PHYSICAL HABITAT MAPPING AND ASSESSMENT IN BLUEFIELDS BAY FISH SANCTUARY, WESTMORELAND, JAMAICA

A Masters Thesis

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Of the Requirements for the Degree

Master of Science, Geospatial Sciences in Geography and Geology

By

Jennifer Denise Carroll

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PHYSICAL HABITAT MAPPING AND ASSESSMENT IN BLUEFIELDS BAY FISH SANCTUARY, WESTMORELAND, JAMAICA

Geography, Geology, and Planning

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ABSTRACT

Rising population in the coastal Caribbean have caused the decline of marine resources as demands exceed sustainable levels. The decline of fish populations and fish habitats like seagrass beds, coral reefs, and mangroves is costly because the regional economy depends heavily on tourism and fishing. Major causes of damage are overfishing, climate change, pollution, and sedimentation. In order to address this problem in Jamaica, the Agriculture Ministry created a network of marine protected areas in 2009 including the Bluefields Bay Fish Sanctuary (BBFS) in Westmoreland. The legislation specified the need for a baseline survey of each new fish sanctuary. This study reports on the baseline physical habitat survey of BBFS which is located between Belmont and Savanna-La-Mar and is about 8 km long, 2 km wide, and 10 m at maximum depth. Satellite imagery and field observations were used to map benthic habitat. GPS photologging was completed to map and assess intertidal habitat. Depth, water quality, and benthic habitat type were recorded via GPS along offshore transects. Bathymetry contours were generated from a kriging interpolated surface with a 95% confidence level and error of ± 2.3 ft. Diver validation of benthic habitat yielded 90% accuracy. The most common type of habitats were mangroves (41.7%) for intertidal and seagrass beds (82%) for benthic. Patch reefs with total area 0.77 km^2 made up 6% of the benthic habitat; but some small coral reefs may have not been detected given the scale of the assessment.

KEYWORDS: Jamaica, marine protected area, habitat, bathymetric, kriging

This abstract is approved as to form and content

Robert T. Pavlowsky
Chairperson, Advisory Committee
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CHAPTER 1

INTRODUCTION

In today's globally connected world, the oceans are the last true commons that everyone shares. For the past decade, the ocean has been the receiving body of water for an annual average of 36,055 km^3/y global freshwater discharge which is an amount equal to about 40% of all fresh water available from surface sources on the planet (Shiklomanov, 1993; Syed *et al*., 2010). Nearly half of the world's population lives within 200 km of a coast. Coastal and marine associated services are valued at $22.6 trillion annually (Heyman and Wright, 2011). Several studies indicate that the current level of extensive harvesting of marine resources is not sustainable, yet not enough is being done to slow or stop the resulting damage to marine ecosystems (Martinez *et al*., 2007). For the most part, marine ecosystems worldwide are either fully exploited or are in decline due to human activities (Jackson *et al*., 2001). Among the most destructive hazards to coastal, intertidal, and marine ecosystems are overfishing, other human activities like tourism and pollution, and global warming effects like erosion and acidification (UNEP, 2001; Villasol and Beltran, 2004). In most cases, several environmental pressures act in combination to cause rapid decline of marine ecosystems, including a loss of biodiversity and habitat destruction (Roberts *et al*., 2002; Sebens, 1994).

Coastal Marine Resources Problems in the Caribbean

The rapid growth of coastal human populations in Caribbean Sea nations has caused the decline of coastal marine environments as demands on marine resources exceed sustainable levels. The unique characteristics and biodiversity in the Caribbean are the region's most important marine resource (Roberts *et al*., 2002). Coastal marine habitats like mangroves, seagrass beds, and coral reefs are important commercial and artisanal fishing grounds (Munro, 1983) as well as fish spawning and nursery habitats (Beck *et al.,* 2001). The physical effects of these habitats also offer coastal protection from waves and storm surges (Moberg and Folke, 1999). Even with the decline of marine resources, much of the Caribbean's coastal population depends on the sea not only for their livelihood, but also as their sole source of protein (FAO, 2009). Approximately 54% of fish stocks in the Caribbean and Western Atlantic were categorized as overexploited with another 40% classified as fully exploited by 2009 (FAO, 2011). The Caribbean contains approximately 7% of the world's coral reefs and the net annual benefits provided by the Caribbean's coral reefs are between US$3.1 billion and US$4.6 billion (Burke and Maidens, 2004; Villasol and Beltran, 2004). Yet 64% of the Caribbean's coral reefs are threatened by human activities such as excess sedimentation by deforestation, nutrient loading from raw sewage, and overfishing (Burke and Maidens, 2004). The degradation of seagrass beds, coral reefs, fish populations, and mangroves poses a potential financial loss of millions of dollars because tourism and fishing make up a significant portion of the regional economy (Villasol and Beltran, 2004).

Coastal Marine Resources at Risk in Caribbean. It is estimated that the Caribbean has 10% of its original habitat remaining due to losses by human alteration

(GEF, 2004). Approximately 742 square kilometers of coral reefs are at medium to high risk from human activities. Of the total square kilometers of coral reefs at medium to high risk, 61% are threatened by overfishing, 33% are threatened by coastal development, 35% by sedimentation and inland agricultural practices, and 14% by marine based pollution sources (Burke and Maidens, 2004). Sea level rise, ocean acidification, and rising global temperatures in the ocean and atmosphere are also projected to reach levels that would cause massive mortality in coral reefs, seagrass beds, and mangrove forests (MoAF, 2008).

Caribbean Efforts Toward a Sustainable Future. Awareness of the condition of marine resources in the region has risen steadily over the past couple decades. In 1981 the cumulative effort of the United Nations Environment Programme (UNEP), Economic Commission for Latin America and the Caribbean (ECLAC), and government and nongovernment representatives of the Caribbean community resulted in the Caribbean Action Plan. The plan outlined objectives such as the coordination of international assistance activities, strengthening regional and sub-regional institutions, and technical cooperation in the use of the region's natural resources. On a more local scale, there are many places where coastal waters have been designated as marine protected areas in order to protect essential fish breeding and nursery habitats like coral reefs, mangroves, and seagrass beds. Currently, only 18.7% of the world's roughly 527, 072 km^2 of coral reefs lie within any kind of marine protected area (MPA) (Mora *et al*., 2006; Villasol and Beltran, 2004). The majority of the Caribbean's MPAs have specific objectives in their mission statements aimed at attracting tourism to the area, protecting sensitive ecosystems, and reaching a sustainable level of usage of marine resource through good management practices (Geoghegan *et al*., 2001).

Coastal Marine Degradation in Jamaica

The present condition of marine resources in Jamaica is typical of those throughout the Caribbean. The island's economy has developed largely dependent on industries associated with its natural resources. Of Jamaica's total US$7.8 billion gross national product in 2001, 61.3% was made up of tourism and financial services (UN, 2003; UNDP, 2003; CIA, 2003*)*. The annual number of visitors to Jamaica in 2004 was almost equal to the total population of the island at 2.5 million (Table 1). Tourism by itself generates just under a third of Jamaica's total GDP (CIA, 2007 *cited in* Carr and Heyman, 2008). Moreover, 27% of Jamaica's total population of 2.78 million was employed by tourism related industries in 2007 (WTTC, 2007 *cited in* Carr and Heyman, 2008). As the urban population in Jamaica increases from 56% of the population in 2001, the percentage of the population employed by the tourism industry and service related industries is most likely to also increase. In comparison, the fishing industry was responsible for US$1.1 billion of Jamaica's gross domestic product in 2003 (MoAF, 2008). Approximately 20,000 to 40,000 Jamaicans are completely dependent on fishing for their livelihood and that number does not include those whose livelihood is in any way partially dependent on Jamaica's natural resources.

Decline of Fisheries in Jamaica. As the Jamaican economy developed with a high dependency on marine resources, the island experienced ecological deterioration. Both the average catch weight and size of fish caught have declined in Jamaica since the 1960s (Koslow *et al.,* 1988). Jamaican fishermen target fish with the highest market value

Table 1. Geographic, demographic, and economic characteristics of Jamaica.

Land area[1]	10,831 km^2
Coastal shelf area (including Pedro Bank)[1]	3,568 km^2
Population – 2007[2]	2,780,132
Population density – 2007 (persons/km^3)[2]	257
Population growth rate – 2001[3]	0.5%
Urban Population – 2001[3]	56%
Urban Population growth rate (1995-2001)[3]	1.8%
GDP per capita – 2007[2]	4,600
Fisheries	
Fishing effort (persons)[4]	23,000-40,000
Fisher density (persons/km^2 coastal shelf)[1]	1.88-3.28
Capture production (US$ million)[4]	48.1
GDP fishery industry – 2007 (% total GDP)[2]	0.4
Tourism	
Total visitors – 2004[5]	2,514,586
Cruise visitors – 2004[5]	1,099,800
GDP tourism economy – 2007 (US$ million)[2]	3,769
GDP tourism economy – 2007 (% total GDP)[2]	31.1
Employment tourism industry – 2007[6]	92,037
Employment tourism economy – 2007[6]	289,414
Tourism employment – 2007 (% total employment)[6]	27.4
10 year tourism growth[6]	2.7%

[1] WRI, 2003; WRI, 2007 *cited in* Carr and Heyman, 2008
[2] CIA, 2007 *cited in* Carr and Heyman, 2008
[3] Encyclopedia Microsoft Encarta, 2002; Collard, 2000; UNDP, 2003 *cited in* Villasol and Beltran, 2004
[4] Myers, 2006 *cited in* Carr and Heyman, 2008
[5] CTO, 2006 *cited in* Carr and Heyman, 2008
[6] WTTC, 2007 *cited in* Carr and Heyman, 2008

or the largest fish for the dinner table. This tendency eliminates first the predatory fish, and then the larger herbivorous fish as fishers "fish down the food chain" (Pauly *et al*., 1998). When the larger fish are lacking from marine ecosystems, there is opportunity for invasive species like lionfish to flourish (Schofield, 2009). Experienced fishermen are also likely to target fish populations at vulnerable times such as migration, spawning, or other aggregation events (Koenig *et al*., 1996). Seine nets, which are banned in other countries because they ensnare juvenile fish as well as adults, are still used in Jamaica. Destructive fishing practices like the use of dynamite also destroy coral reefs, seagrass, and eggs laid by female fish and are devastating to marine ecosystems (Koslow *et al*., 1988). Many craters from dynamite fishing were visible in aerial photography of the fringing coral reef along the Jamaican coastline from Belmont to Savannah-La-Mar (Goreau, 1994).

Decline of Coral Reefs in Jamaica. As an island that was never connected to another land mass, Jamaica is home to many endemic species and what may have once been the most biologically diverse coral reefs in the Caribbean since the last Ice Age (Goreau, 1992; Roberts et al., 2002). Yet now, 1,010 square kilometers of Jamaica's coral reef, or 68% of its total coral reefs, are categorized at medium and high risk (Burke and Maidens, 2004). Between 1977 and 1993 the percentage of live coral covering Jamaican coral reefs dramatically decreased from 52% coverage to 3% coverage (Burke and Maidens, 2004). Out of the percentage of Jamaican coral reefs classified at medium or high risk, 69% were primarily threatened by overfishing. Independently from other threats, 61% of the reefs at risk in Jamaica were threatened by sedimentation and inland pollution (Burke and Maiden, 2004). Sedimentation reduces light attenuation through the water column, a necessity to both seagrasses and corals with photosynthetic zooxanthellae. Of Jamaica's coral reefs at risk, 56% are threatened by coastal development (Burke and Maidens, 2004). Coastal development generally outpaces adequate sanitation facilities; for example, 30,000 to 40,000 m^2 of improperly treated sewage are discharged per day into Kingston harbor (UNEP and CEP, 2001). Marine-based pollution also threatens 31% of Jamaica's coral reefs (Burke and Maidens, 2004).

Coastal Marine Conditions in Jamaica. Although the importance of seagrass beds and mangroves as critical fish habitat is well documented, little is known about the extent of damage to Jamaica's seagrass beds except that many of the same factors affecting Jamaica's coral reefs are also detrimental to the health and productivity of seagrass beds. Mangroves covered approximately 12,000 hectares in 1980, but at a steady annual loss of 1%, only 9,600 hectares remained in Jamaica by 2005 (FAO, 2007). Deforestation in the coastal basins of Jamaica has led to the erosion of 80 million tons of top soil annually (WWF, 2012). Sedimentation limits the flow of essential fresh water supplies to mangroves and increases turbidity in shallow waters. Pollution is also among the most severe problems because it degrades water quality below the standards for human usage and fish habitat requirements (Griffin *et al.,* 2001). Rivers and streams act as transport systems for pollutants from upstream sources to coastal waters; for example Jaffe *et al*. (2003) found that Montego River and North Gully both dump trace metals, pesticides, and petroleum hydrocarbon transport into Montego Bay. A detailed study conducted by the Global Coral Reef Alliance connected excessive coastal nutrient loading to anthropogenic sources in western Jamaica. Most reefs near developed shores were observed as being seriously degraded by algal overgrowth (Goreau, 1992).

Bluefields Bay Marine Protected Area

In 2003, Jamaica drafted a National Fisheries Policy that recognized "the increased efficiency of fisheries is critical to the industry's ability to develop in a sustainable way…this underscores the need for an ecosystem based fisheries management" (MoAF, 2008; Waite *et al*., 2011). Marine protected areas were created to protect essential fish habitats like mangroves, coral reefs, and seagrass beds. Protecting these marine environments has the benefit of preserving biodiversity and allowing a spill-over of fish into surrounding areas where fishing is allowed (Roberts *et al*., 2001). For long term sustainable fishing, it is imperative that management of marine protected areas continue to improve with better monitoring, enforcement, research, and data collection (Waite *et al*., 2011). Jamaica took its original marine park system a step farther in May, 2008 and set a national target of 20% of marine and coastal habitats protected by 2020 in accordance with the Caribbean Challenge (UNEP-WCMC, 2008). In 2009, as part of that initiative, the Minister of Agriculture created nine new fish sanctuaries including Bluefields Bay Fish Sanctuary in Westmoreland. Less than 0.1% of the world's coral reefs are located within MPAs that have no poaching and are no take sanctuaries (Mora *et al*., 2006). As a no-take fish sanctuary, Bluefields Bay Fish Sanctuary in Westmoreland is the most effective type of marine reserve because it protects whole ecosystems and their inhabitants rather than just select species. While singularly beneficial, each MPA is vulnerable to any local threats that originate outside the protected area (Gubbay, 1995). A network of marine protected areas is more effective in addressing multiple threats to marine environments because they spread the risk of reduced viability of a habitat or community type following a large scale disturbance and allow for protection of marine ecosystems at an appropriate scale by protecting a diverse array of marine environments (Ballantine, 1997; Salm *et al*., 2000; Allison *et al*., 2003; Roberts *et al*., 2003; Mora *et al*., 2006; McLeod *et al.,* 2008). As one no-take marine sanctuary among nine new, no take marine sanctuaries, Bluefields Bay Fish Sanctuary is not only effective as an individual marine reserve but also as part of a marine protected area network.

History of Bluefields Bay MPA. An initial overview of Bluefields Bay was conducted to identify the characteristics that qualified it for candidacy as a fish sanctuary (Hayman, 2007). The shallow reefs surveyed in Bluefields Bay by the Global Coral Reef Alliance in 1992 were observed to be in good condition and some of the best in Jamaica. Seagrass beds in the bay were observed at a depth of two to three meters (Goreau, 1992). Despite the previous survey, no data collected so far are comprehensive enough either as a resource inventory or as a baseline assessment upon which to base fishery management decisions. Neither is Bluefields Bay isolated from the factors like over fishing and pollution like raw sewage causing the decline of marine resources elsewhere in Jamaica. Peace Corp volunteers took water samples at Bluefields Bay during 2007 and 2008. They were tested for fecal coliform and two sites exceeded the limit set by the United States Environmental Protection Agency standard of 200MPN/100mL for full body immersion during sampling (Ebert, 2010). In addition, with the declaration of Bluefields Bay as a new, no take fish sanctuary, detailed habitat and bathymetric maps are necessary for effective management and monitoring.

Setting and Community at Bluefields Bay. Bluefields Bay Fish Sanctuary is set within a rural portion of Westmoreland's coast and as such, its coral reefs, mangroves, and seagrass beds have the high potential of providing social benefits to local communities. At Bluefields Bay, local efforts to increase awareness of the harmful consequences of current fishing and developmental practices predate the formation of the fish sanctuary. The Bluefields Bay Fisherman's Friendly Society (BBFFS) is a society of fisherman who formed the group in 2006 with the goal of educating its members in sustainable fishing practices, developing employment alternatives that will enhance the quality of life, and preserve the natural environment of Bluefields (BBFFS, 2012). An education video shot at Bluefields Bay in 2009 was credited by Dr. Owen Day, of Caribsave, as playing a key role in educating people and changing their attitude towards the fish crisis. Ten Jamaicans from local communities also participated in the Nature Conservancy's *Massa God Fish Can Done* workshop in Belize where the success of the Hol Chan Marine Reserve was showcased. One of the most critical needs of Jamaica's fish sanctuaries as identified by the Management Effectiveness Assessment and Capacity Development Report for Jamaica's System of Protected Areas was law enforcement (Hayman, 2007). The need for park wardens has provided employment opportunities for local fishermen, turning their experience and knowledge into an effective enforcement tool for protection of the fish sanctuary. Another effective tool of enforcement and protection of the bay is the recent placement of marker buoys denoting the beginning of the protected area of the fish sanctuary. It is anticipated that along with the cooperative efforts of the BBFFS the continued protection and management of the fish sanctuary will help to reverse the decline in fish populations, protect the biodiversity of the reef, and preserve the natural wonder of the bay that makes it a desirable tourist destination.

Need for Benthic and Bathymetric Maps for Bluefields Bay. Although much can be inferred from nearby or generalized from information for the parish or the country, no information of the sort has been compiled for Bluefields Bay Fish Sanctuary. There is a pressing need to have sufficient data on benthic habitats, water quality, and habitat affinities at adequate resolution (NOAACSC, 2003). GIS-based mapping approaches and data analysis offer the advantages of assisting in the visualization of natural resource data, assessing spatial data relationships, resource queries and evaluations, hazard identification, and programme coordination (UNEP-CEP, 1996).

Purpose and Objectives

For my thesis project, I did an initial baseline survey and habitat assessment of Bluefield Bay Marine Protected Area in Westmoreland. The area of the sanctuary is bounded by the coastline from Bluff Point to Belmont Point and sectioned off from the surrounding waters by a boundary running from Belmont Point to Bluff Point (Figure 1). The purpose of this study was to perform a baseline survey of the Bluefields Bay MPA to determine and evaluate habitat, substrate, and shoreline conditions within Bluefields Bay. Part of the survey will be to bathymetrically map the bay floor along with classifying the distribution of bottom substrate.

The main objectives of this thesis are:

1. *Determine the spatial distribution of marine habitats, quantify benthic characteristics, and evaluate factors controlling the condition of the bay.*

    In 2003, collective interviews from a number of coastal managers, scientists, and technology specialists involved with marine protected area

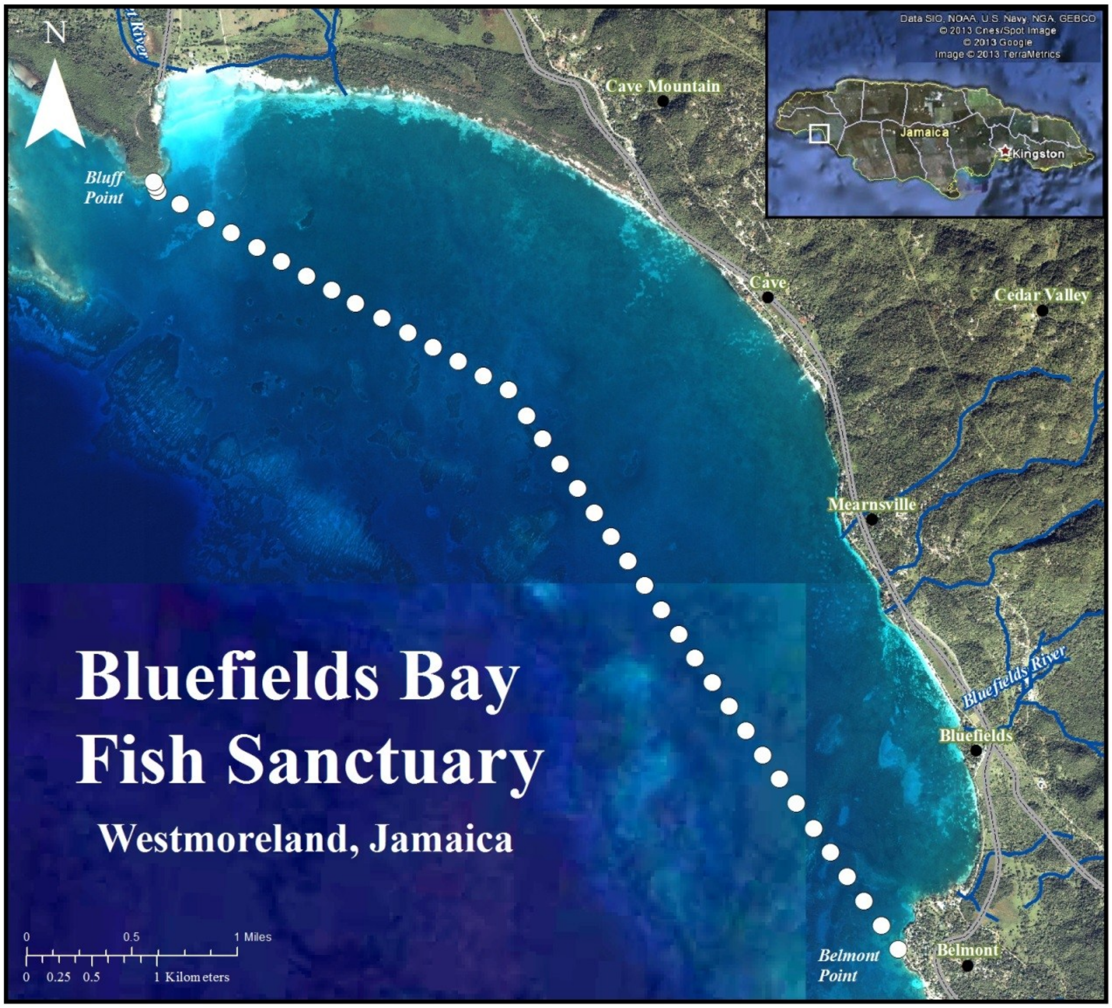

Figure 1. Study Area. Shoreline and location of buoys denote the boundaries of the marine protected area (MGI, 2010; Penobscot Corp., 2012).

management identified the areas of the highest concern being the marine habitats, enforcement and boundaries, and monitoring the marine environment. Feedback from these interviews specifically identified the need for benthic habitat maps and more useful benthic data at a proper scale with improved spatial coverage (NOAASCS, 2003). A benthic cover map of a marine protected area is used to inventory natural resources, establish current conditions, monitor habitat loss, analyze changes, and identify specific areas that need further research or greater protection (NOAASCS, 2003).

2. *Classify shoreline conditions, evaluate their spatial distribution, and identify sources of bay pollution or sedimentation.*

   Shorelines in the Caribbean Sea are frequently changing due to storm surges, seasonal hurricanes, and trade currents. Coastal areas are also becoming more and more populated so coastal ecosystems, including mangroves which stabilize and protect the inner coast from storm damage, are an important component of coastal areas. Wetlands like mangroves and salt marshes act as a carbon and nutrient sink as well as trap sediments, helping to prevent excessive amounts from flooding coastal waters. Where these buffer habitats are absent, fresh water runoff and related sediment and nutrients flow directly into shallow marine environments. A shoreline habitat map along with correlated water quality data identifies potential sources of pollution and sedimentation as well as ecosystems of interest such as mangroves.

3. *Provide the local community with assessment information and maps for management purposes*.

   Bluefields Bay Fish Sanctuary is run by the non-governmental agency Bluefields Bay Fishermens Friendly Society. As a NGO-run MPA, Bluefields Bay is under the management of the local community. Policy decisions and enforcement happens on the local level. One of the vulnerabilities identified for nearby Negril Marine Park was the clash of cultural practices, beliefs, and traditional uses with the objectives of the protected area (Hayman, 2007).Visualization and interactive tools have been observed to be especially effective in communicating potential results of a proposed activity when involving local groups in decision making (NOAACSC, 2003). The visual tools of a benthic cover and detailed bathymetric map are essential to communicating spatial relationships and quantities of marine resources, as well as identifying areas of specific interest such as coral reefs.

Research Questions

There is an immediate need for a spatially quantitative inventory of critical habitats within Bluefields Bay Fish Sanctuary as well as a spatially explicit habitat map denoting associations between neighboring and cooperative ecosystems like coral reefs, mangroves, and seagrass beds. There is also a need for the critical examination of the resulting data and field observations for any characteristic that is indicative or might be indicative of a potential threat to essential fish habitats. Along with the primary objectives of this baseline survey, this study seeks to answer the following questions:

1. Are there any indications of potential threats or problems revealed by a cross examination of the associations, extent of, or percentage of biological cover of mapped marine habitats?

2. According to the study completed by Goreau in 1992, coral reefs and marine conditions at Bluefields Bay were among the best in Jamaica. How do the conditions in Bluefields Bay now compare to the conditions described in the previous study and how do they compare to other marine protected areas in Jamaica now?

3. Are the essential fish habitats within the bay internally threatened or externally threatened, or both?

4. Describe the overall conditions at Bluefields Bay, including spatial extent and association of habitats, water quality, field observations, and socioeconomic aspects that affirm Bluefields Bay as a marine protected area.

Benefits

Baseline studies have been conducted elsewhere in Jamaica, independently or as part of environmental impact assessments, but studies of the southwest coast of Jamaica are sparse. This study will be the first detailed baseline survey addressing habitat condition and distribution as well as producing a detailed bathymetric map of the bay. A detailed bathymetric map can be used to infer sea bed geology, identify potential sources of ground water upwelling, and identify features in local sea floor topography that are not readily recognizable from boat or diver vantage points. A baseline, benthic habitat map will allow for tracking of temporal changes in habitat coverage as well spatial interactions between habitat types.

The maps from this study will be beneficial to local residences and coastal communities around Bluefields Bay. Previous benthic habitat maps have been used for mitigating the impact of growing local communities that depend on coastal marine resources for their livelihoods. A benthic cover map will allow for the efficacy of Bluefields Bay Fish Sanctuary to be evaluated over time. As an example, the best way to track the health of seagrass beds is to know the expansion or loss of individual beds over time. For other benthic habitats this is also true.

The data from this study will provide an in depth inventory of the extent and condition benthic marine habitats and coastal buffer habitats as the crucial first step of monitoring and managing Bluefields Bay Fish Sanctuary. The benthic cover map and bathymetric map are important key bits of information to be added to the overall database of compiled and used to manage Jamaica’s marine protect area network. The information will be useful for the long-term management towards sustainability goals and to mitigate the impact potential threats may be causing.

The map products will be given to the sanctuary's wardens as a vital tool in effectively protecting the sanctuary, reporting any activity, and tracking locations of traps found. This study will inform residents of how their everyday activities are affecting the critical ecosystems they depend on for a myriad of benefits as well as how alternatives can ensure the long term health of the marine resources they rely on.

This study will improve the scientific understanding of the unique factors of the marine ecosystems on Jamaica's southwest coast. When linked with the fish species survey performed by Rudolph (2013), the benthic habitat and bathymetric map can be used to estimate fish populations and distribution in Bluefields Bay. The collective results will allow for summarizing, analyzing, and reporting the habitat characteristics in association with fish populations and their movements as well as other marine resources. The biological component with the physical and chemical components will allow for the specification of what indicators should be chosen to evaluate the condition of marine ecosystems by reporting back relationships between habitat characteristics, the productivity of different habitat types in regard to fish species densities, and the type or extent of various threats (NMFS, 2010).

CHAPTER 2

THREATS TO AND PROTECTION OF ESSENTIAL FISH HABITATS

Archeological evidence from shell middens proves that human populations have long settled the coastal areas of the Caribbean Sea and depended on the sea as a primary source of food (Atkinson, 2006). Later on, like many Europeans who wrote of abundance of marine wildlife in Caribbean, Christopher Columbus wrote of the sea turtle populations as being “inexhaustible” (IUCN, 2013). Europeans that heavily exploited the Caribbean’s natural resources during the time when Jamaica’s heyday as a major port of trade are commonly blamed as initiating the decline of biodiversity, fish populations, and marine ecosystems. Yet progressively smaller sizes of queen conch shells in middens suggest that there were instances of local overharvesting in the Caribbean (Beckman, 2013).

Regardless of the past, the persisting misconception that the sea’s bounty was an endlessly renewable resource has changed into an awareness of the magnitude of the impact human exploitation of ocean resources can have. The dwindling size of fish catches and decline of coral reefs were some of the evidence that lead to human efforts to protect and conserve what was remaining (Gayle and Woodley, 1998). As part of that effort, marine protected areas are set aside to preserve biologically productive areas like coral reefs, mangroves, and seagrass beds (Ellison and Farnsworth, 1996). Without baseline data and successive monitoring, the effectiveness of MPAs cannot be evaluated nor the management strategy adapted in a timely manner. Understanding the causes producing the adverse effects on marine ecosystems as well as having up to date, detailed information on current conditions in the MPA via survey and mapping is vital to effective management and protection (Haynes-Sutton, 2009).

The degradation of marine resources in the Caribbean is not the result of any one obvious cause. It was not until anthropogenic sources altered the environmental factors of the Caribbean that it was clearly understood how important the optimum conditions found in the Caribbean are to essential fish habitats like coral reefs (EPA, 2012; FAO, 2011). The clear link between human activity and the destructive exploitation of valuable natural resources made it necessary for legislation, including formation of a national park system, to be passed to protect and regulate the use of remaining resources (Donaldson, 2008). In response to the declining condition of marine resources, a national fishery policy was drafted and a network of marine protected areas was created. However, the effectiveness of a marine protected area network is built sequentially from designation to success by the effectiveness of each marine protected area within it (Geoghegan *et al.,* 2001). As part of the process of effective management and protection, physical habitat mapping, assessment, and inventory acts first as a baseline point upon which to construct management and protection protocols and later as an evaluation of how management and protection can be improved upon (Gombos *et al.,* 2011; Hayman, 2007).

From anthropogenic inputs to overfishing, management and protection for an individual marine protected area must address internal and external threats alike. The first step in effectively mitigating or eliminating potential threat factors of a new marine protected area is the identification of current threat factors and the status of coastal and marine ecosystems. An overall understanding of the characteristic indicators of persisting problems as well as habitat characteristics within the region, within the nation, and within the immediate area is necessary prior to pending field work for accurate interpretation of resulting data. An intrinsic conception of the history of legislation, management, and protection is also necessary in order to custom tailor resulting map products to their intended audience of MPA management and park wardens. Finally, a collective review of all available information is necessary to understand the specific deficiency in knowledge addressed by this study.

Habitat Factors and Threats

Pollution. Pollution is the most devastating, reoccurring problem across the regional Caribbean (Villasol and Beltran, 2004). The major contaminants are untreated sewage, solid waste, sediments, petroleum hydrocarbons, pesticides, and agricultural run-off (GEF *et al*., 1999). Anthropogenic sources of contamination threaten the health of 61% of Jamaica's coral reefs (Burke and Maden, 2004). Anthropogenic sources of pollution account for 80 percent of the overall pollution while the remaining 20 percent pertains to marine sources of pollution, such as shipping, oil spills, and toxic and solid waste discharged from vessels (Miller, 1996).

Anthropogenic pollution comes from two types of sources. A point source of pollution is from a single, identifiable localized source whereas the more common origin of pollution is from several, nonpoint sources. A nonpoint source of pollution is where the pollution diffuses from several potential sources and is non-traceable to any one source. Industrial plants, municipal waste treatment plants, and oil refinery discharge outlets are point sources of water pollution that discharge pollutants directly into the water (Fulweiler and Nixon 2005). Storm runoff acts as a conduit for pollutants derived from diffuse, non-direct human or natural sources and is an example of a nonpoint source of water pollution (Carpenter *et al*., 1998; Humenik *et al*., 1980). Another nonpoint source of water pollution is pollutants that leak into the groundwater that flows into estuaries (Lewis, 1987). Nonpoint pollutions from agricultural and land use practices draining into coastal waters degrades populations, diversity, and the quality of coastal ecosystems (Basnyat *et al*., 1999; Carpenter *et al*. 1998). Rivers and streams also act as transport systems for pollutants from upstream sources to coastal waters; for example Jaffe *et al*. (2003) found that Montego River and North Gully both dump trace metals, pesticides, and petroleum hydrocarbon transport into Montego Bay.

Eutrophication and Excessive Nutrient Loading. Under unaltered conditions, the input of nutrients from inshore sources serves as an essential chemical and physical component of shallow marine ecosystems. Excessive inputs, or "nutrient loading" of coastal marine waters degrades seagrass productivity and produces favorable conditions for algae to overtake other shallow marine ecosystems. Phosphorus is a naturally occurring, necessary element for growth in plants and animals and is a growth limiting nutrient in water ecosystems (Carpenter *et al*., 1998). Nitrogen is a growth limiting factor for plants in estuaries and coastal ecosystems (Hinga *et al*., 1991). Biological marine environments have been found to favor nitrogen limitation over phosphorus. As a result, excessive levels of nitrogen may have more of an effect on marine ecosystems (Smith, 1984). A site specific problem with eutrophication also exists in the Caribbean. In 1983 a disease wiped out the algae grazing *Diadema antillarum* urchin population in the region, altering marine ecosystems in the Caribbean in such a way that they were already prone to algal growth overtaking coral reefs (Lessios *et al*., 1984).

Surface waters and runoff that pass through coastal watersheds transport nutrients left by human activities into receiving coastal ecosystems (Valiela *et al*., 1992; Valiela *et al*., 1997; Corell *et al*., 1992). Agricultural products like fertilizers, sewage products, industrial waste, and livestock pastures are all sources of excess nitrogen in fresh water runoff (Valiela *et al*., 1997). Urbanization along the coastal area of Kingston harbor has altered nutrient circulation patterns as well as increase the amount of domestic and industrial waste discharged into the bay, causing eutrophication (Bigg and Webber 2003). Eutrophication due to excessive phosphorus and nitrogen inputs is a common problem in surface waters in North America (Elser *et al*., 1990). A detailed study conducted by the Global Coral Reef Alliance connected excessive coastal nutrient loading to anthropogenic sources in western Jamaica. Most reefs near developed shores were observed as being seriously degraded by algal overgrowth (Goreau, 1992). The main inputs of excessive nutrients into coastal marine ecosystems are human activities, but atmospheric deposition and acid rain are potential causes of contamination as well (Hinga *et al*., 1991).

Coastal Development and Raw Sewage Problems. Just over a third of Caribbean's reefs at risk are threatened by coastal development (Burke and Maidens, 2004). Poor water quality downstream of high human impact areas is typical (Wang, 2001). Increased development upstream negatively affects water chemistry parameters like dissolved oxygen and conductivity, impacting all biota downstream such as mangroves which depend on fresh water inputs (Gage *et al*., 2004). Coastal development also generally outpaces adequate sanitation facilities, leaving Jamaican waters open to contamination by effluent and sewage discharge (Ebert, 2010). One study found that 30,000 to 40,000 m^2 of improperly treated sewage are discharged per day into Kingston

Harbor (UNEP and CEP, 2001). When coastal development exceeds proper waste treatment, pollution like raw sewage causes an abnormal influx of nutrients which in turn can cause algal blooms that out compete other marine life for vital resources like space (Beck *et al*., 2001). Contamination levels of bacteria that are indicative of fecal matter contamination are measured by total coliform and fecal coliform or *Escherichia coli*, the bacteria that makes up the majority of fecal coliform (Davis *et al*., 2005). Contamination by fecal matter comes from more than just raw sewage; other sources of fecal coliform are agriculture, forestry, wildlife, and urban runoff (Griffin *et al*., 2001; Wickham *et al*., 2006). Suspended solids originate from sewage treatment plants and industrial runoff and increase the suspended sediments in water, which is associated with longer survival periods of E. coli in sea water (Gerba and McLeod, 1976).

Agriculture. Sedimentation and inland agriculture places over a third of the Caribbean's coral reefs at medium or high risk (Burke and Maidens, 2004). Small farms cover about 25% of Jamaica's landscape and belong roughly to 170,000 farmers in Jamaica (Chemonics International Inc., 2003). Poorly planned agricultural practices and intense land cultivation on steep slopes are a direct cause of exposing soils to erosion which lead to high sedimentation rates during rainy season in local waterways (McGregor and Barker, 1991). Control of soil erosion is minimal and along with excessive sedimentation, there is contamination of rivers by agricultural chemicals during participation events (Beckford, 2002; Davis-Morrison, 1995). Fertilizers applied to agricultural plots and pesticides applied to food forests are typical sources of non point pollution from the coffee plantations in the Blue Mountains to the coastal waters of eastern Jamaica (Robinson and Mansingh, 1999). Pesticides like DDE and other organochlorated products that are prohibited in many countries due to the harmful effects they have on human health and ecosystems are used in parts of Jamaica and make up part of the agro-pollution contaminating coastal waters (Villasol and Beltran, 2004). Cattle grazing does significant damage to wildlife habitat and erosion buffers and vegetation along stream banks, causing fine sediments to wash into roads and fields and ultimately into coastal waters (Kauffman and Krueger, 1984).

Deforestation. The historical land cover for Jamaica was predominately forest with the exception of swamps and wetlands (Ebert, 2010). Just less than a third of land cover in Jamaica is now forest, with 30% being mixed forest and cultivation and 39% being non forest (Chemonics International Inc., 2003). Aggressive clear cutting of forests leaves fragile soils exposed that are quickly eroded and transported off by runoff from high rainfall periods (Madramootoo and McGill, 2000). The typical Jamaican waterway is narrow and located on a steep, mass movement scarred slope (Ahmad *et al*., 1993). Unsustainable practices like harvesting riparian vegetation, clear cutting land adjacent to streams, and abatement practices aggravate the erosion of channel and banks in waterways that are already susceptible to erosion (Clark and Wilcock, 2000). It is estimated that 80 million tons of top soil has been lost annually in Jamaica due to deforestation in coastal basins (WWF, 2012). Large sediment loads being released into coastal waters reduce how deep light can penetrate to reach the coral reefs and seagrass that depend on sunlight (Mallela *et al*., 2004; Vincete and Rivera, 1982).

Marine Pollution. Marine based pollution accounts for 14% of the threats putting Caribbean coral reefs at risk whereas the percentage of Jamaica's coral reefs at risk from marine pollution is significantly higher at 31% (Burke and Maidens, 2004).

Approximately three-fourths of marine debris comes from shipping traffic through the Caribbean such as packing material from merchant shipping vessels, solid waste from cruise ships, and tar balls and oily residues from tankers (Villasol and Beltran, 2004; UNEP, 2000). Nets and fishing gear from fishing vessels also accounts for some of the marine debris. Plastic and discarded fishing lines kill many marine animals due to entanglement or accidental ingestion. A study in the Bahamas found that floating waste resulted in higher mortality and lower reproduction of sea turtles, marine mammals, and sea birds (BEST, 2002). A major underlying problem is that countries in the Caribbean lack the proper waste reception facilities at ports and lack the funds to invest in building any. The cruise industry continues to expand but there are little in the way of incentives or enforced penalties to make ships comply with international protocols and dispose of waste at ports rather than dumping it at sea. Wind and waves then carry the waste, especially paper and foam, across sea boundaries to other islands (Villasol and Beltran, 2004). Approximately 35 million tourists visit the wider Caribbean region each year, generating over 7,000 tons of solid waste (UNEP, 2000). The amount of marine pollution will only increase as the tourism industry continues to grow.

Climate Change. There are enough cumulative observations of average sea levels rising globally, widespread melting of snow and ice, and increases in global average air and ocean temperatures since temperatures were first being recorded by instruments in 1850 to "unequivocally state that the global climate system is warming" (IPCC, 2007). There has been an average surface temperature warming of 0.2-1.0 degrees Celsius since 1970 for most of the Caribbean region including Jamaica (IPCC, 2007). Sea surface temperatures in the Caribbean are predicted to rise by 1 degree Celsius by 2050 (GoJ, 2011). For coral reefs, a small change of as much as 1 degree Celsius has been shown to be enough to trigger a coral bleaching event (Goreau, 1992). There is evidence from collective data from as far back as 1961 that show that the ocean has been acting as a heat sink, absorbing over 80% of the heat being added to the climate system.

The absorption of heat by the oceans results in sea level rise. Thermal expansion of ocean waters is attributed as to being approximately 57% in the sum of estimated individual contributions to sea level rise while glacier, ice cap, and polar ice melt make up the rest. By 2100 the ocean is predicted to rise between 0.18 m to 0.59 m (IPCC, 2007). Sea level rise results in higher ground becoming the new tidal zone, which in turn makes it vulnerable to erosion (UNESCO, 1998). Coral which contain symbiotic bacteria that produces food for coral via photosynthesis are limited to the depth at which adequate light penetrates the water column for continued survival. The average annual rate at which the sea must rise to reach predicted levels exceeds the average annual growth rate of coral, which is about 4 millimeters per year. Massive coral mortality will result once depths above coral reefs exceed the level at which enough light is able to penetrate for photosynthesis to occur (Beckman, 2013). For seagrasses, which also depend on photosynthesis, sea level rise will mean mortality for deeper grass beds.

Since the mid-1700s the level of carbon dioxide in the atmosphere has increased by 30% (NOAA, 2012 *cited in* Beckman, 2013). Increased CO_2 levels are leading to ocean acidification and decreasing the solubility of certain compounds necessary to coral health and growth in sea water (Hoegh-Guldberg *et al*., 2007). Sea water is typically basic, having a pH range of 7.6-8.2. The acidification of ocean waters is detrimental to calcium carbonate secreting organisms like reef building corals.

Research completed by Dasgupta *et al*. (2007) predicted that Jamaica was one of the top ten developing nations with the most land exposure to erosion by a sea level rise of one meter. Sea level rise will mean the retreat of wetland and mangrove ecosystems inland (Gilman *et al.,* 2007; GoJ, 2011). Currently, legal setbacks from the shoreline are a minimum of fifty meters from the water line for new buildings in Jamaica (Robinson *et al.,* 2006). The legal setback minimum in Jamaica is based on the predicted amount of erosion and other damage expected to result from a storm of particular intensity, or a "one hundred year storm" (Robinson *et al*., 2006). Prediction modeling by Mona GeoInformatics Institute at the University of West Indies conservatively projects a loss of land area of 101.9 km^2 if sea levels rise by 0.18 m by the year 2070 (Richards, 2008).

Jamaica's National Park System

In response to the environmental problems, Jamaica began to look towards conservation programs to protect critical areas. Prior to 1970, the physical planning of Jamaica had been legally established in the form of the Town and Country Planning legislation but in 1971 the concept of a National Physical Plan was introduced that included legal management of the use or conservation of the country's natural resources (Town Planning Dept., 1971). The National Physical Plan of Jamaica (1970-1990) stated a need for "an integrated regional system of a wide range of parks, recreational and conservation areas reflecting Jamaica's social needs and natural environment" (NRCD and Field, 1987). Among the all the potential setbacks for a national park system, six major ones were identified for Jamaica in the 1980s: (1) low level of public awareness and political support, (2) lack of protected area legislation, (3) lack of a comprehensive park system policy statement, (4) need for definition of priority areas, (5) restrictions of management capacity, and (6) limited involvement in international and regional conservation programmes (Thorsell, 1981 *cited in* IUCN, 1992).

Since then, Jamaica has taken several steps towards building a strong national park system. A number of activities over the last decades have promoted public awareness like the recent "A Climate Change Symposium" where participants were informed about how climate change could potentially affect energy, water resources, coastal resources, and biodiversity (GoJ, 2011). On a government level, the Fisheries Division of the Ministry of Agriculture and Lands has made a number of contributions to the local fishing industry under the enactment of the Fisheries Act (1976) in recognition of the fact that fisheries provide the means by which thousands of Jamaicans make a living (MoFA, 2008). The aforementioned PARC provided system wide regulations for the establishment, management, and operation of marine parks (IRF, 1992). Originally in 1970 the Natural Resources and Conservation Division conducted resource inventories to identify priority areas and the ecological branch began the process of establishing protected areas in 1979 with the help of the Organization of the American States (Allen, 1990). The National Physical Plan recommended that an independent, non-profit National Parks and Protected Areas Trust be founded for the enforcement of parks and protected area legislation, serve a major role in building institutional precedents, and define the processes by which areas are selected for protection (Allen, 1990). In 1987 the Jamaica Conservation and Development Trust (JCDT) was established as a non-government organization capable of assuming leadership of responsibilities outlined under the PARC project and serve in the role recommended by the National Physical Plan (IRF, 1992).

Jamaica has also actively become in involved regional and international conservation programmes. In 1981 the cumulative effort of the United Nations Environment Programme (UNEP), Economic Commission for Latin America and the Caribbean (ECLAC), and government and nongovernment representatives of the Caribbean community resulted in the Caribbean Action Plan. The plan outlined objectives such as the coordination of international assistance activities, strengthening regional and sub-regional institutions, and technical cooperation in the use of the region's natural resources. In 1983 the Cartagena Convention was adopted as the legal instrument for implementing the plan and was signed by Jamaica in March of that year. The Specially Protected Areas and Wildlife (SPAW) Protocol from the Convention's Protocols was signed by Jamaica in January, 1990 (PNUMA *et al*., 1999 *cited in* Villasol and Beltran, 2004). In August 1992, Phase I of the Protected Areas Resources Conservation Project (PARC), a project agreement between United States Agency for International Development (US-AID) and the Jamaican government, was executed and included creation of the protected areas of Blue Mountain/John Crow Mountain Park and Montego Bay Marine Park as well as laying the foundation of policy, legal and financial and institutional, for a national system of protected areas (Allen, 1990; IRF, 1992).

Jamaica's Marine Protected Areas

In the thirty years since Thorsell (1981) identified the six issues that needed to be overcome, Jamaica has made major strides in rectifying them and establishing a national network of protected areas. One of the remaining needs was a lack of a comprehensive park system policy statement. In 2008 the Ministry of Agriculture and Lands Fisheries

Division drafted a National Fisheries Policy with the main goals being to contribute to economic growth, reduce poverty, achieve a sustainable livelihood through employment in fisheries and related activities, and contribute to the provision of food security (MoAF, 2008). Approximately 15,000-20,000 artisanal fishermen in Jamaica are supported solely by catching fish that depend all or part of their life cycle on coral reef and related ecosystems (ECOST Project 2007; Murray, 2008). The value of fish consumed domestically and not sold on the market is estimated to be US$1.2 million per year in the early 2000s (Waite *et al*., 2011). That does not include the part time fishermen, vendors, gear makers, boat builders, ice suppliers, and others whose livelihood is indirectly dependent on Jamaica's coral reefs and coastal ecosystems. Fisheries are also important in that they provide food security and livelihood for coastal communities in times of need (Kong, 2003; MoAF, 2008). Reaching a sustainable level of marine resources is vital for Jamaica's economy long term (Waite *et al*, 2011).

Some of the world's first coral reef marine parks were planned to be formed in Jamaica as early as the 1950s. In 1979 Jamaica's reefs were regarded as being more biologically diverse than elsewhere in the Caribbean due to being a place of refuge for marine flora and fauna as during the Ice Age. The net worth of Jamaica's approximately 400 kilometers of coral reef out of the total 1,022 km of its coastline was valued in billions of U.S. dollars per year as of 1992. Understanding of the many causes leading to coral reef degradation and the actions needed to counter them were first developed in Jamaica. However, little to no discernible progress was made to act upon that knowledge until the 1990s when a number of marine protected areas were formed in Jamaica. Montego Bay Marine Park was formed in 1992, the same year as the report Goreau wrote on coral reef protection in western Jamaica. Montego Bay was followed by Negril Marine Park, Ocho Rios Marine Park, and Portland Bight Protected Area in 1998, 1999, and 1999 respectively (Geoghegan *et al*., 2001).

Marine protected areas are "clearly defined geographic space, recognized, dedicated and managed, through legal or other effective means, to achieve the long-term conservation of nature with associated ecosystem services and cultural values" (IUCN and WCPA, 2008). Put more simply, MPAs are created to protect ecosystems of interest like those that are essential fish habitats. Essential fish habitat includes but is not limited to breeding and nursery environments like mangroves, coral reefs, and seagrass beds. In a comparison between the MPAs in regards to which essential fish habitats were present within the protected area, all reported having coral reefs while all but Negril also reported having seagrass beds. Montego Bay and Portland Bight area also have mangroves and Portland Bight was the MPA with the largest diversification of environments both marine and terrestrial as of 2001 (Geoghegan *et al*., 2001). Protecting these essential fish habitats has the benefit of preserving biodiversity and allowing a spill-over of fish into surrounding areas where fishing is allowed (Roberts *et al*., 2001). Marine protected areas have a secondary benefit of providing alternative livelihoods for artisanal fishers such as wardens for the enforcement of protection (Waite *et al*., 2011).

The potential social benefits of fisheries and marine protected areas for fishing communities, which are for a large part rural with high rates of poverty, is also particularly high (MoAF, 2008). At Negril and Montego Bay the MPAs have won local support from fishermen with management strategies that include consideration of the needs of the community (Geoghegan *et al.,* 2001). The incremental benefits of the coral reefs and mangroves in Portland Bight Protected Area were estimated to be between US$40.8 million and US$52.6 million with fisheries accounting for more than a third of that value, tourism accounting for almost another third, and carbon sequestration, coastal protection, and biodiversity making up the last third in estimated benefits (Cesar *et al.,* 2000). The net present value of Montego Bay Marine Park's reefs is approximately US$400.0 million with tourism and recreation accounting for US$315.0 million of that total, fisheries making up US$1.3 million, and coastal protection valued at US$65.0 million (Ruitenbeek and Cartier, 1999).

The existence of MPAs in Jamaica is not an accurate indicator of overall conservation, however. The effectiveness of each MPA is varied due to the comprehensiveness or lack of restrictions protecting the marine life within the area. A strong correlation has been drawn between coral reef health and the presence of several functional groups of different types of fish including large herbivorous fish and predatory fish (Gubbay, 1995; Hughes *et al.*, 2007). Only 15% of all MPAs worldwide are regulated strictly as no-take sanctuaries (Geoghegan *et al.,* 2001). Less than 0.1% of the world's coral reefs are located within MPAs that have no poaching and are no take sanctuaries (Mora *et al*., 2006). While there are benefits of singular marine protected areas on surrounding fish stock densities, each MPA is vulnerable to any local threats that originate outside the protected area, such as over sedimentation, an abnormal influx of nutrients due to improper waste treatment, and coastal development (Gubbay, 1995). A network of marine protected areas is more effective in addressing multiple threats to marine environments because they spread the risk of reduced viability of a habitat or community type following a large scale disturbance and allow for protection of marine ecosystems at an appropriate scale by protecting a diverse array of marine environments (Ballantine, 1997; Salm *et al.,* 2000; Allison *et al*., 2003; Roberts *et al*., 2003; Mora *et al*., 2006; McLeod *et al.,* 2008).

As the vulnerability of singular marine protected areas became better known, international movement towards developing marine protected networks was taken. When it became a Party to the Convention on Biological Diversity (CBD), Jamaica agreed to establish a "comprehensive, effectively managed, and ecologically representative national and regional system of protected areas" by 2012 (UNEP-WCMC, 2008). In 2009, Jamaica took a major step towards establishing a network of marine protected areas by passing legislation to create nine new marine protected areas that were no-take fish sanctuaries. In addition to the established fish sanctuaries, Bowden Bay and Bogue Island Lagoon, Orange Bay, Bluefields Bay, Malcolm Bay, Discovery Bay, Montego Bay in St. James, Oracabessa Bay, Galleon Harbor and Three Bays Area in Old Harbor, and Salt Harbor add up to a cumulative total area of about 50 km^2.

Sanctuary Assessment Program and Procedures

According to Jamaican government protocols, a baseline survey to establish existing conditions within the fish sanctuary is needed so that the effectiveness of protection measures can be assessed over time (Haynes-Sutton, 2009). In regards to marine protected areas, the primary baseline is defined as the most pristine condition of the site, as identified by scientific and historic evidence, and represents the site in an undisturbed state. The secondary baseline is the conditions that exist at the time the marine protected area was first formed (CEC, 2011). Because the information upon which to base a primary baseline is often nonexistent, the baseline study at the time a MPA is created is usually the most comprehensive benchmark against which to measure future changes. The main purpose of the physical component of the baseline study is to establish the existing extent and conditions of target ecosystems the marine protected area was designated to preserve. Habitat surveys are used in habitat management, restoration, and conservation. Habitat surveying yields better information about distribution, abundance, and functions of essential fish habitats (NMFS, 2010).

The specific goals and the specific setting of the site needing a baseline survey is the primary factor that dictates which surveying technique should be utilized. Regardless of technique used the technique chosen “should aim fulfill multiple criteria. It should incorporate a number of biological, physical, and chemical variables in order to provide an eco-holistic assessment of the area; the technique must be relatively rapid with the ability to be easily repeated to allow assessment of large areas potentially containing a diverse range of habitats” (Markham and Browne, 2007). Primary limitations of any baseline survey and habitat assessment are time, equipment, weather, and available personnel. In the particular case of the new fish sanctuaries created by the Jamaican government, the goal of the initial survey is to document the current conditions inside the marine protected area and establish a baseline point for comparison so that the effectiveness of protection measures might be evaluated over time (Haynes-Sutton, 2009). This is a part of the overall goal of the Jamaican Fish Sanctuary Network to manage Jamaica’s coastal resources for sustainable use, to enhance biodiversity, and increase human livelihoods (Haynes-Sutton, 2009). The specific goals of the environmental and physical habitat portion of the baseline survey is to establish the status and conditions of habitats in and around the fish sanctuary, to identify threats to habitats, and to provide a basis for comparing Jamaican fish sanctuaries to others across the region (Haynes-Sutton, 2009).

Procedures. There are a number of surveying techniques used in marine and coastal environments. Several of them are tailored exclusively to coral reefs and include the Benthic Ecological Assessment for Marginal Reefs or BEAMR that is used to assess the health of a coral reef habitat over time as well as the BEAMR's predecessors the Atlantic and Gulf Rapid Reef Assessment and the Caribbean Coastal Marine Productivity Program (Linton and Warner, 2003; Kramer and Lang, 2003; Makowski *et al*., 2009). Other surveying techniques include a broader database for habitat assessment like the Phase 1 habitat survey method and the Marine Nature Conservation Review or MNCR (JNCC, 1996; JNCC, 2010).

One of the best overall, comprehensive marine survey methods for both the biological and physical components of the study is the Baseline Survey Protocol that incorporates the Line Intercept Technique into its protocol (Montebon, 1992). "The Baseline Survey Protocol is a quantitative coral reef survey methodology recently developed in order to conduct eco-holistic assessments of marine habitats…The physical and environmental assessments include sea surface temperature and salinity, horizontal and vertical visibility levels, and human activities on the surface. In addition, water and sediment samples are collected for further chemical analysis" (Markham and Browne, 2007). Standardized techniques are still broad enough that variations will occur between surveys conducted using the same technique due to adaptations made by the surveyors to fit the custom needs of their particular site or the particular goals of their study.

Assessment Needs of MPAs. During March 2003 to July to 2003 the National Marine Protected Area Center's Training and Technical Assistant Institution interviewed a number of coastal managers, scientists, and technology specialists from federal and state entities involved with marine protected area management or enforcement. The concerns given the highest priority were marine habitats, enforcement and boundaries, and monitoring the marine environment. Feedback specifically identified the need for benthic habitat maps and more useful benthic date at a proper scale with improved spatial coverage (NOAASCS, 2003). A benthic cover map of a marine protected area is used inventory natural resources, establish current conditions, monitor habitat loss, analyze changes, and identify specific areas that need further research or greater protection (NOAASCS, 2003). A baseline survey sets a scientifically sound foundation for the effectiveness of the marine protected area to be evaluated (Gombos *et al*., 2011).

Habitat, or the place where species live, can be characterized and described by the physical, chemical, biological, and geological components of the ocean environment. A habitat assessment of essential fish habitats considers the physical state of the habitat with the biological and chemical components being classified as characteristics of the overall physical state. The description of the physical state of the habitat should take into consideration currents and circulation, tidal amplitude, turbidity, water temperature, variability of depth, morphology, substrate type, biological cover, structure, erosion and sedimentation rates. The primary concern of the chemical conditions of marine habitats is associated with water quality. Chemical testing should include dissolved oxygen, carbon dioxide, acidity, dissolved solids, nutrients, organics, salinity, and pollutants such as heavy metals (NYSDOS, 2013). Potential threat identification involves comparing field chemistry data against typical conditions and isolating any abnormalities that fall outside expected ranges. The comparison of the physical state of marine and intertidal habitats against equivalent habitats within optimal conditions indicates the overall health of the various ecosystems. When conditions vary from what is normal in the Caribbean, shallow marine and intertidal ecosystems will show indicative signs of stress.

Essential Fish Habitats and Health Indicators. Under optimum conditions, coral reefs are predominately populated by calcium carbonate producing organisms and have bathymetrically extensive reef framework structures (Mallela *et al*., 2004). The amount of fresh water runoff entering a coral reef environment and how much it may affect the health of the reef depends on watershed size and slope, volume and intensity of rainfall, soil condition, and land use. Photosynthesis is necessary for the endosymbiotic zooxanthellae, or bacteria in the coral tissue that perform photosynthesis and help feed the coral, and the deposition of the calcium carbonate that makes up the coral reef framework. High turbidity and suspended sediments block the amount of light coral receive through the water column. The resulting reaction is bleaching, reduction in growth, and decrease in productivity. Two deviations away from ideal salinity resulted in up to 50% less productivity in coral reef communities and 4 deviations resulted in the death of the community. Prolonged temperature changes result in mild to severe bleaching in coral heads. The length of exposure of coral reefs to abnormal levels directly correlates to severity of damage (Keller *et al,* 2009).

Mangroves are mature ecosystems dominated by pioneer species that occur in tidal zones that have adequate nutrients, fresh water input, and sediment conditions. Mangroves are vulnerable to hydrological fluxes, sedimentation, changes in temperature, and modification of topography. Mangroves catch much of the sediment brought in by rivers and absorb upland nitrogen inputs. Mortality in mangroves is caused by over sedimentation smothering roots, salinity over tolerant threshold levels, lack of oxygen supply to roots, and high water temperatures. Regeneration after clear cutting of even a single hectare of mangrove forest is slow due to soil acidification. Pollutants like heavy metals cause stands to die, reduced ecosystem species richness, and heavy metal content in seedlings (Ellison and Farnsworth, 1996).

Productive seagrass beds support biodiversity, filter fine sediments out of the water, slow wave action, stabilize the sea floor, and provide many marine grazers with food in the form of debris. Seagrasses are particularly sensitive to over sediment and excessive nutrient inputs, physical disturbance, and global warming, which cause seagrass beds to shrink and lose abundance within the bed (Orth *et al*., 2006).

For coral reefs, bleaching, algal cover, and banding are signs of coral reef decline while biodiversity and extent of live coral cover is an indicator of a healthy coral reef. For mangroves, decrease of species diversity, stand thinning, and dead stands are signs of mangrove decline from what usually is anthropogenic pollution while the width and extent of the live mangrove forest is directly proportional to the health of the ecosystem. The thickness and extent of seagrass beds is a fair visual indicator of health while temporal tracking of the shrinking of the area seagrass beds cover is a clear sign of seagrass decline.

Habitat Assessments in Jamaica

The coral reefs around Jamaica have been studied since the 1950s but the ecological significance of seagrass beds and mangroves has only become widely known and studied in the past few decades. Some of the earliest assessments in Jamaica were completed to inventory the national resources of the island nation. A successive survey was performed with the goal of identifying and assessing potential sites for national parks. More recent legislation in Jamaica now calls for a habitat assessment as part of an ecological impact assessment of proposed building projects in ecologically sensitive areas. As part of the process of proposal, management, or evaluation, habitat assessments of other marine parks in Jamaica have also been completed. Various habitat assessments at the sites of other marine parks have been performed using a variety of methods. Some of the key ones have been summarized for comparison.

Montego Bay Marine Park. Montego Bay Marine Park is located on the northwest coast of Jamaica and the protected area extends from the shoreline to the 100m depth contour. Major disturbances to the area are dredge and fill development of the fringing mangrove forests and mangrove islands of Bogue Sound; sedimentation and nutrient loading in the Montego River; alteration of natural coastline by coastal development; and high utilization of the area for fishing and tourism (Sullivan *et al*., 1999). The two main objectives set for the assessment were to prepare a benthic community map with descriptions that report the health and conservation concerns affecting each type and to track the trends associated with point and non- point pollutants. Methodology consisted of three stages; "preliminary mapping of marine benthic communities from 1:12,000 natural color aerial photographs, field surveys to ground-truth imagery and identify gradients of anthropogenic disturbance from known point-source of pollution and construction of a final marine benthic community map with assessment and ranking of communities" (Sullivan *et al.,* 1999). In all 25 types of benthic communities were mapped.

In the 5 subdivisions of Montego Bay, the near shore areas in the western area had the lowest diversity and the highest levels of disturbance based on substrate life form characterization and belt quadrant assessments. On the spur and groove reefs in the eastern portion, sponges showed more diversity, density, and biomass than sponges on the western reefs. Stony corals occurred in higher densities on the western reefs. Total area coverage of live corals was similar through the park, which was lower than expected (Sullivan *et al*., 1999). The northeastern edge of the park had the most coral species diversity and was dominated by boring sponges rather than vase or tube sponges. There was a general loss of large coral colonies, loss of diversity of species, and notable change in size-frequency distribution of benthic organisms. Overall the shallow benthic marine communities in Montego Bay Marine Park showed the symptoms of degradation associated with being adjacent to a major city (Sullivan *et al*., 1999). Recommendations made were restoration of natural water flow and circulation, restoration of water quality, and minimizing consumptive or utilization damage to resources (Sullivan *et al*., 1999).

Ocho Rios Marine Park. Ocho Rios Marine Park lies between Drax Hill and Mammee Bay on Jamaica's west coast and is bordered by 13.5 km of shoreline. There is a mostly continuous reef crest with natural and human made breaks for ship to pass through. Four rivers, various storm drains, sewage outfalls from treatment facilities, and gullies drain into the park area. The marine and coastal resources at Ocho Rios Marine

Park were estimated to have an economic value of US$245.2 million per year and an estimated US$60.8 million would be lost per year if the quality of coastal and marine resources were to degrade to an unacceptable level. The objective of the study was then to "quantify the economic and social value of the marine and coastal zone resources" (EMU-UWI, 2001). As part of that umbrella objective, a rapid assessment of coastal and marine resources was performed. Coral reefs within the new park boundary were assessed using the Atlantic Gulf Reef Rapid Assessment (AGRRA). The condition of coral reefs was classified as degraded since all were found to have less than 10% live coral cover. There was also very little recruitment in coral colonies, less than 3 per meter squared. The Hawksbill turtle, which is protected under the Wildlife Protection Act, was found to be numerous on the fore-reef (Mailer, 1984 *cited in* EMU-UWI, 2001).

Water quality testing included testing for fecal coliform, total suspended solids, dissolved inorganic phosphorus, and dissolved inorganic nitrogen. In total 25 sites were sampled including marine and river sites for both fresh water and sea water testing. When tested for fecal coliform, only three marine sites exceeded the USEPA concern level of 200 MPA/100ml while all but one river site exceeded the level of concern. Total suspended solids are regulated to concentrations of 20 mg/l in discharge; while all marine sites fell below that limit, all river sites except one were found to exceed the limit in January, 2000. Dissolved inorganic phosphorus exceeding 0.1 µmol/l with dissolved inorganic nitrogen present or vice versa are favorable conditions for algae to overgrow coral and ultimately destroy the reef (Lapointe, 1997 *cited in* EMU-UWI, 2001). Some of the marine sites exceeded 0.1 µmol/l and most of the rivers exceeded the limit with annual variations between 0.5 µmol/l and 2.0 µmol/l. Overall, threats to marine and coastal ecosystems were found to be improper sewage and waste disposal, over fishing, shipping, construction activities on the coast, and global warming. Some recommendations made were restrictions on minimum mesh size for fishing gear, an environmental programme to raise awareness, and better integration with government agencies to use the data to better implement restorative and rehabilitative actions (EMU-UWI, 2001).

Discovery Bay. Discovery Bay is a horse-shoe shaped embayment with a diameter of 1.5km along Jamaica's north coast. The northern seaward side of the bay is fringed by coral reefs through which a channel for bauxite barges was deepened from 5m to 12m. From historical data starting in 1976, corals have greatly been reduced in abundance and algae has become more common (Vieria *et al*., 1995). The shift from coral to algae was attributed to the increase of human wastes from forest clearing, agriculture, and coastal development which have resulted in siltation of coral and eutrophication (Woodley, 1987 *cited in* Vieira *et al*., 1995).

Port Bight. Portland Bight is the largest bay in Jamaica and located on the southern coast of the island. For thirteen months near shore habitats including mangroves and seagrass beds were sampled for fish diversity (Aiken *et al*., 2002). Overall, species richness was high and Jaccard's coefficient was used to measure similarity between sample stations and areas in regards to diversity (Aiken *et al*., 2002). Mangroves and seagrasses in eastern Portland Bight supported more diversity than the western part despite having nearly the same ecological, physical, and chemical characteristics. Portland Bight and the area just west of it were identified as important juvenile fish habitats and as nursery habitat for many commercially important species.

Recommendations were made for protection and conservative management for the entire area (Aiken *et al*., 2002).

Rio Bueno. Rio Bueno is a small, steep sided embayment on the north coast of Jamaica. The Dornock River, a river with seasonal pulses of high river discharge and suspended sediments, empties into it (Gayle and Woodley, 1998 *cited in* Mallela *et al.,* 2004; WRA, 2001-2001 *cited in* Mallela *et al.,* 2004). Usual coastal sedimentary entrapment factors like mangroves had previously been completely cleared from the embayment along with the selective clearance of seagrasses. The study found that as proximity to the mouth of the Dornock River increased, the benthic community structure changed with an overall increase in coral cover and species diversity, coral morphologies shifted to dome and plate shapes, and spatially and bathymetrically restricted reef development. The open, coastal sites at Rio Bueno were minimally impacted by fluvial inputs and processes of sediment entrapment with favorable levels of light penetration and high wave energy. They exhibited the typical zonation of Jamaican clear water reefs (Mallela *et al*., 2004).

A gap assessment was carried out with the assistance of TNC identifying potential sites for marine protected areas in Jamaica in 2007. Jamaica's current marine protected area network was analyzed with minimum standard of 10% protection for each of the twelve conservation features, including rocky and sandy shores, seagrass beds, mangroves, and coral reefs. The western coast of Jamaica scored the poorest (UNEP-WCMC, 2008). The gap assessment was completed before the addition of the nine new fish sanctuaries to Jamaica's network of marine protected areas and no equivalent assessment has yet to been performed including Bluefields Bay and the other new fish sanctuaries.

Specific Needs of Bluefields Bay

One of the greatest needs at Bluefields Bay Fish Sanctuary is for a clear and detailed summary of the current conditions, habitat and marine resource inventory, and identification of potential threats. The ratio of urban to rural distribution of Westmoreland's population has increased at a rate of 0.64 percent per year after 1991 and was over 25% in 2001 (STATIN, 2008 *cited in* GoJ, 2011). With that number only predicted to increase in the future, there is immediate need for the implementation of effective management of the fish sanctuary. In 2007 threats to Jamaican protected areas was scored and while some of the highest current threats identified were invasive species, land clearing, pollution, and tourism, the threats to protected areas that are expected to increase the most in the future are pollution and climate change (Hayman, 2007).

Another commonality Bluefields Bay shares with Jamaica overall are the problems associated with rising sea levels. As sea level rises, constructed barriers like sea walls will lead to the disappearance of any beach between the wall and the sea. On cliffs and limestone bluffs the rise in sea level raises the likelihood that storm surges will exceed cliff tops (GoJ, 2011). Fractured hard rock cliffs will be more prone to collapse and shoreline regression will be greatest for soft rock cliffs. Coastal mangrove wetlands are particularly vulnerable to sea level rise due to their micro-tidal regime and proximity to the sea. No data currently exists on the vertical accumulation rate of wetland sediment and whether it will be able to keep up with sea level rise in Jamaica (GoJ, 2011).

Adverse effects on the southwest coast of Jamaica were found to be caused by poor water quality from runoff released from coastal communities and inland watersheds has been (Wels, 2000). Chlorine is added to drinking water throughout the Bluefields area and often leaks from pipes running through water systems. Pump houses located on several streams in the area are the facilities that chlorinate the water in the piping system. Often residents will disconnect pipes and allow the chlorinated water to discharge back into the stream (Ebert, 2010). Chlorine gas dissolved in water will react quickly with other substances in the water and becomes even more toxic when combined with other toxic substances (Vess *et al*., 1993). Even at low levels, small doses start to effect fish fry.

Although threats and vulnerability can be inferred from nearby or generalized from information from the parish or the country, no information of the sort has been compiled for Bluefields Bay Fish Sanctuary. There is a pressing need to have sufficient data on benthic habitats, water quality, and habitat affinities at adequate resolution (NOAACSC, 2003). One of the most critical needs yet to be addressed as identified by the Management Effectiveness Assessment and Capacity Development Report for Jamaica's System of Protected Areas was law enforcement (Hayman, 2007). Digitally mapped boundaries allow for more effective enforcement and communication of the existence and extent of the protected area (NOAACSC, 2003). One of the vulnerabilities identified for nearby Negril Marine Park was the clash of cultural practices, beliefs, and traditional uses with the objectives of the protected area (Hayman, 2007).Visualization and interactive tools have been observed to be especially effective in communicating potential results of a proposed activity when involving local groups in decision making

(NOAACSC, 2003). Overall, GIS maps produced offer the advantages of assisting in the visualization of natural resource data, assessing spatial data relationships, resource queries and evaluations, hazard identification, and programme coordination (UNEP-CEP, 1996).

Summary

In the past, Jamaica has been used as a cautionary tale of a worst case scenario for what happens when marine resources are exploited past sustainable levels. But more recently with the addition of the nine new fish sanctuaries, Jamaica ranks high among the Caribbean countries with the most marine protected areas so the building blocks for recovery and a sustainable future of marine resources has been provided (Carr and Heyman, 2009). A network of marine protected areas is an effective tool in conservation because the wider distribution of protected areas minimizes the risk that disaster will wipe out any one type of ecosystem. Coral reefs, seagrass beds, and mangroves are all essential fish habitats that are interconnected; marine protected areas that are “no take” protect these critical, connected ecosystems. Before a marine protected area can become an effective countermeasure there is a need for an in depth, holistic consensus of the intertidal and marine resources. A detailed benthic habitat map, a shoreline habitat map, and an up to date bathymetric map are all essential visual tools for management and protection.

CHAPTER 3

STUDY AREA

Bluefields Bay Fish Sanctuary (BBFS) is located on the southwest coast of the island nation of Jamaica in the parish of Westmoreland between Savannah-La-Mar and Belmont. It covers a bay that is approximately 8 km long by 2 km at its widest part with maximum depths of 8-10 m along the seaward boundary. The marine boundary of BBFS runs southwest from Bluff Point to Belmont Point turning at a midpoint at N 18^{o} 11'28.147"; W 78^{o} 3' 40.638" that is located about a mile to the west-southwest of the town of Cave (Figure 1) (Ebert, 2010). The protected waters of the bay are differentiated from the open waters by buoys (Figure 1). The larger communities of Bluefields, Cave, and Belmont are located along its coastline along with several smaller communities. The major waterways that drain into the bay are the Bluefields River, Sweet River, Bluehole Spring, and Sawmill River as well as several smaller ephemeral streams (Ebert, 2010). Ground water upwelling into the bay from the marine floor has been observed but not documented. Natural characteristics of the coastline vary from weathered limestone bluffs and mangrove forests to sand and gravel beaches. Artificial structures along the coastline and in the bay are sea walls, riprap, old dock pilings, and a new artificial reef aimed to facility reef and fish improvements (Figure 2) (Rudolph, 2013).

Geography

In the northern Caribbean Sea lies the Greater Antillean Islands and of those islands, Jamaica is the third largest with a SSE to NNW orientation (Mitchell, 2004). The


Figure 2. Artificial Reef in Bluefields Bay Fish Sanctuary (Beckman, 2013).

island of Jamaica is approximately 230 km long and 80 km wide with a total area of 10,990 km^2. It is separated from the rest of the Greater Antilleans and Cuba by the Cayman Trench (Ahmad *et al*, 1993). Jamaica's coastline stretches a total of 1,022 km, with approximately 25 km of it set aside for public recreation, 13 km designated fishing beaches and over 400 km of it ringed by coral reefs (Chemonics International Inc., 2003; Goreau, 1992). Over 10% or 100 km of Jamaica's marine shelf and coastal area were encompassed by marine protected areas in 2007 (Corrigan *et al*., 2007).

Geology

The island of Jamaica lies on the 200 kilometer wide, seismically active margin between the North American and Caribbean plates (McCann and Pennington, 1990; Mann *et al*., 1990). The boundary between the two plates, the Cayman Trough, runs between Cuba and Haiti and offshore of Jamaica's coastal shelf along the northwest part of the island. The island has never been connected to another land mass; rather it is the emergent part of the easternmost end of the Nicaraguan Rise (Wadge *et al*., 1984).

The geological history of the island can be broken down into first a late Mesozoic (145.5-65.5 million years ago) island-arc trench (A), a Maastrichtian Age (70.6-65.5

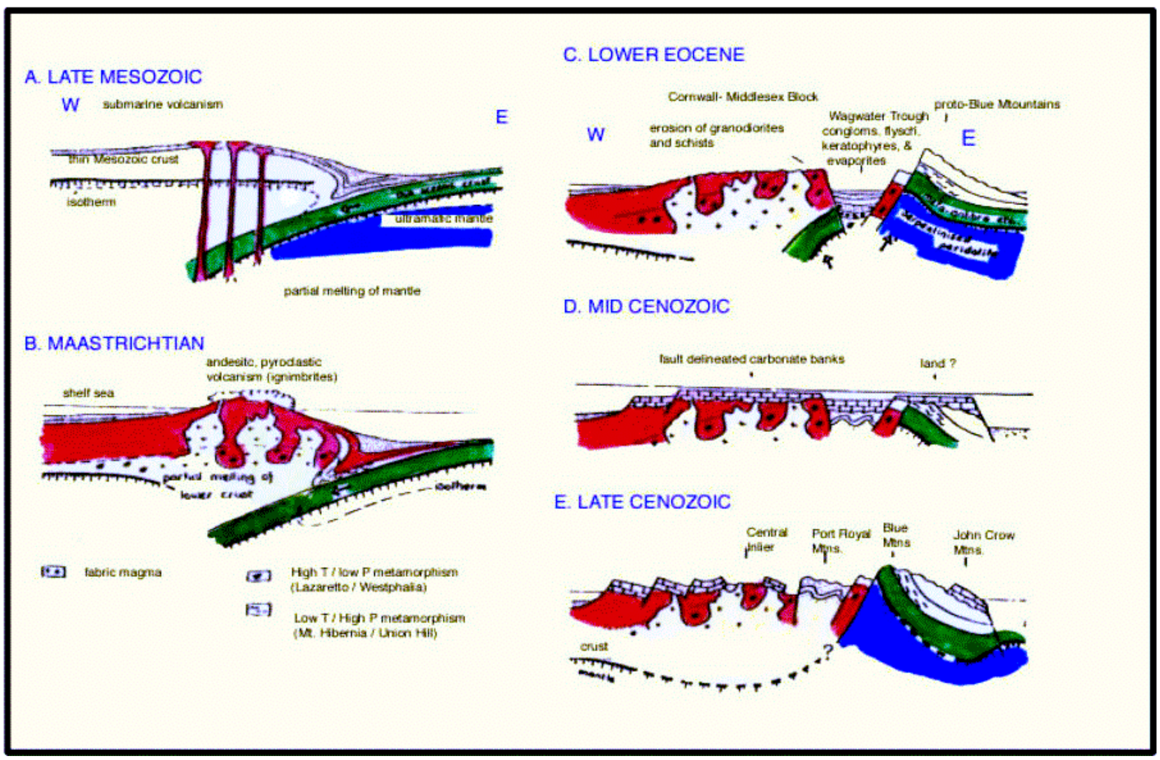

Figure 3. Sketched Cross Section of Jamaica at successive stages of the island's evolution (Horsefield and Roobol, 1974).

(Horsefield and Roobol, 1974)

million years ago) subaerial arc and basin (B), an Eocene (55.8-33.9 million years ago) mountain range with flysch and a keratophhyre-filled (alkali-rich igneous rocks with a volcanic texture) trough (C), a Mid-Cenozoic (23.03-2.588 million years ago) submerged platform (D), and a Late Cenozoic (2.588-0 million years ago) uplifted fault block (E) (Figure 3) (Horsefield and Roobol, 1974 *cited in* Wishart, 2000). Three regions, east to west, exist of the Cretaceous volcanic, volcano-clastic, and plutonic basement rock. The westernmost region of the island is identified as a subduction zone with complex faulting and a back arc basin (Jackson and Smith, 1979).

Stratigraphy. Paleocene clastic rocks overlay the Cretaceous basement rock, overlaid by Tertiary carbonate rocks, which are overlaid by partial carbonates intercalcated with clastic sequences from Late Tertiary to Quaternary (Woodley and Robinson, 1977). In western Jamaica the Paleocene age rocks are made up of the Masenmure Beds (Table 2). In the Mid-Eocene, calcareous parasequences of the Yellow Limestone Group were continuously deposited on top of the Masenmure Beds. The yellow limestone is typically interbedded with layers of clay and tuff with the youngest, topmost units being prone to karsting (Sweeting, 1985). In the late Eocene to Mid-Miocene deposition of the Yellow Limestone Group was replaced with deposition of the White Limestone Group (Wishart, 2000). This upper white limestone is typical highly fissured, course, crystalline, and well jointed but not continuous throughout the island (Sweeting, 1985). The surface geology of the western part of Jamaica is primarily carbonates from the White Limestone Group, which make up approximately 65% of the overall islands surface geology (Figure 4) (Michell, 2004). In some places Quaternary alluvium from river and lagoon deposits sit on top of the White Limestone Group.

Table 2. Simplified Stratigraphic Column for Western Jamaica (MoA, 1989; Wishart, 2000)

Group	Lithology	Period	Age
(N/A)	Recent Alluvium	Pleistocene and Holocene	2.588 million years ago to present
	Inland Basin deposits	Pleistocene	2.588 million to 11,700 years ago
White Limestone Group	Montpelier Limestone Formation Bonny Gate Limestone Formation Troy Limestone Formation	Mid-Miocene to Mid-Eocene	23.03 to 5.332 million years ago 55.8 to 33.9 million years ago
Yellow Limestone Group	Masenmure Formation Jerusalem-Thickett River Limestone Morelands Beds Green Island Limestone Dias-Jericho Formation Mount Peace Formation Tom Spring Formation Birch Hill Formation	Paleocene to Late Cretaceous	65.5 to 55.8 million years ago 99.6 to 65.5 million years ago
Shale and Conglomerates	Titano-Sarcolites Veniella Shale	Mid Cretaceous	145.5 to 99.6 million years ago

Soils. The formation and development of soil from limestone is determined mainly by the composition of the calcareous material and topography (Duchaufour, 1982 *cited in* MoA, 1989; Scholten and Andriesse, 1986). Two thirds of the soil currently covering the island can be traced back to the white and yellow limestone as the parent rock (Johnson *et al.,* 1996). The primary surface formation of the Bluefields Bay's watershed is the Bonny Gate Formation of the White Limestone Group. The Bonny Gate formation is associated with the genesis of non-calcareous, very "humic" top soil due to

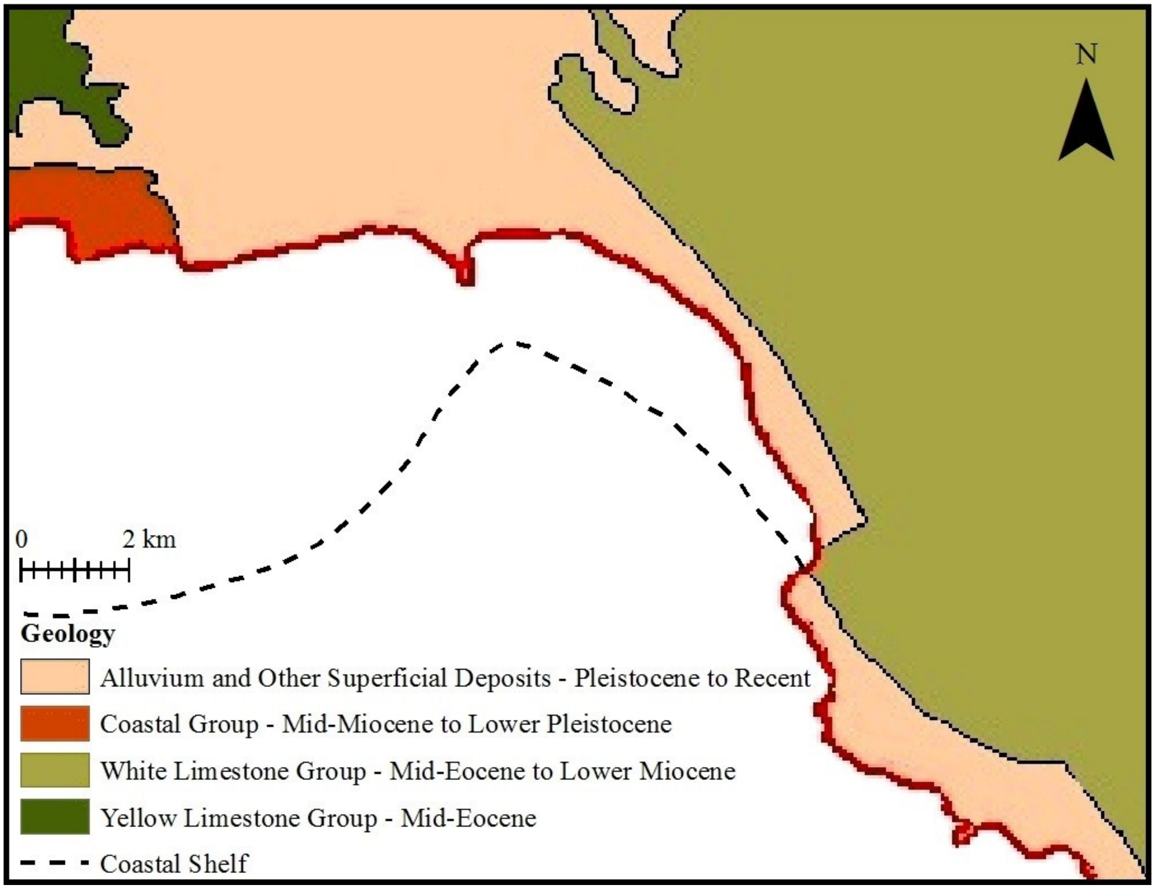

Figure 4. Simplified Geological Map of Bluefields Bay. (GSJ, 2012)

the high amounts of silica in the limestone as well as the humid climate (MoA, 1989). Soil composition has been observed to vary from high contents of clay on the coastal flats to more of a “stony loam” on mountain slopes in the Bluefields watershed (Ebert, 2010). The western portion of the Bluefields Bay watershed is characterized by mixed soil from the Bonny Gate formation, Carron Hill, Shrewsbury Ball, and Fontabelle formations. The alluvial plains are observed to be made up of fine gravel, sand, and loam with marine originating sediments with high clay content overlaying river alluvium in places up to 3-4 feet thick (Ebert, 2010; Hardy, 1951).

Karst Topography. With approximately two thirds of the overall landscape composed of carbonates, much of the land surface of the island’s topography is shaped by karsting. The dissolution of underlying layers of carbonate rock (karsting) is accelerated by the high temperatures and precipitation rates of the tropical climate. As underlying limestone erodes chemically and preferentially along existing fault lines, surface water runoff is diverted down into underground aquifers (Sweeting, 1958). Ground water upwelling into the shallow marine embayment of Bluefields has been observed and is a potential source of contamination of nutrients, agrochemicals, and untreated sewage.

Structural. The morphotectonic units of Jamaica have been broken down into “blocks” and “belts” by Versey (1960) (Figure 5) as the concept used to describe the structures left by extensional tectonics (Donovan 1993). Bluefields Bay is an inlet along the southwest coast that runs roughly parallel to the NNW-SE faulting trend of the karst highlands and is considered part of the Savanna-la-Mar Belt (Draper, 1987). The Mid-Eocene NNW-SSE trending fault set are features of the transcurrent deformation of Jamaica by the sinistral sheer on the North Caribbean Plate Boundary and the formation of a restraining bend through the east side of the island. East to west sinistral strike-slip faults that intersect and postdate the NNW-SSE trending set along the south coast are associated with an east-west trending left lateral sheer that occurred during the late Pliocene in a 200-km-wide zone in the north Caribbean (Zans, 1962). Downthrow along the South Coast Fault, as indicated by a decrease of Bouguer gravity gradients, is resulting in thickening of the basement rock and subsidence of the southern coast of Jamaica (Horsefield, 1974).

Seismology. The Earthquake Unit of the University of the West Indies monitors the seismic activity of Jamaica. For the period of 1997 to 2007 there were small earthquakes within 10 km of Bluefields Bay (Figure 6). Most of them were less than a

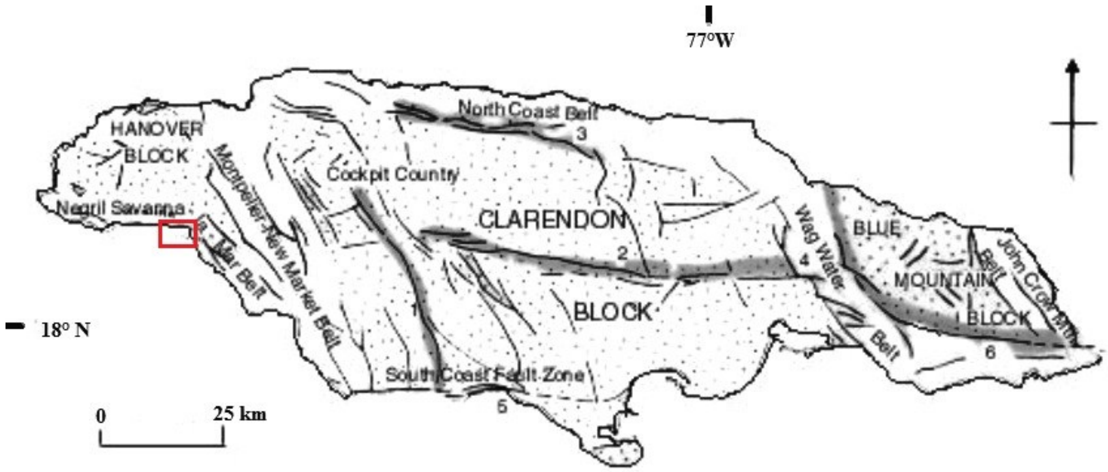

Figure 5. Simplified “Belts” and “Blocks” fault map of Jamaica. Study area denoted in red. (Modified from Wishart, 2000; Draper, 1987 cited in Wishart 2000)

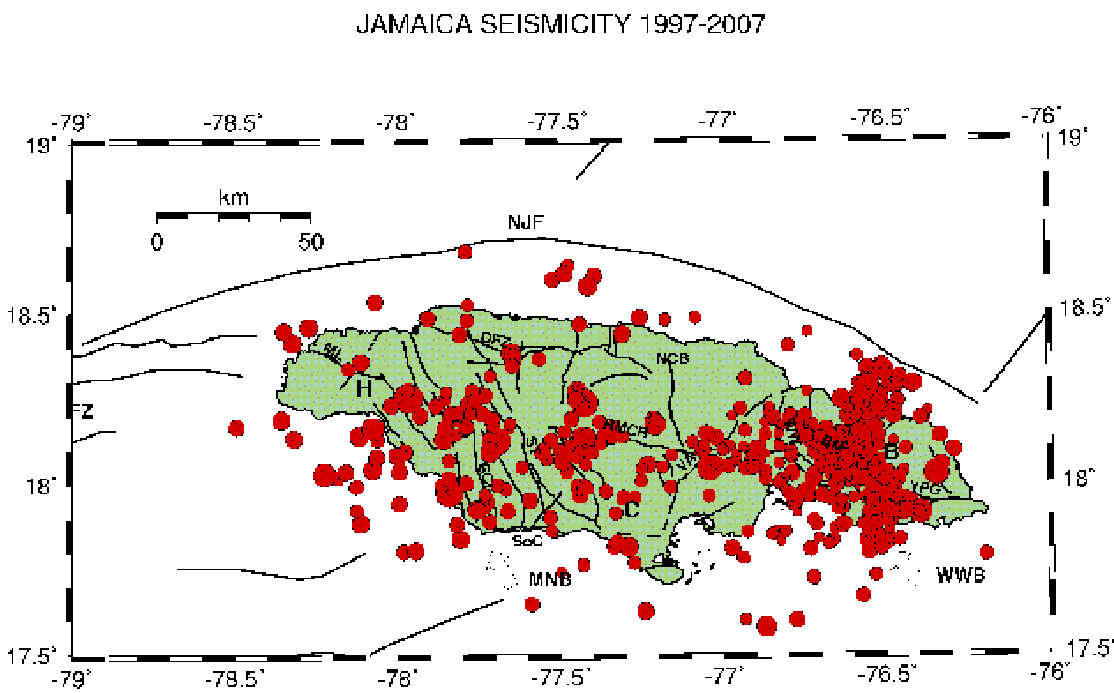

Figure 6. Recorded seismic activity less than magnitude 4 for Jamaica. (Wiggins-Grandison, 2005 cited in Parish Council of Westmoreland, 2008).

magnitude of 4 (Parish Council of Westmoreland, 2008). Historically three earthquakes were significant enough to affect western Jamaica. In 1839 an earthquake of magnitude 7 hit Montego Bay and St. James, causing damage to the point that government buildings were declared unsafe to be occupied (Wiggins-Grandison, 2005). Many landslides in St. Elizabeth were caused by the magnitude 7 earthquake in 1943. The most significant earthquake to date would be the magnitude 8 on March, 1957 which hit affected St. James, Westmoreland, and Hanover. Damage to bridges, churches, the civic center, churches and infrastructures was extensive and there was a death toll of four people from the earthquake (Wiggins-Grandison, 2005). A survey based on felt earthquakes from 1880-1960 in Jamaica calculated a damage frequency rate of less than 5 earthquakes per century for the western part of the island (Shepherd and Aspinall, 1980).

Sea Level Rise

During the last Ice Age approximately 18,000 years ago, sea level was 120 meters below present day sea levels due to massive amounts of water being locked in large ice sheets (Figure 7). Prior to 14,000 years ago sea level rose by approximately 6 mm a year but after 14,000 years ago sea level began rising at a rate of 45 mm per year for a period of about 500 years (Robinson *et al.,* 2005). Combined with another periodic high of sea level rise occurred around 11,500 years ago, both of which coincided with major melting of great northern ice sheets, sea level rose from about 95 m below current sea level to about 75 m below current sea level. A third period of rapid sea level rise occurred around 7,500 years ago, bringing sea levels up to approximately 10 m below present levels. By 2,000 to 3,000 years ago sea level had reached present day levels (Robinson *et al.,* 2005).

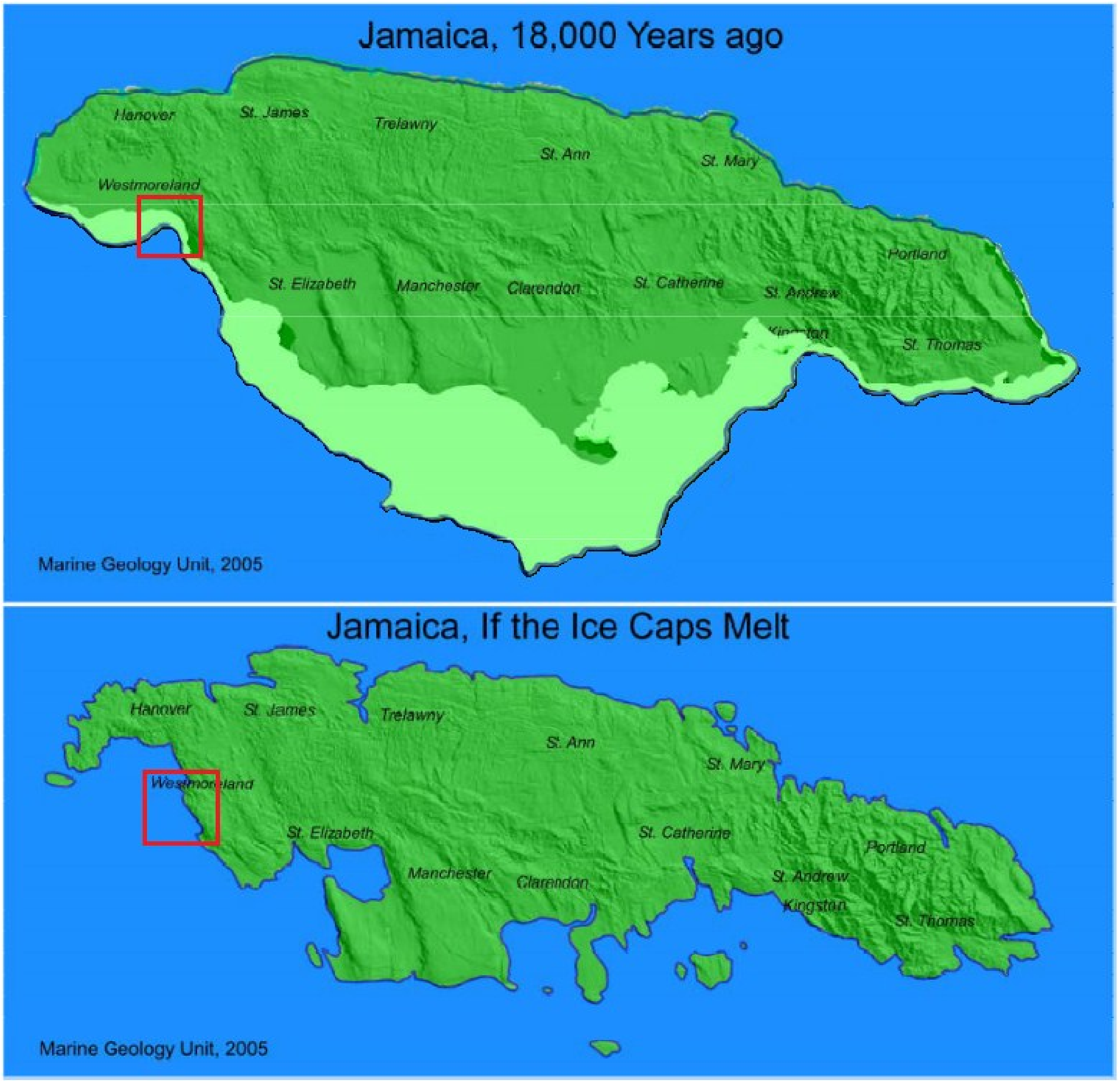

Figure 7. Land mass of Jamaica during last Ice Age and at future predicted sea levels (Robinson *et al.,* 2005). Study area is denoted in red.

Tidal gauge records from across the globe indicate that sea level is rising presently due to global warming (Robinson *et al.,* 2005). One hundred years into the future, sea level is expected to be 0.18 to 0.59 m above present levels (IPCC, 2007). The majority of current sea level rise is attributed to the thermal expansion of ocean waters while glacier, ice cap, and polar ice melt make up the rest (Beckman, 2013). Jamaica is one of the top developing nations with the most potential land exposure a sea level rise of one meter or more (Dasgupta *et al*.,2007). Prediction modeling by Mona GeoInformatics Institute at the University of West Indies conservatively projects a loss of land area of 101.9 km^2 if sea levels rise by 0.18 m by the year 2070 (Figure 7) (Richards, 2008). Coastal plain areas adjacent to the bay are expected to be inundated or threatened by wave attack and erosion.

Climate

Jamaica lies within the north boundary of the tropics and has a tropical maritime climate (Whitbeck, 1932). The northeast trade winds blow north and north-east year round over the island, with higher wind speeds greater than 16 kph during the cooler months between December and February (Parish Council of Westmoreland, 2008). Overall temperatures vary from 26 degrees Celsius to 30 degrees Celsius with August being the hottest month and February the coolest in Jamaica. Recorded temperatures for Negril Point Light House in Westmoreland were 20.7 and 20.6 degrees Celsius for January and February while July, August, and September were the hottest months with temperatures between 31.7 and 32.2 degrees Celsius (Parish Council of Westmoreland, 2008). Humidity peaks in the early morning with relative humidity around 81-87% and abates to 61-69% during the afternoon hours according to data recorded at Negril Point Light House (Parish Council of Westmoreland, 2008). The hours of sunshine Jamaica receives per day vary by approximately an hour and 20 minutes from winter to summer. The shortest day is in January with an average of 6.1 hours of sunshine and the longest day is in July with an average of 8.2 hours of sunshine (Parish Council of Westmoreland, 2008).

Jamaica primarily has two rainy seasons with peak rainfall in October and a secondary annual peak in May that account for most of its 1,981 mm annual rainfall average (Figure 8) (Nkemdirm, 1979). January through March is relatively dryer with July briefly being a dry period before hurricane season, which stretches from July to November. The area of the watershed that drains into Bluefields Bay receives significantly more rainfall with an average of 2,286 mm per year (MetService, 2002). The parish of Westmoreland on average for the past 30 years has not experienced a secondary dry spell between May and October and on average receives higher rainfall during the wet months than Jamaica as a whole (Figure 8).

Historical Rainfall/Flood Events

In June of 1979 over 600 mm of rain fell within a 24 hour period in the Belmont area and caused major inland flooding due to the low permeability of the underlying limestone, high saturation of the ground, and high groundwater levels (Parish Council of Westmoreland, 2008; Wiggins-Grandison, 2005). The communities of Bluefields, Cave, Auchindow, and Colloden as well as the surrounding area were flooded. Present gullies were widened and deepened even as new gullies formed with the rising water levels

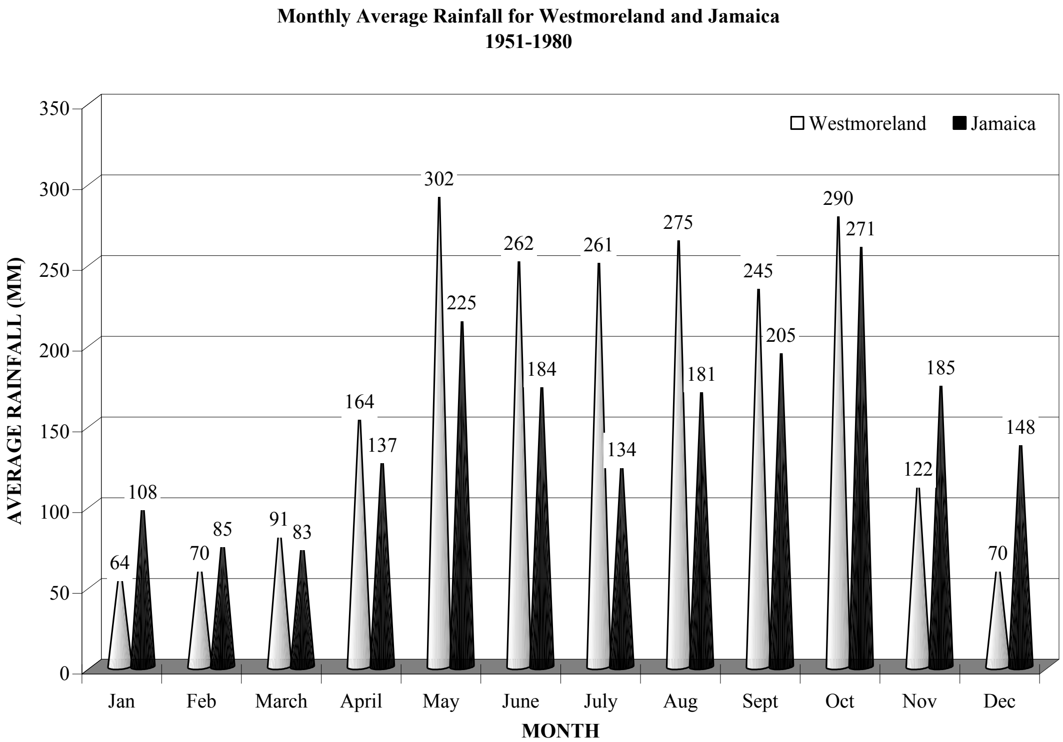

Figure 8. Bimodal Rainfall Patterns for Jamaica and Westmoreland (MetService, 2002)

(Dryer, 2010). Overland flows, debris, and sheet wash as well as debris flows displaced large volumes of sediments and deposited them near the coast (Wiggins-Grandison, 2005). While the heavy rainfall coincided with a 100 year return period, the 600 mm of rainfall was considered an extreme abnormality (Parish Council of Westmoreland, 2008).

Hurricanes and Tropical Storms

The northern Caribbean, including Jamaica, has an inter-annual variability of hurricane occurrence with a mean strike rate of one per year as opposed to the southern Caribbean which has a mean strike rate of 0.4 per year (Spence *et al.,* 2005). One of the byproducts of a category five hurricane is sea waves up to 5 m height or more. A storm surge assessment conducted by the Mines and Geology Division following Hurricane Ivan, a category 4, in September 2004 showed that “surge heights of up to 1.5 m with a run up distance of 50 m was experienced in the Bluefields and Cave areas” (Parish Council of Westmoreland, 2008). Historical accounts tell of the nearby community of Savanna-la-mar being wiped out by sea surge in 1780 (Halcrow, 1998). However, Bluefieds Bay is relatively protected since hurricanes typically come from the south east and the shoreline protects the bay from the highest waves.

Ocean Conditions

The Caribbean Current combines the flow of the North Equatorial Current and the South Equatorial Current into a current that runs east to west along Jamaica’s southern and western coast. It is estimated that the average of the current ranges from 50 cm/s to 75 cm/s (Vellasol and Beltran, 2004). Water is circulated throughout the Caribbean in a combination of winds, sea level variance, and rotation of the Earth as well as the equatorial currents. Although summer and winter circulation patterns vary in the Caribbean, currents in proximity of the study area remain mostly directionally consistent (Figure 9).

Surface temperatures in the Caribbean are influenced by the currents from the Atlantic and upwelling from the deeper sea. Overall the temperature of the sea’s surface remains between 21-30° Celsius year round. The trade winds can cause differences of up to 1° Celsius on a local scale (Villasol and Beltran, 2004). During the spring and summer months before hurricane season the surface waters remain warm between 28-30° Celsius. In the future, sea surface temperatures for the Caribbean are

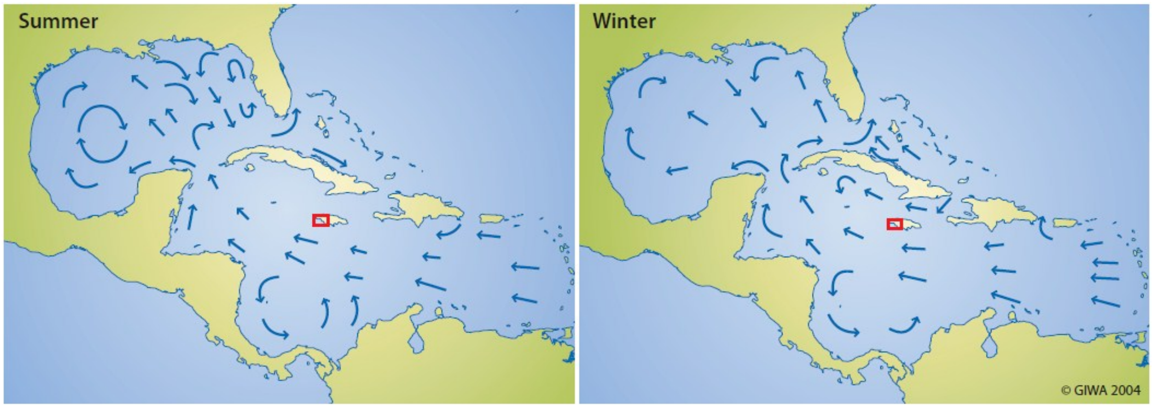

Figure 9. Summer and Winter Currents in the Caribbean. Study area is marked in red. (Modified from Villasol and Beltran, 2004; NIMA, 2000 *cited in* Villasol and Beltran, 2004)

projected to rise by 1 degree Celsius by 2050 from available data (GoJ, 2011). At one hundred to two hundred meters of depth temperature tends to fluctuate more due to upwelling. At greater depths, water temperature mostly constant at 4.5° Celsius (Encyclopedia Microsoft Encarta, 2004 *cited in* Villasol and Beltran, 2004). Surface temperatures along the southwest coast of Jamaica fluctuate from approximately 27° Celsius in February to 31° Celsius in August and September (Samuels, 2004).

Incidental solar radiation, fresh water input from rivers, and marine currents determine salinity in the Caribbean. Yearly fluctuations of surface salinity in the Caribbean are between 34‰ to 37‰. In general the western Caribbean is more saline than the eastern region due to inputs by equatorial currents (Encyclopedia Microsoft Encarta, 2004 *cited in* Villasol and Beltran, 2004). The annual salinity of the southwest coast of Jamaica averages right around 36‰ with the averages in the winter months falling just below the average and summer months averaging above 36‰ but staying under 37‰ (Gray and Wilson, 2004). Salinity decreases with depth in the Caribbean, falling to 35‰ at depths greater than 500 m (Encyclopedia Microsoft Encarta, 2004 *cited in* Villasol and Beltran, 2004).

Hydrology

Coastal estuaries in the Caribbean typically receive fresh water inputs from groundwater upwelling and from rivers that have short courses with limited flow rates (Villasol and Beltran, 2004). Bluefields Bay serves as the receiving body of water for contact springs, blue hole springs, rivers, and ephemeral streams. Bluefields Bay's watershed falls within the Deans Valley River sector of the Water Resources Authority's division of water quality control zones. The total available fresh water resources for the area were estimated to be 64.5 million cubic meters per year with 4.1 million m^3/yr in reliable surface water and 60.4 million m^3/yr in safe ground water. Of the total available resources, 4 million cubic meters were used for municipal use, 1.1 million were used for irrigation, and 0.4 million were used for environmental purposes which left a surplus of 8.5 million cubic meters per year of exploitable fresh water (WRA, 2011).

Three rounds of water sampling tests were performed in the Cabarita Basin, which makes up a large portion of the parish of Westmoreland and includes the coastal and inland watershed of Bluefields Bay (Figure 11). In May 2009, only water samples from three sampled sites met the IJAM Drinking Water Standard. The rest of the sampled site fell outside the IJAM Standard due to pH levels below the lower limit of 7, ranging from 6.3 to 6.9 pH. In April 2010, all but one sampled site were within IJAM Water Quality Standards. Manganese levels and pH were outside

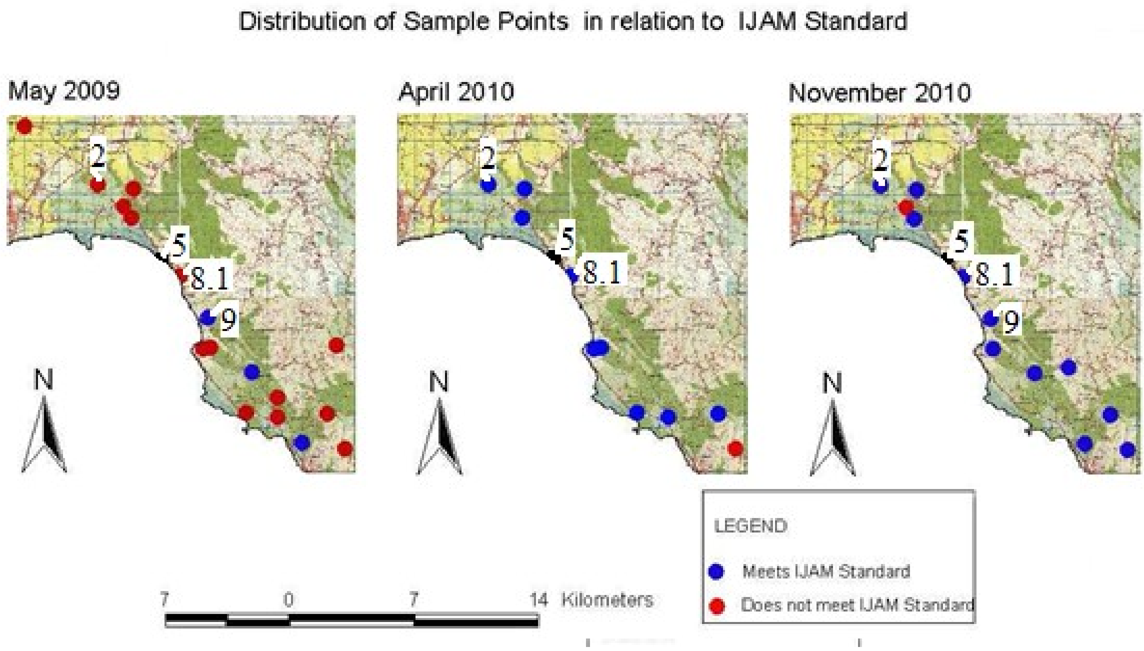

Figure 10. Sampled water quality points at Bluefields Bay in Deans Valley River and Black River Subwatershed Management Units. (*Modified from* WRA, 2011)

the limits for the sampled site that did not meet quality standards. The sites that did not fall within IJAM Water Quality Standards in November of 2010 were predominately groundwater source that had Manganese levels higher than the upper limit of 0.05 mg/l (WRA, 2011).

The topography of Bluefields Bay's coastal area is such that fresh water in underground aquifers is discharged at the surface into the bay in the form of springs. The region is predominately two types of springs, blue hole springs and contact springs (Mylroie *et al*., 1995). A blue hole spring forms when underlying rock formations weaken (eg. due to karsting) and collapse, forming a depression below the water table that fills with water (Ebert, 2010). Contact springs form when a permeable rock layer is fractured and the water stored flows out of the cracks (Ebert, 2010; Springer *et al*., 2008). The source aquifer of the springs in the Blufields Bay region is classified as being medium to highly vulnerable to pollution by the Water Resources Authority of Jamaica (2012). Several factors including depth to water table, net recharge, aquifer and soil media, topography, impact of vadose zone, and hydraulic conductivity were taken into account to yield the overall vulnerability of the aquifer.

The Natural Resources Conservation Authority's Watershed Protection Branch rated Bluefields Bay's associated watershed as being in moderately degraded condition (NRCA-WPB, 1997 *cited in* Ebert, 2010). During wet periods, ephemeral stream beds that are dry the rest of the year become active, temporarily reviving nearby flora and fauna. Tropical storms produce flow that is sudden and voluminous enough to cause streams to move their beds and carry large volumes of eroded sediments to receiving lagoons and swamps downstream (Villasol and Beltran, 2004). Heavy rain can also cause coastal sewage systems to be overwhelmed, flooding raw sewage directly into coastal waters (Beckman, 2013). Of the 133 gauges monitored by the Water Resources Authority of Jamaica, four are located in Bluefields Bay. The mean annual discharge of rivers flowing into the bay are: 3.03 m^3/s from the Sweet River; 0.003 m^3/s from the Sawmill

Table 3. Historical discharge values of Water Resources Authority gauges located at Bluefields Bay (WRA, 2010 *cited in* Ebert, 2010)

Site	Name	Mean Q m^3/s	High Q m^3/s	Low Q m^3/s	Period of Record
2	Sweet River	3.03	22.77	0.31	10/9/05 - 7/11/09
5	Sawmill River	0.003	0.0007	0.0001	4/19/00 - 12/31/09
8.1	Waterwheel	0.005	0.052	0.001	5/19/70 - 12/31/09
9	Bluefields River	0.15	1.81	0.02	5/19/70 - 12/31/08

River; 0.005 m^3/s from the Waterwheel River; and 0.15 m^3/s from the Bluefields River (Table 3) (NRCA-WPB, 1997 *cited in* Ebert, 2010).

In Bluefields Bay, previous testing for bacterial levels was conducted from November 2007 to April 2008 by Scott and Carrie Eklund at nine sites. Funded by Bluefields Environmental Protection Association and stationed at the Westmoreland Health Department, the two Peace Corp volunteers collected samples on November 11, 2007, January 16, 2008, and April 16, 2008 (Figure 11). All samples were tested for fecal coliform. When compared to the United States Environmental Protection Agency standard for full body contact of 200 MPN/100mL, only two sites, the Belmont fisherman's beach and the mouth of Blue Hole River, exceeded the limit during the rainy season sampling in November (Ebert, 2010). Overall the fisherman's beach near Belmont, the mouth of the Bluefields River, and the mouth of the Blue Hole River had the highest levels of fecal coliform during each round of testing, suggesting that Bluefields Bay is at risk for potential eutrophication. Beaches also retain contaminates after they are no longer present in intertidal waters and the presence of fecal coliform suggests that the beaches of Bluefields Bay associated with fresh water outputs into the bay may contain harmful levels of pollutants not evident in the water (Beckman, 2013).

Settlement and Historic Land Use

The Arwakan speaking Taino people migrated from South America and settled the Greater Antillies, including Jamaica, and the Bahamian archipelago roughly somewhere between 600 and 650 AD. The Taino were heavily dependent on the sea but also grew cotton, tobacco, tubers like sweet potatoes, and various fruits. They built

Site	Location
1	Mile Stone Cottage
2	Gully between Mullion Cove and the Hermitage
3	Edge of property and Bluefields Beach
4	In middle of beach near old lifeguard station
5	On south end of beach at the end of sand
6	Mouth of Bluefields River
7	Belmont fisherman's beach on south side of pier
8	North side of mouth of Blue Hole river
9	San Michele

Site	Units	11-Nov-07	16-Jan-08	16-Apr-08
1	MPN/100mL	<3	9	14
2	MPN/100mL	9	<3	30
3	MPN/100mL	3	4	8
4	MPN/100mL	<3	DNS[1]	DNS[1]
5	MPN/100mL	4	4	16.7
6	MPN/100mL	DNS[1]	93	34
7	MPN/100mL	>= 2400	<3	23.7
8	MPN/100mL	1100	4	17
9	MPN/100mL	43	9	37

[1] Did not sample.

Figure 11. Water Testing Results by Peace Corps (*cited in* Ebert, 2010)

wooden houses and cleared substantial agricultural plots on the alluvial plains (Ebert, 2010). Fishing would have been for sustenance from Tainan canoes, spear fish diving, and traps, nets, or lines in coastal, shallow waters. Mangroves would have provided food in the form of benthic organisms like shrimp and clams, as well as fire wood and shelter. The coastal and marine resources that were easily exploited would have been the most affected by the Taino people, so the coral reefs and seagrass beds close to shore would have been fished more extensively and coastal lowlands would have been favored for clearing for cultivation. It can be determined that there was a large Taino village at Bluefields based on artifacts found in the alluvial plains of the Bluefields River and the fact that the Spanish would have selected Bluefields for a settlement because of readily available supply of slaves in the form of a large population of indigenous people (Ebert, 2010). Taino settlement of Jamaica lasted for the duration of approximately 900 years before the Spanish arrived in 1494 (Atkinson, 2006).

Christopher Columbus claimed Jamaica for Spain in 1494 and the Spanish had settled on the island by 1510, conquering and enslaving the Taino people almost to the point of extermination. Jamaica was never highly populated by the Spanish and was divided into plantations that supplied food to Spanish ships. In the early 16th century Africans were imported as slave labor for the plantations (Gardner, 1971). The Spanish settled Bluefields in 1519, most likely because of the large Taino population preexisting there. The exact location of the Spanish settlement remains unknown but the use of Bluefields as a key port can be inferred due to its convenient proximity to major shipping routes in the Caribbean during that time (Ebert, 2010). Marine animals like sea turtles and the now extinct monk seal of the Caribbean would have been easily exploited as a readily available source of food for sailors.

The English invaded Jamaica in 1655 and the remaining Spaniards retreated to Cuba. Plantations were built in the 1720s but were not exclusively sugar like those located west of the Sweet River Valley. During this time the land was used to raise cattle, wood was cleared for export, and various crops were grown (Higman, 2001). Pimento trees, which are the source for allspice and oil for perfume, were predominately harvested in the area and are still currently harvested in Bluefields today (Ebert, 2010). Bluefields, Cave, and Belmont was used as a primary shipping ports for export and Bluefields appears on a number of different naval maps as an inset, or place of interest. One or two prominent reefs such as Moors Reef are also recorded as well as a string of spur and groove reefs off of the bay. Several remnants of British colonization remain in the form of water wheels, dock posts, and drainage ditches as well as sunken anchors, cannons, and other shipping debris that litter the marine floor of Bluefields Bay. Most of the debris is clustered around Belmont point, where a fort used to stand. In the early 18th century there was heavy cultivation and land clearing. Evidence of this can be seen on historical maps of Bluefields Bay (Figure 12). The most likely impacts the English occupation of Bluefields had on the bay was a loss of mangrove habitat, an increase in turbidity due to sediment overloading, pollution in the form of raw sewage, and dumping of debris from ships. Following the Emancipation in 1838, cleared land was left fallow and allowed to reforest, which would have benefitted the marine ecosystems of the bay in the form of sediment stabilization.

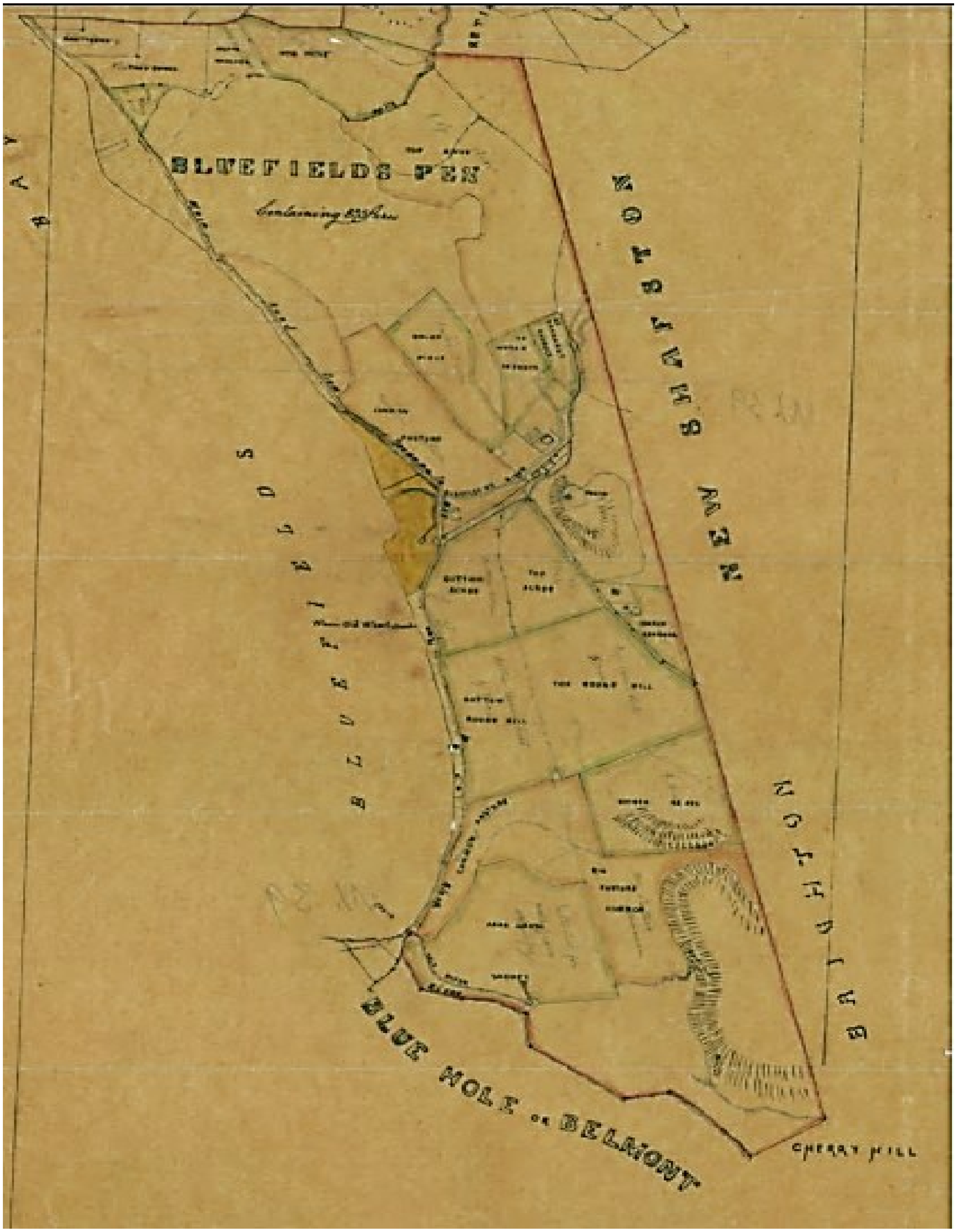

Figure 12. Historic Map of the south end of Bluefields Bay from late 1700s. (National Library of Jamaica cited in Ebert, 2010)

Current Land Use

Westmoreland is one of the top parishes in domestic food crop production. The total amount of food produced in 2000 was 51,249 tons and in 2001 was 52,247 tons, which accounts for approximately 20% of the island's total food production. Sugar cane, cocoa, coconut, coffee, citrus and pimento are part of the exported food produced (Parish Council of Westmoreland, 2008). Currently the coastal area around Bluefields Bay is made up of small scale subsistence farms, pasture, and cropland gone to forest. Further up in elevation from the coast there are disturbed broadleaf forest, bamboo, and fields (Ebert, 2010). Overall 50% of the land use around Bluefields Bay classifies as disturbance in the area. Urbanization of the coastal area and up the steep slopes surrounding Bluefields is increasing as new housing developments are built and is a likely source of over sedimentation and nutrient loading of fresh water inputs into the bay. Shanty dwellings are scattered throughout the forested areas around streams and are another potential source of pollution into fresh water streams. Current land use in Bluefields Bay Watershed can be broken down as seen in Figure 13.

Demographics

Westmoreland's total population was 138,947 in 2001 according to census data Figure 14. Savannah-la-Mar made up approximately 14% of that with a population total of 19,893 (Parish Council of Westmoreland, 2008). In the six districts that border Bluefields Bay's coastline there was a total population of 6,575 people. Of that total, 3,133 people made up the community of Bluefields on the southern end of the bay (Ebert, 2010). From 1991 to 2001 there was an average annual growth rate of about 0.80% for the population of Westmoreland (Figure 14). Assuming that the annual growth rate remains consistent, a conservative estimate for Westmoreland's total population in 2010 is 150,194 people and 156,201 people by 2015 (Parish Council of Westmoreland, 2008). Those estimates are conservative due to that fact that coastal populations in the Caribbean are increasing at a faster annual rate after 2000 than they did in previous decades.

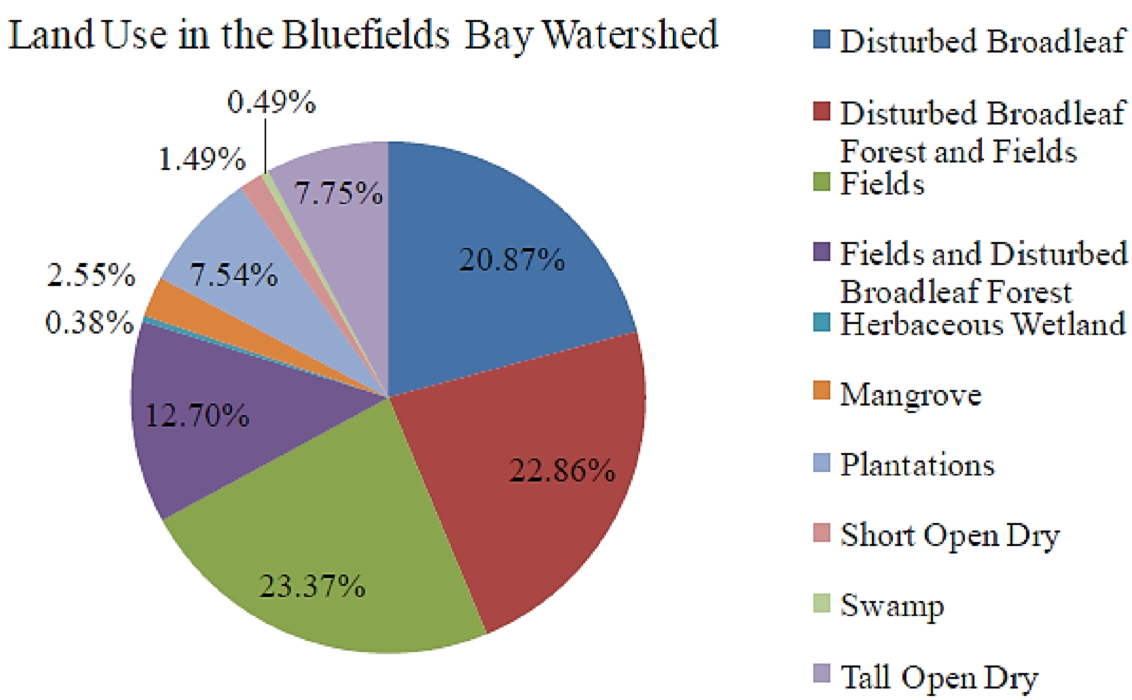

Figure 13. Pie chart of percentages of current land cover at Bluefields Bay. (Chemonics International Inc., 2008 *cited in* Ebert, 2010; Ebert, 2010)

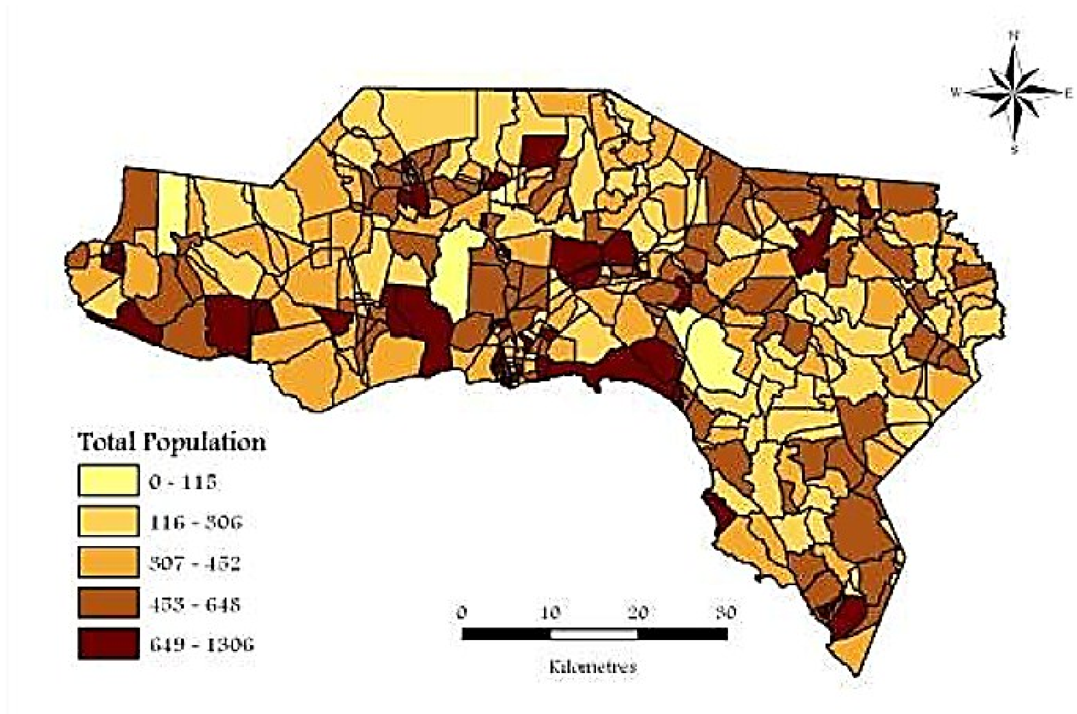

Figure 14. 2001 Population Distribution of Westmoreland by Enumeration District. (*Modified from* Parish Council of Westmoreland, 2008; STATIN cited in Parish Council of Westmoreland, 2008)

CHAPTER 4

METHODS

The requirements of the baseline survey at Bluefields Bay Fish Sanctuary was a clear and detailed habitat map, an updated, detailed bathymetric map of the protected area of the bay, and an assessment that both flagged any indicators of potential threats as well as highlighted the key components of Bluefields Bay Fish Sanctuary such as coral reefs, mangroves, and seagrass beds. The field surveying technique chosen was modified from *Use of the Line Intercept Technique to Determine Trends in Benthic Cover* (Montebon, 1992) in such a way that both allowed for expediency of point collection and adequate coverage for detailed bathymetry and benthic habitat ground-truthing. The goal of the initial survey was part of the overall goal of the Jamaican Fish Sanctuary Network to manage Jamaica's coastal resources for sustainable use, to enhance biodiversity, and increase human livelihoods (Haynes-Sutton, 2009).

For the data processing involved with generating a bathymetric map from field data, the data processing methodology used was adapted from *Case Study: Mapping Half Moon Caye's Reef Using the Adaptive Bathymetric System* (Ecochard *et al.,* 2003) and *A Unique Approach to Bathymetric Mapping in a Large River System* (Long and Chapman, 2008). Adaptations were necessary because the depth measurements from Bluefields Bay did not follow a strict grid system like that used in the *Case Study: Mapping Half Moon Caye's Reef Using the Adaptive Bathymetric System* (Ecochard *et al*., 2003) due to time and personnel restrictions and the methodology used to model the river channel was a poor fit to the overall shape of the bay from *A Unique Approach to Bathymetric Mapping in a Large River System* (Long and Chapman, 2008).

Part of data processing for bathymetric mapping involved preliminary data exploration in order to determine whether the assumptions of the interpolation models were satisfied. In the case of kriging, preliminary data exploration was also performed to identify characteristics of the data set such as potential global trends and whether the properties of the semivariogram changes with direction. The data processing methodology in NOAA manual detailing methods used to map benthic habitat at Puerto Rico and the Virgin Islands was used to map benthic and shoreline habitat for Bluefields Bay (Kendall *et al.,* 2001). Data processing involved preliminary delineation of benthic habitat polygons from remotely sensed imagery and then the use of GPS recorded surface observations to further delineate benthic habitat polygons.

Preexisting Data Review

A preliminary step is to assemble the information that is currently available on the distribution, abundance, habitat requirements, habitat use, and habitat conditions for the study area. Since recent field survey data is not available, aerial and satellite photo interpretation was used as a source for previewing fish habitat conditions. IKONOS 2004 satellite imagery was reviewed to identify coral reef structures, other benthic marine habitats, shoreline restrictions like coastal road placement and sea walls, as well as preliminary shoreline habitat identification. All this information went into the construction of data sheets and the data library for use in the Terrasync program in the Trimble GeoXH.

Geographic Information System (GIS) data was obtained from GeoInformatics institute at the University of the West Indies, Mona. Layers in the geodatabase used include polygon land use, linear rivers, and point locations for major communities. The extent of coverage was for the Jamaican parish of Westmoreland. Some discrepancies in river location were amended by river channel layers created by Jackie Ebert in the process of her thesis work. Admiralty and naval maps are scanned from originals at the Jamaican National Archives and were used to make inferences to land use and history at Bluefields Bay. Aerial photography taken in 1991 of Bluefields Bay was georectified and mosaicked. IKONOS satellite imagery from 2004 for Bluefields Bay was also obtained from GeoInformatics institute. 2001 IKONOS, 2009 and 2012 Geoeye satellite imagery was obtained from Penobscot Corporation (Table 4).

Table 4. Imagery Database.

Imagery	**Remote Sensing**	**Year**	**Resolution**	**Source**
JAM91-001-77	Aerial Photography	1991	5 m	The Nature Conservancy
Jamaica NC South West	IKONOS	2004	1 m	The Nature Conservancy
Jamaica NC West	IKONOS	2004	1 m	The Nature Conservancy
po_843223	GeoEye	2012	0.5 m	Penobscot Corporation

Field

The protected area of the bay was surveyed using approximately 100 m spaced transects perpendicular to the seaward boundary of the sanctuary across the width of the bay and at key points like at the mouth(s) of fresh water ways such as Bluefields River, Water Wheel, and Sweet River. GPS points were recorded at equally spaced intervals along transect width using a Trimble GeoXH unit and a Trimble 6000 GeoExplorer unit (Figure 15-17). The resulting data set included over 500 points collected. Depth was collected using a handheld sonar depth reader. Substrate was classified into type—seagrass, coral, fine to coarse sedimentation, or hard bottom—using an AquaScope II viewing scope. A Horiba water quality probe was used to record water quality data

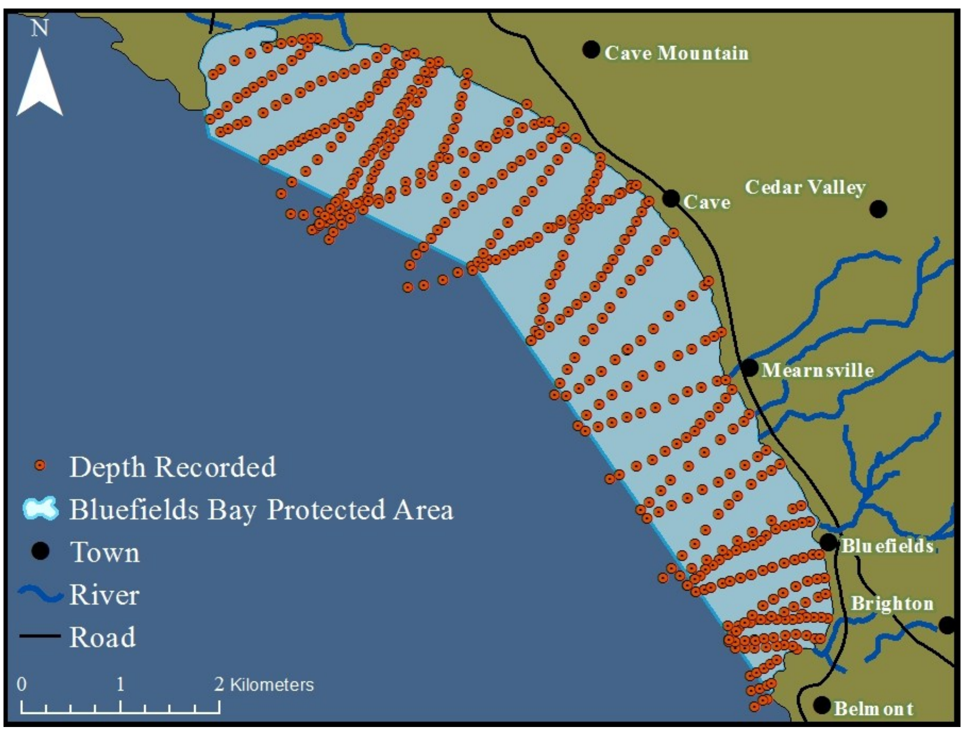

Figure 15. Bluefields Bay Fish Sanctuary Bathymetric Mapping Transects (MGI, 2010).

Figure 16. Bluefields Bay Fish Sanctuary Water Quality Sampling (MGI, 2010).

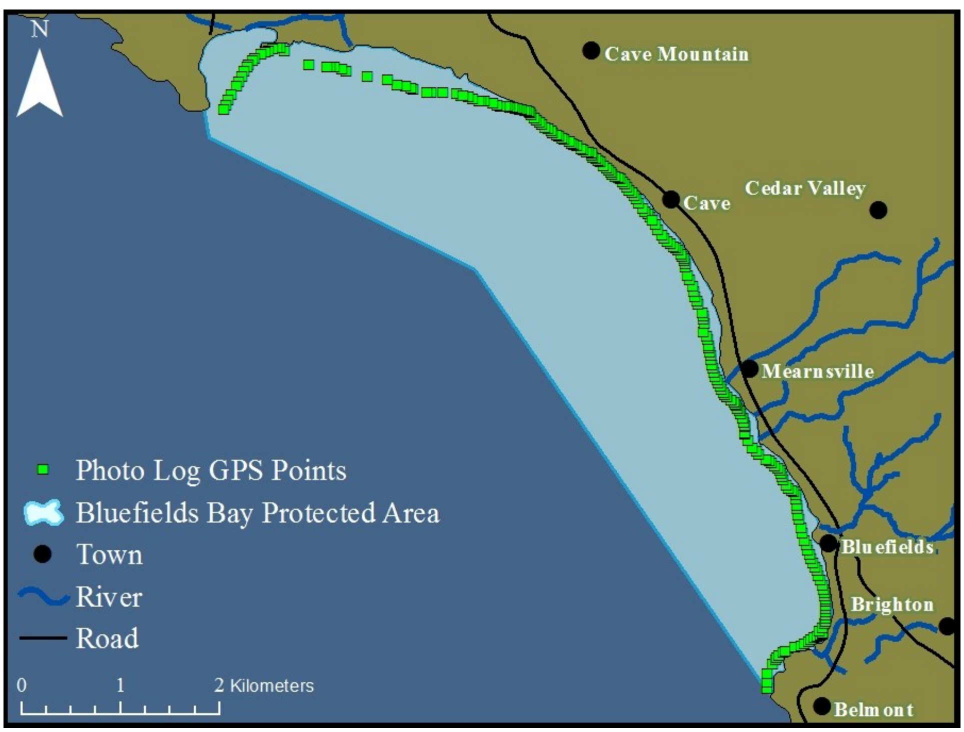

Figure 17. Bluefields Bay Fish Sanctuary Shoreline Photologging (MGI, 2010).

like temperature, salinity, and dissolved oxygen. All findings were recorded into fields previously programmed into a data library in Terrasync to allow for efficient data collection. A GPS camera was used to record a photo log the entire length of the shoreline, looking specifically at shoreline habitat, beach composition, and evidence of erosion and near shore water quality data was collected at each shoreline GPS point also using the Horiba water quality probe. Of special interest are coral reefs, so divers and GPS were used to ground truth coral reef structures identified in aerial and satellite imagery.

Bathymetry Mapping

In order to generate a contoured, topographic map of the sea floor inside the protected area of Bluefields Bay, a spatial interpolation model was used to predict depth values between the point measurements of depth from the field. Kriging and Inverse Distance Weighted (IDW) are two types of interpolation techniques commonly used to generate a smooth surface for a natural, continuous phenomenon like depth (Ecochard *et al*., 2003; Bello-Pineda and Hernandez-Stefanoni, 2007). A comparison of the two models was performed in order to find the best fit model for the digital bathymetric model.

Inverse distance weighted (IDW) is a deterministic interpolation technique that honors the data values inputted by assigning the same value to the same location in the output surface. It uses a weighted function to predict an averaged value for any particular point based on the values of the point's nearest neighbors. The values of data points closer to any particular location are weighted in such a way in the calculation of the prediction that as the distance between the prediction location and the data point increases, the weight or "influence" the value of the data point has on the weighted average decreases. As the power of the equation in inverse distance weighted increases, the weight of distant points decreases more rapidly (Slocum, 2005).

Kriging is a spatial interpolation technique that uses the distance between sampled points as a spatial correlation that can be used to estimate the depth values of un-sampled locations. An autocorrelation function is fitted to the variability of the data using a semivariogram, which is then used to predict values for all points. It is not a deterministic interpolation model in that the predicted values assigned to the location of data points are not the exact values inputted into the spatial modeling. Kriging allows for a more customized spatial interpolation process and is often referred to as the "optimum" spatial interpolation technique (Slocum, 2005).

Field to GIS Data Processing

Field data was collected in the form of Terrasync data files and stored on the internal memory of the Trimble GeoXH and Trimble 6000 unit. Transect data files were first downloaded and converted to shapefiles using GPS Pathfinder Office in the case of the Trimble Geo XH to perform the conversion and the option in Terrasync to convert data files to shapefiles in the case of the Trimble 6000 GeoExplorer. A projected coordinate system of Universal Transverse Mercator, Zone 17N, Datum NAD 1983 was chosen and implemented for all transect data files using ArcCatalog. All data files were loaded into ArcMap and made into one complete point shapefile using the Merge tool from the Geoprocessing menu. Data values for depth were recorded as positive numbers in the field, so all the depth values were converted to negative values in a new column called Depth2 by multiplying the Depth column in the Attribute table by -1.

Preliminary Data Exploration

Spatial interpolation models require preliminary data exploration in order to choose the proper parameters during the interpolation process. The following steps are mainly applicable to the kriging technique's need for user specified inputs. IDW is a more simplistic model that requires less user input to run.

Data Distribution. In the Geostatistical Analysis menu the Histogram option under Explore Data sub menu was used to generate a histogram of Depth2 from MergedTransect.shp file. The histogram was then used to check the distribution of the data and whether it conformed to a normal distribution. As shown in Figure 18, the distribution does conform to a bell shaped curve of a normal distribution, but is skewed by a value of -0.2895. The outliers were also identified and examined for possible error using the histogram. All of the lowest value outliers were examined in the first interval (-4.18, -3.77). Second, the highest outliers in the interval (-0.52, -0.12) were examined for possible error. The outliers were compared to their nearest neighbors. A total of two points were found to be significantly different than their neighbors and were excluded as erroneous points. The first outlier was a point with a recorded depth of zero that was located in the midsection of a transect across the bay's width. Examining the preceding and immediate follow points in the transect, it was concluded to be erroneous due to data entry error. The second lowest outlier with a recorded depth of zero was excluded as redundant because of the shoreline being manually added as the zero contour line. Further examination was necessary for determining the removal of the two deepest outliers, but the final histogram shows a normal distribution curve skewed by -0.16343. The similarity between the mean (-14.912) and the median (-14.4) affirmed the assumption of normal distribution.

The normal quantile-quantile plot for Depth2 of MergedTransects.shp was created to compare the data to a standard normal distribution (Figure 19). The distribution of depth measurements in the data as compared to the 45 degree line through the data points shows that the shallow depth measurements less than 3 feet deviate from the standard normal distribution line. While the majority of the data conforms to the normal distribution line, there are also a few outliers that are deepest measurements that depart from the overall trend of the data as well.

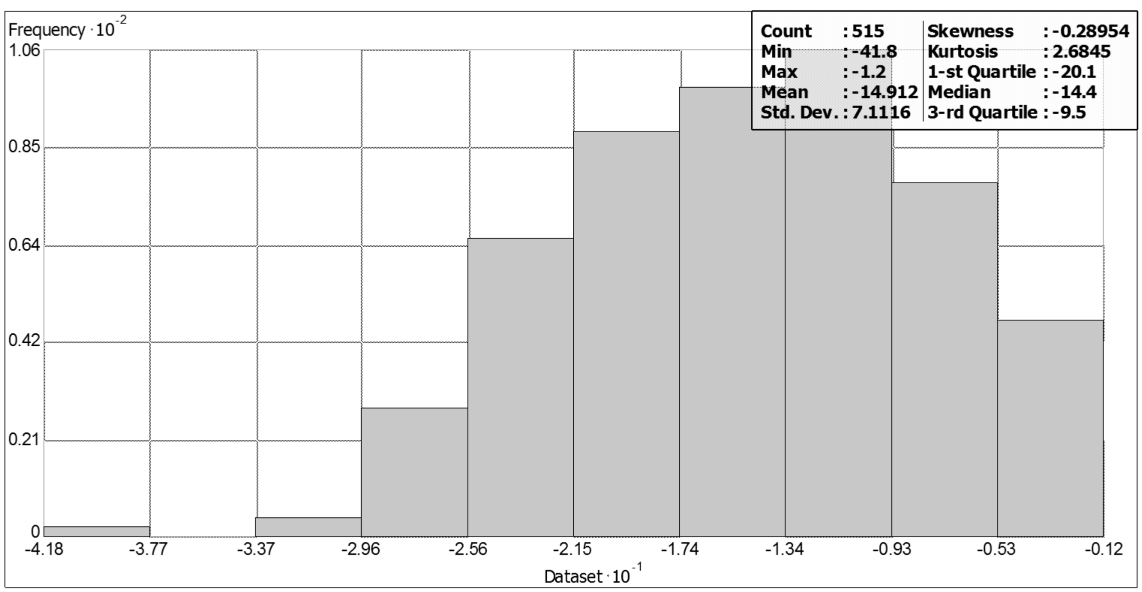

Figure 18. Histogram of Depth2 from MergedTransects.shp with outliers.

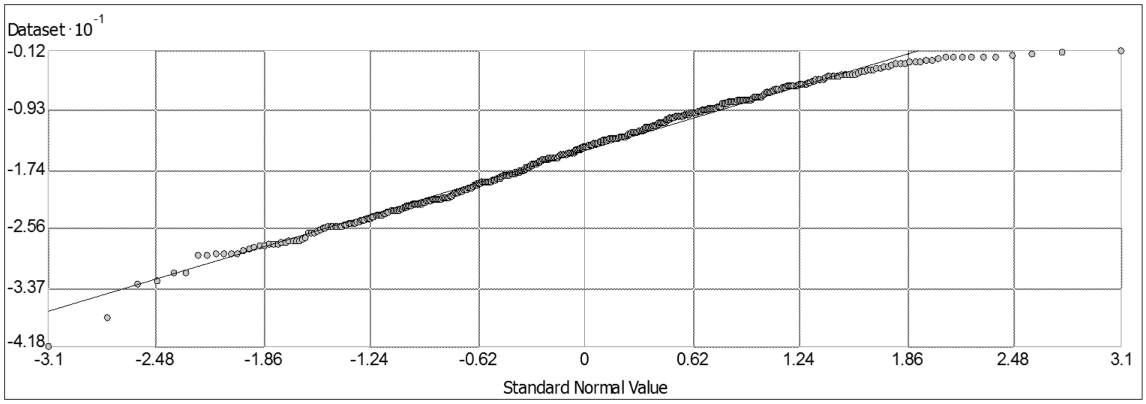

Figure 19. Normal QQ Plot for Depth2 from MergedTransects.shp.

Trend Analysis. In the Geostatistical Analysis, the Trend Analysis function was used to plot the global trends of the latitude values (x axis) and the longitude values (y axis) to the depth values (z axis) in Figure 20. The global trends of the data as represented by the green and blue curves were both a concave curve. Rotation of the graph in the Trend Analysis showed that the concave curve was a universal trend regardless of the direction at which the values were graphed. A second order polynomial trend removal was used when applying the interpolation process to the data to account for the global trend. The global trend was automatically added back to the data by the software after the spatial interpolation technique calculated the local variability.

Spatial Autocorrelation. The semivariogram cloud for the data, which plots the difference squared between the values of each pair of locations, was examined for the distance at which points are no longer correlated. From the plotting of the semivariogram cloud, the sill, range, and nugget were estimated for the kriging interpolation models. Examining the cloud yielded estimations of a sill equal to 280, a range of 150, and a nugget value close to 0. A directional influence was also noted after changing the directional angle the semivariogram cloud was plotted for. Depth changed rapidly from a northeast to southwest direction while exhibiting a gradual change along a northwest to southeast direction. The anisotropy option in the interpolation models was set to True during the interpolation process.

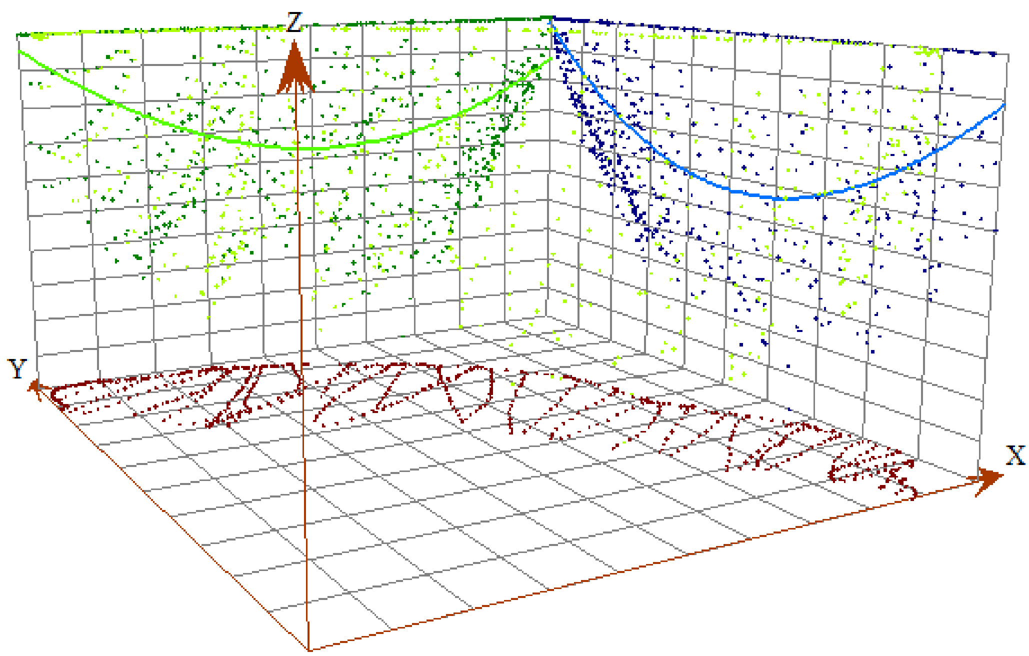

Figure 20. Trend Analysis graph for Depth2 from MergedTransects.shp.

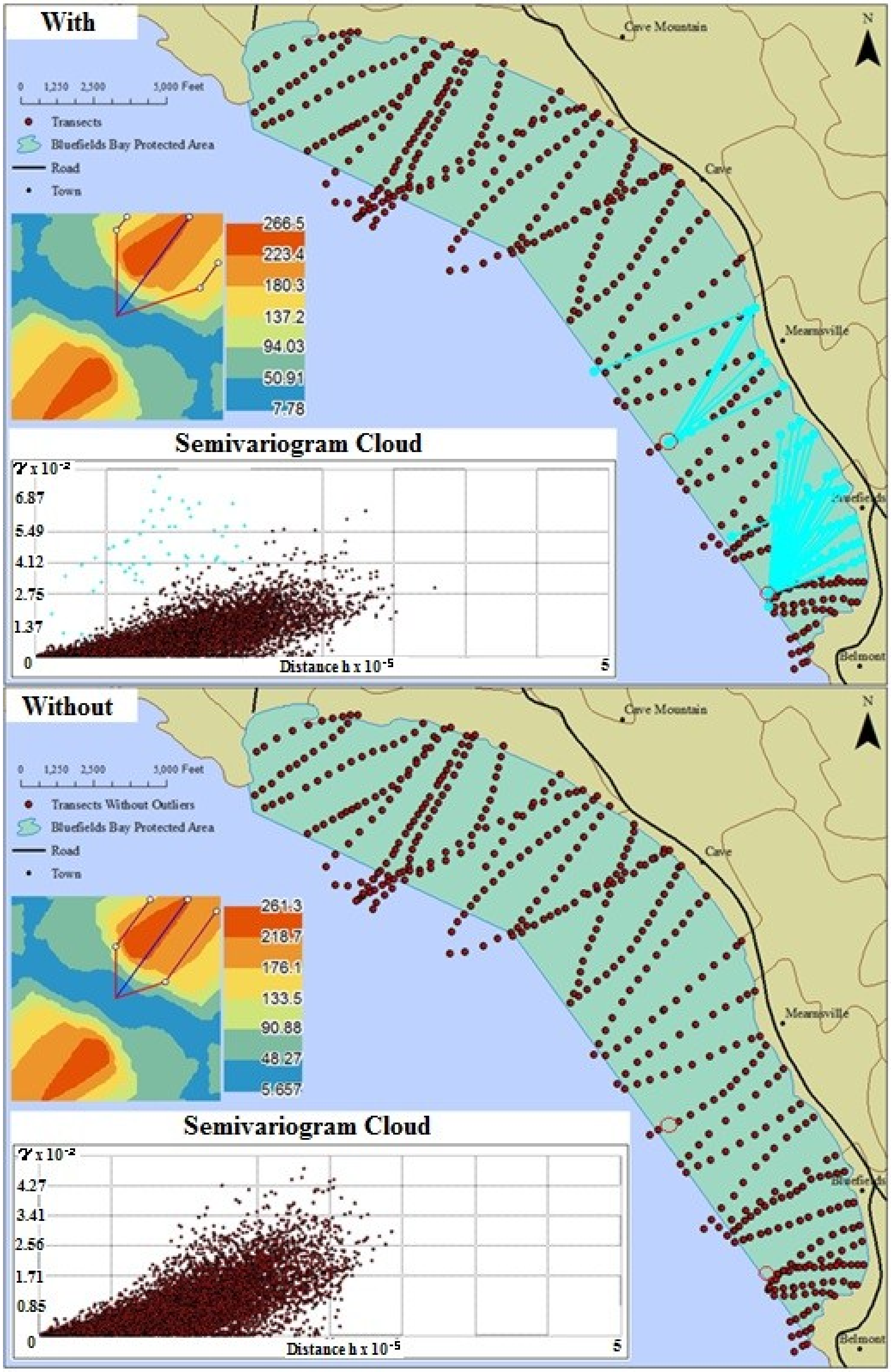

Figure 21. Comparison between semivariogram clouds with and without outliers at search direction 35.5 degrees (MGI, 2010).

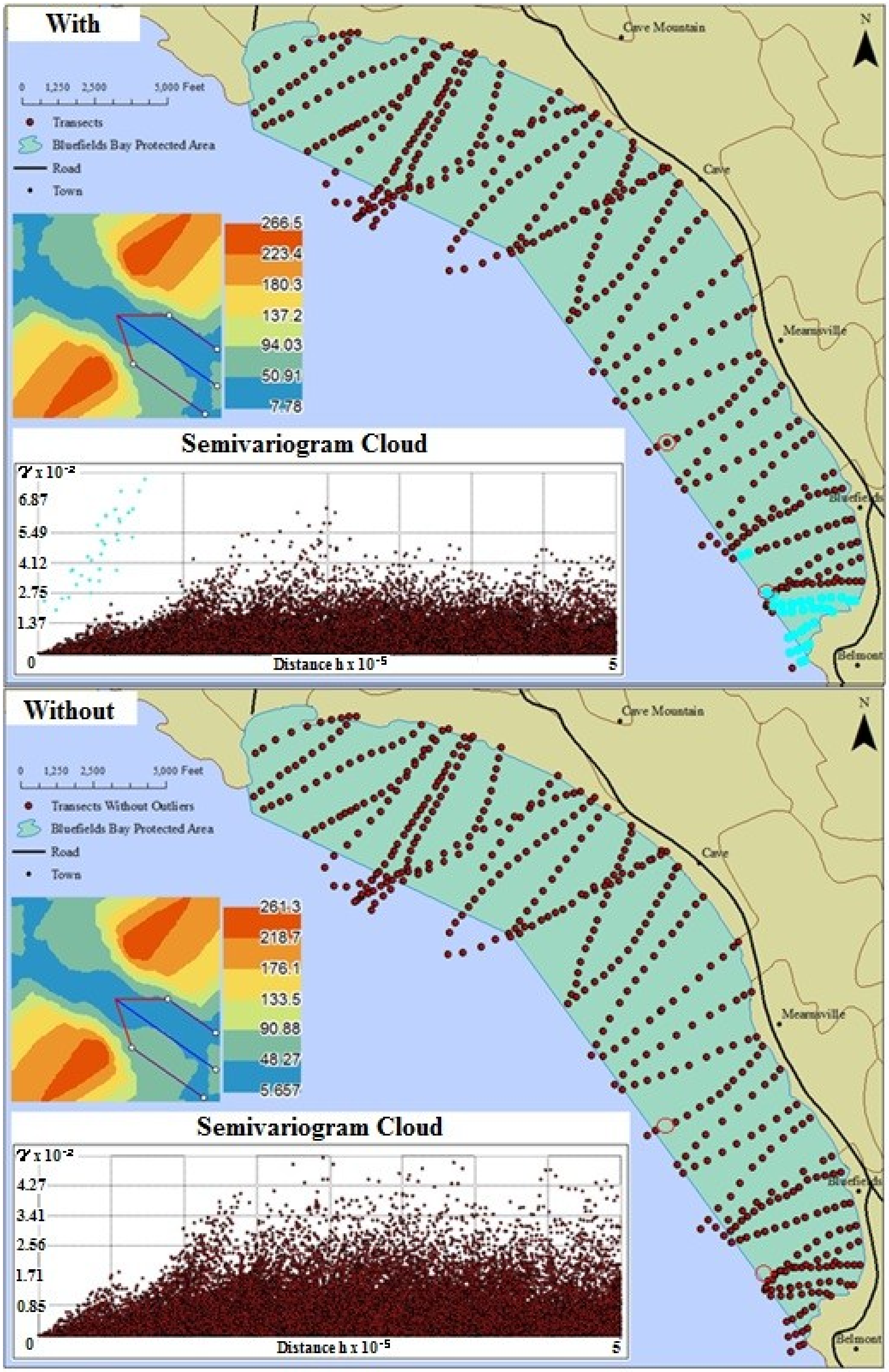

Figure 22. Comparison between semivariogram clouds with and without outliers at search direction 125.5 degrees (MGI, 2010).

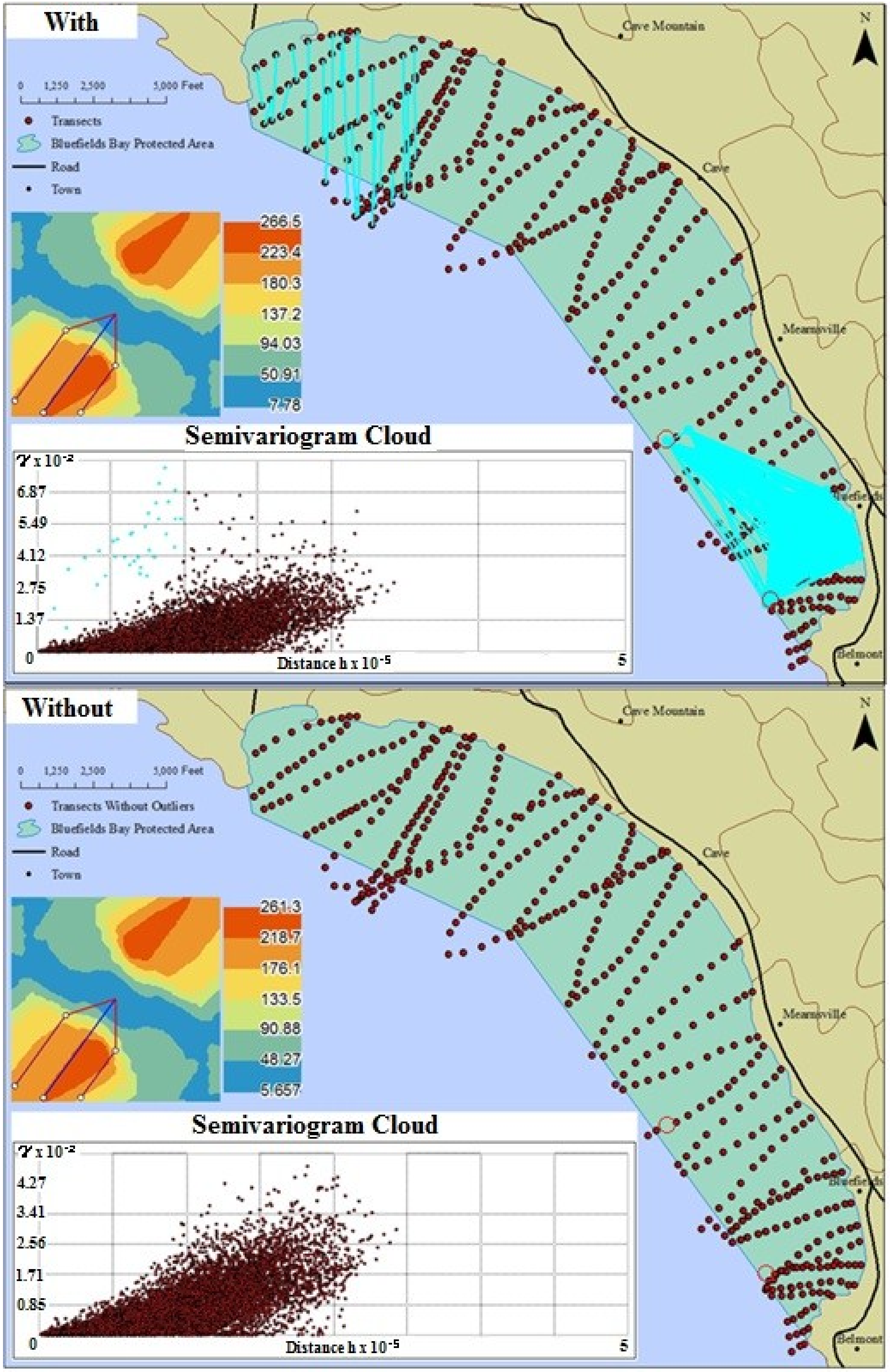

Figure 23. Comparison between semivariogram clouds with and without outliers at search direction 215.5 degrees (MGI, 2010).

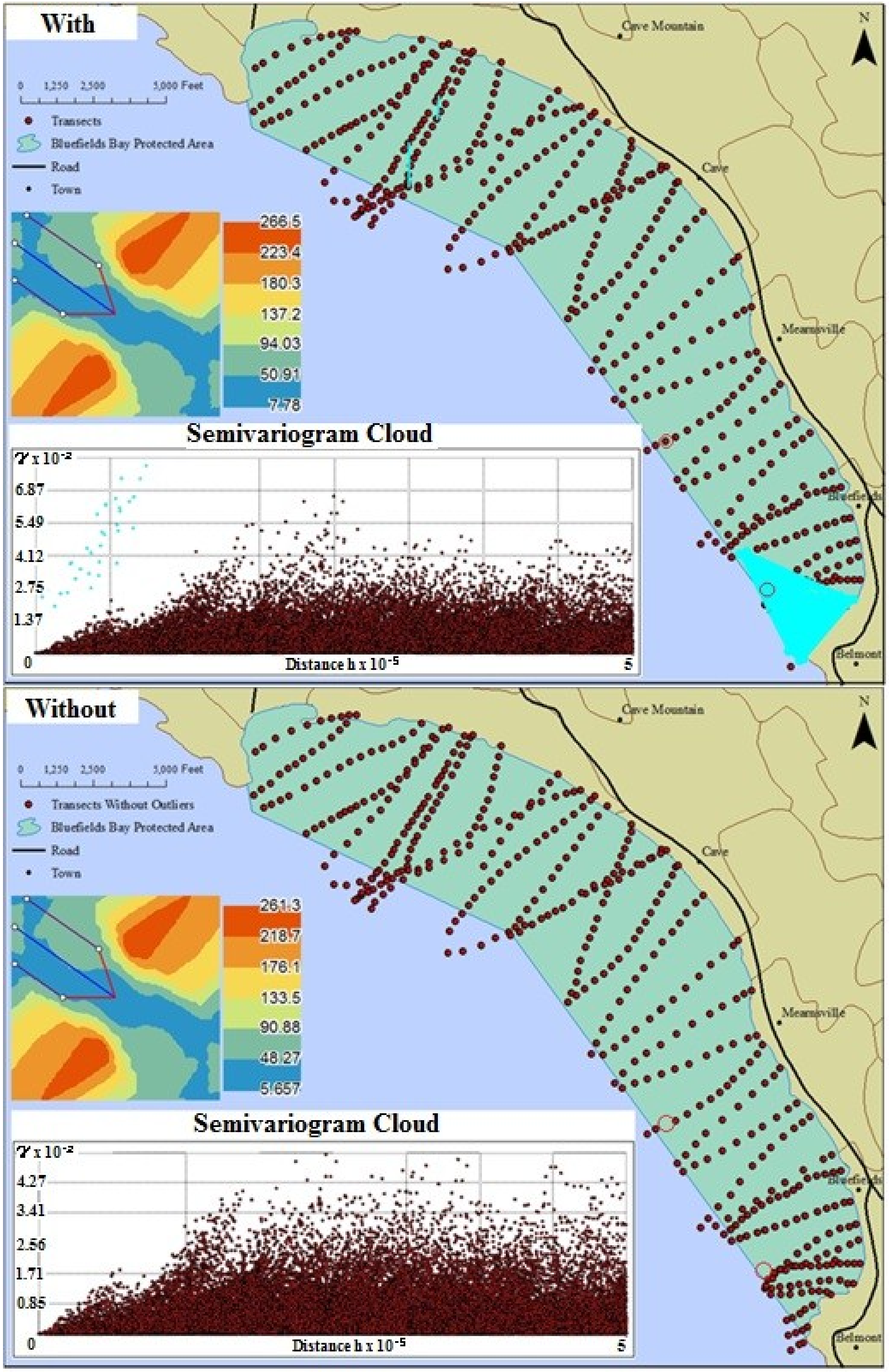

Figure 24. Comparison between semivariogram clouds with and without outliers at search direction 305.5 degrees (MGI, 2010).

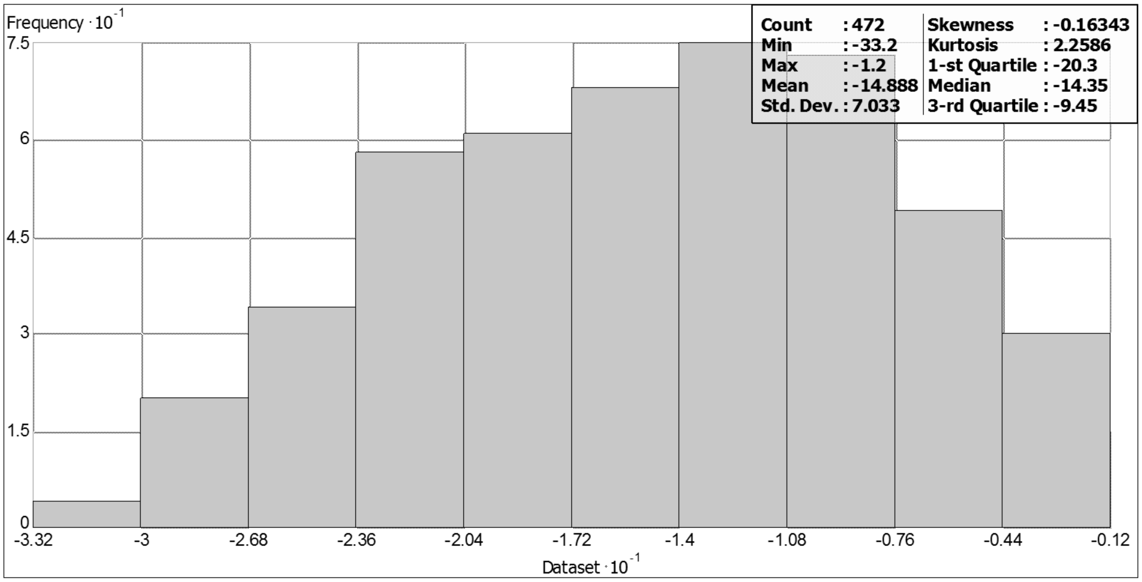

Figure 25. Histogram of Depth2 from MergedTransects.shp with outliers removed

Further examination of the histogram and the four directional semivariograms (Figure 21-Figure 24) led to the removal of the two deepest outliers as possible erroneous points from Depth2 of the MergedTransects.shp. As the baseline survey of Bluefields, the removal of these points was based on their abnormality when compared to the overall nature of the data set. The removal of the two deepest outliers is noted because further study may suggest the deepest outliers as a correct representation of the bathymetry of Bluefields Bay. The final histogram, denoted by Figure 25, supported the assumption of normal distribution of the data with reasonable accuracy.

GIS Interpolation

A copy of MergedTransects.shp was exported that excluded the outliers. Previous studies indicate that inverse distance weighting (IDW) and kriging are the best interpolation methods for modeling bathymetry from point data. The interpolation surface generated by IDW was compared along kriging using the following kernel function types: Gaussian, Exponential, Quartic, and Constant. The optimized model feature of the Geostatistical Analyst was used to create the IDW model for comparison. The software automatically calculates the root mean square prediction error (RMSPE) using leave one out cross validation for multiple powers for the specified data set. It then fits a curve to the points using quadratic local polynomial interpolation and from the curve the power that results in the lowest RMSPE is selected as being optimal for the data set. During kriging the characteristics of the data set, as determined by the preliminary data exploration, that were accounted for via user input were a global second order polynomial trend, an approximate sill value of 280, an approximate range value of 150, a nugget value close to zero, and anisotropy. The optimize model feature of the Geospatial Analyst, which calculates optimum values for the parameters of the kriging model using an iterative cross validation technique, was then utilized to "best fit" each kernel function type to the data set.

Each kernel function was used in interpolation and then the errors resulting from the leave one out cross validation were compared. The errors compared were the Mean Error, the Root Mean Square Error, the Mean Standardized Error, the Root Mean Square Standardized Error, and the Average Standard Error. The interpolated surface with the smallest overall errors and best fit was chosen. Then the interpolated surface was exported as a raster and one foot incremental bathymetry contours were derived from the raster using the Contour tool in the Spatial Analyst toolbar set. The polygon shapefile of the protected area of the Bluefields Bay Fish Sanctuary was used to Clip the interpolated raster and contour line shapefile. The resulting clipped layers were then cross checked against a 1980 Savannah-La-Mar naval map. The result is a more detailed bathymetric map of the protected area of Bluefields Bay.

Benthic and Intertidal/Shoreline Habitat Mapping

Benthic habitat maps spatially quantify the specific distribution and association of target ecosystems in relation to each other with the area of interest. As a no take fish sanctuary, Bluefields Bay is a marine protected area that encompasses multiple essential fish habitats and so an ecosystem based management approach is necessary. One of the key components of effective management of fish and their habitat is a benthic and intertidal habitat map (Zitello *et al.,* 2009). The original methodology from 2001 was used to create the preliminary benthic habitat map and then the 2009 revision of mapping methodology was used to refine the preliminary map because the more recent schema for classifying benthic habitat in shallow waters deviates from a classification scheme dictated by the presence and percentage of coral cover to one that classifies benthic habitat by whichever cover is biologically dominate with an addition live coral coverage component (Appendix B) (Zitello *et al*., 2009).

Imagery Acquisition. Aerial photography of Bluefields Bay (Courtesy of Dr. Bill Wedenoja) taken in December of 1991 at a scale of 1:15,000 was georectified and mosaicked. Two sets of mosaicked 2004 IKONOS satellite imagery of the west and south west coast of Jamaica were obtained from Mona GeoInformatics Institute. Multiple color bands from Geoeye satellite imagery from 2012 for Bluefields Bay were obtained from Penobscot Corporation. ENVI was used to consolidate the red, green, and blue bands into a true color image, which was then exported to ArcGIS. Due to the size of the 2004

IKONOS imagery causing delay in loading time, a region of interest (ROI) was used to subset the coverage of Bluefields Bay from both sets of 2004 IKONOS imagery. In order to create a benthic habitat of the protected area of Bluefields Bay, a georeferenced mosaic of the bay was created from the multiple imagery sets. The Geoeye 2012 imagery with 0.5 m resolution was layered on top of the mosaic, then the 2004 IKONOS imagery with 1 m resolution, and finally the aerial photography was layered last to fill in a small gap left by the other imagery.

Habitat Boundary Delineation. A first draft of the benthic and intertidal habitat map was created using the habitat classification scheme from the 2001 NOAA benthic habitat mapping manual (Kendall, 2001). In order to apply the hierarchal habitat classification scheme from the manual, it was first determined which geographical zones were present within the protected areas of the fish sanctuary. The three major zones present within the boundary of the bay were the shoreline or intertidal zone, the lagoon zone, and the back reef zone. The categorical list of habitats found within the three zones were unconsolidated sediments, submerged vegetation, coral reef and hard bottom, mangroves, and artificial. The map scale was then set at 1:6,000 for optimal habitat digitization using visual interpretation of the satellite imagery. Clearly defined benthic habitats like large individual patch reefs, aggregated patch reefs, continuous seagrass beds, and unconsolidated sediment sand beds were first digitized as polygons via visual inspection of the remote sensed mosaicked imagery. In order to enhance recognition of certain features or interpretation of subtle boundaries, the brightness, color, and contrast of the source imagery as well as individual bands was manipulated in ArcGIS. In the case of seagrass, the blue and green bands were isolated and the contrast ramped up in order to identify areas where density was previously unclear enough to make the delineation between Continuous Seagrass and Patchy Seagrass. Certain textures of light and dark were also used to delineate other types of habitat cover such as Sand with Scattered Coral and Rock as opposed to Sand.

The rough draft of the benthic and intertidal habitat map was then refined using an adaptation of the updated classification from the 2009 NOAA manual (Zitello *et al.,* 2009). Original benthic habitat polygons were further classified with four primary ecosystem attributes. The four classifications were a broad geographic zone, a geomorphological structure type, dominant biological cover, and degree of live coral cover. Due to the placement of an artificial reef within the protected area of Bluefields Bay Fish Sanctuary, a further delineation of riprap and artificial reef were specified within the artificial geomorphic structure category (Appendix B).

The digitizing scale for delineating polygons within ArcGIS recommended by Zitello *et al.* (2009) was 1:2,000 rather than the previous 1:6,000 scale recommended by Kendall *et al*. (2001). Otherwise, the habitat boundary delineation and attribution techniques from Kendall *et al.* (2009) were repeated unless specified by the updated manual. The resulting benthic and intertidal habitat map generated was a more detailed refinement of the original rough draft.

Ground Validation. As per the course of collecting field data, geomorphological structure and percent of biological cover were classified for each transect point via surface observations with an AquaScope IV. Field work was conducted during the calm hours of the morning when water clarity was optimum. Ground validation for the intertidal habitat polygons were derived from continuous GPS photologging of the shoreline. Each photolog photograph was placed under a grid template divided into ten vertically divided segments. Each vertical cell was classified as the geomorphic structure and biological cover that occurred at the water line. The corresponding GPS point was then classified as the geomorphic structure and biological cover that occurred greater than fifty percent of the image. In the case of equal percentages of geomorphic structure or biological cover, the geomorphic structure or biological cover occurring beneath the middle, vertical dividing line of the photograph at the horizontal horizon of the water line was assigned to the point. The purpose of recording these observations was first to classify the geomorphic structure and biological cover of areas that were otherwise unclear in the remotely sensed imagery and second to record habitat morphology along the transition from shallow to deeper waters. Field observations were also relied on in cases where habitat types appeared different because of water depth and sea conditions.

The recorded field observations were used to establish more accurate habitat attributes and delineations by first classifying transect points according to the recorded percentages of biological cover and geomorphology. Then the points were buffered with the attributes of the points assigned to the circular polygons that resulted. The circular polygons were symbolized and laid over the categorized polygons from the refined benthic and intertidal habitat map. Next, the preexisting habitat polygons were cross checked for accuracy and the polygon values were used to classify remaining unknown areas.

CHAPTER 5

RESULTS

Upon the completion of field work and data processing, the physical habitat mapping and assessment of Bluefields Bay has resulted in timely baseline information on the spatial relationship of benthic and intertidal habitats as well as a detailed bathymetric map that shows the physical characteristics of the sea floor. The detailed intertidal and benthic habitat maps developed in this study describe the local-scale variations of the key ecosystems like coral reefs, seagrass beds, and mangroves, refining the more generalized indications of these habitats on previous maps. The bathymetric mapping from this study has resulted in a small interval, complete set of bathymetry contours for the shallow area of the bay that replace the discontinuous, large interval contours previously denoted on a 1980 naval map. The assessment of habitat was primarily based on the quality of physical and chemical water parameters and whether conditions fell within the coastal water quality standards of the Government of Jamaica and associated international agencies like the USAID. The overall result was the overview of collected data complied into four maps, multiple cross sections, and water quality results as well as an intertidal and benthic habitat inventory.

Bathymetric Mapping

The bathymetric map uses 1 ft contours to describe the bottom structure of Bluefields Bay Fish Sanctuary (Figure 27). Some of the key characteristics of the bay can be seen in the contouring of the bathymetric map. For example, the gentle slope and shallow northeast end of the bay is where Sweet River flows into the bay and sand dominates the substrate (A). Mangroves dot the shoreline here, blurring the zero depth contour line due to partial and sporadic inundation in this area. The extension of the 13 ft depth contour line seaward in the middle of the north end of the bay that indicates a higher area indicates the location of the north patch reef (B). The high area near the intersection point of the seaward boundary of the fish sanctuary is indicative of where the numerous patch reefs occur in the back reef zone (C). The patches of small “hillocks” northwest of Belmont Point coincide with an area of aggregated reefs and individual patch reefs (D).

The resulting bathymetric map from field data and GIS interpolation is a far more detailed map than what was previously available for Bluefields Bay in Westmoreland, Jamaica. In comparison to the 1980 naval map of nearby Savannah-La-Mar (Figure 26), the current map has better resolution and more bottom detail (Figure 27). The map produced by this study has a higher density of data points combined with a kriging-produced bathymetric interpolated surface has resulted in more accurate contouring and a DEM that is a closer representation of the natural phenomena.

Accuracy

Field Accuracy. The average error of GPS points taken in the field was plus or minus 5 feet in the latitude and longitude position after autocorrection by the Trimble unit. Depth was recorded by use of a handheld single bean echo sounder, a Speedtech Depthmate Portable Sounder. On average, field surveying was conducted during calm,

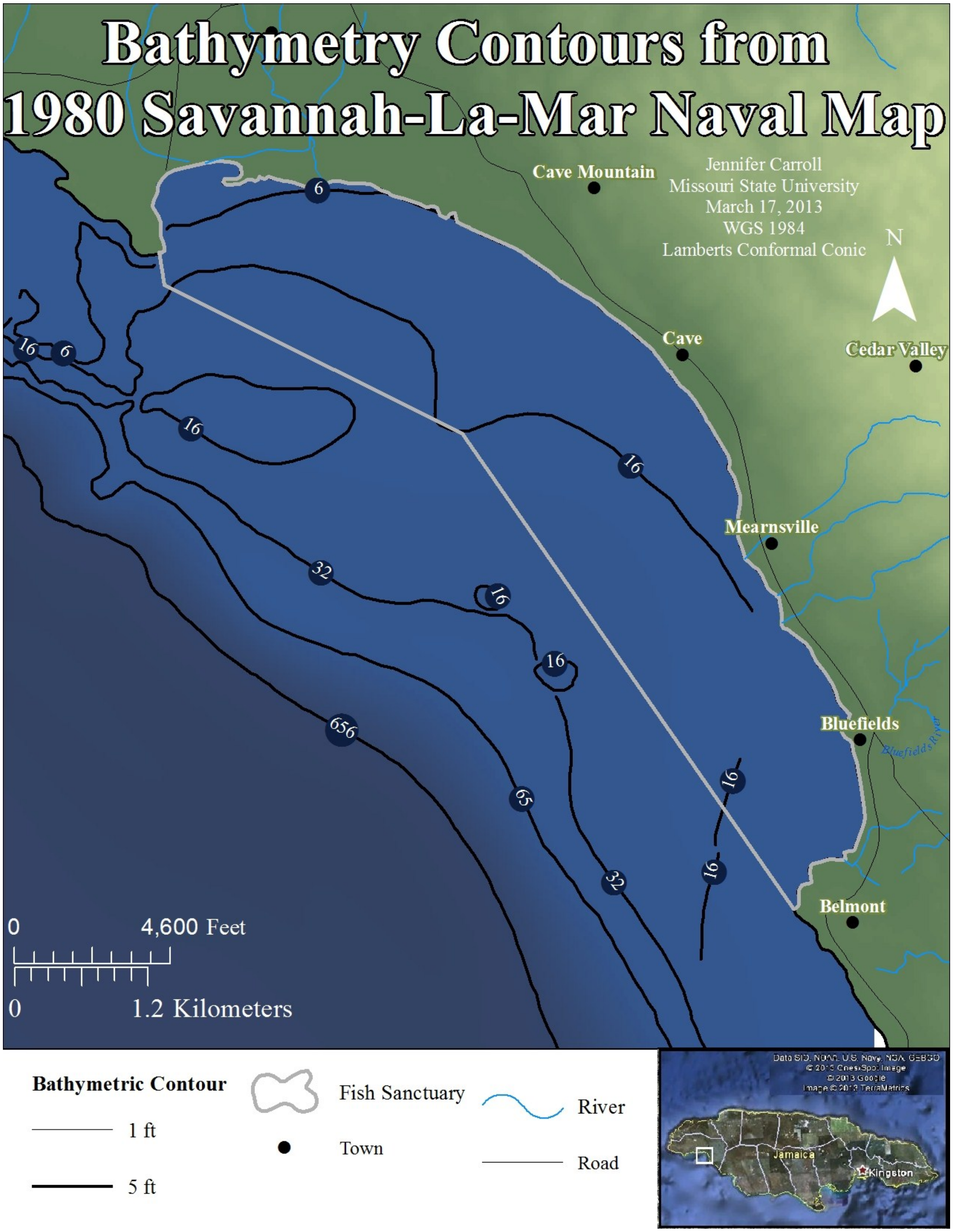

Figure 26. Contour Set from 1980 Naval Map (MGI, 2010).

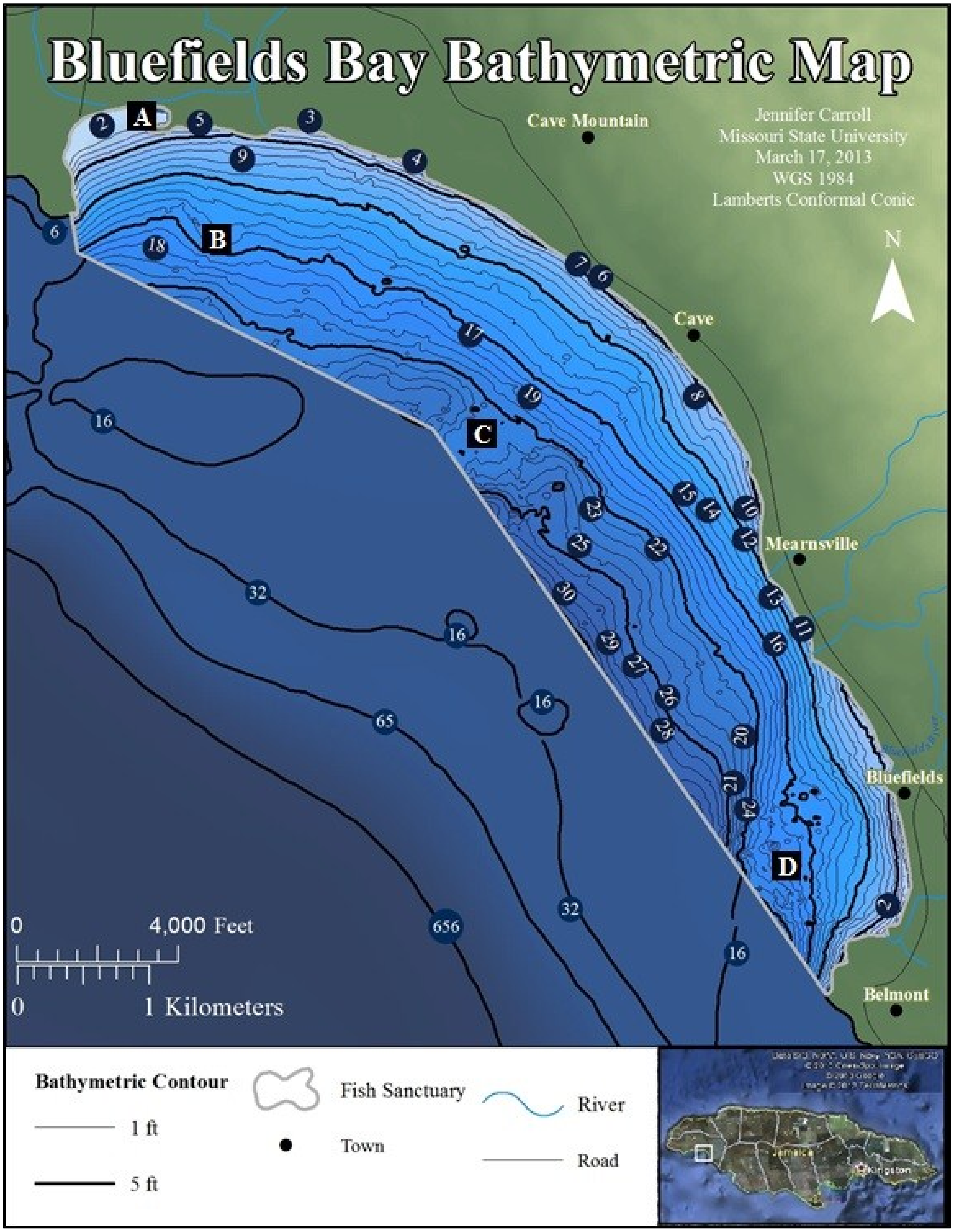

Figure 27. Bathymetric Map of Bluefields Bay Marine Protected Area (MGI, 2010).

optimum conditions with minimal pitch and roll. The wide beam angle of the echolocator was sufficient to compensate for any variation in vertical boat position due to either. Error in depth measurements resulted from the default echolocator speed of sound setting in seawater (1,500 m/s) and the actual speed of sound in seawater in the field based on averaged recorded conditions (1,647.83 m/s) using Del Grosso's speed of sound in saltwater equation (Dushaw *et al*., 1992). The higher speed of sound in the seawater is primarily the result of the higher salinity recorded in the calm conditions of the sheltered bay than is typically found in the open ocean. The greatest margin of error would have occurred at the deepest recorded depth of 33.2 ft with an error in the time used to calculate the depth being approximately 0.000121 seconds. This converts to an error margin of plus or minus approximately 3.27 ft, which is consistent with other studies that have reported the accuracy of the Speedtech Depthmate Portable Sounder to be plus or minus one meter, or 3.28 ft (SSQC, 2006).

Interpolation. The interpolated surface from the Gaussian kriging model was chosen because of its overall best fit to the data set. Because dissimilarity between the values of the root mean squared error and the average standard error would indicate a problem with the model, a comparison was preformed between the root mean squared error (1.197 ft) and the average standard error (1.192 ft) **(**Table 5). Both error values were concluded to be similar enough to not be indicative of an underlying problem with the model. The average standard error of the Gaussian kriging model underestimates the variability of the predicted values by 0.38% as indicated by a root mean squared standardized value of 1.004, which is slightly greater than the ideal value of 1.The distribution of the prediction errors follows a normal distribution (Figure 28). For the

Gaussian kriging model with a normal distribution of errors, there is a 95% confidence level that the predicted *z* value is within plus or minus 1.96 times the root mean squared error of 1.192, which is equal to plus or minus 2.337 ft of the actual value (O'Sulivan and Unwin, 2010).

Cumulative. The cumulative errors associated with the final bathymetric map are plus or minus 5 ft for the horizontal *x* and *y* axis values of latitude and longitude and plus or minus 3.27 + 2.337 = 5.607 ft for the *z* axis values of depth.

Table 5. Interpolation Model Errors from Leave One Out Cross Validation.

Interpolation Model	**Mean Error**	**Root Mean Square Error**
IDW (Optimized Power = 2.8275)	0.051241914	1.509543178
Exponential Kriging	0.022349164	1.188428547
Gaussian Kriging	0.013284480	1.196637651
Quartic Kriging	0.025193647	1.199897188
Constant Kriging	0.016300828	1.231271112

Interpolation Model	**Mean Standardized**	**Root Mean Square Standardized**	**Average Standard Error**
IDW (Optimized Power = 2.8275)	N/A	N/A	N/A
Exponential Kriging	0.019871413	1.085710087	1.092125898
Gaussian Kriging	0.007932389	1.003773987	1.192354822
Quartic Kriging	0.020615241	1.019009975	1.170846643
Constant Kriging	0.012931537	0.968071605	1.264887671

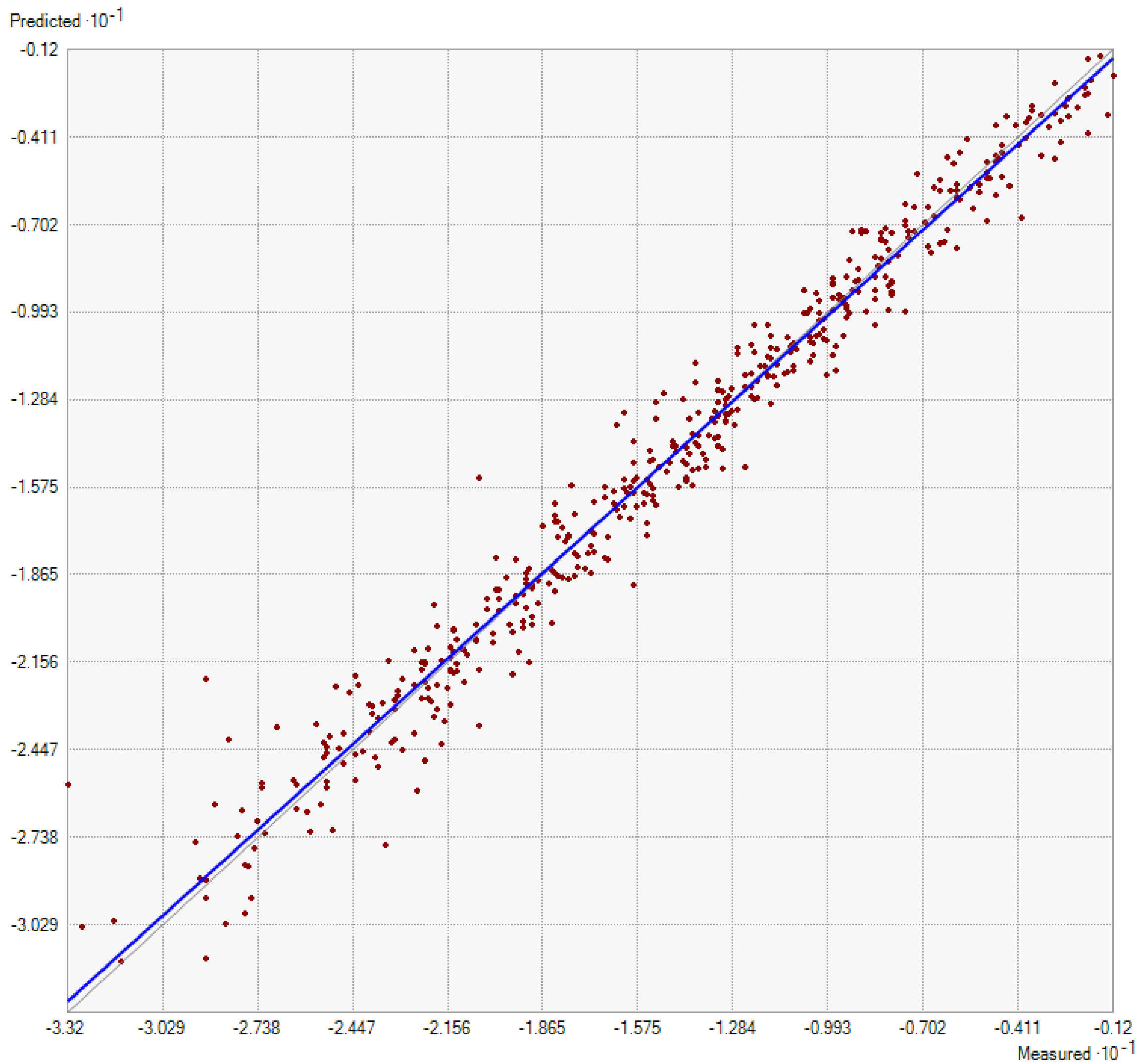

Figure 28. Error Distribution of Gaussian Kriging Model. Each red dot represents an error and the blue trend line represents a normal distribution.

Benthic Habitat Mapping

The resulting, ground-truthed benthic habitat map from this study provides an in-depth assessment of abundance and distribution of marine habitats within Bluefields Bay Fish Sanctuary displayed in three sections (Figure 29, 30, 31). The resulting intertidal habitat map also provides a visual association between water quality data and shoreline environment as well as the accessibility of mangroves to fish populations within the

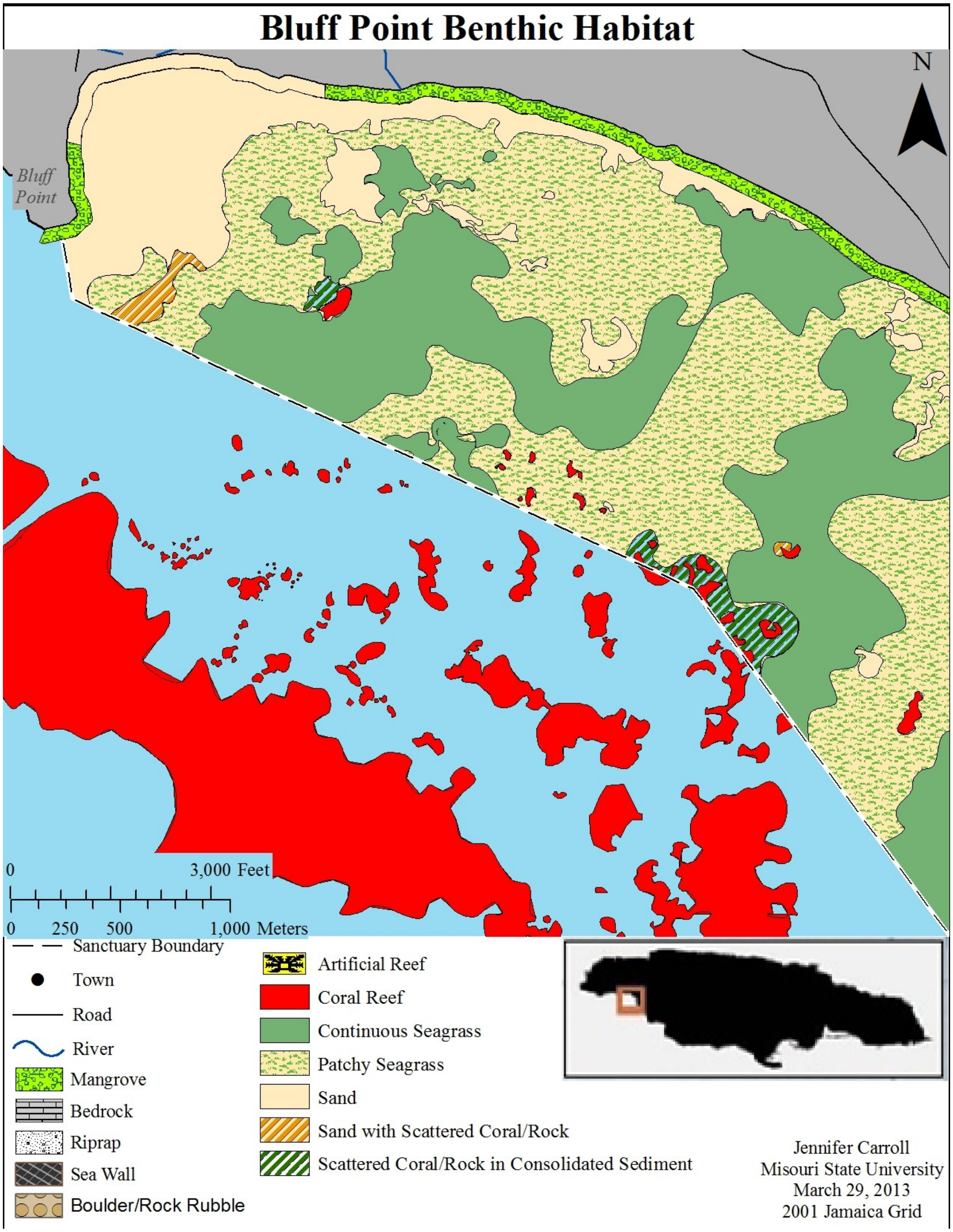

Figure 29. Bluff Point Benthic and Intertidal Habitat Map (Ebert, 2010; MGI, 2010). The red polygon in the middle of the north end is one of the largest patch reefs found within the fish sanctuary.

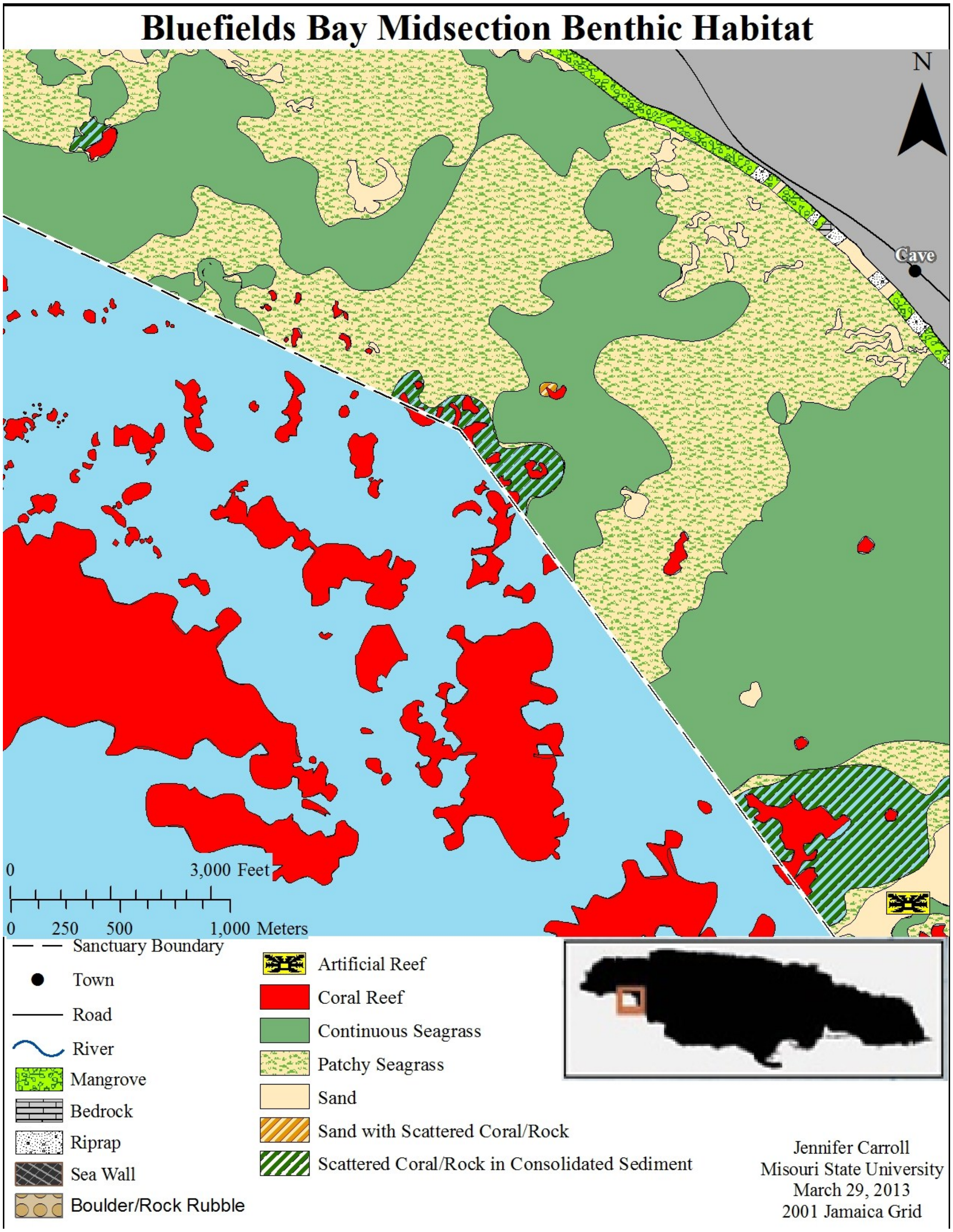

Figure 30. Bluefields Bay Midsection Benthic and Intertidal Habitat Map (Ebert, 2010; MGI, 2010). The large red polygons to the north west of Belmont Point are some of the largest found in the fish sanctuary. The yellow icon indicates the placement of the artificial reef.

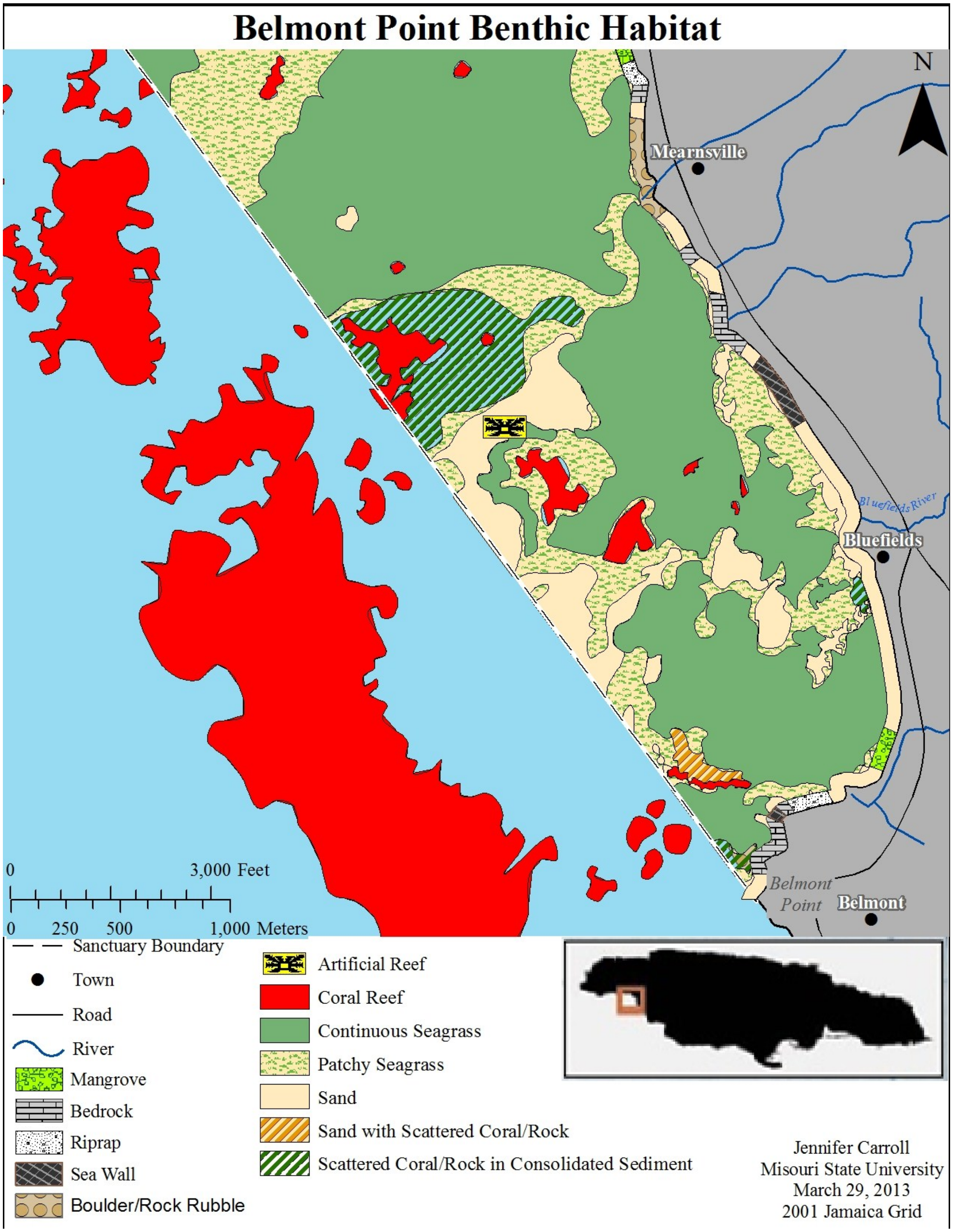

Figure 31. Belmont Point Benthic and Intertidal Habitat Map (Ebert, 2010; MGI, 2010). The yellow icon indicates the placement of the artificial reef.

sanctuary. On a larger scale, it will serve as a visual tool for more effective management and conservation of marine resources within the marine protected area network.

Accuracy

The IKONOS and Geoeye images used in ArcGIS during digitization of the initial benthic habitat map have a resolution of 1 m and 0.5 m respectively. Because the benthic habitat polygons were directly derived from features in the imagery, the initial benthic cover habitat was accurate to 0.5 to 1 m for clearly defined features like the fringing coral reefs, large individual patch reefs, and moderately sized, uncolonized sandy areas. The aerial photography was only used in the southwest corner of the fish sanctuary to delineate clearly recognizable features like the coral reefs. Surface observations were recorded in the field for each GPS point as percentages of biological cover, such as seagrass beds or coral, or percentage of geomorphic characteristic, such as hard bottom or sand, in the absence biological cover.

Field observations were then used to ground-truth the initial benthic cover polygons and to delineate similar looking features such as patchy seagrass vs. continuous seagrass. Further points in unclear areas like the mouth of the Bluefields River were used to delineate smaller polygons. Field data has an error of plus or minus 5 ft and the polygons created from field data, such as patchy seagrass, continuous seagrass, and small sand beds, have a corresponding error of plus or minus 5ft. Finally, the centroid points of randomly selected polygons were converted into a point data set and loaded onto the Trimble GeoExplorer 6000. In the field, nine out of ten centroid points from coral reef polygons determined by remote sensing methods were diver verified to be delineated as the correct benthic habitat, yielding an accuracy of ninety percent. Delineated sand and continuous seagrass bed polygons were double checked against fish survey control points and corrected. Incorrect placements of polygons were later corrected on the final map.

Benthic and Intertidal Habitat

Distribution. The hierarchy of habitat types in Bluefields Bay can be broken down first into zones, then described as potentially having a biological or habitat cover type as well as a geomorphological, or physical structure in the absence of apparent biological cover. The zonation units are defined based on bands of areas with similar overall conditions starting with proximity to shore and sequentially getting deeper until reaching the base of the seaward side of the fringing reef. Physical structures are based on the type of substrate while biological/habitat types are classified by well know, previously defined ecosystems with well recognized biota. The approximate placement of the seaward boundary of the fish sanctuary is displayed in Figure 34.

Intertidal. The shoreline intertidal zone is self-explanatory in that it encompasses the region from the lowest line of the spring tides to the mean high water mark or the landward edge of emergent vegetation such as mangroves. The shoreline intertidal zone of Bluefields Bay includes a wide variety of habitat types. These habitat types are mangroves (42% or 4.97 km), limestone caves that are periodically inundated, sandy beaches (36% or 4.22 km), artificial structures like unconsolidated rip rap (7.3% or 0.87 km) and sea walls (3.9% or 0.46 km), and limestone cliffs with large boulder sized rubble (4.1% or 0.49 km).

The most common type of habitats was mangroves (41.7%) for intertidal (Table 7). Along the northern portion of the bay where there is significant land area between the road and the shoreline is where the majority of the mangroves occur (Figure 33). The health and productivity of a mangrove mangal is dependent not only on its length along the coastline but also by the width of the stand (Ellison and Farnsworth, 1996). The mangroves that occurred along the coastline where the coastal road runs parallel to the intertidal zone were observed to be occupying a thin strip of land five to ten meters wide. Red mangroves, the primary species found in Bluefields Bay, are among the most hardy of the mangroves species and to a certain extent has adaptations like turning its leaves away from the angle of the sun during the hottest part of the day that allow it to cope with hot temperatures (Gayle and Woodley, 1998).

Other habitat types like limestone cliffs, rocky boulder and rubble, riprap, and sea walls occur primarily along the southern half of the coastline (Figure 33). One of the primary reasons for the location of sea walls is to protect the coastal road. Riprap is unconsolidated material that has been placed around residences to preserve or expand the property. Limestone cliffs and boulder strewn or rocky rubble lined coastline occurs naturally along the southern central coastline of Bluefields Bay where the up-thrown side of an old set of faults meets the shoreline.

Benthic. Coral reefs represented 6% of the protected area of the bay which is a total area of 0.77 km^2. The greatest clustering of coral reefs within the fish sanctuary is the large patch reefs that occur within the back reef zone near the seaward boundary of the MPA. The placement of artificial reef that is a “reef-like” habitat available for fish populations dates after the completion of this study and is relatively small in area. The majority of the fringing reef falls outside the protected waters of the MPA. The reef crest at Bluefields Bay is typically not emergent except for the crown-like structure outside the southern end of the bay that is singularly called Moor's Reef and is indicated on a number of maps from the 1800s to present. Probably the largest patch reef present within the marine sanctuary is located in the northern end of the bay

Seagrass beds are best represented within the protected area at 82% of the benthic area of the bay. The shallow marine floor of Bluefields Bay has long been covered by extensive sea grass beds (Goreau, 1992). For sea grass, the spatial extent of the one collective bed is indicative of overall health and continued robustness. The sea grass beds are the most abundant habitat in the protected area of Bluefields Bay (Table 7). Most of the seagrass beds found within the protected area of the bay were observed to be a mix of manatee grass and turtle grass. The continuous sea grass bed southwest and deeper than the north reef (Coral Reef 109, Appendix C-3) was observed from the surface to be predominately turtle grass. Turtle grass is a key food source for the endangered Green Sea Turtle and is a long lived, hardy species. Turtle grass is resilient to storm damage, as well as having one of the more complex rhizome and root system which help trap and stabilize the sea floor. In the shallow sub-tidal zone of the central area of the north end, manatee grass was observed to be the predominate species making up the sea grass beds in the subtidal region off of Sweet River mouth.

Sand represented 12% of the benthic cover. One of the most significant features is the sand bed that occurs at the very northeastern end of the bay (Figure 29, Figure 32). The lack of seagrass along the shallow end may also be due suspended sediment from deposition by long shore drift and wave transport.

Table 6. Benthic and Intertidal Habitat Inventories.

Benthic Habitat

Class	Number of Polygons	Percentage (%)	Total Area (km^2)
Coral Reefs	31	1.8	0.23
Consolidated Sediment, with Scattered Coral/Rock	3	0.5	0.07
Sand, with Scattered Coral/Rock	5	3.5	0.47
Sand	47	11.8	1.57
Sea Grass (Continuous)	17	45.1	6.01
Sea Grass (Scattered)	145	37.2	4.95
Total		100	13.32

Intertidal Habitat

Class	Count	Percent of Coast (%)	Length (km)
Mangrove	11	41.7	4.97
Sand	12	35.5	4.22
Bedrock	6	7.5	0.90
Sea Wall	3	3.9	0.46
Boulders/Rock Rubble	1	4.1	0.49
Riprap	9	7.3	0.87
Total		100	11.91

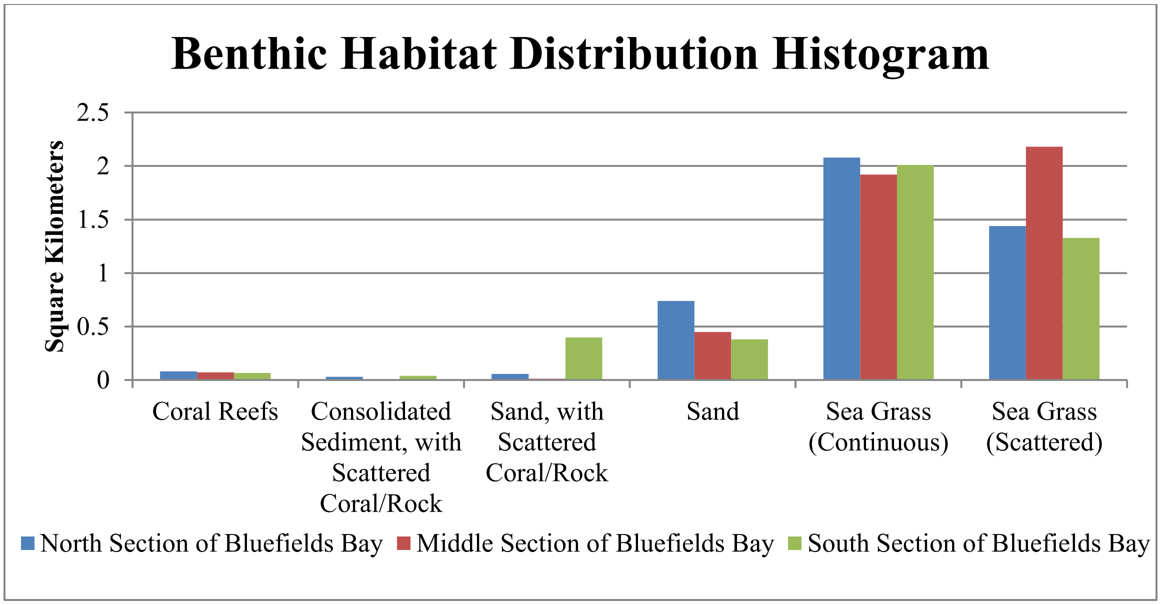

Figure 32. Benthic Habitat Distribution Histogram.

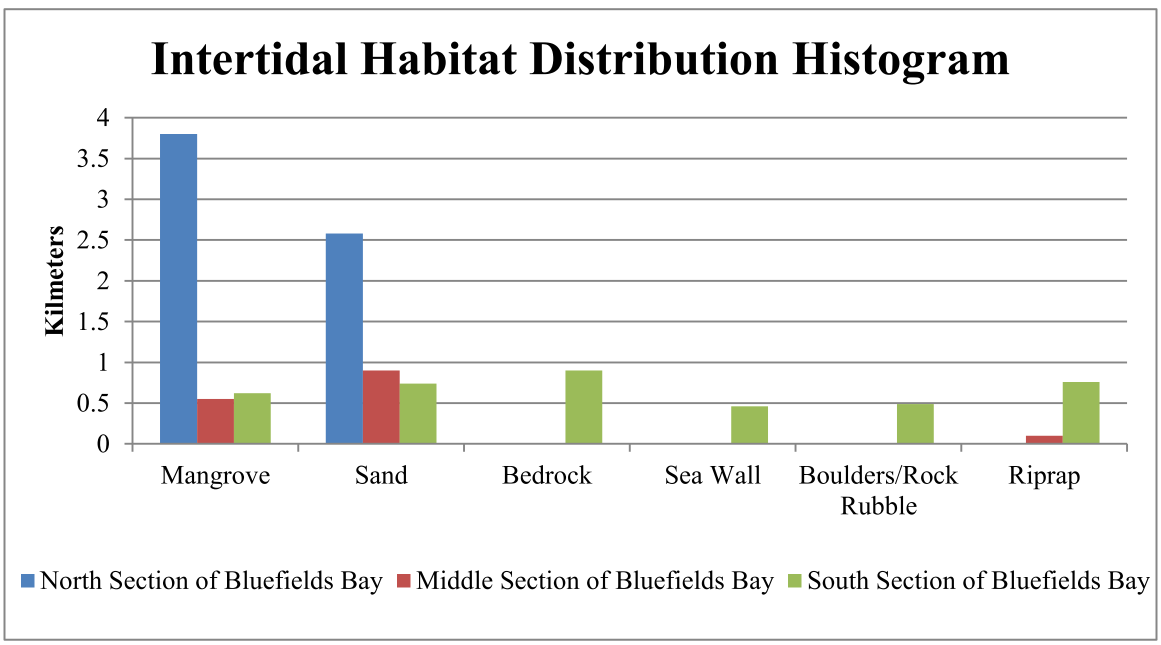

Figure 33. Intertidal Habitat Distribution Histogram.

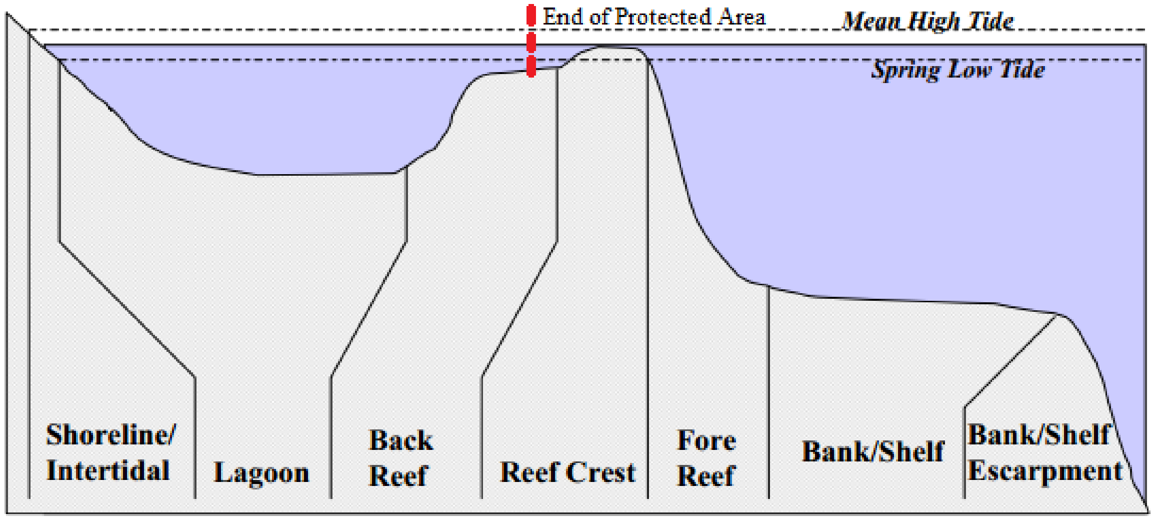

Figure 34. Representation of Zones and General Placement of Seaward Boundary of Bluefields Fish Sanctuary (*Modified from* Kendall *et al*., 2001).

Intertidal and Benthic Zones. The next zone is the lagoon and is classified as the shallow area between the shoreline intertidal and the back reef. The fringing reef protects this area from high artificial reef structures. The habitat type that occurs most often in the lagoon area is the continuous sea grass at 45% cover.

The next zone is the back reef zone of the fringing reef behind the reef crest. In Bluefields Bay the habitat types vary from seagrass, sand beds, to aggregations of coral heads that increase in size as distance from the fringing reef decreases. Overall the type of sea life found here includes seagrass, macroalgae, encrusting and coralline algae, live coral, and turf algae. The seaward boundary of Bluefields Bay Fish Sanctuary is drawn through this zone as seen in Figure 36-Figure 38.

The reef flat zone includes the sheltered part of the reef just behind the reef crest and the flattened, emergent, or nearly emergent part of the reef that absorbs most of the wave action. The sheltered, shoreline side of the reef crest is

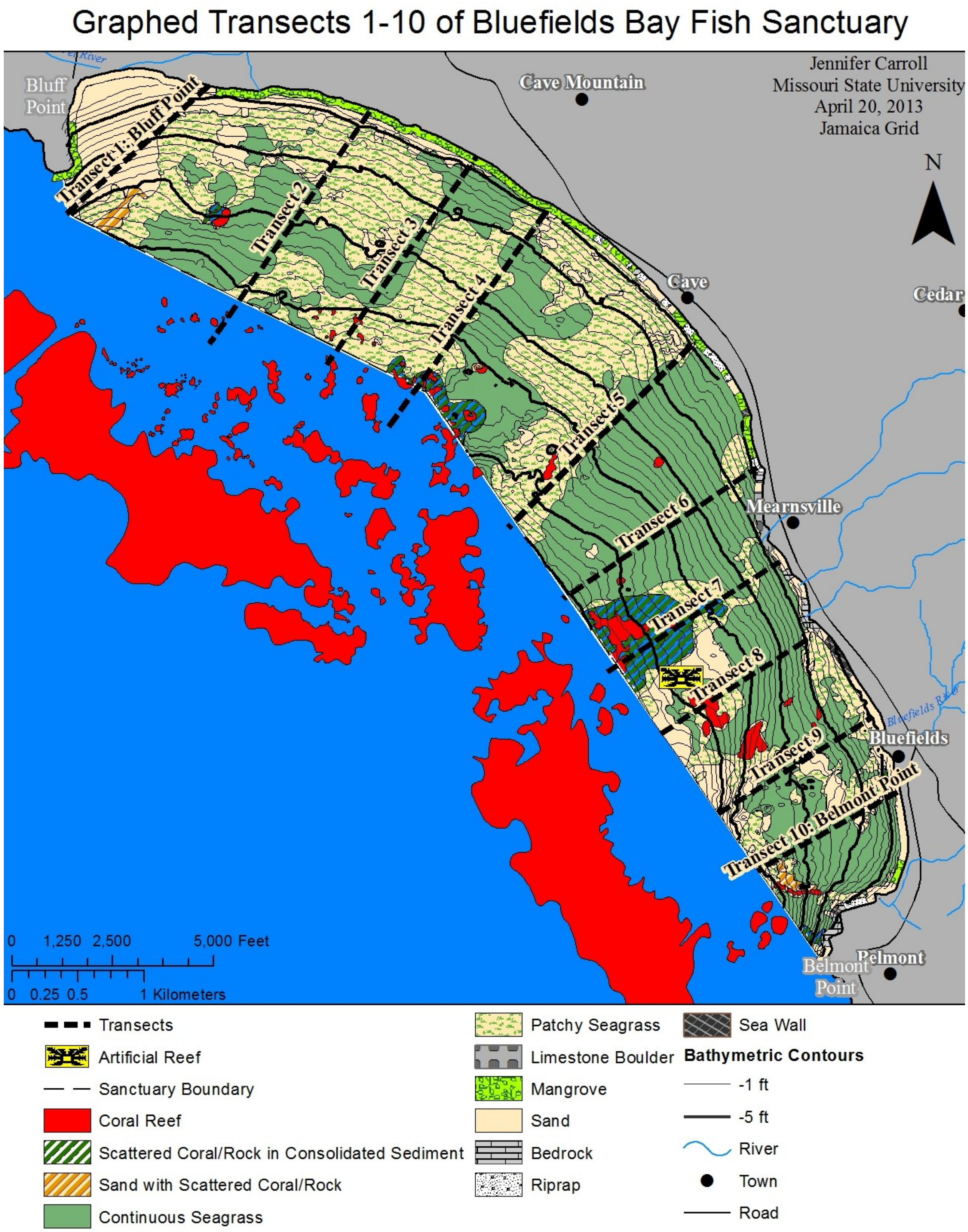

Figure 35. Cross-section Transects (MGI, 2010).

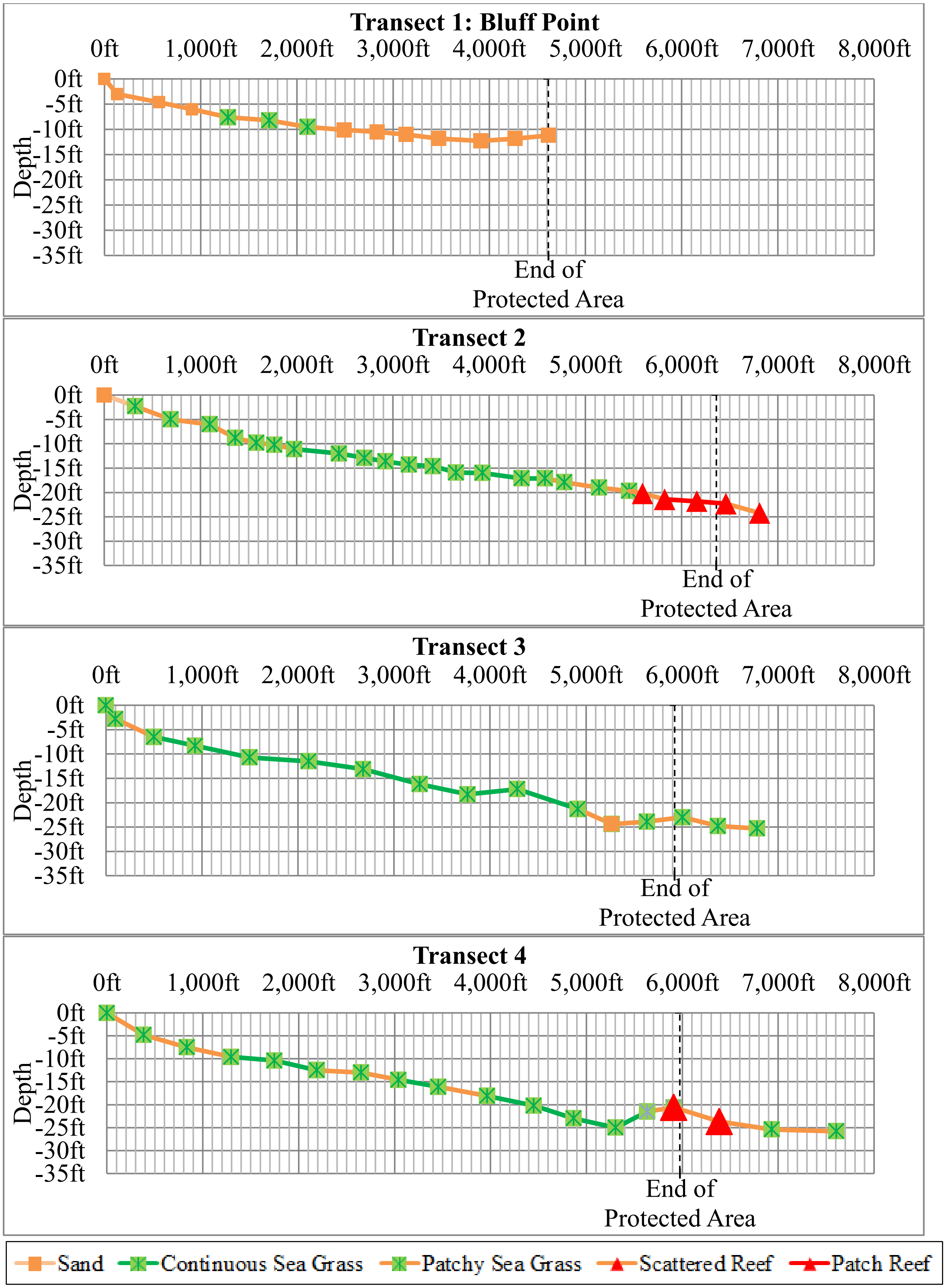

Figure 36. Cross Section Transects 1-4 of Bluefields Bay.

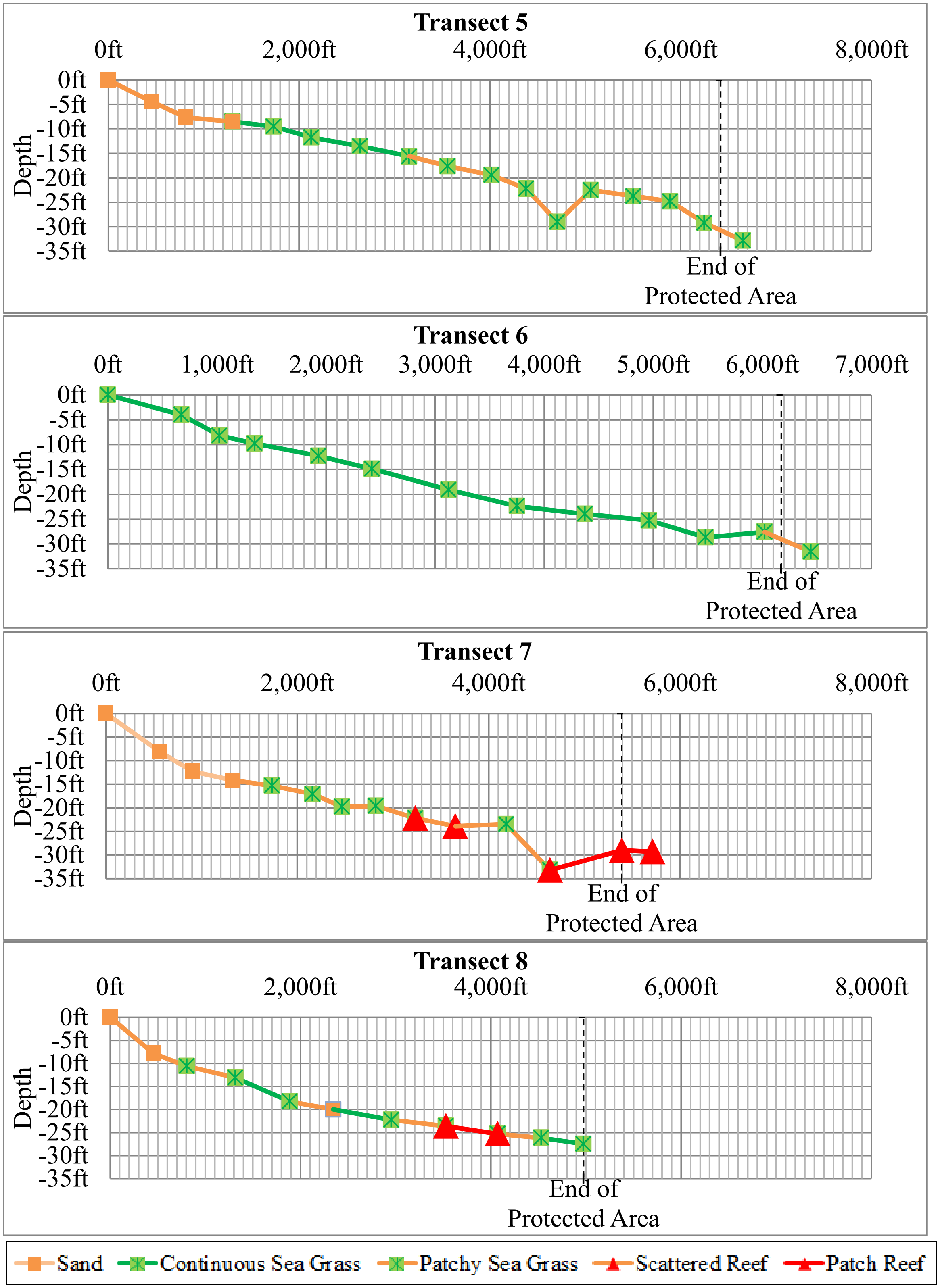

Figure 37. Cross Section Transects 5-8 of Bluefields Bay.

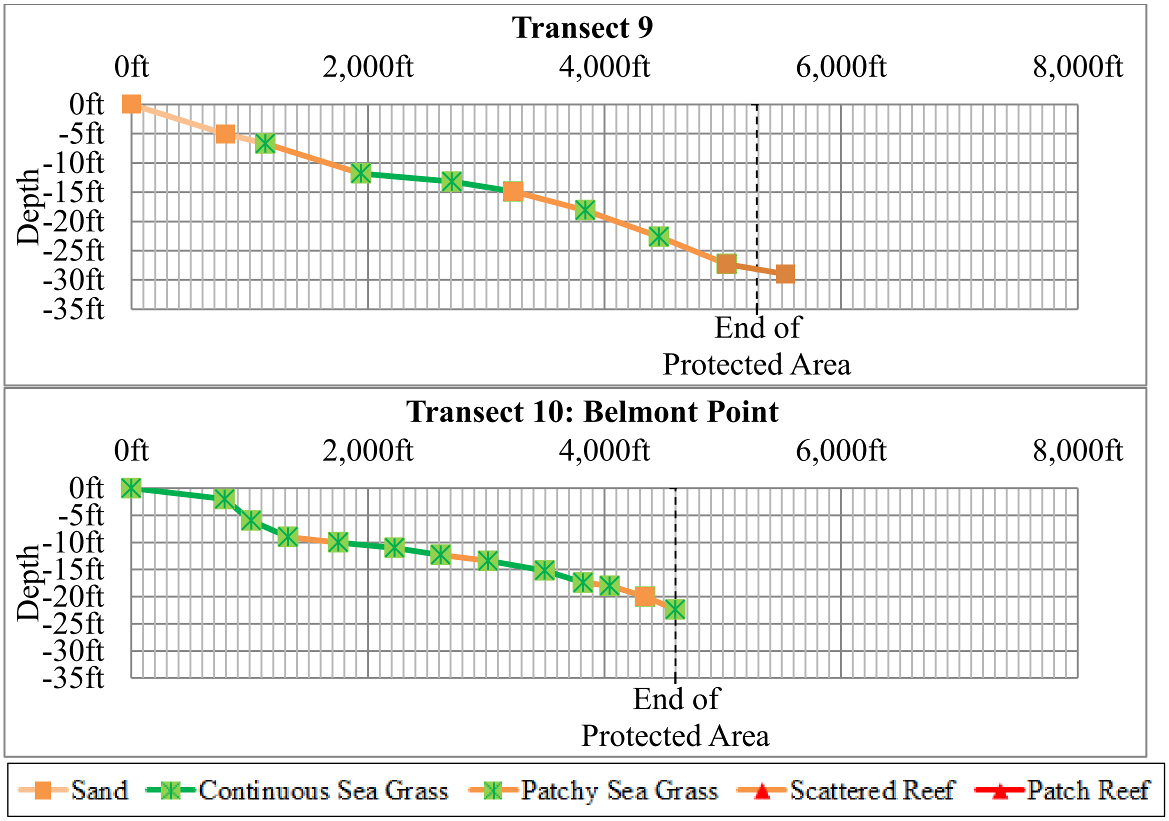

Figure 38. Cross Section Transects 9-10 of Bluefields Bay

predominately populated by live coral and zooxanthallae. In Bluefields Bay this zone of the reef is characterized by large coral reef beds with sandy bottom channels, or "chutes" that run between them perpendicular to the shoreline. Two major chutes appear to coincide with the mouths of the Sweet River and Bluefields River. The reef crest at Bluefields Bay is typically not emergent except for the crown-like structure outside the southern end of the bay that is singularly called Moor's Reef. It is often emergent during low tide and can be seen by the breaking waves on aerial photographs. Live coral of the *Palmata* genus are typically found on Jamaican coral reefs in this zone, however it is unclear whether this could also be said of Bluefields Bay. It is assumed that other coral species are present in this zone in Bluefields Bay.

The fore reef includes the seaward side of the fringing reef from the reef crest down to the fore reef slope. Typical geomorphic features are terraces, sills, scarp mounds and shoots, as well as detrital cones. Typical biological covers found in this zone are live coral and encrusting or coralline algae. The chutes between the scarp mounds are characterized by live coral, seagrass beds, macroalgae, and turf algae. This zone can be defined from aerial photographs in Bluefields Bay but the biological cover assemblage of this zone in Bluefields Bay is unknown.

The last zones, coastal shelf and shelf escarpment, includes the seaward base of the fringing reef. The slope is typically deposits of coral debris and characterized by outcrops, pinnacles, gullies, silt, and mud. Biological cover includes corals of the genus *Agaricia* in the upper portion of this zone as well as chunks of other types of coral that have become detached from the coral reef head and found conditions still viable for continued growth. These zones are harder to define in aerial photographs in Bluefields Bay but are assumed to be present as is typical of Jamaican coral reefs.

Water Quality

Water quality testing was done via a Horiba water quality probe during the course of field work. It should be noted that all water quality sampled data was collected from the surface of the water column to a maximum depth of 3-5 ft. Overall data points were collected during the morning hours when water clarity was at its peak and wave action was calmest. Field work was limited to the pre-hurricane months of May and June and should not be interpreted to encompass possible seasonal changes that may occur during peak storm months or winter fluctuations in currents. The purpose of collection of water quality data was primarily to identify any abnormal values that may indicate problematic factors that are detrimental to the health of intertidal and marine ecosystems within the protected area of the bay. Also, to identify fresh water input points from rivers, mangrove marshes, and groundwater upwelling zones.

Salinity. The overall average salinity of sea water on the southwest coast of Jamaica is around 36‰ with the averages in the winter months falling just below the average and summer months averaging above 36‰ but staying under 37‰ (Gray and Wilson, 2004). The surface average salinity in the bay is 38.2‰ and is higher than the overall region of the island (Table 8). It is within the possible natural conditions of a sheltered lagoon such as Bluefields Bay to be more saline than surrounding open waters. The intertidal average of surface salinity was slightly lower at 37.8‰. This is in concordance with the fact that several fresh water inputs occur with some regularity along the coastline of Bluefields Bay. Higher salinities in Jamaican coastal marine waters were also measured during water quality sampling at Negril. In that study, 53 out of 101 samples were greater than 36‰ in shallow marine waters (Goreau and Goreau, 1997).

Temperature. Surface temperatures along the southwest coast of Jamaica typically fluctuate from around 27° Celsius in February to 31° Celsius in August and September (Samuels, 2004). The average temperature of the intertidal region of Bluefields Bay was 31.88°C from data collected in May and June in 2011 (Table 8). It is abnormal for temperatures to reach that high in coastal waters that early in the year. Higher temperatures for longer periods of time cause stressful conditions for shallow marine ecosystems.

Table 7. Intertidal and Shallow Marine Water Quality Average Values.

Measurement	**Intertidal**	**Shallow Marine**
pH	9.56	DNS[7]
Temperature	31.88°C	DNS[7]
Salinity	37.83‰	38.15‰
Specific Conductivity	5.69 S/m	5.72 S/m
Dissolved Oxygen	5.13 ppm	5.77 ppm
Total Dissolved Solids	34,010 ppm	DNS[7]

Dissolved Oxygen. The average dissolved oxygen present in the surface waters of Bluefields Bay was 5.13 ppm for the intertidal surface waters and 5.77 ppm for the surface waters of the shallow bay (Table 8). Marine waters are considered hypoxic below 2.0 ppm and will not support fish (EPA, 2012). Levels of 3 ppm dissolved oxygen are considered stressful to some organisms and fatal for about half of marine species (Vaquer-Sunyer and Duarte, 2008). A dissolved oxygen level of 5-6 ppm is necessary for growth and activity in most fish and other marine species (Karna, 2003). The dissolved oxygen levels in the surface water of Bluefields Bay fall within the levels needed for growth and activity for fish and other marine species.

Specific Conductivity. Pure distilled water is a poor conductor of electrical currents and so specific conductivity as a physical property of salt water that is higher for a salt water solution with more chemicals in solution than a salt water solution with fewer chemicals in solution. The average specific conductivity of sea water is 5 S/m (Miller *et*

[7] Did Not Sample

al., 1988). The average specific conductivity of the surface waters of Bluefields Bay was 5.69 S/m for intertidal waters and 5.72 S/m for the shallow marine (Table 8). A lower specific conductivity for intertidal waters than for the shallow marine waters was expected due to fresh water inputs. The overall higher specific conductivity of surface waters of the bay as opposed to the average of sea water overall is likely due to the sheltered conditions of the lagoon.

pH. The Government of Jamaica has set a pH standard range of 8.0 to 8.4 for coastal marine waters (USAID, 2005). In this case, the average pH of the intertidal waters of Bluefields Bay exceeded the target range set by the Jamaican government with an average pH of 9.56 (Table 8). While the basic pH of the intertidal waters of Bluefields Bay suggests that ocean acidification is not a problem at this locale, the abnormally high pH value is possibly due to probe sensitivity error or high evaporation of surface waters and testing of pH value of waters within the bay should be repeated. Further monitoring is would determine whether this average can be explained by diurnal and seasonal fluctuations of pH that typically occur in shallow coastal waters (Pelejero *et al.,* 2005). It is also possible that the high pH can be explained by natural processes such as photosynthesis within the calm waters of the bay (Hanson, 2002).

Total Dissolved Solids. Total dissolved solids are compounds such as salts in water that dissociate in water to form ions. These salts as typically have positively charged and a negatively charged ions that separate and mix with water molecules. Some common salts in sea water are sodium ($Na+$), sulfate (SO_4 2-), chloride ($Cl-$), calcium (Ca_2 2+), magnesium (Mg 2+), and bicarbonate (HCO_3-). Sea water typically has a total

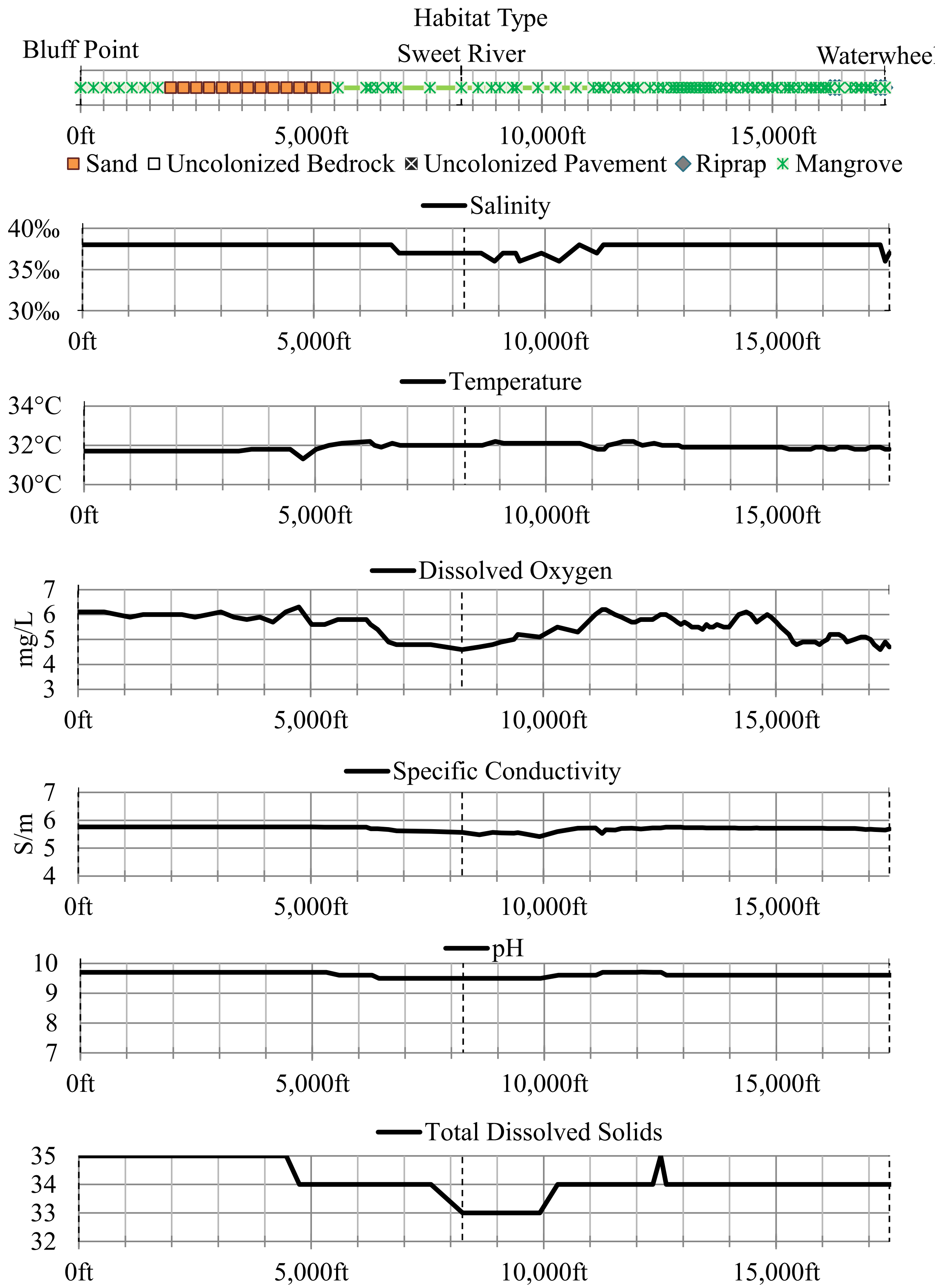

Figure 39. Shoreline Water Quality and Habitat Profile from Bluff Point (0 ft) south to Waterwheel River mouth (17,438 ft).

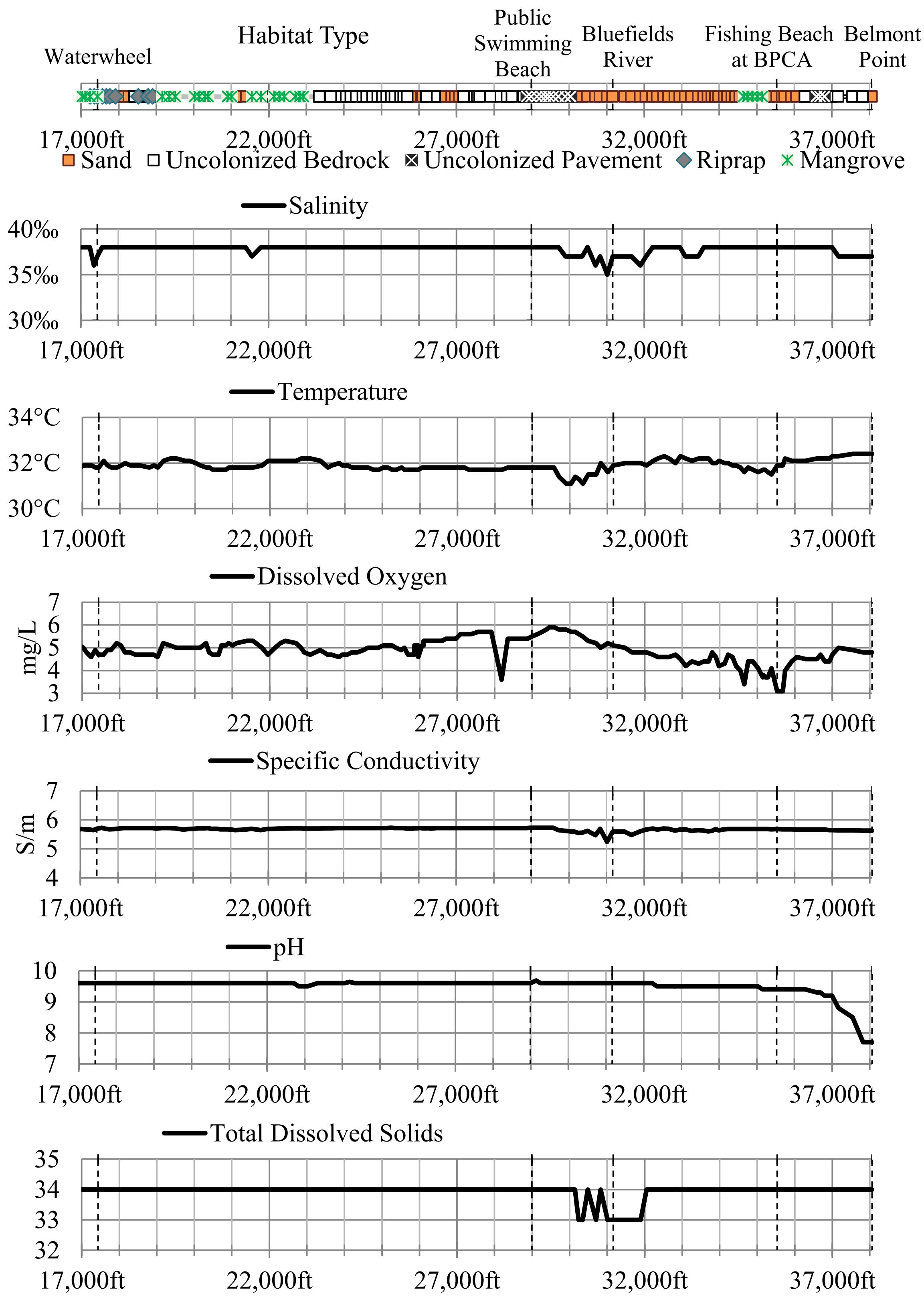

Figure 40. Shoreline Water Quality and Habitat Profile from before Waterwheel River mouth (17,438 ft) south to total shoreline length at Belmont Point (38,059 ft).

dissolved solid value of 35,000 ppm. The average surface total dissolved solids for the intertidal waters of Bluefields Bay were lower than the typical value with an average of 34,010 ppm (Table 8). While an average higher than the normal would have been indicative of potentially excessive anthropogenic inputs, the lower than average value is most likely due to the mixing of fresh water inputs with the marine waters of the bay.

CHAPTER 6

DISCUSSION

Bluefields Bay was most likely favored as a potential site for a marine sanctuary from the study of the coral reefs of western Jamaica in 1992 that described the coral reefs there as some of the better ones found in Jamaica and because of its exceptionally clear waters (Goreau, 1992). The efforts of the Bluefields Bay Fishermen Friendly Society to increase awareness among the public about the local benefits of marine protected areas have also attributed to the support and success of the Bluefields Bay Fish Sanctuary since its creation in 2010. The purpose of this baseline study is to provide further information on the factors affecting habitats within the marine protected area. The spatial knowledge portrayed by the maps from this study can be used as a tool for government officials and local groups to develop effective management policies and tailor protection activities to key "hotspots" like large patch reefs within the protected area of the bay. Applications of this research to better understand the distribution and quality of marine habitats and their management in Bluefields Bay are discussed below.

Comparative Advantages of Bluefields Bay as a MPA

Bluefields Bay has long been known for its exceptionally clear waters compared to other locations in Jamaica. Indeed, during water quality testing in Negril to the west of Bluefields Bay, poor water clarity due to the resuspension of marine sediments, coastal erosion, and excess inputs of soil and peat by fresh water runoff was noted at multiple locations (Goreau and Goreau, 1997). Compared to other marine protected areas in

Jamaica, this characteristic of Bluefields Bay still remains true today due to several factors.

Bluefields Bay lies along the southwestern coast of Jamaica within a natural embayment protected from severe wave attack to a degree. The trade winds blow directionally from southeast to northwest in the Greater Antilles of which Jamaica is a part. Seasonally the circulation of currents in the Caribbean varies, but the direction of flow remains overall consistent from a southeast to northwest direction along the southern coast of Jamaica. As a result, the typical track of hurricanes and tropical storms is a westerly direction from the open Atlantic into the Caribbean before veering northward towards the North American coast. The location of Bluefields Bay along the southwest coast of the island shelters it from the majority of tracks hurricanes and tropical storms usually follow. It also is sheltered from destructive waves caused by hurricanes and tropical storms.

Coastal mangrove ecosystems like those at Bluefields Bay occur at points of fresh water input into shallow marine waters. Water runoff from landward sources is a primary conveyance for nutrients and sediments and mangrove forests act as a sink for nutrients as well as a filter for sediments. The tangle of roots slow water velocities to the point that all but the finest sediments, normally enriched with minerals and nutrients, can settle out. The delicate nutritive roots that hang between the prop roots take up excessive nutrients like nitrates and phosphates (Twilley and Day, 1999). Mangrove soils are anoxic and the growth and productivity of mangroves are strongly related to the nutrient transformations by the microbial decomposition of organic matter. Mangrove ecosystems are highly productive and are capable of depleting excessive nutrient levels (Twilley and Day, 1999).

The extensive seagrass beds that cover 82% of Bluefields Bay's shallow marine habitat (Table 6) consolidate and protect from erosion the mud, sand, and coral debris that make up the benthic sediment. The shallow marine floor of Bluefields Bay has long been covered by extensive sea grass beds (Goreau, 1992). Most of the seagrass beds found within the protected area of the bay were observed to be a mix of manatee grass and turtle grass. Turtle grass is resilient to storm damage, as well as having one of the more complex rhizome and root system which help trap and stabilize the sea floor (Vincete and Rivera, 1982).

Bluefields Bay differs from other bays in Jamaica in that there has been no recent construction projects that involve major alteration of the shoreline and sea floor. There have been no modern dredging activities or sand mining for beach replenishment. In Discovery Bay, at least one channel through the fringing coral reefs has been dredged for bauxite barges (Vieria *et al*., 1995). There also have been no dredge and fill construction at Bluefields like the undertaking of extending the airport runway at Montego Bay (Sullivan *et al*., 1999). With the formation of the fish sanctuary, the key ecosystems within the bay are protected from any future threats of such. The potential addition of a shoreline buffer zone would also further preserve the health and productivity of the essential fish habitats within the fish sanctuary.

Spatial Assessment of Habitat

Bluefields Bay is a location that is home to or adjacent to the three key essential fish habitats: coral reefs, seagrass, and mangroves. One of the objectives of this study was to spatially map the distribution and neighboring relationships of the essential fish habitats for management, protection, conservation, and educational purposes. A visual comparison of habitat quantities, location, and distribution can be completed from the benthic and intertidal habitat maps of this study. Further exploration of the spatial relationships and distribution can be performed using data queries within the ArcGIS software. Exact numbers for habitat inventories are useful as a comparison point for future studies at Bluefields Bay and other similar studies at other Jamaican marine protected areas. Furthermore, interpretation of the benthic and intertidal habitat maps along with application of prior information about the site yields an assessment of factors possibly controlling the spatial distribution of essential fish habitat.

Intertidal Habitat. The shoreline intertidal zone of Bluefields Bay includes a wide variety of habitat types. These habitat types are mangroves (42% or 4.97 km), limestone caves that are periodically inundated, sandy beaches (36% or 4.22 km), artificial structures like unconsolidated rip rap (7.3% or 0.87 km) and sea walls (3.9% or 0.46 km), and limestone cliffs with large boulder sized rubble (4.1% or 0.49 km). The primary human disturbance of the intertidal habitats of Bluefields Bay is the road corridor and related development along it as well as urban development of residences and community property. Along the northern portion of the bay where there is significant land area between the road and the shoreline is where the majority of the mangroves occur. The health and productivity of a mangrove mangal is dependent not only on its length along the coastline but also by the width of the stand (Ellison and Farnsworth, 1996). The mangroves that occurred along the coastline where the coastal road runs parallel to the intertidal zone were observed to be occupying a thin strip of land only five to ten meters wide. With the coastal road and topography limiting the landward spatial extent of the mangroves, the storm surge protection, coastline stabilization, and nutrient and sediment entrapment benefits of the mangrove mangal is severely diminished or negated completely (Geoghegan *et al*., 2001).

Other habitat types like limestone cliffs, rocky boulder and rubble, riprap, and sea walls occur primarily along the southern half of the coastline (Figure 33). The coastal road provides easy access to the southern portion of the coast and as a result intertidal habitats have been cleared or altered as people build residences. Especially around the communities of Bluefields and Belmont, people have altered the shoreline around their properties. One of the primary reasons for the location of sea walls is to protect the coastal road. Riprap is unconsolidated material that has been placed around residences to preserve or expand the property. Limestone cliffs and boulder strewn or rocky rubble lined coastline occurs naturally along the southern central coastline of Bluefields Bay where the up-thrown side of an old set of faults meets the shoreline. The delta of the Bluefields River inputs a significant amount of sediment into the bay without any buffer between the bay waters and the river mouth. Another major potential source of sedimentation during heavy rainfall is land clear cutting and construction on sensitive mountain slopes surrounding the bay (photolog pictures Appendix A- 25 through Appendix A- 30). Careful planning for land development needs to be put in place to control runoff and soil erosion.

Benthic Habitat. The limiting factors effecting the spatial distribution of the benthic marine habitats within the bay are less clear than in the intertidal zone. One of the most significant features of the benthic habitat map is the sand bed that occurs at the very northeastern end of the bay (Figure 29). The lack of seagrass along the shallow end may be due suspended sediment from deposition by long shore drift and wave transport. The sand bed may also be the result of wave erosion on the coral reef platform and shoreline due to sea level rise. The emergence of bedrock on the sea floor of the bay was not classified at the scale of this study, but is a potential source of ground water upwelling as well as a potential hard surface for coral polyps to colonize and should be taken into consideration in future studies. Other factors that are influencing the distribution of biological cover are major sources of sedimentation during heavy rainfall events like the Bluefields River.

Coral Reefs. Coral reefs represented 6% of the protected area of the bay which is a total area of 0.77 km^2. The greatest clustering of coral reefs within the fish sanctuary is the large patch reefs that occur within the back reef zone near the seaward boundary of the MPA. Several smaller aggregates of patch coral reefs were less than 0.5 m in size and thus were too small to individually delineate for the scope of this study. However, occurrences of these aggregates were found in seagrass and sand beds and classified as such for future studies. The total area of these aggregate patch reefs was 0.54 km^2 or 4% of the bay. That number is most likely an underestimation of the entire area where aggregates of patch reefs occur. The placement of artificial reef that is a "reef-like" habitat available for fish population was relatively small in area and not counted in the total area of coral reefs. The majority of the fringing reef falls outside the protected waters of the MPA. The reef crest at Bluefields Bay is typically not emergent except for the crown-like structure outside the southern end of the bay that is singularly called Moor's Reef and is indicated on a number of maps from the 1800s to present. Probably the largest patch reef present within the marine sanctuary is located in the northern end of the bay

Of all the coral reefs mapped in the area, it was observed that the majority occurs outside the protected area of the fish sanctuary (Figure 42, Appendix A-1). The addition of the artificial reef also increases the "reef-like" habitat available for fish populations, but is not the same as an actual coral reef and is relatively small in area. If the seaward boundary of Bluefields Bay were moved 500 m outward from the coast, the number of patch coral reefs protected within the fish sanctuary would double, but would only increase the area of coral to 0.45 km^2, a 1.9% increase of coral reefs within the sanctuary. Another 500 m outward for a boundary set a total of 1000 m out from the current boundary would almost again double the number of coral reefs protected and double the area (1.13 km^2) of coral reef protected in the fish sanctuary, representing an increase of reef area by 4.86% (Appendix A, Table 8). The seaward boundary of Bluefields Bay Fish Sanctuary would have to be moved 2,300 m outward to encompass the total 5.95 km^2 fringing reef offshore, an approximately 14% increase over present bay coral area (Appendix A, Table 8).

Coral Reefs Outside Fish Santuary

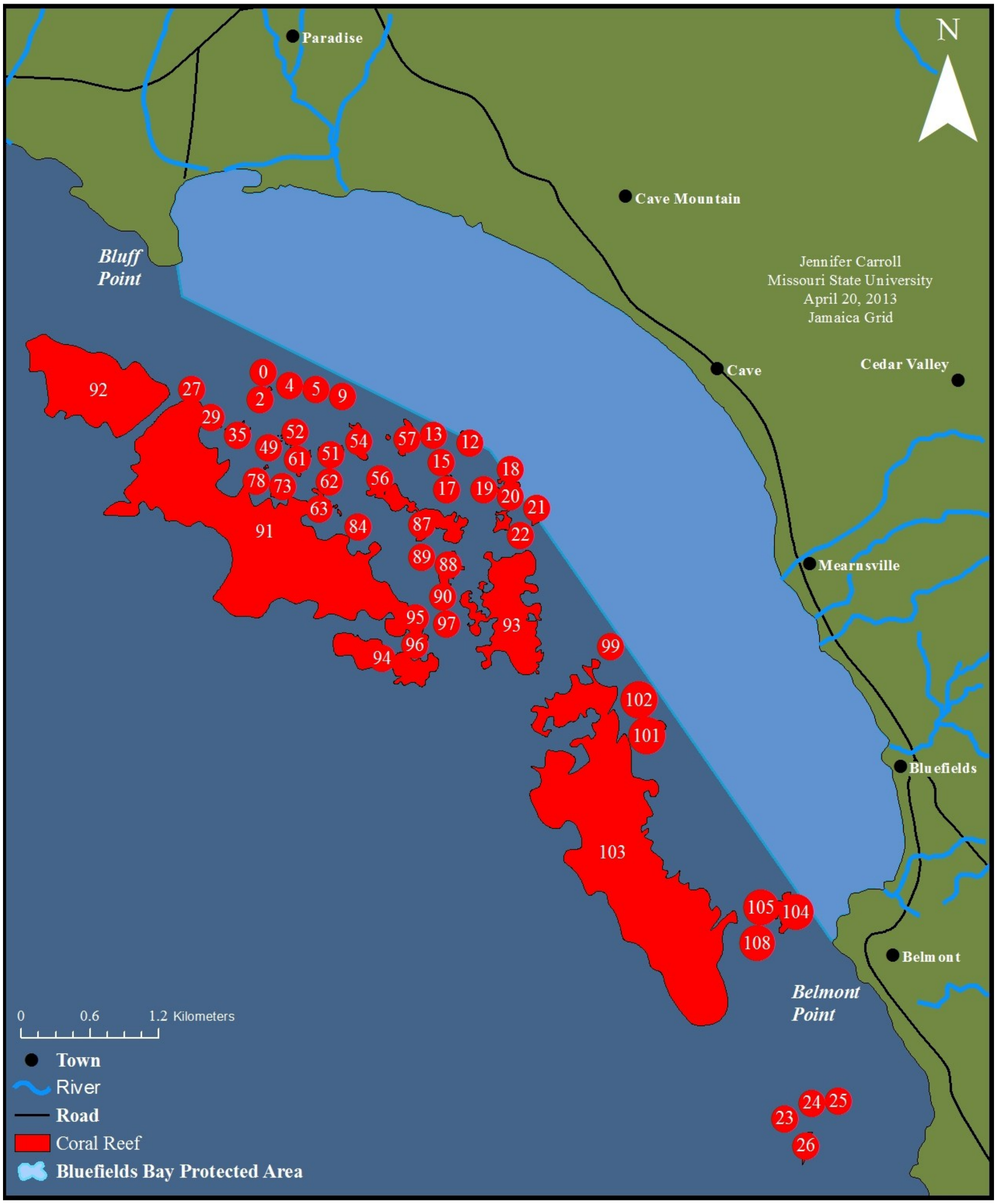

Figure 41. Position and Area of Coral Reefs Outside Fish Sanctuary (MGI, 2010).

Coral Reefs Inside Fish Santuary

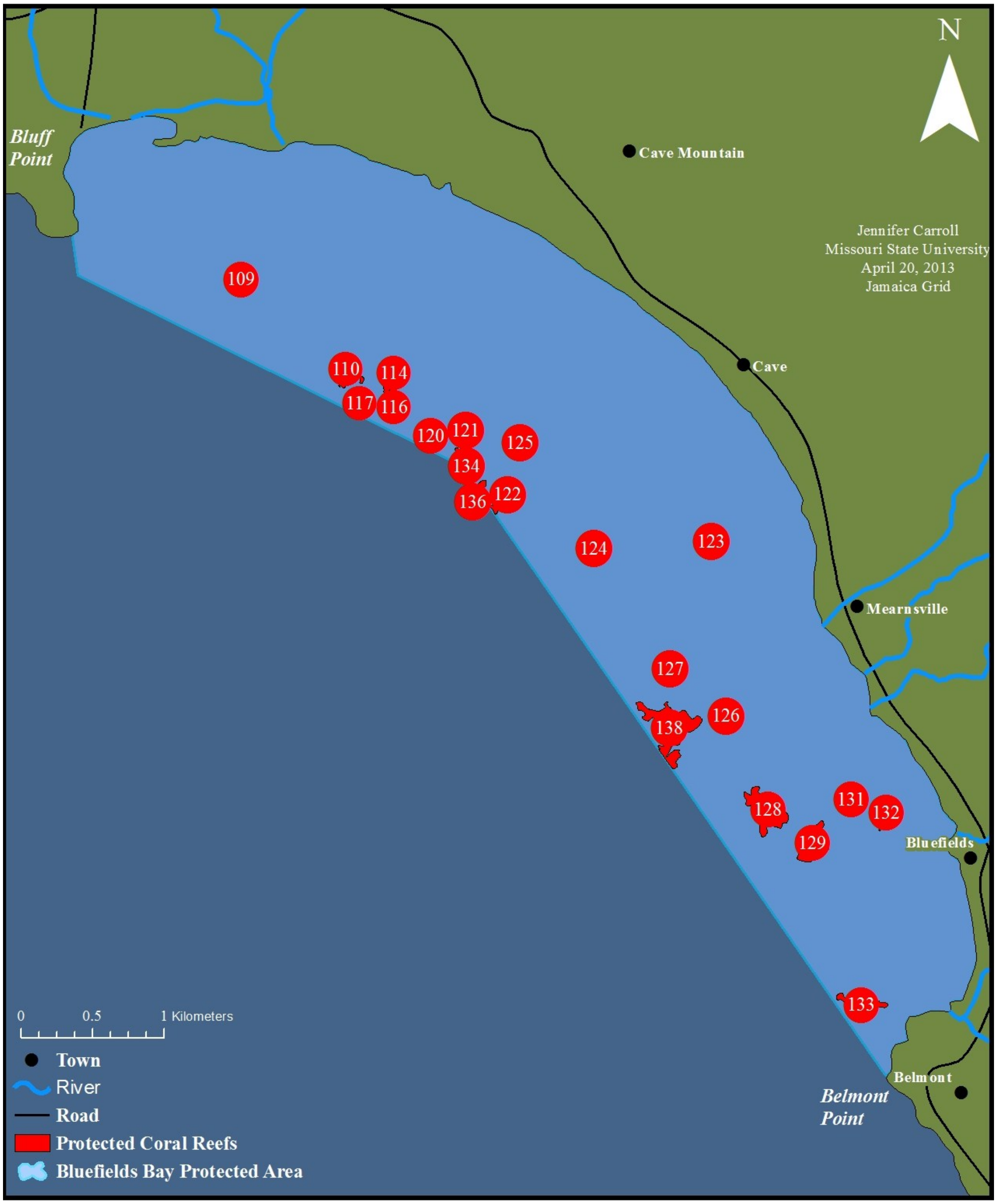

Figure 42. Position and Area of Protected Coral Reefs (MGI, 2010).

Bluefields Bay Fish Sanctuary Possible Boundary Extensions

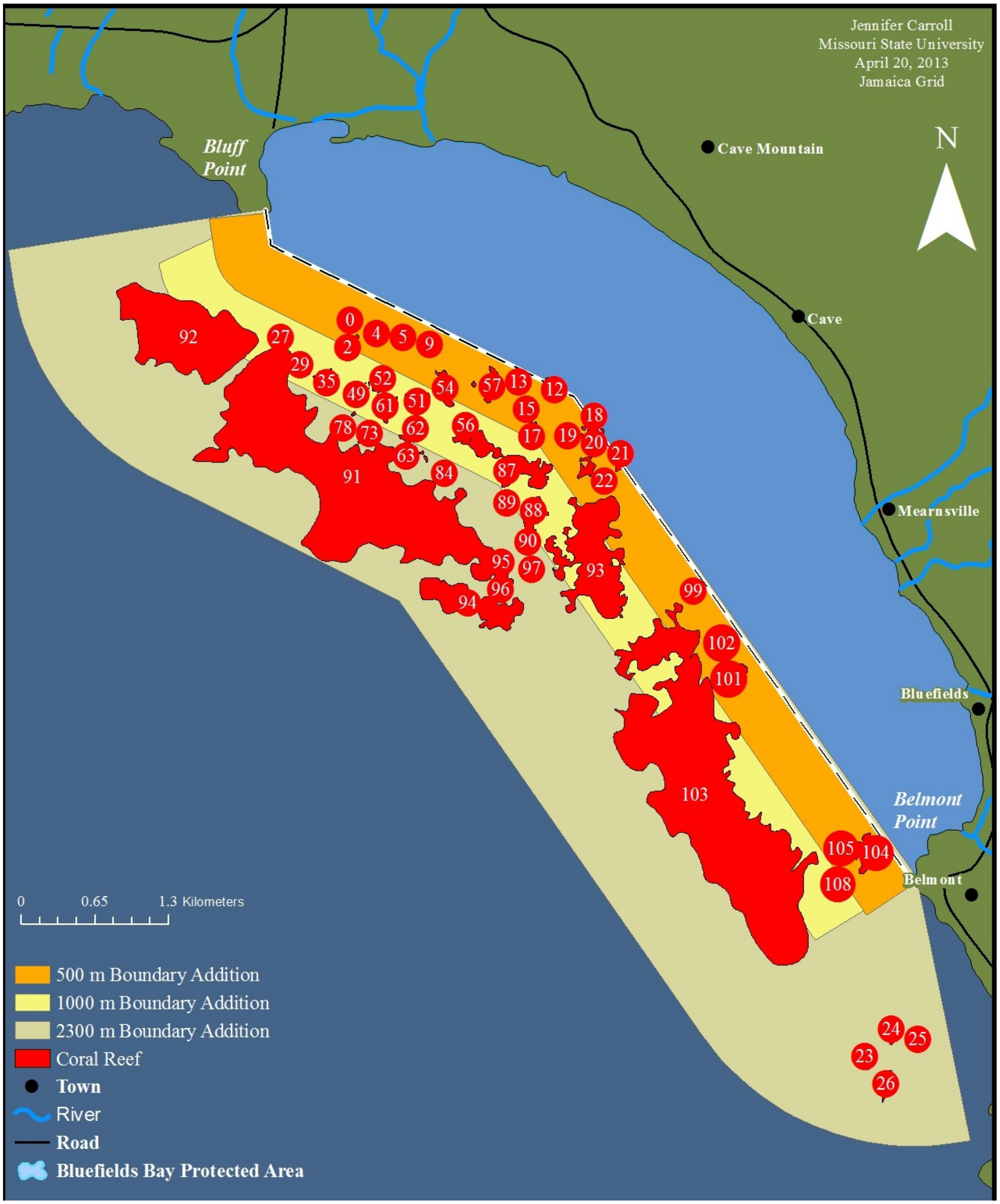

Figure 43. Potential Boundary Extensions for Bluefields Bay (MGI, 2010).

Table 8. Coral Reef Percentage and Area added with Boundary Additions.

Boundary	Coral Reef Count	Coral Reef Area (km^2)	Increase in Reef Area
Current	31	0.234	1
+500 m	64	0.455	1.94
+1000 m	111	1.137	4.86
+2300 m	139	5.949	25.42

The number and distribution of coral reefs at Bluefields Bay may also increase as more detailed surveys of benthic habitat are completed. The count and distribution of coral reefs described in this study can be refined as further data becomes available.

Internal Threats

Potential threats to the benthic and intertidal habitats of Bluefields Bay may come from the physical and chemical factors of the environment as well as anthropogenic factors. In addition to mapping and assessment of bathymetry, benthic habitat, and intertidal habit, water quality data was assessed for possible indicators of underlying problems. In some cases, abnormal averages may be indicators of preexisting problems.

A possible indicator of an underlying problem is the abnormally high pH that was recorded along the shoreline (Figure 39 and Figure 40). It is likely that the upwelling of groundwater through limestone is not the primary factor elevating the pH although it may be an attributing factor. An average of 9.56 may be explained by natural processes since photosynthesis has been recorded to increase pH to 9 and more rarely to 10 in estuaries

(Hansen, 2002). Even if the elevated pH is caused by photosynthesis, it still may be indicative of an underlying problem in the form of macroalgae. Some green macroalgae such as *Ulva lactuca* and *Enteromorpha sp*. are tolerant of pH levels outside this range and are common species in algal blooms (Locke, 2008). During water quality sampling of Negril's watershed (which included Orange Bay), forty-eight sea water samples from shallow marine sites had pH levels above 8.4. The coastal waters around Negril were also observed to be overrun by macroalgae (Goreau and Goreau, 1997). However it is possible that the systematic high pH values during field sampling were due to instrumental error. The Horiba water probe was standardized to pH 7 and not 10. Further investigation and monitoring of pH levels in the bay is needed to quantify the validity of the high pH recorded during data collection.

Typical tropical water temperature on the southwest coast of Jamaica ranges from 29°C to 31°C from August to September (Samuels, 2004). Recording a temperature of 31.88 °C average during field work that was conducted in May and June is a higher than expected sea surface temperature for early summer. A higher than normal temperature during May and June is a concern because assessments of other Jamaican coral reefs have shown that 29.6 °C is a threshold temperature above which temperatures cause coral bleaching (Goreau *et al*., 1993). It is predicted that global warming will eventually result in ocean temperatures that are one degree higher and even an average 1°C greater than normal average monthly maximum sea surface temperatures during the hottest months of the year has been documented to trigger a coral bleaching event (Goreau and Hayes, 1994). The higher than expected average temperature from this study is not immediately indicative of rising ocean temperature averages due to the fact that sea surface temperatures were not recorded below 5 ft during this study and are a probable result of air temperatures and sun warming effects. The densest clusters of coral reefs typically occur at >15 ft in depth, below the water column location sampled for this study. Although no conclusive results of ocean warming were found by this study, it is recommended that water temperatures at both the surface and at the average depth of the coral reefs continue to be monitored due to global trends of ocean warming.

The most distinctive geological factor that potentially influences the presence and distribution of habitat types in Bluefield Bay is the solution and erosion of bedrock limestone. The inflow of ground water from underground aquifers in the form of blue hole springs provide an influx of fresh water that may lower sea temperatures and salinity as well as potentially providing an additional source of nutrients or anthropogenic pollution. Limestone cliffs exclude the ability of mangroves to grow along that portion of the coast but submerged limestone potentially provides a hard surface for encrusting sea life like urchins, sponges, and corals to colonize below the tidal zone. It is also possible that the channels that cut through between fringing reefs 92, 93, and 103 (Figure 42) are the paleochannels of rivers and streams draining to the coast during the previous sea level low during the last Ice Age (18,000 years B.P.).

External Threats

In Bluefields Bay, the habitat types most likely to experience changes due to external threats like climate and sea level change are the coral reefs, the mangrove stands, and the seagrass beds. These three types of habitat are interconnected and provide important nursery and breeding habitat for important marine fish like snappers, groupers, sea bass, and tarpon (Beck *et al.,* 2001). Correspondingly, each habitat only occurs where a multiple of different factors fall within the range of tolerance of the coral, seagrass, and mangrove species that make up the primary characteristic of the habitat.

By 2050 ocean temperatures in the Caribbean are expected to rise by one degree (GoJ, 2011). Global warming will result in warmer ocean temperatures; not just warmer atmospheric temperatures. The coral reefs of Bluefields Bay are most likely to show the effects of global warming with at best slow recovery after storm events, bleaching events, and overall decrease in coral diversity. One study by Hoegh-Guldberg (1999) has shown that sea surface temperatures at or above 29.3°C for a consecutive month or more causes notable coral bleaching and fatality. Red mangroves, the primary species found in Bluefields Bay, are among the most hardy of the mangroves species and to a certain extent has adaptations like turning its leaves away from the angle of the sun during the hottest part of the day that allow it to cope with hot temperatures (Gayle and Woodley, 1998). As both ocean and atmospheric temperatures warm, any other less hardy species will be the first lost in the mangrove stand (Ellison and Farnsworth, 1996). If temperatures exceed the tolerance of the red mangroves for a long enough duration, those too will be damaged to the point of death. Seagrasses are less tolerant of temperature fluctuations as sea weeds and macro algaes. As ocean temperatures increase, replacement of seagrasses by the more hardy macro algae and sea weeds will likely increase (Beckman, 2013).

Sea level rise in the Caribbean is another factor that will affect habitat distribution in Bluefields Bay. Over the past two thousand years, sea level has been steadily rising, increasing over 10 m in that time span (Robinsion *et al.,* 2005). Current records from tidal gauges indicate that sea level is continuing to rise and is predicted to reach future levels 0.1 to 0.5 m above present sea level by 2070 (IPCC, 2007; Richards, 2008). Sea level rise is most likely to inundate coastal mangroves between shore and the coastal road frequently and for extended periods of time, causing them to die and also then possibly erode away the coastal road itself as well (Gilman *et al*., 2007; Dasgupta *et al.,* 2007). The amount of coastal, shallow marine waters with slow moving waters suitable for mangroves will significantly decrease as sea level rise pushes the shoreline closer and closer to the base of the Bluefield Mountains and coastal communities occupy whatever available space may exist (Richards, 2008). Hence, there are only limited areas available to act as a refuge for mangroves as sea level rises. The mangrove stand closer to Bluff Point in the mouth of the Sweet River is likely to be the one with the best chance of adjusting to the sea level rise naturally since there is less urbanization of the north shore and the mangrove mangal appears to be thicker than along the central region. Seagrass beds will move into shallower waters and die off as the rising level of the water also affects the depth at which there is enough light penetration for them to survive (Vincete and Rivera, 1982). The rapid rate of sea level rise is most likely to leave the coral reef unable to naturally and successfully adapt (Beckman, 2013). The very real potential of sea level rise to increase shoreline erosion is also a major way that coral reefs may suffer under over sedimentation. Jamaica is expected to lose approximately 100 km^2 of land area if sea levels reach predicted highs (Figure 7) (Richards, 2008).

Sustainability of Bluefields Bay Fish Sanctuary

Environmental Quality. The rural setting of Bluefields Bay as a fish sanctuary is ideal for the health and well-being of the seagrass beds, coral reefs, and mangroves found there because of a lesser anthropogenic influence over time than elsewhere in Jamaica (Goreau, 1992). Historically the marine resources of Jamaica have always been a major source of revenue, but until recently the exploitation of those marine resources has been independent of the conservation of resources for continued use in the future (Carr and Heyman, 2007). One example would be the overharvest and depletion of fish stock in Jamaican waters in both in size and numbers in the past few decades (Koslow *et al.,* 1988). The creation of a fish sanctuary to protect nursery and juvenile fish habitats like coral reefs, mangroves, and seagrass beds is a major step towards sustainability in that it provides a sheltered environment for the propagation and replenishment of fish stocks via the spill-over effect (Roberts *et al*., 2001). The potential for the inclusion of a shoreline buffer zone would also ensure the continuation of low anthropogenic impacts on the key marine ecosystems of Bluefields Bay. The preservation of the extensive mangrove forest along the north half of the coast of the bay would allow for the continued benefit of the filtration of sediments and nutrients out of fresh water inputs from the Sweet River and other smaller streams. The inclusion of the buffer zone would also mean the regulation of shoreline land use and the setting of water quality standards for fresh water inputs that would not only benefit the key ecosystems of the fish sanctuary, but also potentially improve the quality of drinking water and the water at the public bathing beach that is used by locals and visitors alike.

Economic Development. The two major industries that depend on Jamaica's marine resources are tourism and fisheries (Villasol and Beltran, 2004). Yet the trend of degradation of Jamaica's coral reefs and depletion of fish stocks threatens the continued sustainability of these industries in the future. The fish sanctuary at Bluefields Bay is a potential, major long term factor in local sustainable use of marine resources. Bluefields Bay Fish Sanctuary is run by a local based, non-governmental agency that has promoted understanding within the local community of the benefits of the fish sanctuary to local economy. The fish sanctuary protects the major contributing factors to the exceptional water clarity of Bluefields Bay, like seagrass beds, coral reefs, and mangroves, which makes it an appealing destination to tourists (Goreau, 1992). The presence of the fish sanctuary provides an alternative source of income for fishers to work as wardens. The spill-over effect of fish from the protected waters of the fish sanctuary also will improve fish stocks for food and for sale at market in the surrounding, fishable waters in the future (Roberts *et al*., 2001). In all, the fish sanctuary itself may also serve as a special destination attraction for future tourism.

Social and Cultural Sustainability. One of the major factors qualifying Bluefields Bay as a site for a fish sanctuary was an overwhelming majority of the community and local fishers in favor of the formation of the fish sanctuary (BBFS, 2013). The protection and preservation of Jamaica's natural resources is not only for tourism but for the Jamaican people as well (MoAF, 2008). The sustainable use of marine resources also means that those who have passed down the traditions of fishing from generation to generation will have more than just fish tales to pass on to their children. In keeping with continued efforts towards sustainable use of natural resources, future plans to build an outdoor market at Bluefields will also promote local economy for fisheries and tourism alike. The presence of a fish sanctuary is most potentially beneficial to small rural fishing communities like Bluefields and Belmont which are most at risk to be negatively impacted by the decline of marine resources.

CHAPTER 7

CONCLUSION

Marine ecosystems are the source of ecological benefits and socio-economical services including storm surge and wave action protection, recreation, and tourism activities, as well as a primary source of protein for small coastal communities like Bluefields and Belmont (Kendall et al., 2001). The protection of critical marine areas and their productive habitat is necessary to improve the marine resources of Jamaica (UNEP, 1996). Some of Jamaica's first marine protected areas date back to 1992 and now there are over 30 marine protected areas in Jamaica today with the inclusion of the nine, "no take" sanctuaries created in 2009, with Bluefields Bay in Westmoreland being one. The establishment of a successful marine protected area network must protect diverse, biologically significant areas on a local level as well as reduce the risk on a regional level of any one catastrophic event devastating important ecosystems within protected waters.

The Jamaican government has identified the need for baseline information for the new marine protected areas so that the protective measures can be evaluated and modified over time (Haynes-Sutton, 2009). In general, densities of key marine species were found to be twice or three times more inside the marine protected areas than outside in 2008 (NEPA, 2009 *cited in* Waite *et al.,* 2011). A 2011 survey of Montego Bay Marine Park and Negril Marine Park, two of Jamaica's oldest marine protected areas, reports that fish diversity and coral coverage is increasing within the two marine parks (Newman *et al.,* 2011 *cited in* Waite *et al*., 2011). Without initial, accurate documentation of baseline conditions, the positive changes that are a result of the marine protected areas remains subjective conjecture. It is too soon to document improvements in Bluefields Bay Fish Sanctuary. However, anecdotal reports suggest that young fish are increasing and some predator species are returning (Rudolph, 2012).

Bathymetric Mapping

In total, over five hundred depth measurements from field survey data were used to interpolate a smooth continuous surface to represent the phenomena of the bathymetry of the sea floor. Various interpolation models were used, but of the ones compared, the kriging method with a Gaussian kernel function was the overall best fit of the data set. Kriging is a geostatistical model that both obeys the geographic rule that things that are closer together are more closely related than things farther away from each other and also a statistical model that uses a kernel function fit to the semi variance of all data pairs to predict values for all non-data points. Kriging is often called the optimum method for interpolation because it takes into account the distance at which point pairs are no longer correlated and should not be taking into account into the weighted prediction of non-data point values. With the cumulative error of the handheld depth finder used and the error introduced by the interpolation process, the resulting bathymetric map has a vertical error of plus or minus 5.6 ft as well as a horizontal error of plus or minus 5 ft. This is a significant improvement over the contours denoted by the naval map of Savannah-La-Mar from 1980 for the shallow waters of Bluefields Bay. The bathymetric map is also important in that it can be used to identify areas with different benthic topography where further, more detailed research of both benthic cover and depth measurement is needed.

For example, topographic expressions of several coral reef areas and river paleo-drainage patterns can be observed on the map produced by this study.

Benthic Habitat Inventory

The physical habitat mapping and assessment of Bluefields Bay is a vital step to establishing the success of the Bluefields Bay Fish Sanctuary by providing baseline information upon which to base management plans and evaluation of future success. An initial benthic habitat map was made by delineating visually significant features from remotely sensed data such as coral reefs, sand beds, and the shoreline. Data from field survey were used to refine the initial benthic cover map. Additional fieldwork was conducted to complete point coverage of depth measurements within the protected area and to provide a quality control for the benthic cover map. Diver ground-truthing of predicted coral reef locations verified a 90% accuracy rate.

The inventory of the benthic habitat was then represented as percentages of the total protected area each habitat covered. The sea grass beds are the most abundant habitat in the protected area of Bluefields Bay (Table 7). Seagrass beds are best represented within the protected area at 82% of the benthic area of the bay. The shallow marine floor of Bluefields Bay has long been covered by extensive sea grass beds (Goreau, 1992). Coral reefs represented 6% of the protected area of the bay which is a total area of 0.77 km^2. The greatest clustering of coral reefs within the fish sanctuary is the large patch reefs that occur within the back reef zone near the seaward boundary of the MPA. Sand represented 12% of the benthic cover. One of the most significant features is the sand bed that occurs at the very northeastern end of the bay (Figure 29, Figure 32).

Intertidal Habitat Inventory

The intertidal habitat was classified using a series of GPS located, overlapping photographs. A delineation of the shoreline was buffered 200 ft to symbolize the intertidal zone and categorized into the corresponding intertidal habitats from habitat classified GPS points. The inventory of the intertidal habitats was then represented as the percentage of the total length of the shoreline that was each habitat type.

The shoreline intertidal zone of Bluefields Bay includes a wide variety of habitat types. These habitat types are mangroves (42% or 4.97 km), limestone caves that are periodically inundated, sandy beaches (36% or 4.22 km), artificial structures like unconsolidated rip rap (7.3% or 0.87 km) and sea walls (3.9% or 0.46 km), and limestone cliffs with large boulder sized rubble (4.1% or 0.49 km). Along the northern portion of the bay where there is significant land area between the road and the shoreline is where the majority of the mangroves occur (Figure 33). The mangroves that occurred along the coastline where the coastal road runs parallel to the intertidal zone were observed to be occupying a thin strip of land five to ten meters wide. Other habitat types like limestone cliffs, rocky boulder and rubble, riprap, and sea walls occur primarily along the southern half of the coastline. One of the primary reasons for the location of sea walls is to protect the coastal road. Riprap is unconsolidated material that has been placed around residences to preserve or expand the property. Limestone cliffs and boulder strewn or rocky rubble lined coastline occurs naturally along the southern central coastline of Bluefields Bay where the up-thrown side of an old set of faults meets the shoreline.

Recommendations

National Level. Based on the benthic habitat map and the cross sections of the protected area of the bay, it can be concluded on legislation level that the seaward boundary of the protected area of Bluefields Bay falls short of protecting the significantly sized fringing coral reefs that protect the bay from wave activity. As always, management of marine resources is a finite balance between ecosystems in need of protection and a local populace who is dependent on marine resources for their livelihood. Without a detailed survey of live coral cover, it is difficult to separate one reef among all that is more biologically productive and diverse.

If seaward expansion of Bluefields Bay Fish Sanctuary cannot be implemented, it is recommended that at least the protected area of Bluefields Bay be expanded to include the shallow reef head known as Moor's Reef off of Belmont Point. This reef appears in a number of navigation and naval maps as a prominent feature; meaning that it is not only a spatially significant feature but also a temporally significant one as well. The other fringing reefs would remain open fishing waters for local fishermen who depend on the sea for their livelihood, thereby reducing the opposition that might arise should all the fringing reefs be immediately declared off limits. Moor's Reef is also advantageously situated close to the wardens' station.

Other recommendations for the future of Bluefields Bay from a governmental viewpoint are the completion of a detailed, live coral cover survey and the expert review of resulting map from this study for further quality control. It is also recommended that the public bathing beach within the protected area of Bluefields Bay be considered as a possible site for water quality monitoring programmes such as the Blue Flag certification program, which is a voluntary environmental certification programme designed to promote sound environmental management systems, consistent environmental education, good water quality, and safe bathing facilities (Townsend, 2012). There is also a need for future monitoring of water quality of runoff from local rivers (Ebert, 2010).

Local Level. On a local level, it is recommended that a secondary, north location for a wardens station be considered and established if at all possible. Probably the largest patch reef present within the marine sanctuary is located in the northern end of the bay and is also located beyond the viewpoint of the wardens station on the southern end of the bay's coastline. In the course of field work a pair of dolphins, one adult and one juvenile, were sighted within the vicinity of the north reef. On another day, a nurse shark whose length was roughly estimated to longer than six feet was sighted by snorkelers during a visit to the north reef site. It may be inferred from the sightings of larger predators that the north reef is biologically significant as well as spatially significant as one of the largest patch reefs in the fish sanctuary. From observations of warden enforcement of the no-take status of the protected waters during field work, it seemed that the southern portion of the protected area of the bay was preferentially monitored over the northern portion. A secondary headquarters at the north end is potentially a small change that would significantly improve the effectiveness of enforcement, thereby improving the overall effectiveness of the fish sanctuary. The new dual-engine patrol boat now operating in Bluefields Bay Fish Sanctuary will also help to expand the patrol areas for effective protection of coral and fish resources.

Threats. A number of potential threats exist that will need to be noted when monitoring ecosystem health in the future. Future urban development along coastal road that runs parallel to the southern coast of Bluefields Bay may conflict with the preservation of mangrove forest. Westmoreland is one of the leading parishes in agriculture industries in Jamaica. Specific monitoring for harmful pesticides and chemicals in fresh water runoff should be conducted, especially in the event that the intertidal buffer zone is added to Bluefields Fish Sanctuary. Clear delineation of the fish sanctuary boundaries by buoys and soon to be posted notices of the no fishing status of the bay are some of the countermeasures against the threat of poaching, but sanctuary wardens should be continue to be diligent to prevent trapping, use of dynamite, and other poaching that threatens the effectiveness of the fish sanctuary.

Summary

The physical habitat mapping and assessment of Bluefields Bay has provided a timely, up to date benthic and intertidal habitat map that shows the spatial extent and associations between all habitat types as well as target essential fish habitats like mangroves, seagrass beds, and coral reefs. Bluefields Bay is an ideal location for many reasons, but there are three key spatial ones. The predominate intertidal habitat of the coastline within the fish sanctuary is mangroves (Table 7). The predominate benthic habitat within the shallow marine setting of the protected area is continuous sea grass beds (Table 7). Approximately 5 km^2 of fringing coral reef protects the inner bay from storm surges and wave activity. As ideal a setting as Bluefields Bay is for a marine protected area, only the seagrass beds within the shallow waters of the bay are protected by the current extent of the sanctuary. Every effort should be made towards including the mangroves in an intertidal buffer zone and the fringing reefs beyond the seaward boundary of the bay within the marine protected area. With detailed, initial documentation, the spatial extent and location of these essential fish habitats is now known and can be used for improvement in management, protection, and delineation of Bluefields Bay Fish Sanctuary.

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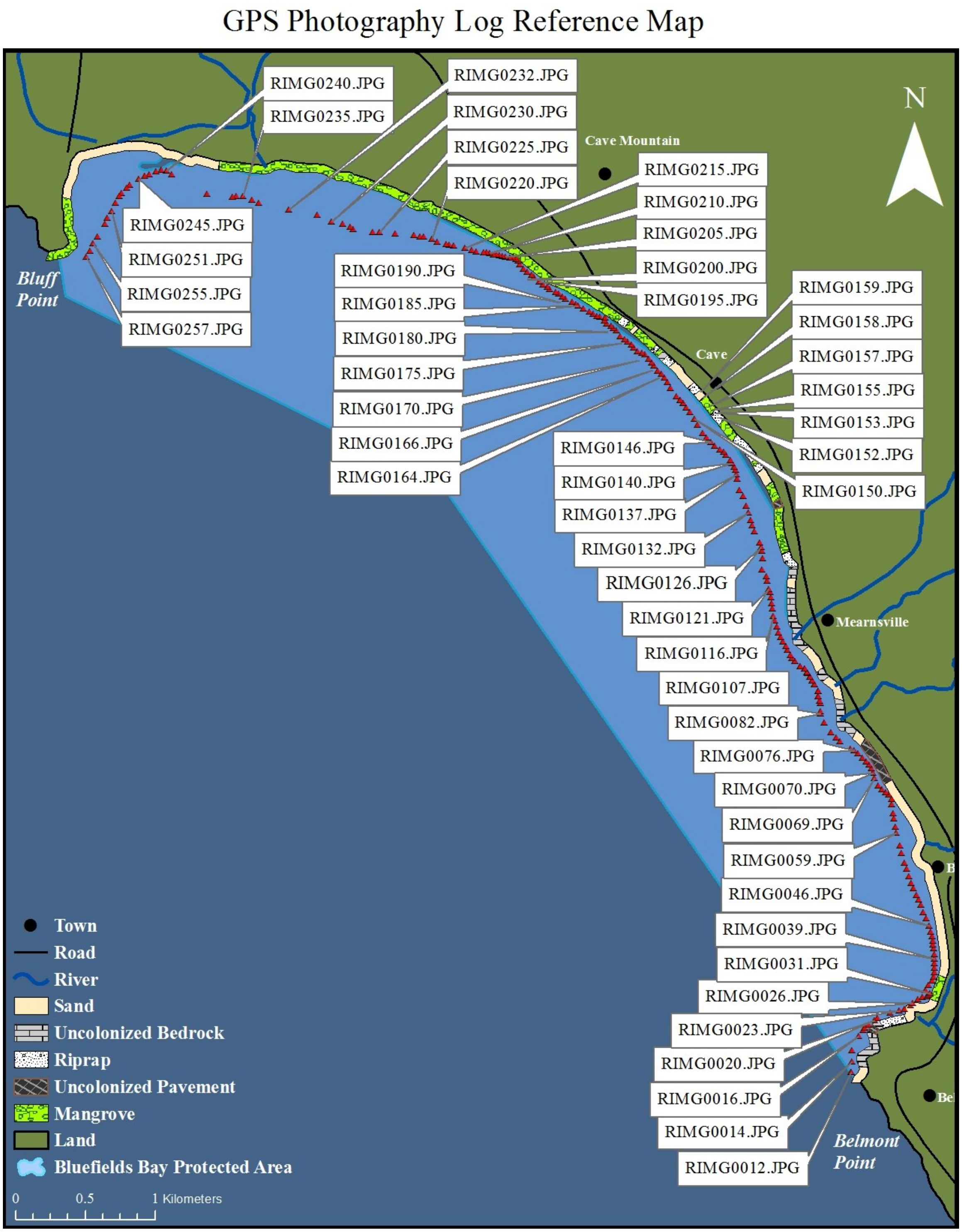
APPENDICES

Appendix A. GPS Photography Log



Appendix A- 1. GPS Photography Reference Map (MGI, 2010).


Appendix A- 2. RIMG0012 - Belmont Point.


Appendix A- 3. RIMG0014 - Bedrock.


Appendix A- 4. RIMG0016 - Sea Wall and Bedrock.


Appendix A- 5. RIMG0020 - Riprap.


Appendix A- 6. RIMG0023 - Blue Hole Creek Mouth.


Appendix A- 7. RIMG0026 – Fishing Beach at BPCA.

Appendix A- 8. RIMG0031 - Mangroves.

Appendix A- 9. RIMG0039 - Sand beach.

Appendix A- 10. RIMG0046 - Sand beach.

Appendix A- 11. RIMG0059 – Bluefields River Mouth.


Appendix A- 12. RIMG0069 - Public Swimming Beach.


Appendix A- 13. RIMG0070 - Public Swimming Beach.

Appendix A- 14. RIMG0076 - Sand Beach before Sea Wall.

Appendix A- 15. RIMG0082 - Limestone Boulder Beach.


Appendix A- 16. RIMG0107 - Limestone Boulder Beach.


Appendix A- 17. RIMG0116 - Limestone Boulder Beach.


Appendix A- 18. RIMG0121 - Limestone Boulder Beach.


Appendix A- 19. RIMG0126 - Limestone Bedrock (left) and Limestone Boulder Beach (right).


Appendix A- 20. RIMG0132 - Sand Beach.


Appendix A- 21. RIMG0137 - Riprap.


Appendix A- 22. RIMG0140 - Mangrove.


Appendix A- 23. RIMG0146 – Riprap and Sea Wall.

Appendix A- 24. RIMG0150 - Riprap.

Appendix A- 25. RIMG0152 - Riprap and cultured vegetation below new development.

Appendix A- 26. RIMG0153 - Riprap, cultured vegetation, and residence below new development.

Appendix A- 27. RIMG0155 - Riprap and residence under new development.


Appendix A- 28. RIMG0157 - Mangroves below new development.


Appendix A- 29. RIMG0158 - Mangroves below new development.


Appendix A- 30. RIMG0159 - Mangroves below new development.


Appendix A- 31. RIMG0164 - Waterwheel.


Appendix A- 32. RIMG0166 - Mangroves.


Appendix A- 33. RIMG0170 - Mangroves.

Appendix A- 34. RIMG0175 - Mangroves.

Appendix A- 35. RIMG0180 - Mangroves.


Appendix A- 36. RIMG0185 - Mangroves.


Appendix A- 37. RIMG0190 - Mangroves.


Appendix A- 38. RIMG0195 - Mangroves.


Appendix A- 39. RIMG0200 - Mangroves.

Appendix A- 40. RIMG0205 - Mangroves.

Appendix A- 41. RIMG0210 - Mangroves.


Appendix A- 42. RIMG0215 - Mangroves.


Appendix A- 43. RIMG0220 - Mangroves.

Appendix A- 44. RIMG0225 - Mangroves.

Appendix A- 45. RIMG0230 - Mangroves.


Appendix A- 46. RIMG0232 - Sweet River Mouth.


Appendix A- 47. RIMG0235 - Mangroves.


Appendix A- 48. RIMG0240 - Sand beach.


Appendix A- 49. RIMG0245 - Sand beach and residence.

Appendix A- 50. RIMG0251 - End of sand beach (right) and mangroves (left).

Appendix A- 51. RIMG0255 - Mangroves.


Appendix A- 52. RIMG0257 - Bluff Point.

Appendix B. Full list of Habitat Types and Zones

NOAA Classification Scheme with four primary attributes and hierarchical levels therein (*Modified from* Zitello et al., 2009).

Geographic Zone

- Land
- Shoreline Intertidal
- Lagoon
- Back Reef
- Reef Crest
- Fore Reef
- Shelf
- Shelf Escarpment
- Unknown

Geomorphological Structure

- Coral Reef and Hard Bottom
    - Bedrock
    - Patch Reef
    - Consolidated Sediment
    - Sand
- Artificial
    - Reef
    - Riprap
- Other Delineations
    - Land

Unknown

Biological Cover

Major Cover

Algae

Coral

Scattered Coral/Rock

Mangrove

Seagrass

Uncolonized

Unknown

Percent Major Cover

10% - <50%

50% - <90%

90% - 100%

Unknown

Coral Cover

0% - <10%

10% - <50%

50% - <90%

90% - 100%

Unknown

Unconsolidated Sediments (0 to less than 10 percent submerged vegetation cover)

- Sand
- Mud

Submerged Vegetation

- Continuous Seagrass (80 percent to 100 percent cover)
- Patchy (Discontinuous) Seagrass (10 percent to less than 80 percent cover)
- Continuous Macroalgae (90 percent to 100 percent cover)
- Patchy (Discontinuous) Macroalgae (10 percent to less than 90 percent cover) Coral Reef and Hardbottom
- Fringing Reef
- Individual Patch Reef
- Aggregated Patch Reefs
- Scattered Coral/Rock in Unconsolidated Sediment (0 percent to less than 10 percent Submerged Vegetation)
- Scattered Coral/Rock in Consolidated Sediment (10 percent to 90 percent Submerged Vegetation)
- Colonized Sea Wall
- Colonized Bedrock
- Colonized Sea Wall with Sand Channels
- Reef Rubble
- Uncolonized Sea Wall
- Uncolonized Bedrock
- Uncolonized Sea Wall with Sand Channels

Artificial

- Artificial Reef

- RipRap

Other Delineations

- Land
- Mangrove
- Unknown

Appendix C. Position and Area of Coral Reefs at Bluefields Bay.

Appendix C- 1. Position and Area of Coral Reefs Outside Fish Sanctuary.

Coral Reef Key	Area (km^2)	Lat	Long	Coral Reef Key	Area (km^2)	Lat	Long
0	0.0024	-78.08	18.19715	28	0.0007	-78.086245	18.195539
1	0.0016	-78.0796	18.19581	29	0.0022	-78.084209	18.193567
2	0.0017	-78.0802	18.19525	30	0.0004	-78.083779	18.192992
3	0.0005	-78.0787	18.19594	31	0.0004	-78.083513	18.192888
4	0.0028	-78.0778	18.19608	32	0.0002	-78.08307	18.192603
5	0.0025	-78.0764	18.1958	33	0.0008	-78.082964	18.192444
6	0.0004	-78.0758	18.19564	34	0.0005	-78.082553	18.192526
7	0.0003	-78.0758	18.19606	35	0.0021	-78.082372	18.192192
8	0.0009	-78.0755	18.1963	36	0.0002	-78.081998	18.192808
9	0.0017	-78.0739	18.19525	37	0.0004	-78.082217	18.192914
10	0.0002	-78.073	18.1954	38	0.0002	-78.081974	18.193174
11	0.0003	-78.0732	18.1955	39	0.0002	-78.081639	18.193228
12	0.0091	-78.0629	18.19184	40	0.0005	-78.081832	18.192471
13	0.0019	-78.066	18.19189	41	0.0005	-78.08151	18.192481
14	0.0009	-78.0656	18.19258	42	0.0005	-78.081187	18.192692
15	0.0184	-78.0653	18.19015	43	0.0001	-78.082588	18.193017
16	0.0003	-78.0649	18.18911	44	0.0000	-78.077746	18.191249
17	0.0031	-78.0648	18.18873	45	0.0002	-78.077704	18.191447
18	0.0019	-78.0604	18.18874	46	0.0003	-78.077432	18.191752
19	0.0048	-78.0609	18.18794	47	0.0000	-78.077508	18.191542
20	0.0355	-78.0599	18.1866	48	0.0001	-78.07845	18.191997
21	0.0046	-78.0576	18.18563	49	0.0087	-78.079403	18.191214
22	0.0069	-78.0587	18.18446	50	0.0015	-78.080146	18.191449
23	0.0123	-78.0367	18.13831	51	0.0199	-78.074402	18.190775
24	0.0014	-78.0344	18.13984	52	0.0017	-78.077961	18.191724
25	0.0022	-78.0322	18.14001	53	0.0005	-78.078662	18.191718
26	0.0177	-78.0349	18.13645	54	0.0224	-78.072132	18.191759
27	0.0013	-78.0859	18.19577	55	0.0014	-78.06971	18.192099

Appendix C- 2. Position and Area of Coral Reefs Outside Fish Sanctuary.

Coral Reef Key	Area (km^2)	Lat	Long	Coral Reef Key	Area (km^2)	Lat	Long
56	0.002246	-78.0703	18.18881	83	0.000646	-78.074	18.18663
57	0.017621	-78.0682	18.19195	84	0.006691	-78.0721	18.18484
58	0.001445	-78.0762	18.19071	85	0.0011	-78.0737	18.18614
59	0.001442	-78.0763	18.19012	86	0.000286	-78.0743	18.18657
60	0.000902	-78.0765	18.18967	87	0.140624	-78.0669	18.18597
61	0.001861	-78.0771	18.18924	88	0.041529	-78.0646	18.18184
62	0.008066	-78.0745	18.18857	89	0.00113	-78.0668	18.1827
63	0.004242	-78.0754	18.18763	90	0.001055	-78.0651	18.17879
64	0.000573	-78.0754	18.1865	91	1.854408	-78.0807	18.18459
65	0.000182	-78.0788	18.19119	92	0.618803	-78.0939	18.19601
66	0.000055	-78.0787	18.19215	93	0.427566	-78.0596	18.17835
67	0.000071	-78.0791	18.19184	94	0.189372	-78.0699	18.17465
68	0.000109	-78.0785	18.19218	95	0.000806	-78.0673	18.17761
69	0.000005	-78.0791	18.19073	96	0.003546	-78.0673	18.1757
70	0.000022	-78.079	18.19068	97	0.003653	-78.0648	18.17739
71	0.000607	-78.0752	18.18806	98	0.001637	-78.0643	18.17682
72	0.000117	-78.0754	18.18799	99	0.002534	-78.0512	18.17567
73	0.008112	-78.0784	18.18811	100	0.006065	-78.0472	18.16956
74	0.001473	-78.0792	18.1875	101	0.018058	-78.0483	18.16867
75	0.000731	-78.0797	18.18972	102	0.01095	-78.0488	18.17059
76	0.000407	-78.08	18.18921	103	2.072221	-78.0496	18.15946
77	0.000288	-78.0799	18.18961	104	0.013826	-78.0358	18.15487
78	0.002185	-78.0804	18.18856	105	0.012628	-78.0373	18.15514
79	0.000319	-78.0801	18.18825	106	0.004798	-78.0367	18.15609
80	0.000579	-78.0808	18.1881	107	0.008436	-78.0368	18.15381
81	0.000501	-78.081	18.18818	108	0.0106	-78.039	18.15293
82	0.003681	-78.0747	18.18679	Total	5.7147		

Appendix C- 3. Position and Area of Coral Reefs Protected Inside Fish Sanctuary.

Coral Reef Key	Area (km^2)	Lat	Long
109	0.0106	-78.0759	18.20287
110	0.0011	-78.0689	18.19666
111	0.0006	-78.0691	18.19616
112	0.0001	-78.0694	18.19616
113	0.0011	-78.0679	18.19655
114	0.0018	-78.0663	18.19603
115	0.0005	-78.0659	18.19584
116	0.0020	-78.0659	18.1948
117	0.0024	-78.068	18.19499
118	0.0003	-78.0684	18.19485
119	0.0006	-78.065	18.19438
120	0.0010	-78.063	18.193
121	0.0037	-78.0609	18.19215
122	0.0052	-78.0581	18.1895
123	0.0044	-78.0446	18.1864
124	0.0101	-78.0524	18.18594
125	0.0033	-78.0573	18.19266
126	0.0027	-78.0436	18.17534
127	0.0027	-78.0473	18.17829
128	0.0428	-78.0409	18.16941
129	0.0335	-78.0378	18.16727
130	0.0015	-78.0334	18.16846
131	0.0026	-78.0352	18.17008
132	0.0024	-78.0331	18.16929
133	0.0113	-78.0346	18.15723
134	0.0057	-78.0607	18.19107
135	0.0026	-78.0614	18.19177
136	0.0026	-78.0599	18.18996
137	0.0018	-78.0595	18.189
138	0.0705	-78.0473	18.17456
139	0.0021	-78.059	18.1884
Total	0.2338		