MANGROVE ECOSYSTEM ASSESSMENT
GRAEME HALL NATURE SANCTUARY
BARBADOS

Prepared for:

Graeme Hall Nature Sanctuary, Inc.
Main Road
Worthing
Christ Church
Barbados

Prepared by:

Environmental
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April 30, 2010

<u>**SIGNATURE PAGE**</u>

Enclosed please find a report detailing investigations by Environmental Engineering Consultants, Inc. of the Graeme Hall Nature Sanctuary (Sanctuary) in Worthing, Christ Church, Barbados. Investigations included sampling of sediments for chemical and benthic analyses and of surface water for chemical analyses. Also included were field reconnaissance and a review of previous drainage studies to help ascertain sources and quantities of flow into the Sanctuary. The investigations were performed at the request of the Sanctuary. This report has been prepared by Environmental Engineering Consultants on behalf of the Sanctuary in accordance with standard scientific and engineering practices.

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TABLE OF CONTENTS

ATTACHMENTS

Executive Summary

On April 12, 2006, the Government of Barbados placed the Graeme Hall Swamp on the international Ramsar List -- so named after Ramsar, Iran, where the first Convention on Wetlands was held in 1971 -- to be protected as a Wetland of International Importance. The Ramsar designation describes Graeme Hall as a “naturally created coastal wetland area with mangrove forests, a seagrass bed, and a shallow near shore coral reef, which includes a 12-acre artificially-created lake that constitutes the largest body of inland water on the island." The designation further hails a waterfowl habitat with 84 bird species and more than 20 freshwater and brackish-water fish species.

This unique ecosystem is a natural resource worthy to be protected for future generations. Private investors in the Graeme Hall Nature Sanctuary have undertaken this task while extending opportunities for public education, scientific research, and ecotourism. The venture began with the acquisition of 34.25 acres of wetlands in 1994, followed by construction of visitor center infrastructure between 1998 and 2004 and further capital improvements to the property between 2006 and 2008.

During this endeavor, however, the Sanctuary has experienced inflows of untreated stormwater, agricultural, and commercial runoff and emergency raw sewage discharges into the lake system, curtailment of seawater interchange, and frequent fish kills and recent crab kills. Concerns over these degradations prompted the Sanctuary to initiate this study of the environmental health of the Graeme Hall Mangrove Ecosystem.

In February 2010, the Sanctuary authorized Environmental Engineering Consultants, Inc. (EEC) of Tampa, Florida, to perform field investigations including sediment sampling for benthic and chemical analysis; surface water sampling for chemical and bacteriological analysis; sampling of fish and crab for chemical and pathogen analysis; surveys of onsite biological indicators; and site reconnaissance for surrounding activities impacting the Sanctuary.

This report describes how the absence of a drainage outlet and periodic tidal influences is compromising the environmental health of the wetland within the Sanctuary, erasing the brackish characteristics that are the signature of a flourishing mangrove community. It explains the increasing disappearance of a diverse community of plant and animal species as a result of assimilating and processing pollutants from upland stormwater runoff, direct pollutant discharges, and unmitigated discharges of raw sewage.

The business mandate of the Sanctuary requires a healthy and diverse ecosystem. As of this writing, the resource has been closed to the general public since March 2009 because of the apparent environmental degradation of its wetland due to pollution source points outside its boundaries. Major reinvestments in interpretative educational systems and environmental control infrastructures are now required in response to recent core changes in the wetland from a brackish to a freshwater system. Findings in this report also suggest the need for corrective measures to control external sources of contaminated stormwater, sewage, and chemical pollutants and to restore biodiversity to the wetland.

The Sanctuary has appealed without success for protections of the ecosystem that only the Government of Barbados can enact and manage.

Through inaction and failed policy, the Government of Barbados has

- permitted contaminants from throughout the catchment area to penetrate "protected" wetlands through groundwater and surface water;
- so neglected maintenance and appropriate operations of a sluice gate at the outlet of the Graeme Hall Bisecting Canal that the device has become inoperable, preventing critical tidal flow into the Sanctuary and discharge of urban stormwater runoff;
- allowed raw sewage to bypass existing sewage systems to infiltrate the Sanctuary, without remediating its deleterious effects;
- operated the sewage treatment plant and local drainage systems, in fact, without a plan or a physical design to prevent such degradation to environmental health; and

- approved plans for residential and commercial development up to the boundaries of the Sanctuary such that future environmental impacts will further threaten its very existence.

This report documents the consequences of those Government practices and omissions, as well as numerous other conditions that jeopardize the existence of the Graeme Hall ecosystem. The water and sediment quality, mangrove assessment, benthic community analysis, drainage investigation, and field observation have led to the following conclusions, explained further in this report:

- **Urban and agricultural runoffs are concentrating pollutants in the water column and sediments of the lake, ponds, marsh and canal systems of the Graeme Hall Swamp.** Future land use changes north and east of the Graeme Hall ecosystem will reduce buffering and bring more pollutants to the Ramsar wetland, which is already deprived of an outlet to the sea.
- **Average salinity in the Sanctuary's mangrove lake has declined from 8.4 ppt in 2002 to 1.9 ppt in 2010, a 77% reduction that correlates with a 75% sodium reduction.** Brackish water is a defining characteristic of the estuaries where most mangrove ecosystems are found worldwide; their salinity is typically an order of magnitude higher than the lake water results at Graeme Hall.
- **Almost every biotic and abiotic indicator points to a freshwater transformation of the mangrove wetlands.** In the absence of brackish water and tidal fluctuations, nearly all of the flora and fauna that typically live in the intertidal zone on red mangrove roots were missing.
- **Lake tributaries were oxygen-poor and high in nutrients, a combination associated with algae overgrowth and low water quality.** The relationship between runoff and water degradation is likely related to recurring fish kills.
- **Water quality analyzed from the Sanctuary and its surroundings in numerous instances, violate proposed Barbadian standards for the protection of the environment and public health.** Poor water quality reflects the lack of a regular influx of seawater and the inability to discharge excess rainfall runoff to the sea. Pesticides have

been detected in the water column and sediments at the Sanctuary and in high concentrations at locations outside of its boundaries.

- **The low biodiversity of the Sanctuary's benthic community, as indicated by taxa and individuals observed, represents a critically endangered Mangrove Ecosystem.** The invertebrate community was composed exclusively of freshwater instead of saltwater species. Analysis also revealed that some disturbance -- likely a sudden change in water chemistry -- had caused the death of otherwise healthy gastropods.
- **The existence of a high-volume emergency raw sewage discharge system into the Ramsar wetland and the Sanctuary presents an ongoing threat to water quality, the wetland ecosystem, and human health.**
- **The dysfunctional Government-owned sluice gate increases the flooding potential for the Sanctuary and adjacent lands.** Lack of operation also prevents the Sanctuary from alleviating low surface water levels during drought.
- **The lack of a drainage outlet and tidal exchange mechanism encourages freshwater competitors to the red mangroves, substantially increasing the risk of loss of a mangrove forest that has been documented to exist for no less than 1,300 years.**

Not only the business enterprise of Graeme Hall Nature Sanctuary, but the Ramsar Mangrove Ecosystem's survival depends on reversing these harmful trends and preventing future negative impacts.

Introduction

Barbados is a small island of 430 square kilometers with a population of about 280,000, located approximately 160 km east of the Lesser Antilles island chain in the southeastern Caribbean. The Graeme Hall Nature Sanctuary is on the southwestern coast, immediately north of Highway 7 in Worthing, Christ Church. It is located within the Graeme Hall Mangrove Ecosystem, a site protected under the Convention on Wetlands of International Importance (the "Ramsar Convention," Ramsar, Iran, 1971). Barbados ratified the Convention Treaty on April 12, 2006, and designated Graeme Hall on the Ramsar List of Wetlands of International Importance for its migratory bird habitat.

The Sanctuary and the Ramsar site are fully encompassed within a 100-year floodplain. Approximately 14+/- acres in the Sanctuary are surface water and 16+/- acres are wetlands, including shallow ponds and a 12-acre lake. (See Attachment 1 for vicinity map and Attachment 2 for Ramsar site boundary.) The wetland is a Barbados National Heritage Site and one of two Caribbean Coast Marine Productivity Program (CARICOMP) sites established in Barbados to monitor ecosystem changes within the Mangrove Ecosystem and adjoining seagrasses in the St. Lawrence Lagoon.

The Ramsar designation (Attachment 3) describes the Graeme Hall location at 13°04' N, 059°35' W as a "naturally created coastal wetland area with mangrove forests, a seagrass bed, and a shallow near shore coral reef, which includes a 12-acre artificially-created lake that constitutes the largest body of inland water on the island." The designation further notes 84 bird species and more than 20 fresh and brackish water fish species. Radiocarbon dating reported by Ramcharam (2005) indicates that red mangroves have dominated the wetland for at least the past 1,300 years.

On no other location on the island can a mangrove wetland, a seagrass bed, and a shallow nearshore hard coral reef be found in close proximity. The purpose of the Sanctuary is not only to preserve this unique ecosystem, but also to utilize its value for education, scientific research, and ecotourism. Without a healthy ecosystem, ecotourism cannot flourish and the Sanctuary cannot operate under its business mandate.

The Sanctuary in recent years has experienced inflows of untreated stormwater, agricultural, and commercial runoff and emergency raw sewage discharges into the lake system, curtailment of seawater interchange, and frequent fish kills and recent crab kills. Concerns over these conditions prompted the Sanctuary to initiate this study of the environmental health of the Graeme Hall Mangrove System.

Scope of Work

In February 2010, the Sanctuary authorized Environmental Engineering Consultants, Inc. (EEC) of Tampa, Florida, to perform the investigations at Graeme Hall Nature Sanctuary, Inc. Field investigations included sediment sampling for benthic and chemical analysis; surface water sampling for chemical and bacteriological analysis; sampling of fish and crab for chemical and pathogen analysis; surveys of on-site biological indicators; and site reconnaissance for surrounding activities impacting the Sanctuary.

Environmental Engineering Consultants (EEC) has been involved in scientific and engineering studies of water, soil, and air for private and public-sector clients since it was established in 1979. The firm has been recognized in Tampa for its pro bono contribution of groundwater studies at the Sulphur Springs Pool, which traced the source of bacterial contamination to urban stormwater runoff into upstream sinkholes. In 1988 the Greater Tampa Chamber of Commerce named EEC the Small Business of the Year.

EEC's principal investigator on site was Richard Pryor, a professional geologist specializing in water quality investigations of both surface and groundwater. Mr. Pryor has 25 years of experience in geology and environmental consulting, including more than 20 years at EEC. He has performed numerous surface water and groundwater investigations and is knowledgeable about U.S. Environmental Protection Agency (EPA) water quality test methods. His past projects include industrial contamination, stormwater runoff, wastewater effluents, underground tank leaks, and wastewater reuse studies.

Mr. Pryor was accompanied in the field by Mr. Angelo Tulimieri, a consulting environmental scientist with a specialty in wetland systems analysis. Mr. Tulimieri also has experience in wetlands management from a regulatory perspective, having served as an environmental scientist for the Environmental Protection Commission of Hillsborough County. Since 1991, he has delineated tens of thousands of linear feet of wetland lines, which required a comprehensive knowledge of wetland plants, wetland hydrology, and wetland soils. He has written more than 2,000 qualitative wetland monitoring reports for review and approval by local, state, and federal regulatory agencies. He previously served as a naturalist guide for Hillsborough Community College (HCC), teaching students about mangrove ecology and benthic sampling at Upper Tampa Bay Park and at HCC's Environmental Study Centers on Cockroach Bay, located within mangrove swamps on the Tampa Bay estuary.

Robert Wallace, founder of EEC, participated in research at Graeme Hall Nature Sanctuary and contributed to the final report. Mr. Wallace is registered as a professional engineer in Florida, Georgia, Alabama, and Tennessee and has more than 35 years of experience in civil and environmental engineering. His projects include domestic wastewater treatment and disposal, industrial treatment and disposal, stormwater attenuation and treatment design, stormwater runoff studies, wetland mitigation and reuse studies, and water quality studies. Mr. Wallace was elected in 1994 to the Florida House of Representatives representing Hillsborough and Pinellas counties and served until 2002 under constitutional term limits.

Resumes for key personnel are shown at the end of the Attachments.

Site Conditions and Surroundings

Background

Some of the history of the Graeme Hall Swamp as researched by the Sanctuary is included here:

> Graeme Hall Ecosystem has been highly impacted by anthropogenic activities during the last 150 years. A coastal roadway was first built on the sand bar separating the mangrove swamp from the sea in the early 1700s, and the bridge over the main north-south channel, which remains today, was built in 1871. Originally, during this period, the economic needs of the Graeme Hall sugar plantation, on whose lands the swamp lay, further reduced its size and eventually led to the creation of a system of canals on the eastern side of the swamp, known locally as 'vales'. Sugar cane was grown here, as were grasses, which were used to provide forage for mules and oxen used on the plantation.
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> The latter part of the century saw the introduction of gun clubs at Graeme Hall. It was the practice of these shooting swamps to clear-cut the mangroves so that migrating birds would have a clear view of the water trays (shallow ponds) and be enticed to fly down. As part of the Graeme Hall Estate, the freshwater marsh was extensively altered by canalled water flow into a series of freshwater trays to attract water birds for shooting, and high grass banks from which mule fodder was cut and sold. Peat and mangrove poles were also known to have been cut and sold. Sometime later, a second hunting club was established in the western quadrant, and a number of shallow ponds were cleared and maintained to attract water birds. There was also an annual cutting of the surrounding mangrove trees. A sluice gate was installed in the narrow exit channel between the swamp and the sea in the 1930s and was opened only at low tide to control the water level in the shooting pools. Tilapia were introduced to the main lake around this time, and commercial seine harvesting took place. In 1972, the main lake was dredged and the cuttings were used to fill in the western ponds and convert the land to pasture. The extensive annual mangrove cutting in the swamp ceased in the 1970s, and shooting in the swamp has been banned since 1981.
>
> In the western quadrant of the Ecosystem, a shallow, roughly rectangular (150 m X 120 m) brackish lake is surrounded by a dense fringe of red (Rhizophora mangle) and white (Avicennia racemosa) mangroves. A detailed survey shows that the shores of the lake drop rapidly to a depth of 1 m or more, except along the northeastern shore which remains very shallow (<0.5 m) due to the presence of a deep layer of soft mud. The average depth of the lake is 1.32 m and the maximum depth is 2.71 m. Red mangroves dominate much of the lake shoreline, although white mangroves dominate the northeastern shore and are also found in isolated clusters along the southern boundary of the ecosystem. A freshwater marsh is located in the eastern quadrant of the swamp, which contains a large stand of mature white mangroves and a network of man-made drainage canals with lotus and water lilies, water lettuce, and filamentous green algae. The banks of the canals support a dense growth of sedges and strips of grassland.

Private investment in Graeme Hall Nature Sanctuary, Inc. began with acquisition of 34.25 acres of wetlands in 1994, followed by construction of visitor center infrastructure between 1998 and 2004. Further capital improvements to the property occurred between 2006 and 2008. The Sanctuary today has underground utility infrastructures, including sewerage, water, electrical, data/voice communications and security systems; civil works, including foot and vehicular bridges, paved walkways and over-water decks; a car-park area; maintenance and storage buildings; office trailers; and two large constructed aviaries. Other improvements include a water treatment facility for the avian captive breeding program, water storage cisterns, a greywater treatment system to recycle irrigation water, and a site-based stormwater drainage system with improved drainage swales and retention and detention areas. (See Site Plan in Attachment 4A.)

Site Description

The 34.25 acres belonging to the Sanctuary occupy the western portion (42%) of the 81.11-acre Ramsar wetland; the Government of Barbados owns the remainder. A stormwater ditch runs along the Sanctuary's western and southern property boundaries. The north-south Graeme Hall Bisecting Canal, defining the east boundary, drains the entire ecosystem and flows southward.

Northwest of the Sanctuary is Amity Lodge, a residential area with household grey- and blackwater disposal systems discharging to the surficial aquifer that flows to the ecosystem. Small businesses, hotels, restaurants, and some residences line the north and south sides of Highway 7. Stormwater rainfall and contaminated runoff from businesses north of the highway drain to a swale/drainage ditch system that flows eastward through the Sanctuary into the Bisecting Canal.

East of the canal and within the Ramsar site/100-year floodplain is a marsh owned by the Government of Barbados. Mangroves dominate the southwestern portion of the Government property; the northern and eastern areas are spikerush. The spikerush marsh is periodically cut and trenched to allow for more open habitat for fish that control insects and for better drainage to the canal, which is connected to the marsh by ditches and culverts. The South Coast Sewage Treatment Plant, completed in 1997, lies immediately outside the northeast corner of the spikerush marsh and adjacent to the Ramsar site.

The Government of Barbados owns and operates about 160 acres of agricultural lands north of the Mangrove Ecosystem and outside the 100-year floodplain. These lands drain to the spikerush marsh and west into the Bisecting Canal. Groundwater recharge from the fields flows to the ecosystem in the surficial aquifer. In 1988 the Barbadian National Physical Development Plan set aside this agricultural area as a greenbelt buffer around the Mangrove Ecosystem to protect it from urban impacts. (See Attachment 4A for Site Plan with Surface Water Inputs.)

Within the Sanctuary, the lake, canal, and two “trays” (shallow ponds) support an ecosystem consisting of migratory birds, fish, crabs, mangrove, spikerush, trees and shrubs, and numerous other flora and fauna. The 12-acre lake lies in the central area, bordered by a mangrove stand to the north and east. On the west side, two small mangrove islands are heavily roosted by egrets. Springs in the northwest corner of the property supply water to two freshwater ponds that feed the lake by overland flow. West of the lake is a tray -- traditionally referred to as the “brackish tray” -- that receives water pumped from the lake and overflow from the freshwater tray immediately to the south. Water pumped from the springs supplies the freshwater tray. East of the freshwater tray lies the south pond, which connects directly to the southwest and southeast corners of the lake. (See Attachment 4B for the relative locations of these elements of the Sanctuary.)

Below-normal rainfall was recorded in Barbados for December 2009 and January and February 2010. Average annual rainfall in the coastal regions of the island varies from 1100 mm to 1300 mm. (See Attachment 5 for rainfall data.) During the dry period, the spring was the main source of water for the lake and trays. The lake was approximately 0.7 m (2 ft) below normal seasonal high water levels, based upon biological indicators. The brackish tray was virtually void of standing water, the freshwater tray had less than 0.15 m, and the south pond and stormwater ditch each had about 0.3 m (1 ft) of water. The only direct connections to the Bisecting Canal appeared to be the eastern extent of the southern stormwater ditch and the southeastern corner of the lake. During wetter periods, surface water levels rise and the two halves of the ecosystem interconnect as water backs up through the Bisecting Canal and flows through the mangrove stand along the eastern and northern shores of the lake.

Historically, multiple open natural and later manmade channels connected the lake and the Graeme Hall ecosystem with the sea. Over time, the wetland-to-sea channels have been reduced to just one, the Bisecting Canal. Discharge from the canal into the Caribbean Sea is currently blocked downstream by an inoperative sluice gate located immediately inland from the shoreline.

It has been reported that the sluice gate was opened several times a month in the 1980s and 1990s, not only to allow for drainage of stormwater from the ecosystem, but also in periods of high tide to allow seawater to enter the lake. The Government's Drainage Unit managed the sluice gate under the jurisdiction of the Ministry of Public Works. The Drainage Unit since has been reorganized under the Ministry of Environment, Water Resources and Drainage.

The sluice gate -- the main drainage path from the Graeme Hall wetland and Ramsar site -- has not been operational since 2006, when wooden components rotted to the point of failure. (See photos in Attachment 6.) Since 2006, the Government of Barbados has attempted to manage wetland water levels and allow flows within the Bisecting Canal by removing sand with a front-end loader and backhoe. The staff of the Sanctuary reported that the canal was last allowed to drain off water in August 2009, when government staff manually jacked open the sluice gate and excavated a trench through the beach sands to the open water. This was believed to be the only opening of the sluice gate in 2009.

Barbados Stormwater Drainage Study

Cumming Cockburn Limited, et al., under contract to the Government of Barbados, estimated the flood levels of the Graeme Hall ecosystem in the 1996 Barbados Stormwater Drainage Study. According to the study (see Table 2-6 in Attachment 7), a 100-year storm of 24-hour duration would achieve an elevation of 1.60 m, assuming the normal water level of 0.40 m at the outset of the storm with no outflow during the event. Table 2-6 also shows the estimated flood levels from 3-hour and 24-hour storms for recurrence intervals of 2, 5, 10, 20, 50, and 100 years.

The Barbados drainage study recommended a monitoring program to record lake water levels, gate operation, and outflow volumes. To EEC's knowledge, this has not been undertaken; nor have the study's other recommendations been followed. The study recommended flood proofing via a berm raising the perimeter of the ecosystem to elevation 1.6 m (pages 3-24 and 3-25) and extending the concrete-lined outlet of the Graeme Hall Bisecting Canal approximately 40 m beyond the existing channel, to be coupled with water jet pumps for sand removal.

The study noted that "water draining from the swamp typically has a high level of tannins, resulting in discoloration of the sea water near the outlet," and it acknowledged challenges to its recommendations: "Local tourist operations have frequently expressed concerns…about potential water quality impact on adjacent beaches."

Geology and Hydrogeology

Barbados lies approximately 160 km east of the Lesser Antilles volcanic islands on the eastern edge of the Caribbean tectonic plate. The island is relatively flat, with its highest point just over 330 m above sea level near the center. Reef limestones were deposited on Tertiary aged deep marine strata and subsequently uplifted by subduction as the North Atlantic Plate slipped under the Caribbean Plate (Geological Society of London, 2004). The base of exposed Tertiary rocks consists of sandstones, clay, and shale. The upper part of the Tertiary, up to 1.2 km thick, is composed of Eocene to middle Miocene biogenic and volcanogenic beds of the Oceanic series.

The Oceanic series rocks are fine white clays, locally known as chalk. Shallow-water carbonate deposition began in the Pleistocene in the form of coral-reef tracts as the island was uplifted. Successively younger reef terraces have been exposed. The terraced coral cap cover is up to 100 m thick and covers most of the island, except on the far central-eastern part, where Tertiary rocks are exposed. The dominant features of the topography are two terraces described as the First High Cliff, located in the south part of the island, and the older, higher Second High Cliff, near the center of the island (Banner, J., Musgrove, M., & Capo, R.).

Rainfall averages 1100-1300 mm per year. Groundwater flow patterns in the coral cap are controlled by (1) the markedly higher permeability and porosity of the coral cap relative to the underlying Tertiary aquitard, (2) the distribution of rainfall recharge, which is greatest in the central, elevated part of the island, and (3) the topography of the Pleistocene-Tertiary contact (Banner, J., Musgrove, M., & Capo, R.). Groundwater in the area of Graeme Hall is depicted to be a freshwater lens approximately 15 m thick and extending about 6 km inland, overlying saline water that extends 4 km inland. (See Attachment 8 for plan and cross-sectional views of the island.)

The Graeme Hall ecosystem occupies an 81 +/- acre relict sinkhole immediately below the First High Cliff. It is located within the Christ Church Groundwater Catchment Area, one of the largest of 19 groundwater water catchment areas in Barbados (Attachment 9, The National Natural Resources Data Base, Government of Barbados, 1998).

Within the 19 large groundwater catchment areas are smaller surface water catchment areas, based upon surface water runoff and the connection of gullies formed in the limestone. The Graeme Hall ecosystem receives surface water runoff from an estimated 1,156 acres of the Hilbury Watershed (Government of Barbados, Gully Ecosystem Management Study, 2004). After filtering and deposition through the ecosystem, the surface water runoff and groundwater discharges flow into the Graeme Hall Bisecting Canal.

Two freshwater springs are located on the northwest corner of the Sanctuary. At least one spring has been reported in the marsh east of the Bisecting Canal (University of West Indies, 2004). Freshwater irrigation wells are reported to exist on Ministry of Agriculture lands immediately northeast of the Sanctuary. Upland recharge and groundwater flowing through the coral cap supply freshwater to these wells and springs.

Groundwater and coastal water quality throughout Barbados is influenced by urban, commercial, industrial, recreational, and agricultural activities and the coral limestone underlying the island, which is highly permeable (Arriola, 2008).

Barbados' groundwater protection zones (Attachment 10) are designed to protect public water supply sources from bacteriological contamination. The Graeme Hall ecosystem and associated catchment area lie within Zone 5, which currently has no restriction for physical development. Blackwater and graywater are routinely discharged into the limestone through suckwells. Surface water directed to the ecosystem consists of rainwater runoff of varying quality, based upon precipitation rates, land use, and discharge practices. Similarly, groundwater quality of percolated rainwater varies with the pollutant load, precipitation rates, and filtering capacity of the underlying limestone.

Mangrove Quality Assessment

This report addresses the qualities of the mangrove wetland and 12-acre lake (mangrove-lake ecosystem), based on field information collected February 7-14, 2010. Changes within the Graeme Hall Nature Sanctuary are described by Angelo Tulimieri in Attachment 11. More on the dominant flora and fauna, as well as wetland definitions and mechanisms, can be found in the full report. In Attachment 12, the former chief naturalist at the Sanctuary, Ryan Chenery, provides an inventory of birds observed February 8-13, 2010, as well as a historical account of the Sanctuary garnered over a 5-year period.

An ecosystem is the interaction of living (biological) components with nonliving components (i.e., water and sediment quality) within a scaled boundary, as well as an exchange of energy, materials, and organisms across that boundary. This report addresses the biological changes in the Sanctuary's mangrove-lake ecosystem that are related to a freshwater transformation. Indicators of this transformation, such as salinity measurements and benthic community analysis, are derived from other parts of this report.

Historically, water flowed in both directions across the Sanctuary's mangrove-lake ecosystem boundary when the sluice gate was regularly opened to the sea. For at least the last 3.5 years, only freshwater has entered the ecosystem. This water departs via seepage, evaporation, and evapotranspiration. Organic wastes enter the mangrove-lake ecosystem via drainage basin runoff or are generated from within the ecosystem. Some of the organic wastes are converted to nutrients and biomass via biogeochemical cycles; the degree of conversion was not measured in this study. In a normal mangrove wetland, some of the generated biomass and nutrients flow out to sea with tides. Wastes other than organic matter enter the ecosystem boundary; among them are organophosphate pesticides, for which no comparable biogeochemical cycling is readily available and which may be lethal, depending on the concentration.

Normal mangrove wetlands -- synonymous, for purposes of this report, with mangrove forest and mangrove swamp -- provide important functions. They are very effective at converting wastes into minerals and nutrients for biomass production. They provide nursery grounds and breeding sites for various species, including birds, fish, crustaceans, reptiles, and mammals (Alongi, 2002). They provide nutrients to nearshore fisheries, seagrasses, and coral reefs. Mangroves have been shown to act as a vegetative buffer zone between disturbed freshwater sources and coastal water (Lin, 2004).

By definition, mangrove wetlands inhabit brackish water and dominate the area between the highest and lowest tides, i.e., the intertidal zone. One way to classify mangrove wetlands is by their position along a salinity gradient, with salinity decreasing the closer the mangroves get to their freshwater source, such as when they begin to move into rivers from estuaries. An estuary is an embayment where freshwater and saltwater mix, resulting in brackish water with salinities of 5-30 ppt. This is the expected range of salinity for a healthy mangrove ecosystem that supports saltwater flora and fauna. The average salinity in the Sanctuary's mangrove-lake ecosystem was found to be 1.9 ppt, which is considered freshwater. Mangroves survive well in freshwater, yet mangrove forests don't emerge there because of freshwater plant competition.

According to research by Simberloff (1983) and Tomlinson (1986) as reported on the Smithsonian Web site, "One reason mangroves do not develop in strictly freshwater communities is due to space competition from freshwater vascular plants. By growing in saline water, mangroves reduce competitive threat, and thus are able to dominate the areas they grow in."

In 1986, Christopher Parker from the University of West Indies found water salinity in the Bisecting Canal in the range of 29-34 ppt, which indicated a seawater connection. The salinity reading in the canal was 1.3 ppt in February 2010. Salinity results are in the Surface Water Quality section of this report.

The wetland hydroperiod in the Sanctuary's ecosystem resembles that of an isolated freshwater wetland. Normal mangrove wetlands develop in intertidal zones, areas between the highest and lowest daily tides, and or in subtidal zones that are saturated daily with brackish water. It was evident that water levels in the Sanctuary mangrove ecosystem change slowly in the absence of daily tidal fluctuations and that the water levels were well below the level of the historic low tide. A severe drought had been in effect since at least December 2009.

By definition, wetlands are less than 3 m in depth, since this is the maximum depth in which vascular wetland plants such as waterlily can root. Graeme Hall contains the following wetlands within the Sanctuary and the Government-owned land:

- The Sanctuary's mangrove wetland, which is reportedly one of the largest and most significant of its kind in Barbados and which constitutes the major portion of the mangroves within the preserve.

- The two waterlily (*Nymphea*) ponds in the northwest corner of the Sanctuary, just outside the white mangrove portion of the forest. Each is dominated by a different species of waterlily; one pond also supports a significant amount of spikerush (*Eleocharis mutata*), which is in the sedge family (*Cyperacae*).
- The freshwater marsh on Government property, consisting of an almost monoculture of the same spikerush.
- The Bisecting Canal, which was supporting emergent freshwater vascular plant species.

Whereas wetlands are surface waters, not all surface waters are wetlands because not all surface waters support wetland vegetation. Swamps are wetlands dominated by wetland trees; marshes are wetlands dominated by wetland herbs. Classically, three parameters define a wetland: wetland hydroperiod, wetland plants, and wetland soils. Surface waters lack wetland plants and wetland soils.

The surface waters found at Graeme Hall included but were not limited to several ditches inside and outside the Sanctuary boundaries, as well as four open water bodies in the Sanctuary as follows:

- The Sanctuary's 12-acre lake, which is shallow enough to permit the growth of freshwater vascular plants; these were absent, possibly because of the tilapia -- voracious herbivores -- that thrive there.
- The small pond, connected to the south side of the lake at two points.
- The temporal freshwater pond or tray on the west side.

The temporal "brackish" tray, so named before the end of seawater inputs.
Water levels in the surface waters mentioned were below normal when first encountered on February 8, 2010. The stain line on the red mangrove roots around the lake indicated that the water level was as much as 0.6 m below normal. At the same time, water levels in the two "trays" were below ground. These trays have very shallow bottoms that are as much as several feet higher than the lake bottom.

In periods of drought, the Sanctuary pumps freshwater from the springs to assist with hydration. Such pumping occurred during the monitoring event, and subsequently the freshwater tray, but not the higher "brackish" tray, filled with water. Although no overland connection between the pump(s) and the lake was found, the lake water rose by several centimeters without the aid of rainfall. It was also noted at the end of that week that soils were saturated around the white mangrove pneumataphores on the north side of the Sanctuary’s mangrove forest at an intermediate elevation. The pneumataphores would have developed during periods when this area was wetter.

Two small red mangrove islands in the lake have been in constant use by wading birds, primarily egrets. The future of these islands is uncertain, as the lower branches on the red mangroves there were dead, and attempts to replant them were reported to have been less than successful. Mangroves are known for their island building ability, but in the absence of daily tidal fluctuations, the islands’ soils could be subsiding. Their loss would be very detrimental to the wading birds that find protection there from local predators such as mongooses and monkeys. There are also two small mangrove islands in the so-called brackish tray, but their bottom elevations appeared to be perched above the mostly empty bottom of the tray, and there was relatively no wading bird activity there.

The Bisecting Canal inside the eastern edge of the Sanctuary crosses under Highway 7 and stops a few meters short of the sluice gate, bifurcating the Graeme Hall mangrove forest with one part inside the Sanctuary and the other inside Government-owned land. The canal was filled in large part with arrowhead (*Sagittaria*) and waterlily plants.

The following table identifies the major plant species associated with the Graeme Hall wetlands.

Graeme Hall Sanctuary's Most Important Wetland Plant Species

Habit	Scientific Name	Common Name	Wetness Rating	Location
Tree	*Conocarpus erectus*	Buttonwood	FACW	Upper white mangrove forest
Tree	*Ficus citrifolia*	Bearded fig	FAC / FACU	Disturbed edges of Sanctuary mangroves
Tree	*Laguncularia racemosa*	White mangrove	OBL	Sanctuary mangrove forest
Tree	*Rhizophora mangle*	Red mangrove	OBL	Sanctuary mangrove forest
Shrub	*Cordia obliqua*	Clammy cherry	FAC?	Disturbed edges of Sanctuary mangrove
Herb	*Cladium jamaicense*	Sawgrass	OBL	Government marsh
Herb	*Eleocharis mutata*	Spikerush	OBL	Government marsh + north lily pond
Herb	*Nymphea odorata* (exotic)	Waterlily	OBL	North lily pond
Herb	*Nymphea ampla* (native)	Waterlily	OBL	South lily pond

Remarks:
(OBL) Obligate wetland species occur more than 99% of the time in wetlands.
(FACW) Facultative wetland species occur in wetlands 67-99% of the time or in uplands 1-33% of the time.
(FAC) Facultative species occur in wetlands or uplands 34-66% of the time. They tolerate wet and dry conditions.
(FACU) Facultative upland species occur in uplands 66-99% of the time or in wetlands 1-33% of the time.
(UPL) Upland species occur more than 99% of the time in uplands.

The Sanctuary mangroves, verdant and healthy, were found in textbook zonation patterns: red mangroves at the lower, wetter elevations and white mangroves at the higher, drier locations. Red mangroves dominated in terms of area, whereas white mangroves tended to dominate in height, some being upwards of 20 m. The median red mangrove height around the edge of the lake appeared to be about 5-6 m, with some red mangroves appearing to reach about 10 m. Buttonwood (*Conocarpus erecta*) was located in the more elevated parts of the white mangrove forest but provided less than 5% coverage overall. Bearded fig (*Ficus citrifolia*), a tall tree with a wide canopy, was found near white mangroves at comparable or slightly higher elevations in disturbed soils that were dry or moist. Its seedlings were found in some moist soils, which is consistent with their wetness rating as a facultative or transitional species.

On Government land, a red mangrove forest was surrounded and in some places infiltrated by freshwater spikerush, which left scattered patches of red mangroves. The exposed soils in the marsh varied from moist, to saturated, to inundated by what appeared to be shallow water.

Laboratory analysis of the benthic community in the lake found that all of the saltwater macroinvertebrates had been replaced by freshwater species: segmented worms (Annelida), freshwater snails (Mollusca), and freshwater insects (Arthropoda). Analysis also revealed that the benthic community had experienced a disturbance that caused the death of snails or gastropods, attributable to a sudden change in water chemistry.

No intertidal community was encountered on the mangroves within Graeme Hall. In a healthy intertidal mangrove ecosystem, algal collars composed of fungus and chlorophyte filaments grow on the roots in the intertidal zone. Small algal collars were found on only a few red mangrove roots in the Sanctuary and Bisecting Canal. These appeared to be surviving by wicking water.

Several fauna normally associate with these algal collars in a mangrove ecosystem. These include the spotted mangrove tree crab (*Goniopsis cruentata*) and the mangrove periwinkle (*Littorina angulifera*, which were not encountered during the monitoring event and may be considered a missing part of the food chain. Ryan Chenery reported that he had never seen them in the Sanctuary. If daily tidal fluctuations were reestablished, reintroducing these species and their associates would be a method to increase diversity and enhance the food chain. The spotted tree crab, which has been found in Barbados, feeds on fallen mangrove leaves (Raulerson, 2004) and is a favorite in the ibis diet.

Blue land crabs (*Cardisoma guanhumi*) inhabit the upper parts of the mangrove forest in both white and red mangrove zones. A substantial number of blue land crab burrows in the upper part of the white mangrove zone were either abandoned or plugged in order to preserve moisture. An equal or greater number of active burrows were encountered at lower elevations, and their density or number of holes per area appeared to be high. Blue land crabs are most active at night and therefore may not be expected to be observed in daylight, when the Sanctuary was open to perform the monitoring.

Reports by Chenery and others indicate that both blue land crabs and fiddler crabs (*Uca bergersi*) have declined in numbers. A small number of fiddler crabs and their burrows were found. A historical newsletter mentioned that fiddler crabs were once so abundant that they swarmed over the Sanctuary sidewalks. Their reduced numbers may be attributable to a combination of factors, including susceptibility to pesticides. Massive fogging with malathion, an organophosphate associated with toxicity to fish species, has been reported within the Government's wetlands.

Glossy ibis (*Plegadis falcinellus*) was identified in the Sanctuary during this monitoring period. This wading bird is a tactile forager with a long curved beak adapted to probing inside fiddler crab burrows. One study in a Brazilian mangrove forest found that an ibis species there fed mostly on fiddler crabs (*Uca*) taken directly from their burrows (Olmos, et al., 2001).

During the February 2010 sampling, Chenery identified 37 bird species in the Sanctuary, including 16 migratory species (Attachment 12). Chenery also identified two wild mongooses (*Herpestidae*) entering the Sanctuary from the west. Easily spotted almost daily around the Sanctuary parking lot were several green monkeys (*Chlorocebus*), individually and in groups of up to five. In the lake, dozens of tilapia (*Oreochromis mossambicus*) and several Atlantic tarpon *(Megalops atlanticus*) were observed. Several termite nests (*Isoptera*) were found on the west side of the Sanctuary amid white mangroves, both on the ground and in tree crotches.

One freshwater species that may compete with white mangroves if given an opening is clammy cherry (*Cordia obliqua*), which was scattered around the edges. Clammy cherry is a shrub capable of reaching heights of 7-8 meters and providing significant canopy coverage. If gaps were to open in the white mangrove canopy, then clammy cherry could become established there and in time begin to dominate. Already clammy cherries were found to have infiltrated some of the white mangrove part of the forest. This may happen within the red mangrove forest as well.

Currently the interior of the mangrove forest is dense enough to prevent sunlight from reaching the forest floor. Without sunlight, nothing else can grow there, which in part accounts for the lack of plant diversity in mangrove forests. If an opening in the mangrove canopy were to occur through a fire, lightning strike, hurricane, or other event, then sunlight could penetrate and freshwater plants could invade and eventually outcompete the mangroves.

Summary

Reports of fish kills and raw sewage inputs prompted an ecosystem study of the mangrove-lake ecosystem within the Sanctuary. Almost every biotic and abiotic indicator pointed to an advanced state of freshwater wetland transformation for the mangrove forest, which by definition should be an intertidal wetland dominated by salt-tolerant flora and fauna. Although mangroves grow well in freshwater, they have no defense against being outcompeted by freshwater plants in a freshwater environment. Examples of this were found in the Government's adjacent mangrove wetland, where patches of red mangroves were surrounded and in some places infiltrated by freshwater spikerush herbs.

In hydroperiod and water salinity, the Sanctuary mangrove wetland and lake are identical to isolated freshwater wetlands. Freshwater plants found in Sanctuary ponds and in the adjacent Government-owned wetlands were growing in water salinities only 1 ppt lower than the salinity found in the lake. The lake is shallow enough to support the growth of emergent freshwater plants, but the large number of herbivorous tilapia may be preventing this. All of the benthic saltwater macroinvertebrates have been replaced by freshwater species; in time, the same may be expected of the plants as well. Water salinities at all wetland sample stations were below the brackish water salinities required by mangroves to maintain their dominance against freshwater plants in the long term.

This transformation to a freshwater wetland threatens the very survival of a mangrove community that provides all-important habitat for Barbados' wading birds and waterfowl, of which 37 species were identified during the monitoring period, including 16 migratory species. A restoration of regular, if not daily, tidal fluctuations within the Sanctuary mangrove ecosystem would begin to restore its estuarine condition. Without reconnection to the sea, the eventual loss of the Sanctuary's mangrove ecosystem, including its wading bird community, can be expected.

The conversion from a brackish mangrove wetland to a freshwater wetland in which freshwater plants replace mangroves may take a long time; nonetheless, it could be accelerated by a major

perturbation, which may be inevitable. Such a change at Graeme Hall would permanently eliminate the mangrove ecosystem and the wading bird and waterfowl community it supports, hallmarks of this internationally recognized site.

Surface Water Sampling

The sampling plan prepared by EEC for the 2010 event called for performing surface water and sediment sampling for chemical analysis at the same locations presented in the two initial Sanctuary Water Quality Monitoring Reports (2000-2001 and 2002-2003). However, some locations did not have sufficient surface water to sample. (See Attachment 4B for sample locations and Attachment 13 for the correlation of 2010 locations to previous locations and the rationale for choosing alternative locations.)

Richard Pryor performed the sampling in accordance with the Florida Department of Environmental Protection's Standard Operating Procedures for Field Activities, dated March 2008. Field readings were obtained within measured depths of water columns by holding respective probes within the approximate middle of the water column. The following field readings were recorded and instruments used:

- Temperature, using a Hach HQ30d
- pH, using an Oakton pH 6
- Conductivity, using an Oakton Con 6
- Dissolved oxygen, using a Hach HQ30d
- Salinity, using a YSI 63

The Government of Barbados provided containers to EEC for bacteria samples, which were collected first because of the limited 6-hour hold times allowed prior to analyses. Sampling was performed by submerging each container approximately 6 inches below surface and subsequently removing the cap until the container was close to full. Once filled, containers pre-labeled with sample name and analysis had date and time recorded and then were put on ice in a cooler. Samples were collected for:

- Fecal coliform
- Fecal streptococci
- Fecal enterococci

Bacteria samples were delivered within 6 hours of sampling to the Ministry of Agriculture, Government Analytical Services laboratory in St. Michael, Barbados.

Chemical analyses required a laboratory out of the Caribbean region. EEC selected Test America's laboratory in Tampa, which shipped empty sample containers to Barbados in coolers with chain-of-custody seals. EEC performed sampling at each station by submerging each container approximately 6 inches below surface and subsequently removing the cap until the container was close to full. Containers with preservative were not allowed to overfill. Once filled, containers pre-labeled with sample name and analysis had date and time recorded and then were put in a cooler with ice cubes double-bagged in 1-gal plastic bags. For shipping purposes, EEC maintained a chain of custody to the lab. Samples were appropriately iced and coolers were sealed with chain-of-custody seals and all appropriate shipping documentation.

Samples for chemical analyses were shipped on the day of collection to Test America's laboratory in Tampa, using FedEx Priority overnight delivery. Sample coolers all arrived at Test America two days after shipping rather than one day because of customs inspections. Sample temperatures were all within the prescribed 4° C upon receipt, as shown on the laboratory analytical receipt sheets. Laboratory analyses were performed for:

Nutrients and Other Water Quality Parameters	**Metals**
Turbidity	Magnesium
Biological Oxygen Demand (BOD)	Sodium
Tannin	Chloride
Nitrate	Copper
Nitrite	Iron
Ammonia	Lead

Sulfate	Phosphorus
Sulfide	Mercury
Chemical Oxygen Demand (COD)	Potassium
Alkalinity	Sulfur
Carbon Dioxide (CO_2)	Zinc
Chlorophyll A	
Total Suspended Solids (TSS)	
Chlorinated Herbicides (EPA Method 8151)	
Organochlorine Pesticides (EPA Method 8081)	
Organophosphorous Pesticides (EPA Method 8141)	

Surface Water Quality

Lake and South Pond

Water in the lake was very low, based on stain lines observed on bridges and mangroves. The water level was approximately 0.6 meters below seasonally high water levels and about 1.3 m below a flood stage indicator under one of the walking bridges. The connection at the southeast corner of the lake between the south pond and the lake was unsaturated. Water depth in the south pond (S6B) was 0.16 m (0.5 ft) to 0.3 m (1 ft); depths around the edges of the lake -- S3A, S3B, S7A, S7B, and S10 -- averaged 0.5 m (1.5 ft). Temperatures averaged 29.2° C. (Complete laboratory analytical results are shown in Attachment 14. A review of field collected results and analytical data appears in Attachment 15.)

Comparisons of 2002 and 2010 water quality results indicate that these water bodies have changed from brackish to freshwater. Brackish water is defined as a mixture of saltwater, which ranges from 16 to 30 parts per thousand (ppt), and freshwater, which has 5 ppt or less of salts. Brackish water ranges from 6 to 15 ppt (Texas A&M University, 2006). In April 2002, average salinity for the five on-site water quality stations sampled within the lake and south pond was 8.4 ppt; average sodium concentration was 2,426 mg/l. In February 2010, average salinity was found to be reduced by 77% to 1.9 ppt from the six stations sampled within the lake and south pond;

average sodium concentration had diminished by 75% to 598 mg/l. (A review of historic and current data compiled for five sampled wetland and stormwater control areas is shown in Attachment 16.)

Concentrations of the analyzed dissolved metals were relatively low compared with other sampled areas. There were no occurrences of lead, mercury, or copper above laboratory detection limits and relatively low concentrations of iron, potassium, zinc, and magnesium. However, the average zinc concentration of 0.01 mg/l was higher than the recorded 2002 concentration of <0.005 mg/l. Concentrations of copper, lead, and mercury were below the Government's proposed Marine Pollution Control standards, as shown in Attachment 15. Although these standards are only proposed, they are referred to by the Barbados Environmental Protection Department and industry as compliance criteria.

Within the lake, dissolved oxygen values generally ranged from 5.99 to 8.32 mg/l. Sample location 7A in the very southeastern corner of the lake exhibited the lowest concentration, 3.17 mg/l, similar to the average recorded at this location throughout the 2002-2003 sampling period. The reading likely reflects a mixing zone of lake water with water from the Bisecting Canal and areas eastward. Samples from 3A and 7B exhibited supersaturated concentrations of dissolved oxygen -- that is, concentrations greater than the theoretical maximum for the respective temperature at atmospheric pressure. The most likely cause is that aquatic algae and plankton have produced additional oxygen through photosynthesis during daylight hours. During darkness, the reaction is reversed: Oxygen is consumed from the water, and carbon dioxide is released and dissolved as carbonic acid. Both supersaturated and low levels of dissolved oxygen can be toxic to fish.

The average biological oxygen demand (BOD) was a relatively low 4.5 mg/l. The Barbadian Government has proposed that BOD -- a measure of the amount of oxygen used by bacteria to decompose organic substances in 5 days -- not exceed 30 mg/l within a 50:1 mixing zone with discharged domestic waste. The average chemical oxygen demand (COD) was 52 mg/l. COD is a measure of the quantity of oxygen required to oxidize organic matter into carbon dioxide and water. The COD/BOD ratio of approximately 12 indicates that most of the dissolved organic matter is not easily biodegraded. While reviewing monthly data from the 2002-2003 sampling period from station 7B, EEC noted that the BOD peaked in August 2002 to 20.43 mg/l and dissolved oxygen dropped to 2.95 mg/l, coinciding with a prolonged period of hot weather and a spike in rainfall. Similarly, at S7A, BOD rose and dissolved oxygen dropped in the summer months in 2001, when 36 fish were reported killed in July and 3,000 fish killed in September.

Alkalinity averaged 440 mg/l, reflecting the limestone (calcium carbonate) geology of the island; pH averaged 8.23. Alkalinity greater than 400 mg/l is relatively high (EPA, 1988). The alkalinity of ocean water near Barbados has been reported at 120 mg/l (U.S. Department of Energy, 2006). High alkalinity provides good buffering capabilities against pH swings; thus pH values tend to remain above neutral.

Ammonia levels had declined from 0.5 mg/l in 2002-2003 to approximately 0.1 mg/l in 2010; levels in the south pond, 0.11 mg/l, were similar to the average exhibited in 2002-2003. Ammonia toxicity is enhanced by warmer temperatures, pH values over 7 su, low dissolved oxygen, and elevated zinc or copper concentrations. Different species of fish can tolerate different levels of ammonia (Tucker, 1998). While reviewing data for station 7B from the 2002-2003 sampling period, EEC noted that ammonia levels were relatively high in August 2002, pH values were near 8 standard units (su), BOD peaked, dissolved oxygen was relatively low, and temperatures were relatively high. Around the time of the reported 2001 fish kills, temperature peaked in August and September, ammonia levels peaked, dissolved oxygen was low (0.93 mg/l), and pH values were near 8 su at station 7A.

Turbidity levels averaged 5.4 nephelometric turbidity units (NTU), more than three and half times the Barbadian Government's proposed marine water quality standard of 1.5 NTU. Tiny soil particles that wash into a water body from the land often cause turbidity. These particles can contain nutrients that, when combined with water and sunlight, cause explosive growth of algae. The various substances increasing turbidity can also have a high biological oxygen demand. The highest turbidity and BOD results were observed from sample 6B from the south pond.

Nitrogen, sulfur, phosphorus, and carbon dioxide are important nutrients when analyzing the health of a water body. In general, high levels can lead to excessive algae growth and subsequent changes in dissolved oxygen content. Phosphorus levels were higher than Barbados' proposed marine standard of 0.015 mg/l, ranging from 0.11 mg/l to less than 0.1 mg/l. Nitrate concentrations were all less than 0.1 mg/l, similar to the average of the 2002-2003, and nitrite concentrations were all less than 0.1 mg/l. Sulfate concentrations averaged 150 mg/l, and chloride concentrations averaged 1000 mg/l. Carbon dioxide results averaged approximately 50 ug/l.

Fecal coliform averaged 684 colonies/100 ml; fecal streptococcus, 325 colonies/100ml -- results far in excess of the ambient marine surface water standards, which would limit fecal coliform to 200 colonies/100 ml and fecal streptococcus to 35 colonies/100 ml. Bacterial counts were similar in April 2002, also a dry period.

The trophic state classification system is designed to rate individual lakes and ponds based on the amount of biological productivity occurring in the water, as indicated by decreasing clarity and rising concentrations of chlorophyll, phosphorus, and nitrogen. In increasing order of productivity, the classifications are oligotrophic, mesotrophic, eutrophic, and hypereutrophic. Based primarily on chlorophyll-a results in the range of 30 ug/l, the lake exhibited a high level of biological productivity. Therefore, the lake and south pond may be classified as eutrophic.

Tannins and lignins averaged 1.7 mg/l, reflecting decomposition of leaf matter from the surrounding mangroves. There typically are no drinking water or surface water standards for tannins. However, based upon the high level of biological activity and the relatively high coliform concentrations outside prescribed limits, the lake is not suitable for swimming.

In summary, the lake and south pond have decreased in salinity since 2002 to the point of becoming primarily freshwater. Alkalinity is relatively high, which tends to keep pH above neutral. Dissolved oxygen, ammonia, and BOD results within the lake were for the most part good, although they are expected to degrade in summer months, based upon past results. Ammonia toxicity is directly related to elevated pH and temperatures, low dissolved oxygen, and elevated zinc and copper concentrations. The average zinc concentration in the lake and south pond rose from <0.005 mg/l in 2002 to 0.01 mg/l in 2010. Drainage and regular tidal influxes would alleviate the low dissolved oxygen readings expected in summer months, a condition associated with areas east of the Bisecting Canal, as described below.

Bisecting Canal

The Bisecting Canal receives water from the lake, stormwater ditch, and freshwater marsh. Water from the canal either seeps into groundwater or moves into the lake or adjacent mangroves via culverts and openings in the mangroves. Water levels were low, based on stain lines observed on mangroves. Depths averaged 1 ft at the three sample locations, S8A, S11A and S12. Temperature averaged 27.3° C. The northern third of the canal was unsaturated. The sluice gate at the southern end was not operational, and culverts leading from the east were dry. (A review of field collected results and analytical data, as compared with the Barbadian Government's proposed ambient marine standards, is shown in Attachment 15. Average results for the canal, compared with other sampled areas and historic results, are shown in Attachment 16.)

Like the lake, the Bisecting Canal is exhibiting fewer saltwater characteristics and is more appropriately classified as freshwater. Results showed that salinity decreased 67% from 3.98 ppt in 2002-2003 to 1.33 ppt in 2010. The average sodium concentration decreased 66% from 1237 mg/l to 420 mg/l. Sulfate concentrations averaged 117 mg/l; chloride, 690 mg/l. Concentrations of iron, potassium, and magnesium were relatively low, and no occurrences of lead, mercury, or copper above laboratory detection limits were found. The average zinc concentration of 0.018 mg/l was greater than the 2002 average of <0.005 mg/l and marginally above the Barbadian Government's proposed ambient marine standards.

Within the Bisecting Canal, dissolved oxygen values ranged from 0.5 to 5.01 mg/l. Sample location 8A, near the northern extent of the saturated canal, exhibited the lowest concentration. Higher results near the southern end are related to mixing from the lake, which was shown to have higher dissolved oxygen concentrations. Turbidity levels ranged from 3.5 to 45 NTU, with the highest result exhibited at the southern end.

The average biological oxygen demand was less than 2.0 mg/l. The average chemical oxygen demand was 29 mg/l. The COD/ BOD ratio, approximately 15, was similar to that of the lake, indicating that most of the dissolved organic matter is not easily biodegraded.

Nitrate concentrations were all less than 0.1 mg/l, similar to the average of 2002-2003, and nitrite concentrations were all less than 0.1 mg/l. Alkalinity averaged a moderately high 277 mg/l (200-400 mg/l, EPA, 1988), indicating a pH above neutral (readings averaged 7.48) and good buffering capabilities against pH swings. Ammonia levels declined from 0.42 mg/l in 2002-2003 to approximately 0.27 mg/l in 2010. Phosphorus levels were all less than 0.1 mg/l, and carbon dioxide results averaged approximately 112 ug/l. Chlorophyll-a results averaged 17 ug/l. Tannins and lignins averaged 1.1 mg/l. Based upon the chlorophyll-a, phosphorus, and nitrate results, the Bisecting Canal exhibited a high level of biological productivity and can be classified as eutrophic.

Bacteria results in 2010 were lower than in the similarly dry period of April 2002. Fecal coliform averaged 67 colonies/100 ml. The average for fecal streptococcus, 64 colonies/100ml, was marginally above the standard of 35 colonies/100 ml proposed by the Barbadian Government for ambient marine surface water quality.

In summary, the Bisecting Canal is a freshwater body and has decreased in salinity since 2002. Based on chlorophyll levels, the canal may be classified as eutrophic. Average dissolved oxygen results within the canal were moderate, reflecting an average of the east side of the Ramsar site and the lake on the west side. Nutrient and dissolved metal concentrations, with the exception of zinc, and ammonia levels were low in this relatively dry period.

Onsite Stormwater Ditches

Connecting stormwater ditches run north to south near the western boundary of the property. The culminating ditch turns eastward at the southwest property corner and runs along the south property boundary. The ditches collect stormwater from residences and light industrial properties to the west and south, as well as runoff from the Sanctuary itself. The ditch discharges near the southern end of the Bisecting Canal. Water also backs up from the canal into the stormwater ditch system. The southern ditch lies adjacent to a large number of blue land crab burrows and an area of reported crab kills in 2009.

Water levels in the ditches were low, based upon observed floodplains, low flows, and unsaturated sections. Depths averaged 0.23 m (0.75 ft) at the four sample locations, S4B, S4C, S4D, and S4E. Temperature averaged 26.2° C. (A review of field collected results and analytical data is shown in Attachment 11.) Salinity results averaged 1.2 ppt, down 50% from 2.4 ppt in 2002, and reflected mixing from the canal and stormwater inputs. Average sodium concentration decreased 63% from 947 mg/l to 350 mg/l. Sulfate concentrations averaged 82 mg/l, and chloride concentrations averaged 523 mg/l. (A review of current and historical data is shown in Attachment 16.)

Average concentrations of the analyzed dissolved metals were highest in the stormwater ditches and an offsite stormwater swale (S4F) relative to the other areas sampled. Onsite, the results for metals from S4B primarily influenced that ranking. The sample exhibited concentrations of 0.095 mg/l for lead, 0.044 mg/l for copper, and 0.041 mg/l for zinc -- higher than the Barbadian Government's proposed standards of 0.0044 mg/l, 0.0013 mg/l and 0.015 mg/l, respectively, as shown in Attachment 15 -- as well as an iron concentration of 5.1 mg/l. The average zinc concentration (0.041 mg/l) was higher than in 2002 (0.001 mg/l). These results reflect contaminants in stormwater runoff from residential, highway, and commercial uses in the catchment area. Metals in the other ditch locations were within proposed standards.

The average BOD was a relatively low 7.99 mg/l. COD ranged from 41 mg/l to 270 mg/l. The 270 mg/l result was recorded from S4B, along with relatively low BOD; these results indicated a dissolved recalcitrant organic material. Excluding the result from S4B, COD averaged 51 mg/l. The COD/BOD ratio of approximately 6 indicates that, compared with the conditions in the lake and the Bisecting Canal, most of the dissolved organic matter is relatively easily biodegraded. Within the ditches, dissolved oxygen values averaged 1.50 mg/l, indicating a hypoxic condition. Turbidity levels averaged 12 NTU. Nitrate concentrations were all less than 0.1 mg/l, similar to the average of 2002-2003, and nitrite concentrations were all less than 0.1 mg/l. Sulfate concentrations averaged 82 mg/l, and chloride concentrations averaged 523 mg/l, reflecting freshwater conditions.

Alkalinity averaged 538 mg/l, the highest compared with the other areas, and pH averaged 7.49. Average ammonia levels increased from 0.18 mg/l in 2002-2003 to approximately 0.33 mg/l in 2010. Average phosphorus levels were relatively high at 0.3 mg/l, compared with the other sampled areas; the average concentration of phosphate was less than 0.005 mg/l in 2002. Carbon dioxide results were relatively high, averaging approximately 243 ug/l. Chlorophyll-a ranged from 3.2 ug/l to 91.8 ug/l, with the highest results at stations S4C and S4D, where a light green algae was observed (see pictures in Attachment 6). Stations S4B and S4C were the only onsite stations to exhibit sulfide with respective concentrations of 1.3 and 1.1 mg/l. Sulfide is indicative of anaerobic processes, typical in sediment layers, and associated with low oxygen conditions. Hydrogen sulfide is very toxic to fish. Tannins and lignins averaged 3.2 mg/l, also relatively high. Overall the conditions are eutrophic with decaying organics in a relatively low oxygen environment.

Bacteria results were higher in 2010 than in the dry period of April 2002. Fecal coliform averaged 1583 colonies/100 ml, and fecal streptococcus averaged 2275 colonies/100ml, exceeding the proposed standards limiting fecal coliform to 200 colonies/100 ml and fecal streptococcus to 35 colonies/100 ml. The highest onsite results for fecal streptococcus were observed at S4C and S4D.

In summary, the ditches represent a mixing of stormwater inputs and water from the Bisecting Canal. Water levels were exceptionally low with little or no flow. Water quality was eutrophic with low dissolved oxygen, visible algae growth, elevated phosphorus levels, and high bacteria levels. Elevated results for metals were observed at location S4B, where stormwater enters the property from the west, suggesting an offsite commercial source. The average zinc concentration in the ditches rose from 0.001 mg/l in 2002 to 0.041 mg/l in 2010.

Freshwater Ponds

The springs in the northwest corner of the property receive groundwater from upland areas in the southern part of the island. These areas are classified as Zone 5 with no restriction for physical development as it pertains to groundwater quality. Blackwater and graywater are routinely discharged into the upland limestone through residential suckwells on properties within the associated catchment area. Within the Sanctuary, water from the springs is pumped to the freshwater tray and the water treatment tank and discharges into the two adjacent freshwater lily ponds. The ponds also receive overland stormwater flow from adjacent residential neighborhoods and likely the agricultural fields north of the Sanctuary.

Average salinity at S1 in the west pond and S2A in the east pond decreased 50% from 1.2 ppt in 2002-2003 to 0.6 ppt in 2010. Average sodium concentration decreased 61% from 252 mg/l to 98 mg/l. The results suggest that the ponds have been influenced by brackish water in the past, likely from high lake levels, but in 2010 can be classified as freshwater. Temperature averaged 26.0° C. (A review of current and historical data is shown in Attachment 16. A review of field collected results and analytical data is shown in Attachment 15.)

Copper concentrations were relatively high, averaging 0.004 mg/l for the two ponds. The average zinc concentration of 0.029 mg/l was similar to the average observed from all onsite and offsite sample locations with the exception of the lake, which averaged 0.01 mg/l, but represented an increase over the ponds' 2002 concentration of <0.005 mg/l. The copper and zinc averages exceeded the Barbadian government’s proposed marine ambient standards of 0.0013 mg/l and 0.015, respectively. Concentrations of dissolved lead and mercury were less than laboratory detection limits. Potassium and magnesium concentrations were relatively low, reflecting the freshwater condition of the ponds.

The average concentration of iron -- likely a natural component of the limestone -- was higher from the two ponds than from other sampled areas. This result, 1.35 mg/l, taken together with dissolved oxygen averaging a relatively low 1.79 mg/l, suggests that groundwater from the springs was oxygen-poor -- iron dissolves more readily in groundwater with dissolved oxygen levels of less than 1 mg/l. Large influxes of oxygen-poor groundwater have adverse implications for the health of the lake, into which these two ponds feed. The average biological oxygen demand was a relatively low 5.88 mg/l; the average chemical oxygen demand, 30 mg/l. The COD/BOD ratio of approximately 5 indicates that organic matter was more easily degraded in the freshwater ponds than in the lake or the Bisecting Canal.

The eastern pond exhibited a nitrate concentration of 0.33 mg/l, marginally above laboratory detection limits; the western pond exhibited a nitrate concentration of less than 0.1 mg/l. Nitrate concentrations in 2002-2003 were less than 0.02 mg/l. The nitrate result, although relatively low, reflects nutrients within the discharge from upland areas or is a result of natural organic decay. Relatively high phosphorus concentrations, averaging 0.16 mg/l, were exceeded only by those in the stormwater ditches, suggesting influence from offsite sources or mobilization of phosphorus from sediment as a result of hypoxic conditions.

The average ammonia level from the two ponds increased from 0.021 mg/l in 2002-2003 to 0.141 mg/l in 2010. The average alkalinity, 275 mg/l, twice the alkalinity of seawater near Barbados, suggests that groundwater discharging from the springs has a moderately high alkalinity attributable to the carbonate geology of the island.

Phosphorus levels averaged 0.16 mg/l, compared with phosphate levels in 2002 of less than 0.005 mg/l. Chlorophyll-a results ranged from 25.3 ug/l in the east pond to 137 ug/l in the west pond. The high reading reflected the most algae of all onsite and offsite sample locations, indicating potentially high nutrient load and eutrophic conditions. Tannins and lignins averaged a relatively low 0.8 mg/l, reflecting the groundwater source for the ponds. Fecal streptococcus averaged 565 colonies/100ml, approximately 325% higher than results from April 2002. Fecal coliform averaged 460 colonies/100 ml, down approximately 50% from 2002.

In summary, dissolved oxygen was low and iron concentrations were high, likely reflecting the discharge of oxygen-poor groundwater from upland areas. The occurrence of nitrate is attributable to the upland discharge or organic decay. Abundant algae growth is a reflection of relatively high levels of nutrients. Elevated phosphorus concentrations, possibly being mobilized from sediments in the hypoxic conditions, are another indicator of nutrient impacts. The average zinc concentration increased from <0.005 mg/l in 2002 to 0.029 mg/l, above the proposed Barbadian standard, possibly reflecting transport from upland areas.

Eastern Offsite Area

The area east of the Bisecting Canal is characterized by spikerush over approximately 75% of the area, with mangrove adjacent to southern extremities of the canal comprising the remaining 25%. At the time of sampling, northwestern parts of the area were dry. Although flow was negligible, water appeared to emanate from the northeastern corner of the swamp, where the sewage treatment plant was located, and move southward toward the coast and westward toward the Bisecting Canal. An access road to the sewage treatment plant marked the south edge of the area, and Government-owned agricultural fields on top of the First High Cliff lay adjacent to the northern property boundary.

Samples S9A, 13, and 14 were obtained from areas east of the Bisecting Canal. Sample 9A was obtained from the northern extent of saturation, approximately 100 feet east of the canal. Samples 13 and 14 were obtained within a cleared waterway that ran parallel to the access road along the southern edge of the wetland. Water appeared to emanate from the northeastern corner of the wetland, where the sewage treatment plant was located. In 2002-2003, water along the access road was not sampled, but two locations east of the Bisecting Canal were sampled, including water near a spring (location 9).

At the time of the sampling in 2010, the average water depth was 0.25 m (0.8 ft). Temperatures averaged 26.7° C. Average salinity was 0.7 ppt, down 66% from 2002. Average sodium concentration was 177 mg/l, down 74% from 2002. These results indicate more freshwater characteristics. (A review of current and historical data is shown in Attachment 16.)

Analyses for dissolved metals showed moderate concentrations of iron and zinc, low concentrations of potassium and magnesium, and no occurrences of lead, mercury, or copper above laboratory detection limits. The average zinc concentration increased from 0.004 mg/l in 2002 to 0.023 mg/l in 2010 and was marginally above the Barbadian Government's proposed marine standard, as shown in Attachment 15.

Alkalinity averaged a moderately high 290 mg/l with pH of 7.46. Average ammonia level increased marginally from 0.045 mg/l in 2002-2003 to approximately 0.14 mg/l in 2010. Dissolved oxygen concentration was 2.18 mg/l, down 58% from the average in April 2002. Average biological oxygen demand was 1.63 mg/l.

Nitrate concentrations averaged 2.04 mg/l, down approximately 50% from 2002, when a high reading of 10.6 mg/l near the spring raised the average, but highest among the sample areas in 2010. The location nearest the sewage treatment plant yielded the highest nitrate value from sample S13, 5.8 mg/l, and the only result for nitrite above laboratory detection limits during the sampling event, 0.016 mg/l. The proposed marine ambient standard for total nitrogen compounds is 0.1 mg/l. Phosphorus levels were all less than 0.1 mg/l. Carbon dioxide results averaged approximately 140 ug/l. Chlorophyll-a results averaged 36 ug/l. Tannins and lignins averaged a relatively low 0.9 mg/l.

Fecal streptococci results were approximately 100% higher than results from April 2002, averaging 790 colonies/100ml. Fecal coliform averaged 290 colonies/100 ml, down approximately 50%. Ambient marine surface water standards proposed by the Barbadian Government would limit fecal coliform to 200 colonies/100 ml and fecal streptococcus to 35 colonies/100 ml.

In summary, the freshwater marsh east of the Bisecting Canal exhibited the highest concentrations of nitrate, possibly from the sewage treatment plant, and bacteria counts exceeding proposed marine water quality standards. Average dissolved oxygen was 2.18 mg/l, just above the level classified as hypoxic, a low oxygen condition. The condition suggests that the area would have difficulty digesting a heavy organic load such as was reported to have occurred at the sewage treatment plant in 2005. An expected consequence of such an event would be lower dissolved oxygen conditions and further reduced water quality for the Graeme Hall ecosystem. The average zinc concentration increased from 0.004 mg/l in 2002 to 0.023 mg/l in 2010, above the Barbadian Government's proposed marine standard.

Western Offsite Sample 4F

Offsite sample 4F was obtained from a stormwater swale behind a restaurant/bar on Highway 7. The water, directed there by a stormwater gutter, contained debris from the restaurant and mosquito larvae. It was cloudy gray with no visible sheen and had a sewage smell. Water depth was 0.3 m (1.0 ft), temperature was 24.6° C, and salinity was 0.4 ppt. Other areas of the swale were dry. (A review of field collected results and analytical data is shown in Attachment 15.)

The sample from S4F exhibited concentrations of 0.0069 mg/l for lead, 0.018 mg/l for copper, and 0.056 mg/l for zinc. The results were relatively high, compared with other sample locations. The Barbadian Government's proposed marine standards would limit those concentrations to 0.0044 mg/l, 0.0013 mg/l, and 0.015 mg/l, respectively, as shown in Attachment 15. Concentrations of potassium, magnesium, sodium, sulfate and chloride were relatively low, reflecting the low salinity of the sample. Iron concentrations were 1.4 mg/l.

This site yielded the lowest dissolved oxygen result observed during 2010 sampling, 0.2 mg/l, and the highest BOD result, 88 mg/l, indicating a relatively high mass of biodegradable organic matter in the water. Alkalinity, at 160 mg/l, was lower than levels from other sample locations, suggesting a source other than surface water. Nitrate and nitrite concentrations were less than 0.1 mg/l; pH was 7.37. Results for sulfide, at 5.3 mg/l, and ammonia, at 1.1 mg/l, were the highest observed during the sample event.

The elevated ammonia and sulfide levels, together with low nitrate/nitrite, low dissolved oxygen, and the appearance of the water, indicate anaerobic decomposition of organics. The relatively high results for carbon dioxide, 310 ug/l, and chlorophyll-a, 98.9 ug/l, are other indicators of decomposing organic waste in a relatively oxygen-poor surface water. The phosphorus result of 1.3 mg/l was an order of magnitude higher than observed from any other sample location. Potential sources include detergent in the water or additional phosphorus mobility from sediments in anaerobic conditions. The chlorophyll and phosphorus results indicated hypereutrophic conditions.

Bacteria results showed fecal coliform too numerous to count -- no other sample station had higher levels -- with fecal streptococcus at 4500 colonies/100 ml and enterococcus at 1600 colonies/100 ml.

In summary, the appearance and smell of the sample suggest the swale behind the restaurant/bar contained wastewater, possibly old wash water, as opposed to stormwater. The water exhibited hypereutrophic qualities with high concentrations of lead, copper, and zinc, high bacteria counts, low oxygen, and byproducts of anaerobic decomposition, ammonia and sulfide, that are very toxic to fish.

Freshwater Tray Sample 5A

Results were similar to the pond results with a few exceptions. The iron concentration, 8.5 mg/l, was the highest recorded during the sampling event -- approximately four times higher than that observed from the ponds. Copper (0.012 mg/l) and lead (0.0099 mg/l) concentrations also were relatively high. Dissolved oxygen of 15.55 mg/l indicated supersaturated oxygen conditions attributable to the mechanical pumping from the spring in the northwest corner of the property or to photosynthesis of algae in the very small amount of water that occupied the northwestern corner of the tray. However, the location exhibited average chlorophyll-a results of 22 ug/l.

Surface Water Trends

Notwithstanding the difficulty of comparing one sampling event in 2010 to multiple sampling events in 2002-2003, EEC looked at average concentrations for locations within the Sanctuary that were identical over the two sampling periods. All 13 common locations exhibited a clear trend of reduced temperatures -- attributable to the February sampling time -- and downward concentrations of salinity, fecal coliform, fecal streptococcus, and biological oxygen demand. Reduced rainfall at the time of the 2010 sample event would account for lower levels of bacteria, which is carried with organic debris in runoff. Salinity has been discussed as a result of the inoperative sluice gate. Trends over the 7-year interval were mixed for pH, dissolved oxygen, nitrate, phosphorus, and total suspended solids.

Pesticides in Surface Water

The Barbadian Government's proposed marine standards call for undetectable concentrations of pesticides, based upon best available technology. Several onsite and offsite locations showed concentrations indicating that agricultural runoff from upland areas has impacted the ecosystem. Samples 1 and 2A, obtained from the two spring-fed ponds in the northwest corner of the property, exhibited dieldrin at 0.0027 ug/l and 0.035 ug/l, respectively. The sample from the freshwater tray, which receives water pumped from the freshwater ponds, also exhibited dieldrin at 0.0034 ug/l. Samples 13 and 14, collected on the Government side of the ecosystem, showed respective dieldrin concentrations of 0.016 ug/l and 0.0028 ug/l. Offsite sample S4F behind the restaurant/bar exhibited 0.25 ug/l of the organophosphorous pesticide malathion, a typical residual from spraying for mosquitoes.

Sediment Sampling for Chemical Analysis

Protocol: After surface water sampling, sediment samples were collected at 12 of the 20 locations by dropping a stainless steel Petite Ponar Grab vertically onto the sediment. Pulling up the sampler would close the clamshell device and collect a sample. Samples were emptied onto clean plastic trays, homogenized using a stainless steel spoon, and then spooned into the respective sample containers. Once filled, containers pre-labeled with sample name and analysis had date and time recorded and then were put in a cooler with ice cubes double-bagged in 1 gal plastic bags. Samples were shipped the same day using FedEx Priority overnight delivery.

Sample temperatures were all within the prescribed 4° C upon receipt at the laboratory. Laboratory analyses were performed for:

- Cadmium
- Chromium
- Copper
- Iron
- Lead
- Manganese
- Mercury
- Zinc
- Arsenic
- Aluminum
- Boron
- Barium
- Calcium
- Cobalt
- Magnesium
- Phosphorus
- Sodium
- Strontium
- Sulfur
- Titanium
- Vanadium
- pH
- Nitrate
- Nitrite
- Sulfate
- Sulfide
- Total Organic Carbon (TOC)
- Orthophosphate
- Ammonia
- Organochlorine Pesticides (EPA Method 8081)
- Chlorinated Herbicides (EPA Method 8151)
- Organophosphorous Pesticides (EPA Method 8141)

Sediment Quality

Lake and South Pond

Compared with 2002 results, average sodium concentration declined 88% from 9540 mg/kg to 1170 mg/kg, and magnesium dropped 92% from 16,600 mg/kg to 1,300 mg/kg. Concentrations of zinc, which was found in fish tissue, averaged 7.3 mg/kg. Metals concentrations in general dropped approximately 75% and were lower than in other sampled areas. The change to freshwater from a lack of seawater is the most plausible explanation for the reduction of metals in sediment.

The northeast corner of the lake yielded the highest result for orthophosphate onsite or offsite, 3.9 mg/l. The location is closest to the Government of Barbados' agricultural site, suggesting influence from agricultural runoff. Orthophosphate is a soluble form of phosphorus that occurs naturally but is commonly found in fertilizers and other manmade products. Within the lake, ammonia levels were also highest in the northeast corner at S10, possibly associated with the cattle egret nesting area in the adjacent mangrove area. Ammonia is a natural byproduct of decomposition in anaerobic sediments. Fecal bacteria results in this area of the lake were also high.

Bisecting Canal

Average sodium concentration in canal sediments declined 82% from 4160 mg/kg to 750 mg/kg, reflecting movement toward freshwater conditions in overlying surface water. The sample from the south end of the canal exhibited relatively high results for arsenic at 0.72 mg/kg and for mercury at 0.024 mg/kg, results, coinciding with elevated metals concentrations in the stormwater ditches. Metals concentrations otherwise dropped 50% or more in the canal, compared with 2002 results.

Onsite Stormwater Ditches

With the exception of offsite sample 4F, the stormwater ditches exhibited the highest average result for arsenic, a relatively toxic substance, at 0.87 mg/kg and the highest concentration of zinc, 51 mg/kg. The average result for mercury, 0.023 mg/kg, also was relatively high. In general, the ditches exhibited the second-highest concentration of metals, after the freshwater ponds. Compared with 2002, results for magnesium, manganese, lead, strontium, titanium, and vanadium decreased by approximately half. Samples in 2010 were taken from 4B and 4E because 4A, the location farther north where the 2002 sediment sample was obtained, was dry.

Freshwater Ponds

The increased result for mercury, 0.023 mg/kg, was higher than at other sample locations and suggested a source related to human activity. The ponds also exhibited the highest concentrations for barium, cadmium, cobalt, iron, manganese, strontium (with the exception of the offsite sample 13), titanium, and vanadium. Relatively high concentrations of metals may be associated with the presence of iron, which is more mobile in anaerobic groundwater. Average zinc concentration of 8.2 mg/kg was similar to that of the lake. Metals concentrations in general (excluding mercury and titanium) dropped 50-75% in comparison with 2002 results. Average sodium concentration declined 77% from 2,605 mg/kg to 595 mg/kg, reflecting increasing freshwater conditions in overlying surface water.

Station 1A in the west pond exhibited the highest result for ammonia, onsite or offsite, at 65 mg/kg. The result reflects degradation of nitrogen compounds within anaerobic sediments and the low-to-moderate dissolved oxygen content in surface water. The presence of the relatively soluble compound orthophosphate -- the second-highest such result at 3.5 mg/l -- suggests potential impacts from fertilizer or other manmade compounds.

Eastern Offsite Area

The sample from the south end of the canal exhibited the highest result for strontium, 3100 mg/kg, and relatively high results for titanium, 43 mg/kg. as well as averages of 6.4 mg/kg for vanadium, 0.023 mg/kg for mercury, and 2,500 mg/kg for iron. As in the freshwater ponds, metals may be binding with iron. The average zinc concentration of 21 mg/kg was second-highest among the sample areas. No comparisons were made to 2002 results, as samples were obtained in widely different locations.

Western Offsite Sample 4F

The sample from a commercial site north of Highway 7 exhibited the highest concentrations of arsenic, chromium, copper, and zinc and a relatively high concentration (3.1 mg/kg) of orthophosphate, suggesting the presence of fertilizer waste or other manmade products. In general, metals concentrations in sediments were reduced from the 2001 and 2002 samplings. The loss of seawater, which has trace levels of all metals and minerals, could explain this reduction. Increases in some select metals could be due to stormwater runoff impacts. The sample also exhibited the highest concentration of sulfide, indicating strong anaerobic degradation. Hydrogen sulfide is very toxic to fish.

Pesticides in Sediment

The pattern of surface water and sediment results suggests that pesticides have entered the Sanctuary from offsite areas. (Attachment 15 lists the sediment chemical analysis results by location. Attachment 17 discusses historical pesticide use.) Sediment at sample station 4B exhibited 0.19 ug/kg dieldrin. Further downstream within the stormwater ditch at 4E, dieldrin was exhibited at 0.42 ug/kg and 4.4 DDE at 0.51 ug/kg. Concentrations of dieldrin at 0.29 ug/kg and chlordane at 14 ug/kg were found in the south pond at location 6B. Offsite concentrations of dieldrin were present west of the Sanctuary at 4F (1.4 ug/kg) and east of the Sanctuary in the freshwater marsh at sample location S13 (1.0 ug/kg). Chlordane was present at 4F in a concentration of 85 ug/kg, as was heptachlor epoxide at 0.17 ug/kg.

Sampling for Benthic Analysis

The benthic community is a useful indicator of the health of a key element of an ecosystem. At 10 locations within the Sanctuary and the Bisecting Canal, sampling for benthic analysis was performed similar to the sediment sampling for chemical analysis, using a Petite Ponar sampler. Samples were emptied into clean plastic trays. A portion was put into a sample container, and the rest was sieved with a 45 micron sieve. The sieve material was used to half-fill as many sample containers as necessary, and the containers were filled with formalin (3.7% formaldehyde). Once filled, containers were labeled with sample name, date, and time and then put in a cooler for shipping purposes. Because of the preservative, no icing was required. Angelo Tulimieri hand-carried the samples, which were shipped by American Airlines passenger baggage service.

Benthic Community

Dr. Bruce Barber of Terra Environmental Services, Inc. in St. Petersburg, Florida, prepared the benthic sample analysis in conjunction with Dr. Gregg Brooks of Eckerd College Sediment Laboratory. They analyzed the samples for species richness, abundance, Shannon Diversity

Index, sediment grain size, carbonate percentage, and organic percentage. The complete report is in Attachment 18.

From the 10 samples taken throughout the Graeme Hall ecosystem, 777 benthic macroinvertebrates representing 17 taxa were identified. All were exclusively freshwater. (See Attachment 4B for locations of benthic samples.) Of the 17 taxa identified, 8 were Annelids, 4 were Molluscs and 5 were Arthropods. The greatest biodiversity was in Sample B4 in the north end of the “brackish" tray. The lowest biodiversity was in Sample B9 in the southeast corner of the lake at the interconnect with the Bisecting Canal. Samples B6 and B10, in close proximity on the lake, were the most similar in taxonomy. Samples B1 and B3 were similar, as calculated on the Bray-Curtis Similarity Index. B3 is in the stormwater ditch nearest the entry to the Sanctuary, and B1 is at the discharge point of the emergency raw sewage line from the sewage treatment plant. Apparently, similar benthic communities adapt to these conditions. The small grain size of the samples overall is indicative of poor circulation and sediment from land drainage.

According to the report, “There is evidence of sudden disturbance to the freshwater community of the Graeme Hall Nature Preserve. Eight of the ten samples examined for this project contained numerous dead gastropod shells (mostly *Melanoides tuberculatus* and *Hydrobiidae* spp.) that appeared to be in otherwise good condition. This might be the result of low dissolved oxygen levels occurring at night and exacerbated by the high organic content of sediments and high water temperature.”

The fish and crab kills that have been reported could be attributable to one or more such disturbances. The raw sewage discharge of 2005, which entered the ecosystem from the east, could explain this finding. It is worthy of note that the two sample sites without dead gastropod shells, B3 and B4, were the westernmost, farthest from the sewage treatment plan. The one with the highest biodiversity, B4, was farthest from stormwater impacts from all ditches and culverts draining to the lake. The lack of dead gastropods in the stormwater ditch at B3 tends to relieve stormwater as the sole cause of the "sudden disturbance."

All locations indicate an ecosystem low in biodiversity. A red mangrove community in Florida had benthos of more than 300 taxa and densities of 22,591 to 52,914 individuals. The Graeme Hall results, by contrast, reported 17 taxa and densities from 304 to 10,609 individuals. If the connection to the seawater were restored, it is likely the biodiversity of the lake and canal would increase.

Tilapia and Crab Sampling

The Sanctuary's biological reports record a historical tendency toward fish kills following periods of heavy rains and high temperatures, including one affecting 3,000 fish in September 2001. Fish kills also were reported anecdotally in association with a massive untreated wastewater release into the Graeme Hall wetland in July 2005. Other reports of fish kills from 2005 to 2009 are documented in Attachment 19. The crab kills started in 2009.

Tilapia and blue land crabs were sampled from the lake and shoreline -- some iced and shipped whole, others dissected and placed in a 10% formalin solution and shipped by Federal Express overnight delivery. The fish samples were taken near location S6B; the crab samples, between S4C and S4D.

Denise Petty, DVM, at the University of Florida's College of Veterinary Medicine and Fisheries and Aquatic Sciences in Gainesville, Florida, performed an array of tests as follows:

- necropsy with parasitic exam and bacterial culture
- bacterial identification
- histology
- virology
- copper
- lead
- zinc
- mercury

- organochlorine analysis

Tilapia and Crab Analysis Results

Seven dead tilapia were shipped to the University of Florida for analysis, all appearing to be in good body condition. No parasites were observed on any external tissue. A few small granulomas were observed in the liver, spleen, and kidneys of all fish; all other organs appeared to be within normal limits. Bacterial cultures were negative for growth. No viral particles were observed by electron microscopy. Low numbers of metacercariae (encysted nematode larvae) were found in the liver, spleen, and kidneys of all fish.

Tissues were analyzed for lead, mercury, zinc, copper, and toxic organic compounds. The concentration of 91.8 ppm of zinc in the gills of the tilapia was higher than anticipated. Dr. Petty referred to a paper by Hilmy reporting that elevated water temperatures can make tilapia more susceptible to zinc toxicity.

The full report is in Attachment 20. Dr. Petty suggested that the fish be sampled again during the hotter summer months to determine whether higher water temperatures were affecting the fish due to zinc toxicity. Addressing the finding of trematode larvae in some organs of the tilapia, the report included a copy of a paper by Keiser and Utzinger on human health concerns associated with eating improperly cooked tilapia.

The two blue land crabs were observed to have no significant pathogens, lesions, or remarkable features. Bacterial cultures revealed an environmental organism (Halomonas sp.) on one crab; the other crab showed no growth.

The Sanctuary's monthly biologist reports from 2000-2001 provide data to support a correlation between rainfall and fish kills. In Attachment 19, a table records heavy rainfall followed by a time lag and then a fish kill after temperatures increased. Two graphs in Attachment 21 show rainfall vs. time and temperature vs. time. The data indicate that the recorded fish kills were all between July and October, when rainfall and temperature are highest. These data show the fish kills correlate with rainfall and temperature.

This pattern is consistent with a phenomenon much reported in scientific literature: a low dissolved oxygen (DO) fish kill. Inadequate DO in aquatic environments is a well-established cause of fish morbidity and mortality (Choi, 2007). It is attributed to stormwater runoff carrying large amounts of sediments, organic debris, nutrients, and other chemicals that increase the oxygen demand of the water column. This, coupled with an increase in temperature, reduces the water's ability to hold oxygen; DO and temperature have an inverse relationship. Oxygen depletion in the water kills fish.

This is the most likely explanation of fish kills in the Graeme Hall Mangrove Ecosystem. Other possible explanations include algal blooms, zinc toxicity with elevated water temperatures, ammonia toxicity, or a combination of chemical or biological influences. A major fish kill in a fish farming area in the Philippines in 2002 was the consequence of a DO sag followed by a bloom of dinoflagellate Prorocentrum (San Diego-McGlone, 2008). It has also been demonstrated that Nile tilapia exposed to acute hypoxia (low DO) have a weakened immune system and become more susceptible to disease (Choi, 2007).

Sources of Surface Water Impacts

A total catchment area of approximately 1156 acres (468.2 ha) flows into the Graeme Hall Mangrove Ecosystem. Starting from an elevation of 100-110 m at Upton and Kent, water flows toward the shoreline through swales, ditches, and culverts to larger and larger drainage conveyance systems. Storm events carry runoff from residential, commercial, and agricultural activities, as well as schools and highways. Each type of land use produces different pollutant loads.

Two large ditches enter the Sanctuary from the west, conveying a significant stormwater load. Stormwater ditches at the north end of the Graeme Hall Bisecting Canal convey runoff from the agricultural lands and beyond. The eastern flow to the Sanctuary comes through the spikerush marsh, fed into the Bisecting Canal by ditches and culverts. The main lake is the ultimate reservoir of the flow. (See Attachment 4C for aerial photographs of The Graeme Hall Catchment Area.)

Historical records and studies of surface runoff for the island of Barbados are “very limited, with little reliable data available” (Arriola, 2008). Because Barbados is similar in its geological and hydrogeological characteristics to Florida, EEC researched published literature from Florida stormwater runoff studies. The Florida Department of Environmental Protection has accumulated data on typical pollutants and nutrients and runoff rates expected from various types of land use -- namely, agriculture row crops and pasture, residential, low-intensity commercial, and forested lands. These stormwater pollutant concentrations can be utilized to estimate the impact of stormwater events on biochemical oxygen demand, total suspended solids, nutrients, and heavy metals carried off the generating site and discharged to Graeme Hall Sanctuary.

The continual dosing of urban and agricultural runoff into a system that cannot itself discharge regularly to the sea ultimately leads to a concentrating effect of pollutants in the water column and sediments of the lake, pond, and canal system. Attachment 22 provides an estimate of the accumulated pollutants on an annual basis. Based on the average annual rainfall of 1266 mm (49.9 in), the catchment area is estimated to produce annual runoff containing 4468 lb of total nitrogen, 727 lb of total phosphorus, 15,830 lb of biochemical oxygen demand (BOD), 100,344 lb of total suspended solids, 34 lb of copper, 9 lb of lead and 137 lb of zinc.

Historically, seawater did enter the ecosystem by way of the sluice gate that controls the hydraulic connection between the mangrove ecosystem and the coastal near shore. Since the early 2000s, the gate has been opened only infrequently, and in 2006 it fell into permanent disrepair, stuck in the closed position. Since 2004, appeals to the Government to get the gate repaired and operational have failed despite the Sanctuary's written offers of technical and financial assistance.

It should be noted that the Government-owned spikerush marsh receives runoff from surrounding urban lands, residences, and commercial properties north and east of the marsh. Near the northern end of the Bisecting Canal are other drainage paths from agricultural lands owned by the Barbadian Government.

North and west of the Graeme Hall Sanctuary, residential subdivisions discharge street and surface runoff into the ecosystem. West of the lake, two large drainage ditches and a smaller stormwater swale drain urban lands, road systems, commercial properties, and undeveloped land to the west. On the south side, commercial entities along the highway back up to the Graeme Hall Nature Sanctuary and discharge stormwater. In one case, poor water quality in a stormwater ditch behind a restaurant indicated a wastewater discharge along the southern perimeter of the Sanctuary. Each of these sources in its own way discharges pollutants that accumulate in the Graeme Hall Nature Sanctuary.

From west, south, north and east, stormwater runoff conveyances bring significant loads of organic debris, nutrients, bacteria, chemicals, and suspended solids into the Sanctuary. The present operational scenario does not allow these to be discharged out to sea in any manner.

At 8 of 20 sample points in the Graeme Hall lake and pond system, fecal bacteria concentrations exceeded the proposed water quality standards for Barbados' marine protection (Appendix F: Marine Pollution Act, Proposed Discharge Standards, 2004), which would limit fecal coliform to 200 col/100 ml. These results dictate that no swimming or human contact with the water is advisable. A study conducted along the West Coast of Barbados in the mid-1990s showed that 80% of the beaches sampled should have been posted “closed for swimming” for exceeding national bacteriological beach bathing water quality standards (Arriola, 2008).

For primary contact recreation, the United Nations Environment Program (UNEP) recommends fecal coliform counts of less than 100 col/100 ml for 50% of the samples collected. The World Health Organization (WHO) guidelines are less stringent, recommending that 90% of the samples show less than 1000 col/100 ml. The Blue Flag Organization, an international nongovernmental organization, uses a fecal bacteria count of 100 col/100 ml as an international bathing standard. Barbados unsuccessfully sought Blue Flag certification for Worthing Beach in the early 2000s.

In other testing by EEC in February 2010, sample results were abnormally high compared with the proposed Barbadian water quality standards for fecal streptococci, enterococci, nitrate, total phosphorus, total suspended solids, chlorophyll-a, and turbidity. The results were abnormally low compared with the water quality standards for salinity and dissolved oxygen. The following table, also contained in Attachment 23, compares the on-site results and the Barbados standard.

Graeme Hall Water Quality vs. Marine Water Quality Standards

Parameter (unit)	2010 Graeme Hall Result (avg)	Barbados Proposed Marine Standard	Parameter Notes	Human Health Consideration
Enterococci (cols/100 ml)	842	35	Indication of waste from animals	Disease
Nitrate (mg/l)	0.15	0.0098	NO_3 oxide of nitrogen nutrient/fertilizer	Drinking water less than 10 ppm
Total phosphorus (mg/l)	0.4	0.015	Nutrient/fertilizer	Drinking water
Total suspended solids (mg/l)	39	5	Amount of material suspended in water column: sewage 200+/-	Drinking water less than 5 ppm
Chlorophyll-a (ug/l)	33	0.0005	Indicator of eutrophication	N/A
Turbidity (NTU)	12.3	1.5	Clarity of water	N/A
Zinc (ug/l)	0.029	0.015	Trace metal bioaccumulation	Drinking water standard
Salinity (ppt)	1.4	n/a	Brackish 6-15 ppt Seawater 30-35 ppt	N/A
Dissolved oxygen (mg/l)	4.6	90% sat. (7.01 mg/l at 27.7°C, 3000 uS)	Greater than 5 mg/l for fish recommended	N/A

South Coast Sewage Treatment Plant and the Emergency Discharge Structure

The South Coast Sewage Treatment Plant, located east of the Graeme Hall ecosystem, was constructed to provide preliminary treatment of wastewater prior to repumping to an ocean outfall. This is simply a screening system -- the least intensive among three levels of sewage treatment: primary, which utilizes sedimentation; secondary, which reduces biochemical oxygen demand and total suspended solids; and tertiary, which removes nutrients. The treatment plant was designed within an emergency bypass line directed into the Graeme Hall Bisecting Canal. Two 8-inch lines constructed in 2003 release raw sewage into the canal when the treatment plant has an emergency situation. (See the location of the discharge pipes on the Site Plan Attachment 4A.)

The Barbados Storm Water Drainage Study (excerpts, Attachment 7) reported how an emergency sewage discharge would occur with the sluice gate controlling the overflow. "If an emergency overflow were to occur the discharge to the sea could be controlled and monitored in order to minimize environmental impacts. . . . Some cleanup of the channel banks may be required to remove plastics, rags and other objectionable floating debris." The design of the emergency discharge structure depended on the sluice gate to be fully operational to allow the discharge of raw sewage out to sea. With the sluice gate closed, the pipes allow raw sewage to flow freely into the main lake of the Sanctuary.

It was reported in 2005 that a raw sewage spill from the treatment plant discharged anywhere from 3 million to 6 million gallons of raw sewage via overland flow that made its way across the Government-owned spikerush marsh and ultimately into the lake. That discharge brought organic waste, nutrients, and pathogens, as well as chemicals, cleaners, oil and grease, and all the other components of urban sewage. Benthic sampling in February 2010 indicated that some "sudden disturbance" had killed the gastropods in 8 of 10 locations, a finding consistent with the impact of just such an event.

Other discharges, either by overland flow or by emergency discharge pipe, have not been logged for public review, such that the total quantity of raw sewage discharged into Graeme Hall Sanctuary cannot be quantified at this time. The discharge of untreated raw sewage has human health implications -- diseases such as hepatitis, typhoid, cholera, and salmonella, to name a few. Any pathogens discharged into the ecosystem without being recovered or disinfected in some manner present a disease threat to persons who come in contact with the water.

Public health protocols typically require that disinfectants be used to minimize the impact of pathogens from a raw sewage spill. A typical response to such an emergency would require containment and retrieval of the waste to put it back into the treatment system. None of these measures appears to have been implemented during the raw sewage spill that flowed to the Graeme Hall Nature Sanctuary in 2005. Rather, the Government seems to have used the wetland itself as the containment area.

The Barbados Storm Water Drainage Study confirmed this de facto Government policy to allow dumping of sewage into the wetland ecosystem. Upon inquiry, the Barbadian Environmental Protection Department advised that there was no formal protocol for dealing with sewage spills and that each occurrence would be dealt with on an individual basis. As designed and built, the emergency sewage discharge lines have no automatic controls to open the downstream sluice gate when the emergency raw sewage discharge is activated. In fact, the discharge structure appears to have been abandoned.

The discharge of raw sewage into the spikerush wetland, as happened in 2005 with no remediation, can only exacerbate the accumulation of pollutants in the Graeme Hall lake system. Any future emergency discharge of raw sewage in the canal -- an inevitability, given the potential for mechanical failure at the sewage treatment plant -- will further degrade the water quality and sediment at the Sanctuary.

Future Considerations: Managing the Sanctuary’s Health

Municipal point sources and urban runoff are the two leading sources of water quality impairments to estuaries, according to the most recent U.S. National Water Quality Inventory reports (EPA, 2000). Of 15,676 square miles of estuaries that this inventory determined to be impaired, 5,045 square miles (32%) were polluted by urban runoff, and 2,811 square miles (18%) were impaired by agricultural runoff (EPA, 2000). Urban development is one of the major contributors to mangrove destruction (Alongi, 2002).

Consequently, Graeme Hall Nature Sanctuary faces a potentially greater problem from stormwater runoff than from agricultural runoff. EEC estimated nutrient loadings on the Sanctuary based on existing and proposed land uses within the entire stormwater catchment area. Increased nitrogen, phosphorus, metals, biological oxygen demand, and total suspended solids are the expected result as Government land use changes and the 2003 National Physical Development Plan diminish environmental buffers. (See Attachment 22A for the future estimated increases.)

Agricultural lands owned by the Government of Barbados have been redesignated to allow residential and commercial development, with resulting stormwater runoff and contaminants, right up to the edge of the Ramsar site and the Sanctuary. Approximately 160 upgradient agricultural acres adjoin the Ramsar site. Compounding the issue, the Sanctuary's main lake is on the receiving end of the 1156-acre catchment area. Further groundwater impacts can be expected if blackwater and greywater suckwells are constructed upgradient of the Sanctuary.

Additionally, the benefits of a recharge area and vegetation buffer stand to be lost as residential and commercial uses proliferate right up to the ecosystem boundary.

Given the stresses from manmade impacts that have impeded its original purpose of promoting preservation, tourism, and education, the Sanctuary found it necessary to close its doors to the public in March 2009. Recognizing that the health of the Mangrove Ecosystem is paramount to the preservation of the resource as a vital habitat for waterfowl and for future generations of Barbadians, the Sanctuary acknowledges its position:

- The Sanctuary cannot control the agricultural runoff that flows to it from lands owned by the Government of Barbados. There is insufficient land in the Sanctuary to attempt to pretreat the runoff before it enters the Sanctuary.

- The Sanctuary cannot regulate or enforce clean stormwater runoff standards or prosecute wastewater violations by commercial entities that border it on the south.

- The Sanctuary cannot control the influx of stormwater runoff and groundwater discharges driven by force of gravity from the suburban residential development to the north. Water quality issues from blackwater and greywater systems contribute contaminants to the shallow aquifer, affecting the onsite springs.

- The Sanctuary cannot restrict or treat the inflow from the large ditches on the western boundary, which bring contaminants of all sorts from the highway, pastureland, institutional, and residential runoff in the catchment area.

- The Sanctuary cannot restrict the flow of raw sewage from the emergency overflow lines designed by the Government-owned Water Authority to use the Mangrove Ecosystem as a dumping ground when the inevitable mechanical failure of the South Coast Sewage Treatment Plant occurs. The Sanctuary cannot protect itself from the human pathogens present in this sewage.

- The Sanctuary cannot control the regular and consistent operation of the Government-owned sluice gate to help restore natural salinity to the Mangrove Ecosystem. The long-term deprivation of this salinity is having devastating consequences for the future health of this ecosystem.

- The Sanctuary cannot restore the natural flushing that historically cleansed the lake, ponds, wetlands, and canal. The Government's failure to maintain the sluice gate is imposing a burden on the Sanctuary not imposed on any other catchment area on the island, namely, the prohibition of discharge from natural rainfall events. This runoff discharge during critical storm events is vital to maintaining water quality within the Sanctuary.

Any of these by itself is enough to warrant concern. Taken in aggregate, they constitute a harmful Government policy that will continue to degrade the natural Mangrove Ecosystem. This is the same mangrove system that Barbados recognizes as a National Heritage Site, worthy to be placed on an International Registry of Important Wetlands -- a resource of paramount importance not only to the waterfowl its habitat sustains, but to generations of Barbadians.

Conclusions

- **Urban and agricultural runoff are concentrating pollutants in the water column and sediments of the Sanctuary's lake, pond, and canal system.** The catchment area of 1,156 acres (468.2 ha) delivers tons of organic matter, nutrients, oils and greases, trace metals, and chemicals in annual stormwater runoff. Septic waste from suckwells permeates upland limestone and coral rock. A swale behind a business on Highway 7 contained wastewater exhibiting high levels of ammonia and sulfide, which are very toxic to fish, and fecal coliform bacteria too numerous to count. All of these pollutants drain toward the Sanctuary without the discharge to the sea that is typical of other catchment areas. Some can be processed and assimilated in the natural cycles of a healthy mangrove forest; others, such as heavy metals and pesticides, accumulate in the system.
- **Average salinity in the Sanctuary's mangrove lake has declined from 8.4 ppt in 2002 to 1.9 ppt in 2010, a 77% reduction that correlates with a 75% sodium reduction.** Brackish water is a defining characteristic of the estuaries where most mangrove ecosystems are found worldwide; their salinity is typically an order of magnitude higher than the lake water results at Graeme Hall. Salinity in the Bisecting Canal, reported at 29-34 ppt in 1986, was 1.33 ppt in 2010.

- **Almost every biotic and abiotic indicator points to a freshwater transformation of the mangrove wetlands.** In the absence of brackish water, nearly all of the flora and fauna that typically live in the intertidal zone on red mangrove roots were missing. Benthic analysis indicated the invertebrate community consisted exclusively of freshwater rather than saltwater species. Analysis also revealed that some disturbance -- likely a sudden change in water chemistry -- had caused the death of otherwise healthy gastropods in all but two sample sites: those farthest from the sewage treatment plant.
- **Lake tributaries were oxygen-poor and high in nutrients, a combination associated with algae overgrowth, low water quality, and fish kills.** Poor circulation in the absence of tidal flushing contributes to low dissolved oxygen in the ponds, ditches, canal and marsh. Heavy nutrient loads from stormwater runoff stress the ecosystem's ability to metabolize nutrients and support aquatic life. High chlorophyll-a and phosphorus readings correspond to ratings of eutrophic to hypereutrophic on the Trophic State Classification Index, indicative of high-nutrient water bodies with algae growth. The relationship between high quantities of stormwater runoff and water degradation is likely a factor in recurring fish kills.
- **Water quality analyzed from the Sanctuary and its surroundings in numerous instances, violate proposed Barbadian standards for the protection of the environment and public health.** Some surface water samples fell below desired levels for salinity and dissolved oxygen and exceeded the limits for fecal coliform, fecal streptococci, fecal enterococci, nitrate, total phosphorus, total suspended solids, chlorophyll-a, and turbidity. Poor water quality reflects the lack of a regular influx of seawater and the inability to discharge excess runoff to the sea.
- **Fish analysis revealed trematode larvae and elevated levels of zinc in tilapia.** Zinc, which some water samples exhibited in amounts exceeding the proposed standard, can be toxic to fish, especially in oxygen-poor water during periods of high temperature. Trematode larvae identified in fish organs can lead to human health concerns from eating improperly cooked fish.
- **Pesticides were detected in the water column and sediments at the Sanctuary and found in high concentrations offsite.** Samples from the freshwater marsh and the

spring-fed freshwater ponds exhibited dieldrin, chlordane 4,4 DDE, and heptachlor epoxide, pesticides that persist in the environment and tend to bioaccumulate. Together with the orthophosphate found in sediments, they indicate an impact on the Sanctuary from agricultural runoff.

- **The dysfunctional Government-owned sluice gate increases the flooding potential for the Sanctuary and adjacent lands; it also precludes a remedy for low surface water levels during drought.** The Barbados Drainage Study in 1996 indicated that a 100-year rainfall event of 24 hours would flood the wetland to at least 1.6 m. Cumming Cockburn, et al., advised in that report that a perimeter berm be installed around the ecosystem to this elevation to prevent flooding of adjacent residences and businesses. No such precaution has been undertaken.
- **The existence of a high-volume emergency raw sewage discharge line into the Ramsar wetland and the Sanctuary presents an ongoing threat to water quality, the wetland ecosystem, and human health.** The disrepair of the sluice gate makes it likely that any emergency bypass of the South Coast Sewage Treatment Plant will bring raw sewage and low-oxygen water to the Sanctuary, further degrading water quality and stressing aquatic life.
- **Land use changes north and east of the Graeme Hall ecosystem will bring more pollutants and reduce greenbelt buffering.** Zoning of 160 acres of Government-owned agricultural lands will allow residential and commercial development right up to the ecosystem boundary. This will funnel more pollutants into an ecosystem already deprived of an outlet to the sea.
- **The low biodiversity of the Sanctuary's benthic community, as indicated by taxa and individuals observed, represents a critically endangered mangrove ecosystem.** Seventeen taxa were identified in densities from 304 to 10,609 per square meter; by comparison, a healthy red mangrove community in Florida had 300 taxa and densities from 22,591 to 52,914 per square meter. Benthic biodiversity was highest in sites farthest from stormwater runoff inputs and would likely increase if connectivity to the ocean were reestablished. The Sanctuary staff has also noted the decline of fiddler crab and blue land crab populations, yet another indicator of an ailing ecosystem.

- **A red mangrove forest that has existed for no less than 1,300 years is at substantial risk of being lost unless its connection to seawater and tides is restored.** Salt-tolerant mangroves lose their competitive edge in a freshwater environment**.** Any openings in their canopy that would allow sunlight to reach the forest floor -- especially the sudden impact of a fire, hurricane, lightning, or disease -- could permit their displacement by an invasion of freshwater plants. Many freshwater species already are present, indicating an increased risk for failure of the Graeme Hall Mangrove Ecosystem.

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