INTEGRATED WATERSHED MANAGEMENT IN BLUEFIELDS BAY, JAMAICA

A Masters Thesis

Presented to

The Graduate College of

Missouri State University

In Partial Fulfillment

Of the Requirements for the Degree

Master of Science, Geospatial Sciences in Geography and Geology

By

Jackie Elizabeth Ebert

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INTEGRATED WATERSHED MANAGEMENT IN BLUEFIELDS BAY, JAMAICA

Geography, Geology, and Planning

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ABSTRACT

Water supplies for drinking and ecological support in Jamaica are threatened due to poverty and poor infrastructure, and the coastal waters into which they flow are polluted in some areas. Recently, Bluefields Bay, located on the southwest coast of Jamaica, has been designated a national fish sanctuary and there are questions about the condition of water quality in the area and its ability to support both human uses and fish habitat requirements. Integrated watershed management is a holistic approach that connects water quality problems to the land use practices and environmental conditions affecting them. The objectives of this study are to (i) utilize GIS to delineate and characterize sub-watersheds; (ii) complete water quality testing along all the rivers and major springs flowing into the bay; and (iii) classify the subwatersheds according to the risk of water degradation. The best stream channel and water conditions were found where streams flow through healthy wetland environments, are located away from settled areas, and have relatively wide or established riparian corridors. Most of the water problems observed are related to poor solid waste management, domestic water treatment, and the lack of protection of critical watershed areas such as riparian buffer zones, freshwater and coastal wetlands, and spring recharge areas. A community-based water monitoring program can be used to increase awareness of water issues, train the next generation of environmental managers, assess the condition of river quality through time, and improve acceptance of conservation practices to control pollution problems.

KEYWORDS: Jamaica, stream health, GIS, water quality, land use

This abstract is approved as to form and content

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CHAPTER 1

INTRODUCTION

Resource depletion and stress are growing problems throughout developing countries in the Caribbean. Characterized by their lack of infrastructure, industrialization, and sophisticated technology, developing countries are known for their poor economies and poverty (Cohen, 2006). As they continue to experience population growth, the effect that humans have on local ecosystems and resources is maximized. Population growth increases development, which decreases the availability of the land surface and resources required to meet the increased demand for basic necessities including food, fuel, and building materials (Datta, 1995). The economies of cities in the developing Caribbean rely heavily on the environment and natural resource production to support their livelihoods, making it pertinent to improve the productivity and sustainability of natural resource bases.

Water Problems in the Developing World

As developing populations expand, increased stress is placed on the availability and allocation of water resources (Granger, 1983). The world's fastest growing cities are located in low income countries and are characterized by poor water infrastructure and waste water treatment facilities (Huang and Xia, 2001). The continued extraction of freshwater for drinking, agriculture, and every day living practices threatens the available water supply. As the demand for natural resources by a growing global population continues to increase, fresh water will be the first resource to run short (Wagner et al., 2002). The growing level of contamination in water resources increases health concerns, making it critical to investigate sustainable management and use of not only the water resources but also the land use and all encompassing factors affecting the water.

Developing countries are particularly susceptible to the harmful effects of land use practices on their water resources, influenced by the minimal regulations for sewage treatment, waste disposal, land management, and water quality standards practiced (Wels, 2000). Forests are cut down to clear land for agriculture and cattle grazing, lumber for building material, fuels to be turned into charcoal and firewood, and land used for urban development (Allen and Barnes, 1985). Deforestation in turn leads to loss of habitat and biodiversity, increased soil erosion, and disruption to the water cycle (Evelyn et al., 2003; Bullard, 1966). Pesticides are applied in large amounts to supplement the increased demand for raw living materials, and these agro-chemicals pose a major potential environmental hazard for human and biological health when introduced into water sources. A majority of people will then use the empty pesticide containers to fill and store drinking water, which poses extreme health risks and contamination of water (Igbedioh, 1991). Both rural and urban populations in developing countries struggle with access to community water supply and have inadequate disposal of waste excrement. The challenges associated with acquiring safe drinking water and properly treating sewage threaten water quality (Subrahmanyam, 1977). Improper land use practices further exacerbate already existing water quality problems, so there is need to implement sustainable practices and regulations.

Coastal waters are susceptible to degradation due to the interconnectedness between the landscape and the coast. Disturbances in coastal watersheds are widespread and increasing as development and community growth occurs, increasing loading to the coast (Valiela et al., 1997, Caraco et al., 1987). Nutrient transport by surface runoff and streams has been well documented and human activities in coastal watersheds provide major sources of nutrients that enter coastal ecosystems (Valiela et al., 1992; Valiela et al., 1997; Correll et al., 1992). Pollutant contributions also leak into groundwater, which flows into receiving estuaries (Lewis, 1987). Nutrient inputs to coastal waters are largely human-induced from watersheds but several far-shore processes, such as atmospheric deposition and acid rain, may contribute to nutrient concentrations (Hinga et al., 1991). In order to implement management practices in coastal waters, it is important to understand the connections among land use practices, watersheds, and the sources into which they flow.

Coastal resources within the Caribbean are being degraded by poor land use practices within contributing watersheds. In order to remedy the damage and depletion caused to the coastal ecosystems it is necessary to implement land and water assessments to evaluate resources (Sheng, 1999). Coastal communities depend on coastal and estuarine waters to support their fishing livelihoods, eco-tourism ventures, subsistence lifestyles, and economic stability, and would benefit from environmental planning that links the natural resource base to economic development (Gleick, 1998). Historical approaches to water planning were often one-sided and neglected the ecological and environmental impacts of the project. More intelligent water resources management is necessary to protect the aquatic biological resources and support the economy of the coastal communities.

Bluefields Bay Watershed Concerns

The small island state of Jamaica has the unique geographical classification as being a 'ridge to the reef' environment (Pantin et al., 2008). Small islands exist within the coastal zone, with the understanding that whatever happens upstream and inland eventually finds its way to the coast. The larger watershed can generally be divisible into five main sub-regions, or subwatersheds. The ridge is followed by the upper subwatershed, which usually consists of mainly forested and undisturbed cover. The middle subwatershed is also forested, but shifts towards agriculture, food forest plots, and settlements. The lower subwatershed is composed of higher intensity settlements and agriculture, roads, and other varying land uses. The final two sub-regions, the coastal fringe and near-shore ecosystems vary in the degree of land use and development, be it fishing villages, housing, or tourism. Figure 1 provides a conceptual model of a typical watershed in a 'ridge to the reef' system.

The southwest coast of Jamaica is being adversely affected by poor water quality in runoff released from coastal communities and inland watershed areas (Wels, 2000). In Jamaica many residents rely on coastal resources for their livelihoods (Goreau, 1994). Stresses on the coastal ecology of the region are being amplified by other human activities including poor domestic water treatment, disposal of effluent and garbage, and over fishing practices. Along with increased pressure from expanding development along the coast, these impacts threaten basic environmental conditions necessary to support healthy communities and a stable economy (Thomas-Hope and Jardine-Comrie, 2007).

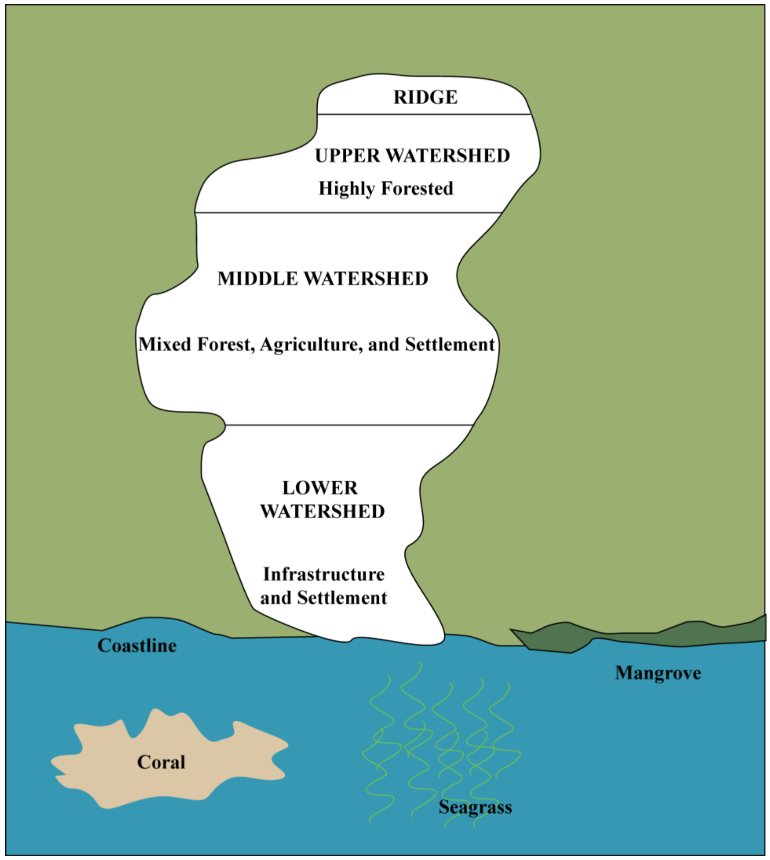


Figure 1. Subwatershed breakdown of the 'ridge to the reef' system (adapted from Small & Island Developing States (SIDS) Greening Policy, Pantin et al., 2008).

This problem is particularly heightened in Bluefields Bay where it is believed that chronic effects of excessive nutrient inputs are degrading coastal fisheries and coral reef resources (Figure 2). In response to the degrading environmental conditions, the Jamaican government, on December 31, 2008, announced the establishment of Bluefields Bay as a fishing sanctuary, one of eight new critical areas around the island. Fisheries in developing countries are under increasing pressure from competing uses of resources and the unsustainable practices of Jamaican fishermen, such as harvesting juvenile fish, using seine nets that are banned in most countries, and destroying sea grass, corals, and eggs laid by female fish, cause overfishing throughout the bay and inhibit the sustainability of

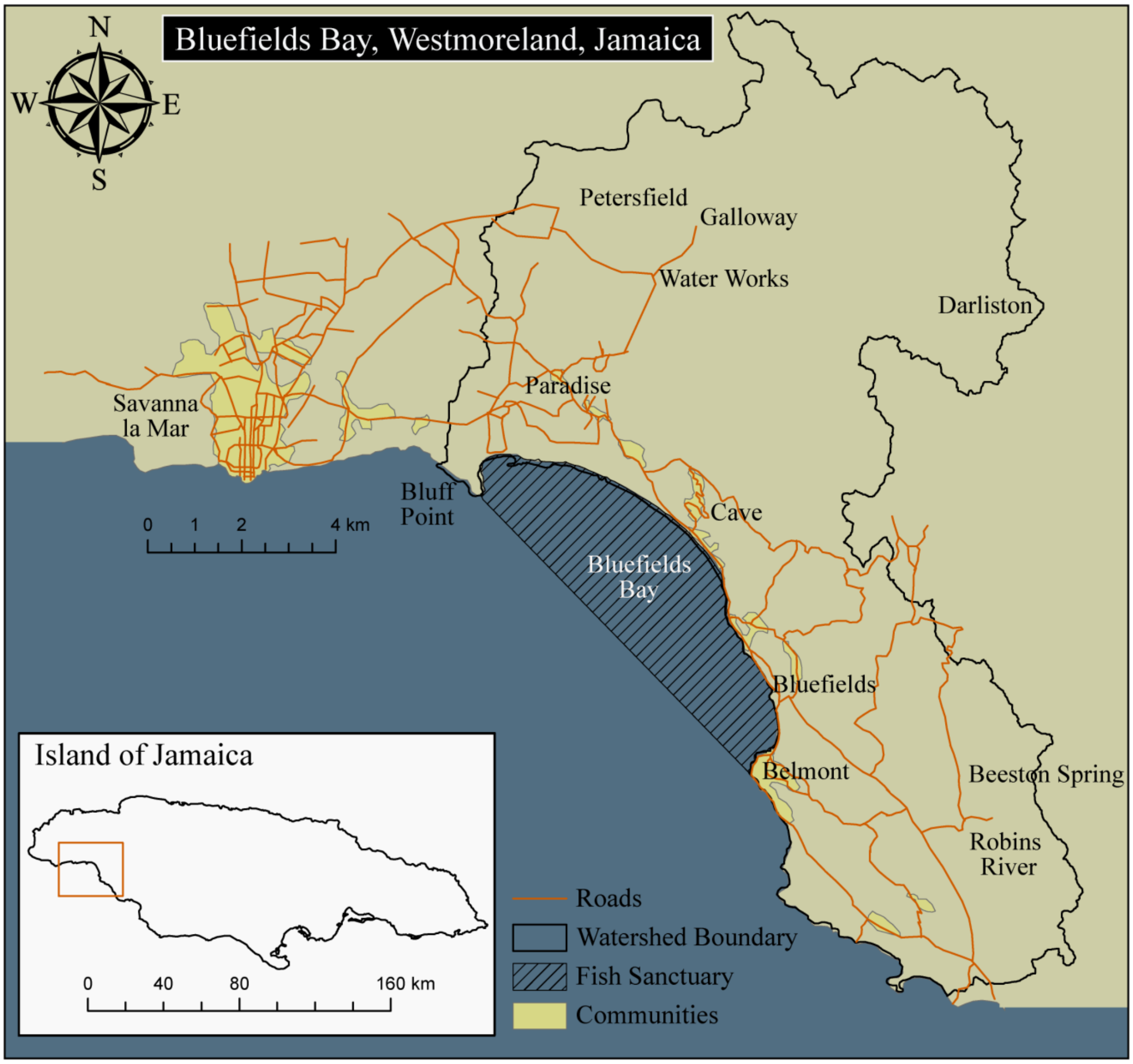


Figure 2. Location of Bluefields Bay, Westmoreland, Jamaica. Bluefields Bay stretches between Bluff Point and Belmont Point.

coastal resources (Koslow et al., 1988; Nielsen et al., 2004). Establishing Bluefields Bay as a sanctuary (Figure 3) means that fishermen may only fish outside of the established boundaries of the bay, leaving the protected area to enhance and promote sea grass and juvenile fish habitat and rearing. The government provides funding to support the protection and management of the marine habitats and coral reef systems that are located within about 1.5 miles of the coastline. The establishment of the bay as a sanctuary, or

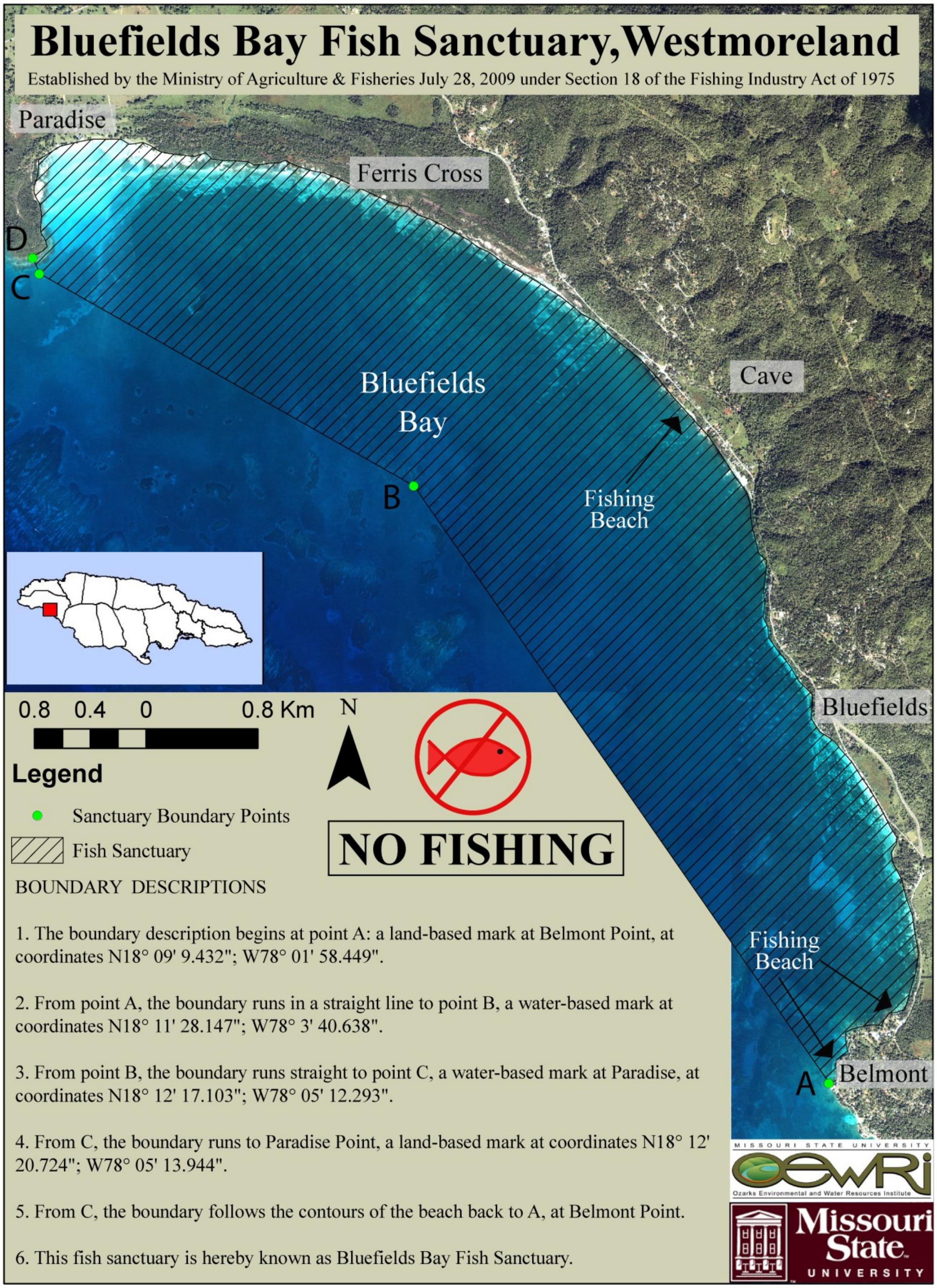


Figure 3. Bluefields Bay Fish Sanctuary. This map is posted at fishing beaches along the coast, notifying residents of the recent establishment.

critical area, demonstrates the importance of conserving the resources within the bay in order to improve the life of local residents and develop sustainable economies focused on fishing and tourism.

The establishment of the sanctuary promotes the need to study the water quality of the rivers and streams draining Bluefields Bay and the land use practices influencing those waters. Land use change may be one of the single greatest factors affecting ecological resources (Hunsaker and Levine, 1995). Residents rely on the fishing industry as a source of income, food, recreation, and tourism and there are questions about the condition of the water quality in the area and its ability to support both human uses and fish habitat requirements (Griffin et al., 2001). While threats to Bluefields Bay have generally been identified, the distribution and extent of specific pollution sources within communities and contributing inland watershed areas is not well understood (Basnyat et al., 1999). Both domestic and commercial activities pollute inland rivers and coastal waters, which can reduce opportunities for economic growth and community tourism. These activities negatively affect both the economy and ecology of the region, as well as demonstrate the interconnectedness between landscape surface waters and the bay.

Studying the relationship between land disturbance and water quality contributions to the bay requires environmental planning on a watershed approach (Wang, 2001). Bluefields Bay is affected directly by fishing practices, but also by water and chemical inputs from adjacent coastal land area. In general, up to 80% of the pollution load in coastal waters can originate from land-based activities (United Nations Environment Program, 2010). In order to adequately evaluate and manage the resources of the bay information is needed concerning the water quality of rivers flowing into the bay, as well as sources and threats of pollution with contribution from watersheds surrounding areas of the bay (Villasol et al., 1998). Land-use activities occurring in the surrounding watersheds affect the water quality by altering sediment, chemical loads, and watershed hydrology and it is important to understand the effect these activities have on the environment and the water resources located in the watershed (Basnyat, et al., 1999). Conditions in the watersheds draining Bluefields Bay directly affect the ecology of the bay. Assessing the health of each contributing watershed is a local-scale and personal approach to environmental planning (Wagner et al., 2002).

Watershed-Based Planning

When assessing a watershed and developing a plan, it is useful to consider the watershed's configuration and associated terminology. A watershed is most commonly defined as an area of land that contributes runoff to a particular drainage point along a waterway (Caraco et al., 1998; U.S. Environmental Protection Agency, 1998). The total surface area of land drained by a river and its tributaries is known as a drainage basin. The drainage, or hydrographic basin, is separated topographically from adjacent basins by geographical units such as a ridge or mountain. Watersheds come in all shapes and sizes, and can be subdivided into smaller management or geographic units known as subwatersheds (Caraco et al., 1998). These units are of a size that can be managed according to land use units and practices within the specific subwatersheds, and specific plans for each subwatershed can be crafted accordingly. Figure 4 below illustrates the concept of multiple planning units within a larger water system.

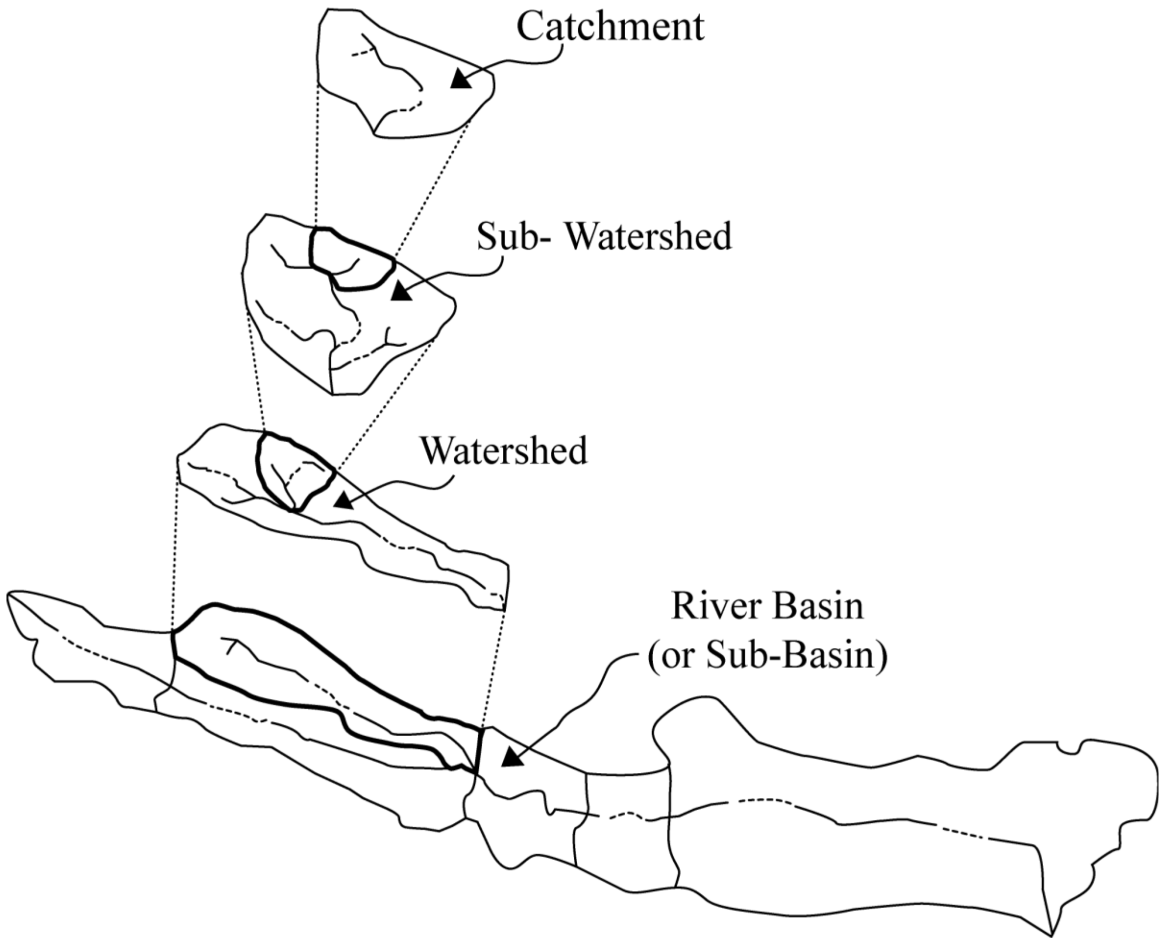


Figure 4. River basin management units within a watershed (adapted from Clements et al., 1996).

For planning purposes, watersheds and subwatersheds can be classified according to specific land use practices and water resources within their delineated boundaries (Cambareri and Eichner, 1998; Hunsaker and Levine, 1995). A specific watershed may have any number of individual subwatersheds delineated within its boundary, and local watershed classification proves most effective in narrowing down and properly identifying stressors and resources in a specific system. Implementation of watershed planning for each unit can be structured according to the size, landscape features, distance from the coast, and current land uses, and the effect those uses are having on the watershed (Finkl, 2004). Stream classification within a watershed context determines local impacts of land-use practices and the cumulative impacts of human activity on stream biota and ecological conditions (Frissell et al., 1986; Detenbeck et al., 2000). Watershed classification on a local, subwatershed level allows detailed management that addresses specific goals designed for each watershed.

Nutrient and heavy metal pollutants are contributed to surface, ground, and coastal water areas from both point and non-point sources. A point source of water pollution can be identifiable at a single location, where pollutants are discharged from sources such as industrial plants, municipal waste treatment plants, and oil refinery discharge outlets directly into a body of water (Fulweiler and Nixon, 2005). Nonpoint pollution affects a water system from diffuse, non-direct sources, including pollutants delivered by storm runoff derived from natural and human sources (U.S. Environmental Protection Agency; Carpenter et al., 1998; Humenik et al., 1980). Fertilizers applied to agricultural plots and pesticides applied to food forests are typical sources of nonpoint pollution runoff that contributes to degrading water quality in Bluefields Bay (Robinson and Mansingh, 1999). Livestock also frequently graze along stream banks, washing fine sediment into fields and roads. Cattle also cause significant damage to wildlife habitat and erosion buffers and vegetation, ultimately impacting the water column and degrading water quality (Kauffman and Krueger, 1984). The water quality of the bay and contributing sources are influenced by both point and nonpoint pollutants, and the sources of these pollutants should be taken into consideration within the planning context.

Watershed risk assessments investigate the probability of a certain risk, or environmental event occurring within a watershed (Graham et al., 1991). These environmental events range from species extinction, exceedance of water contact standards, fish kills, and toxic chemical pollution spills. Classification provides the basis for increased risk prevention and provides goals for rational watershed restoration and planning (Detenbeck et al., 2000). Table 1 provides examples of watershed and landscape classification schemes and references for those approaches. The endpoint, or risk indicator, in a risk assessment represents the measure or variable being studied. Risk assessment mapping in the watersheds surrounding Bluefields Bay contributes to the watershed planning objectives of the bay, which include understanding and improving water quality threats and degradation (Chen et al., 1996). Watershed risk assessments help focus efforts on the highest priority or targeted environmental problems within a watershed.

Table 1. Watershed Risk Classification Schemes (adapted from Detenbeck et al., 2000).

Classification Approach/Purpose	Reference
Ecoregions	Omernik and Gallant, 1988
Ecological units	Maxwell et al. 1995
Landscape influences on stream habitats and biota	Richards et al. 1996
Landscape pattern types	Wickham and Norton, 1994
Flow regimes for planning basin-wide monitoring programs	Richards, 1990
Regional analysis, streamflow patterns	Poff and Ward, 1990
Identification of basins sensitive to NPS sediment inputs and transport	Whiting and Bradley, 1993
Stream habitat classification	Frissell et al. 1986
Stream reach classification	Rosgen, 1996

A watershed-level approach is sensible when attempting to protect water resources and quality throughout a community (Serveiss, 2002). Watersheds consist of a complex variety of resources such as trees, wildlife, soil, rocks, and water. Interactions between these components are intertwined, and a change in one resource can have a profound effect upon the condition of other components (Tecle et al., 2003). The interconnectedness of land and water processes in a watershed makes it critical to study not just the water itself but also all the other components interacting in the watershed. Collecting watershed-based information can be used to support broader planning initiatives that ultimately support the sustainable economic goals of communities that rely on the ecological integrity of Bluefields Bay and the contributing waters.

Purpose and Objectives

The purpose of this thesis is to carry out the initial watershed assessment in order to support the sustainable development and ecological progression of Bluefields Bay. The watershed assessment will be used to make recommendations for natural resource protection and sustainable community growth.

The four main goals of this plan include:

1. Protect drinking water and overall natural water quality;
2. Reduce pollution load in freshwater streams draining Bluefields Bay;
3. Promote land conservation in critical areas; and
4. Protect marine wildlife and habitat in the Bluefields Bay sanctuary.

This study uses three rounds of in-situ water quality monitoring data, census data, hydrologic data, and geographic information systems (GIS) data to assess and classify the rivers and subwatersheds as they contribute to the quality of water and health of the Bluefields Bay, Jamaica coastal area. The geographic area within the landscape surrounding Bluefields Bay was divided into five physiographic regions, which are presented in Table 2 below. Physiographic regions are defined based on their physical landscape characteristics, terrain, and valued resources and features.

Table 2. Physiographic regions of the Bluefields landscape.

Geographic Area	Definition	Valued Resources/ Key Features	Reference
(1) Reef	Underwater colonies of living animals found in marine waters	Diverse ecosystem/ provides shelter and home for fisheries/ valued tourism resource	Goreau, 1992 Lapointe, 1997
(2) Bay			
Offshore	Deeper water system supporting fisheries and valuable marine ecosystem	Marine biota/ reef formation vegetation growth/bed formation/ income source	Cooper and McLaughlin, 1998
Near shore	Shoreline setting shaped by geomorphic processes host to ecosystems and ecological functions	Rocky coast/ sandy beaches/ embayments/ river deltas	Finkl, 2004 Shipman, 2008
(3) Coastal Lowland	Narrow strip of lower land that stretches between the sea and a significant change in elevation	Wetlands/ mangroves/ wetter climate/ coastal development heavy water use/ high level of plant diversity and endemism	Shipman, 2008 Heijnis et al. 1999
(4) Mountain Transition	Central valleys and plateaus between the lowland and inland mountain range	Dynamic landscape/ water systems springs and karst/ agriculture	Robinson and Mansingh, 1999 Asprey and Robbins, 1953
(5) Inland Mountain	Steep forms and highest point in the landscape/ upland areas lack water	Less developed/ fragile slope practices/ headwater streams	Falkland, 2000 Goreau et al. 1997

The three main physiographic areas include coastal lowlands and valleys, transitional mountain ranges along the edge of a limestone plateau, and inland mountain. The bay is divided into reef and the bay, being either near shore or offshore. Subwatershed classification, watershed risk mapping, and water quality monitoring can be used to establish recommendations that link economic sustainability and development to a holistic watershed-based approach to environmental planning and resource conservation.

The four main objectives of this thesis are:

1. Subwatershed Mapping: delineate the topographic boundaries of the Bluefields Bay watersheds and subwatersheds using a watershed-based planning approach;

2. Watershed Classification: classify the Bluefields Bay subwatersheds as they relate to water quality and supply, landform and cover, and present human settlement;

3. Water Quality Monitoring: monitor discharge and water quality of permanent rivers draining into Bluefields Bay; and

4. Risk Assessment: develop a subwatershed risk approach to understand concerns and threats to the water supply and resources throughout Bluefields Bay.

Bluefields Bay Watershed

The Bluefields Bay topographic watershed is extremely dynamic and composed of hydrological, ecological, biological, and cultural sub-regions. These regions are continually interacting with one another, thus in order to investigate the concerns and threats to water supply and natural resources in the watershed, it is critical to understand the components which comprise the different regions. The Bluefields topographic profile can be divided into four main classification zones (Figure 5).

The Bluefields Bay watershed flows in to the coastal water body of Bluefields Bay, therefore also making it imperative to examine the coastal region as it is affected by the watershed flowing in to it. Components of the watershed are linked by flows of water, sediment, chemicals, and organic matter and these flows coexist within the watershed.

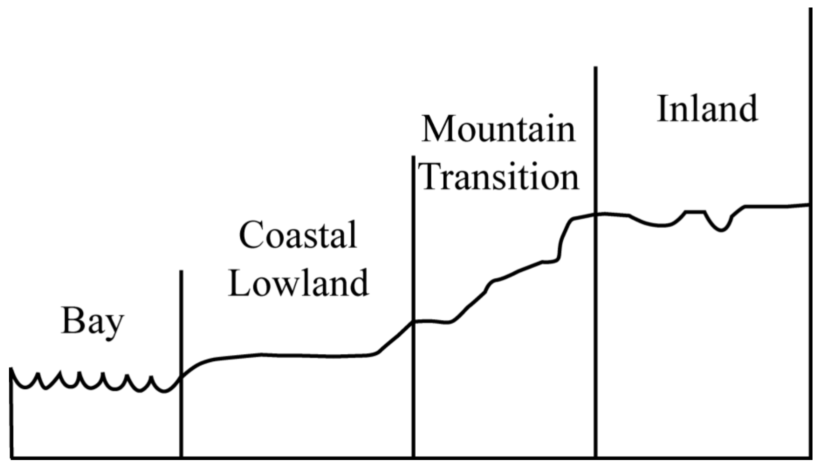


Figure 5. Physiographic regions in the Bluefields Bay watershed.

Inland mountain areas rise about 500 m above sea level. These upland areas are hilly and pocketed and usually require piped water systems and truck delivery to access water. The coastal range contains water sources including groundwater recharge and delicate headwater streams, which are directly affected by landscape changes within the watershed. Communities with water supply systems (natural drainage and public systems) are established in the uplands, and these communities have connected road, trail, and channel networks, as well as agriculture plots and water ways. These alterations to the landscape produce soil and vegetation erosion and morphology to the natural water systems.

Mountain front streams flow through the coastal areas into the bay, and varying subsistence farms are planted on land adjacent to these streams. Coastal lowlands are established between the mountain fronts and the coast, and these areas also feature numerous components. Coastal areas have a landscape of wetlands and mangroves, and well-established waterways. They also have relatively level land areas for agriculture and community development. Spring-fed stream systems on coastal plains also emerge as freshwater wetland areas due to the karst topography in the region. These coastal regions have stronger road and trail structures as well as industries and housing with built-in water supply systems. The shoreline areas stretching these coastal communities vary from muddy, sandy, and cobble beaches to shore rock and coral formations. The coast is developed with small villas, homes, and fishing villages. Coral reefs are located about half a kilometer to five kilometers off shore and sea grass beds are located on the ocean floor of the bay, which is important to juvenile fish habitat and rearing. The Caribbean Sea extends from the bay into open water. Since all of these components of the Bluefields Bay watershed (Figure 6) interact with one another, a landscape change affects not just one component but many.

The Bluefields Bay boundary can be defined according to several different boundaries. The bay has been established by coordinated geographic location boundaries which are considered the official sanctuary boundaries. The bay can also be generally defined according to the reef line that follows the shore. The location of the bay may also be described according to the cultural identification of specific locations and landscape features. This thesis identifies Bluefields Bay according to the government established location boundaries of the protected fish sanctuary.

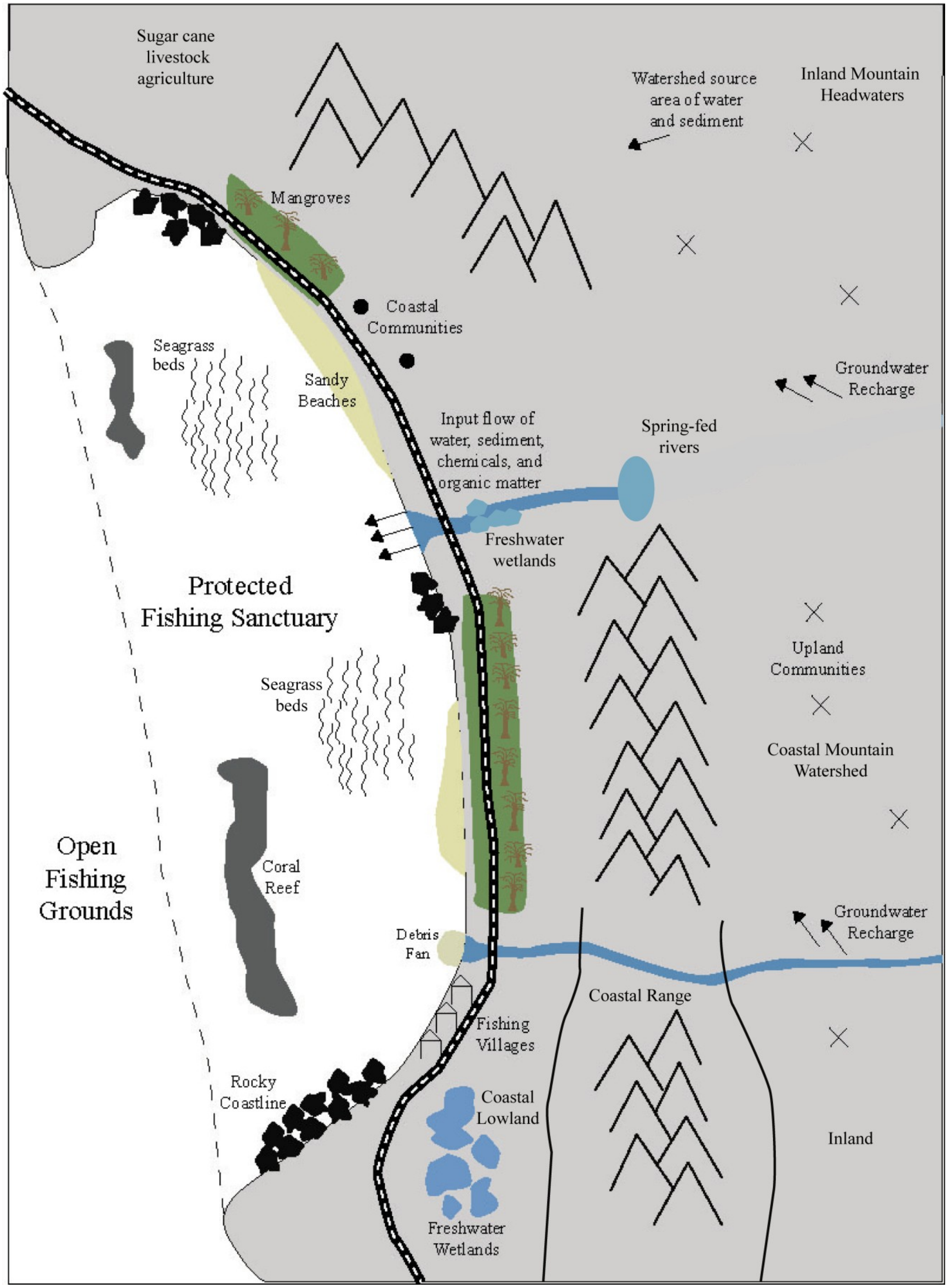


Figure 6. Hydrological, ecological, and cultural components of the Bluefields Bay watershed.

Benefits

The results of this study will be beneficial to residents and coastal communities surrounding Bluefields Bay. This research will determine the quality of river and spring waters being used by local communities within the context of an environmental planning framework involving integrated watershed management. The information developed can be applied to other similar areas in Jamaica. Nevertheless, communities within the Bluefields Bay watershed rely on the local water supplies for drinking water, bathing, laundering facilities, and recreation, and would greatly benefit from efforts to analyze and improve their surface water and pollution runoff. This study will inform residents on how to implement better management and land use practices that affect the quality of their permanent streams and drainages (Sliva and Williams, 2001). Research was conducted side-by-side with local community members and tour guides, and it is the hope to teach them about the methods and findings involved in this project in order to support continued monitoring efforts.

The island of Jamaica as a whole has had research conducted pertaining to its coastal water resources but literature is lacking for the southwest coast of Jamaica. This study will be one of the first in the area to address inland water quality in developing areas. The study improves our scientific understanding of the area and the causes and distribution of water quality problems in southwest Jamaica.

CHAPTER 2

INTEGRATED WATERSHED MANAGEMENT

Watersheds, also referred to as catchments, are functional and geographical areas that integrate a variety of environmental processes and human impacts on the landscape. Integrated assessments recognize the interdependence of resources and components that make up a watershed (Aspinalla and Pearson, 2000). Due to their complexity, managers and planners have traditionally managed watersheds to optimize only one or a few resources. A more holistic approach is needed that addresses watershed resources and other components while stressing the importance of maintaining the sustainable uses of all the resources within a watershed (Tecle et al. 2003; Buller, 1996). Recently there has been a growing recognition that in order to quantify and assess environmental systems it is necessary to conduct an integrated assessment. Integrated assessment accounts for multiple land uses while implementing the concept of sustainability through community-based catchment management (Bellamy and Johnson, 2000). Watersheds, are often subject to multiple land uses, including recreation, agriculture, range management, mining, forestry, and development. Understanding watershed interactions while assessing a watershed requires a thorough understanding of physical, biological, social, and economic components within that watershed (Roni et al., 2002).

Integrated watershed management is recognized as a management process that "promotes coordinated development and management of water, land and related resources, in order to maximize economic and social welfare without compromising the sustainability of vital systems" (Saravanan et al., 2009). To adequately understand watershed-based planning in a developing country, it is important to understand all of the components involved in conducting an assessment and implementing a monitoring program adjacent to a coastal area. Management principles in the country of Jamaica are fragmented and lack integration between people, resources, and development. This chapter will review the history and need for integrated watershed management, the guiding principles behind the concept, and management approaches to integrated assessment. Sources of watershed degradation and the water quality of natural waters in the Caribbean will be discussed, followed by examples of implementation projects and benefits of integrated watershed management.

History: Why is it Needed?

Previous watershed planning strategies tend to be focused on only one discipline, are often one-sided, and are top-down in approach. The topics addressed are only a subset of the issues present in the watershed and fail to address the complexity and interaction between physical, biological, geomorphic, and geochemical processes (Sidle, 2000). Many management approaches focus on short-term needs of decision and policy makers and fail to address the long-term sustainability of a resource. Planning agencies traditionally address currently existing problems and fail to look towards prevention (Wang, 2001). Land-use and watershed plans fail to address certain areas and resources, due to the lack of coordination between varying management and planning agencies. Policy makers and social planners have historically existed in separate realms from environmental management and conservation. Planning strategies need to shift toward integrated of management skills, disciplines, and agencies (Bellamy et al., 1999).

The integration of water quality management, sustainable development, economic prosperity, and increasing populations presents a challenge in 21st century developing countries. The need for integrated management intensifies as current monitoring indicates continuing degradation of watersheds (Tecle et al., 2003). Water quality management has multi-objective, interactive, and dynamic features and the objectives associated with the management of these features are often conflicting (Huang and Xia, 2001). A lack of general knowledge and financial sources contributes to inadequate management and improper uses of natural resources. With increasing water scarcity and growing populations, integrated management is necessary to sustain resources within watersheds (Somlyody, 1995).

Land and resource management in Jamaica is conducted in a very fragmented manner, and planning is not undertaken with a holistic or integrated approach. There is no single agency responsible for the management of land and water, and agencies fall within several government Ministries and departments in Jamaica (Table 3). The Ministries of Water and Housing, as well as the Water Resources Authority (WRA), are generally responsible for the quality of drinking water. The Ministry of Agriculture also focuses its responsibility on irrigation waters. The Ministries of Tourism and Health involve aspects of water resources, such as surface water quality, water supply and demand, and access. The United States Agency for International Development (USAID) quantifies at least 14 different government and nongovernmental offices, ministries, and departments dealing with natural resource management in Jamaica. This dispersal of responsibility often results in conflicts and disputes regarding allocation and use of water and land resources, making it pertinent to develop an integrated approach.

Table 3. Governmental and nongovernmental agencies responsible for water and land resources in Jamaica.

Ministry/ Department	Government (GOV) vs. Non-Governmental Organization (NGO)	Responsibility/ Water Concern
Agriculture and Fisheries	GOV	Stem environmental degradation in critical watershed areas. Monitoring, license, and register fish sanctuaries, farms, and invasive water species.
Education	GOV	Provides special training in agricultural education and practices.
Energy and Mining	GOV	Development energy resources, gas and oil exploration, quarries, and mining.
Health	GOV	Regulations on water health standards and treatment. Monitor and regulate the spread of disease in the water systems.
Industry, Investment and Commerce	GOV	Issue industrial development permits, building inspection, commercial business, and development.
Jamaica Conservation and Development Trust (JCDT)	NGO	Registered charity to promote the conservation of Jamaica's natural resources for sustainable development.
Jamaica Environmental Trust (JET)	NGO	A voice for Jamaica's resources, JET's main focus is to promot environmental education and advocacy.
National Environment & Planning Agency (NEPA)	GOV	Promote sustainable development by ensuring protection of the environment and orderly development. Promote water quality monitoring.
National Environmental Societies Trust (NEST)	NGO	Serves as umbrella for environmental NGOs in Jamaica. Provides developmental assistance and staff training.
Natural Resources Conservation Authority (NRCA)	NGO	Central agency for implementation of mutlilateral environmental agreements (MEAs) in Jamaica. Delegates management functions to NGOs.
Negril Area Environmental Protection Agency (NEPT)	NGO	Promotes, coordinates, facilitates, and implements ridge to reef conservation for sustainable development in the Negril area.
Northern Jamaica Conservation Association (NJCA)	NGO	Dedicated to the protection and wise use of natural and cultural resources in Jamaica. Promotes environmental conservation activities.
Southern Trelawny Environmental Agency (STEA)	NGO	Work with communities in the Cockpit Country to implement environmental conservation practices and sustainable econmic and community development.
Tourism	GOV	Facilitate sustainable development of tourism products.
Transport and Works	GOV	Responsible for the designing and maintaining network structures including bridges, drains, gullies, embankments, and corridors.
Water and Housing	GOV	Provide island with adequate supply and suitable water quality for domestic, commercial, and agricultural purposes.
Water Resources Authority	GOV	Responsible for the regulation, control, and management of water resources. Develop and monitor standards relating to water quality.

Guiding Principles: What are the Key Management Themes?

Three principles of the guided integrated management approach have been recognized by current literature. These principles have been addressed throughout literature and became cohesive in the early 1990's (Bellamy et al., 1999). These three principles are: (1) ecological process; (2) community participation; and (3) coordination of agencies and groups. Principles of this study focus on integrated management of water uses and the hydrological connections guiding them.

The first principle states that the management of interrelated resources must take into regard ecological processes and the maintenance of environmental quality (Bellamy et al., 2002). Management is focused on the continual improvement of resources based on sound scientific data, including monitoring information collected throughout the watershed. Ecological processes should be monitored in order to maintain productive soil and water resources for both human and biota activity (Levin, 1992).

The integrated approach must also involve strong community participation in natural resource management and consider public perception and involvement (Huang and Xia, 2001; Korfmacher, 2001). Stakeholder involvement leads to improved use and management of water resources, as well as perceived benefits including monetary income, food, and family interaction. Community participation results in education of the natural resource system and a shift toward healthier management practices (Haddad et al., 2007). Strong community involvement creates opportunity to not only learn about natural resources but also have to protect those resources and create a higher quality of life.

The final principle stresses the importance of coordinating government, nongovernment, and community natural resource management policies and activities

(Bellamy at al., 2002). Federal agencies are placing emphasis on community-based approaches to environmental protection and have implemented restoration strategies accordingly. When coordinating responsibilities and goals, agencies and groups can formulate guidance structures that assist in conducting integrated resource management. They can also provide support and supplement information that other agencies may have otherwise been lacking (Morrison et al., 2004).

Water Use. Integrated watershed and resource management has recently been recognized as a more coordinated and unified approach to managing water resources in the Caribbean, and more specifically Jamaica (Madramootoo and McGill, 2000; Villasol et al., 1998; McGregor et al., 1995; Sheng, 1999). Management issues extend to developing countries and focus on concepts including land management, erosion control, sedimentation, flooding, and water resources. Cosgrove and Rijsberman (2000) suggest a holistic approach to water resource management that is applicable to the Caribbean islands. They suggest categorizing water uses within a watershed into three categories: (1) water for people (municipal, industrial, health requirements, etc., (2) water for food and rural development (irrigation, etc.), and (3) water for nature (environment and ecosystems). These three categories of water are useful for integrating water resource management with a variety of land uses and practices.

Hydrological Connections. The integrated watershed management approach to investigating water throughout a watershed studies the hydrological connectedness within a system. This section describes three connections that are the guiding principles of the management approach for the Bluefields Bay watershed.

Buffers: Coastal Fringe. Almost half of the world's population lives on the coastal fringe of the earth's landscape and over one third of coastal areas are degraded or seriously threatened (Charlier, 1989). The intense use of coastal resources cannot be investigated without considering the landscape uses and land practices occurring within the watershed draining the coast. Waters that drain to the coast transport nonpoint pollution to coastal estuaries and affect the population, diversity, and quality of coastal waters (Basnyat et al., 1999). It is important to establish a baseline study area in which to focus on connecting land use to coastal water quality and aquatic diversity. In order to establish connections it is necessary to study the landscape immediately adjacent to the coast and the influence that landscape has on the coastal waters. The closer the distance to the bay the more direct affect is going to have on the protected area.

It has been recognized that a land-based study area of the coastal fringe is a logical approach to classifying and constructing a study area to investigate land use (Finkl, 2004). The coastal fringe is a swath zone 5 to 10 kilometers wide along the shoreline and is most commonly used in geomorphologic and land use or disturbance practices. The Bluefields Bay watershed can be divided according to the coastal fringe based on distances to the bay along the river courses. The following are the applicable coastal fringe classes:

1. 0 to 5 km Coastal
2. 5 to 10 km Transition
3. >10 km Inland

Link to Natural Waterways. Perennial and ephemeral stream networks have different hydrologic regimes in the landscape and are perceived differently in Jamaica.

Perennial stream networks have water flowing and available year-round and these streams are perceived as water supply and use areas. The streams generally experience high density use at the key geographic locations that are accessible and close to population centers. Urban areas in Jamaica are linked to natural waterways which generally occur a short distance from the town or population center, and usually are located near a road crossing for accessibility (Scatena, 1990). These streams are threatened by point and nonpoint pollution sources because of their geographic location and the high density use surrounding the stream. Ephemeral streams are often dry and usually only flow during rain and storm events, which poses a flood hazard. These stream waterways are not perceived as a water resource and the network or valley bottom may be developed as residential areas, pasture, and agricultural fields. However, ephemeral streams are still linked to water supply and are contributors to water quality controls via storm water runoff, erosion and sediment transportation, and chemical or nonpoint inputs. Perennial and ephemeral streams both contribute to water supply, but are perceived differently because of their water status, network design, and overall hydrologic regime.

Human Management. Hydrologic connections are linked to human management and development throughout a watershed. The Center for Watershed Protection presents eight subwatershed categories based on the type of water resource and the intensity of the land uses with the subwatershed (Caraco et al., 1998). The categories relate the use and condition of the stream to human values such as impervious surface area. Although each type of water resource has unique management characteristics, it is helpful to differentiate between them and apply similar management techniques and tools to subwatersheds in the same category. Distinguishing between the different aquatic systems also helps define specific uses, goals, and management implications for that particular system. The categories are presented in Table 4 below.

Table 4. Subwatershed Management Categories (Center for Watershed Protection, 1998)

Subwatershed Category	Description
Sensitive Stream	Less than 10% impervious cover High habitat/water quality rating
Impacted Stream	10% to 25% impervious cover Some decline in habitat and water quality
Non-Supporting Stream	Watershed has greater than 25% impervious cover Not a candidate for stream restoration
Restorable Stream	Classified as Impacted or Non-Supporting High retrofit or stream restoration potential
Urban Lake	Subwatershed drains to a lake that is subject to degradation
Water Supply Reservoir	Reservoir managed to protect drinking water supply
Coastal/ Estuarine Waters	Subwatershed drains to an estuary or near-shore ocean
Aquifer Protection	Surface water has a strong interaction with groundwater Groundwater is a primary source of potable water

Management Approach: What are the Key Methods?

GIS-Based Watershed Classification. A geographic information system (GIS) can be used to classify watersheds and assess spatial variation patterns according to water quality monitoring data and land use distribution (Wang and Yin, 1997). Watersheds can be delineated according to topographic boundaries and extracted from digital elevation models (DEMs) (Jenson and Domingue, 1988). Using the idea of the coastal fringe (Finkl, 2004), a GIS system can determine the distance classification schemes for the different swath areas surrounding the coast and can also calculate the stream length that flows through each coastal swath. Rectified aerial photographs and digital elevation models can be used to determine the areas that will be classified according to landscape zones, as shown in Figure 6. GIS-based classifications can be particularly useful to overlay different classification schemes and assess spatial patterns between the classification schemes, and ultimately apply those classifications to watershed management goals (Biswas et al., 1999).

Watershed planning and assessments can be approached on a variety of scales, ranging from the larger basin to the much smaller catchment scale. This thesis classifies watersheds according to the subwatershed and catchment scales as described by the Center for Watershed Protection (1998) because streams obtain their characteristics from their watershed and the practices implemented within the landscape (Hughes et al., 1986). The influence of land use on stream integrity has been found to be scale-dependent (Strayer et al., 2003). Habitat and organic matter inputs are strongly influenced by local conditions, whereas vegetative cover, sediment delivery, hydrology, and channel characteristics are affected by regional conditions (Allan et al., 1997; Roth et al., 1996). Table 5 describes the various management units and provides a comparison of impervious cover influences and possible management options.

Table 5. Watershed Management Units (Caraco et al. 1998).

Watershed Management Unit	Typical Area (Sqaure Kilometers)	Influence of Impervious Cover	Sample Measurement Measures
Catchment	0.3 to 1.3	very strong	BMP and site design
Subwatershed	2.6 to 30	strong	stream classification and management
Watershed	30 to 260	moderate	watershed-based zoning
Subbasin	260 to 2600	weak	basin planning
Basin	2600 to 26000	very weak	basin planning

Water Quality Monitoring. The quality of water sources within a watershed is important in understanding the health of a watershed. Developing countries rely heavily on water resources and it is important to connect their use of water to the use of the landscape surrounding those water systems.

Watershed Protection Tools. The Rapid Watershed Planning Handbook (RWPH) written by the Center for Watershed Protection provides a comprehensive guide for managing urbanizing watersheds on a subwatershed scale, and sets a basis for classifying subwatersheds. The guide presents eight tools of watershed protection which can be applied individually or jointly to a subwatershed. The tools of protection include land use planning, land conservation, aquatic buffers, better site design, erosion and sediment control, stormwater BMPs, non-stormwater discharges, and watershed stewardship programs (Table 6). Each of these tools could be applicable to different subwatersheds and stream systems in Jamaica. Definitions of each tool and examples of their applicability to Jamaica are given next to the protection tool.

Table 6. The Eight Tools of Watershed Protection (Caraco et al., 1998).

Tool	Definition	Example
Watershed Planning	Involves decisions about amount and location of development, and choices about appropriate land use management techniques.	Watershed-based zoning, where watershed and subwatershed boundaries are the foundation for land use planning.
Land Conservation	Involves choices about types of land that should be conserved to protect a subwatershed	Aquatic corridors, area where land and water interact. Examples include stream channels, springs and seeps, steep slopes, estuarine coves, stream crossings, shorelines.
Aquatic Buffers	Involve choices on how to maintain the integrity of streams, shorelines, and wetlands, and protect them from disturbance	A buffer can be placed alongside a stream or shoreline, or around a wetland. Types of buffers usually involve vegetation and shrubs.
Better Site Design	Seeks to design development projects which will reduce impacts to local streams	Design strategies include green pavement opens and headwater streets, where street size decreases with decreasing daily trips
Erosion and Sediment Control	Deals with the clearing and grading stage in development when runoff can carry high quantities of sediment into nearby waterways	Clearing restrictions, erosion prevention practices, and strategies to negate sediment loss.
Stormwater BMPs	Involves choices about how, when, and where to provide stormwater management within a subwatershed, and which BMPs meet management objectives	Maintain groundwater recharge and quality, reduce stormwater pollutant loads, protect stream channels
Non-Stormwater Discharges	Involves choices on how to control discharges from wastewater disposal systems illicit connections to stormwater systems, and reducing pollution from household and industrial products	Regulate and monitor septic systems, sanitary sewers, and wastewater treatment facilities
Watershed Stewardship Programs	Involves choices about how to promote private and public stewardship to sustain watershed management	Promote watershed advocacy, education, pollution prevention, watershed maintenance, indicator monitoring, and restoration

Best Management Practices. Implementation of best management practices (BMP's) is helpful in achieving the management goals and objectives at the watershed scale. BMP's are structural or nonstructural methods designed to prevent or reduce the transportation of pollutants from land to surface or ground water (U.S. EPA, 2007). The best management practices (BMP's) approach is used to reduce or prevent nonpoint and point source pollution (Brown et al., 1993), as well as other environmental degradation. It is important to manage both current and future threats and stressors in a watershed pertaining to future land use, population growth, and resource use, and the incorporation of BMP's is crucial (Butcher, 1999). BMP's have been commonly designed to mitigate erosion-sedimentation processes linked to disturbances such as agriculture, impervious road-related disturbances, and livestock grazing practices (Lynch et al., 1985; Nelson and Booth, 2002). However, the development of BMP's linking disturbance areas to water quality is incomplete. Cause-and-effect relationships between land disturbances in the headwaters of the watershed and the quality of the water downstream need to be continually studied in order to develop the most sustainable and holistic management practices at the watershed scale (Novotny, 1999; Sidle, 2000).

Sources of Watershed Degradation: What are the Problems?

Deforestation. Deforestation is the result of conversion of forested land to another land-use category, and logging a forest degraded by timber and fuel wood exploitation reduces forest cover and diversity. Historically Jamaica was almost entirely covered with trees, with the exception of swamps and wetlands. According to the most current study by the National Forest Management and Conservation Plan, conducted by the Forestry Department in 2001 (Chemonics International Inc., 2003), the present macro land-use breakdown for Jamaica is 31 percent forest, 30 percent a mixture of forest and cultivation, and 39 percent non-forest. While Jamaica is by far a net importer of forest products, Jamaica's forests provide significant quantities of fuel wood, charcoal and yam sticks, and a variety of round wood products used at the rural household level (Chemonics International Inc., 2003). Table 7 below estimates the annual production of forest product for the country of Jamaica.

Table 7. Estimates of Annual Production (Forestry Department, 2001).

Forest Product Type	Annual Offtake (units)	Equiv. Total Volume (m^3)	Forest Cover Type	Average Volume/hectare (m^3/ha)	Existing Total Area (ha)
Charcoal (thousand tons)	37-60	500,000	Closed Broadleaf	195	88,231
Fuelwood (cubic meters)	300,000	300,000	Disturbed Broadleaf	155	178,625
			Open Dry	60	54,102
Yam Sticks (units)	15 million	150,000	Swamps & Mangroves	135	11,978
			Disturbed Broadleaf & Fields	95	165,954
Timber (cubic meters)	60,000	60,000	Pine Plantation	165	4,287
			Hardwood Plantation	185	3,900

Deforestation and watershed deterioration remain growing issues throughout Caribbean and Jamaica landscapes. When valuable land is ruined there is a loss of wildlife habitat and biodiversity (Chemonics International Inc., U.S. AID Report, 2003). Farmers throughout Bluefields have been moving into the upper extremities of the watershed on steep and fragile slopes to build houses and plant banana farms, and many of the farmers employ slash-and-burn clearing practices. The result of clear-cutting forests leads to loss of forest diversity and exposed fragile soils, which, when exposed to high rainfall periods, are rapidly eroded and transported down the hill slope on poorly constructed roads, waterways, and runoff from houses (Madramootoo and McGill, 2000).

Food Forests and Agrochemicals. Developing communities in Jamaica, both located near the coast and inland, practice small-scale subsistence farming and operate larger-scale industrial farms. Agriculture in Jamaica is on a somewhat smaller scale than other Caribbean countries and large farm units with mechanization predominantly crop sugarcane. Small farms cover one-quarter of Jamaica's landscape and there are currently over 170,000 farmers (Chemonics International Inc., US AID, 2003). Food forests were identified on the farms of over 60 percent of the farmers (McGregor and Barker, 1991), which usually consist of multi-tiered gardening, or farming assembles. The three tiers generally include tall trees that product breadfruit, coconut, ackee, and mango, medium sized bushes or vines including coffee plants, yams, and cocoa, and ground level crops, such as herbs, spices, and scotch bonnet peppers (Hills, 1988). Table 8 lists the crops commonly grown by small-scale Jamaican farmers.

Table 8. Main crops produced by small-scale farmers (Beckford, 2002).

Fruits	Legumes	Ground Provisions	Vegetables	Condiments
Breadfuit	Red pea	Yam	Cabbage	Onion
Ackee	Gungo pea	Sweet potato	Carrot	Eskellion
Pear		Irish potato	Cucumber	Thyme
Mango		Cassave	Lettuce	Pepper
Star-Apple		Dasheen	Tomato	
Plantain		Coco	Calaloo	
Banana				

If properly managed, these food forests attempt to implement erosion control practices while maintaining a steady food supply. Improper agricultural practices on steep slopes and intense land cultivation lead to soil erosion, which contributes to the high sedimentation rates of the rivers during the rainy season (McGregor and Barker, 1991). Agriculture plays a strong role in the contamination of rivers by agro-chemical runoff during precipitation events, and current soil erosion control is minimal, necessitating a stronger implementation of conservative and sustainable farming practices (Beckford, 2002; Davis-Morrison, 1995). The protection of hill slopes occupied by small farmers has been recognized as an important perception change to initiative among small farmers and the general public (Edwards, 1995), as many farmers continue to employ the same practices as their ancestors did 300 years ago (Beckford, 2009).

Mining. Bauxite mining occurs throughout Jamaica and is a source of degradation and soil erosion. Jamaica's vast bauxite, or aluminum ore, deposits were first recognized in 1942. Bauxite deposits cover over 20 percent of Jamaica's land surface (Figure 7) and bauxitic soils cover over half of the island (Ahmad et al., 1966). Bauxite deposits in Jamaica occur as surface infillings of karst depressions, and after the deposits are mined the land is reshaped, covered with stockpiled topsoil, and re-vegetated with grass (Greenburg and Wilding, 2007; Zans, 1953). The resulting post-mined soils are steeper, shallower, and higher in limestone rock fragments than pre-mined soils, making these soils susceptible to higher erosion rates and surface transport. Since the mining boom in the 1970's and 80's, the rational and sustainable management of bauxite resources has been recognized as a must in order to prevent the movement of the post-mined soils and deposition of heavy metals and nutrients carried by those soils into surface and ground water (Lyew-Ayee, 2009; Harris and Omoregie, 2008). While the Bluefields watershed is not directly downstream of any major bauxite mines, it is important to take into consideration any land use practice leading to watershed degradation throughout Jamaica. Quarrying does occur on a small scale in several locations in the Bluefields watershed.

Figure 7. Location of bauxite deposits in Jamaica (Lyew-Ayee and Stewart, 1982).

Development and Urban Centers. Developed communities have an impact on the environment, and many studies have been conducted on the influence that larger tourist cities and developed communities have on the coast of Jamaica. Bigg and Webber (2003) researched the impact of coastline change and urban development in Kingston Harbour, Jamaica. Their study concluded increased population pressure and coastal development altered nutrient circulation patterns in the harbor. Controlling the domestic and industrial waste released into it can only reverse eutrophication of Kingston Harbour. Webber and Kelly (2003) studied sources of organic pollution in Kingston Harbour and recommended resolutions to decrease the contributed pollutants. Since they identified river flow as the second largest source of organic pollution, Webber and Kelly suggested improvements in residential runoff systems, gully transport, and overall watershed management practices. Jaffe et al. (2003) investigated surface sediments throughout

Montego Bay, Jamaica and tested for anthropogenic origin of trace metals and organic compounds. The Montego River and the North Gully were identified as the main source of trace metals, pesticides, and petroleum hydrocarbon transport into Montego Bay. Ferguson (1996) addressed the environmental impact of informal settlement in Montego Bay. Informal settlement, shantytowns and housing created outside the city planning process threaten the environment due to the lack of provision for paved roads, sewage treatment, water sanitation, and garbage disposal. This work is significant because it identifies areas of anthropogenic influence on the coastal resources of Jamaica.

Runoff and Nonpoint Sources. Nonpoint pollution is difficult to track in surface waters, but is commonly contributed by untraceable exact sources associated with agricultural and land use practices. Reducing nutrient flow in agriculture and urban runoff can be a method to reduce phosphorus and nitrogen concentrations found in surface waters (Carpenter et al., 1998; Osborne and Wiley, 1988). Nutrient reduction can be carried out by reducing the amount of fertilizer and chemicals applied to crops and fields, using alternative methods to road salting, and using spatial information and GIS to target priority areas, concerns, and farms (Carpentier et al., 1998; DelRegno and Atkinson, 1988; Evans et al., 2002; Borah and Bera, 2004; Luzio et al., 2004). The impact of channelizing streams, especially in a coastal plain, has also shown to elevate nonpoint pollution concentrations of nitrogen and phosphorus (Humenik et al., 1980; Soranno et al., 1996). It is important to preserve the natural state of a stream system and maintain a proper buffer in order to filter out pollutants.

Domestic Waste Treatment. Jamaican waters are susceptible to contamination from the poor management and infrastructure implemented to support sewage systems and effluent discharge. The effluent and sewage discharge into surface streams and groundwater is often contaminated with bacteria measured as total coliform and *Escherichia coli*, or fecal coliform. Bacterial inputs to groundwater are sourced from different land uses, rate and intensities of precipitation, soil properties, amount of suspended sediment, and subsurface conduits (Kelly et al., 2009). *E. coli* make up a large percentage of fecal coliform bacteria and its occurrence in water and sediment is generally an indication of contamination by fecal matter (Davis et al., 2005). The bacteria are contributed from a number of sources, including agriculture, forestry, wildlife, and urban runoff (Griffin et al., 2001; Wickham et al., 2006). Urbanization has been shown to increase the concentration of fecal bacteria. With increased urbanization comes an increase of impervious area and sewer systems, which have been known to have higher counts of fecal bacteria than areas served by septic and discharge directly into surface water systems (Frenzel and Couvillion, 2002).

Direct Water Use. Members of the community also depend on local water sources for their everyday living practices. Residents use rivers and streams for bathing in and clothes laundering. Homes without grounded water sources (piping and routing) collect their supply from many of the same places water is used for other domestic purposes. Washing in the streams contaminates the water from the various soaps and solvents residents are using. Pump houses are located on several streams in the Bluefields area, and these facilities are responsible for chlorinating water in the piping system. However, residents will often disconnect pipe systems (which frequently are placed in the stream themselves) and discharge the chlorinated water in the stream. This can have adverse health effects on flora and fauna otherwise intolerant of chlorine.

Water Quality of Natural Waters: What are the Pollutants of Concern?

Water Chemistry. Increased development upstream negatively affects water chemistry parameters such as dissolved oxygen and conductivity, which degrades biota, ultimately resulting in decreased stream biodiversity (Gage et al., 2004). Poor water quality is typically found in areas downstream of high human impact areas, rather than areas downstream from point sources such as municipal waste water treatment plants (Wang, 2001).

Suspended Sediment/Turbidity. Suspended sediments bind nutrients and heavy metals to their soil particles and transport them between surface and groundwater. Channel and bank erosion acts as a source of sediment transportation and is the result of unsustainable practices including harvesting riparian vegetation, clear cutting land adjacent to the stream, and abatement practices which lead to flooding (Clark and Wilcock, 2000). Jamaican streams are typically narrow and located on steep, mass movement scarred hill slopes, which increases the susceptibility of soil and channel erosion (Ahmad et al., 1993). Excess nutrients found in the eroded soils cause eutrophication, which in turn depletes oxygen from systems and creates algal blooms. Heavy metals contaminate wildlife and food sources and can be harmful in elevated doses to human life. Suspended solids also originate from sewage treatment plants and industrial runoff, and increases in suspended sediment have been linked to increase and transportation of e-coli. E-coli have also been found to survive for longer periods in natural seawater where sediment material was present (Gerba and McLeod, 1976).

Nutrients. Nutrients are substances that enrich the body and systems into which they enter. Phosphorus occurs naturally in rocks and other mineral deposits and is gradually released during the natural process of weathering. It is also a necessary element for the growth of plants and animals, but often tends to be the growth limiting nutrient in lake ecosystems (Carpenter et al., 1998). Nitrogen is a limiting factor that controls plant growth rate in estuaries and coastal ecosystems (Hinga et al., 1991), and reactions in fresh water can cause oxygen depletion. Nitrogen comes from a number of sources, such as agricultural runoff, fertilizers, sewage products, industrial wastes, and livestock pasture and is also a necessary dietary requirement for all organisms (Valiela et al., 1997).

Eutrophication caused by excessive nutrient inputs of phosphorus (P) and nitrogen (N) is the most common impairment of surface waters in the United States (1990). Excessive levels of phosphorus within a stream are not toxic to people or animals in high levels, but they do create anoxic conditions in water systems, which deplete oxygen and result in fish kills (Elser et al., 1990). High levels of nitrogen on the other hand have been known to cause health problems including nausea, stomach aches, and blood oxygen deprivation. Biological marine environments have been found to favor nitrogen limitation over phosphorus and are a major function relative to the adjustment of the ecosystem to N and P availability (Smith, 1984).

Nutrients come from sources that include both anthropogenic and natural processes, but human activities exacerbate the introduction of these nutrients. Regional patterns in nutrient concentrations can be the result of direct anthropogenic impact, deforestation, urbanization, and agricultural practices (Bullard, 1966). The rate and quantity of nutrients transported within a water system can be used to infer the natural controls and human influences on nutrient concentrations. Regional deforestation and urbanization patterns result in changes of in-stream nitrogen and phosphorus concentrations at a wide range of scales, from small pastures to large river systems (Biggs et al., 2004).

Human impacts on nutrient concentrations in large river systems may be dominated by urban areas, shown by large watersheds with urban populations that have higher N and P concentrations rather than smaller pasture watersheds. Filoso et al., (2003) studied anthropogenic N inputs among 10 sub-catchments in the tropics of Brazil and significantly correlated the input and transport of N to human land use. Areas mostly covered with pasture and forest had the lowest concentrations, whereas areas composed of agriculture and urban areas had higher levels. Forested landscapes provide an environment in which to filter out pollutants and mitigate water quality degradation, stressing the importance of keeping them intact on the landscape (Wilke et al., 2001).

Bluefields Bay is probably experiencing the affects of human inputs derived from inland drainage sources. Nutrient transport by surface runoff and streams to other coastal embayments has been well studied (Correl et al., 1992: Fulweiler and Nixon 2005; Valiela et al., 1997). However, recent interest has been taken in studying human impact and influence on nutrient transport to coastal systems, and the need to further expand research in Jamaica has been identified. Development along the coastline often impedes the flushing times and natural filtration of pollutants, and speeds up the transport of nutrients and chemicals from the land into the bay (Bigg and Webber 2003; Valiela et al., 1997). Coastal waters are the most highly fertilized ecosystems on earth and humans are one of the greatest influences.

Bacteria. Total coliforms and *E.Coli* have been used as indicators of potential fecal contamination for almost 100 years (Gentry et al., 2006) and have relationships with water chemistry parameters such as turbidity, pH, conductivity, and temperature. Survival of *E. coli* is dependent upon these water characteristics. Warmer water temperatures propagate bacteria survival and Jamaica has year-round warm temperatures, making seasonal water temperature fluctuations rare. Water temperatures affect the amount of dissolved oxygen available in the water, which is necessary for biota and bacteria to survive. Values of pH that are too high or too low can inhibit bacteria from living and specific conductivity infers the dilution of the water controlling bacteria concentrations.

The Bluefields watershed has mantled karst geology characterized by fractured limestone, where surface water conditions greatly influence ground water quality and chemistry. Fecal bacteria are transported through karst aquifers and into streams, where bacteria is resuspended along with sediment (Davis et al., 2005). Fecal coliform bacteria and *E. coli* inhabit sediments and can survive in these environments for several months. Many of the water systems surrounding Bluefields Bay originate from spring-fed sources and create wetland and pond features. Davies and Bavor (2000) studied wetland and pond sediments and found that a reservoir of viable bacteria may be resuspended back into the water column during precipitation and storm activity. Surface waters transport suspended sediments containing bacteria into Bluefields Bay. Rainfall and runoff have been shown to influence bacteria concentrations (Seurinck et al., 2006). Marine sediments have been shown to harbor viable bacteria for 68 days and the sediment provides a favorable, nonstarvation environment for the bacteria (Davies et al., 1995).

Chlorine. Chlorine is added to drinking water throughout the Bluefields area, and often leaks from pipes running throughout the water systems. The chlorine negatively affects fish populations and can be harmful in high dosages to humans. Chlorine gas dissolved in water will also react quickly with other substances in the water and becomes even more toxic when combined with other toxic substances (Vess et al. 1993). Concentrations in undisturbed areas should be low, and an introduction of chlorine starts to have an effect on fish fry at small doses.

Effective Implementation Projects: What are some Success Stories?

There are several groups and organizations in Jamaica that are dedicated to sustainability, water conservation, and land-use practice improvement. Each organization has attempted, using their own approaches, to study practices to improve environmental conditions on the island, particularly focusing on water resources.

Global Coral Reef Alliance. In 1992 the Global Coral Reef Alliance conducted a detailed study on the ecological status of coral reefs along the entire western half of Jamaica. The study connected excessive coastal nutrient loading to anthropogenic sources and concluded that there was a need for development of stronger sewage treatment regulations. Most reefs near developed shores were observed as being seriously degraded by algal overgrowth, which is contributed by nutrient runoff into the coastal waters (Goreau, 1992). However, the shallow reefs surveyed in Bluefields Bay were in unusually good condition and were to be regarded as some of the best in Jamaica. Seagrass beds in the bay occupied depths between two and three meters and the water quality of the bay was stated as being exceptionally clear.

Coastal Water Quality Improvement Project. The Coastal Water Quality Improvement Project (CWIP) has studied water conservation from 1998-2003 (Associates in Rural Development, 2005). The CWIP Phase I promoted sound environmental practices through integrated coastal zone management, with a particular focus on water quality, proper wastewater treatment, and solid waste disposal. Lessons learned from this CWIP Phase I stressed the need for planning approaches at local government levels. After Hurricane Ivan passed through Jamaica in September 2005 funds were allocated to implement Phase II of the CWIP. This second phase was dedicated to improve coastal water quality and support integrated management approaches (USAID). This project resulted in the creation of water quality monitoring programs and wastewater treatment systems on a local, parish-level scale.

Ridge to Reef Watershed Project. From 2000-2005 the Ridge to Reef Watershed Project (R2RW) focused on reducing hillside deforestation, pollution, and land erosion through an integrated approach that addresses natural and man-made causes of land and water degradation. Three components of the focus of the R2RW project were outlined as (1) sustainable environment practices; (2) compliance and enforcement; and (3) institutional strengthening (Associates in Rural Development, 2004). The R2RW improved watershed management practices and increased public awareness, and attempted to track degradation at the lower end of the watershed, literally from ‘ridge to reef’. The project had a particular focus on sanitation methods being used and their relation to rivers, streams, and gullies. Solutions to improve the technologies being used were presented to communities in the St. James region and Hanover. Both the CWIP and the R2RW were supported by the United States Agency for International Development (USAID).

Summary: Needs

An integrated approach is needed to properly identify and remediate the problems found within a watershed. Management must include a variety of components found within a watershed and the connections between the components must be identified. Especially important is establishing the link between land, rivers, and the bay. Interconnectedness between these resources is demonstrated by the results that actions on the landscape have on rivers, which transport inputs such as nutrients, water, and pollutants to the bay. Integrating management of watersheds connecting these components in a logical and reasonable manner.

Caribbean countries such as Jamaica have a focused human-use based approach to natural resource consumption and often view different resources as physical units on the landscape, such as water, land, and soil. Because these components are connected, it is important for key sources of pollutants to be identified, which include the human-use based activities occurring on the landscape, such as water extraction, bathing, and agriculture. Communities in Jamaica have experienced positive results from implemented watershed management projects designed to negate human-use activities and these success stories can be examples of positive resource management and conservation strategies. A water quality management program planned around community integration is an ideal way to integrate watershed management based upon actual natural resource need and conservation.

CHAPTER 3

STUDY AREA

Bluefields Bay is located 73 km south of Montego Bay, Jamaica on the southwestern coast in the parish of Westmoreland. It stretches from Bluff /Paradise Point to Belmont Point, with the communities of Bluefields, Belmont, Cave, Paradise, and Ferris Cross lying on the coastal draining edge of the bay (Figure 2). These cities lie within the watershed region considered the Bluefields Bay watershed. This watershed is composed of a number of named and unnamed rivers, as well as dry valley drainages which can potentially contribute runoff and sediment into Bluefields Bay, a protected fish sanctuary. Base flow in these rivers and drainages is provided by springs located in mountain headwater areas or along the base of the coastal range mountains. The mountain geography of the Bluefields Bays watershed includes steep slopes with elevation ranging from sea level to a maximum of 794 meters at Bluefields mountain.

Physical Description

The island of Jamaica is located in the northwestern Caribbean Sea and is the third largest of the Greater Antillean Islands (Evelyn et al., 2003). Jamaica is approximately 230 km from east to west and 80 km wide with a total area of 10,990 km^2. The coastline of Jamaica is 1,009 kilometers long with 48 percent considered to be usable coastline by the residents (State of the Environment Report, 2001). Public recreational space accounts for 2.5 percent and fishing beaches for 1.3 percent of total coastline (Chemonics International Inc., USAID/ Jamaica-Caribbean Regional Program, 2003).

Climate. Jamaica has a tropical maritime climate and lies near the northern margin of the tropics in the belt of northeast trade winds (Whitbeck, 1932). The mean annual temperature ranges from a seasonal low of 26 degrees Celsius in February to a high of 30 degrees Celsius in August. With every 300 meter increase in altitude the temperature decreases by an average of 2 degrees Celsius (Water Resources Authority 2009). Precipitation in Jamaica varies both seasonally and spatially. Jamaica has a mean annual rainfall of 1,981 mm (Nkemdirim, 1979). The inland watershed and coastal range surrounding Bluefields Bay has a mean annual rainfall of about 2,286 mm (Jamaica Meteorological Service). Because it is located in the rain shadow of the easterly located Blue Mountains, the south coast receives significantly less rain than the northern coast. January, February, March, and July are the driest months, and tropical storms and hurricanes are prevalent during the period of July to November. Jamaica exhibits a bimodal pattern of mean annual rainfall, with the primary maximum in October and the secondary in May (Figure 8).

Geology and Soils. About two thirds of Jamaica is karst landscape. Karst topography is a landscape that is shaped by the dissolution of underlying layers of carbonate rock. The karstlands of Jamaica are underlain by layers of limestone that have chemically eroded over time, forming underground drainage that diverts surface water flows (Sweeting, 1958). The karst topography complicates tracking water sources throughout the Bluefields Bay watershed. Hazards including drought and flooding associated with karst landscapes become more prevalent with increasing development and urbanization (Day, 2007).

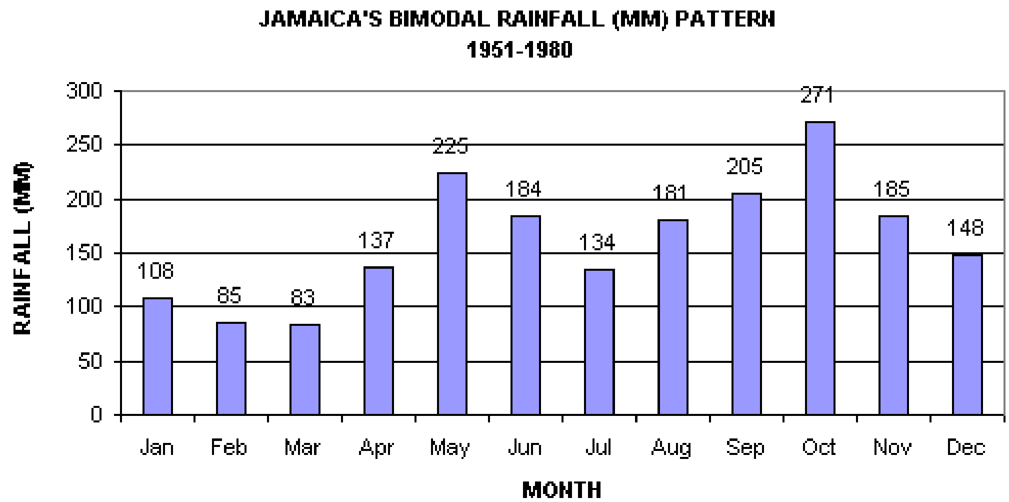


Figure 8. Bimodal Rainfall Patterns in Jamaica (Water Resource Authority, 1980).

The geology of the Bluefields Bay watershed is composed of highly dissected limestone plateaus (Sweeting, 1985). The lithology of the hard white limestones is not continuous throughout the island and consists of fairly course, crystalline, well-jointed, and highly fissured limestones. Drainage in these limestones is considered free, rapid, and vertically-eroded. The white limestone is underlain with upper and lower beds of yellow limestone, which are separated by beds containing clays and tuffs. Karst features, including the underground circulation of water, develop in the layers of upper yellow limestone as well as the beds of clay and tuff. The high temperatures and precipitation rates found in tropical settings accelerate karstification, which leads to the expedited solution of the limestone (Sweeting, 1958).

Jamaican soils are mainly residual in origin. Approximately two thirds of the island is covered by soils formed in white and yellow limestone parent material (Johnson et al., 1996). This parent material covers the entire portion of the Bluefields watershed and is classified under the Bonnygate and Carron Hall formation. The texture of theses soils varies with slope from clayey on flats to stony loam on more sloping areas. The soils toward the western portion of the watershed tend to become less static and more mixed, an intermingling of soils from the Bonnygate, Carron Hall, Shrewbury Ball, and Fontabelle formations. These soils remain fine-controlled with clayey textures.

Cockpit Country in Jamaica is located further inland on the island and it is hypothesized that recharge is released from there by springs along Bluefields Bay. Cockpit relief is characteristically rugged with numerous small u-shaped depressions that are drained by sinkholes. These sink holes absorb recharge from the upland drainage and may release the water into connected karst systems underlying Bluefields Bay (Donaldson and Walters, 1979). Soils of the alluvial plains have been deposited by rivers and are made up of fine gravel, sand, and loam. Some soils also have marine origins and may be composed of clayey material that measures 3-4 feet deep over the sediment deposited by rivers (Hardy, 1951).

Water Resources. The Water Resources Authority reports that water is the most important resource found on the island of Jamaica, with groundwater providing 84% of the island's available water resource. Table 9 is a summary of the national water demand and depicts the amount of water extracted for agricultural and non-agricultural practices.

Karst Hydrology. The karst system underlying Bluefields Bay watershed controls the hydrology of the watershed and the connection between surface and ground water. Surface waters flow on the exterior of the landscape, flowing from the upper topography of the mountain landscape and draining to the coast of Bluefields Bay. However, along the flow path of the stream dissolution features can intercept surface flow and route water underground. These disappearing or losing streams connect surface

Table 9. Summary of Jamaica's National Water Demand (Water Resources Authority, 1995)

Demand Sector	Present (1995)		2000		2015	
	MCM/yr[1]	Percent	MCM/yr[1]	Percent	MCM/yr[1]	Percent
Agricultural	682	75	1149	80	1338	79
Non-Agricultural	231	25	288	20	346	21
Domestic Rural	21	2	46	3	62	4
Domestic Urban	138	15	161	11	181	11
Tourism	10	1	15	1	23	1
Industrial	62	7	66	5	80	5
Total	913	100	1437	100	1684	100

[1]MCM/yr is million cubic meters per year.

and ground water flow. Geologic conditions present in the Jamaican topography can force the underground water storage to discharge at the surface, producing a spring. Springs usually occur toward the downstream end of a karst drainage system. Two natural spring types occur in the Bluefields region, which are blue holes and contact springs (Mylroie et al., 1995). Blue holes are formed when the strata of the underlying structure becomes weakened, causing it to collapse and fill with water. Contact springs occur when water that is trapped in a permeable layer is allowed to freely flow at bedrock fracture points (USGS, 2010). Both types of springs are located near the down gradient end of the drainage system along the Bluefields Bay coast and also influence the locations of estuaries and mangroves.

While groundwater is considered an important source of water on the island, surface water should be considered equally vital to monitor. Groundwater is linked to surface waters through streams, and the hydrology of these Jamaican rivers is particularly unique. Waters running through the underground karst are particularly vulnerable to land use contamination due to the numerous sinks and springs present, therefore it is important to study the quality of the water before it enters the ground (Katz and Griffin, 2008).

Mountain Hydrology Rainfall runoff generated on the impermeable rock surfaces of the landscape becomes channel flow on the surface, and forms rivers and streams. Since the flow of these rivers is dependent on the rainfall, these intermittent channels are usually dry beds and only carry water during precipitation periods. Rivers that form on permeable surfaces with established bed forms tend to be more reliable and less flashy than those channelized on impermeable surfaces. Runoff includes all components of stream flow, such as channel precipitation, surface and subsurface runoff, and groundwater contribution (Nkemdirim, 1979). Mean annual runoff in Jamaica is about 1,283 mm or nearly 65 percent of the mean annual rainfall (Jamaica Geological Survey).

Public and Private Water Supply. Coastal communities draw water from local resources including springs, groundwater wells, and rivers and streams. Water distribution throughout the communities in the Bluefields Bay watershed is limited, and much of the population relies on personal means to collect water. Local populations visit water sources to launder their clothes, bathe themselves in the water, and some even drive their cars into wetland and headwater areas to wash their vehicles. Because the Bluefields population is dependent on local water supply, it is important to address the concern of possible water contamination and pollution.

Public water supply is dependent upon the locations of three main water treatment facilities and public catchment supply centers found in different communities. The area of Bluefields relies on a water treatment center located along the upper Bluefields River below the community of Rivertop. A smaller treatment and pump station is located on the lower reach of the Sawmill River, which provides water treatment for the central portion of the Bluefields Watershed. The final treatment center is located in the headwaters of Deans Valley in the small African village of Abeokuta and treats drinking water for the western portion of the watershed surrounding the bay. These water treatment facilities are important in order to maintain the supplies that communities depend upon, and their spatial distribution throughout the watershed is important in order to maintain a consistent supply of clean water.

Natural Water Sources. The following section describes the natural systems and sources of water in the Bluefields Bay watershed. Water systems are complex and vary between type, including freshwater streams, wetlands, mangroves, and estuaries. The examples of water systems in the figures below are main drainages contributing to Bluefields Bay (Figure 9), and are the water systems that experience the greatest amount of anthropogenic stress. Each of the systems described are also an established monitoring site and represent the general characteristics of their water system. Figures 10, 11, 12, 13, 14, and 15 depict six specific water systems located within the Bluefields Bay watershed.

Environmental History

Bluefields Bay has a unique environmental history that can be divided into three time periods: (1) prior to European settlement/Spanish; (2) British settlement; and (3) post-European settlement. While there has been little written and published specifically for the area of Bluefields, the historical land use disturbance can be pieced together using historical maps, writings, and nautical charts.

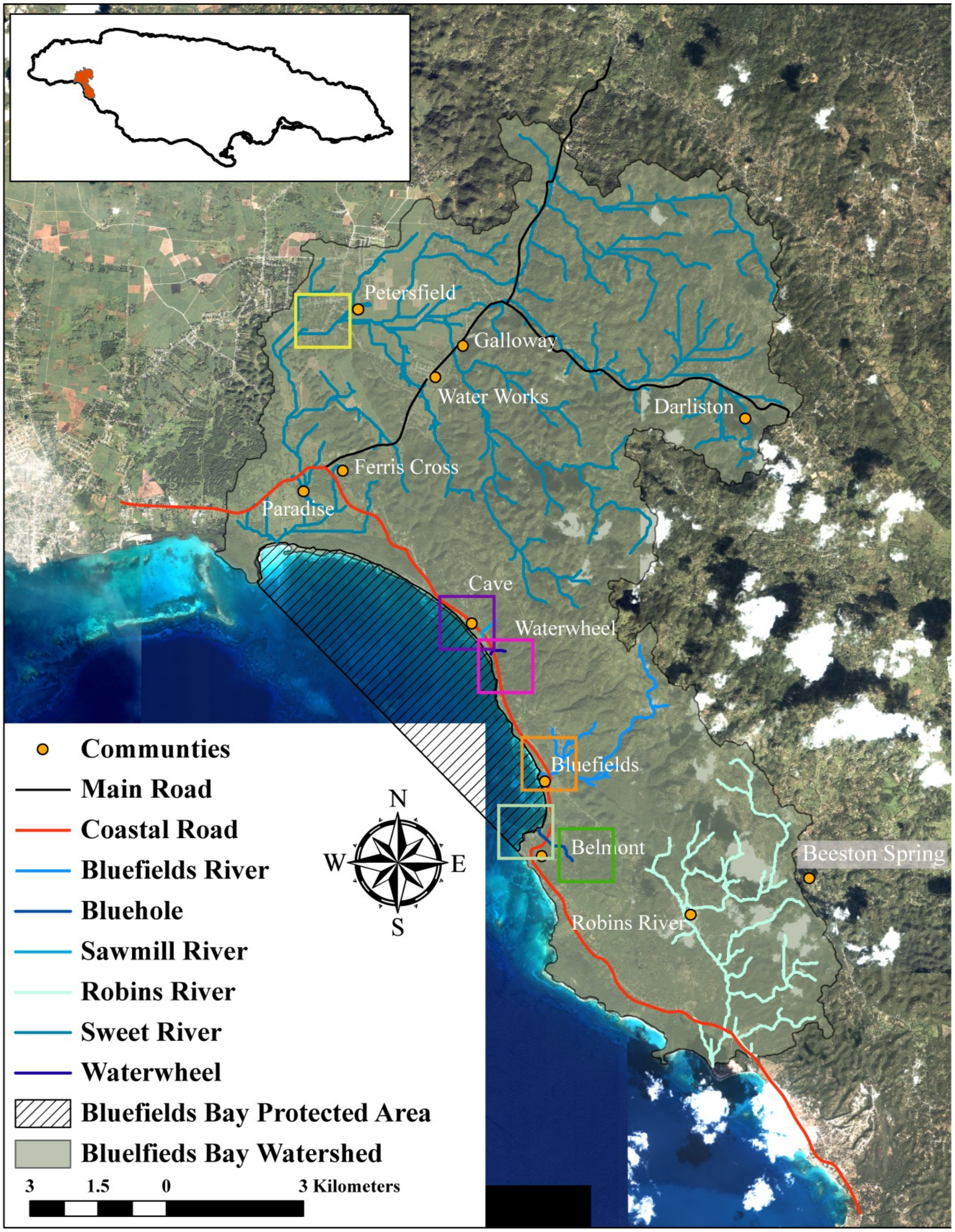


Figure 9. Main drainage systems contributing to Bluefields Bay. The colored boxes each indicate a type of natural water source and coincide with monitoring site locations. These water systems are described below in separate figures.

Figure 10. The Sweet River, Monitoring Site Number 2. The Sweet River has headwaters that are further in the coastal range and drain the coastal fringe of the bay (Genxu and Guodong, 1999).

Figure 11. The Bluefields River, Monitoring Site Number 9. The Bluefields River is a coastal river, meaning that its drainage discharges directly into coastal waters (Villasol et al., 1998).

Figure 12. Bluehole Spring, Monitoring Site Number 13. Bluehole Spring is a coastal spring located in the valley floor of the coastal lowland area adjacent to Bluefields Bay.

Figure 13. Bluehole River, Monitoring Site Number 14. Bluehole River is a mangrove wetland that is fed from Bluehole spring (Nedwell et al., 1994).

Figure 14. Waterwheel, Monitoring Site Number 8. Waterwheel is a coastal contact spring that drains directly into Bluefields Bay.

Figure 15. Sawmill River, Monitoring Site Number 5. The Sawmill River is a freshwater wetland that is contact spring-fed and located on the coastal lowlands of the Bluefields Bay watershed.

Settlement History. The area of Bluefields was settled by the Spanish in 1519, who selected that area due to the large population of native Taino villages already existing in Bluefields. The Taino were heavily adapted to the sea but also cultivated substantial agricultural plots including tubers (sweet potatoes), cotton, tobacco, and various fruits. They built wood houses, making their historical impact on the landscape substantial. Remnants of these large aboriginal villages still emerge as archeological artifacts in the alluvial plains of the Bluefields River. The Spanish settlement, with its exact location unknown, forced the Taino into slavery, making it possible to infer that Spanish settlement in the Bluefields area was large.

The British invaded Jamaica in 1655, forcing the remaining Spanish to retreat to Cuba. The British had the most significant impact on the area of Bluefields. Plantations were built starting in the 1720's, which generally excluded sugar monoculture. Sugar cane plantations were located primarily to the west in the Sweet River/Deans Valley lowland. The estates in the area of Bluefields grew crops throughout different periods of time, cut logwood for export, and raised cattle as well (Higman, 2001). The area of Bluefields was particularly prominent for pimento tree harvesting, which produces allspice and oil used for perfume. Production of pimento oil continues to be practiced throughout the watershed to this day. Heavy cultivation and land clearing occurred in the 18^{th} century, and after Emancipation in 1838 much of the cleared land was neglected and reforested. In addition to plantations the British also utilized the area of Bluefields for commercial shipping and trade, developing ports along areas near Bluefields, Cave, and Belmont. Land clearing on the steep slopes adjacent to the bay is recorded in historical maps of Bluefields Bay (Figure 16).

Figure 16. Historical Map of the southern portion of Bluefields Bay in the late 1700's (Courtesy of the National Library of Jamaica, Date/Author Unknown).

The British had a large impact on the Bluefields area and evidence of land development can still be seen throughout the area, including old plantations, drainage systems, waterwheels, and dock posts. Taino cultivations occurred on easily farmed lowlands, limiting the effect of their agricultural practices on the landscape. Present day land uses, which will be described in the section below, are characterized by the conversion of cropland to forest, pasture, and small-scale subsistence farms.

Land Use. Land use throughout the watershed is not uniform and varies among the different subwatersheds. Savannah-la-Mar, the capital city of the parish of Westmoreland, lies outside the western portion of the watershed in the wide, flatter alluvial basin. The Sweet River drains a large area and transports water from high areas in the mountains to the alluvial basin in the western area of the watershed. The Sawmill River, located in Cave, can be classified as a wetland area. The Bluefields River is a slightly larger, more established channel that is incised and in areas takes on characteristics of a gorge. Bluehole is a spring that is located in a mangrove-dominated area. The Robins River is located outside of the Bluefields watershed, but drains adjacent to Bluefields Bay where the water is subject to long shore drift into the bay. The land use distribution for the Bluefields Bay watershed is shown in Figure 17.

Land use in the Bluefields watershed consists of wetlands and mangroves near the coast, and disturbed broadleaf forest, bamboo, and fields further up the watershed (Figure 18). Over 50 percent of land uses within the watershed are classified as disturbance areas. Urban development is increasing throughout the watershed, with the establishment of several living developments currently taking place. Illegal shanty development occurs sparsely throughout the forested areas along the streams, as well as subsistence farming and scattered commercial businesses. Since the land use and land cover is unique to each stream system, classifying the Bluefields watershed on a subwatershed level will allow for a more specific and accurate description of each system's land use and land cover, and allow development of a spatial connection between the land use and land cover of the stream.

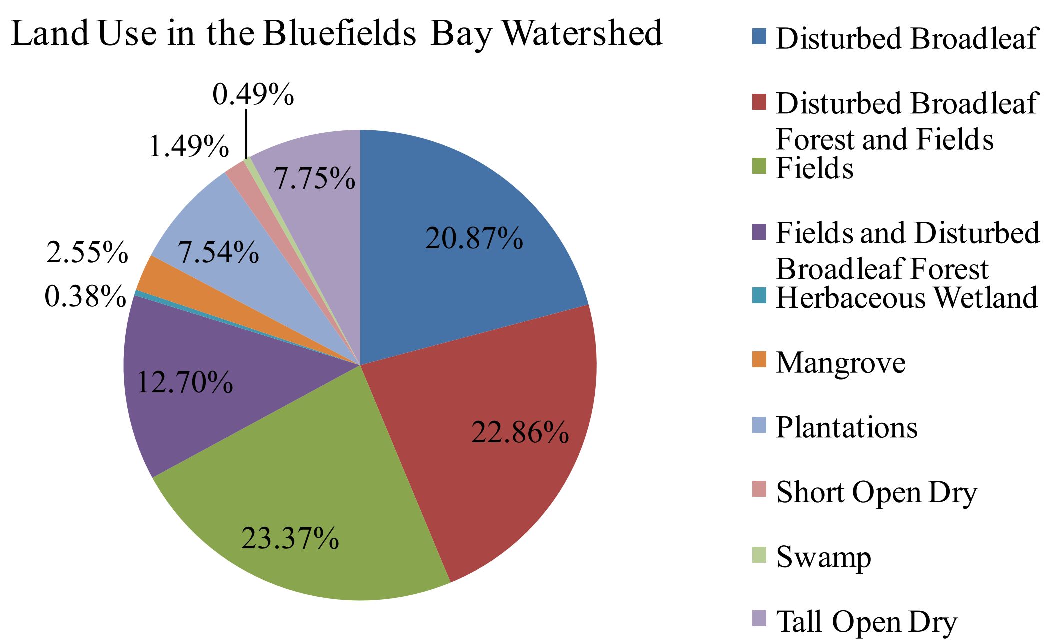


Figure 17. Land use percentages in the Bluefields Bay watershed (Chemonics International Inc., Forestry Department of Jamaica, 1998).

Population. Figure 19 shows the current population and enumeration districts for the areas surrounding Bluefields Bay, derived from the 2001 census data of Jamaica. The area considered the community of Bluefields has a population of about 3,133 people and is composed of 6 districts. The area surrounding the bay including the Bluefields population hosts about 6,575 people and is composed of a total of 15 districts. No current or historical census data was found for the area inland area of the watershed.

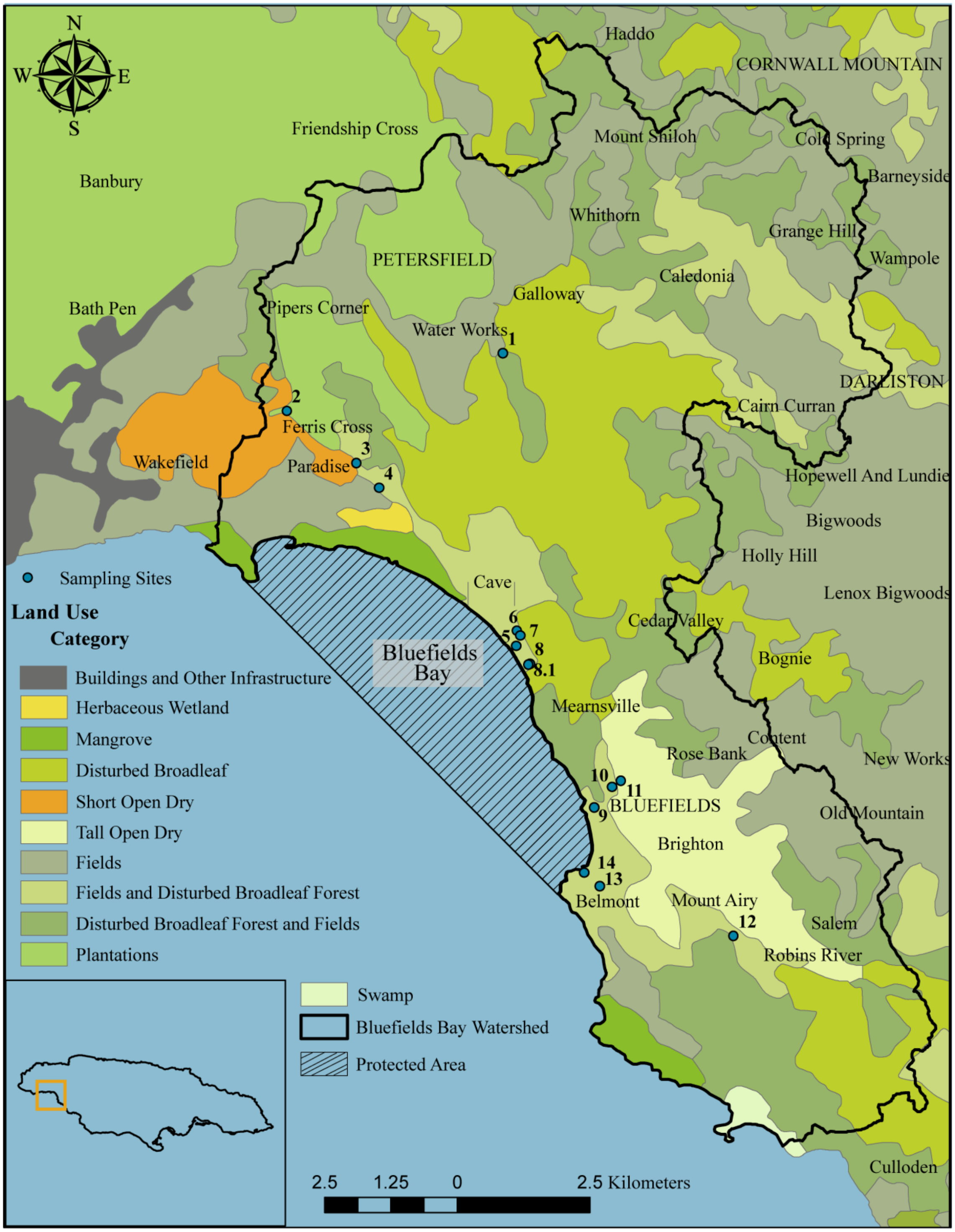


Figure 18. Land cover in the Bluefields Bay watershed using GIS data from MONA (Forestry Department of Jamaica, 1998).

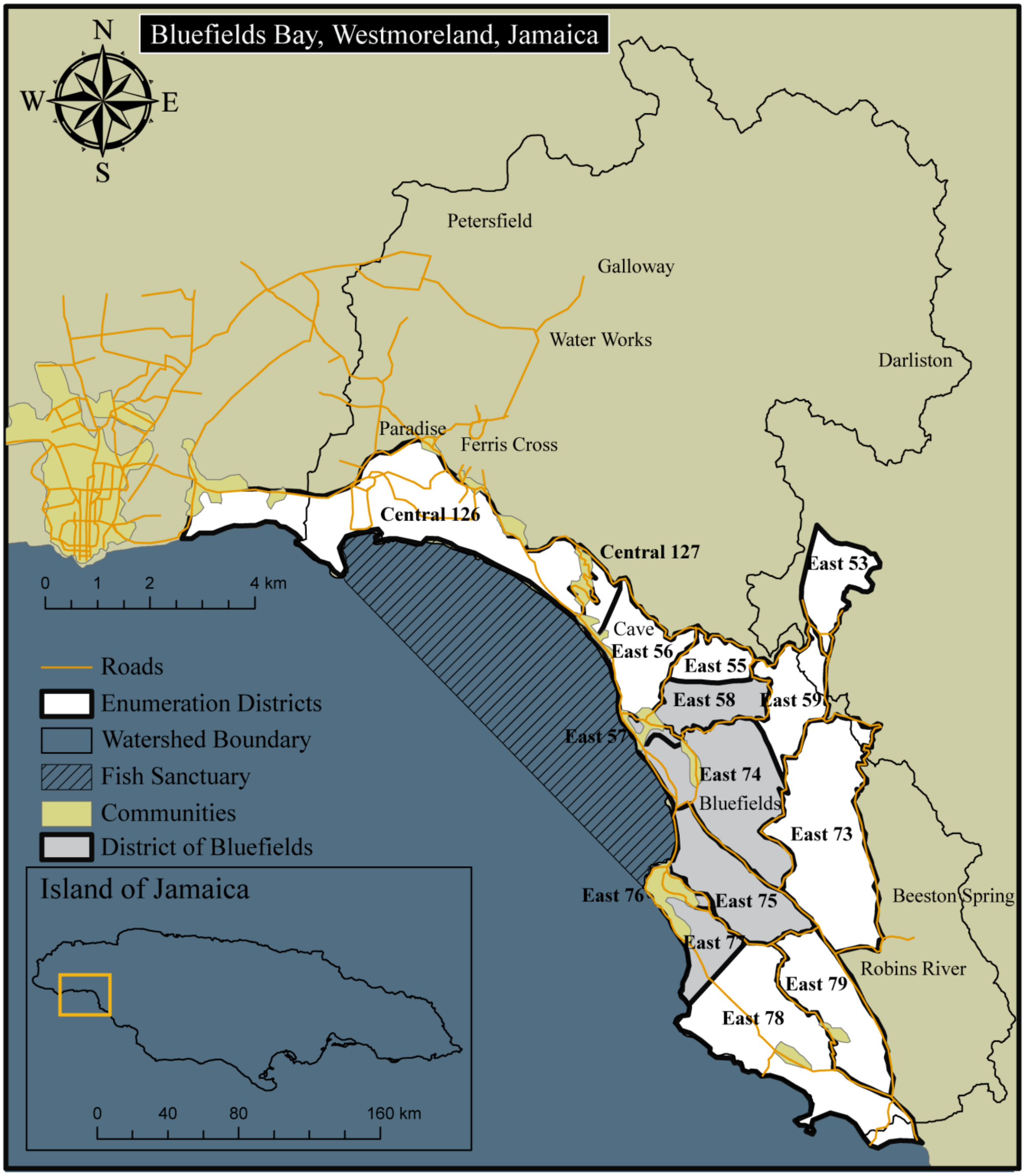


Figure 19. Enumeration districts for areas surrounding Bluefields Bay. The grey district denotes the area considered Bluefields. 3,133 persons is the population of Bluefields and 6,575 persons is the total population of all the districts (Jamaica Census data, 2001).

Current Watershed Conditions

Previous research has been conducted investigating the bacteria levels of Bluefields Bay. Raw water sampling occurred at seven sites (Figure 20) in Bluefields Bay from November 2007 through April 2008. Three rounds of sampling were done with samples taken on November 11, 2007, January 16, 2008, and April 16, 2008. The sampling was performed by Scott and Carrie Eklund, Peace Corp volunteers stationed with the Westmoreland Health Department, and testing was sponsored by the Bluefields Environmental Protection Association, which is run through Bluefields Villa. All samples were analyzed for fecal coliform with the results shown in units of MPN/100mL. The results were compared to the United States Environmental Protection Agency (EPA) standards for full body contact (swimming/bathing) of 200 MPN/100mL. The areas of highest fecal coliform counts were located near the mouth of the Bluefields River and near the fisherman's beach in Belmont. The preliminary results of this study (Table 10) justify the need to study inland water quality and its connection to the bay.

Table 10. Results of Bluefields Bay water sampling conducted by the Peace Corps.

Location	Site	Units	11-Nov-07	16-Jan-08	16-Apr-08
Mile Stone Cottage	1	MPN/100mL	<3	9	14
Gully between Mullion Cove and the Hermitage	2	MPN/100mL	9	<3	30
Edge of property and Bluefields Beach	3	MPN/100mL	3	4	8
In middle of beach near old lifeguard station	4	MPN/100mL	<3	DNS[1]	DNS[1]
On south end of beach at the end of sand	5	MPN/100mL	4	4	16.7
Mouth of Bluefields River	6	MPN/100mL	DNS[1]	93	34
Belmont fisherman's beach on south side of pier	7	MPN/100mL	>= 2400	<3	23.7
North side of mouth of Blue Hole river	8	MPN/100mL	1100	4	17
San Michele	9	MPN/100mL	43	9	37

[1] Did not sample.

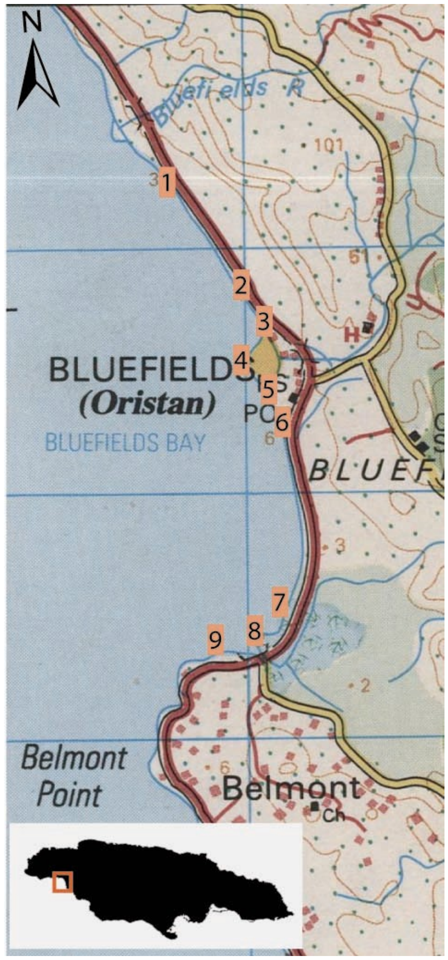


Figure 20. Sampling sites in Bluefields Bay, as sampled by the Peace Corps.

The Natural Resources Conservation Authority's (NRCA) Watershed Protection Branch (1997) mapped watershed conditions throughout Jamaica (Figure 21). The Bluefields Bay watershed drains parts of both the 'Deans Valley River' and the 'Black River' watershed management units in Jamaica, and the areas within the Bluefields Bay watershed are mapped as moderately degraded. This classification further emphasizes the need to assess the direct and inland drainage to the protected area of Bluefields Bay.

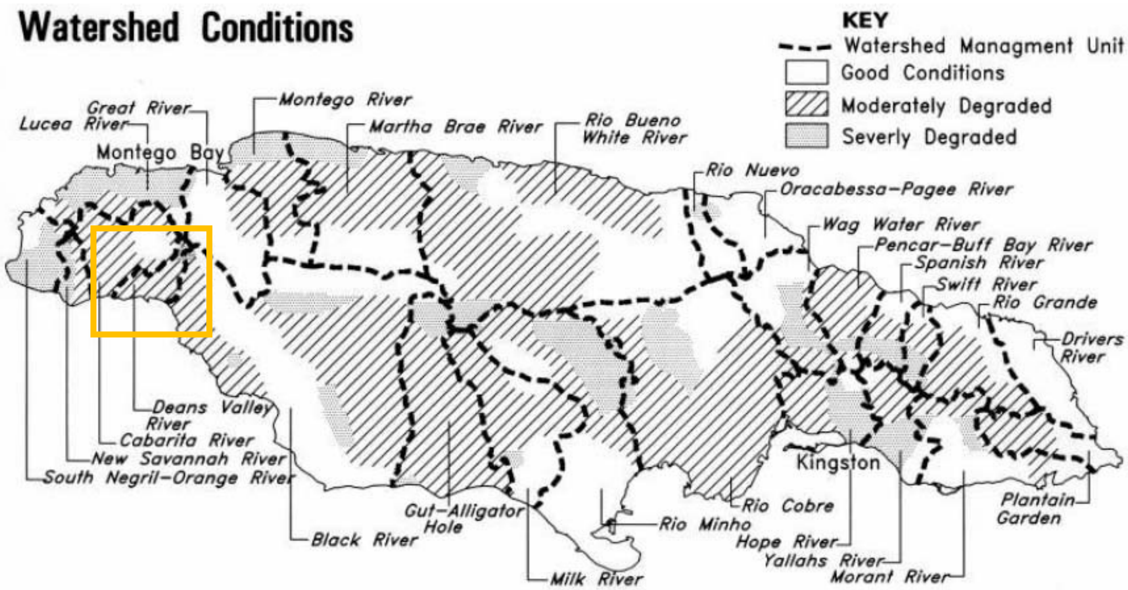


Figure 21. Watershed conditions in Jamaica, as mapped by the NRCA's Watershed Protection Branch (1997). The study area for this thesis is denoted by the orange box.

The Water Resources Authority (WRA), located in Kingston, Jamaica, is responsible for the management, protection, and controlled allocation and use of Jamaica's water resources. While the WRA river gauge networks consist of 133 stations throughout the island, the WRA currently is responsible for four monitoring sites in the Bluefields Bay watershed. These sites have historically been and are currently being monitored for stream flow and discharge measurements. The WRA also tests several ground water sites for water levels and quality in Bluefields Bay, but this information has not been currently released. The historical stream flow (discharge) data can be used to compare with the data collected in this study.

The WRA monitors the discharge of 4 gaging sites within the Bluefields Bay watershed. This information can be used to estimate the approximate rate of pollution and water movement in a stream system. Waters that are moving faster have shorter residence times for the pollutants to remain in the systems. Slower moving waters are unable to flush their systems as quickly and the longer residence time promotes absorbance of pollutants into the stream system. The discharge for these gaging sites is presented in Table 11 below.

Table 11. Historical discharge values for Water Resources Authority gages in the Bluefields Bay watershed (Water Resources Authority, 2010).

Site	Name	Mean Q m^3/sec	High Q m^3/sec	Low Q m^3/sec	Period of Record
2	Sweet River	3.03	22.77	0.31	10/9/05 - 7/11/09
5	Sawmill River	0.003	0.007	0.001	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

CHAPTER 4

METHODOLOGY

In order to conduct the watershed-based assessment of the Bluefields regional watershed, procedures for the monitoring protocol can be divided into five main components: (1) GIS methods, (2) field methods, (3) lab methods, and (4) sampling site information and monitoring protocol.

According to Cendrero and Fisher (1997), watershed managers or planners must first define a set of “good” and “bad” environmental indicators. The indicators can then be used to map environmental quality and monitor its change over time. The environmental health indicator in this study will be the stream health throughout the watershed. Watershed classification will be used to divide the Bluefields Bay watershed into subwatersheds based upon the characteristics described below.

GIS Methods

Geographic Information System (GIS) data was purchased from MONA Geoinformatics Institute, a spatial mapping and GIS company based out of Kingston, Jamaica. Spatial data obtained from MONA included land cover data, soils, geochemistry, groundwater, roads, rivers and streams, watershed boundaries, and community locations. All of the MONA data is in the Jamaica Grid, Lambert Conformal Conic projection. Upon initial analysis of the river system dataset obtained from MONA it was clear that a higher quality hydrologic dataset would be necessary to adequately delineate the watershed’s drainage system. The watershed boundary file also appeared to be delineated according to political boundaries and is not representative of actual topographic water flow.

Using the GIS layers purchased from MONA, a database was created to compile landscape information for the Bluefields Bay watershed area. Land use and land cover classification layers were verified and compared with historic documents and current characteristics of the watersheds. The MONA soils and geology data was compared to published journal articles, the Water Resources Authority's (WRA) GIS information, and on-site field research. MONA population information and city locations were verified and updated using 2001 Jamaica census data, DOQQ's, and hard- copy community maps and coordinates. Road networks, bridges, and human structures in the Bluefields watershed had been previously mapped out and these features were all cross-checked with aerial photography and local knowledge of the area.

Watershed Delineation. In order to efficiently evaluate the Bluefields Bay watershed, this thesis will first focus on delineating the subwatersheds, or basins, draining into Bluefields Bay. All watershed areas contributing to the bay were delineated and all of the drainage inputs were accounted for.

Several different sources of information are used to delineate the individual watershed draining Bluefields Bay. A 6-meter digital elevation model (DEM), also obtained from MONA, was analyzed using the hydrologic toolset in ArcGIS 9.3. The toolset was used to determine the actual stream network derived from the topography of the DEM and the watershed associated with each individual river network (Jensen et al., 1988, and Lyew-Ayee et al,. 2007). IKONOS True Color and Infrared aerial imagery donated from The Nature Conservancy were used to interpret the watersheds visually and topographically. Topographic digital-ortho quadrangles (DOQQs) are also used to determine watershed divides and drainage according to the contours and layout of the landscape. The river networks derived from the DEM were also ground-truthed by physically walking the stream and checking the direction and location of drainage and flow.

Because of the poor quality of the river system data set, a major undertaking of this thesis involved validating and mapping the river system throughout the watershed. Mapping out the rivers involved physically walking each individual stream, marking its location with a global positioning system (GPS), and ground truthing the latitude and longitude data with coordinating elevation data. Land use data, such as settlement structure, location, type, and use of the surrounding landscape was also collected while surveying each stream. Using the DEM and MONA GIS data every stream entering the bay was identified as being either perennial (wet/flowing) or ephemeral (dry).

Subwatershed Classification. Using GIS all of the delineated watersheds contributing to the bay were broken up into physiographic regions according to Table 2. Drainage area from the mouth of each stream system to the most distant divide for each of these subwatersheds was calculated at 1 to 10 km along the upstream channel lengths from the bay. The proportion of each in the coastal lowland, mountain transition, and upland regions was then determined. The following three categories were developed to classify the subwatersheds according to the coastal fringe drainage in the larger Bluefields Bay watershed (Finkl, 2004):

1. Coastal Subwatershed Drainage Area (<5 km from the bay)
    a. Direct Drainage: ephemeral, slope or valley, <1 km

b. Ephemeral and perennial < 5 km

2. Transitional Subwatershed Drainage Area (5 to 10 km from the bay)
3. Inland Subwatershed Drainage Area (>10 km from the bay)

Critical Stream Factors. After the subwatershed classification water use classes were proposed to determine critical stream factors within the Bluefields Bay watershed. Using GIS and knowledge of the area the following water use classes were proposed:

1. Public water supply: where are weirs, pipes, and treatment facilities located;
2. Spring/ aquifer recharge zones: contact and bluehole fed areas;
3. Accessible water supply: perennial and ephemeral stream access, roads; and
4. Population Center Zone: based on proximity to city center and town boundary.

Watershed Condition Class. Using the water quality monitoring data to evaluate watershed conditions the following classes are proposed to quantify the condition, category, and remediation of the watershed. These classes are based upon the eight subwatershed categories presented by the Center for Watershed Protection (Table 4) that are derived from the type of water resource and intensity of land uses within the subwatershed (Caraco et al., 1998). Although each type of water resource has unique management characteristics it is helpful to differentiate between them and apply similar techniques and tool to subwatersheds in the same category.

Because the original subwatershed management categories proposed by the Center for Watershed Protection (CWP) were initially developed for areas within the United States it was necessary to first determine if the category was applicable to the region of Bluefields Bay. Urban lakes are non-existent in Bluefields, so this category was immediately removed. All of the stream systems fall under the coastal/estuarine category, so the remaining 6 categories were condensed into the watershed condition classes for Bluefields Bay.

Condition classes, because they were developed using water quality as an indicator of stream health, were first determined to be either in good, moderate, or poor condition. Then based off of these three water quality conditions zones of protection, conservation, and restoration were established to coincide with water quality levels. Streams with the highest water quality and habitat rating need protection and prevention of future problems (Smith et al., 1997; Caraco et al., 1998). Water systems that are also used for drinking water are usually maintained as a water supply reservoir/ or groundwater/ spring aquifer, so these attributes can generally be added to the zone of protection in order to prevent future contamination. Zones of restoration are defined as completely degraded, have extremely poor water quality, and are poorly supporting streams in regards to habitat and in-stream biology (Frissell et al. 1986). These streams require a major effort to remediate and necessitate the most work. The zone of conservation was developed to classifying water systems that had moderate water quality, population, and land use impact and would benefit mostly from community education and the implementation of best management practices (BMPs). The final watershed condition classes are presented in Table 12.

Table 12. Watershed Condition Classification.

Zone	Water Quality	Description
Protection	Good to Excellent	Prevent future problems
Conservation	Moderate	Education and BMPs
Restoration	Poor	Major effort, needs most work

Risk Assessment Framework. A framework was developed to assess and map the water quality risk throughout the watershed, and the threats posed to community watersheds versus Bluefields Bay (Foxcroft et al., 2007). The framework contains the following components and actions:

1. Define the geographical area of interest: the entire area including the protected area and surrounding watersheds. This was done during the subwatershed classification and delineation.

2. Delineate domain into zones that are both ecologically meaningful and relevant to management in order to identify high areas of risk. The three zones identified for this framework include coastal lowland, mountain transition, and inland subwatersheds (Table 2). Transitional zones provide an area for monitoring and implementing early protection practices because they ultimately drain into the protected fish sanctuary (Bluefields Bay). Coastal lowlands can be subdivided into drainage fringe zones (Finkl, 2004).

3. Identify the appropriate landscape unit at which to conduct the assessment. Dependent upon size, river systems, land use, and available resources in the watersheds. Smaller areas can be more intensely monitored. The landscape areas defined for this framework are derived from the watershed management unit presented in Table 5.

4. Map the distribution and abundance of watershed risk factors. Risk factors for this framework include water quality monitoring data, proximity to road crossings and urban areas, and land use. Road crossings, urban areas, and land uses can be defined as hydrologically sensitive areas (HSAs), which refer to areas in a watershed that are prone to generating runoff and are susceptible to transporting contaminants to perennial surface water bodies (Walter et al., 2000).

5. Define the management options by assessing watershed risk category and index. The watershed risk category assesses the threats posed to the watershed by the risk factors as they contribute to poor water quality that affects the protected area (Bluefields Bay). The watershed risk index delineates the threat posed by current watershed conditions (Table 12) of the risk factors and proximity to protected areas.

Field Methods

The following field methods were used to collect data during water quality monitoring.

Visual Surveying Data. At each monitoring site field observations were taken to characterize and classify the water, bed substrate, channel, and disturbance located within and adjacent to the stream. These parameters are important to understanding the structure, setting, and dynamics of each sampling site, or stream system. Table 13 below shows the list and options that were used to describe the stream characteristics of each site.

Table 13. Monitoring Site Field Observation Checklist.

Parameters	Decriptors					
Water						
Flow:	dry	pools	stagnant	laminar	turbulent	rapid
Color:	none	blue	green	brown	red/orange	white/yellow
Smell:	fresh	rotten eggs	chemical	sewage		
Turbidity:	clear	cloudy	turbid			
Substrate						
Bed Material:	sand	gravel	cobble	boulder		
Mud on Bottom:	none	10%	25%	50%	75%	>90%
Algal Cover:	none	10%	25%	50%	75%	>90%
Macrophyte:	none	10%	25%	50%	75%	>90%
Channel						
Type:	coullvial	bedrock	step-pool	braided	plane-bed	riffel-pool
Artificial:	concrete basin/weir		channelized	road ditch	near bridge	
Setting:	upland-step	alluvial	wetland	mangrove	coastal	spring
Disturbance						
Human:	bathing	washing	soil erosion			
Misc:	trash	cattle	crops	large-woody debris		

Rapid Assessment Procedure. The United States Environmental Protection Agency (EPA) has designed a stream habitat assessment procedure to support their Semi-Quantitative Macroinvertebrate Stream Bioassessment Project Procedure (Barbour et al,.

1999). The goal of the stream habitat assessment supports their understanding of the relationship between habitat quality and the biological community. The riffle/pool rapid habitat assessment form (Appendix A) from the Bioassessment Project was filled out at each monitoring site. The information collected from this form was then used to score habitat parameters at the fifteen monitoring sites within the Bluefields Bay watershed.

Habitat assessment parameters were scored on a numerical one to 20 scale, with a score of 20 being optimal and a score of zero being poor. The scores for each site were added together and divided by two, which produces a percentage of optimum reference condition. Temporary habitat assessment categories are as follows:

1. Comparable to Reference >90%
2. Supporting 75-89%
3. Partially Supporting 60-74%
4. Non-supporting <59%

River Discharge. The discharge of each stream was surveyed at each sample site. A FP101-FP201 Global Flow Probe was used to measure the velocity of the stream flow. The Flow Probe is used to measure the average velocity along a cross-section within the stream, so a tape measure is first strung across the stream. Since the velocities vary throughout the flow's cross section, the stream is divided into incremental subsections along the strung measuring tape and the average velocity is measured at each subsection. In this study most of the streams were only wide enough to sample two or three velocity subsections across the stream. Using the USGS "6 tens method", the Flow Probe is placed at the center of each subsection at a depth from the surface of 0.6 of the total depth. The 0.6 depth represents the average velocity point for the vertical profile. Once the average velocity is measured it is then multiplied by the area of the subsection, which equals the flow for that subsection (Q=VxA). After calculating the flow of each subsection all of the subsections are added together to obtain the Total Stream Flow, or discharge.

Measuring the velocity and volume of discharge in a stream is critical to understanding the amount of water moving through the stream channel and the rate at which the water is moving. These flow characteristics can then be linked to the concentrations and rate of the nutrient transport in the stream channel.

Laboratory Methods

Water Chemistry. In order to investigate the surface water quality of the Bluefields Bay watershed, the water chemistry was tested in-situ at a number of established sites along each river in the watershed. A Horiba U-22XD Multiparameter Water Quality Monitoring meter was used to test the quality of the water. The meter measures the following parameters: temperature, conductivity, dissolved oxygen, pH, turbidity, total dissolved solids, and depth of the Horiba in the water.

The temperature of the water, measured in degrees Celsius, is important because it influences the conductivity of the water. Generally, as the temperature of the water increases, the amount of dissolved oxygen decreases, negatively affecting the biota present in the stream. An increase in temperature also leads to a tendency for the amount of pollutants to increase. Conductivity, a measure of the ability of the water to carry an electric current, increases with an increase in temperature, due to the increased movement of ions in the solution. Higher measures of conductivity lead to decreased water quality and lower resistivity of the water. Conductivity is reported as mS/cm (milli Siemens per centimeter).

Higher values of dissolved oxygen measured in the stream are an important health indicator because biota necessitate oxygen to survive. Measurements of dissolved oxygen are reported as mg DO/L (milligrams dissolved oxygen per liter). Values less than 5 mg/L DO put a stress on aquatic life and approach anoxic conditions. Hydrogen potential (pH) is used to show the degree of acidity present in the system on a scale of 0 to 14 by measuring the hydrogen ion (H^+) activity in a solution. The lower the pH, the higher the acidity. pH is measured on a logarithmic scale; therefore a decrease of 1 pH unit is equivalent to a ten fold increase in hydrogen ion activity and ten times more acidic. pH is important in stream quality because it determines the amount of solubility and biological availability of chemical constituents in the stream. Nutrients and metals tend to be more soluble in lower pH (higher acidity) systems (Molles, 1999).

Turbidity is measured in NTU (Nephelometric Turbidity Unit) and is detected using the light-transmission scattering method. Turbidity in water is caused by suspended matter such as clay, silt, organic and inorganic matter, and plankton and other microscopic organisms. Measuring turbidity in as stream is an important health indicator. High concentrations of particulate matter can decrease habitat quality by depositing excess sediment in a system, increasing sedimentation rates in that stream. Presence of suspended solids in a stream also provides attachment areas for pollutants; therefore a higher presence of suspended solids increases a streams susceptibility to high nutrient levels. Total dissolved solid measurements are also an indicator of stream health, because the source of the dissolved solids in the streams is related to pollution runoff and sources.

Salinity was measured, but the only readings occur in the brackish water areas immediately adjacent to Bluefields Bay.

Nutrient Analysis. In addition to testing the chemistry of the streams, the nutrient levels of the water were analyzed for each site. This information is used to identify areas of pollution and degradation. 500 mL of water samples were collected at each sample site and brought to be post-processed at a separate location.

Orthophosphate concentrations were measured using an Orbeco Hellige SC400 Colorimeter, which was used to test water samples June 2009 to June 2010. An inorganic type of phosphate often referred to as 'reactive phosphate', orthophosphate is an important nutrient for aquatic plant growth and the amount found in a healthy system is usually less than 0.1 ppm. Water containing a concentration larger than 0.1 ppm, or 1.0 mg/L is often polluted from sources such as wastewater treatment facilities and drainage from agricultural practices. Excess phosphorus present in a stream system increases aquatic plant growth, which is also known as eutrophication. When the algae and plants die an increased amount of oxygen is used in decomposition, which often results in fish kills. Phosphate concentrations are recommended not to exceed 0.1 mg/L in streams that do not directly discharge into lakes or reservoirs (Mueller and Helsel, 1999).

Water samples were also analyzed for Nitrate/Nitrite and Total Chlorine using LaMotte Insta-Test Test Strips. Nitrate was measured over a range of 0-50 ppm and Nitrite was measured over a range of 0-10 ppm. Nitrogen is essential for plant growth, but excessive amounts in water supplies present major pollution and health problems, such as "blue babies" (methemoglobinemia) in infants less than six months of age. The United States Public Health Service Drinking Water Standards state that 10 ppm nitrate nitrogen should not be exceeded. Sanitary and industrial engineers consider concentrations of less than 1 ppm acceptable.

Total Chlorine was measured at 0-5 ppm using the Insta-Test test strips. Chlorine is used as a disinfectant in wastewater treatment plants and is commonly added to most drinking water supplies in the U.S., as well as in developing countries such as Jamaica.

Bacteria. An IDEXX Quanti-Tray /2000 system using Colilert reagent was used to determine *Escherichia coli* and Total Coliform counts at each sample site. Samples were taken using EPA-accepted Whirl-Pak Coli-Test bags, which contain 10 mg of sodium thiosulfate to neutralize chlorine. A colilert powder packet was added to each 100/mL surface water sample. After the colilert was completely dissolved, the water sample was transferred to a Quanti-Tray/2000 which was run through the Quanti-Tray Sealer. Bubbles in the tray were allowed to dissipate, and the trays were incubated at about 35 degrees Celsius for 24 hours. The temperature at which samples are incubated mimics the internal body temperature for which bacteria are cultured.

Because of travel and set-up in a developing country, formulating methods by which to incubate the samples necessitated a creative approach. Usually the sealed trays are incubated in a laboratory oven. The oven has a set, maintained temperature that circulates a constant flow of heat throughout the oven. Since all of the field and lab equipment was transported from the state of Missouri via airplane to Jamaica, the oven was too large to take down.

During the first bacteria sampling round January 2010, the sample trays were incubated in a large plastic cooler (Figure 22a) heated with two heating pads. After 24 hours, the samples from the cooler were checked and it appeared that, although the thermometer from the cooler maintained a 35 degree Celsius temperature, the air was not circulating and the dry heat over cooked and killed the bacteria samples. For the second sampling round January 2010, the sample trays were incubated in a metal gas oven (Figure 22b), which was heated using only the two heating blankets. Because the oven was designed for proper exchange of heat flow, the oven was able to maintain a steady temperature and accurately incubated the samples with indirect heat. This method was used to incubate the remaining sampling rounds.

Figure 22. Bacteria sample incubation techniques. (a) Cooler incubator and (b) oven incubator.

The number of small and large positive cells were counted and referred to an MPN table to find the most probable number for Total coliform. E. Coli results were obtained by placing the wells under a black light and counting the number of fluorescent wells. Once again, the MPN table was referred to determine the E. Coli concentration. The presence of E. Coli in a water sample is an indicator of fecal contamination.

Monitoring Sample Site Selection

Monitoring sites (Figure 23) within the Bluefields Bay watershed area were chosen for a number of reasons. The design of this monitoring protocol was set up to attempt to understand where and how the various water systems present in the watershed contribute inputs into the bay. It was important that the monitoring sites be accessible, as well as located near the coastal draining edge of the watershed, or near Bluefields Bay. Fifteen sites along major waterways were selected based upon accessibility, location up or downstream, and proximity to the location of communities and populated places. Four monitoring sites also coincided with gaging stations that are monitored by the Water Resources Authority (WRA). A total of fifteen monitoring sites were established and Tables 14 and 15 below show descriptions of each site. Site location photographs can be found in Appendix B. These sites were sampled for two week periods over the course of a one year monitoring study. Using the methods described in the previous sections, the monitoring protocol was broken down into three monitoring rounds. It should be noted that the site downstream of monitoring site number 8, ds of 8 or site 8.1, was only monitored during the last round of sampling.

Sweet River Watershed. Four sites are located within the Sweet River watershed. Site number one, Deans Valley, is located outside of the community of Water Works in the African village of Abeokuta. Deans Valley is a headwater stream produced

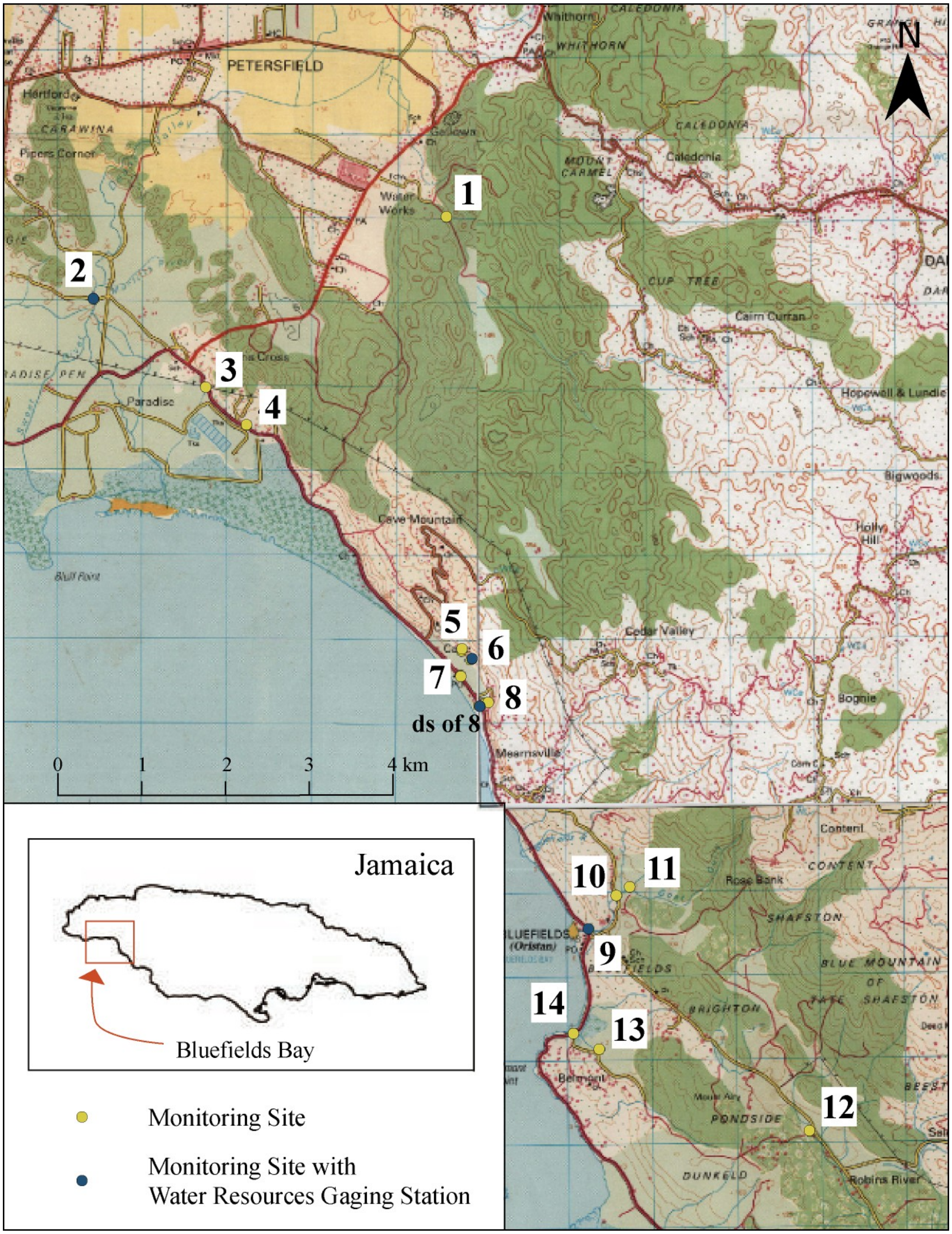


Figure 23. Fifteen monitoring site locations, including the sites monitored by the Water Resources Authority (WRA).

Table 14. Monitoring site summary information.

Site	Name	Watershed Area (km^2)	Drainage Length (km)	Road	Community	Longitude	Latitude	WRA[1] Site
1	Deans Valley	81.67	11.12	Unpaved	Water Works	78°4'54.268"W	18°14'4.517"N	
2	Sweet River	81.67	3.57	Parochial Class A	Paradise	78°2'36.074"W	18°14'40.704"N	yes
3	Ferris River	81.67	2.21	Coastal Road	Ferris Cross	78°4'9.556"W	18°13'32.801"N	
4	Watercress River	81.67	2.69	Coastal Road	Ferris Cross	78°3'54.821"W	18°13'17.544"N	
5	Sawmill River @ watering hole	0.05	0.45	Unpaved	Cave	78°2'25.926"W	18°11'50.316"N	yes
6	Sawmill River @ pimento Factory	0.05	0.35	Unpaved	Cave	78°2'23.788"W	18°11'47.461"N	yes
7	Sawmill River @ road crossing	0.05	0.12	Coastal Road	Cave	78°2'26.383"W	18°11'41.021"N	
8	Waterwheel	0.02	0.12	Coastal Road	Cave	78°2'17.39"W	18°11'30.17"N	
8.1	downstream of Waterwheel	0.02	0.10	Coastal Road	Cave	78°2'18.442"W	18°11'29.728"N	yes
9	Bluefields River at road crossing	5.15	0.41	Coastal Road	Bluefields	78°1'18.707"W	18°10'18.588"N	yes
10	Bluefields River at Rivertop	5.15	0.81	Parochial Class A	Rivertop	78°1'24.751"W	18°10'16.237"N	
11	Shafston Tributary of the Bluefields	5.15	1.01	Parochial Class A	Shafston	78°1'35.749"W	18°10'2.179"N	
12	Robins River at road crossing	19.67	4.5	Parochial Class A	Robins River	78°0'5.987"W	18°8'43.728"N	
13	Bluehole Spring	0.59	0.51	Parochial Class A	Belmont	78°1'31.987"W	18°9'13.885"N	
14	Bluehole River at road crossing	0.59	0.12	Coastal Road	Belmont	78°1'41.992"W	18°9'22.025"N	

[1]Water Resources Authority

from the upper forested region of the mountains and immediate access is walk-in only. The approximately 100 residents of Abeokuta draw water from this monitoring site and often place cattle along the banks of the stream. Old and renovated aqueducts have been constructed downstream of the site and channel a portion of the water flow. Site number two, the Sweet River, is located outside of the community of Paradise in an area classified as pasture according to the topographic quadrangle. The Sweet River site is downstream from a stone bridge and adjacent to the remains of a historic Great House. A dirt road leads up to the site, but vehicle access is restricted upon reaching the bridge. The river flows through an alluvial land-savanna setting and is a popular area for cattle and goats to roam. This site has been a gaging station monitored by the WRA since 2005.

Sites three and four are both located near the community of Ferris Cross and are adjacent to the main coastal road that runs along the coast of Bluefields Bay. Site three is located on the Ferris River. The Ferris River site is located between two houses and is upstream of the bridge that flows under the road. Several polyvinyl chloride (pvc) pipes run down the stream and under the road. This site is frequently used to collect water, launder clothes, and bathe, and is fairly level with the road. Site four is on the Watercress River and is upstream of the bridge that flows under the road. The Watercress River site flows through a wetland system and into a coastal mangrove. This site is about 2 meters lower than the road and does not host much direct human activity.

Sawmill Catchment. Monitoring sites number five, six, and seven are all in the Sawmill watershed and are located on the Sawmill River in the community of Cave. Site number five is located near the headwaters where the Sawmill River drains from the forested upper hill slope. The monitoring site is immediately downstream of a small concrete catchment and weir, which overtops constantly with flowing water. The river is channelized about ten meters by concrete walls downstream from the weir. This site encounters heavy use from vehicles parking on the right bank and community members use this site to bathe, launder their clothes, and gather water from the catchment..

The sixth monitoring site is about 115 longitudinal meters downstream of site number five. Site six is accessed by a gravel road that follows the length of the Sawmill River. The forest along the stream between the two sites was slashed, burned, and cleared, placing this site downstream from a system that has increased erosion, unstable banks, and increased sedimentation. The stretch of stream between sites five and six flows through a wetland environment into an old degraded concrete catchment, which is upstream of the monitoring site. There is a concrete bridge downstream of site six as well as two currently operating pimento factories. This site is used by locals for bathing and laundering, and has been monitored for discharge by the WRA since 2000.

Site number seven, located on the Sawmill River, is about 250 meters downstream of site six. The river flows through a wetland until it reaches site seven, and this wetland is being filled in for the development of houses. This site is immediately upstream of a bridge which flows underneath the main coastal road. The river is channelized and straightened about 20 meters upstream of the monitoring site and is used to collect drinking watering. The banks of the stream are lined with houses both up and down stream of the monitoring site, where it flows into a coastal mangrove.

Waterwheel Catchment. Sites number eight and downstream (ds) of eight are located at Waterwheel, a wetland system located near the edge of the community of Cave. Both of the monitoring sites are located near the main coastal road. Monitoring site number eight is about five meters upstream of the bridge that flows under the coastal road. This area has extremely high traffic crossing the bridge and is a very popular spot, due to its accessibility, for taxi drivers, bus drivers, and members of the community to drive their vehicles directly into the water to wash them. Many locals also launder clothes at this site, as well as gather water.

Downstream (ds) of eight is on the downstream side of the main coastal road. The water coming under the road bridge drains in to a catchment and then spills over a flowing weir. This monitoring site is downstream of the weir and flows into a coastal mangrove that extends to the coast. The catchment upstream of the site is a popular place for bathing and is also the location of a WRA gaging station since 1970.

Bluefields River Subwatershed. There are three monitoring sites in the Bluefields River watershed. According to the government, topographic quadrangles, and historical documents, the Bluefields River also is known as Goat Gully.

The first site on the Bluefields River, site number nine, is located upstream of the main coastal road. In 1979 there was a catastrophic flood that entrenched this area of the Bluefields River and destroyed the old bridge. The bridge was rebuilt and the current river flows through a large storm tunnel about 10 meters high. This monitoring site is a high traffic area for bathing and several human-modified structures have been built to divert and pool the water. This site is located in the community of Bluefields and has been a WRA gaging station since 1970. This reach of the Bluefields River has a larger riparian corridor and little development adjacent to the stream bank.

Site number ten is located on the Bluefields River in the center of the community of Rivertop. This site is upstream of site nine, as well as upstream of the bridge on the main road that runs through the community. The members of the community have placed boards and a tarp over the opening of the bridge to dam up the water and they use this area for water supply, bathing, and laundering upstream. Homes and several small shops line the banks of the river up and down stream of this monitoring site and a goat pasture is adjacent to the river further upstream of this site.

The final site on the Bluefields River, site number eleven, is located on the Shafston tributary of the Bluefields. This arm of the Bluefields is remotely located further upstream closer to the headwaters of the river. The site is accessed by vehicle via a dirt road that leads to a single home built near the monitoring site. An aqueduct and concrete waterway is in place upstream and a small abandoned factory sits adjacent to the river bank. This site is used primarily for drawing water, especially for residents that live on the mountainside and upstream of Rivertop.

Robins River Subwatershed. Site number twelve is located in the Robins River watershed on the Robins River. The site is adjacent to a road crossing near the community of Robins River and downstream of the bridge. This is the primary location for community members to launder their clothes, which occurs upstream of the bridge. Vehicles are able to drive directly into the water at this monitoring site, making this a popular place for car washing. The river is channelized downstream of the monitoring site by concrete embankment structures, but generally forested up and down stream.

Bluehole Catchment. The final two monitoring sites are located in the Bluehole watershed near the community of Brighton. The Bluehole Spring originates from a wetland area adjacent to a community road. The community used to depend on this spring as a water source, but over the past ten years most of the residents have been able to pipe water to their homes. The pasture surrounding the wetland area is primarily used for cattle and goat grazing and animals are often tied up near the spring. The Bluehole spring flows downstream from the pastures to a mangrove.

Monitoring site number fourteen is located on the downstream end of the Bluehole River, after it has traveled through the mangrove. This site is located upstream of the main coastal road near the bridge that flows under the road. The Bluefields Peoples Community Association (BPCA) and the Bluefields Friendly Fisherman Society’s fishing beach are across the street and this site is used by many fishermen to clean fish and discard the carcasses. This site is also located close enough to the coast for the water to be brackish.

CHAPTER 5

RESULTS AND DISCUSSION

Subwatershed Mapping and Classification

The subwatersheds within the larger Bluefields Bay watershed, or all contributing watersheds flowing into Bluefields Bay, were each individually mapped, classified, and delineated. The following section describes the results of the subwatershed delineation, characterization, and hydrologic features. The watersheds will be organized based upon main watershed management units as described by the Center of Watershed Protection in Table 5. The monitored watersheds surrounding Bluefields Bay fall into the categories of catchment, subwatershed, and watershed (Table 15).

Table 15. Monitored Watershed Size and Management Units (Center for Watershed Protection 1998).

Watershed Name	Size (km^2)	Percent of Bluefields Bay Watershed Area	Management Unit
Bluefields River	6.26	4.62%	Subwatershed
Bluehole River	0.59	0.44%	Catchment
Robins River	19.67	14.51%	Subwatershed
Sawmill River	0.45	0.33%	Catchment
Sweet River	81.67	60.23%	Watershed
Waterwheel	0.36	0.27%	Catchment
Bluefields Bay Watershed	135.6	100%	Watershed
Total Monitored Area	109	80.38%	Watershed
Unmonitored Area	26.6	19.62%	subwatershed/catchment

Subwatershed Delineation. This section presents all of the watershed units and drainages as delineated from the 6-meter digital elevation model (DEM). Any areas of questionable drainage were ground-truthed using topographic maps and physical examination of the landscape upon actual visitation to the drainage area. Delineated streams were classified as being either perennial (wet) or ephemeral (dry). There were 15 ephemeral streams that were classified as having direct drainages into Bluefields Bay and these were drainages that were unmonitored. These sites appear to be well-developed on the DEM-derived stream network, but that was not the case when visiting the physical locations. The unknown drainages and their associated watersheds had no relevant access points or important river uses by the surrounding populations and were typically dry, ephemeral streams. The delineated watersheds and drainages are presented in Figure 24 along with the established physiographic regions presented in Table 2. The percentage of physiographic regions was calculated for each subwatershed in the Bluefields Bay watershed and is presented in Table 16. These percentages will be used to develop the subwatershed risk map.

Coastal Fringe Mapping. The Bluefield Bay watershed was divided into categories based on the coastal fringe drainage distance from the fish sanctuary. The distance that each of the stream networks drained from the fish sanctuary were generalized into three categories: 0 to 5 km, 5 to 10 km, and >10 km. The monitored watersheds were then superimposed on the coastal fringe classifications and the physiographic regions (Figure 25). Nearly all of the monitoring sites were located on the coastal fringe of 0 to 5 km drainage distance. The Deans Valley site, a spring-fed mountain source stream, drains over 10 miles to the coast. However, it is a losing stream

Table 16. Area (km^2) and percentage of physiographic regions within the Bluefields Bay subwatersheds.

Subwatershed		Physiographic Region			Total Watershed Area km^2
		Coastal	Transitional	Upland	
Bluefields	Area (km^2)	0.34	1.34	3.47	5.15
	%	7%	26%	67%	
Bluehole	Area (km^2)	0.59	0	0	0.59
	%	100%	0	0	
Robins	Area (km^2)	2.49	17.14	0.04	19.67
	%	13%	87%	0%	
Sawmill	Area (km^2)	0.05	0.33	0.07	0.45
	%	12%	72%	16%	
Sweet	Area (km^2)	8.03	20.96	52.67	81.66
	%	10%	26%	64%	
Waterwheel	Area (km^2)	0.06	0.23	0.07	0.36
	%	17%	64%	19%	
Bluefields Bay	Area (km^2)	25.98	46.99	62.59	135.56
Total Watershed	%	19%	35%	46%	

where it disappears and re-emerges along its valley within in mountain areas. The Robins River site drains about 6 km to the coast and is the only other site with contributing drainage located in an upland forest setting. When compared to the physiographic regions, all of the drainages less than 5 km overlapped with the coastal lowland classification. Robins River is located in the transition zone, and Dean's Valley is considered to be in an upland setting.

Flat areas in the western portion of the watershed are alluvial plains used for agriculture and grazing, and overlap with the transitional coastal fringe classification. Because these areas are flatter and the quality of the DEM is so poor, this may be an example of a physiographic region classification that is unclear or fuzzy.

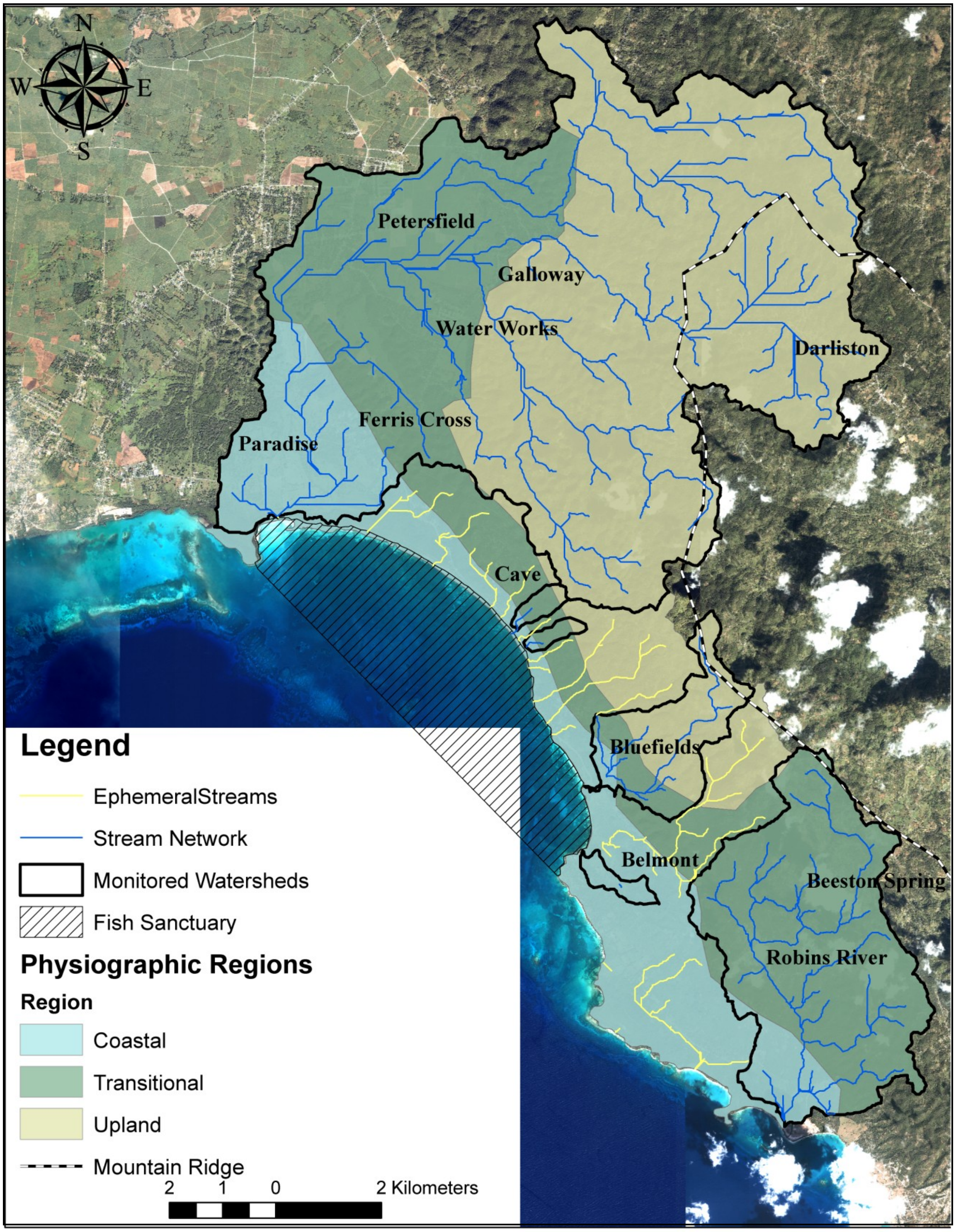


Figure 24. Drainage networks and physiographic regions in the Bluefields Bay watershed (Data Source: MONA Informatics).

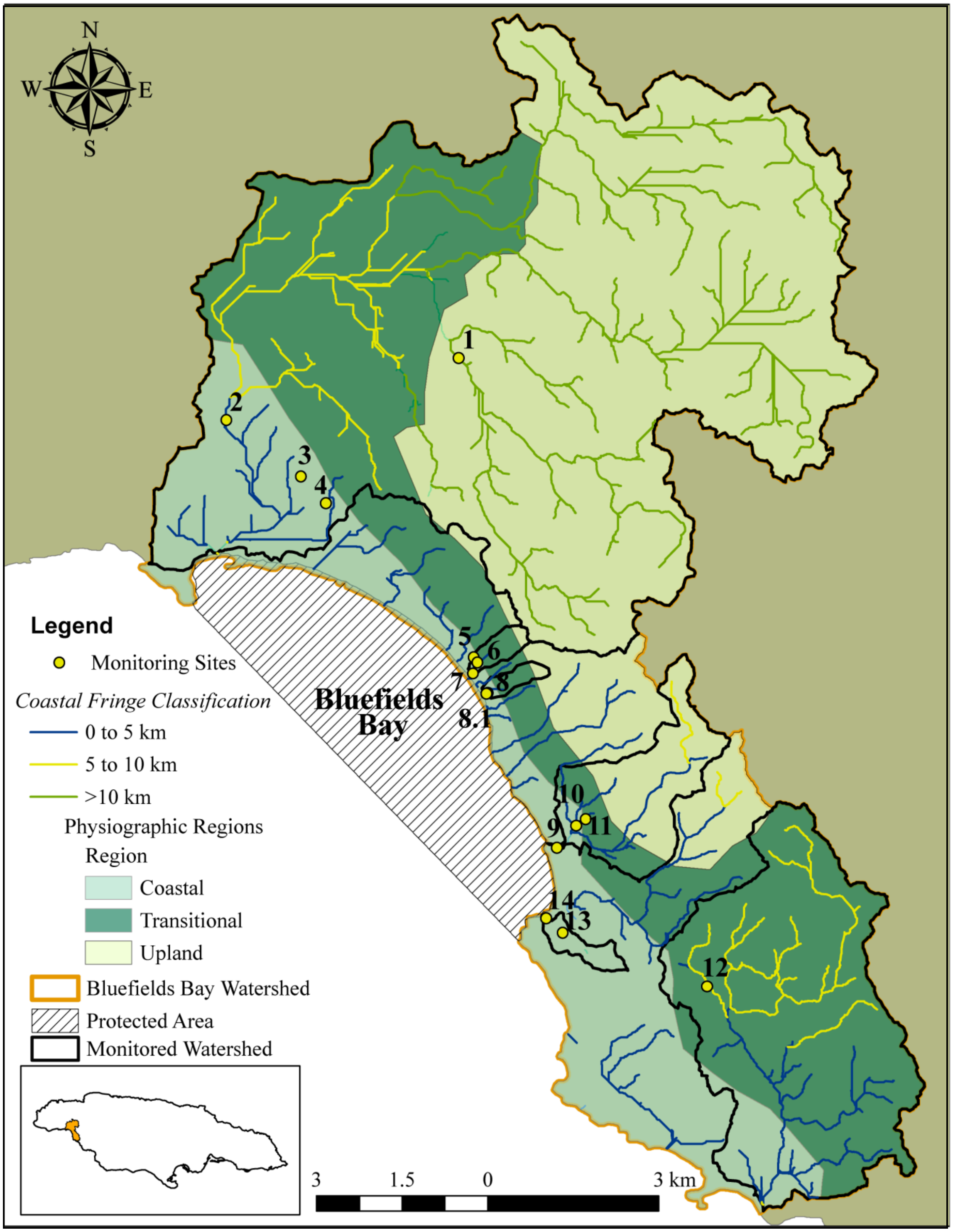


Figure 25. Coastal fringe mapping in the Bluefields Bay watershed, using the coastal fringe distance classification.

Monitoring Subwatershed Characterization. Six main watersheds are host to the 15 monitoring sites surrounding Bluefields Bay. This section describes the characterization of each catchment, subwatershed, and watershed.

Catchment. Three study basins can be classified as catchments, with drainage areas being 1.3 km^2 or less. Catchments are heavily influenced by developed areas and other intense land use practices since buffer areas are relatively small.

The Sawmill River catchment drains two enumeration districts which are considered rural and host a total population of 1,067 people. There are three monitoring sites along the Sawmill River within this watershed and these sites experience heavy use from residents living in the community of Cave for bathing and washing. Significant to this watershed is the active conversion of wetland areas and fields into areas for development and housing. While this disturbance is on a relatively small land area, the sensitivity of the stream system is being compromised, particularly immediate adjacent to the stream and near site 6, which is an important area for nutrient and pollutant filtration. The characterization of the Sawmill watershed is presented in Figure 26a and 26b.

The Waterwheel catchment lies within the rural enumeration district east 56, as does the Sawmill, and has a population of 575 people. There are two monitoring sites in the watershed, one upstream of the coastal road and one downstream. Smaller than the Sawmill River, this area is a typical flowing wetland system that drains directly into Bluefields Bay. The heavy traffic on the coastal road over the waterwheel river affects the downstream water quality, which has no opportunity to filter out before it drains into the bay. Site characterization of this watershed is presented in Figures 27a and 27b.

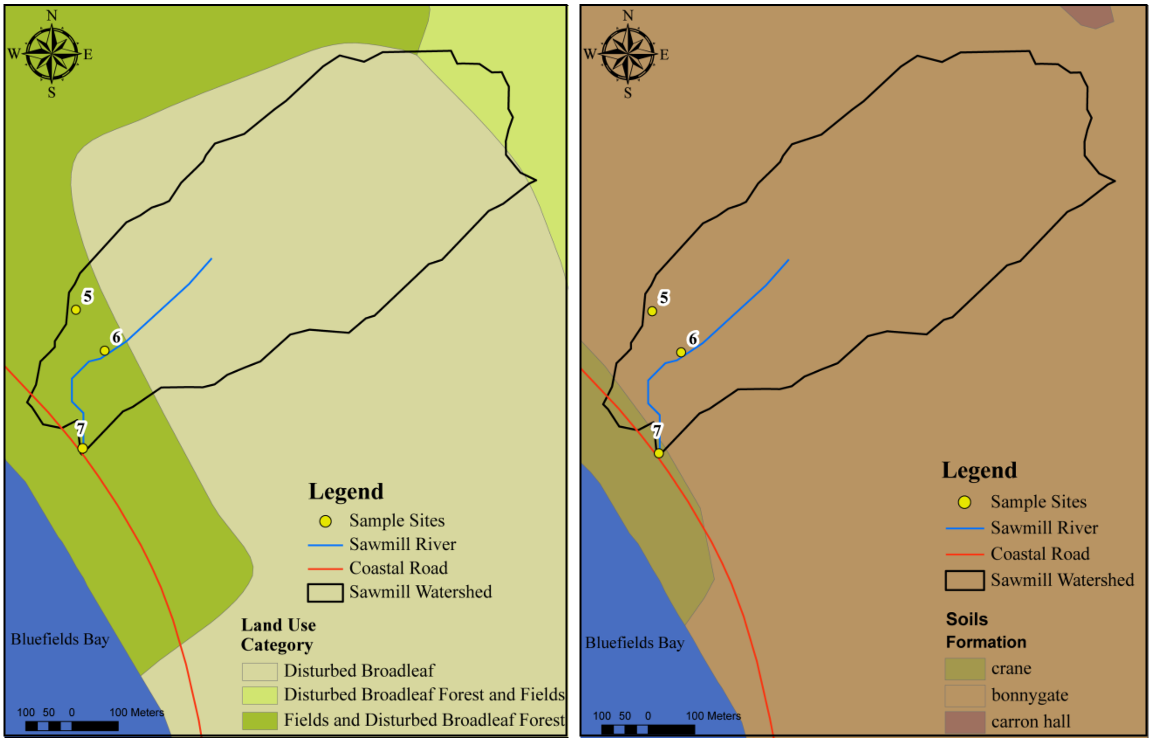


Figure 26. (a) Land use of the Sawmill River and (b) soil formation of the Sawmill River.

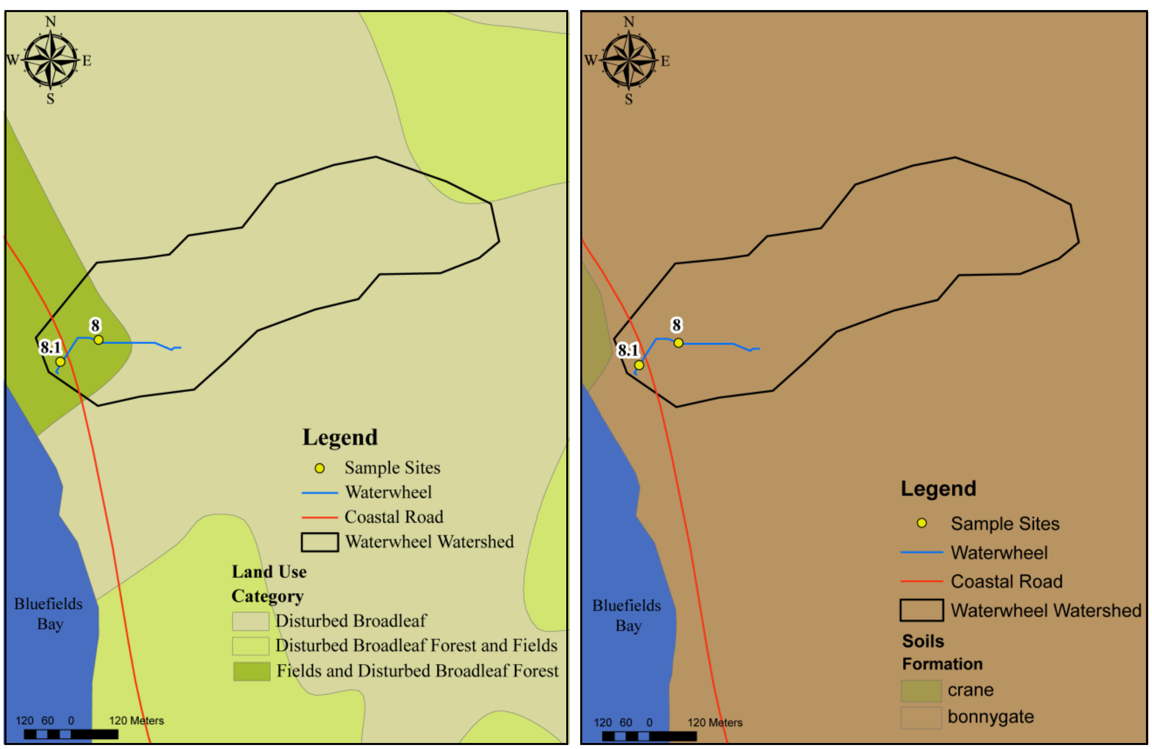


Figure 27. (a) Land use of Waterwheel and (b) soil formation of Waterwheel.

The Bluehole catchment overlaps the boundaries of three enumeration districts, all three of which are in the district of Bluefields, or non-rural. The population of the three combined districts is 1,749--a significant increase compared to the previous two catchments. The Bluehole system is a typical wetland in the upper two-thirds of the watershed, when it then flows into a small mangrove as it enters the bay. There are two monitoring sites on this system, one in the wetland portion of the watershed and one near the road crossing and mangroves. Site characterization for this watershed can be seen in Figures 28a and 28b below.

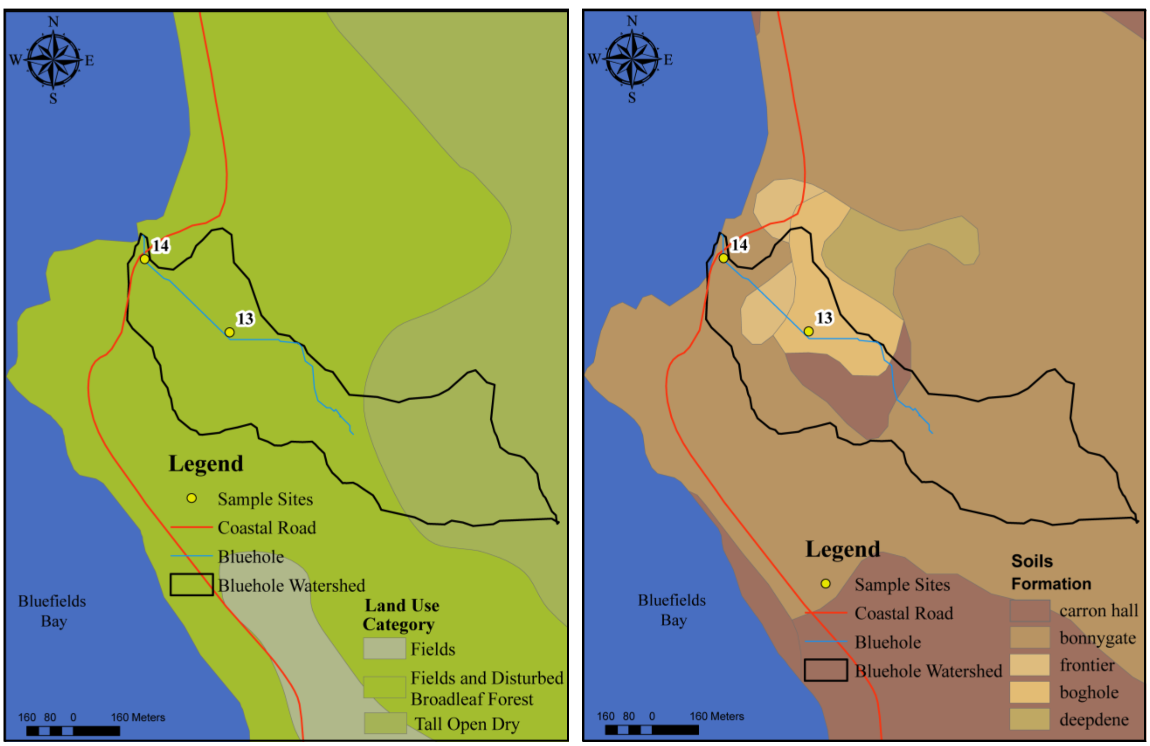


Figure 28. (a) Land use of Bluehole and (b) soil formation of Bluehole.

The three above watersheds were also characterized according to the population data. Table 17 compares catchment-sized information collected from the 2001 Census of Jamaica.

Table 17. Enumeration data table for catchment-size watersheds (2001 Jamaica Census).

Enumeration District	Population	Housing Units	HH Units on Public Source Water[1]	HH Units with Toilet Facilities[2]	HH Units with Kitchen Facilities[3]
RURAL	*Sawmill and Waterwheel Watersheds*				
Central 127	492	129	113	134	109
East 56	575	154	29	160	72
Total	1067	283	142	294	181
BLUEFIELDS	*Bluehole Watershed*				
East 75	207	66	23	72	34
East 76	821	182	95	194	151
East 77	721	202	175	219	136
Total	1749	450	293	485	321

[1]Includes water piped into dwelling, yard, standpipe, and catchment.
[2]Includes water closets and pit toilets, with facilities both shared and not shared.
[3]Includes household sinks and waste pipes, with facilities both shared and not shared.

Subwatershed. Two of the monitored watersheds fall into the subwatershed category, which is between 2.6 and 30 km^2. Urban areas can have a strong influence on water quality of they cover more than 15% of the drainage area. At this scale, stream classification is used to determine management practices for individual stream segments.

The Bluefields subwatershed drains the Bluefields River and its main tributary, Goat Gully. Because of the larger size of this watershed land use is more diverse between the headwaters and the mouth of the river. This watershed also has a history of channel erosion and instability since a catastrophic flood in 1979. There are three monitoring sites within the Bluefields watershed, all chosen because of their location, accessibility, and representation throughout the watershed. The Bluefields watershed is located in two enumeration districts, one rural and one considered Bluefields. Site characterization can be seen in Figure 29a and 29b.

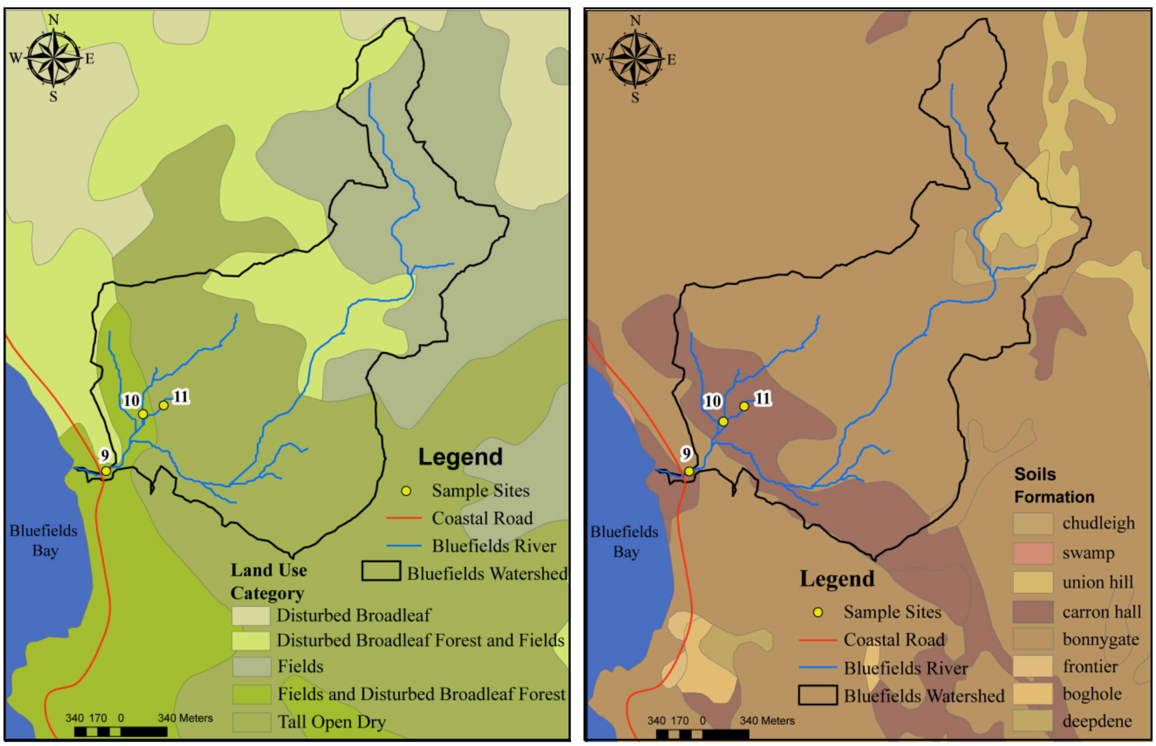


Figure 29. (a) Land use of the Bluefields watershed and (b) soil formation of Bluefields.

The Robins River subwatershed doesn't directly drain into Bluefields Bay. However, one monitoring site was located there to fulfill the need to evaluate an upland/mountain rural water use area. The Robins River watershed covers three different enumeration districts that are considered rural and is composed of several different land uses (Figures 30a and 30b). Table 18 compares subwatershed-sized information collected from the 2001 Census of Jamaica.

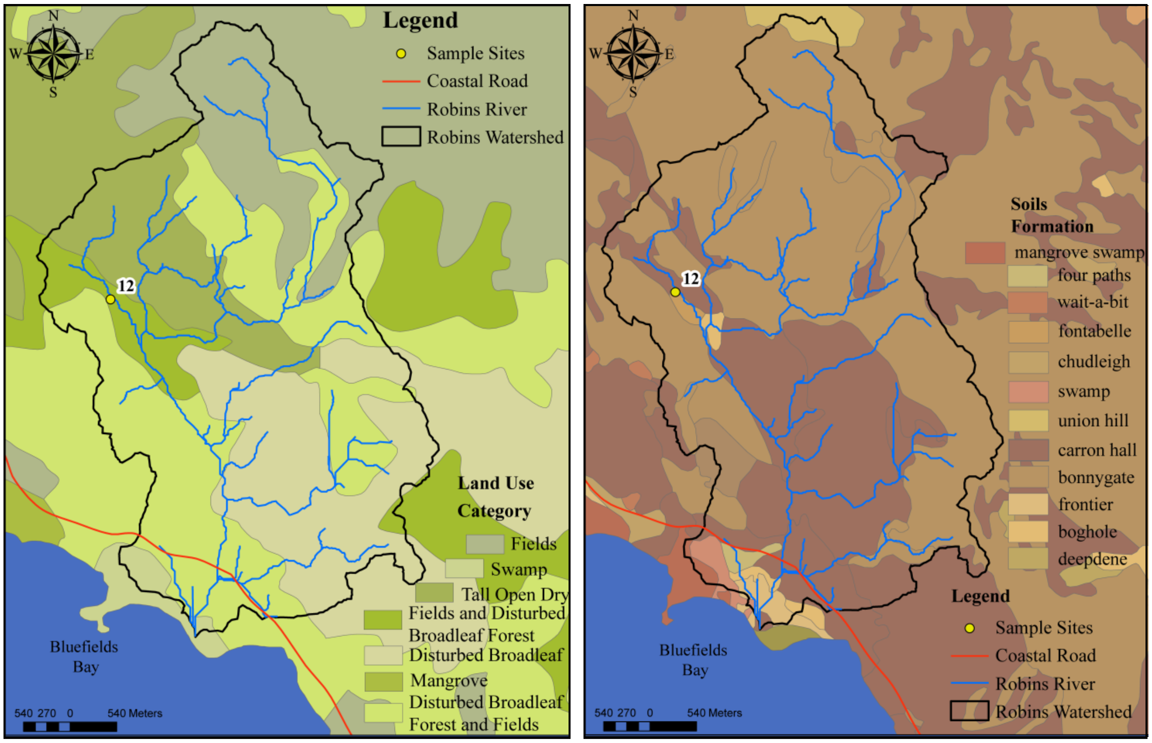


Figure 30. (a) Land use of the Robins watershed and (b) soil formation of Robins.

Watershed. One monitored watershed was classified in the watershed category, which encompasses drainages 30 to 260 km^2. Watersheds are best management by implementing watershed-based zoning practices that control major land use distribtion.

The Sweet River watershed is the largest river draining into Bluefields Bay and is not divided into among several subwatersheds. There are four monitoring sites within this watershed and each site is situated in a unique location. Sites two and three are located on the coastal road, whereas site one is located up the watershed on the mountainside and side two is located in the alluvial plain of the Sweet River. The Sweet watershed overlaps one enumeration district surrounding Bluefields Bay, both of which are considered rural. Land use in this watershed is slowly being converted to grazing areas and farm plots, and the alluvial basin is currently harvested for sugar cane. Figures 31a and 31b

Table 18. Enumeration data table for subwatershed sized watersheds (2001 Jamaica Census).

Enumeration District	Population	Housing Units	HH Units on Public Source Water[1]	HH Units with Toilet Facilities[2]	HH Units with Kitchen Facilities[3]
RURAL	*Robins Watershed*				
East 73	212	59	0	56	42
East 78	438	106	98	102	66
East 79	311	95	67	71	20
Total	961	260	165	229	128
BLUEFIELDS	*Bluefields Watershed*[4]				
East 74	609	171	13	140	141
Total	609	171	13	140	141

[1]Includes water piped into dwelling, yard, standpipe, and catchment.
[2]Includes water closets and pit toilets, with facilities both shared and not shared.
[3]Includes household sinks and waste pipes, with facilities both shared and not shared.
[4]The Bluefields watershed overlaps with the rural district East 59, which has no available census data. It has been excluded from this table.

show the characterization of the Sweet watershed, and Table 19 shows the enumeration table for watershed-sized management.

All Monitored Watersheds. Land use percentages were calculated for all of the monitored watersheds in the Bluefields Watershed. The classification percentages according to land use are presented in Table 20 below. The most common land uses typical to all of the watersheds are fields, forest, and broadleaf, all of them being disturbed to some degree by historical and recent human activity. The condition of these land uses represents the degradation common among the watersheds surrounding Bluefields Bay. The largest percentage of non-degraded land use cover, tall open dry, was found in the Bluefields River watershed. Tall open dry accounted for almost 50% of the land use surrounding the Bluefields River, all mostly found in the upper headwaters of the stream system. The current land use classifications of the watersheds draining Bluefields Bay, along with soil types and population pressures, attest to the degradation and vulnerability of the watersheds.

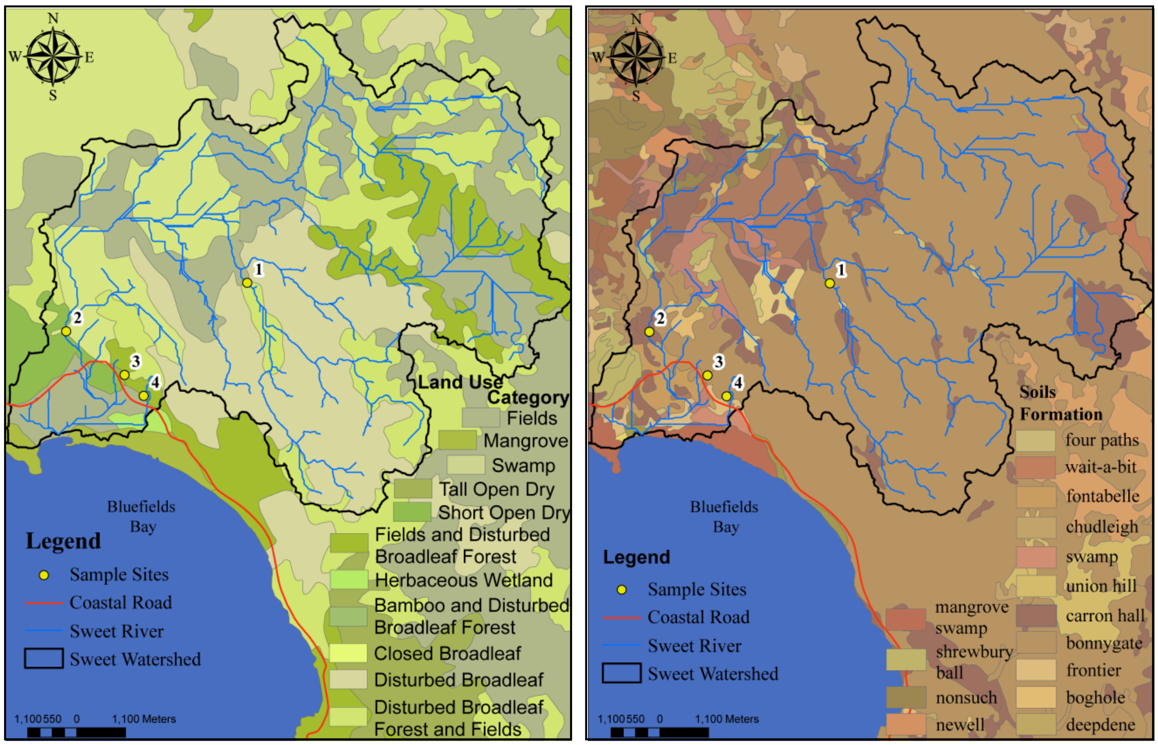


Figure 31. (a) Land use of the Sweet watershed and (b) soil formation of Sweet.

Table 19. Rural enumeration data table for the Sweet watershed (2001 Jamaica Census).

Enumeration District	Population	Housing Units	HH Units on Public Source Water[1]	HH Units with Toilet Facilities[2]	HH Units with Kitchen Facilities[3]
RURAL	*Sweet Watershed*				
Central 126	824	245	180	224	209
Total	824	245	180	224	209

[1]Includes water piped into dwelling, yard, standpipe, and catchment.
[2]Includes water closets and pit toilets, with facilities both shared and not shared.
[3]Includes household sinks and waste pipes, with facilities both shared and not shared

Site Assessment

Individual site assessments were compiled for each monitoring site in the Bluefields Bay watershed. Based upon the rapid assessment, visual survey, and site characteristic information characteristics of the watershed can be described and the condition of the watershed can be inferred in correlation with the water quality monitoring data presented in the following section. The site assessment data collected at each monitoring site can be viewed specifically in Appendix C. The data sheets that were used to perform the rapid assessment can be seen in Appendix A.

Water Quality Monitoring Program

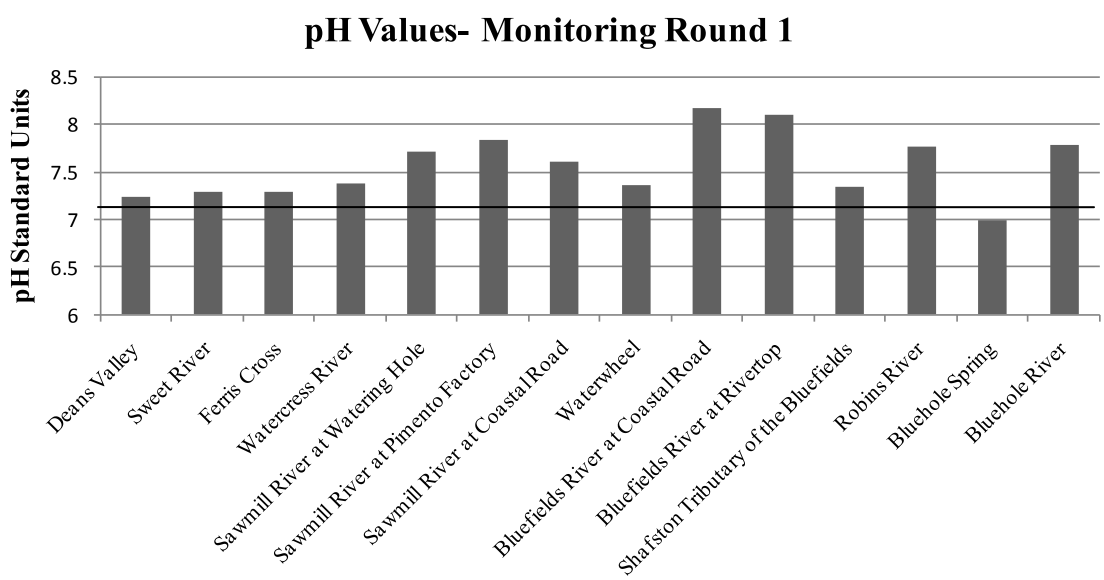
Monitoring Round One. The first period of sampling occurred December 31, 2008 through January 10, 2009. This was the initial research trip to Jamaica and a majority of the trip was spent investigating the area and learning about the locations and physical characteristics of the landscape. Assisted by Mr. Wolde Kristos from RAJ, time was spent investigating and walking each visible waterway, flowing or dry. After exploring the area surrounding Bluefields Bay, sampling sites were established and initial measurements were taken. Measurements of water chemistry were collected at each site, photographs were taken, and the coordinates were collecting using a Trimble Geo XH GPS Receiver.

Table 20. Land use percentages per watershed in the Bluefields Bay watershed.

Land Use	Area (km^2)	% Of Total
Bluefields River Watershed 5.15 km^2		
Disturbed Broadleaf Forests and Fields	0.97	19%
Fields	1.41	27%
Fields and Disturbed Broadleaf Forest	0.32	6%
Tall Open Dry	2.45	47%
Bluehole Watershed 0.59 km^2		
Fields and Disturbed Broadleaf	0.37	63%
Tall Open Dry	0.22	37%
Robins Watershed 20.38 km^2		
Disturbed Broadleaf	4.83	24%
Disturbed Broadleaf Forests and Fields	7.15	35%
Fields	3.14	15%
Fields and Disturbed Broadleaf Forest	1.94	10%
Swamp	0.26	1%
Tall Open Dry	3.06	15%
Sawmill River Watershed 0.45 km^2		
Disturbed Broadleaf	0.38	84%
Disturbed Broadleaf Forest and Fields	0.02	4%
Fields and Disturbed Broadleaf Forest	0.05	12%
Sweet River Watershed 0.45 km^2		
Disturbed Broadleaf	19.80	24%
Disturbed Broadleaf Forest and Fields	16.51	20%
Fields	23.77	29%
Fields and Disturbed Broadleaf Forest	8.67	11%
Herbaceous Wetland	0.26	0%
Mangrove	0.40	0%
Plantations	10.23	13%
Short Open Dry	2.03	2%
Waterwheel Watershed 0.36 km^2		
Disturbed Broadleaf	0.31	86%
Disturbed Broadleaf Forest and Fields	0.00	1%
Fields and Disturbed Broadleaf Forest	0.04	13%

Measurements of water quality parameters pH, SC, Turbidity, DO, TDS, and temperature were collected at each site and show consistency between sites with a few exceptions described below (Figure 32). All monitoring data can be found in Appendix F.

pH. Mean pH measurements for this sampling round were at a reading of 7.57, with values collected from all 14 sites (Figure 32) typically ranging from 7.1 to 8.1, which is between the normal carbonate-buffered ranges of 5.5 to 8.3 for water in areas with limestone bedrock (Drever, 1997). Exceptions to these ranges were found at sites 9 and 10, which had values of 8.18 and 8.1, respectively, and at site13 which had a value of 7.0. Site 13, which is Bluehole Spring, has water quality parameters which are different from most of the other sites, most importantly pH and DO levels. The low pH and DO levels found in Bluehole spring infer anoxic conditions, which are the result of eutrophic systems. Sites 9 and 10 are located on the Bluefields River and have direct contact with carbonate-rich limestone rock exposures along the stream reach, which increases the pH of the water (LeFevre and Sharpe, 2002).



Median value= 7.49

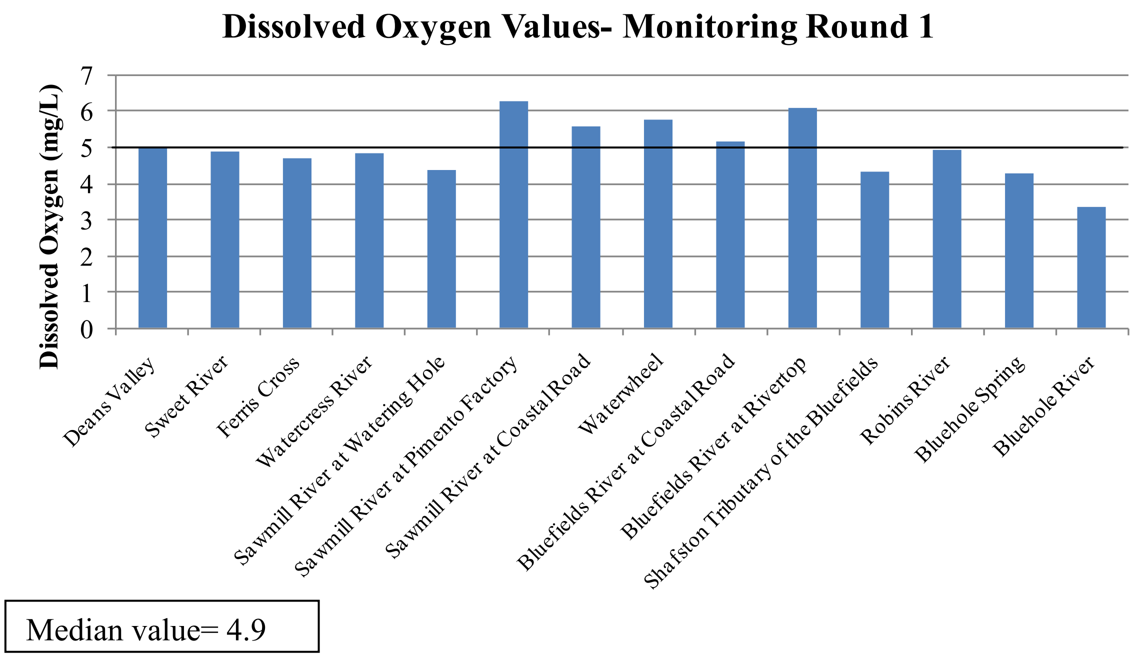


Figure 32. pH and DO values from monitoring round one. The horizontal line indicates median concentration of the parameter being measured.

Dissolved Oxygen. Dissolved oxygen is an important indicator of a healthy aquatic system. When dissolved oxygen concentrations fall below 5.0 mg/L aquatic life is put under stress and lower concentrations can result in fish kills (U.S. EPA). The median value for DO during the first monitoring round was 4.9 mg/L, which is just under the standard for tropical warm-water systems. DO levels ranged from 3.34 to 6.29 (Figure 32), which is a fairly significant range of values. Sites 6, 10, and 8 had the highest DO levels, which can be explained for several reasons. Site 6 is downstream of an old weir structure, which provides oxygenation when stirring the water as it comes in over the weir. Site 10 is located in the shallow, faster moving headwaters of the Bluefields, which stirs up oxygen, and site 8 is a spring-fed system where surface water is actively interacting with groundwater. Site 13 again stands out with a significantly low DO level, probably due to the near anoxic conditions caused by excessive aquatic vegetation. The eutrophic conditions affect the available downstream DO concentrations in Site 14, which is downstream of Bluehole Spring.

Temperature. Water temperatures vary between monitoring sites (Figure 33). Temperatures ranged from 23.2 to 25.3 ^{o}C and the sites with the warmest temperatures were in the Sweet River watershed. These three sites had very little available stream cover in the form of trees or shrubs, which increases light penetration and ultimately water temperature. The sites with the coolest temperatures were in the forested monitoring sites with water that was being well mixed.

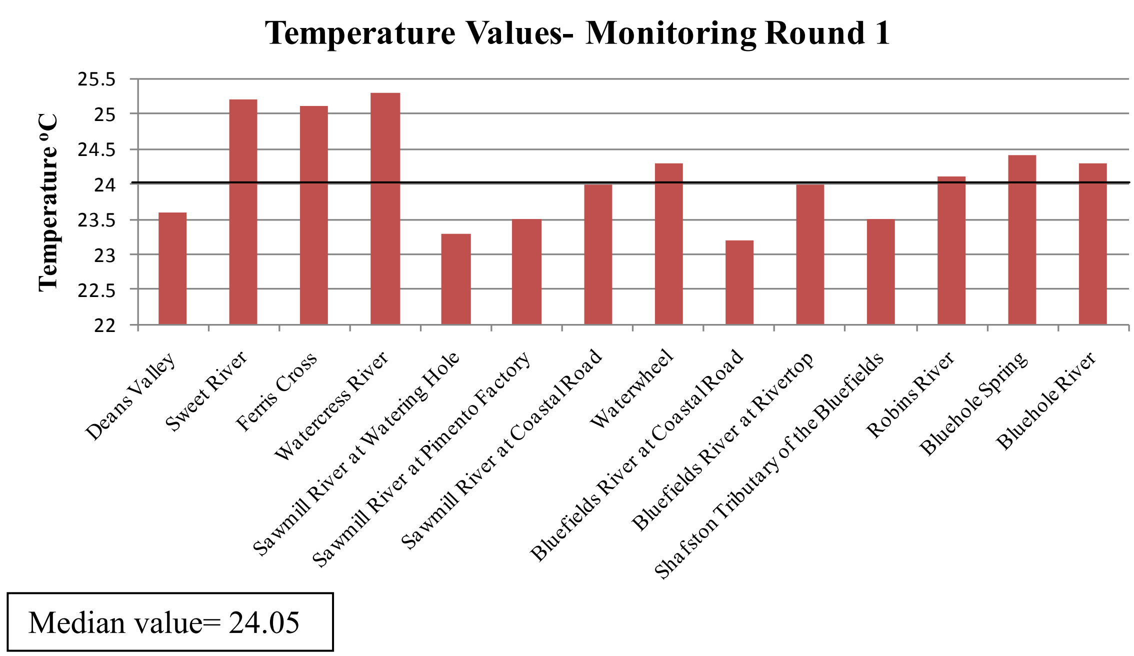


Figure 33. Temperature values from monitoring round one. The horizontal line indicates median concentration of the parameter being measured.

Other Parameters. No unusual trends were observed in the remaining water quality parameters sampled. Total dissolved solid values typically ranged from 0.31 to 0.39, with the only outlier valued at 1.2. This reading was at site 14, which is the only area of brackish water that is flowing from a small mangrove. Specific conductivity measures lower with cooler water temperatures and turbidity values have a range of 0 to 42.5 NTU.

Monitoring Round Two. The second period of sampling occurred the first two weeks in June of 2009. Three rounds of sampling occurred: June 2, June 5, and June 7, 2009. Sample site 8.1 was not included in this sampling round. Water chemistry parameters were again collected at each site, as well as new photographs. The channel width and depth was measured at each site, as well as the velocity of the flowing water. Visual surveying information was recorded according to the field observation list (Table 13 in the Methods section). Water samples were collected in situ at each site, and transported back to a temporary laboratory set up using equipment transported from the Ozarks Environmental and Water Resources Institute (OEWRI) at Missouri State University, Springfield, Missouri. The water samples were analyzed for total coliform and E-coli, as well as for phosphate concentrations.

Water Chemistry. Water chemistry values collected over the second sampling round had similar trends as the results collected during the first sampling run. pH values increased slightly all-around, most notably at sites 8, 11, and 13, which were the lowest sites during round one. The rainy season in Bluefields occurs through the months of May through October, but this would explain a lowering of pH values. However, the weather was particularly dry prior to this sampling round. Temperatures also increased all-around, with significant increases at sites 14, 11, and 9. Air temperatures surrounding Bluefields Bay increase about 5 to 10 degrees over the summer (Jamaica Meteorological Survey), which affects the temperatures of the streams. Residents also spend more time in the water systems, which can also influence the water temps. The increased use of the water systems also leads to a slight increase in dissolved oxygen levels, but DO overall remained similar to values collected in round two.

Bacteria Sampling. Three rounds of bacteria sampling were conducted during the second monitoring round in June 2009. Because of the difficulty and variability of incubating samples the results of this sampling round are not statistically accurate and can only be used as a general indicator of water quality. Figure 34 below shows the E-coli counts collected during this sampling round. The variability between sampling rounds is clearly depicted, with the highest counts being generally found at sites with heavy anthropogenic use.

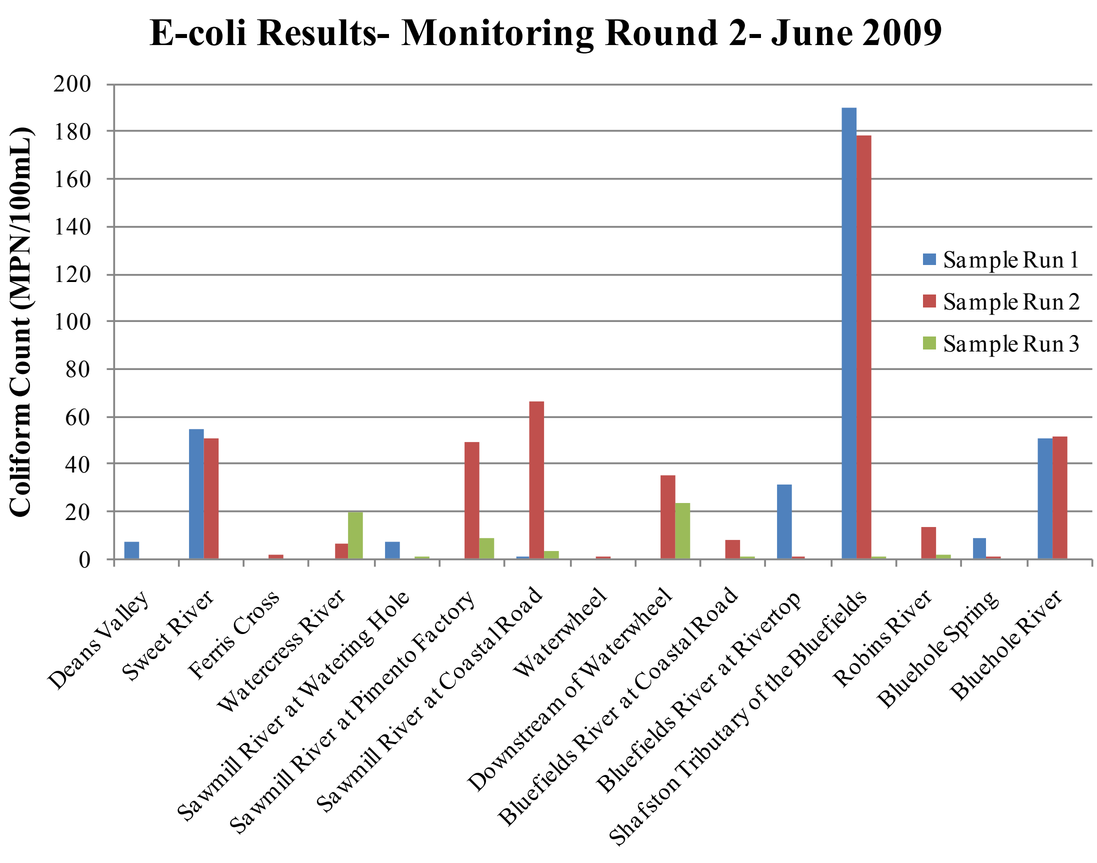


Figure 34. Bacteria results from the second monitoring round in June 2009.

Orthophosphate. Phosphorus occurs naturally in rocks, mineral deposits, and animal droppings, and due to the natural process of weathering rocks will gradually release soluble phosphate ions (US EPA; Parry, 1998). While orthophosphate forms are produced naturally they are also heavily introduced by man-made influences and are readily available for plant and biological intake. Levels of phosphorus at the monitoring sites appeared to decrease between each sampling event, with the highest levels being recorded at sites 3, 4, 5, 11, 12, and 14. Sites 3 and 4 are adjacent to the coastal road and are wetland systems with excessive vegetation. These sites also lack a riparian corridor to filter out nutrients. Sites 5, 12, and 14 experience heavy use by residents who bathe and launder clothes in the water, and the residents introduce phosphates with their use of soaps and solvents.

Visual Survey Information. Site survey information describes the water, substrate, channel, and disturbance characteristics of each sampling site. All of the sites experienced disturbances, such as bathing, washing, water collection, fish spearing, and trash dumping. A variety of settings, including upland-steep, forest, wetland, and coastal-alluvial are represented among sites, as well as a variety of channel types and artificial channels or structures. Bed material within the streams generally consisted of sand and gravel, with only two sites having any material considered cobble. The visual information collected at each site is used to classify the monitoring sites and make observations and connections to the physical sampling data. This data are found attached in Appendix C.

Discharge and Channel Information. Channel width, water depth, and discharge were calculated for each site. This information is available in Appendix D. Monitoring site 2, the Sweet River, had the deepest water and greatest discharge, at a mean discharge of 27.27 m^3/sec. The remainder of the sites had mean discharges between 0 and 3.21 m^3/sec. Measuring the velocity and calculating the discharge for each stream infers the rate of pollutant transportation and residence time within that water system.

Monitoring Round Three. The third and final monitoring round was conducted during the month of January 2010. Sampling rounds were conducted January 5, January, 7, January 8, and January 10, 2010. Water chemistry parameters were again collected at each site, as well as new photographs. Water samples were collected in situ at each site and transported back to the temporary laboratory. Samples were analyzed for total coliform and E-coli, phosphate, total chlorine, and nitrate/nitrite concentrations. Rapid habitat assessment forms were also scored at each sampling site.

Water Chemistry. The water chemistry trends from the final sampling round differed slightly from rounds 1 and 2. Overall pH increased slightly and temperatures decreased, with a corresponding increase in dissolved oxygen. Turbidity significantly increased which indicates an increased surface area for pollutants to attach to and also acts as an indicator of other pollutants in the stream.

Bacteria Sampling. Three sampling runs were made during the final monitoring round. These bacteria samples were incubated in an actual kitchen oven which accurately maintained the 35^{o}C temperature using heating blankets that evenly circulated the air. Figure 35 presents the mean results of the final round of E-coli bacteria sampling. The body contact limits for the World Health Organization (WHO) and the Environmental Protection Agency (EPA) have been overlain on the E-coli counts. Three monitoring sites had bacteria counts over the EPA body contact and 6 sites had counts over the WHO body contact standards. The sites that tested over body contact standards are heavily used by community residents and downstream from disturbance areas including agriculture, grazing, and development sites. Lowest bacteria counts were found at springs and the highest counts were located at population centers. Table 21 below shows the quality assurance/quality control (QA/QC) data of the bacteria samples. The duplicate samples prove the reliability of the samples collected during monitoring round three, compared to the extremely variable data that was collected in earlier rounds. The full data set is located in Appendix E.

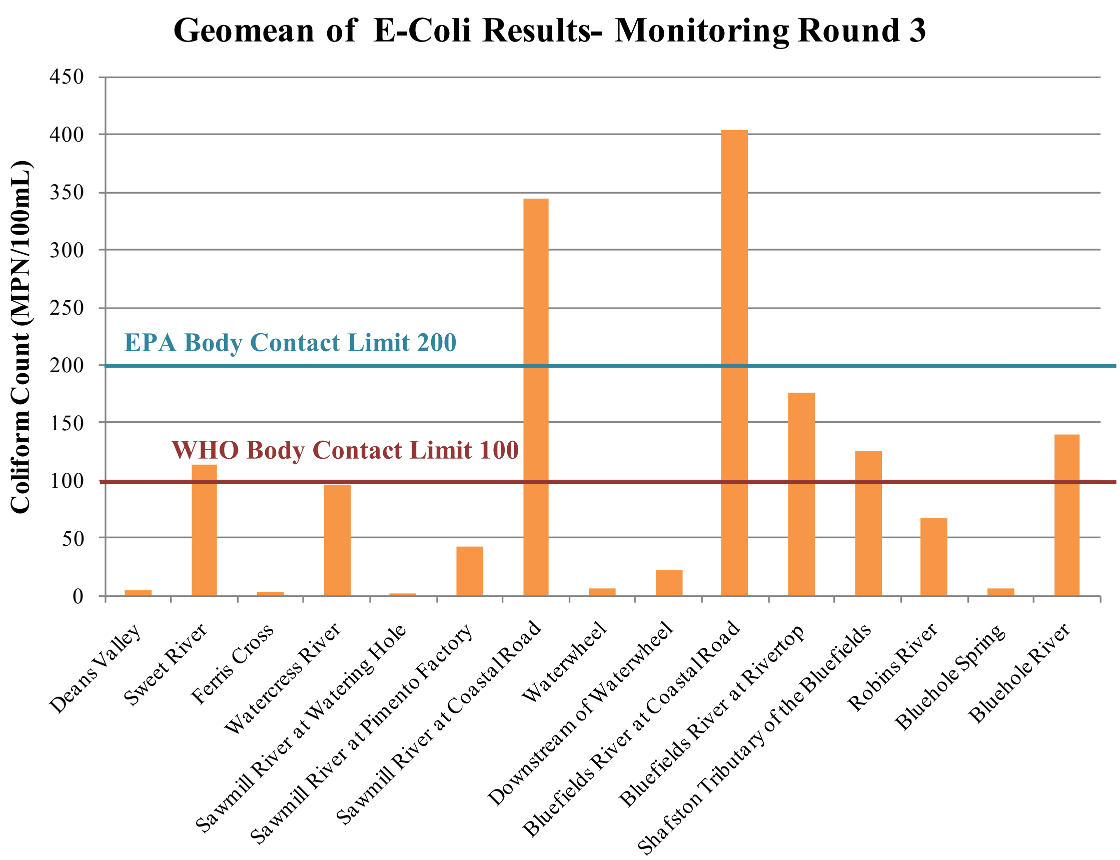


Figure 35. Geomean of final bacteria sampling results from monitoring round 3.

Orthophosphate, Chlorine, and Nitrate/Nitrite Levels. Trends in orthophosphate levels decreased overall and showed slight variation from the second monitoring round. The sites that had the highest mean concentrations of orthophosphate were at site 2, 7, 8.1, and 11. These sampling sites experience heavy pressures from anthropogenic uses and the phosphate levels reflect the human impact. Insta-test strips were used on the water samples to collect levels of chlorine, nitrates, and nitrites. Because of the volatility

Table 21. QA/QC bacteria duplicate data from monitoring round 3.

		IDEXX- Bacteria				IDEXX- Bacteria	
		E-Coli MPN n=3	Total Coliform MPN n=3			E-Coli MPN n=3	Total Coliform MPN n=3
Site	Date			Site	Date		
1	1/10/2010	13.2	816.4	8	1/7/2010	31.3	284.1
1	1/10/2010	12	1119.4	8.1	1/7/2010	17.5	41
2	1/8/2010	36.4	89.6	8.1	1/7/2010	33.1	>2419.6
2	1/8/2010	21.3	43.8	8.1	1/8/2010	33.1	920.8
2	1/10/2010	235.9	>2419.6	8.1	1/8/2010	31.7	1011.12
2	1/10/2010	275.5	>2419.6	9	1/7/2010	770.1	2419.6
3	1/10/2010	6.3	144.5	9	1/7/2010	7.5	7.5
3	1/10/2010	13.1	44.5	9	1/8/2010	248.1	>2419.6
4	1/8/2010	8.6	12.2	9	1/8/2010	166.4	>2419.6
4	1/8/2010	96	>2419.6	9	1/10/2010	344.8	>2419.6
5	1/10/2010	1	40	9	1/10/2010	344.8	>2419.6
5	1/10/2010	0	41.2	11	1/8/2010	76.7	>2419.6
6	1/8/2010	48.7	342.8	11	1/8/2010	104.6	>2419.6
6	1/8/2010	52.1	>2419.6	12	1/8/2010	56.3	>2419.6
7	1/5/2010	12	29.3	12	1/8/2010	53.7	2419.6
7	1/5/2010	0	0	13	1/7/2010	1	1203.3
7	1/10/2010	866.4	>2419.6	13	1/7/2010	0	28.2
7	1/10/2010	1119.9	>2419.6	14	1/10/2010	78.9	>2419.6
8	1/7/2010	3.1	3.1	14	1/10/2010	86	>2419.6

of nitrites in water sources none were detected within the Bluefields watershed. There were, however, positive readings for nitrates at sites 2, 3, 6, 8, 8.1, 12, and 13. These sites receive inputs from adjacent agricultural practices and surface runoff from road crossings. Numerous sites also tested positive for chlorine hits, most notably sites that have water pipes running down the actual stream. The water pipes transport water to communities and community housing, and the water traveling through the pipes is treated with chlorine. The hits of chlorine found in the surface water can be attributed to the degraded quality of the water pipes, which leak the chlorinated waters into the streams. This threatens the health of in-stream biota and causes fish kills.

Trends. The following section presents the main water quality results and trends between parameters sampled more than once, which are a result of the watershed monitoring program.

Water Chemistry. Several trends were examined in the water chemistry data. Between the three monitoring rounds, pH increased slightly over the one-year period. Temperature was higher during the second round of monitoring, which is to be expected during the summer month of June. Dissolved oxygen was highest during the final monitoring round, as well as total dissolved solids (TDS). There was an above average amount of rain during the third monitoring round, which can explain the higher dissolved oxygen values and the amount of TDS. pH is generally lowered during the rainy season, which is not the case during these monitoring rounds.

Bacteria Sampling. Because of the unreliability of the bacteria data collected in monitoring round two, trend analysis is based on the results of the third sampling round. Figure 36 below shows the comparison of mean values between the data sets from each round. The samples that did count positive during the second sampling round also had bacteria counts during the third sampling round, indicating that there are bacteria in the water systems. However, whether there is a correlation or trend between the two sampling rounds is unknown.

Orthophosphate, Chlorine, and Nitrate/Nitrite Levels. The phosphate levels measured during monitoring rounds 2 and 3 indicate that levels were lowering during the winter month. The rainy summer season transports more nutrients via surface runoff and

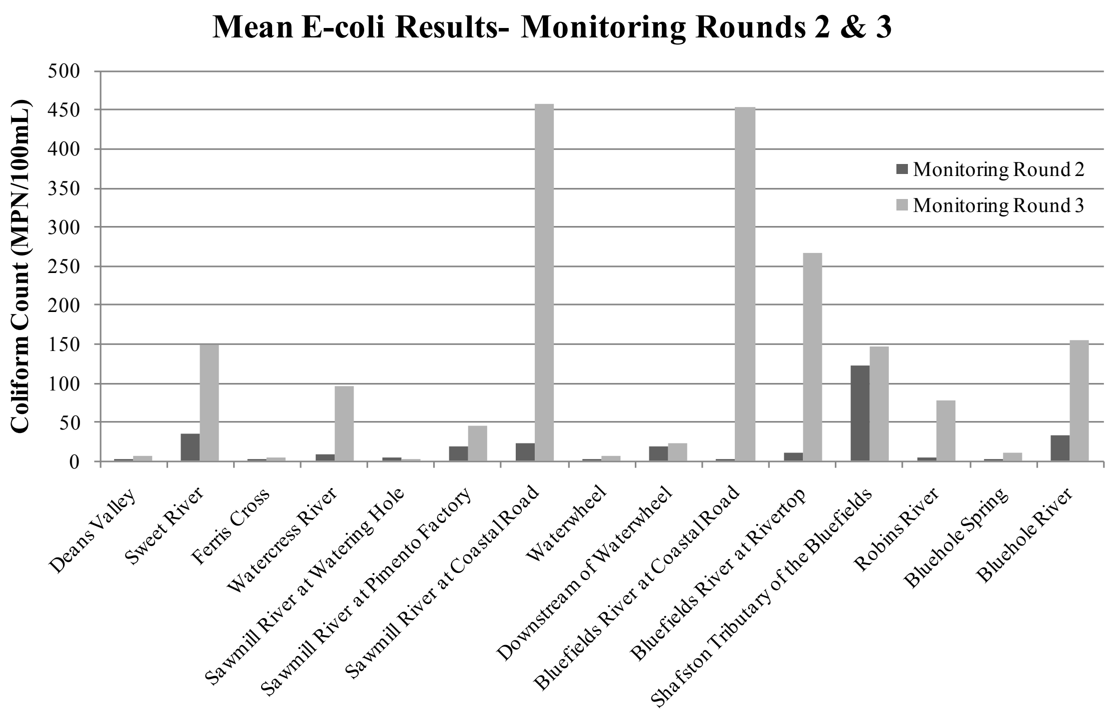


Figure 36. Mean E-coli results of the second and third monitoring round.

because plants are more productive during the summer months more vegetation, a sign of excess nutrients, is found in the streams. There were visual differences in macrophyte cover between the summer and winter season monitoring rounds, particularly at spring-fed wetland systems including Waterwheel, Bluehole, and the Sawmill River. The positive hits of chlorine and nitrate in the water systems can be used to infer areas of stream degradation and pollution introduction. These positive readings are found near road crossings and water treatment systems where water supply pipes located in the stream channel itself and may be leaking chlorinated water directly into the flow.

Primary Threats and Concerns. As a result of the water quality monitoring program primary threats and concerns were identified in the Bluefields Bay watershed. These activities and environmental conditions within the watershed threaten water quality and natural resources dependent on the water. The main indicators of pollutants are bacteria concentrations, nutrient levels, and chlorine hits.

<u>Bacteria.</u> Monitoring sites testing positive with high counts of E-coli demonstrated several interesting trends. Areas heavily used for bathing and laundering had high bacteria counts, as well as areas with agriculture infringing on the riparian corridor, or stream bank vegetation. The Bluefields River had the highest bacteria counts, which can be a result of dumping garbage, diapers, and effluent into the stream. Community members throw a majority of their trash into the dry arm of the Bluefields known as Goat Gully. This area between Rivertop (site 10) and the coastal road crossing (site 9) basically acts as garbage storage area until heavy precipitation occurs and flushes it downstream. Housing located along the Bluefields River near Rivertop also contributes effluent from leaking septic systems. The fishermen in the village of Belmont frequently use the mangrove adjacent to the Bluehole River as an area to defecate, causing the water to take on a poor smell and have higher bacteria levels. The Sawmill River also has poor water quality, due to the increasing development occurring on stream bank and wetland areas in the Sawmill watershed.

Nutrients. Nutrients entering the watersheds surrounding Bluefields Bay generally have moderate residence times and are affected by a number of sources. Based on the results of the monitoring program, wetland sites appeared to have the best water quality when it concerned bacteria, but had higher nutrient levels such as phosphates. This can be explained by the excessive amount of vegetation already developed, as well as the longer resident times wetlands have to absorb the nutrients. These wetlands, however, play a critical role in filtering out nutrients and pollutants within a system and prevent contamination from occurring downstream. Several sites with the highest nutrient concentrations, such as the Sweet River (site 2) and the Shafston Tributary (site 10) often have livestock grazing on the banks and defecating in the water. Areas that generally had the highest nutrient levels can be associated with strong anthropogenic disturbances.

Chlorine. Stream systems that have concentrations of chlorine are associated with local public water supply facilities and piping. Chlorine-treated drinking water is introduced into water systems when it leaks from piping systems running in the rivers and streams surrounding Bluefields Bay. All of the sites that had positive hits of chlorine have visible evidence of piping systems inlaid in the stream or are near a pump house/ chlorination station. Leaking infrastructure and pirating of waters by illegally breaching pipes cause chlorine contamination.

Watershed Risk Assessment

Based on the subwatershed classification, characterization, and the one-year water quality monitoring program, the following watershed risk and classification scheme was developed for the watersheds surrounding Bluefields Bay. After critical areas were classified, each stream system was fit into a management template that combines classification, characterization, water quality, and risk factors. This template can be used to categorize and manage the water resources within each water system and rank the watershed classes accordingly.

Risk Assessment. Figure 37 below shows the final watershed risk map created for the watersheds surrounding and impacting Bluefields Bay. Various levels of risk and threat are presented, as well as areas that are critical to protect within the watershed. The areas and zones of risk were mapped according to the physiographic regions, coastal fringe drainage, population density, soils, land use, and road network. The prominent trends and zones of threat and highest risk are identified as:

1. 0 to 5 km coastal drainage located in the coastal lowland area. These areas typically have greater population densities, and the soils surrounding the bay area are mapped as having high erosion potential.

2. 5 to 10 km coastal drainage located in the transitional mountain area. These areas typically have increased economic potential for agriculture, which increases potential erosion risk.

3. 10 km coastal drainages located in the steeper inland area. These areas typically have lots of disturbance, including agriculture and road networks.

Hydrologic Conditions and Management Templates. Templates were created for each management category (overall watershed condition) and are presented in Figures 38 and 39 below. Each template provides a brief description of the watershed, goals and objectives of the management plan, and special watershed analyses. The water courses are complex and often times can be merged into several categories. All of these streams eventually drain into Bluefields Bay, classifying them all into the category of coastal/ estuarine waters. Figure 40 provides examples of templates applicable to coastal waters.

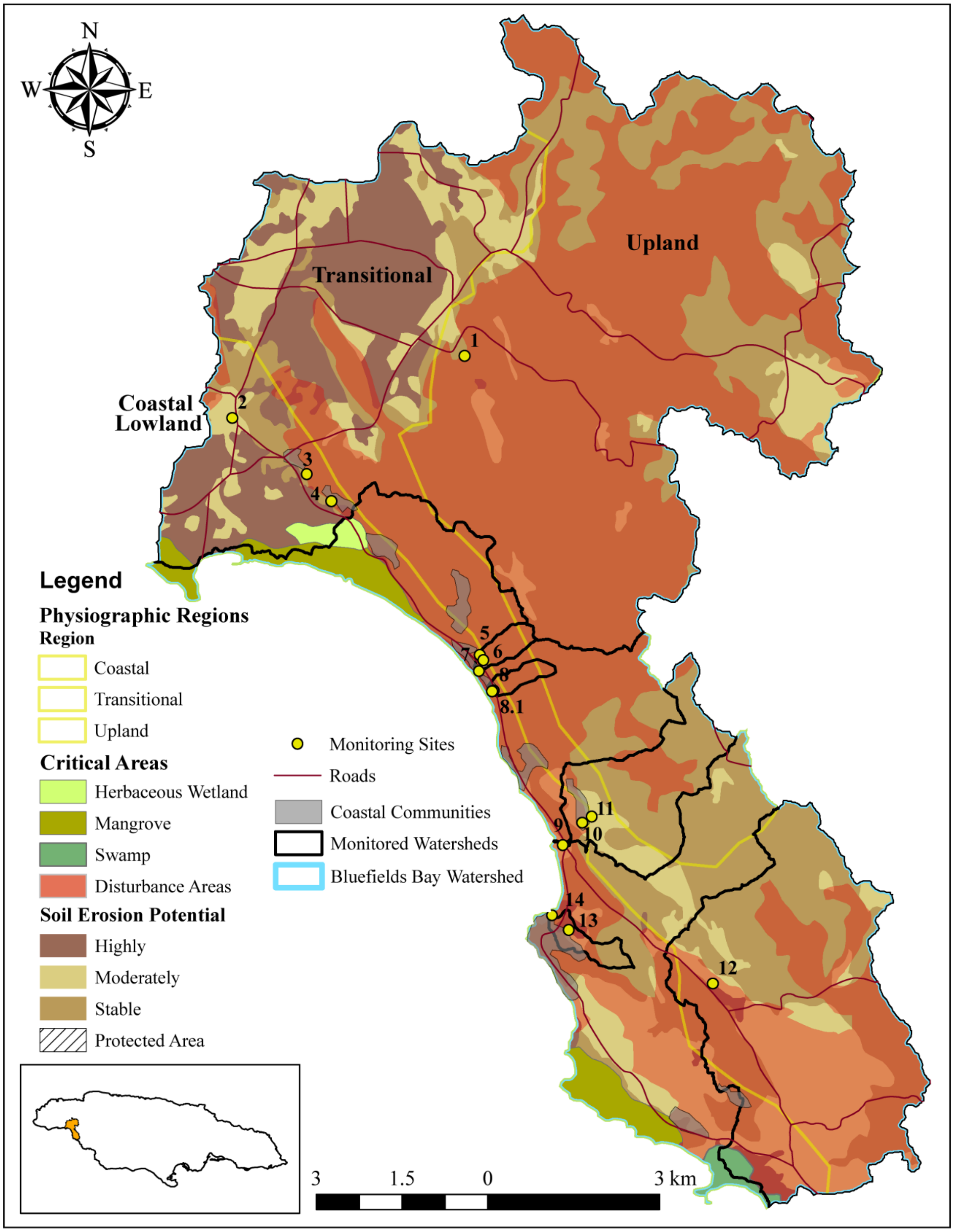


Figure 37. Watershed risk map and critical areas for the Bluefields Bay watershed.

	**<u>Subwatershed Category:</u>** **Conservation Zone**
Water Courses:	Robins River, Bluefields River, Sawmill River, Sweet River, Bluehole River
Description:	Subwatershed typically has 10% to 25% impervious cover, and monitoring indicates a decline in physical, biological, or water quality indicators. Moderate to poor water quality.
Goal:	1. Limit the degradation of stream habitat quality. 2. Maintain a ‘good’ biological community (fishable/swimmable).
Planning Objectives:	• Provide removal of designated pollutants of concern (especially bacteria and phosphorus) • Maintain channel stability • Decrease garbage and sewage influx
Special Watershed Analyses:	• Mapping of sensitive areas • Stream system monitoring using Rapid Technique (USEPA Form) and basic water quality sampling • Inventory of riparian and wetland areas • Implement best management practices (BMPs) • Educate and inform residents
Indicators of Success:	• Physical and biological stream indicators • Meeting water quality standards for full body contact • Stable stream morphology

Figure 38. Management template for water courses classified as a conservation zone.

	**<u>Subwatershed Category:</u>** **Protection**
Water Courses:	Ferris Cross, Watercress, Waterwheel, Bluehole Spring, Deans Valley
Description:	The stream supports designated uses and is characterized by good to excellent water quality. Generally have an intact riparian corridor and vegetation.
Goal:	1. Protect existing biota and stream conditions 2. Minimize downstream pollutant loads 3. Prevent future problems
Planning Objectives:	• Control hydrologic regime • Remove/ prevent urban pollutants • Maintain stream habitat • Augment riparian corridor • Protect stream substrate
Special Watershed Analyses:	• Bacteria source surveys/ sampling • Simple method storm water pollutant load estimates • Inventory of riparian and wetland areas • Surveys and public education of residents
Indicators of Success:	• Favorable trends in designated water quality parameters • Positive change in resident's living practices and public awareness • Implementation of management and protection plan.

Figure 39. Management template for water courses classified as a protection zone.

	**<u>Subwatershed Category:</u>** **Coastal/Estuarine Waters**
Water Courses:	Waterwheel, Sawmill, Bluefields, Robins, Bluehole, Ferris, Watercress,
Description:	Subwatershed drains to estuary or near-shore ocean.
Goal:	1. Maintain designated uses in the estuary or along the coast 2. Enhance biological community and species diversity
Planning Objectives:	• Reduce nitrogen inputs • Decrease inputs of metals, toxins, and hydrocarbons. • Maintain and enhance fish population and spawning habitat • Protect coral reefs and beds from bacterial contamination • Minimize degradation impacts on tidal/non-tidal wetlands
Special Watershed Analyses:	• Computing nutrient budgets • Mapping sensitive areas • Identification of permeable soils • Biological (i.e. fish) habitat sampling and survey
Indicators of Success:	• Fisheries improvements (increases in catch size, amount, and diversity • Sea grass bed and coral reef growth • Positive trends in nutrient concentrations and algal growth

Figure 40. Management template for water courses classified as coastal/estuarine waters.

Primary Threats to Water Quality

The quality of water courses within the Bluefields Bay watershed is compromised and threatened by a number of sources. This section discusses the threats that occur in the water systems of Bluefields Bay and solutions to negate those threats.

Agriculture and Farming. Many of the residents in the Bluefields area plant subsistence-type farms and gardens, or food forests. These food farms are major sources of their dietary intake, thus making it important to maintain them for a proper food source. However, these farming practices degrade the condition of the watersheds, alter the hydrologic cycle, and reduce water quality. Farming practices are thought to be responsible for widespread land clearing, which increases run-off and soil erosion that contributes to high sediment loads in streams and rivers (Sheng and Michaelsen, 1973). This leads to downstream sedimentation and damaging floods, which transports excess nutrients and pollutants into both surface and ground water. Many farmers establish plots of agriculture on steep or fragile hill slopes, creating the same erosion and run-off problems (McGregor and Barker, 1991). Clear-cutting and burning the vegetation to create an area for their farms, known as slash-and-burn agriculture, generally degrades water quality downstream because of the high available sediment loads and the nutrient and chemical particles attached to that sediment. Farmers also apply agro-chemicals to their fields, which eventually end up in streams and rivers. Ground water pollution occurs if chemicals, especially nitrates from fertilizers, leaches to aquifers. Excess fertilization of agriculture eventually contributes to the over fertilization of streams and rivers, which causes algal blooms and eutrophication.

There are several ways to improve the quality of water sources affected by agricultural practices and land clearing. It is important to maintain the stability of the soil in order to prevent soil erosion. To do this, farmers should maintain responsible farming practices such as tiering, terracing, and contour cropping and drainage (Sheng, 1999). This decreases runoff and surface erosion. Farmers should attempt to avoid farming on steep slopes and loose soil. It is also important to reduce the amount and toxicity of fertilizers and pesticides applied to the agricultural products, so it would be important to educate or inform farmers about sustainable alternatives to harsh fertilizers and pesticides. Other farming conservation practices could include reforestation of denuded hill sides, practicing agro forestry (planting food crops between rows of trees), and use of drip irrigation and mini-sprinkler irrigation systems (Sheng, 1999; Beckford, 2009).

Livestock and animal grazing also plays a role in land and stream degradation. This can be reduced by not allowing animals to graze or stomp along stream banks or steep slopes, implementing waste handling and disposal measures rather than dumping animal wastes into the river, and increasing the use of animal manures as a solution to increasing soil productivity and organic matter levels (Madramootoo and McGill, 2000). Outreach and education programs need to demonstrate these practices and help work them into the farming culture of the area.

Commercial Water Use. Water throughout the community is extracted and used for industrial and commercial uses. There are several car washes along the coastal road to which vehicles can pull up and be washed, basically with a bucket, soap, and sponge. This method creates runoff and surface erosion, as well as a pollution source through the use of the soap. Many commercial taxi and bus drivers will also pull directly into streams and wetlands to wash their vehicles. These practices decrease the stability of the stream, increase erosion, and contribute nonpoint pollutants such as phosphates, nitrates, and bacteria. There are several pimento factories in the area of Bluefields. These factories create wastes in the form of discarded vegetation and organic matter biomass (Tanner, 1980; Rodriquez, 1969). Two of the factories are adjacent to the Sawmill River, and the discarded pimento waste is piled on the stream bank and absorbed into the stream. This can cause an increase in decaying organic matter and a depletion of oxygen (Tanner et al. 1990). Members of the communities also rely on freshwater systems as a fish and crayfish source, both for food and income.

There are several ways to protect water systems from these commercial uses. It is important for people to realize the detriment caused by driving a vehicle into a stream, so it would be helpful to inform the taxi and bus drivers and provide them with an alternate resource for vehicle washing, such as a community washing structure. Conservation practices can be implemented at the existing car washes, such as water recycling measures, the construction of grassed waterways or rock chutes to prevent gully formation from runoff, and the use of eco-friendly plant-based solvents and cleaning solutions. At the pimento factories it would be important to maintain a vegetated buffer between the stream and the factories, stabilize any failing banks, and implement compost practices for the used pimento leaves and other vegetation rather than discharging them into the stream.

Everyday Use. Members of the community also depend on local water sources for their everyday living practices. Residents constantly use rivers and streams to bathe in and launder their clothes. Homes without grounded water sources (i.e. piping and routing) collect their supply from many of the same places where people are laundering and bathing. Washing in the streams contaminates the water from the various soaps and solvents residents are using. Pump houses are located on several streams in the Bluefields area, and these facilities are responsible for chlorinating water in the piping system. However, residents will often disconnect pipe systems (which frequently are placed in the stream themselves) and discharge the chlorinated water in the stream. This can have adverse health effects on flora and fauna otherwise intolerant of chlorine. Community residents also have poorly managed effluent systems which overflow and runoff into streams during rain events, causing bacterial contamination.

There are several ways to improve the water quality from resident's everyday living practices. Again, using ecologically friendly or plant-based soap products is one way to keep excess nutrient concentrations from entering streams. It would be beneficial to inform the Bluefields residents on the importance of chlorine and phosphate-free and non-petroleum based products. It is also pertinent to maintain a secure and connected water piping system because this will reduce contamination and spread of bacteria. Many residents are also under the mindsets that if they throw their effluent and garbage into the stream that it will simply disappear. They often do not consider the effect it will have downstream, which results in outbreaks of bacteria and fecal coliform counts exceeding full body contact standards. To remediate this it would be helpful to construct community waste collection structures and educate the residents of the effect their discharge is having on the stream. The Bluefields area also lacks any real detention structure or collection basin to treat their water supply, so it may be beneficial to construct a city-wide filtration system.

Fishing. Many residents of the Bluefields area are fishermen that depend on resources extracted from Bluefields Bay. The water use throughout the communities on the coast discharges directly into the bay, transporting nutrients, pollution, and sediment. Therefore, it is critical to implement conservative and sustainable practices relative to land use and water supply protection throughout the watershed as it drains into Bluefields Bay. All of the above problems and solutions affect the greater health of the coastal waters, and it is important to connect activities of the landscape to water quality.

Recommendations and Programs. This final section discusses possible recommendations and programs to implement within the Bluefields Bay watershed that would improve water quality, land use, and fishing practices.

<u>Community-Based Water Quality Monitoring Program.</u> The community members surrounding Bluefields Bay express concern and willingness to learn about the quality of their surface and ground water, as well as trends, patterns, and sources of degraded water quality. It would be beneficial to implement a short-term water quality monitoring program to give residents the opportunity to gain hands-on experience investigating and learning about their water courses. Simple procedures and testing measures can be practiced, such as the use of insta-test strips, monitoring meters, and outsourcing of bacteria testing to Kingston.

Stream teams can also be established to assist public education and involvement. These teams promote community involvement, participation, and cooperation between various entities. Team members are trained in at different levels of monitoring participation and assist in design, sampling, and reporting. Streams teams not only monitor water quality but also sample biota and perform rapid channel assessments. Stream team lessons can also be taught to groups and students through the local schools.

Blue Flag Program. The Blue Flag program is a voluntary, eco-label that is awarded to beaches and marinas in 41 countries internationally. According to their public statement (http://www.blueflag.org/), the Blue Flag "works toward sustainable development at beaches/marinas through strict criteria dealing with water quality, environmental education and information, environmental management, and safety and other services (2010)." While this exact program may not be able to apply specifically to the small fishing and public beaches along the Bluefields coast, a similar program created for the parish of Westmoreland may benefit not only the resources but also the users of the beaches. The program entails a schedule of water quality sampling, reef and coral monitoring, and fish surveys. Emphasis should be placed on educating fisherman and residents about sustainable fishing practices and management of the beach area, including proper waste and sewage management, animal control, and maintenance of structures (i.e. docks) and beach equipment.

Small-Scale Sanitation Programs. The communities surrounding Bluefields Bay would benefit greatly from the implementation of small-scale sanitation programs such as the Rural Water Supply Program, which was initiated by the Government of Jamaica to expand the coverage of potable water and sanitation throughout Jamaica. Not only would this improve non-point surface runoff but it would also educate residents about best management practices at their residencies. Small-scale systems improve the sustainability of sanitation systems, which close the connection between water and nutrient flows

(Green and Ho, 2005). They also involve community members and provide healthier living situations and drinking water.

Fish Sanctuaries. Establishing and protecting fish sanctuaries is an important measure to protect coastal resources. Bluefields Bay was established on July 28, 2009 as a fish sanctuary by the Ministry of Agriculture and Fisheries under section 18 of the Fishing Industry Act of 1975. Fish sanctuaries are coastal water areas declared as no-fishing zones, and are specifically reserved for the reproduction of fish populations. Bogue Islands Lagoon and Bowden Inner Harbour were declared as sanctuaries in 1979 and 1986, respectively, in order to combat the declining fish populations. However, marine areas continue to degrade due to increased fishing pressure and land-based nonpoint-source pollution, leading to the establishment of 8 new sanctuaries throughout the island of Jamaica. According to the Ministry of Agriculture and Fisheries, sanctuaries are selected based on the following criteria:

1. Ecological characteristics: presence of seagrass beds, a reef system, and/or shallow waters abutting mangrove stands;
2. General agreement of the primary stakeholders: fishers, investors, hotel and tourism businesses;
3. The presence of a management entity with whom the Fisheries Division may form partnerships with;
4. The potential impacts that point-source pollutants may have on these sites.

Fish sanctuaries have many benefits along with increasing fish populations. These no-fishing zones gradually increase biodiversity within the waters, reducing the chance of extinction. Because marine species are able to reach full maturity, the chances of them reproducing significantly increases. Economic benefits are also provided through the establishment of fish sanctuaries. Increasing fish populations create higher catch limits for fisherman, improving their economic opportunities. Greater species diversity and marine populations also increase eco-tourism opportunities for visitors and residents. The management of the established sanctuaries is collaborated between the government and local community organizations. This creates job opportunities for patrollers and enforcement, and encourages community participation. The Bluefields Bay sanctuary is patrolled by the local entity in Westmoreland called the Bluefields Bay Fisherman's Group, or better known as the Bluefields Bay Fisherman's Friendly Society.

Toward Healthy Streams and Good Water Quality

Monitoring Program Results. Monitoring results from the Bluefields Bay watershed indicate that some rivers and springs have excellent water quality. Terrestrial and aquatic vegetation play an important role in reducing water quality problems. Bacterial levels were low in streams with wide riparian corridors with established tree and shrub forest. In addition, water quality was good where rivers flowed through wetland areas that were in relatively good condition. Vegetation growth within riparian buffer and wetland areas were probably able to filter out bacteria and harmful pollutants in the water. Moreover, the existence of healthy buffers and wetlands by itself is an indicator of low levels of human disturbance and access to the river. Nutrient levels were relatively low where livestock grazing, car washing, laundry, and bathing and soil disturbances were not common near rivers. Overall, results of the water quality monitoring are promising. More outreach and conservation efforts aimed to reduce or control the disturbances described above will produce improvements in water quality.

Basis for Hope. Recovery of the rivers with more negative monitoring results is possible. Because the areas of poor water quality have been identified, remediation and recovery can begin at these sites or other river segments with similar land use problems. Most importantly an increased buffer from the monitoring sites should occur, recognizing the importance of the riparian corridor, vegetation, and structure. Community groups and organizations are active and concerned about the Bluefields Bay and its contributing watershed areas and they have already invested in the sustainability and protection of their community's water and wildlife supply. Community members can use the strategies and practices previously described to manage water pollution sources and further reduce high bacteria levels and excess nutrients in these streams.

CHAPTER 6

SUMMARY AND CONCLUSIONS

Developing countries suffer from poor land use management and need technical assistance to gain information vital to developing community-based solutions to water supply and quality problems. The communities surrounding Bluefields Bay, Jamaica depend on water and soil resources to sustain their communities as well as fishing and tourism industries. This thesis used topographic information to delineate the Bluefields Bay watershed, connect the water quality of the watershed to land use, and identify areas that require improvements. Non-point pollution source contributions of bacteria and nutrients are identified by water quality monitoring and connected to the human activities responsible for all major subwatersheds. Integrated resource management benefits the communities adjacent to Bluefields Bay, as well as other developing communities throughout Jamaica that necessitate water quality improvements and resource planning.

Key Findings

Bluefields Bay Watershed. The Bluefields Bay watershed has a total watershed area of 135.56 km^2 and contains six main subwatersheds (Table 17). Subwatersheds include the Bluefields, Bluehole, Robins, Sawmill, Sweet, and Waterwheel subwatersheds. Three of these, Bluehole, Sawmill, and Waterwheel, were further broken down and classified as catchment systems. Populations in these watersheds varied, with the majority of the population dwelling along the coastal fringe of the watershed.

However, no census data were available for the inland mountain regions of the watersheds.

Physiographic Regions. The Bluefields Bay watershed was classified into three physiographic regions, including the coastal zone, transitional, and mountain inland/upland areas (Table 2 and Figure 24). While the watersheds drained all three physiographic regions of the landscape, a majority of the monitored watersheds fell in the transitional category. Of the entire Bluefields Bay watershed 35% was located in the transitional region and 46% was located in the mountain inland region. The remaining 19% drained the coastal zone. This finding indicates that the quality of coastal waters can be affected by activities occurring in farther inland areas, particularly during rainfall periods when storm runoff increases discharges and connects upland valley drainage to the sea.

Water Resources. Water resources in the Bluefields Bay watershed have been classified according to source and setting. The Bluefields River is a coastal stream that discharges directly into Bluefields Bay. Bluehole Spring is a coastal spring located in the valley floor of the coastal lowland area adjacent to Bluefields Bay, and Bluehole River is a mangrove wetland that is fed from Bluehole spring (Nedwell et al., 1994). The Sawmill River is a freshwater wetland that is contact-spring fed located on the coastal lowlands of the Bluefields Bay watershed. The Sweet River has headwaters that are further in the coastal range and drain the coastal fringe of the bay (Genxu and Guodong, 1999). Waterwheel is a coastal contact spring that drains directly into Bluefields Bay. The classification of actual water resources is important in understanding the water systems and the measures needed to protect and conserve its water resources.

Water Chemistry. Water chemistry values for the monitoring sites provided interesting results. The sites with the lowest dissolved oxygen values were found at the Bluehole River, which is brackish, and at the Sawmill River. Low DO values cannot support fish without increased stress and ultimately result in fish kills. Highest readings of pH were found at the Bluefields River at the road crossing and at Rivertop, which could be the result of contact between calcium carbonate, which covers the streambed surface. Many wetland areas had lower pH values, possibly because the increased vegetation will slightly decrease the pH due to photosynthesis. Turbidity and specific conductivity were relatively uniform and correlated with water temperatures. However, low flows were targeted during this study and turbidity may increase measurably during runoff events during the rainy season.

Bacteria. Bacteria counts were generally lowest at springs, due to the short flow path from groundwater source point and the tendency for abundant riparian vegetation to surround springs. Bacteria levels were highest at population centers,which is a direct effect of bathing, garbage dumping, and sewage contamination. High bacteria levels are also found in some rural rivers draining agricultural lands with relatively heavy cattle and goat grazing near the stream. The quality of the results of bacteria analysis was affected by field laboratory conditions and problems in finding a sufficient method to incubate bacteria samples at a warm and constant temperature. Round two monitoring was inconsistent and probably under-predicted the actual bacteria levels present. However, round three provided relatively precise and reliable data. Several sites typically contained bacteria levels that exceeded U.S.E.P.A health standards.

Nutrients and Chlorine. The imprint of human activities on poor water quality is an obvious result of this study for the pollutants evaluated in this study. Orthophosphate concentrations were highest at sites near population centers and road crossings or access points. Nitrate readings also generally occurred near road crossings. The presence of chlorine was correlated with water treatment facilities, leaky pipes, and illegal pirating of water sources. The methods used to test for these parameters can be used as good indicators of nutrient location and areas that may need attention by community groups.

Fringe Mapping. The Bluefield Bay watershed was divided into categories based on the coastal fringe drainage distance from the fish sanctuary. The distance that each of the stream networks drained from the fish sanctuary were generalized into three categories: 0 to 5 km, 5 to 10 km, and >10 km. Nearly all of the monitoring sites were located on the coastal fringe of 0 to 5 km drainage distance, but upstream contributing drainages extended into more inland physiographic regions in most cases. More detailed GIS data is necessary to more accurately map and classify regions and drainages surrounding Bluefields Bay. The GIS layers currently available for Jamaica do not have the resolution required to develop digital elevation models (DEMs) capable of producing accurate drainage networks for the karstic limestone areas investigated for this study.

Risk Assessment. The risk of watershed degradation has been determined for the entire Bluefields Bay watershed (Figure 37). Mapped disturbance-prone areas not only have highly erodible soils, but also disturbed vegetation and a history of mountain agriculture. It is possible that these disturbed lands are slowly recovering from the colonial plantation period. However, present-day agricultural activities may also be contributing to poor land condition in some areas. Degradation risk was evaluated and management templates created for each management category: conservation, protection, and coastal/estuarine (Figures 38,39,40). Communities can use these templates as a basis for managing and planning their watersheds.

Solutions. The findings of this thesis, using the integrated resource management approach to protect water resources, are pertinent in protecting drinking water supply and quality. By implementing best management practices throughout a watershed, water resources can be protected, pollutant loads can be reduced, and water quality can be improved. Integrated resource management also promotes the establishment of critical and sensitive areas, and provides ideas on how to protect them. Surface water streams and rivers ultimately affect the water sources into which they flow, and maintaining water quality and conservation practices throughout a watershed will also protect coastal resources, as would the implementation of water quality management throughout the Bluefields Bay watershed. Monitoring the quality of surface water streams and springs also proves as an effective indicator of watershed health and stream quality throughout a watershed. It may be helpful to establish a community-based water quality monitoring program using scientific principles to increase awareness of water problem and improve the acceptance and effectiveness of conservation practices in the region.

Within the Bluefields Bay watershed several sources of pollutants are identified. Excessive nutrient inputs are discharged to streams through the every-day living practices of residents, including water supply collection, bathing, laundering, and car washing. High bacteria levels can be attributed to not only the bathing practices and human contact in the streams but also the disposal of garbage and effluent runoff into surface rivers and streams. Out-dated and degraded water treatment facilities leak chlorine into surface water, which causes harm to in-stream biota and also compromises the economic viability of the streams. Identifying these pollutants is the first step in creating and educating residents on how to better improve their water sources, as well as how to implement stream monitoring and conservation practices.

Classifying watersheds and ranking the critical areas also proves to be an effective method of integrated management. Using a GIS system to spatially map different characterizations and features of the landscape allows for a comprehensive and methodologically approach to threat identification and pollutant source contribution. It also is an effective tool for developing an understanding of watershed processes and components interacting within that system.

Future Work

While there are certainly a number of groups and organizations working to protect Jamaica's resources, there is still a need for more scientific research linking both natural controls and human activity to water quality conditions throughout the country. Improvements in the resolution of GIS data available for Jamaica are also needed to improve the accuracy of hydrologic and landform mapping. The communities surrounding Bluefields Bay can strongly benefit from local, watershed-based community planning. Thus in the future, it will be beneficial to involve residents in monitoring not only their surface water but also groundwater and recharge areas. A StreamTeam approach aimed at both adults and students, that combine elements of environmental education, stream study, conservation projects, and water quality monitoring, may be useful in this regard. Community-based environmental monitoring programs will help increase water management awareness and conservation practice acceptance in the Bluefields Bay watershed.

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APPENDICES

Appendix A. Stream Habitat Assessment Project Procedure

Stream Habitat Assessment Project Procedure
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Missouri Department of Natural Resources
Stream Habitat Assessment Procedure
Riffle/Pool Habitat Assessment Form

Date:	Analyst:	Station #: Sample #:	Location:

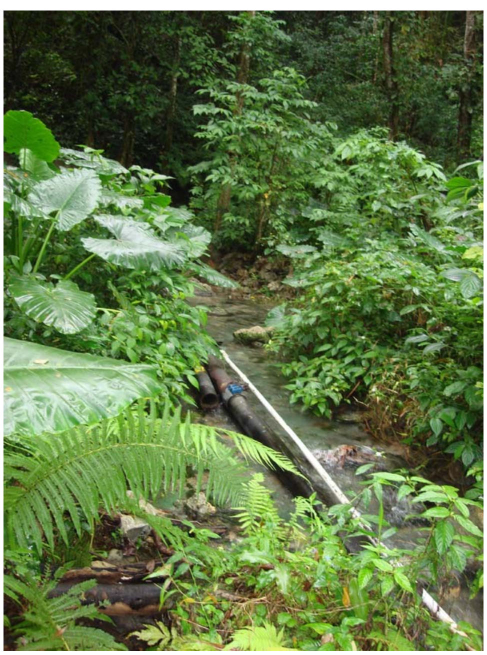
Habitat Parameter	Optimal	Suboptimal	Marginal	Poor
A. Epifaunal substrate/ available cover	Greater than 50% mix of cobble, large gravel, submerged logs, undercut banks, or other stable habitat. 20-16 _______	A 50-30.1% mix of cobble, large gravel, or other stable habitat. Habitat adequate for maintenance of populations. 15-11 _______	A 30-10.1% mix of cobble, large gravel, or other stable habitat. Habitat less than desirable. Substrate frequently disturbed or removed. 10-6 _______	Less than 10% mix of cobble, large gravel, or other stable habitat. Lack of habitat is obvious. Substrate unstable or lacking. 5-0 _______
B. Embeddedness	Gravel, cobble, or boulders are between 0-25% surrounded by fine sediment or sand. 20-16 _______	Gravel, cobble, or boulders are between 25.1-50% surrounded by fine sediment or sand. 15-11 _______	Gravel, cobble, or boulders are between 50.1-75% surrounded by fine sediment or sand. 10-6 _______	Gravel, cobble, or boulders are over 75% surrounded by fine sediment or sand. 5-0 _______
C. Velocity/ depth regime	All four velocity/depth regimes present. Slow(< 0.3 m/s) - deep (> 0.5 m) ; slow- shallow (< 0.5 m) ; fast(> 0.3 m/s) - deep ; fast-shallow. 20-16 _______	Only 3 of the 4 regimes present (if fast-shallow is missing score lower than if missing other regimes). 15-11 _______	Only 2 of the 4 regimes present (if fast-shallow or slow-shallow are missing receive lower score). 10-6 _______	Dominated by one velocity/depth regime (usually slow-deep). 5-0 _______
D. Sediment deposition	Little or no enlargement of islands or point bar and less than 5% of bottom affected by sediment deposition. 20-16 _______	Some new increase in bar formation, mostly from coarse gravel, sand or fine sediment From 5-30% of bottom affected by sediment deposits. Slight sediment deposition in pools. 15-11 _______	Moderate deposition of new gravel, sand, or sediment on old and new bars; pools partially filled with silt. From 30.1-50% of bottom affected. Deposits at obstructions, constrictions, and bends. Moderate deposition of pools prevalent 10-6 _______	Heavy deposits of fine material, increased bar development. More than 50% of the bottom changing frequently. Pools almost absent due to substantial deposition. 5-0 _______
E. Channel flow status	Water reaches base of both lower banks, and minimal amount of channel substrate is exposed 20-16 _______	Water fills 99.9-75% of the available channel; or <25% of channel substrate exposed. 15-11 _______	Water fills 74.9-25% of the available channel, and/or riffle substrates are mostly exposed 10-6 _______	Very little water in channel (<25%) and mostly present as standing pools 5-0 _______
F. Channel alteration	Channelization or dredging absent or minimal (<5%) stream with normal pattern 20-16 _______	Some channelization present (5-39.9%), usually in areas of bridge abutments; evidence of past channelization, i.e. dredging (greater than 20 years) may be present, but recent channelization is not present. 15-11 _______	Channelization may be extensive; embankments or shoring structures present on both banks; and 40- 80% of stream reach channelizes or disrupted. 10-6 _______	Banks shored with gabion or cement; over 80% of the stream reach channelized or disrupted. Instream habitat greatly altered or removed entirely 5-0 _______

G. Riffle Quality	Well developed riffle and run; riffle is as wide as stream and length extends two times the width of stream; abundance of cobble.	Riffle is as wide as stream but length is less than two times width; abundance of cobble; gravel common.	Run area may be lacking; riffle not as wide as stream and its length is less than 2 times the stream width; gravel or bedrock prevalent; some cobble present.	Riffles or runs virtually nonexistent; bedrock prevalent; cobble lacking.
	20-16 ________	15-11 ________	10-6 ________	5-0 ________
H. Bank stability - Score each bank	Bank stable; evidence of erosion or bank failure absent or minimal; little potential for future problems; <5% of bank affected.	Moderately stable; infrequent, small areas of erosion, mostly healed over; 5-29.9% of bank in reach has areas of erosion.	Moderate unstable; 30-59.9% of bank in reach has areas of erosion; high erosion potential during floods.	Unstable; many eroded areas; "Raw" areas frequent along straight sections and bends; obvious bank sloughing ; 60- 100% of bank has erosion scars.
Left Bank	10-9 ________	8-6 ________	5-3 ________	2-0 ________
Right Bank	10-9 ________	8-6 ________	5-3 ________	2-0 ________
I. Vegetative protection – Score each bank	More than 90% of the streambank surfaces and immediate riparian zone covered by native vegetation, including trees, understory, or herbaceous growth; vegetative disruption through grazing or mowing minimal or not evident; almost all plants allowed to grow naturally.	90-70% of the streambank surface covered by native vegetation; but one class of plants is not well represented; disruption evident but not affecting full plant growth potential to any great extent; more than one-half of the potential plant stubble height remaining.	69.9-50% of the streambank surface covered by vegetation; disruption obvious; patches of bare soil or closely cropped vegetation common; less than one-half of the potential plant stubble height remaining.	Less than 50% of the stream bank surface covered by vegetation; disruption of streambank vegetation is very high; vegetation has been removed to 5 centimeters or less in average stubble height.
Left Bank	10-9 ________	8-6 ________	5-3 ________	2-0 ________
Right Bank	10-9 ________	8-6 ________	5-3 ________	2-0 ________
J. Riparian vegetative zonewidth - Score each bank	Width of riparian zones > 18 meters; human activities (i.e., parking lots, roadbeds, clear-cuts, lawns, or crops) have not impacted zone.	Width of riparian zones 17.9-12 meters; human activities have impacted zone minimally.	Width of riparian zones 11.9-6 meters; human activities have impacted zone a great deal.	Width of riparian zones <6 meters; little or no riparian vegetation due to human activities.
Left Bank	10-9 ________	8-6 ________	3-5 ________	2-0 ________
Right Bank	10-9 ________	8-6 ________	3-5 ________	2-0 ________

Total ________

Appendix B. Monitoring Site Photograph Log

Site 1: Sampling site, Deans Valley River at Abeokuta.



Site 1: Upstream of sampling site and downstream of sampling site.

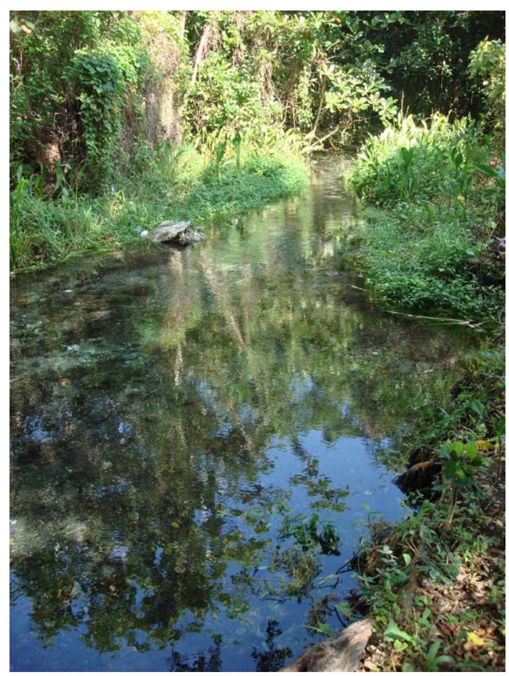
Site 2: Sampling site, Sweet River near Paradise. The WRA gage is located at the left base of the bridge and mounted on the right side of the bridge.

Site 2: Upstream of the sampling site and downstream of the sampling site.

Site 3: Sampling site, Ferris River at coastal road crossing in Ferris Cross.

Site 3: Upstream of sampling site and downstream of sampling site.

Site 4: Sampling site, Ferris River at Ferris Cross, upstream of the main coastal road.



Site 4: Upstream of site and downstream of site.

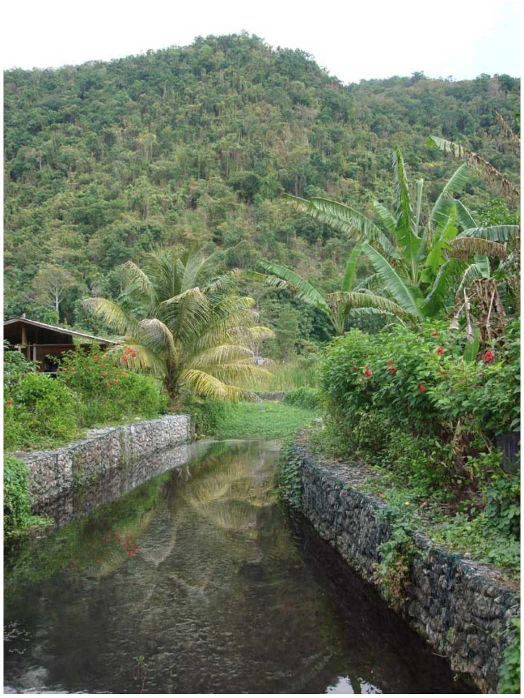
Site 5: Sampling site, Sawmill River below watering catchment near Cave.

Site 5: Upstream of the sampling site and downstream of the site.

Site 6: Sampling site, Sawmill River near pimento factories in Cave.

Site 6: Upstream of sampling site and downstream of site.

Site 7: Sampling site, Sawmill River at coastal road crossing near Cave.



Site 7: Upstream of sampling site and downstream of site.

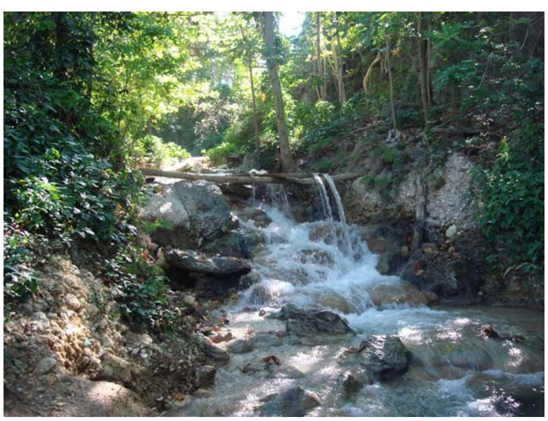
Site 8: Sampling site, located near in the upper left hand corner near the rocks.
Waterwheel near coastal road crossing in Cave.

Site 8: Upstream of the sampling site, looking downstream from the headwaters.

Site 8 ds: Sampling site, Waterwheel downstream (ds) of site 8 on the other side of the coastal road.

Site 8 ds: Catchment and weir upstream of site and view downstream (ds).

Site 9: Sampling site, Bluefields River under main coastal road crossing.



Site 9: Upstream of the sampling site and downstream.

Site 10: Sampling site, Bluefields River at Rivertop. The photo on the right is the condition of the site January 2009 and June 2009. The photo on the left is the condition of the stream after damming up the bridge, January 2010.

Site 10: Upstream of the sampling site after the bridge was dammed and the downstream discharge of the sampling site under the bridge.

Site 11: Sampling site, Shafston Tributary of the Bluefields River.

Site 11: Upstream of the sampling site and downstream view of the sampling site, looking upstream towards the site.

Site 12: Sampling site, Robins River near the community of Robins River.

Site 12: Upstream of the sampling site (and the road) and downstream of the site.

Site 13: Sampling site, Bluehole Spring near Belmont.

Site 13: Pasture upstream of the sampling site and downstream of the sampling site.

Site 14: Sampling site, Bluehole River near coastal road crossing in Belmont.

Site 14: Upstream view of sampling site

Appendix C. Visual Survey and Site Characterization Data

Site	Name	Water				Substrate			
		Flow	Color	Smell	Turbidity	Bed Material	Mud on Bottom	Algal Cover	Macrophyte
1	Deans Valley	laminar/turbulent	none	fresh	clear	cobble	none	10%	10%
2	Sweet River	laminar	green/blue	fresh	cloudy	sand/gravel	none	25%-50% ds	10%
3	Ferris River	laminar	none	fresh	clear	sand/gravel	none	none	25%
4	Watercress River	laminar	none	fresh	clear	sand	none	10%	75%
5	Sawmill River @ watering hole	laminar	none	fresh/ chemical	clear	sand/gravel	none	25%	10%
6	Sawmill River @ pimento Factory	slow laminar	none	fresh	clear/murky	sand/gravel	50%	25%	75%
7	Sawmill River @ road crossing	slow laminar	none	chemical	clear/murky	sand	50%	50%	50%
8	Waterwheel	laminar	none	fresh	clear	90% sand 10% gravel	none	10%	50%
ds of 8	downstream of Waterwheel	rapid/turbulent	none	fresh	clear	sand/gravel	none	10%	10%
9	Bluefields River at road crossing	laminar	none	fresh	clear	gravel/sand	none	10%	none
10	Bluefields River at Rivertop	laminar	none	fresh	clear	large cobble/ gravel	none	10%	10%
11	Shafston Tributary of the Bluefields	laminar/turbulent	none	fresh/rust	clear	large cobble	none	10%	25%
12	Robbins River at road crossing	laminar	none	fresh	clear	sand/gravel	40%	sparse	sparse
13	Bluehole Spring	stagnant	none	fresh	murky	sand	50%	75%	75%
14	Bluehole River at road crossing	laminar-slow	none	fishy/sewage	murky	gravel/cobble	10%	25%	10%

Site	Name	Channel			Disturbance	
		Type	Artificial	Setting	Human	Misc.
1	Deans Valley	riffle-pool	channelized ds	upland-steep	washing, watering	trash, cattle
2	Sweet River	plane-bed	ds of bridge	alluvial/savanna	fishing	trash, cattle
3	Ferris River	alluvial/riffle	near bridge	alluvial/ coastal	bathing, washing	trash, water supply pipes
4	Watercress River	alluvial/ plane-bed	near bridge	wetlamd	watering	trash
5	Sawmill River @ watering hole	plane-bed	channelized, ds of concrete basin/weir	forest/wetland	bathing, washing, soil erosion	trash
6	Sawmill River @ pimento Factory	plane-bed	us of bridge, concrete basin	forest/wetland	bathing, fishing, washing	trash, water supply pipes
7	Sawmill River @ road crossing	plane-bed	channelized, us of bridge	coastal-alluvial	watering, washing	trash
8	Waterwheel	plane-bed	road crossing at bridge	coastal-alluvial	bathing, washing, watering	trash, washing vehicles
ds of 8	downstream of Waterwheel	plane-bed	ds of basin/weir	coastal-alluvial	bathing	trash
9	Bluefields River at road crossing	step-pool	artificial step structure, flow under bridge	mangrove/coastal	bathing, washing	trash
10	Bluefields River at Rivertop	plane-bed	us of bridge, channelized walls	upland-community	bathing, watering	trash
11	Shafston Tributary of the Bluefields	riffle-pool	aquaduct and concrete basin us	forest/upland	watering	water supply aquaduct us
12	Robbins River at road crossing	plane-bed	flow directed under bridge, channelized	wetland/forest	watering, bathing, soil erosion, washing	trash, washing vehicles
13	Bluehole Spring	spring	none	wetland	bathing	cattle, trash
14	Bluehole River at road crossing	plane-bed	us of road/bridge	mangrove from coastal wetland	fishing discards	trash, water supply pipes

Appendix D. Channel Measurements and Discharge

	Channel Parameters- Monitoring Round 2- Sampling 1						Channel Parameters- Monitoring Round 2- Sampling 2					
Site	Channel Width	Channel Width	Water Depth	Velocity	Discharge	Discharge	Channel Width	Channel Width	Water Depth	Velocity	Discharge	Discharge
#	m	ft	ft	ft/sec	cfs	cms	m	ft	ft	ft/sec	cfs	cms
1	1.6	5.25	0.6	3.49	10.99	0.31	1.7	5.58	0.9	2.16	10.84	0.31
2	7.4	24.27	12.1	1.46	428.84	12.14	7.6	24.93	12.1	0.95	286.58	8.12
3	2	6.56	1.6	1.47	15.43	0.44	3.9	12.79	1.4	1.75	31.34	0.89
4	5	16.40	1.1	1.32	23.82	0.67	5.8	19.03	1.2	0.97	22.15	0.63
5	3	9.84	0.9	0.33	2.92	0.08	3.6	11.81	0.85	0.4	4.02	0.11
6	11.8	38.71	1.85	0.45	32.22	0.91	11.5	37.72	0.9	0.32	10.86	0.31
7	5.2	17.06	1	0.47	8.02	0.23	1.6	5.25	5.2	0.43	11.74	0.33
8	9	29.52	0.8	0.3	7.09	0.20	11.2	36.74	0.75	0.3	8.27	0.23
9	5.7	18.70	0.55	0.83	8.54	0.24	4.5	14.76	0.5	0.36	2.66	0.08
10	3.5	11.48	0.45	1.61	8.32	0.24	3.9	12.79	0.4	1.82	9.31	0.26
11	1.1	3.61	0.3	0.93	1.01	0.03	1	3.28	0.3	0.32	0.31	0.01
12	2.9	9.51	0.5	0.16	0.76	0.02	4.6	15.09	0.6	0.65	5.89	0.17
13	19.4	63.64	2.4	0	0.00	0.00	15.8	51.83	3.46	0	0.00	0.00
14	6.5	21.32	0.5	0.36	3.84	0.11	7.3	23.95	0.4	0.26	2.49	0.07

Appendix D Continued.

	Channel Parameters- Monitoring Round 2- Sampling 3						Mean Channel Parameters- Monitoring Round 2 (n=3)					
Site	Channel Width	Channel Width	Water Depth	Velocity	Discharge	Discharge	Channel Width	Channel Width	Water Depth	Velocity	Discharge	Discharge
#	m	ft	ft	ft/sec	cfs	cms	m	ft	ft	ft/sec	cfs	cms
1	1.5	4.92	0.8	2.27	5.90	0.17	1.60	5.25	0.77	2.64	9.25	0.26
2	7.4	24.27	12.10	2.27	2173.57	61.55	7.47	24.49	12.10	1.56	963.00	27.27
3	3.3	10.83	2.05	1.25	73.23	2.07	3.07	10.06	1.68	1.49	40.00	1.13
4	2	6.56	1.30	1.48	17.06	0.48	4.27	14.00	1.20	1.26	21.01	0.59
5	0.8	2.62	0.18	1.90	0.38	0.01	2.47	8.09	0.64	0.88	2.44	0.07
6	11.8	38.71	0.32	0.98	146.16	4.14	11.70	38.38	1.02	0.58	63.08	1.79
7	5.2	17.06	1.30	0.38	115.31	3.27	4.00	13.12	2.50	0.43	45.02	1.27
8	11.2	36.74	0.79	0.35	325.08	9.21	10.47	34.33	0.78	0.32	113.48	3.21
8.1	1	3.28	0.96	1.10	3.15	0.09	1.00	3.28	0.96	1.10	3.15	0.09
9	0.7	2.30	0.86	2.09	1.38	0.04	3.63	11.92	0.64	1.09	4.19	0.12
10	3.9	12.79	0.45	1.60	22.45	0.64	3.77	12.36	0.43	1.68	13.36	0.38
11	0.65	2.13	0.30	0.64	0.42	0.01	0.92	3.01	0.30	0.63	0.58	0.02
12	2	6.56	0.56	0.55	7.35	0.21	3.17	10.39	0.55	0.45	4.66	0.13
13	15.8	51.83	3.46	0.00	0.00	0.00	17.00	55.77	3.11	0.00	0.00	0.00
14	6.5	21.32	0.40	0.18	55.44	1.57	6.77	22.20	0.43	0.27	20.59	0.58

Appendix E. Duplicate Data

Appendix E-1. Monitoring Round Two.

		IDEXX- Bacteria		Hellige Colorimeter
		E-Coli	Total Coliform	Phosphate
		MPN	MPN	mg/L
Site	Date	n=3	n=3	n=7
1	6/7/2009	0	0	
1	6/7/2009	0	0	
2	6/5/2009	51.2	73.8	
2	6/5/2009	0	0	
2	6/7/2009	0	0	
2	6/7/2009	0	0	
3	6/7/2009	0	0	0.37
3	6/7/2009	0	0	0.38
4	6/7/2009	0	0	
4	6/7/2009	19.8	46.9	
5	6/7/2009	1	3.1	
5	6/7/2009	0	0	
6	6/7/2009	8.6	13.5	
6	6/7/2009	0	0	
7	6/7/2009	3.1	3.1	
7	6/7/2009	0	0	
8	6/7/2009	0	0	
8	6/7/2009	0	0	
9	6/7/2009	1	2	
9	6/7/2009	0	0	
10	6/7/2009	0	0	
10	6/7/2009	0	0	
11	6/5/2009	178	>2419.6	0.55
11	6/5/2009	0	0	0.6
11	6/7/2009	1	1	0.28
11	6/7/2009	0	0	0.26
12	6/7/2009	2	3	
12	6/7/2009	0	0	
13	6/7/2009	0	0	
13	6/7/2009	0	1	
14	6/5/2009	51.8	98.8	
14	6/5/2009	51.8	144.6	
14	6/7/2009	0	0	
14	6/7/2009	0	0	

Appendix E-2. Monitoring Round Three.

		IDEXX- Bacteria		Hellige Colorimeter	Test Strips		
Site	Date	E-Coli	Total Coliform	Phosphate	Total Chlorine	Nitrite	Nitrate
		MPN	MPN	mg/L	ppm	ppm	ppm
1	1/5/2010			0.15	0.25	0	0
1	1/5/2010			0.18	0.25	0	0
1	1/10/2010	13.2	816.4	0.16	0	0	0
1	1/10/2010	12	1119.4	0.16	0	0	0
2	1/8/2010	36.4	89.6	0.27	0.5	0	0
2	1/8/2010	21.3	43.8	0.26	0	0	0
2	1/10/2010	235.9	>2419.6	0.24	0	0	2.5
2	1/10/2010	275.5	>2419.6	0.25	0	0	2.5
3	1/10/2010	6.3	144.5				
3	1/10/2010	13.1	44.5				
4	1/8/2010	8.6	12.2				
4	1/8/2010	96	>2419.6				
5	1/10/2010	1	40				
5	1/10/2010	0	41.2				
6	1/8/2010	48.7	342.8				
6	1/8/2010	52.1	>2419.6				
6	1/10/2010			0.22	0	0	0
6	1/10/2010			0.32	0	0	0
7	1/5/2010	12	29.3	0.25	0.5	0	0
7	1/5/2010	0	0	0.08	0.25	0	0
7	1/10/2010	866.4	>2419.6				
7	1/10/2010	1119.9	>2419.6				
8	1/7/2010	3.1	3.1	low	0	0	0
8	1/7/2010	31.3	284.1	0.12	0	0	0
8	1/8/2010			0.16	0	0	0
8	1/8/2010			0.17	0	0	0
8.1	1/7/2010	17.5	41				
8.1	1/7/2010	33.1	>2419.6				
8.1	1/8/2010	33.1	920.8				
8.1	1/8/2010	31.7	1011.12				
9	1/7/2010	770.1	2419.6				
9	1/7/2010	7.5	7.5				
9	1/8/2010	248.1	>2419.6				
9	1/8/2010	166.4	>2419.6				
9	1/10/2010	344.8	>2419.6				
9	1/10/2010	344.8	>2419.6				

Appendix E-2 Continued. Monitoring Round Three.

Site	Date	IDEXX- Bacteria E-Coli MPN	IDEXX- Bacteria Total Coliform MPN	Hellige Colorimeter Phosphate mg/L	Test Strips Total Chlorine ppm	Test Strips Nitrite ppm	Test Strips Nitrate ppm
10	1/5/2010			0.12	0.25	0	0
10	1/5/2010			0.11	0	0	0
11	1/8/2010	76.7	>2419.6	0.21	0	0	0
11	1/8/2010	104.6	>2419.6	0.32	0	0	0
11	1/10/2010			0.13	0	0	0
11	1/10/2010			0.25	0	0	0
12	1/8/2010	56.3	>2419.6				
12	1/8/2010	53.7	2419.6				
13	1/7/2010	1	1203.3	0.09	0	0	2
13	1/7/2010	0	28.2	0.28	0	0	2
13	1/8/2010			0.09	0	0	2
13	1/8/2010			0.09	0	0	2
14	1/7/2010			0.19	0	0	0
14	1/7/2010			low	0	0	0
14	1/10/2010	78.9	>2419.6				
14	1/10/2010	86	>2419.6				

Appendix F. Water Quality Monitoring Data

Appendix F-1. Monitoring Round 1, December 2008/January 2009.

Site #	Sampling Date	pH	Conductivity (mS/m)	Turbidity (NTU)	Dissolved Oxygen (mg/L)	Temperature (^{o}C)	TDS (g/L)
1	1/5/2009	7.24	57.7	13.7	5.03	23.6	0.37
2	1/5/2009	7.29	60.2	3.9	4.88	25.2	0.38
3	1/5/2009	7.3	58.5	0.5	4.7	25.1	0.37
4	1/5/2009	7.38	60.9	0.2	4.82	25.3	0.39
5	1/1/2009	7.72	48.6	0	4.38	23.3	0.32
6	1/1/2009	7.84	48.3	0	6.29	23.5	0.31
7	1/1/2009	7.6	50.4	0	5.59	24	0.32
8	1/1/2009	7.37	48.3	0	5.78	24.3	0.31
9	12/31/2008	8.18	47.1	2.5	5.15	23.2	0.31
10	12/31/2008	8.1	49.3	22.5	6.1	24	0.32
11	1/10/2009	7.34	53.8	10	4.34	23.5	0.34
12	1/10/2009	7.77	59.6	10	4.92	24.1	0.38
13	1/1/2009	7	61.7	42.5	4.3	24.4	0.39
14	1/1/2009	7.79	0.187	0	3.34	24.3	1.2
	# of Samples	14	14	14	14	14	14
	Mean	7.57	50.33	7.56	4.97	24.13	0.41
	Minimum	7	0.187	0	3.34	23.2	0.31
	Maximum	8.18	61.7	42.5	6.29	25.3	1.2
	Median	7.49	52.1	1.5	4.9	24.05	0.355
	Stand Dev.	0.35	15.43	12.16	0.79	0.69	0.23
	Coeff Var.	5%	31%	161%	16%	3%	56%

Appendix F-2. Monitoring Round 2, Sampling Run One, 6/2/2009.

Site #	Sampling Date	pH	Conductivity (mS/m)	Turbidity (NTU)	Dissolved Oxygen (mg/L)	Temperature (^{o}C)	TDS (g/L)	Phosphate (mg/L)	E. coli (MPN)	Total Coliform (MPN)
1	6/2/2009	7.53	54.3	99.6	4.95	23.5	0.35	0.07	7.5	48.7
2	6/2/2009	7.32	57.8	17	4.88	25.4	0.37	0.11	54.6	146.6
3	6/2/2009	7.45	55.1	20.1	5.2	25.1	0.35	1.04	0	0
4	6/2/2009	7.52	58.1	28.3	4.86	25.4	0.37	0.81	0	0
5	6/2/2009	7.88	44.3	143	6.48	23.5	0.29	1.19	7.5	770.1
6	6/2/2009	7.83	44.3	94.6	6.99	23.9	0.29	0.39	0	0
7	6/2/2009	7.95	46.2	111	5.67	24.4	0.33	0.13	1	0
8	6/2/2009	7.99	46.6	97.4	6.92	24.3	0.3	0.39	0	0
9	6/2/2009	8.43	43.9	54.4	6.53	24.8	0.29	0.23	0	0
10	6/2/2009	8.22	47.7	62.9	6.53	24.4	0.31	0.25	31.7	38.9
11	6/2/2009	8.25	46.5	61	6.4	25.2	0.3	0.96	190.3	1011.2
12	6/2/2009	7.9	56.6	77.6	5.97	24.1	0.36	0.97	0	0
13	6/2/2009	7.65	62.2	45.5	5.4	25	0.4	0.24	8.5	16
14	6/2/2009	7.93	0.132	31.8	4.27	26.7	0.8	1.24	50.5	78.3
	# of Samples	14	14	14	14	14	14	14	14	14
	Mean	7.85	47.41	67.44	5.79	24.69	0.37	0.57	25.11	150.70
	Minimum	7.32	0.132	17	4.27	23.5	0.29	0.07	0	0
	Maximum	8.43	62.2	143	6.99	26.7	0.8	1.24	190.3	1011.2
	Median	7.89	47.15	61.95	5.82	24.6	0.34	0.39	4.25	8
	Stand Dev.	0.32	14.94	37.91	0.87	0.86	0.13	0.44	51.22	319.78
	Coeff Var.	4%	32%	56%	15%	3%	36%	76%	204%	212%

Appendix F-3. Monitoring Round 2, Sampling Run Two, 6/5/2009.

Site #	Sampling Date	pH	Conductivity (mS/m)	Turbidity (NTU)	Dissolved Oxygen (mg/L)	Temperature (^{o}C)	TDS (g/L)	Phosphate (mg/L)	E. coli (MPN)	Total Coliform (MPN)
1	6/5/2009	7.22	54.5	135	4.7	23.6	0.35	low	0	<1
2	6/5/2009	7.32	58	21.7	4.87	25.6	0.37	0.33	51.2	73.8
2	6/5/2009	7.32	58	21.7	4.87	25.6	0.37	0.33	0	0
3	6/5/2009	7.35	54.9	19.7	5.16	25.2	0.35	0.37	2	<1
3	6/5/2009	7.35	54.9	19.7	5.16	25.2	0.35	0.38	2	<1
4	6/5/2009	7.56	58.1	55	5.1	25.5	0.37	0.7	6.3	11.9
5	6/5/2009	7.62	45	64	6.29	23.8	0.29	0.62	<1	5.1
6	6/5/2009	7.7	44.6	56.6	7.05	24.3	0.29	0.66	49.6	104.3
7	6/5/2009	7.69	48.9	40.7	5.33	25.2	0.32	0.56	66.3	78.9
8	6/5/2009	7.51	46.7	50.7	5.98	24.3	0.3	0.29	1	1
8.1	6/5/2009	n/a	n/a	n/a	n/a	n/a	n/a	n/a	35.5	325.7
9	6/5/2009	8.19	43.9	99.2	6.61	24.9	0.28	0.73	8	25.3
10	6/5/2009	8.19	47.5	93	6.64	24.9	0.31	0.31	1	4
11	6/5/2009	8.07	47	65	6.49	25.7	0.3	0.55	178	>2419.6
11	6/5/2009	8.07	47	65	6.49	25.7	0.3	0.60	0	0
12	6/5/2009	7.95	55.9	50.1	6.15	25.2	0.36	0.56	13.7	23.8
13	6/5/2009	7.47	62.3	101	5.07	24.6	0.4	0.66	1	1
14	6/5/2009	7.91	0.18	57.6	4.16	27.2	1.1	0.77	51.8	98.8
14	6/5/2009	7.91	0.18	57.6	4.16	27.2	1.1	0.77	51.8	144.6
	# of Samples	18	18	18	18	18	18	18	19	19
	Mean	7.69	45.98	59.63	5.57	25.21	0.42	0.54	28.84	59.88
	Minimum	7.22	0.18	19.7	4.16	23.6	0.28	0.29	0	0
	Maximum	8.19	62.3	135	7.05	27.2	1.1	0.77	178	325.7
	Median	7.66	48.2	57.1	5.245	25.2	0.35	0.56	7.15	23.8
	Stand Dev.	0.32	17.57	31.42	0.90	0.96	0.25	0.17	44.14	87.39
	Coeff Var.	4%	38%	53%	16%	4%	60%	32%	153%	146%

Appendix F-4. Monitoring Round 2, Sampling Run Three, 6/7/2009.

Site #	Sampling Date	pH	Conductivity (mS/m)	Turbidity (NTU)	Dissolved Oxygen (mg/L)	Temperature (^{o}C)	TDS (g/L)	Phosphate (mg/L)	E. coli (MPN)	Total Coliform (MPN)
1	6/7/2009	7.14	54.7	65.8	4.64	23.6	0.35	0.17	0	0
1	6/7/2009	7.14	54.7	65.8	4.64	23.6	0.35	0.17	0	0
2	6/7/2009	7.22	58	26.2	4.32	25.3	0.37	0.23	0	0
2	6/7/2009	7.22	58	26.2	4.32	25.3	0.37	0.23	0	0
3	6/7/2009	7.21	55	23.2	4.77	25	0.35	0.32	0	0
3	6/7/2009	7.21	55	23.2	4.77	25	0.35	0.32	0	0
4	6/7/2009	7.33	58.1	20.1	4.54	25.1	0.37	0.2	0	0
4	6/7/2009	7.33	58.1	20.1	4.54	25.1	0.37	0.2	19.8	46.9
5	6/7/2009	7.47	45.2	61.1	6.18	23.3	0.29	0.26	1	3.1
5	6/7/2009	7.47	45.2	61.1	6.18	23.3	0.29	0.26	0	0
6	6/7/2009	7.73	45	59.7	6.53	23.7	0.29	0.19	8.6	13.5
6	6/7/2009	7.73	45	59.7	6.53	23.7	0.29	0.19	0	0
7	6/7/2009	7.71	47.5	75	5.41	24.2	0.31	0.2	3.1	3.1
7	6/7/2009	7.71	47.5	75	5.41	24.2	0.31	0.2	0	0
8	6/7/2009	7.64	46.7	183	6.7	24.8	0.3	0.25	0	0
8	6/7/2009	7.64	46.7	183	6.7	24.8	0.3	0.25	0	0
8.1	6/7/2009	n/a	n/a	n/a	n/a	n/a	na	n/a	23.8	61.4
9	6/7/2009	8.23	44.8	88.5	6.6	24.2	0.29	0.47	1	2
9	6/7/2009	8.23	44.8	88.5	6.6	24.2	0.29	0.47	0	0
10	6/7/2009	7.95	47.8	64.9	6.68	23.9	0.31	0.29	0	0
10	6/7/2009	7.95	47.8	64.9	6.68	23.9	0.31	0.29	0	0
11	6/7/2009	8.02	46.8	46.2	6.43	24.4	0.3	0.28	1	1
11	6/7/2009	8.02	46.8	46.2	6.43	24.4	0.3	0.26	0	0
12	6/7/2009	7.81	56	45.5	6.1	24.3	0.36	0.35	2	3
12	6/7/2009	7.81	56	45.5	6.1	24.3	0.36	0.35	0	0

Appendix F-4 Continued. Monitoring Round 2, Sampling Run Three, 6/7/2009.

Site #	Sampling Date	pH	Conductivity (mS/m)	Turbidity (NTU)	Dissolved Oxygen (mg/L)	Temperature (^oC)	TDS (g/L)	Phosphate (mg/L)	E. coli (MPN)	Total Coliform (MPN)
13	6/7/2009	7.61	62.1	48.5	5.84	24.6	0.4	0.35	0	0
13	6/7/2009	7.61	62.1	48.5	5.84	24.6	0.4	0.35	0	1
14	6/7/2009	7.81	0.166	39.5	4.45	25.5	1.1	0.24	0	0
14	6/7/2009	7.81	0.166	39.5	4.45	25.5	1.1	0.24	0	0
	# of Samples	28	28	28	28	28	28	28	29	29
	Mean	7.63	47.70	60.51	5.66	24.42	0.39	0.27	2.08	4.66
	Minimum	7.14	0.166	20.1	4.32	23.3	0.29	0.17	0	0
	Maximum	8.23	62.1	183	6.7	25.5	1.1	0.47	23.8	61.4
	Median	7.675	47.65	54.1	5.97	24.35	0.33	0.255	0	0
	Stand Dev.	0.32	14.60	39.69	0.91	0.65	0.21	0.08	5.74	14.09
	Coeff Var.	4%	31%	66%	16%	3%	53%	29%	276%	303%

Appendix F-5. Monitoring Round 3, Sampling Run One, 1/5/2010.

Site #	Sampling Date	pH	Conductivity (mS/m)	Turbidity (NTU)	Dissolved Oxygen (mg/L)	Temperature (^{o}C)	TDS (g/L)	Phosphate (mg/L)	E. coli (MPN)	Total Coliform (MPN)	Total Chlorine (ppm)	Nitrite (ppm)	Nitrate (ppm)
1	1/5/2010	6.97	57.2	159	6.02	23.7	0.37	0.15	0	0	0.25	0	0
1	1/5/2010	6.97	57.2	159	6.02	23.7	0.37	0.18	0	0	0.25	0	0
2	1/5/2010	7.37	59.2	232	5.78	25.1	0.38	0.22	0	0	0	0	0
3	1/5/2010	7.36	58	253	5.87	25	0.37	0.13	0	0	0.25	0	2.5
4	1/5/2010	7.34	60.5	422	5.81	25	0.39	0.14	5.2	12	0.5	0	0
5	1/5/2010	7.63	49	381	6.49	23.3	0.32	0.14	0	0	0	0	0
6	1/5/2010	7.67	48.9	332	6.27	23.2	0.32	0.06	0	0	0.5	0	0
7	1/5/2010	7.67	50.1	265	6	23.7	0.32	0.25	12	29.3	0.5	0	0
7	1/5/2010	7.67	50.1	265	6	23.7	0.32	0.08	0	0	0.25	0	0
8	1/5/2010	7.56	47.8	240	6.02	24	0.31	0.12	0	0	0.25	0	2.5
8.1	1/5/2010	7.5	48.4	237	6.03	24.1	0.31	low	1	2	0.25	0	2.5
9	1/5/2010	8.03	46.5	297	6.35	23.3	0.3	0.05	20	3.1	0.5	0	2
10	1/5/2010	8.11	49.4	204	6.31	23.2	0.32	0.12	0	0	0.25	0	0
10	1/5/2010	8.11	49.4	204	6.31	23.2	0.32	0.11	0	0	0.25	0	0
11	1/5/2010	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
12	1/5/2010	7.92	58.7	167	6.12	23.8	0.38	0.09	0	0	0.5	0	0
13	1/5/2010	7.72	62.4	265	5.87	24.3	0.4	0.34	332.5	25.7	0	0	0
14	1/5/2010	7.94	0.13	147	6.02	23.9	0.8	0.06	n/a	n/a	0.5	0	0
LRB	1/5/2010	n/a	n/a	n/a	n/a	n/a	n/a	0.19	0	0	1	0	0
FB	1/5/2010	n/a	n/a	n/a	n/a	n/a	n/a	low	0	0	0.5	0	0
	# of Samples	17	17	17	17	17	17	19	18	18	19	19	19
	Mean	7.62	50.17	248.76	6.08	23.89	0.37	0.14	20.59	4.01	0.34	0.00	0.50
	Minimum	6.97	0.13	147	5.78	23.2	0.3	0.05	0	0	0	0	0
	Maximum	8.11	62.4	422	6.49	25.1	0.8	0.34	332.5	29.3	1	0	2.5
	Median	7.67	50.1	240	6.02	23.7	0.32	0.13	0	0	0.25	0	0
	Stand Dev.	0.35	13.92	77.14	0.20	0.63	0.12	0.08	78.02	9.04	0.24	0.00	1.00
	Coeff Var.	5%	28%	31%	3%	3%	31%	53%	379%	226%	70%	0%	200%

Appendix F-6. Monitoring Round 3, Sampling Run Two, 1/7/2010.

Site #	Sampling Date	pH	Conductivity (mS/m)	Turbidity (NTU)	Dissolved Oxygen (mg/L)	Temperature (^{o}C)	TDS (g/L)	Phosphate (mg/L)	E. coli (MPN)	Total Coliform (MPN)	Total Chlorine (ppm)	Nitrite (ppm)	Nitrate (ppm)
1	1/7/2010	7.5	57.3	154	6.47	23.7	0.37	0.19	3.1	265	0	0	0
2	1/7/2010	7.45	59.4	122	5.66	25.1	0.38	0.2	172.3	>2419.6	0	0	0
3	1/7/2010	7.47	58.1	279	5.58	25.1	0.37	0.19	8.6	218.7	0.25	0	0
4	1/7/2010	7.53	58.8	305	5.73	25.1	0.38	0.1	83.3	344.8	0	0	0
5	1/7/2010	7.65	49.2	433	6.2	23.6	0.32	0.16	3	416	0	0	0
6	1/7/2010	7.93	47.4	445	6.29	23.7	0.31	0.17	23.1	>2419.6	0	0	2.5
7	1/7/2010	8	50.5	488	6.28	23.6	0.32	0.18	121.1	2419.6	0.5	0	0
8	1/7/2010	7.87	48.1	401.8	6.1	24.1	0.31	low	3.1	3.1	0	0	0
8	1/7/2010	7.87	48.1	401.8	6.1	24.1	0.31	0.12	31.3	284.1	0	0	0
8.1	1/7/2010	7.64	48.9	383	6.05	24.2	0.32	0.22	17.5	41	0	0	0
8.1	1/7/2010	7.64	48.9	383	6.05	24.2	0.32	0.22	33.1	>2419.6	0	0	0
9	1/7/2010	8.3	46.4	419	6.36	23.3	0.3	0.05	770.1	2419.6	0	0	0
9	1/7/2010	8.3	46.4	419	6.36	23.3	0.3	0.05	7.5	7.5	0	0	0
10	1/7/2010	8.36	49.3	429	6.36	23.7	0.32	0.12	81.6	172.7	0	0	0
11	1/7/2010	8.28	1.3	423	6.44	23.6	0	0.33	72.3	>2419.6	0	0	0
12	1/7/2010	8.2	33.6	426.1	6.34	24.1	0.36	0.2	135.4	>2419.6	0.25	0	2
13	1/7/2010	7.8	62.7	416	6.36	24.7	0.4	0.09	1	1203.3	0	0	2
13	1/7/2010	7.8	62.7	416	6.36	24.7	0.4	0.28	0	28.2	0	0	2
14	1/7/2010	8.23	0.124	485	6.38	23.7	0.8	0.19	139.6	272.3	0	0	0
14	1/7/2010	8.23	0.124	485	6.38	23.7	0.8	low	139.6	139.6	0	0	0
LRB	1/7/2010	n/a	n/a	n/a	n/a	n/a	n/a	0.12	0	0	0.5	0	0
FB	1/7/2010	n/a	n/a	n/a	n/a	n/a	n/a	0.16	0	0	0.5	0	0
	# of Samples	20	20	20	20	20	20	22	22	22	22	22	22
	Mean	7.90	43.87	385.69	6.19	24.07	0.37	0.17	83.94	484.44	0.09	0.00	0.39
	Minimum	7.45	0.124	122	5.58	23.3	0	0.05	0	0	0	0	0
	Maximum	8.36	62.7	488	6.47	25.1	0.8	0.33	770.1	2419.6	0.5	0	2.5
	Median	7.87	48.9	417.5	6.315	23.9	0.32	0.175	27.2	218.7	0	0	0
	Stand Dev.	0.32	19.89	99.09	0.26	0.59	0.17	0.07	163.54	781.98	0.18	0.00	0.84
	Coeff Var.	4%	45%	26%	4%	2%	46%	42%	195%	161%	200%	0%	218%

Appendix F-7. Monitoring Round 3, Sampling Run Three, 1/8/2010.

Site #	Sampling Date	pH	Conductivity (mS/m)	Turbidity (NTU)	Dissolved Oxygen (mg/L)	Temperature (^{o}C)	TDS (g/L)	Phosphate (mg/L)	E. coli (MPN)	Total Coliform (MPN)	Total Chlorine (ppm)	Nitrite (ppm)	Nitrate (ppm)
1	1/8/2010	7.59	57.4	329	6.46	23.7	0.37	0.17	3.1	60.2	0.25	0	0
2	1/8/2010	7.4	59.5	296	5.49	25.2	0.38	0.27	36.4	89.6	0.5	0	0
2	1/8/2010	7.4	59.5	296	5.49	25.2	0.38	0.26	21.3	43.8	0	0	0
3	1/8/2010	7.47	58.2	300	5.59	25.1	0.37	0.26	0	12.2	0.5	0	0
4	1/8/2010	7.55	60.8	284	5.6	25.2	0.39	0.24	8.6	12.2	0	0	0
4	1/8/2010	7.55	60.8	284	5.6	25.2	0.39	0.24	96	>2419.6	0	0	0
5	1/8/2010	7.68	49.3	302	6.1	23.5	0.32	0.27	1	870.4	0	0	0
6	1/8/2010	7.85	47.4	332	6.19	23.6	0.31	0.18	48.7	342.8	0.5	0	0
6	1/8/2010	7.85	47.4	332	6.19	23.6	0.31	0.18	52.1	>2419.6	0.5	0	0
7	1/8/2010	7.84	50.3	300	6.04	24.1	0.32	0.2	387.3	416	0	0	0
8	1/8/2010	7.85	48.4	285	6.08	24.4	0.31	0.16	9.8	29.9	0	0	0
8	1/8/2010	7.85	48.4	285	6.08	24.4	0.31	0.17	9.8	29.9	0	0	0
8.1	1/8/2010	7.7	48.5	301	6.05	24.4	0.31	0.38	33.1	920.8	0	0	0
8.1	1/8/2010	7.7	48.5	301	6.05	24.4	0.31	0.38	31.7	1011.12	0	0	0
9	1/8/2010	8.14	46.8	324	6.2	23.8	0.3	0.06	248.1	>2419.6	0	0	0
9	1/8/2010	8.14	46.8	324	6.2	23.8	0.3	0.06	166.4	>2419.6	0	0	0
10	1/8/2010	8.08	49.4	327	6.14	23.8	0.32	0.08	108.1	>2419.6	0	0	0
11	1/8/2010	8.29	50.2	350	6.16	24.1	0.32	0.21	76.7	>2419.6	0	0	0
11	1/8/2010	8.29	50.2	350	6.16	24.1	0.32	0.32	104.6	>2419.6	0	0	0
12	1/8/2010	8.04	58.9	308	6.19	24.2	0.38	0.12	56.3	>2419.6	0	0	0
12	1/8/2010	8.04	58.9	308	6.19	24.2	0.38	0.12	53.7	2419.6	0	0	0
13	1/8/2010	7.84	62.5	340	6.22	24.7	0.4	0.09	22.6	1553.1	0	0	2
13	1/8/2010	7.84	62.5	340	6.22	24.7	0.4	0.09	22.6	1553.1	0	0	2
14	1/8/2010	8.03	0.125	332	6.17	24.4	0.8	0.26	248.9	1299.7	0.25	0	0
LRB	1/8/2010	n/a	n/a	n/a	n/a	n/a	n/a	0.12	0	0	0.5	0	0
FB	1/8/2010	n/a	n/a	n/a	n/a	n/a	n/a	0.14	0	0	0.5	0	0
	# of Samples	24	24	24	24	24	24	26	24	24	26	26	26
	Mean	7.83	51.28	313.75	6.04	24.33	0.36	0.19	71.03	592.47	0.13	0.00	0.15
	Minimum	7.4	0.125	284	5.49	23.5	0.3	0.06	0	0	0	0	0
	Maximum	8.29	62.5	350	6.46	25.2	0.8	0.38	387.3	2419.6	0.5	0	2
	Median	7.845	50.2	308	6.15	24.3	0.32	0.18	34.75	216.2	0	0	0
	Stand Dev.	0.26	12.34	21.45	0.27	0.56	0.10	0.09	94.67	726.95	0.21	0.00	0.54
	Coeff Var.	0.03	0.24	0.07	0.04	0.02	0.28	0.47	1.33	1.23	1.60	0.00	3.53

Appendix F-8. Monitoring Round 3, Sampling Run Four, 1/10/2010.

Site #	Sampling Date	pH	Conductivity (mS/m)	Turbidity (NTU)	Dissolved Oxygen (mg/L)	Temperature (°C)	TDS (g/L)	Phosphate (mg/L)	E. coli (MPN)	Total Coliform (MPN)	Total Chlorine (ppm)	Nitrite (ppm)	Nitrate (ppm)
1	1/10/2010	7.31	57.4	351.4	6.41	23.7	0.37	0.16	13.2	816.4	0	0	0
1	1/10/2010	7.31	57.4	351.4	6.41	23.7	0.37	0.24	12	1119.4	0	0	0
2	1/10/2010	7.49	59.2	235	5.86	25	0.38	0.24	235.9	>2419.6	0	0	2.5
2	1/10/2010	7.49	59.2	235	5.86	25	0.38	0.25	275.5	>2419.6	0	0	2.5
3	1/10/2010	7.62	58.3	233	5.99	25	0.37	0.24	6.3	144.5	0.25	0	0
3	1/10/2010	7.62	58.3	233	5.99	25	0.37	0.24	13.1	44.5	0.25	0	0
4	1/10/2010	7.77	60.6	205	6.03	25	0.39	0.33	111.9	2419.6	0	0	0
5	1/10/2010	7.99	49.2	258	6.39	23.3	0.32	0.14	1	40	0	0	0
5	1/10/2010	7.99	49.2	258	6.39	23.3	0.32	0.14	0	41.2	0	0	0
6	1/10/2010	8.07	48.9	260	6.33	23.3	0.32	0.22	66.3	665.3	0	0	0
6	1/10/2010	8.07	48.9	260	6.33	23.3	0.32	0.32	66.3	665.3	0	0	0
7	1/10/2010	8	50.3	237	6.11	23.4	0.32	0.34	866.4	>2419.6	0	0	0
7	1/10/2010	8	50.3	237	6.11	23.4	0.32	0.34	1119.9	>2419.6	0	0	0
8	1/10/2010	7.96	47.9	213	6.14	24.1	0.31	low	6.3	>2419.6	0	0	0
8.1	1/10/2010	7.98	48.6	239	6.21	24	0.32	0.08	19.9	>2419.6	0	0	0
9	1/10/2010	8.39	46.6	359	6.44	23.1	0.3	0.13	344.8	>2419.6	0	0	0
9	1/10/2010	8.39	46.6	359	6.44	23.1	0.3	0.13	344.8	>2419.6	0	0	0
10	1/10/2010	8.34	49.2	408	6.25	23.4	0.32	0.13	613.1	>2419.6	0	0	0
11	1/10/2010	8.37	50.4	328	6.34	23.1	0.32	0.13	261.3	1119.9	0	0	0
11	1/10/2010	8.37	50.4	328	6.34	23.1	0.32	0.25	261.3	1119.9	0	0	0
12	1/10/2010	8.08	58.8	202	6.13	23.9	0.38	0.22	39.9	>2419.6	0.25	0	0
13	1/10/2010	7.91	62.4	491	7.67	24.5	0.4	0.08	12.1	>2419.6	0	0	0
14	1/10/2010	8.16	0.141	282	7.93	23.7	0.9	0.09	78.9	>2419.6	0	0	0
14	1/10/2010	8.16	0.141	282	7.93	23.7	0.9	0.09	86	>2419.6	0	0	0
LRB	1/10/2010	n/a	n/a	n/a	n/a	n/a	n/a	0.13	0	0	1	0	0
FB	1/10/2010	n/a	n/a	n/a	n/a	n/a	n/a	0.13	0	6.3	0.75	0	0
	# of Samples	24	24	24	24	24	24	26	26	26	26	26	26
	Mean	7.95	48.68	285.20	6.42	23.84	0.39	0.19	186.78	630.95	0.10	0.00	0.19
	Minimum	7.31	0.141	202	5.86	23.1	0.3	0.08	0	0	0	0	0
	Maximum	8.39	62.4	491	7.93	25	0.9	0.34	1119.9	2419.6	1	0	2.5
	Median	7.995	50.3	259	6.33	23.7	0.32	0.16	66.3	665.3	0	0	0
	Stand Dev.	0.33	15.78	72.04	0.58	0.70	0.16	0.08	284.06	708.20	0.25	0.00	0.68
	Coeff Var.	4%	32%	25%	9%	3%	41%	44%	152%	112%	256%	0%	353%

Appendix F-9. Monitoring Round 2, All Three Sampling Runs, June 2009.

Monitoring Round Two	pH	Conductivity (mS/m)	Turbidity (NTU)	Dissolved Oxygen (mg/L)	Temperature (^{o}C)	TDS (g/L)	Phosphate (mg/L)	E. coli (MPN)	Total Coliform (MPN)
# of Samples	61	61	61	61	61	61	61	62	62
Mean	7.70	47.12	61.87	5.66	24.72	0.39	0.42	15.26	54.19
Minimum	7.14	0.132	17	4.16	23.3	0.28	0.07	0	0
Maximum	8.43	62.3	183	7.05	27.2	1.1	1.24	190.3	1011.2
Median	7.705	47.6	57.6	5.84	24.7	0.35	0.32	1	0.5
Stand Dev.	0.33	15.37	36.49	0.89	0.86	0.20	0.27	36.02	169.82
Coeff Var.	4%	33%	59%	16%	3%	52%	65%	236%	313%

Appendix F-10. Monitoring Round 3, All Four Sampling Runs, January 2010.

Monitoring Round Three	pH	Conductivity (mS/m)	Turbidity (NTU)	Dissolved Oxygen (mg/L)	Temperature (^{o}C)	TDS (g/L)	Phosphate (mg/L)	E. coli (MPN)	Total Coliform (MPN)	Total Chlorine (ppm)	Nitrite (ppm)	Nitrate (ppm)
# of Samples	85	85	85	85	85	85	93	90	90	93	93	93
Mean	7.84	48.58	309.62	6.19	24.04	0.37	0.18	96.96	411.73	0.16	0.00	0.29
Minimum	6.97	0.124	122	5.49	23.1	0	0.05	0	0	0	0	0
Maximum	8.39	62.7	491	7.93	25.2	0.9	0.38	1119.9	2419.6	1	0	2.5
Median	7.85	49.4	301	6.17	23.9	0.32	0.165	20.65	41.1	0	0	0
Stand Dev.	0.33	15.62	84.87	0.40	0.64	0.14	0.08	188.76	668.90	0.24	0.00	0.76
Coeff Var.	4%	32%	27%	6%	3%	37%	47%	195%	162%	153%	0%	263%

Appendix F-11. Summary of all Monitoring Rounds, December 2009-January 2010.

All Monitoring Rounds	pH	Conductivity (mS/m)	Turbidity (NTU)	Dissolved Oxygen (mg/L)	Temperature (^{o}C)	TDS (g/L)	Phosphate (mg/L)	E. coli (MPN)	Total Coliform (MPN)	Total Chlorine (ppm)	Nitrite (ppm)	Nitrate (ppm)
# of Samples	160	160	160	160	160	160	154	152	152	93	93	93
Mean	7.76	48.18	189.53	5.88	24.30	0.38	0.27	64.39	244.49	0.16	0.00	0.29
Minimum	6.97	0.124	0	3.34	23.1	0	0.05	0	0	0	0	0
Maximum	8.43	62.7	491	7.93	27.2	1.2	1.24	1119.9	2419.6	1	0	2.5
Median	7.79	49.3	183	6.1	24.2	0.32	0.22	7.5	9.7	0	0	0
Stand Dev.	0.34	15.44	145.67	0.76	0.80	0.17	0.22	153.15	530.94	0.24	0.00	0.76
Coeff Var.	4%	32%	77%	13%	3%	45%	80%	238%	217%	153%	0%	263%