calculated by determining the sum of all the reef's areas in a bathymetry zone and dividing by the area of that 0 to -50m bathymetry zone.

$$\text{Percent Zone Area, } A_Z = \frac{\Sigma A_{i,k} \times 100}{\Sigma A_k}$$

where $A_{i,k}$ = total area of individual reefs for that bathymetric segment
A_b = total area of entire bathymetric segment

Adjusted weighted class bathymetric segment score $B_A = B_W \times A_Z$

5.2.4. Coastland Typology

SI calculations were carried out on individual Coastland segments (SI_C) to quantify their complexity. Higher values reflected greater complexity in a two-dimensional shape, and was assumed to be less vulnerable to surge events[13,14]. These values were used to adjust those of the Reef Typology on the premise that with or without the reef, complexity of the shoreline above the mean sea level mark influences how it is affected by a surge.

5.2.5. Final Reef Protection Typology

The final reef protection typology score for each bathymetric segment was created by doubling the protection provided by the segment's reef (B_A), and dividing this by the complexity of the zone's coastland (SI_C). This final typology was used to determine whether the segment received low, medium or high protection from inundation.

Final adjusted weighted class bathymetric segment score $B_F = (B_A*2)/SI_C$

5.2.6. Limitations and Assumptions of Reef Protection Typology

The assumption was made that the three pilot sites were representative of the main coastal typologies, therefore the classification extrapolated to the rest of the island is based on the physical attributes of these pilot sites. No socio-economic factors were taken into consideration in determining the protection classes. Bathymetry between 0 and -50 m was made the delimiter of the reef zone with assumptions that very little protection is offered by reef deeper than 50 m. The coastal land delimiter was 15 m elevation based on the MIKE21 models applied by University of Texas A&M showing that inundation did not advance beyond this elevation. Coastline was generalized from the vertices of the extreme edges of the shoreline, and as such did not explain variations in reef coastline relationships within each coastal zone. A heavier weighting was given to reef type score in the project because of the primary use of reef systems in the oceanographic analysis as the source of protection and the range of protection offered by the different reef types. This coastal characterization approach is, by necessity, a simplification of very complex, 3-dimensional coastal environments.

5.3. Coastal Inundation

This section describes the approach used to map coastal inundation in the absence and presence of reef structure scenarios. Water-level estimates from the wave attenuation modelling were incorporated into the GIS in order to visualize inundated areas and to subsequently estimate the existing infrastructure that would be within the inundated area. Results from the Reef Typology were applied to the GIS inundation model where the typology of the pilot sites were matched to similar segments island-wide, assuming they undergo similar inundation.

5.3.1. Elevation Classification

Inundated areas for the pilot sites were defined by means of elevation classification, wherein a 6-m resolution Digital Elevation Model (DEM) was queried for all land area less than or equal to the specific shoreline water level. At island-wide level, the DEM was queried for all land area within each coastal segment less than or equal to the shoreline water levels used for the medium and high protection community segments.

5.3.2. Extrapolation of Shoreline Water Levels

The reef typology assessment for the pilot sites showed that Negril receives medium protection from its reef system, whilst Discovery Bay receives high protection. The coastal segments in Jamaica with similar reef typology to Negril were assumed to receive medium reef protection, and thus similar shoreline water levels. Of the 31 segments, 12 were found to have medium protection (Oracabessa, Montego Bay, Green Island, Bull Bay, Ocho Rios, Sandy Bay, Port Maria, White House, Negril, Lucea, Long Bay and Annotto Bay); as a result the shoreline levels for Negril were used for these:

- 1-yr Storm
    - ✓ With Reef = 0.8 m
    - ✓ Without Reef = 1.3 m

- 25-yr Storm
    - ✓ With Reef = 1.3 m
    - ✓ Without Reef = 1.7 m

Six (6) coastal segments were found to have reef typologies similar to Discovery Bay, and thus depicted highly protective reef systems. These are Discovery Bay, Falmouth, Savanna-La-Mar, St. Ann's Bay, Southern Negril, Coral Gardens and Morant Point. The following final water shoreline levels were utilised for inundation modelling of these segments:

- 1-yr Storm
    - ✓ With Reef = 0.6m
    - ✓ Without Reef = 1.4 m
- 25-yr Storm
    - ✓ With Reef = 1.4 m
    - ✓ Without Reef = 2.0 m

The Kingston/ Port Royal pilot site, and thus the nine (9) “low protection” coastal segments, were disregarded for the inundation modelling and analysis component of the project as negligible differences in protection were found.

5.3.3. Infrastructure Analysis

The number of buildings existing within the modelled inundated areas was obtained by means of spatial queries. In addition, the following types of infrastructure were identified and counts for each type tabulated:

- Fire Station;
- Police Station;
- Hospital;
- Health Centre;
- Airports, Airfields, Aerodromes;
- Sea Port;
- Postal Services;
- Hotel;
- School;
- Church; and
- Lighthouse.

The number of buildings, as well as the various types of infrastructure existing within the inundated areas, was obtained by means of spatial queries.

In addition, the area inundated within each coastal segment was calculated.

5.3.4. Limitations and Assumptions of Coastal Inundation Analysis

Areas classified as “low protection” showed such negligible differences in protection by associated reef systems that they were disregarded. Scenarios “Without reef” scenario do not signify a complete loss of reef but a decrease in reef height. All listed infrastructure included in the analysis were mapped by OSD-MGI via Global Positioning System (GPS) field survey between 2008 and 2009; point building locations were digitised by OSD-MGI from 2001 satellite imagery. The estimation of land and infrastructure inundated relies on the results of the application of the MIKE 21 hydrodynamic model for Discovery Bay. The coastal typology was used to identify communities (shoreline segments) with characteristics similar to Discovery Bay, which are likely to experience similar shoreline water levels during storm events (both with and without the reef). This analysis is indicative of the relative protection provided by coral reefs along the Jamaican coastline.

6. Results

In summary, reef typology classification scores were based upon:

1. Reef type,
2. SI (Shape Index) of reef,
3. Distance of reef from shore,
4. Absolute Degree Difference (between reef and shoreline orientation), and
5. Reef percent of 0 to -50m zone;

while coastland typology classification scores were based upon:

6. SI of 0 to +15 m zone (coastland).

Scores calculated for the Reef Typology are divided by the Coastland SI to create the final reef protection value for the coastal segment (+15 m to -50 m). The range in scores was broken into 3 classes by the Jenks Natural breaks method[15] to derive final protection classes for Reef Protection Typology (Table 4):

- 0.020 – 2.041: Low - represents a zone receiving little protection from its reef;
- 2.042 – 6.107: Medium - represents a zone receiving medium protection from its reef;
- 6.108 – 15.572: High - represents a zone receiving a great amount of protection from its reef.

Final Reef Protection Typology classification results showed that for the pilot sites; Kingston received low protection from its reef, Negril received medium protection, and Discovery Bay received high protection with scores of 0.53, 4.36 and 7.20 respectively. Other communities receiving similar high protection as Discovery Bay include Savanna-La-Mar, St. Ann's Bay, Southern Negril, Coral Gardens, Southern Negril, and Morant Point (See Table 5, Figure 5). The community with the least protection from reefs was Treasure Beach with a value of 0.02, while the community afforded the highest protection was Morant Point with 15.57.

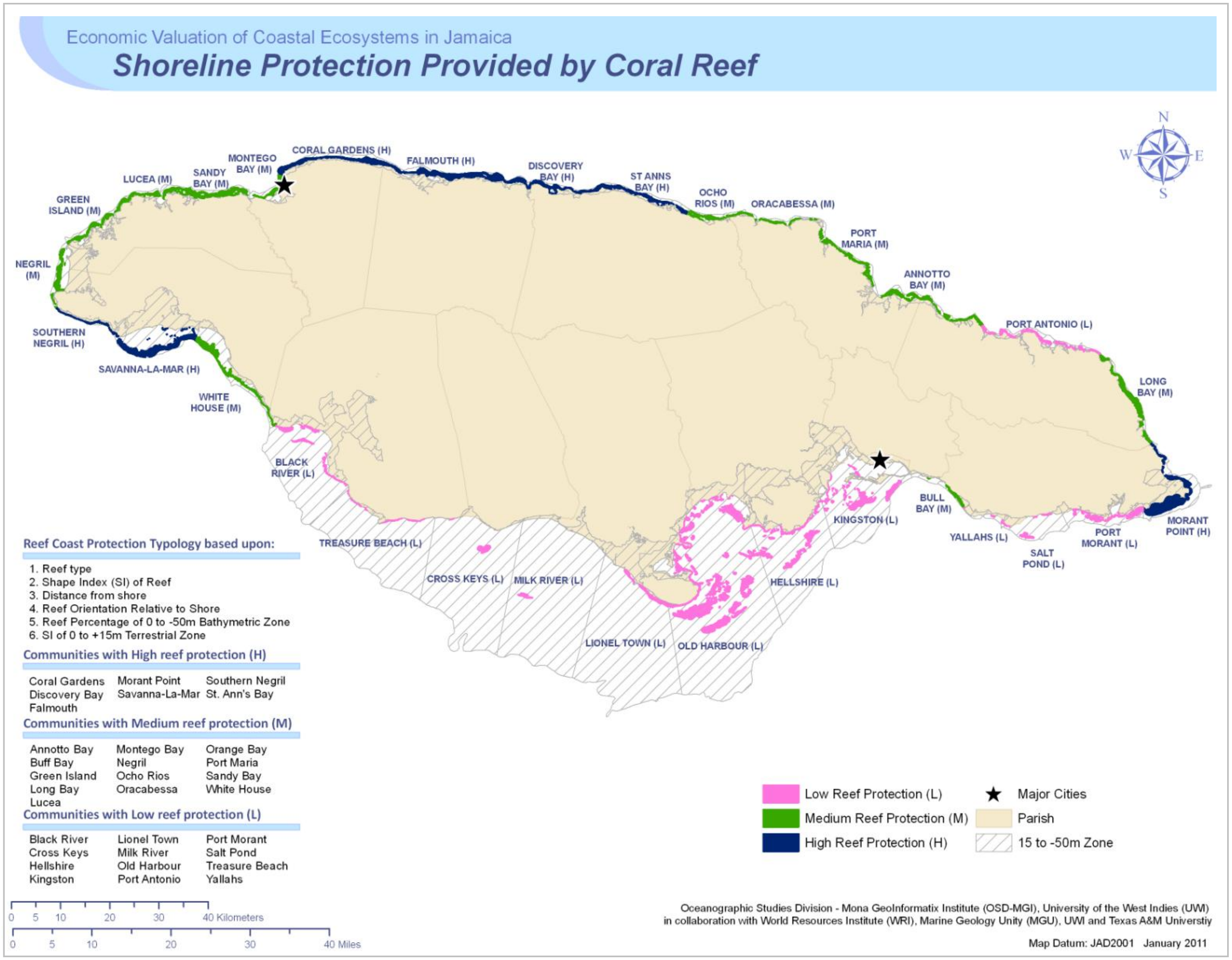

Figure 5. Island-wide distribution of low, medium and high protection provided by coral reefs, and their associated bathymetric segments

Table 4. Summary of Final Reef Protection Classification Results*

SEGMENT*	CLASS				WEIGHTED VALUE				COMPOSITE CLASSIFICATION	PERCENT ZONE AREA	ADJUSTED WEIGHTED COMPOSITE	COASTLAND SI	FINAL CLASSIFICATION	PROTECTION CLASS
	REEF TYPE	BATHYMETRIC SEGMENT SI	DISTANCE FROM SHORE	ABSOLUTE DEGREE DIFFERENCE	REEF TYPE	BATHYMETRIC SEGMENT SI	DISTANCE FROM SHORE	ABSOLUTE DEGREE DIFFERENCE						
Annotto Bay	3	4	4	4	6.0	6.0	4.0	4.0	20.00	45.8	9.16	3.0	6.11	medium
Black River	3	2	4	4	6.0	3.0	4.0	4.0	17.00	2.7	0.46	2.0	0.46	low
Bull Bay	3	3	4	4	6.0	4.5	4.0	4.0	18.50	21.1	3.90	2.0	3.90	medium
Coral Gardens	3	4	4	4	6.0	6.0	4.0	4.0	20.00	48.8	9.76	2.0	9.76	high
Cross Keys	1	2	1	4	2.0	3.0	1.0	4.0	10.00	0.5	0.05	3.0	0.03	low
Discovery Bay	**3**	**4**	**4**	**4**	**6.0**	**6.0**	**4.0**	**4.0**	**20.00**	**54.0**	**10.80**	**3.0**	**7.20**	**high**
Falmouth	3	4	4	4	6.0	6.0	4.0	4.0	20.00	58.8	11.76	3.0	7.84	high
Green Island	3	3	4	4	6.0	4.5	4.0	4.0	18.50	36.7	6.79	4.0	3.39	medium
Hellshire	3	1	1	4	6.0	1.5	1.0	4.0	12.50	5.7	0.71	2.0	0.71	low
Kingston	**3**	**2**	**2**	**4**	**6.0**	**3.0**	**2.0**	**4.0**	**15.00**	**5.3**	**0.80**	**3.0**	**0.53**	**low**
Lionel Town	3	4	4	4	6.0	6.0	4.0	4.0	20.00	1.0	0.20	2.0	0.20	low
Long Bay	3	3	4	4	6.0	4.5	4.0	4.0	18.50	64.3	11.90	4.0	5.95	medium
Lucea	3	4	4	4	6.0	6.0	4.0	4.0	20.00	35.8	7.16	3.0	4.77	medium
Milk River	3	2	1	4	6.0	3.0	1.0	4.0	14.00	0.2	0.03	2.0	0.03	low
Montego Bay	3	4	4	2	6.0	6.0	4.0	2.0	18.00	16.8	3.02	2.0	3.02	medium
Morant Point	3	2	4	4	6.0	3.0	4.0	4.0	17.00	45.8	7.79	1.0	15.57	high
Negril	**4**	**1**	**3**	**4**	**8.0**	**1.5**	**3.0**	**4.0**	**16.50**	**26.4**	**4.36**	**2.0**	**4.36**	**medium**
Ocho Rios	3	2	4	4	6.0	3.0	4.0	4.0	17.00	35.1	5.97	3.0	3.98	medium
Old Harbour	3	2	1	4	6.0	3.0	1.0	4.0	14.00	8.4	1.18	4.0	0.59	low
Oracabessa	3	3	4	4	6.0	4.5	4.0	4.0	18.50	26.8	4.96	4.0	2.48	medium
Port Antonio	1	2	4	4	2.0	3.0	4.0	4.0	13.00	31.4	4.08	4.0	2.04	low
Port Maria	3	4	4	4	6.0	6.0	4.0	4.0	20.00	40.8	8.16	4.0	4.08	medium

SEGMENT*	CLASS				WEIGHTED VALUE				COMPOSITE CLASSIFICATION	PERCENT ZONE AREA	ADJUSTED WEIGHTED COMPOSITE	COASTLAND SI	FINAL CLASSIFICATION	PROTECTION CLASS
	REEF TYPE	BATHYMETRIC SEGMENT SI	DISTANCE FROM SHORE	ABSOLUTE DEGREE DIFFERENCE	REEF TYPE	BATHYMETRIC SEGMENT SI	DISTANCE FROM SHORE	ABSOLUTE DEGREE DIFFERENCE						
Port Morant	3	3	4	4	6.0	4.5	4.0	4.0	18.50	21.1	3.90	4.0	1.95	low
Salt Pond	4	1	2	4	8.0	1.5	2.0	4.0	15.50	4.2	0.65	1.0	1.30	low
Sandy Bay	3	2	3	4	6.0	3.0	3.0	4.0	16.00	49.9	7.98	4.0	3.99	medium
Savanna-La-Mar	4	2	1	4	8.0	3.0	1.0	4.0	16.00	25.0	4.00	1.0	8.00	high
Southern Negril	3	4	4	4	6.0	6.0	4.0	4.0	20.00	43.7	8.74	2.0	8.74	high
St. Ann's Bay	3	4	4	4	6.0	6.0	4.0	4.0	20.00	40.1	8.02	2.0	8.02	high
Treasure Beach	3	4	4	4	6.0	6.0	4.0	4.0	20.00	0.2	0.04	4.0	0.02	low
White House	4	3	2	4	8.0	4.5	2.0	4.0	18.50	23.3	4.31	2.0	4.31	medium
Yallahs	1	1	4	1	2.0	1.5	4.0	1.0	8.50	4.3	0.37	1.0	0.73	low

***Segments highlighted in grey blocks indicate Pilot Sites results**

Table 5. Segments with high protection level by final classification. Segments highlighted in grey represent pilot sites.

HIGH PROTECTION SEGMENTS	FINAL CLASSIFICATION
DISCOVERY BAY	7.20
Falmouth	7.84
Savanna-La-Mar	8.00
St. Ann's Bay	8.02
Southern Negril	8.74
Coral Gardens	9.76
Morant Point	15.57

6.1. Pilot Site Inundation

The MIKE 21 model was run for both storm scenarios (1-yr and 25-yr return period) and reef scenarios (“with reef” and “without reef”) for the three pilot sites, resulting in an estimated change in run-up and water level estimates at the shoreline (See Table 6). The difference in water-level between the “with reef” and “without reef” scenarios were highest at Discovery Bay, with a difference of 0.74 m for the 1-yr return period storm and 0.60 m for the 25-yr storm. Smaller differences were seen in Negril (0.6 m and 0.5 m for the 1-yr and 25-yr return periods respectively) and Kingston/ Port Royal (0.35 m and 0.22 m for the 1-yr and 25-yr return periods respectively).

Table 6. Results of modelling wave attenuation by reefs at three pilot sites

PILOT SITE	Storm Scenario	Water Level (m)	Wind Speed (m/s)	Offshore Wave Height (m)	Offshore Wave Period (s)	Reef Scenario	Reef Height (m)	Run-up (m)	Water Level at Shoreline (m)	Difference in Water Level: Reef vs. No Reef (m)
Negril	1-yr	0.2	12.1	2.2	10.0	With Reef	-1.0	0.60	**0.80**	**0.50**
						Without Reef	-5.0	1.10	**1.30**	
	25-yr	0.5	41.0	5.1	10.0	With Reef	-1.0	0.82	**1.32**	**0.40**
						Without Reef	-5.0	1.24	**1.74**	
Discovery Bay	1-yr	0.2	12.1	1.4	10.0	With Reef	-1.0	0.44	**0.64**	**0.74**
						Without Reef	-6.0	1.18	**1.38**	
	25-yr	0.7	41.0	5.1	10.0	With Reef	-1.0	0.70	**1.40**	**0.60**
						Without Reef	-6.0	1.30	**2.00**	
Port Royal/ Kingston	1-yr	0.4	11.9	2.3	10.0	With Reef	-1.0	0.68	**1.08**	**0.35**
						Without Reef	-6.0	1.03	**1.43**	
	25-yr	1.4	39.0	4.7	10.0	With Reef	-1.0	1.26	**2.66**	**0.22**
						Without Reef	-6.0	1.48	**2.88**	

Source: Chris Houser, Texas A&M University, “2-D Analysis of Wave Attenuation and Run-Up for Select Sites in Jamaica, (unpublished analysis summary for WRI[16])

Outputs of the MIKE 21 model for run-up and resulting water level at the shoreline were used to map inundated area for Negril and Discovery Bay, as these two pilot sites had the greatest change in water level. Figures 6 through 9 depict the pilot site inundation maps for Negril and Discovery Bay. Inundation extent is seen to be more or less uniform along the Negril coastline. Slight differences existed between the “with reef” and “without reef” scenario for the 1-yr period towards the southern section of pilot area. On the other hand, such differences between the “with reef” and “without reef” scenarios are not seen for the 25-yr period. In the case of Discovery Bay, differences between the “with reef” and “without reef” scenarios for both the 1-yr and 25-yr storms are noticeable.

Only 3 buildings in the Negril pilot area were seen to be located within the the 1-yr storm inundation area with reef, and 5 without. In the case of the 25-yr storm, the difference in number of buildings within was similar, with only 2 additional buildings falling within the inundation area when there was loss of reef. In the case of Discovery Bay however, though the water shoreline levels are generally higher than in Negril, less infrastructure appears to be located within the inundation area. There were 5 buildings within inundation by the 25-yr storm “without reef”, whilst only 1 is observed within inundation by the yearly storm scenario .

2D wave attenuation and run-up heights modelled by Texas A&M University for two (2) pilot sites in Jamaica, namely Discovery Bay and Long Bay (Negril) for the 1-yr and 25-yr storm events, with and without reef were considered. Mapped inundated areas are defined by means of elevation classification, wherein a 6 metre Digital Elevation Model (created by MGI though a series of interpolation of 1-metre elevation data) was queried for all land area less than or equal to the shoreluine water level for each scenario. All infrastructure displayed were mapped by MGI via GPS field survey. Reef is a combination of reef areas digitised by MGI from the 1:50,000 national topographic map series for Jamaica and The Millennium Coral Reef Mapping Project, University of South Florida.

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Figure 6. Pilot Site Inundation Map: Negril 1- year Return Period

2D wave attenuation and run-up heights modelled by Texas A&M University for two (2) pilot sites in Jamaica, namely Discovery Bay and Long Bay (Negril) for the 1-yr and 25-yr storm events, with and without reef were considered. Mapped inundated areas are defined by means of elevation classification, wherein a 6 metre Digital Elevation Model (created by MGI though a series of interpolation of 1-metre elevation data) was queried for all land area less than or equal to the shoreluine water level for each scenario. All infrastructure displayed were mapped by MGI via GPS field survey. Reef is a combination of reef areas digitised by MGI from the 1:50,000 national topographic map series for Jamaica and The Millennium Coral Reef Mapping Project, University of South Florida.

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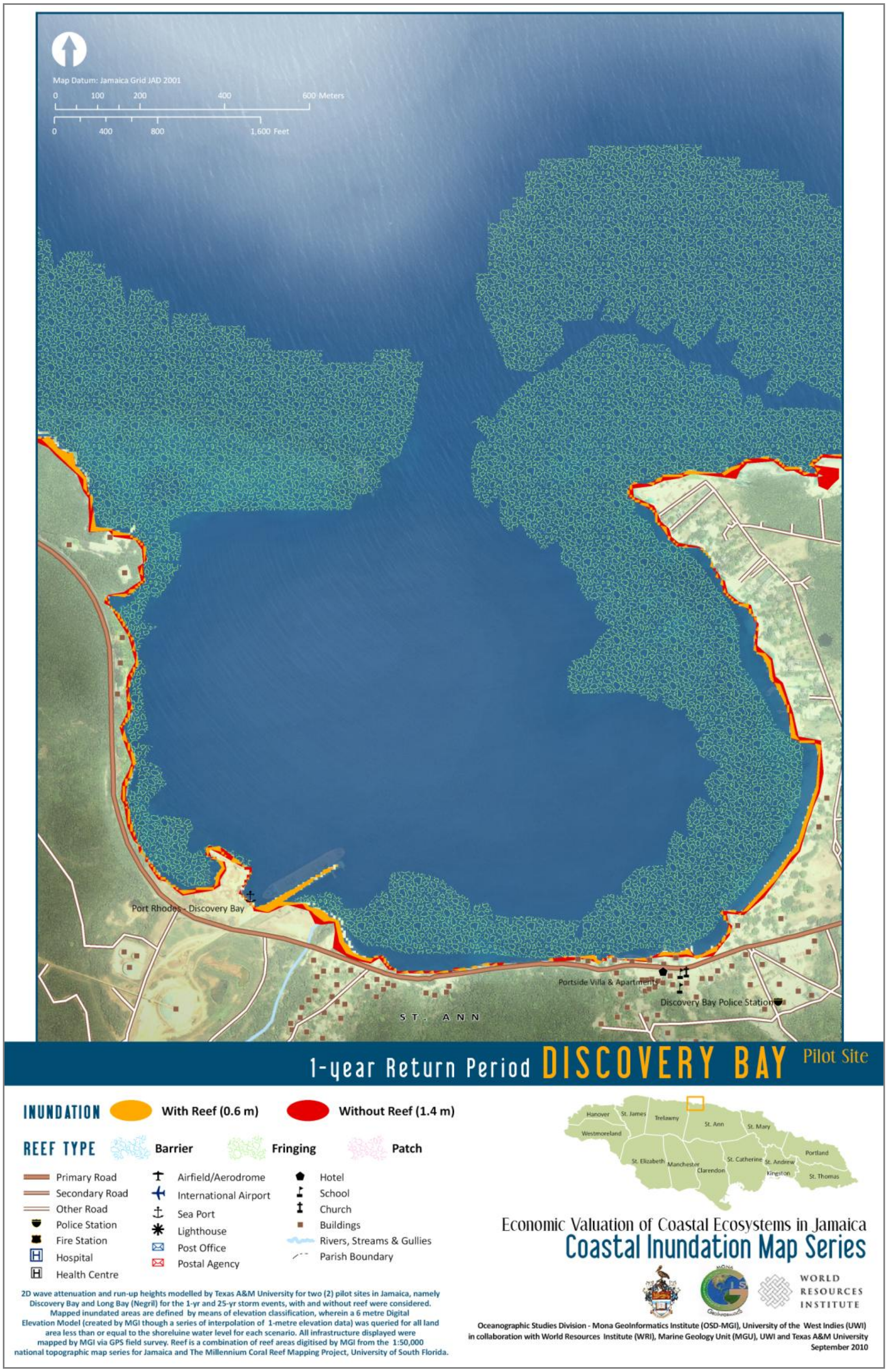
Figure 7. Pilot Site Inundation Map: Negril 25 – year Return Period



2D wave attenuation and run-up heights modelled by Texas A&M University for two (2) pilot sites in Jamaica, namely Discovery Bay and Long Bay (Negril) for the 1-yr and 25-yr storm events, with and without reef were considered. Mapped inundated areas are defined by means of elevation classification, wherein a 6 metre Digital Elevation Model (created by MGI though a series of interpolation of 1-metre elevation data) was queried for all land area less than or equal to the shoreluine water level for each scenario. All infrastructure displayed were mapped by MGI via GPS field survey. Reef is a combination of reef areas digitised by MGI from the 1:50,000 national topographic map series for Jamaica and The Millennium Coral Reef Mapping Project, University of South Florida.

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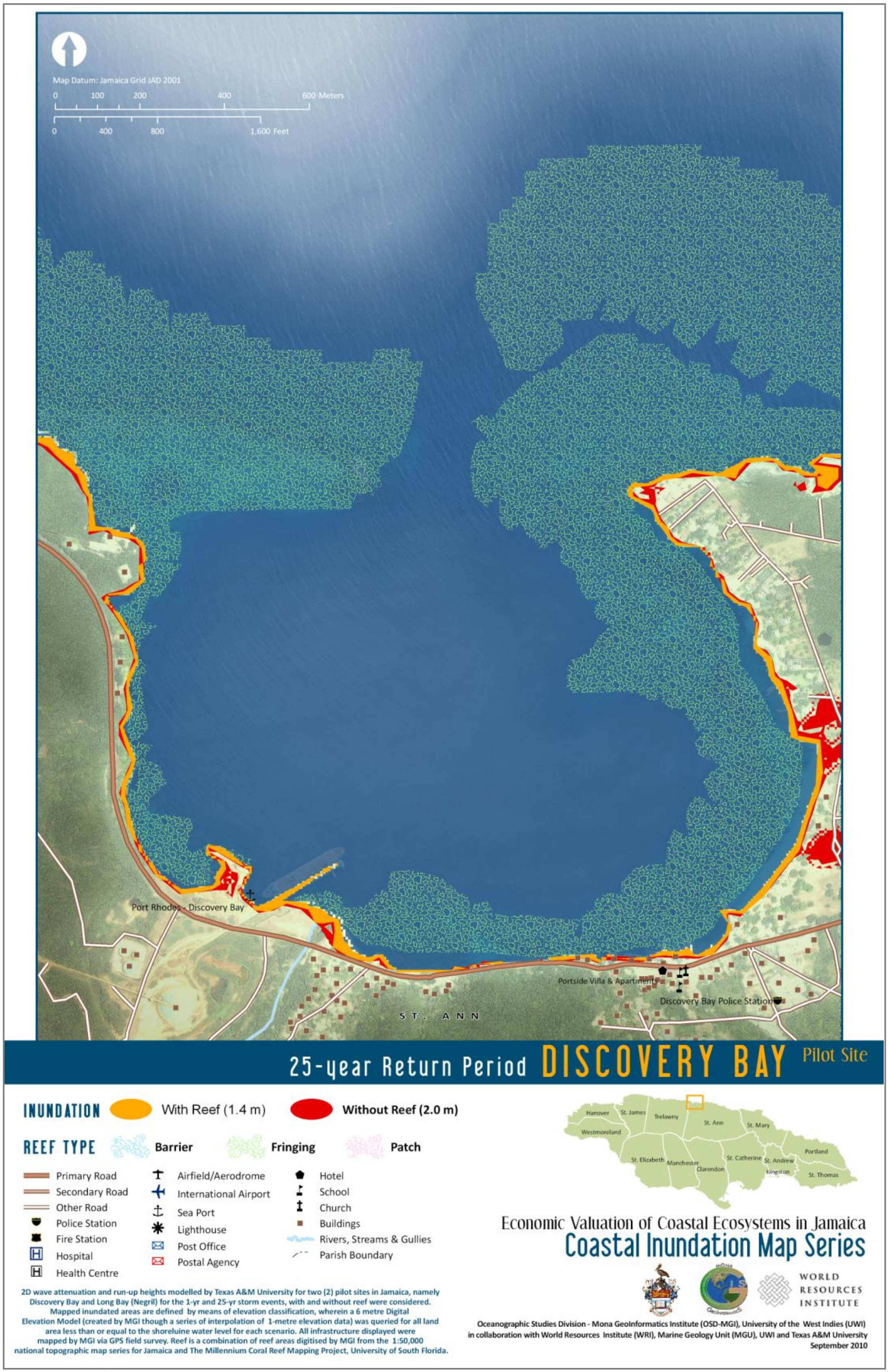
Figure 8. Pilot Site Inundation Map: Discovery Bay 1- year Return Period



2D wave attenuation and run-up heights modelled by Texas A&M University for two (2) pilot sites in Jamaica, namely Discovery Bay and Long Bay (Negril) for the 1-yr and 25-yr storm events, with and without reef were considered. Mapped inundated areas are defined by means of elevation classification, wherein a 6 metre Digital Elevation Model (created by MGI though a series of interpolation of 1-metre elevation data) was queried for all land area less than or equal to the shoreluine water level for each scenario. All infrastructure displayed were mapped by MGI via GPS field survey. Reef is a combination of reef areas digitised by MGI from the 1:50,000 national topographic map series for Jamaica and The Millennium Coral Reef Mapping Project, University of South Florida.

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Figure 9. Pilot Site Inundation Map: Discovery Bay 25 – year Return Period

6.2. National Level Inundation

Coastal inundation scenarios for only those areas receiving high protection from coral reefs are presented (see Figures 10-12).

6.2.1. High Protection Coastal Community Segments

For the 1-yr storm scenario, 1 of the 7 high-protection coastal segments had negligible damage to infrastructure, namely Morant Point. Savanna-la-Mar appears to have been the most affected, with 97 and 507 buildings being inundated with and without reef present respectively (see Table 7). A school and church were located within the inundated areas for this coastal segment for the without reef 1-yr scenario. A hotel in the Discovery Bay segment was also affected for the without reef 1-yr scenario. For the 25-yr storm (see Table 8). Again, Morant Point was unaffected in terms of number of buildings inundated, and Savanna-la-Mar was seen to be the most affected (507 versus 655 buildings for “with reef” and “without reef” scenarios respectively). Amongst the infrastructure affected by the 25-year without reef scenario in the 7 high-protection coastal segments were three hotels, two churches, a hospital, health centre, airport/airfield/aerodrome, sea port, postal service and school.

The greatest portion of area inundated was also seen in Savanna-la-Mar, with just over 9% having been inundated “without reef” for the 1-yr storm and over 3% for the “with reef” scenario. For the 25-yr storm, over 9% area was inundated with the reef present, whilst 12% was inundated with the reef being present. This suggests that the significance of the reef, as it relates to affected area and building infrastructure, was greater for the 1-yr storm in this coastal segment. However, this is not the case in all coastal segments; for example in the Discovery Bay segment, the difference between affected infrastructure and area for the “with reef” and “without reef” scenarios was greater for 25-year return period storm.

In terms of percentage, Discovery Bay and Coral Gardens segments had the highest percentage area and buildings inundated for the 25-yr scenarios, and Savanna-la-Mar and Discovery Bay for the 1-yr scenarios.

1-YR

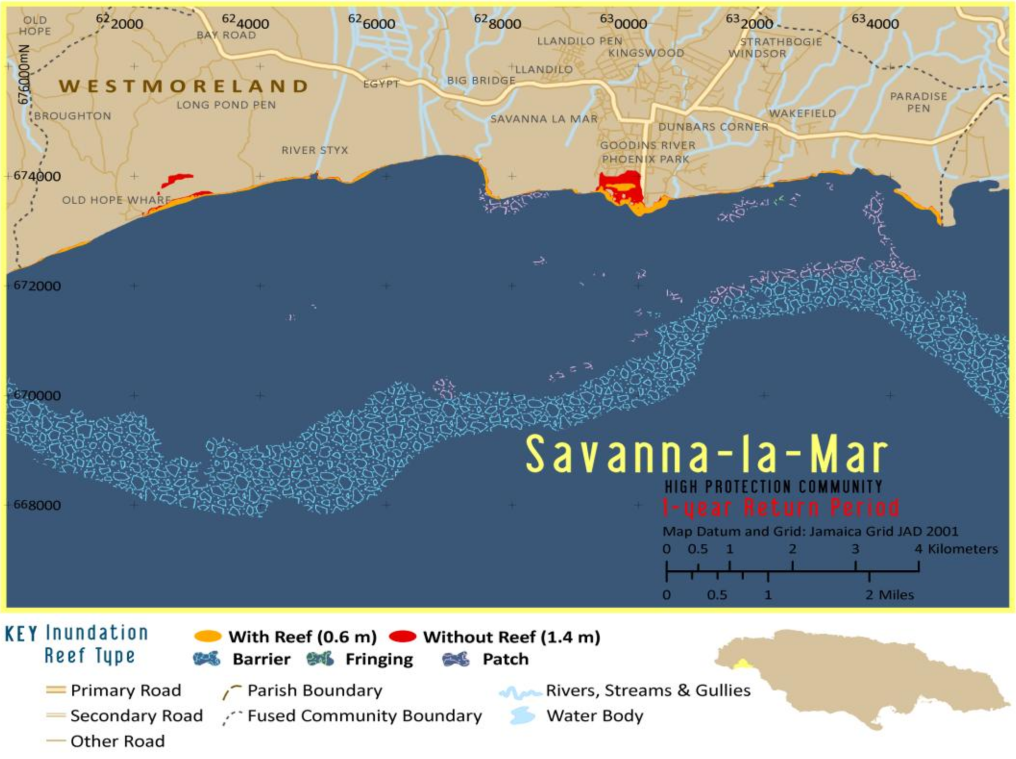
25-YR

Figure 10. National Level Inundation Map, High Protection: Coral Gardens

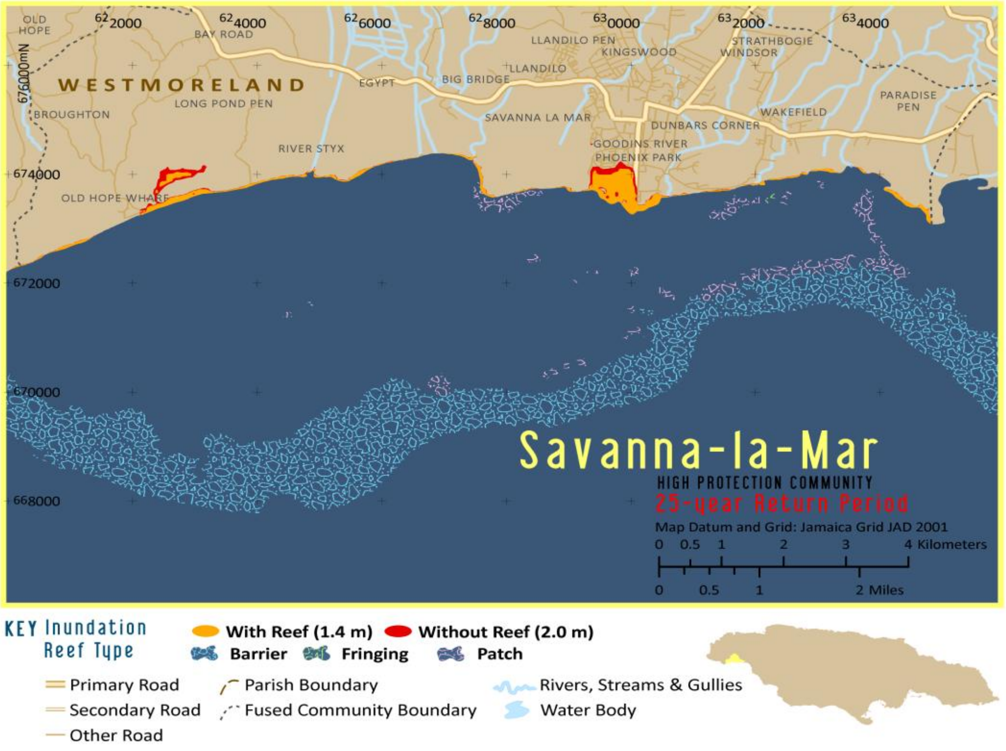
1-YR

25-YR

Figure 11. National Level Inundation Map, High Protection: Discovery Bay



1-YR



25-YR

Figure 12. National Level Inundation Map, High Protection: Savanna-la-Mar

Table 7. Number of buildings, type of infrastructure* and area affected by inundation under the 1-yr storm scenarios (for high protection coastal segments only)

Segment	Reef Scenario	Water Level at Shoreline (m)	Percentage Area (%) Affected	Difference in Percentage Area Affected Between Reef Scenarios	Number Buildings Affected	Percentage Buildings (%) Affected	Difference in Number Buildings Affected Between Reef Scenarios	Number of Specific Infrastructure* Affected
Coral Gardens	With Reef	0.6	0.00%	2.6%	0	0.00%	28	0
	Without Reef	1.4	2.60%		28	3.00%		0
Discovery Bay	With Reef	0.6	0.00%	8.0%	0	0.00%	39	0
	Without Reef	1.4	8.00%		39	2.60%		1
Falmouth	With Reef	0.6	0.00%	4.7%	0	0.00%	29	0
	Without Reef	1.4	4.70%		29	1.30%		0
Morant Point	With Reef	0.6	1.20%	0.3%	0	0.00%	0	0
	Without Reef	1.4	1.50%		0	0.00%		0
Savanna-la-Mar	With Reef	0.6	3.30%	6.0%	97	1.20%	410	0
	Without Reef	1.4	9.30%		507	6.20%		2
Southern Negril	With Reef	0.6	0.50%	0.2%	2	0.30%	1	0
	Without Reef	1.4	0.70%		3	0.50%		0
St. Ann's Bay	With Reef	0.6	0.00%	4.6%	0	0.00%	1	0
	Without Reef	1.4	4.60%		1	0.30%		0

*Infrastructure includes fire stations, police stations, hospitals, health centres, airports, airfield and aerodromes, sea ports, postal services, hotels, schools, churches and lighthouses.

Table 8. Number of buildings, type of infrastructure* and area affected by inundation under the 25-yr storm scenarios (for in high protection coastal segments only)

Segment	Reef Scenario	Water Level at Shoreline (m)	Percentage Area (%) Affected	Difference in Percentage Area Affected Between Reef Scenarios	Number Buildings Affected	Percentage Buildings (%) Affected	Difference in Number Buildings Affected Between Reef Scenarios	Number of Specific Infrastructure* Affected
Coral Gardens	With Reef	1.4	2.60%	15.9%	28	3.00%	121	0
	Without Reef	2	18.50%		149	16.00%		2
Discovery Bay	With Reef	1.4	8.00%	23.1%	39	2.60%	115	1
	Without Reef	2	31.10%		154	10.20%		5
Falmouth	With Reef	1.4	4.70%	6.5%	29	1.30%	42	0
	Without Reef	2	11.20%		71	3.10%		3
Morant Point	With Reef	1.4	1.50%	0.2%	0	0.00%	0	0
	Without Reef	2	1.70%		0	0.00%		0
Savanna-la-Mar	With Reef	1.4	9.30%	2.7%	507	6.20%	148	2
	Without Reef	2	12.00%		655	8.00%		2
Southern Negril	With Reef	1.4	0.70%	0.1%	3	0.50%	0	0
	Without Reef	2	0.80%		3	0.50%		0
St. Ann's Bay	With Reef	1.4	4.60%	4.2%	4	1.30%	6	0
	Without Reef	2	8.80%		10	3.20%		0

*Infrastructure includes fire stations, police stations, hospitals, health centres, airports, airfield and aerodromes, sea ports, postal services, hotels, schools, churches and lighthouses.

7. Discussion and Conclusion

At an island-wide scale, community segments on the north coast of Jamaica were shown to be better protected by their reef systems than those on the south. This was likely due to the dominance of fringing reef on the north coast as opposed to dominance of shelf marginal and patch reef on the south coast. Eastern and northern coastlines for the most part were offered relatively high protection by their reef structures; western Jamaica predominantly medium protection, and southern Jamaica predominantly low protection. The Savanna-la-Mar segment on the south coast was exceptional, showing the greatest difference between the two scenarios of with and without reef for the inundation 1-yr return scenarios, as it affects exposure in the form of number of buildings. Barrier reef dominates this segment, unlike the rest of the south coast that is dominated by less protective shelf marginal and patch reef. Therefore, when taking in to account exposure, Savanna-la-Mar's associated reef system provided the greatest protection compared to the entire island for the 1-yr return. The protection offered is also significant for the 25-yr scenario, however, it is overtaken by that of the reef system associated with the Discovery Bay segment to the north, where the greatest difference in exposure affected was observed for this extreme event.

The differences in exposure for with and without reef scenarios add to the case for prioritizing reef preservation strategies for the 1-yr over the 25-yr event, or vice-versa. This difference factor is an indicator of whether or not the presence of the reef contributes to protection, regardless of the intensity of the inundation return event. The reef degraded, for example, in the Savanna-La-Mar segment (south coast) for the 1-yr inundation event resulted in greater difference in buildings damaged and area inundated (410 and 6% respectively) when compared to the reef being present. For the 25-yr event, however, this difference was less (148 and 2.7% respectively). This suggests that the presence of the reef offers more protection should storms with a greater chance of occurring cause inundation. The more intense storms likely with a 25-yr event will, instead, result in greater inundation whether the reef is present or not.

Other places showed greater differences in exposure for the 25-yr event when the reef was degraded. The Discovery Bay segment (north coast), for example, showed greater differences in number buildings damaged and area affected (115 and 23.1% respectively) than those of the 1-yr return (39 and 8% respectively). Discovery Bay, therefore, is offered greater protection than Savanna-La-Mar by its reef should inundation occur during a more intense, 25-yr storm event.

This information is also useful in identifying the relevance of targeting particular organizations for support and funding, as the various types of infrastructure vulnerable to inundation are specified. The government and private organizations with mandates for improving medical services, for example, could be lobbied to have a greater stake in reef protection strategies for the Falmouth segment where a state-owned hospital and health center fall within the inundation area for the 25-yr storm event. The hotel industry and tourism services sector could be targeted for support along the Coral Gardens segment, where at least 2 hotels were located within the inundation area. Non-governmental organizations and social support services may be targeted for support in Savanna-La-Mar where a school and church were also shown to fall within the area of inundation. There were only twelve functions of buildings identified for this study, and so it is recommended that this be expanded to include more building types with specific purposes, as the number of unidentified buildings located within the inundation area was far greater than those with identified functions.

In comparing pilot sites (locations where the MIKE21 model were directly applied), Discovery Bay model outputs showed the greatest inundation difference between the presence and absence of a reef structure, while Kingston showed the least difference. Similar trends were observed by the geomorphological and statistical GIS methods utilized to assess the importance of reef in protecting the coastline. Results for expected inundation based on reef typology agree with relative extents of run-up and inundation modelled for the Pilot Sites using the MIKE21 model applied by Texas A&M. Reef protection classification were derived from calculations based on scores for geomorphologic parameters, a method that may be utilized as a rapid assessment of the relative protection offered by reef systems along coastlines in the absence of sophisticated wave and hydrodynamic data and analysis. This classification can therefore be used as a preliminary, medium-scale assessment of the protection given by reef systems to inform broader mitigation strategies for protection of coastal infrastructure.

Classifying the relative protection offered has implications for strategies to re-habilitate and preserve reef structure, ensuring their continued growth. This was shown to be crucial particularly on the north coast, where reef systems were classified to be highly protective and a great deal of economic exposure exists in the form of major hotels, mining and manufacturing infrastructure and workforce, along with burgeoning population centers such as Montego Bay, Falmouth and Ocho Rios. Barrier and fringing reef structures are important economically in areas where they are shown to offer high protection - particularly to people, infrastructure and assets - from surge damage. These results raise awareness of the importance of living coral reefs along parts of the coastline where they offer the greatest protection, and are useful as an additional tool or rationale in augmenting conservation measures.

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