ASSESSING THE IMPACT OF GROUNDWATER POLLUTION FROM MARINE CAVES ON NEARSHORE SEAGRASS BEDS IN BERMUDA

A Thesis

by

JENIPHER ROSE CATE

Submitted to the Office of Graduate Studies of
Texas A&M University
in partial fulfillment of the requirements for the degree of

MASTER OF SCIENCE

August 2009

Major Subject: Wildlife and Fisheries Sciences

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Approved by:

Chair of Committee,	Thomas M. Iliffe
Committee Members,	Stephen E. Davis, III
	Ernest Estes
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ABSTRACT

Assessing the Impact of Groundwater Pollution from Marine Caves on Nearshore Seagrass Beds in Bermuda. (August 2009)

Jenipher Rose Cate, B.S., Texas A&M University at Galveston

Chair of Advisory Committee: Dr. Thomas M. Iliffe

This investigation characterized karstic and nearshore environments of Bermuda to describe 1) behavior and periodicity of cave springs; 2) submarine spring water quality; and 3) nearshore marine seagrass density. Caves can be conduits for groundwater pollution where terrestrial anthropogenic processes leach nutrient enriched water into marine caves springs that flow directly into coastal waters. Seagrass may serve as an environmental indicator due to its susceptibility to anthropogenic pollution.

In 2007, environmental water monitoring devices were moored at the entrance of coastal cave springs throughout Bermuda to retrieve data on water quality, flow volume, velocity and direction. Nutrients (nitrate, phosphate, nitrite, and ammonium) and fecal bacteria (*Enterococcus* spp. and *Escherichia coli*) were measured in each cave. To qualify a link between terrestrial pollution and the nearshore environment, seagrass density within 100 m from cave entrances were measured.

Bermuda caves were tidally influenced. Caves in Harrington Sound showed a delayed tidal flux with smaller ranges due to the restricted tidal inlet. Four caves exhibited a 1:1 in:out flow ratio. Caves with an imbalance flow ratio could be influenced by additional entrances, connection to an alternate water body, or cave geometry. Cave water was similar between caves. Environmental parameters and nutrients changed together, excluding seasonal variations in temperature (17.89 to 22.94 ˚C). Higher nutrients and fecal coliforms within caves indicated sewage may be leaching into the subsurface ground water system.

Three seagrass species were evenly distributed within patchy meadows. Densities ranged from 0.91 to 4.5 (on a Braun-Blanket Scale). Higher mean densities in Harrington Sound, suggested the enclosed, protected nature of the sound allowed for reduced wave and current action. *Syringodium filiforme* decreased in density towards the ocean signifying a direct influence of cave water on seagrass beds. Tidal in and out-flux allowed for a constantly changing environment suitable for a mixture of seagrass species. Higher dissolved inorganic nutrient concentrations were associated with locations lacking seagrass.

This study found 1) cave springs connected groundwater and nearshore seagrass ecosystems; and 2) components associated with terrestrial sewage pollution (DIN, $HPO_4^{=}$, and *Enterococcus* spp.) were higher within caves than nearshore waters.

DEDICATION

Granny Cate and Granny Fischer

ACKNOWLEDGEMENTS

I want to thank all those individuals who gave of their time to help with this research project. First, thank you Dr. Iliffe for the opportunity to research and dive in Bermuda caves. Also, this project would not have been possible without the support and help of the people in Bermuda. I would also like to thank Dr. Davis and Dr. Estes for their help in the writing and editing process.

This project was supported by the Bermuda Conservation Services and The Bermuda Biodiversity Project. A special thanks to Dr. A. Glasspool, Dr. S. Manuel, Dr. K. Coates, Dr. T. Murdoch, and J. Ward.

My research would not have been possible without the help of G. Nolan, a local Bermuda Cave Diver. His help and knowledge of the area was a great asset to the project. He gave many long hours of personal time be a dive member of the research team, proof that he is a strong advocate for the protection of these caves, and has his heart in the right place. You are a great friend and a great dive buddy. I am also very thankful to the other local cave divers for their help, especially L. Kemp. Thank you for donating your time.

This project was made possible by the diligent help of K. Janusaitis and M. Hammond. Thank you for keeping my spirits up, and being of great assistance. P.T. Leung helped in methodology and analysis of flow volume. This part of the project would not have been possible without you. Additional support was given by Dr. A. Armitage in the seagrass analysis, and Patricia Edwards for statistical help.

Without the gracious support of the funding agencies, this project would not have been possible: NOAA- International Coral Reef Conservation, Texas A&M University, and Bermuda Zoological Society/ Bermuda Aquarium Museum and Zoo.

Last but not least, a special thanks to my family for keeping me motivated.

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CHAPTER I

INTRODUCTION

Purpose

The principal objective of this research was to characterize groundwater from karstic tidal springs and its potential effect on nearshore seagrass beds in Bermuda. Caves can be conduits for groundwater pollution where nutrient enriched water from marine caves flows directly to bays and inshore waters. Anthropogenic substances such as cesspit seepage and rain water runoff of surface contaminants (especially fertilizers and oil) add nitrogen and phosphorus to the environment (von Bodungen 1982). Seagrass serves as an environmental indicator because of its susceptibility to anthropogenic pollution (Bricker et al. 2003). A change in seagrass density and species distribution near cave springs, as compared to offshore beds, could indicate a problem due to nutrient loading.

This study measured water flow from tidal cave springs, assessed nutrient concentrations, and examined potential impacts on seagrass ecosystems. Nutrients, such as nitrate (NO_3^-), nitrite (NO_2^-), ammonia (NH_4^+), and phosphate ($HPO_4^=$), are indicators of sewage pollution. Seagrass density within 100 m from spring outflows was compared to surface development and nutrient input. Nutrient load and examination of seagrass health will help to better understand how pollutants from land are transmitted through caves and groundwater to impact the marine environment.

Background

Bermuda is 1030 km east of Cape Hatteras, North Carolina at 32° N latitude and 64° W longitude (Fig. 1). It is one of the most densely populated countries in the world with more than 66,000 persons inhabiting a land area of 53.3 km^2 (CIA World Factbook 2008).

This thesis follows the style of Marine Ecology Progress Series.

The island has a high concentration of caves, most situated inland, that extend below sea level into deep, clear anchialine pools. Some caves are tidal springs with entrances along the coastline, at or under sea level, and exhibit a reversal of flow depending on the tides.

Fig. 1. Photograph of Bermuda. Caves in this study are located around the northwest to northeast borders of Harrington Sound. (NASA World Wind v. 1.4).

Bermuda caves are extreme environments necessitating specialized adaptations for organism to survive, such as reduced eyes and enlarged antennae. There are 78 stygobitic (aquatic cave-adapted) species in Bermuda (Iliffe 2008). Since many of these species are limited to a single cave, pollution or destruction of caves could result in species' extinctions. In Bermuda, 25 endemic, cave-limited species are classified as critically endangered on the IUCN Red List (IUCN 2007). Thus, caves are important biological habitats but are vulnerable due to their limited geographical distribution.

Water movement through coastal caves is directly related to tidal fluctuations. Bermuda tides are semi-diurnal, with two high and two low tides per day. Cave currents are caused by tidally induced imbalances in the water level between the ocean and nearly enclosed bodies of water such as Harrington Sound. The imbalance of water creates a pressure gradient where water either flows into caves (siphon) or out of them (spring) (Exley 1977). Seagrass beds in close proximity to cave entrances are therefore exposed to cave outflows for at least 12 hours per day.

Due to the natural beauty of the island and its high standard of living, Bermuda attracts an estimated 360,000 tourist to the island annually (CIA World Factbook 2008). Bermuda's population rose from 37,000 in 1950 to 66,163 in 2007 (CIA World Factbook 2008). Open spaces are diminishing in order to accommodate tourists and residents. The need for more housing and related infrastructure leads to the possibility of building over or into a cave (Fig. 2).

Bermuda Geology

There are two primary theories regarding the formation of Bermuda. Reynolds and Aumento (1974) believed Bermuda was created approximately 110 million years ago as a mid-ocean volcanic seamount in the Mid-Atlantic Ridge. The seamount would have migrated to its present position via global plate migration. Then, a second phase of eruptions, occurring 33 million years ago, created the bulk of the Bermuda Platform (Reynolds & Aumento 1974). However, a more recent and now widely accepted theory by Vogt & Jung (2006) put Bermuda's origin at 30+ million years ago.

They believed that the driving force behind the volcanic activity came from the closing of the Tethys Ocean caused by plate movements. This weakened the interior of the tectonic plates, allowing magma to rise along fractures, creating the Bermuda Rise (the raised mound supporting the seamount).

The top of the volcanic pedestal was eroded to its present depth of 75 m below sea level by wave action, allowing coral settlement and creating the only atoll in the North Atlantic (Aumento & Gunn 1975). Periodic deposition of marine carbonates, especially by corals and calcareous algae, formed the limestone making up the cap of the Bermuda pedestal (Knox 1940, Gees & Lyall 1969, Aumento & Gunn 1975, Thomas 2004). Eolian limestone (e.g. wind blown sand lithified into rock) was deposited during glaciations starting in the early Pleistocene as the platform was transgressed and submerged (Hearty & Kindler 1995, Vacher et al. 1995). The majority of Bermuda caves are in the Walsingham Formation, the oldest carbonate rock in Bermuda, whose topography has been heavily modified by karst solution. Caves in this rock are characterized by interconnecting, semi horizontal chambers containing extensive speleothems (Harmon et al. 1978). The high porosity of Bermuda's caprock permits rainwater to flow rapidly into the ground leaving no permanent standing water. Even the marshes and ponds at sea level are brackish, except after periods of heavy rainfall (Wingate 1965).

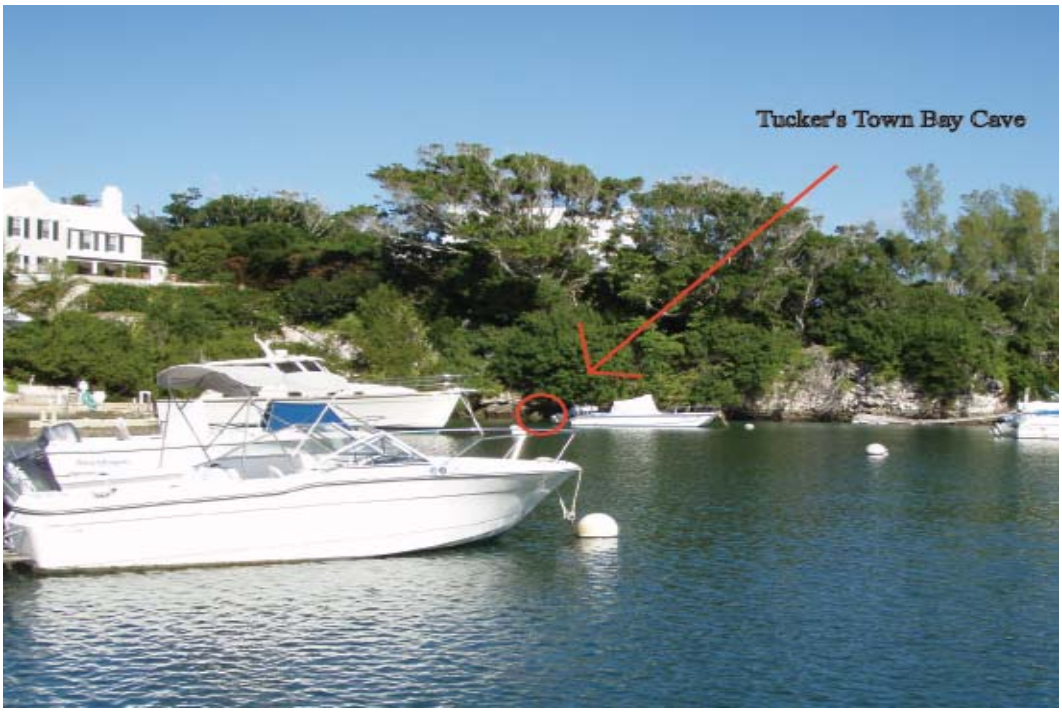


Fig. 2. Human impacts in cave areas. Water flows out of Tucker's Town Bay Cave from the direction of the white house located to the left. There was an alternate entrance to the cave 10 m inland that opens up near the back porch of this house.

Speleology

Anchialine caves are inland coastal caves found in karstic limestone or volcanic rock, fully or partially underwater (see example in Fig. 3) (Iliffe & Bishop 2007). They contain tidally influenced marine water with relatively long water residence times of months to years (Iliffe & Bishop 2007). Anchialine systems generally have well stratified water masses divided by a chemo or thermocline. In contrast, marine caves, are on the coastline, or fully submerged under the sea floor (Iliffe & Bishop 2007). They exhibit freely moving water, exchanging with the sea on each tidal cycle. Typically, marine caves (Fig. 4) exhibit strong tidal currents creating a habitat for filter feeding organisms such as sponges, hydroids, anemones, tunicates, and some corals which attach to the cave walls (Iliffe & Bishop 2007). In Bermuda, coastal caves are marine at the entrance and gradually transform into anchialine as the system extends farther into the island, whereas those located inland are wholly anchialine.

Bermuda caves formed during periods of glaciation when the exposed seamount allowed groundwater to collect and dissolve the limestone (Garrett & Scoffin 1977, Mylroie & Carew 1995). This is evident from the speleothems (secondary cave mineral deposits such as stalactites and stalagmites) present in submerged passages (Fig. 3). Speleothems are only created in air by the precipitation of carbonates from water droplets over hundreds to thousands of years, so their presence in Bermuda's now submerged caves indicates they must have been dry for long periods of time when sea level was lower.

Fig. 3. Speleothems. Water stratification is indicated by horizontal staining in the anchialine Green Bay Cave System (photo provided by Tamara Thomsen).

Fig. 4. Typical passageway in the Red Bay Cave system. Note diver's guideline on the left side of the photo. Filter feeding organisms, such as the yellow and orange sponges shown here, are characteristic inhabitants of marine caves (photo provided by Tamara Thomsen).

Surface water in Bermuda's cave pools results from percolation of rainwater though the soil and bedrock, and from direct surface runoff. This fresh, or brackish, water layer is separated by a halocline from the underlying saline water of the caves. The thickness of the fresh water lens is dependent on meteorological and geomorphological events such as storms, rainfall, and the porosity of the limestone (Sket & Iliffe 1980, Mylroie & Carew 1995). Caves are lightless environments, lacking photosynthetic oxygen producers, and thus have low dissolved oxygen (DO) levels. Usually surface DO levels are near saturation (8.6 mg O_2 l^{-1} H_2O), but decrease with water depth, and exhibit a dramatic drop below a halocline to 3.75 mg O_2 l^{-1} H_2O (Iliffe 2000). DO solubility is also dependent upon temperature where, cave water temperatures in Bermuda increase with a subsequent decrease in DO below the halocline. This is possibly a result of the seamount's geothermal gradient (Iliffe 2000). Cave water pH is circumneutral, ranging from 6.7 to 8.0.

Bermuda caves are highly interconnected by submerged passageways, at 18-20 m depths, that serve as conduits for tidal currents (Iliffe 2000). Pollutants introduced into one cave can be transmitted through cave water to adjacent caves. Due to the relatively long residence of anchialine cave water, pollutants introduced into these systems can accumulate and are slow to be purged (Iliffe 2000).

Tidal Currents

Bermuda caves contain tidally influenced pools. Tidal currents carry organic matter from the outside waters to the cave interior. Coastal caves exhibit reversing currents generated by the hydrological imbalance between tides in the open sea and enclosed bodies of water, such as Harrington Sound, where tides are out of phase with those in the open ocean by an average delay of two hours and forty-five minutes (Iliffe 2000). Submerged caves surrounding Harrington Sound serve as hydrological conduits that respond to the imbalance of water levels on opposite sides of a land mass. As a result, rising tides along North Shore and Castle Harbour create a higher pressure gradient than the island's ground water table causing water to flow into those coastal caves (Iliffe 2000). However, a rising tide in Harrington Sound will cause the cave water to flow out of the cave entrances located along its margins. This is due to the increased pressure from the inflow of water into cave entrances along the North Shore and Castle Harbour (Iliffe 2000).

Significant currents around the Bermuda Platform and inshore basins are induced by the twice daily ebb and flood tidal flow. These semi-diurnal tides have a phase of 6.21 hours and tidal range approximately 0.75 m (Wunsch 1972). Submerged cave entrances freely exchange marine water with the sea on each tidal cycle. Extensive networks of submerged cave passages serve as tidal conduits for groundwater flow connecting Harrington Sound and the surrounding inshore waters. The tidal differential between partially enclosed bays and the open ocean maintains water circulation in those cave passages closer to the entrance, culminating in karstic coastal springs.

Cave Biology

Bermuda caves are inhabited by a highly diverse spectrum of unusual and rare marine invertebrates. These include ancient relict organisms originating from the Tethys Sea (Hart et al. 1983), which are legitimately referred to as “living fossils” (Sket & Iliffe 1980). These endemic organisms are highly adapted to the extreme conditions, surviving in lightless, almost hypoxic conditions, with limited food (Sket & Iliffe 1980). Stygobites (aquatic cave adapted organisms) have reduced features such as the loss of functional eyes and skin pigments (see example in Fig. 5). They exhibit long antennae to search for food and predators, reduced metabolic rates, smaller bodies than their open water relatives, longer life spans, and fewer eggs with increased amounts of yolk per egg (Gilbert et al. 1994). In an attempt to adapt to their surroundings, stygobites have evolved from their open sea relatives with more efficient anatomical and metabolic adaptations requiring less energy to maintain, such as the loss of eyes (Gilbert et al. 1994). Considering the extreme environment in which these organisms live, they are more susceptible to human-induced changes and have a very low resilience (Hancock 2006). To date, 78 stygobitic species, including 64 crustaceans, 5 mites, 2 ciliates, 2 gastropod mollusk, and 2 worms, have been reported in Bermuda caves (Iliffe 2008).

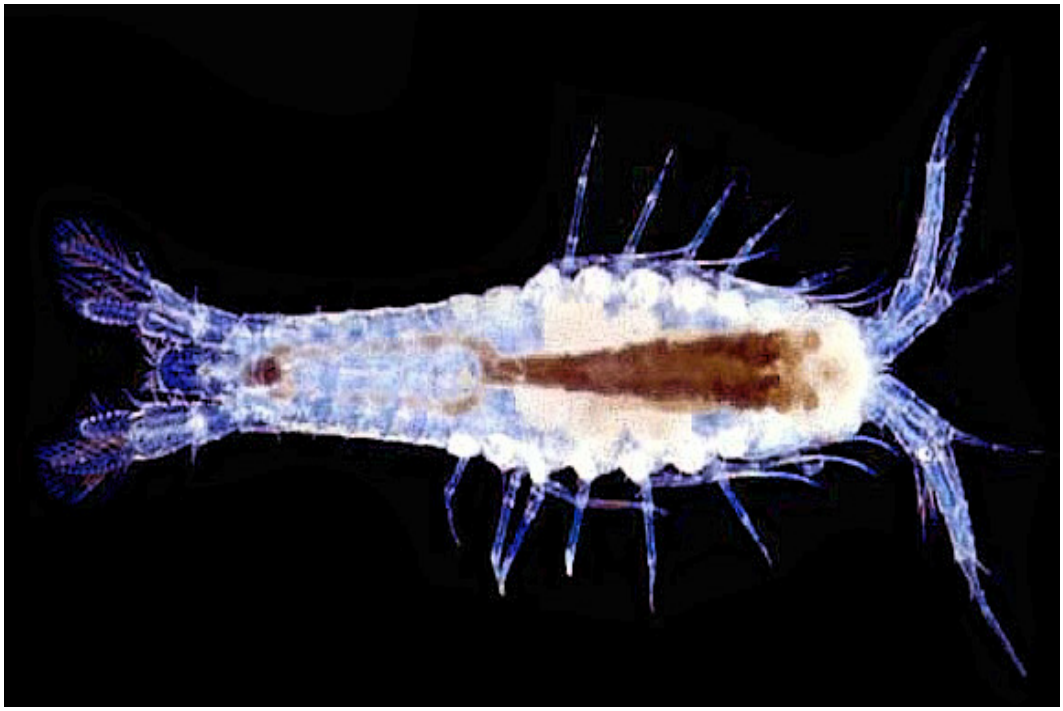


Fig. 5. *Mictocarus halope*. This is an endangered cave-adapted stygobitic crustacean found in Bermuda (IUCN Red List 2008) (photo from www.cavebiology.com).

Seagrass

Like many near-shore ecosystems, seagrass plays an important role in Bermuda's marine environment by providing habitat, breeding, and feeding grounds for crustaceans, worms, fish, and the endangered green sea turtle, *Chelonia mydas.* In addition, seagrass roots hold sediment, preventing erosion, while seagrass leaves trap suspended particles. Seagrass leaves regulate the nutrient load in an ecosystem by filtering and retaining suspended particulate carbon, nitrogen, and phosphorus from the water (Murdoch et al. 2007). Unfortunately, both natural (e.g. storms and hurricanes) and anthropogenic (e.g. boat moorings, dredging, development, and dumping) threats to seagrasses have led to a reduction in seagrass cover along Bermuda's North Shore in recent years (Anderson et al. 2001. Murdoch 2007). Coastal tidal springs discharging nutrient-rich groundwater onto adjacent seagrass beds may promote the growth of harmful algae and phytoplankton, blocking light from seagrass and coral reef ecosystems. The four main

species of seagrass in Bermuda are *Thalassia testudinum*, *Syringodium filiforme*, *Halodule wrightii* and *Halophila decipiens*.

Introduction to Threats

Despite the absence of heavy industry, dense human habitation on Bermuda (~1,300 persons/km^2) poses ongoing pressure from land-based anthropogenic contamination (Ward 2006). Specific threats include sewage pollution, fertilizer run-off, litter, construction, and quarrying. Point sources of pollutants include cesspits and injection boreholes, Due to the lack of a central septic system, domestic waste is deposited in unlined shallow cesspits dug into the bedrock (Fig. 6). In theory, the limestone bedrock acts as a filter and sieves out sewage, with water slowly passing through the rock, allowing for natural decay and absorption of materials (Simmons & Lyons 1994). However in practice, nutrients, particularly nitrates, and other dissolved organics are transmitted to the groundwater. Wastewater injection boreholes (12 to 42 m in depth) are another method of sewage disposal used by hotels and resorts (Anderson et al. 2001). These are similar to cesspits except they are used in areas with a high population density and are dug deeper into the ground. Bermuda's injection boreholes are referred to as leaching fields because injected wastewater leaches out through the surrounding bedrock (Anderson et al. 2001). Both methods do not take into account the increasing population creating more waste, or the presence of any cracks, fissures and caves channelizing and allowing direct flow of sewage into the ground. Porous limestone permits sewage seepage into cave passages such that when a cesspit is dug in the vicinity of tidally influenced springs, pollution can be transmitted to nearshore seagrass beds.

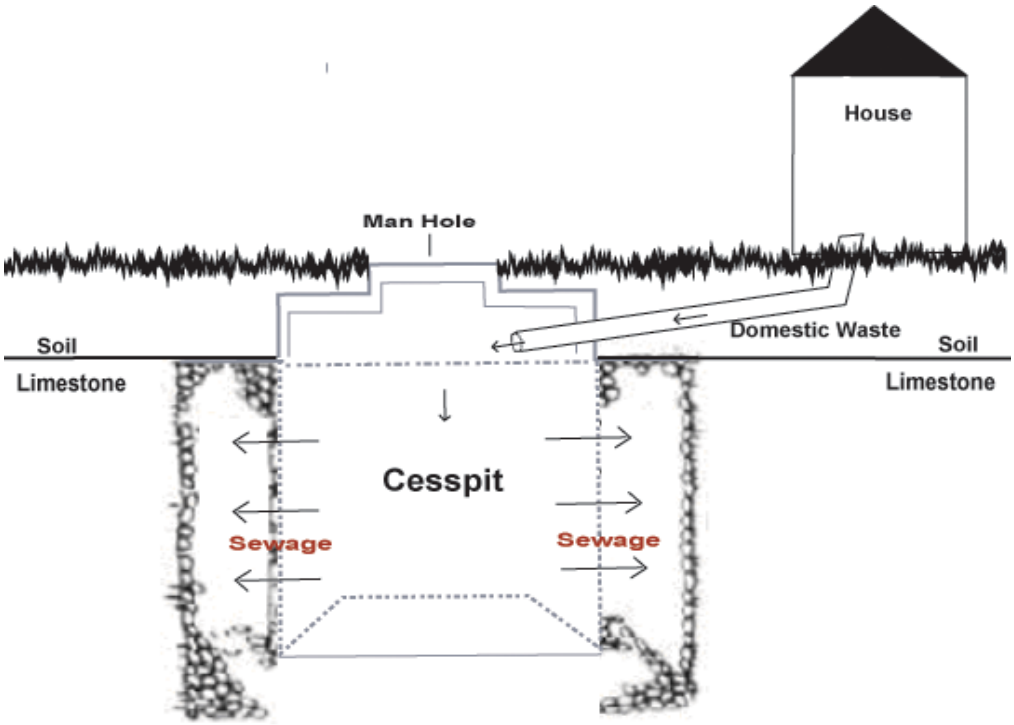


Fig. 6. Cesspit illustrating sewage seepage into surrounding bedrock.

Fertilizers used on golf courses, gardens and residential lawns are a non-point source form of pollution that increases the nutrient input to the nearshore waters and creates an additional environmental threat. Water contaminated with fertilizers percolates through the topsoil, seeping into subterranean water, or is transferred by surface run-off to the inshore waters. If this nutrient enriched water seeps into a cave, contaminants could be transported to inshore waters.

Trash is abundant in some Bermuda caves. Discarded bottles have been thrown or sucked into caves by tidal inflows. Several caves have been used as dumps for household refuse, tires, and even oil drums (Fig. 7). Prospero's Cave at the Grotto Bay Resort, was used as a nightclub. In June 2007, the Bermuda Cave Divers Association removed glasses, light fixtures, chairs, tables, bottles, and other trash during a clean up dive. In tourist caves, pools are used as wishing wells where coins are dropped (Fig. 8). The coins degrade over time and release copper and other metals into the water adding additional stress to cave organisms.

Fig. 7. Oil drums and trash dumped into Bitumen Cave in Tucker's Town (photo by Tamara Thomsen).

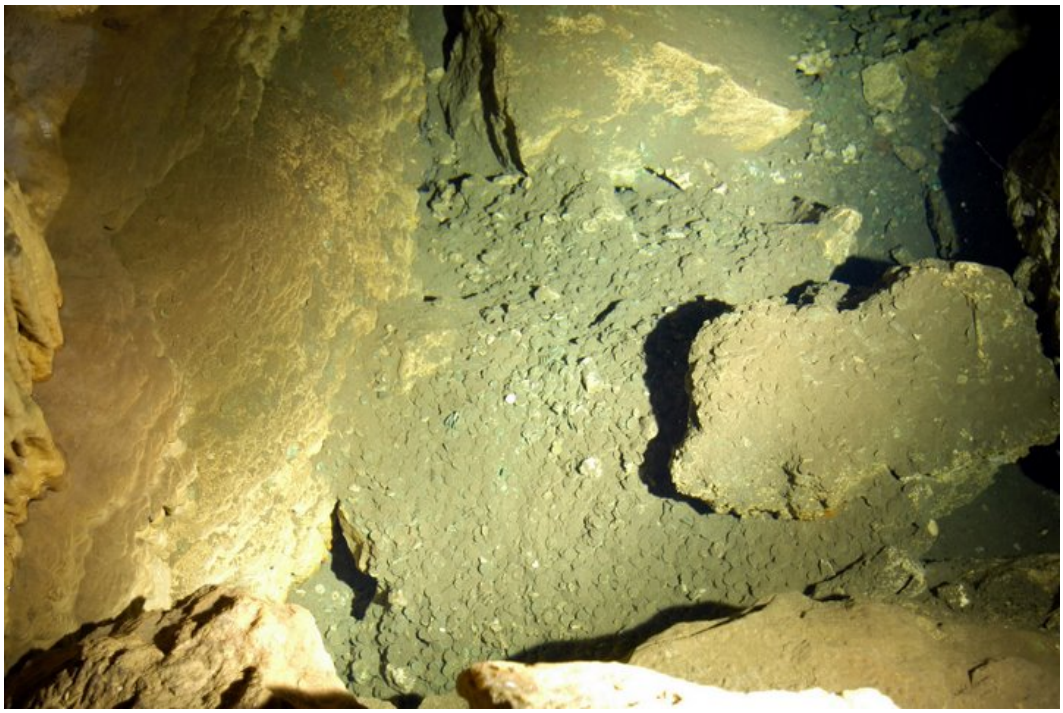


Fig. 8. Piles of coins in a pool in Leamington Cave. This was once used as a wishing well (photo by Tamara Thomsen).

Caves are now specifically protected under the Planning Act 1999 (Glasspool 2005). If a cave is discovered during construction, all work must cease until a survey is conducted to assess the cave's stability and extent. After this, a 30 foot boundary is erected around the entrance where no construction can take place (Glasspool 2005). Unfortunately, newly discovered caves in construction areas are not always reported to the proper authorities and may be filled in to cover up their existence (personal communication, Anne Glasspool).

Quarrying, in which limestone is excavated or blasted by explosives, causes detrimental and irreversible damage to caves (Fig. 9). Two large quarries, Wilkinson and Government Quarry, both obtain rock from the Walsingham Formation. Caves near these areas typically have broken speleothems and collapsed rooms. Wilkinson Quarry Cave, which contains four endangered species of stygobites, was discovered while blasting in Wilkinson Quarry (Iliffe 2004). Today, blasting still happens at the quarry, but there is a 30 foot barrier around the entrance where no quarrying can take place. Another cave was found at Government Quarry Cave in 1980. After its discovery, bulldozers pushed piles of domestic waste and scrap metal into the entrance pool in an attempt to fill in the cave prior to quarrying. Shortly afterwards, nearby caves began to give off a strong odor of hydrogen sulfide (Iliffe et al. 1984), thus confirming that caves are interconnected.

Fig. 9. Blasting resulted in broken flowstone at Wilkinson Quarry. (photo obtained from www.cavebiology.com).

Indications of Water Quality

Nitrogen

Nitrogen, a component of proteins and nucleic acids, is essential for all organisms. Some sources of nitrogen into the marine environment include atmospheric deposition, wastewater seepage, commercial fertilizers, and the natural contributions from soil organic matter (Seitzinger & Kroeze 1998, Slomp & Van Cappellen 2004). Groundwater nitrogen is usually found in the form of nitrate (NO_3^-) due to the nitrification of ammonium (NH_4^+) in the oxic zone (Jordan et al. 1997). The predominant removal method for groundwater nitrogen is through denitrification where NO_3^- is converted to N_2, as seen in Fig. 10 (Slomp & Van Cappellen 2004). However it can also be taken up by plants or leached through the system. N_2 can be converted back into organic nitrogen through nitrogen fixation, thus completing the cycle. In karstic aquifers, high amounts of NH_4^+ are usually only found when NH_4^+ -rich wastewater or organic matter decomposition occurs in anoxic conditions (Ceazan et al. 1989). This process

requires anoxic conditions and NH_4^+ is removed primarily by the adsorption into clay (Ceazan et al. 1989).

Nitrogen added to the marine environment is a primary cause of eutrophication (Lapointe et al.1990) where plant growth, specifically algae and phytoplankton, is stimulated by surplus nutrients in the water (United States Geological Survey 2008). This can be harmful to seagrass growth because increased levels of phytoplankton causes a shading effect, blocking out light needed for photosynthesis (Orth et al. 2006). Organism under this cloud of algae and phytoplankton do not obtain the needed light and nutrients and are more susceptible to death. Bacteria decompose their remains, respiring oxygen causing an aerobic environment to become anaerobic. Increased deposition of organic material encourages flora favored by a rich nitrogen supply to displace other flora (such as those with a lower nitrogen tolerance), thus decreasing diversity (Frink et al. 1999).

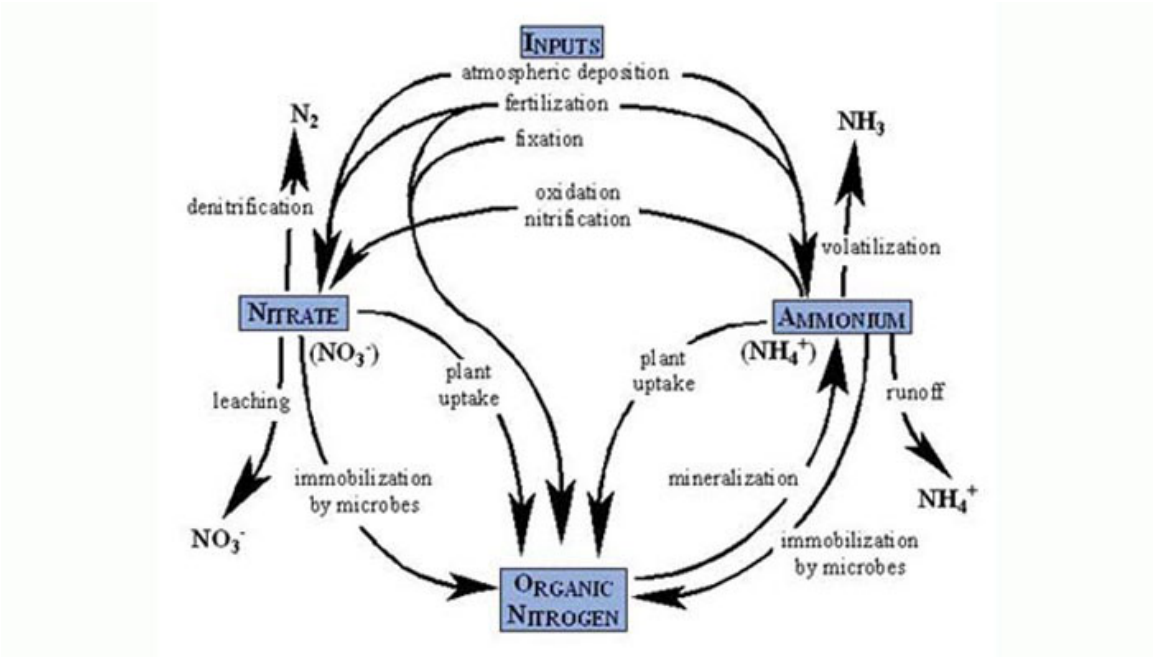


Fig. 10. The Nitrogen Cycle in marine environments. (Diagram from U.S. Department of Interior, National Parks Service).

Phosphorus

Inorganic phosphorus is often found in lower concentrations in the marine environment than nitrogen, limiting algae and plant growth (Slomp & Van Cappellen 2004). Dissolution of minerals in soil and decomposition of organic matter are the primary natural sources of phosphorus to aquatic ecosystems (Slomp & Van Cappellen 2004). Anthropogenic sources of the nutrient include sewage, cesspit seepage, fertilizer runoff, soil erosion, and animal waste (Slomp & Van Cappellen 2004). Phosphorus has a natural affinity to calcium carbonate, thus it is readily binds to limestone through the formation of calcium-carbonate-phosphate minerals (e.g. apatite) (Kitano et al. 1978; Simmons & Lyons 1994). Plants, algae, and bacteria can rapidly uptake dissolved inorganic phosphate (PO_4), also called soluble reactive phosphate (SRP) (Thompson-Bulldis & Karl 1998). Under aerobic conditions, decomposition of organic material on the bottom of the ocean releases usable phosphorus, which becomes converted to a less usable form, soluble nonreactive phosphorus (SNP) (Thompson-Bulldis & Karl 1998). As limestone dissolves, caused by an decrease in pH or natural erosion, phosphate is re-released into the marine environment allowing the uptake by autotrophic organisms that pass it on to heterotrophs when consumed (Fig. 11) (Pomeroy et al. 1963).

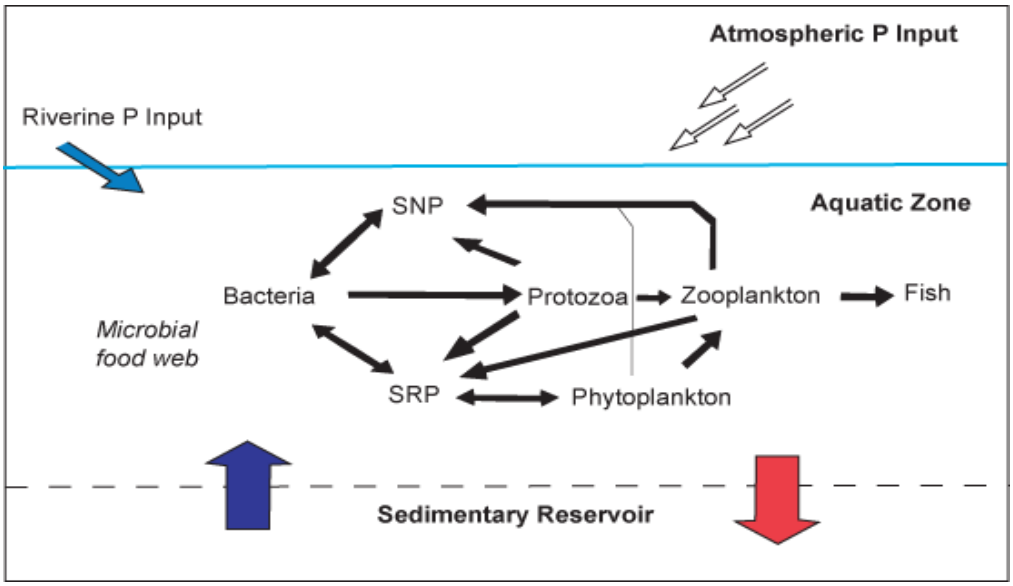


Fig. 11. The Phosphorus Cycle in marine environments. SRP is the biologically available Soluble Reactive Phosphate. SNP is the soluble nonreactive phosphorus that will eventually make its way into the sediment. (diagram adapted from http://www.womenoceanographers.org).

Bacteria

Since fecal coliform bacteria are components of the normal intestinal flora of mammals, *Escherichia coli* and *Enterococcus* spp. can be used as indicators of fecal contamination from cesspit seepage and wastewater injection wells (USEPA 2000). If ingested, pathogens including viruses, bacteria, and protozoans associated with sewage can cause gastrointestinal illness, hepatitis, and other sicknesses (USEPA 1991). USEPA (2000) recommends testing marine water for *Enterococcus* spp. in addition to *E. coli* due to its ability to survive in salt water. Acceptable bacteria levels of each *E. coli* and *Enterococcus* spp. for recreational swimming in marine waters are 104 colony forming unit/100 ml (CFU). It is unsafe to swim in water with higher concentrations (USEPA 1991). Beaches throughout the United States are closed for recreational purposes if bacteria levels exceed these standards.

Description of Study Sites

The caves studied were chosen based on size of the cave entrance (Table 1), presence of nearby seagrass (within 100 m of cave entrance), and the magnitude of water movement. Study sites were on the Harrington Sound side of the North Shore, the main island separating Castle Harbour (on the Walsingham Formation) and Harrington Sound (Fig. 12). Four of these caves, Green Bay Cave, Red Bay Cave, Cripplegate Cave, and Leamington Cave, opened directly to Harrington Sound. Five caves, including Joyce's Dock North and Middle Caves, Castle Grotto Cave, and Tucker's Town Dock and Bay Caves, were located on western side of Castle Harbour extending from North Shore to Tucker's Town Bay. Burchall's Cove East Cave was on the North Shore.

Table 1. Characteristics of study sites. Table includes area and depth of cave entrance at the time of sampling,

Study Sites	Entrance Area (m^2)	Entrance Depth (m)
Green Bay Cave	21.0	4.9
Red Bay Cave	2.5	1.0
Leamington Cave	1.5	0.5
Cripplegate Cave	0.6	0.6
Joyce's Dock North Cave	10.0	1.0
Joyce's Dock Middle Cave	10.0	2.0
Castle Grotto Cave	12.0	1.2
Tucker's Town Dock Cave	1.0	2.0
Tucker's Town Bay Cave	2.5	1.0
Burchall's Cove East Cave	3.0	7.0

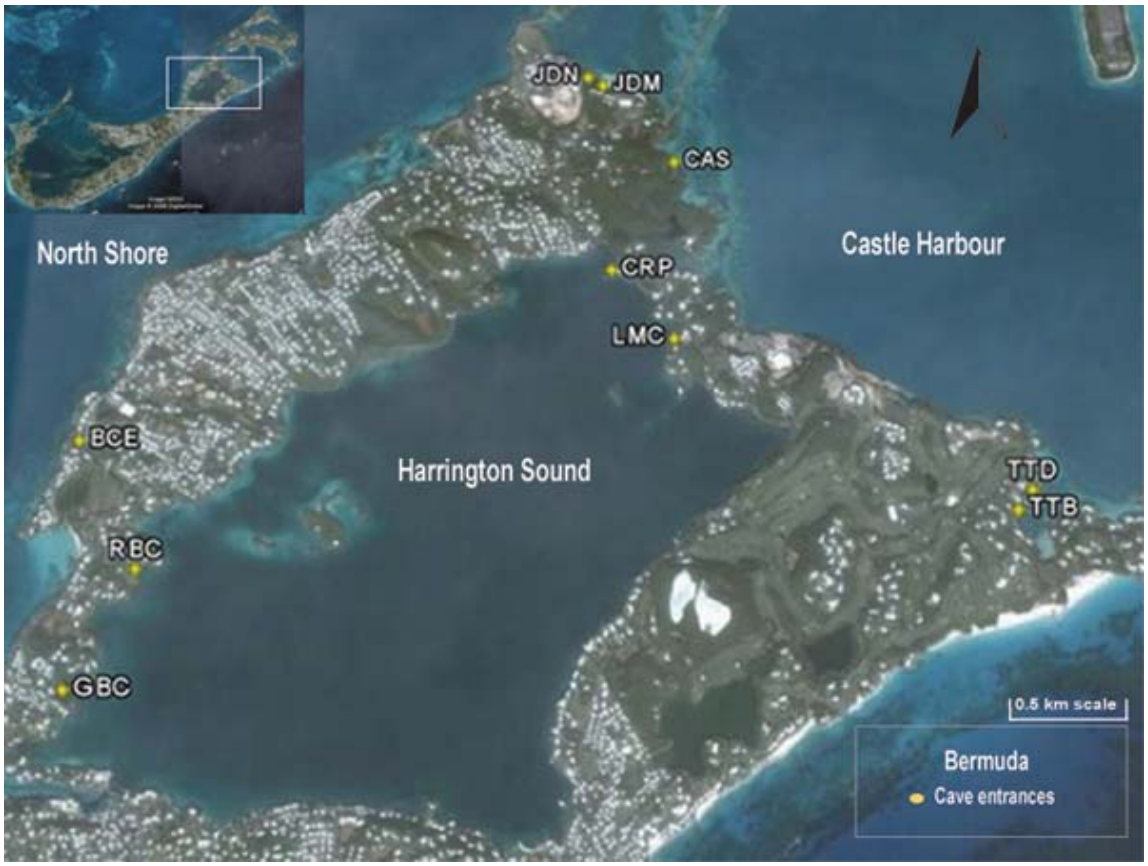


Fig. 12. Location of study sites in Bermuda. Sites included: Green Bay Cave (GBC), Red Bay Cave (RBC), Burchall's Cove Cave (BCE), Joyce's Dock North Cave (JDN), Joyce's Dock Middle Cave (JDM), Castle Grotto Cave (CAS), Cripplegate Cave (CRP), Leamington Cave (LMC), Tucker's Town Dock Cave (TTD), and Tucker's Town Bay Cave (TTB). Yellow circles represent the location of cave entrances, and white blocks represent buildings. (Photos obtained from www.googleearth.com).

GREEN BAY CAVE (GBC), Harrington Sound.

The main Green Bay entrance to the GBC was located at the northwestern end of Green Bay in Harrington Sound (Fig. 13A). This entrance was 0.5 km northwest of the Bermuda Aquarium and Zoo, in front of a small valley with large houses and well kept lawns on adjacent hilltops. GBC has been surveyed to over 2 km in length, making it the longest cave system in Bermuda. The cave has an additional inland entrance, Cliff Pool, located south southwest of the GBC entrance and connected to it through passages easily traversable by divers. Extending back from the Green Bay entrance (Fig. 13B), a silt-floored tunnel divided after 16 m penetration into two main sections: one extending in a loop back towards Harrington Sound and the other connecting to the Cliff Pool entrance and then on to the North Shore Passage. Cave walls in the entrance section of the cave were encrusted with marine filter feeding invertebrates such as sponges and anemones. Beyond this initial junction, the encrusting fauna became less abundant and the cave changed character, become more anchialine. Stalactites and stalagmites are abundant in these sections of the cave. Stygobitic invertebrates (e.g. *Mictocarus halope*) and were present in the anchialine portion. A small school of open water jacks occasionally follow divers into the cave. An unusual feature in GBC was the presence of unstained white limestone in several upper domes within the cave, in contrast to the dark brown staining of the wall rock found elsewhere (Fig. 13C). In the North Shore Passage, erosional features are possibly the result of a stream flowing through the tunnel during periods of lower sea level. The adjoining bay had three species of seagrass, *T. testudinum, S. filiforme,* and *H. wrightii* which were within 10 m of the cave entrance.

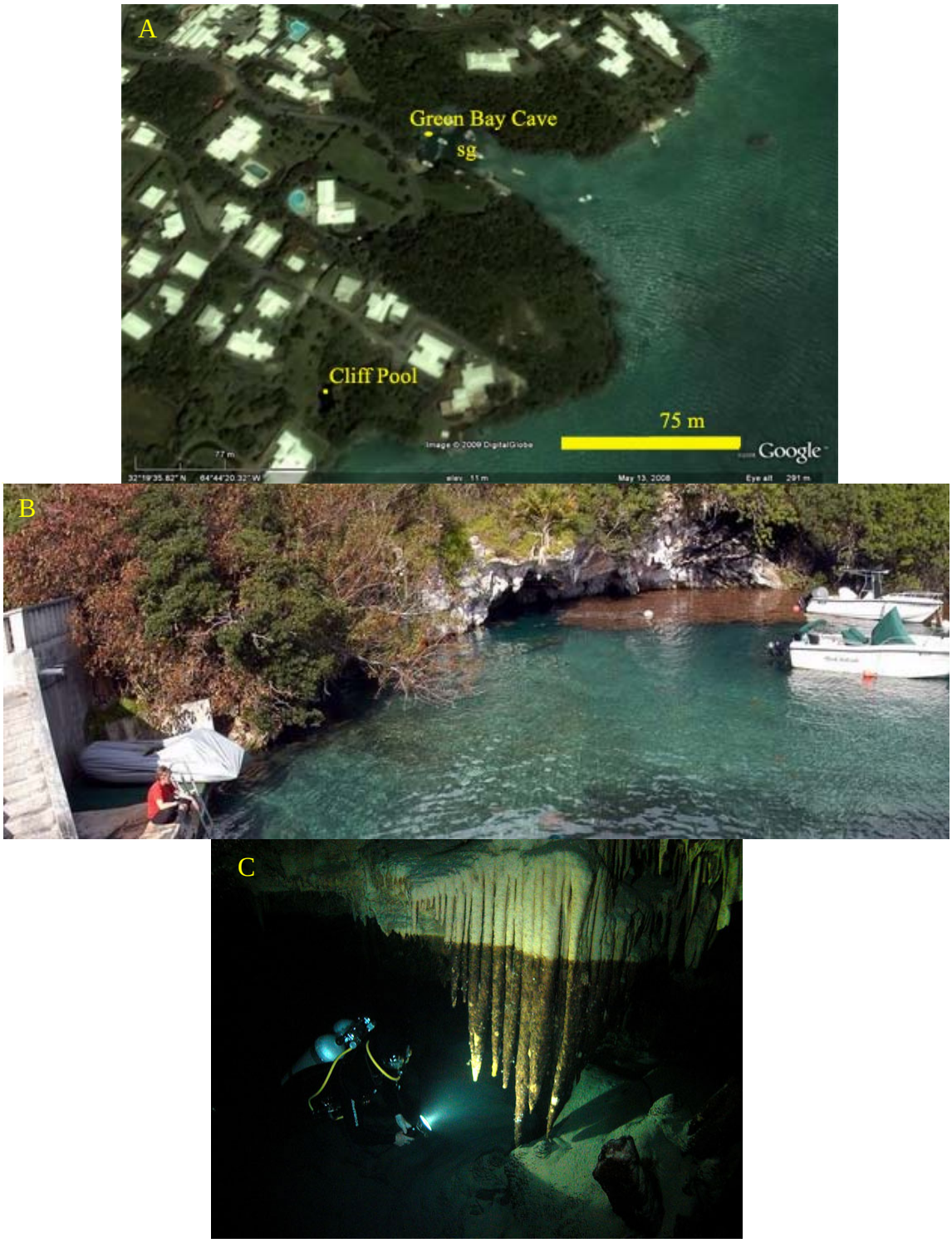


Fig. 13. Green Bay Cave. A) Google Earth view of GBC and Cliff Pool; seagrass is denoted by 'sg'.B) GBC entrance located just to the left of the white buoy. (Photo taken by Tamara Thomsen). C) White 'bath tub' ring. This is located in the anchialine portion of the cave on the upper portion of the stalagtite (Photograph by Daren Long).

RED BAY CAVE (RBC), Harrington Sound.

RBC was found in the south side of a shallow, rocky bottom cove at the western margin of Harrington Sound, 0.5 km north northeast of GBC (Fig. 14A). It was located in the back of a private home where a well manicured lawn extends to the water's edge (Fig. 14B). Land surrounding the cave consisted of rolling low hills with large private homes on spacious lots. The submerged entrance was under a limestone outcropping where a small cavern slopes down to a horizontal bedding plane at 10 m depth. Divers had to use side-mounted tanks in order to negotiate the first 30 m of 50 cm high passage to reach more spacious sections in the interior. The cave extended west toward the North Shore and had been explored for nearly 1 km, reaching depths of 18 m. Numerous speleothems (e.g., stalactites and stalagmites) were present in the back sections of the underwater cave, while one side passage led to a closed air dome room in which tree roots had penetrated the ceiling. Due to the strong tidal currents present at the entrance, the cavern zone was inhabited by densely packed schools of fish and abundant filter feeding organisms including hard star corals, sponges, and anemones (Fig. 14C). The bay 35 m to the north had a sea grass bed composed of *S. filiforme* and *H. wrightii* found in depths ranging from less than 1 m to 2.5 m.

Fig. 14. Red Bay Cave. A) Google Earth view of RBC and surrounding landscape. The sea grass bed to the north of the cave entrance is indicated by 'sg'. B) View of the submerged entrance looking west. The entrance is immediately below the rock outcrop in the center of the photo. C) Dense school of fish cluster at the cave entrance.

CRIPPLEGATE CAVE (CRP), Harrington Sound.

CRP is a coastal entrance to the 1 km long Palm Cave System which contains three other inland, sinkhole entrances and is located on the northeastern corner of Harrington Sound (Fig. 15A). This entrance was the smallest in the study (> 0.5 m wide by 1 m high) and was in less than 1 m water depth. Although CRP's entrance was not large enough to provide entrance to the cave, strong currents were present. Rocks at the entrance were encrusted with profuse growth of filter feeding invertebrates including anemones, star corrals, hydroids, and sponges, while schools of small fish were also common (Fig. 15B). CRP extended north northwest towards the Walsingham karst area and Castle Harbour. The closest house was 20 m south of the cave entrance. *T. testudinum, S. filiforme*, and *H. wrightii* were present directly outside of the cave in a small, finger-shaped bay. This bay was 30 m in length with a depth of <0.5 m close to the cave entrance and gradually increasing to 2.5 m nearer to Harrington Sound.

Fig. 15. Cripplegate Cave. A) Aerial photograph of CRP from Google Earth. Seagrass location is marked with 'sg'. B) Marine invertebrates found outside of cave entrance. The 0.25 m^2 quadrat was used for scale.

LEAMINGTON CAVE (LMC), Harrington Sound.

The coastal entrance to LMC was located on the northeastern side of Harrington Sound, at the end of a medium sized bay and immediately east of a private dock. The underwater passage connecting the coastal entrance to a large cave in the interior of the island cave was too small for divers to traverse and as such the connection was only confirmed by dye tracing. The spring entrance was located behind boulders at the end of a rock-rimmed bay, 70 m from the inland entrance (Fig. 16A). LMC was once used as a commercial tourist attraction and had light fixtures, handrails, and even pennies in small "wishing well" cave pools (Fig. 8). A larger cave pool, 50 m from the commercial entrance, exhibited tidal fluctuation and a series of submerged chambers (Fig. 16B). The connection between the final room in the underwater cave and the spring was confirmed in June 2007 by release of fluorescein dye. The cave pool was crystal clear with a silty floor indicating low water flow. The connecting tunnel to Harrington Sound had considerable plastic trash and other floating debris that had been sucked in by the inflowing tide. Both the dry and underwater portions of the cave have numerous, fragile speleothems hanging from the ceiling. The cave appears to have been formed by collapse into underlying voids as large breakdown boulders from a ridge down the center of the cave. The sea grasses *T. testudinum, S. filiforme,* and *H. wrightii* were most abundant closest to shore in shallower waters and extended to within 0.5 m of the spring entrance. The bay was shallowest by rocks along the shoreline, with a steep increase in depth 16 m out to Harrington Sound.

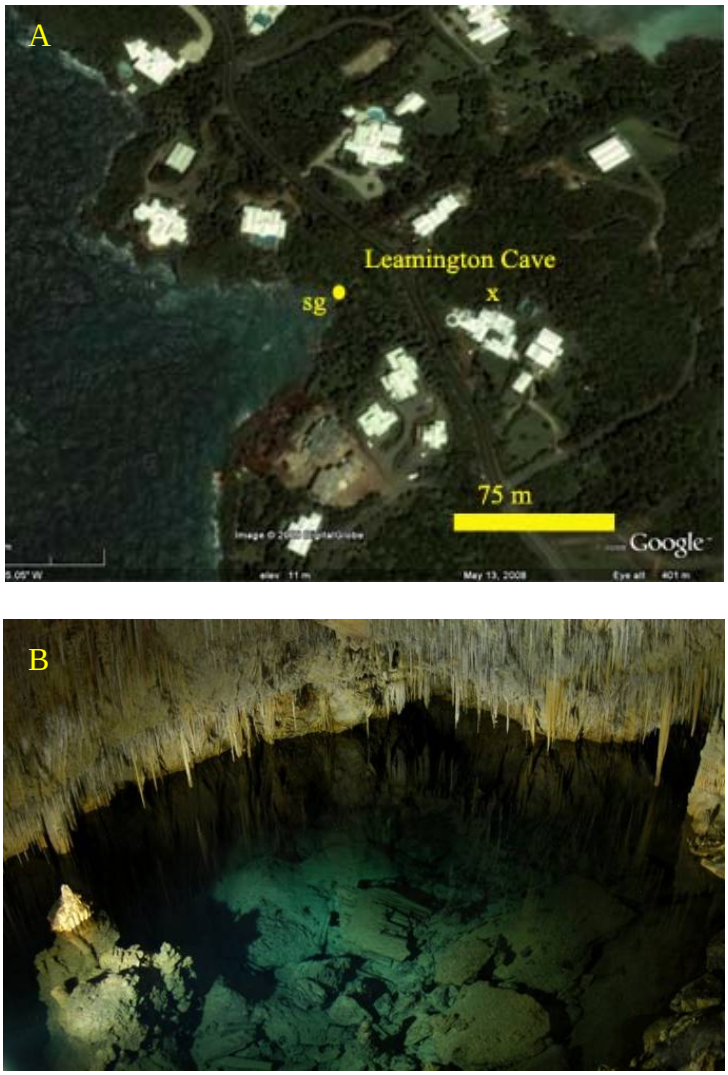


Fig. 16. Leamington Cave. A) LMC location from Google Earth. Cave spring is marked with a yellow circle. The inland entrance is marked with a yellow ‘x’. Seagrass location is denoted by ‘sg’. B) Crystal clear cave pool. Featuring stalactites (top) and underwater breakdown (bottom).

JOYCE'S DOCK NORTH CAVE (JDN), Castle Harbour.

JDN was on the northwestern side of Castle Harbour at a large hotel complex, the Grotto Bay Resort (Fig. 17A). A dock on the eastern side of the spring entrance provided a vantage point for hotel guests (Fig. 17B, JDN). The underwater entrance consisted of a silty slope beneath a rocky outcrop in 1 m depth that descended to a low tunnel, floored with coarse sediment at 20 m. This tunnel was explored by divers for approximately 100 m horizontal penetration before becoming too small to follow. Submerged rocks at the entrance contained coralline algae, sponges, and anemones, while schools of several species of fish congregated under rock ledges. A seagrass bed containing *S. filiforme* and *H. wrightii* was located 20 m northeast of the entrance and 10 m off the resort beach. Bathers were observed to wade through or swim over this seagrass bed. Two other caves nearby on the Grotto Bay Resort with tidally influenced cave pools may connect to JDN. The resort consists of 8-10 larger hotel room complexes, a swimming pool and main lobby and restaurants. Sixty meters to the west, was the large Wilkinson limestone quarry (Fig. 17A).

JOYCE'S DOCK MIDDLE CAVE (JDM), Castle Harbour.

JDM, 10 m southeast of JDN, on the shore of Castle Harbour, was a submerged fissure 3 m from the dock (Fig. 17B, JDM). The spring basin funneled down to a small tunnel at 7 m depth where a boulder blocked further progress. Piles of sunken rubbish and debris ranging from fishing line to discarded tires, collected on the floor of the cavern. The same seagrass bed as was noted for JDN is closest to the cave. Thus, all seagrass data pertained to both caves, and were classified as Joyce's Dock seagrass.

Fig. 17. Photographs of Joyce's Dock North and Middle Caves. A) Google Earth view of JDN and JDM north of Grotto Bay Resort. Seagrass is marked by 'sg'. B) Panorama view of JDN and JDM. The dock on the left leads up to Grotto Bay Resort (photo taken by Tamara Thomsen).

CASTLE GROTTO CAVE (CGC), Castle Harbour.

CAS was found in the Walsingham Trust, a privately owned nature preserve on the western side of Castle Harbour (Fig. 18). The cave is located 0.5 km south of the causeway on a small crescent shaped bay. This former commercial tourist attraction was show to visitors by boat. It had two entrances, about 20 m apart, connect by a low, lake room. The cave lake is shallow, averaging <1 m in depth, with thick silt covering most of the floor. The northern most entrance opens directly to Castle Harbour, allow tidal exchange to occur. CAS likely connected to other more inland caves within the Walsingham Trust. A seagrass bed is located 75 m from the cave entrance in 2.5 m depths and contained *S. filiforme* and *H. wrightii*. Due to the isolated location of the cave in a protected nature reserve, there appeared to be little threat of cesspit pollution.

Fig. 18. Castle Grotto Cave from a Google Earth view. Seagrass sampling site is depicted with a 'sg'.

TUCKER'S TOWN DOCK CAVE (TTD), Tucker's Town Bay.

TTD can be found on the northern edge of Tucker's Town Bay, close to Castle Harbour (Fig. 19A). The entrance was in 2 m of water under a rocky ledge at the shoreline, southwest of the Tucker's Town Public Dock. A low sand and shell floored tunnel extended inland and was inhabited by spiny lobsters, fish, and moray eels (Fig. 19B). Divers were able to penetrate only 10 m into the cave before the passage became too narrow. TTD extended northwest towards the Tucker's Town Resort. The cave entrance is on the north side of the channel leading into Tucker's Town Bay. Water in the Tucker's Town Bay was somewhat murky with an estimated visibility of <3 m and a maximum depth of 9 m. There was no seagrass within 100 m of the cave. Several large houses with large well kept lawns are situated around the bay, while the Mid Ocean Club resort and two golf courses were less than 0.5 km from the cave entrance.

TUCKER'S TOWN BAY CAVE (TTB), Tucker's Town Bay.

TTB is a coastal spring entrance with strong tidal flow on the northern shore of Tucker's Town Bay (Fig. 19A). The cave bottom near the entrance was littered with discarded bottles and other trash. An oil slick originating from moored boats in the bay was evident on the surface of the water (Fig. 20). Beyond the entrance, the cave sediments turned from rocks to silt and sponges and other filter feeders were present on the cave walls. Approximately 20 m into the cave, an inland sinkhole entrance had a deck built into it. The presence of a second entrance adjacent to a house and cesspit put this cave at a high risk for anthropogenic contamination. Tucker's Town Bay was murky with no seagrass. Tucker's Town was home to a large resort and two golf courses with additional large estate homes and well manicured lawns.

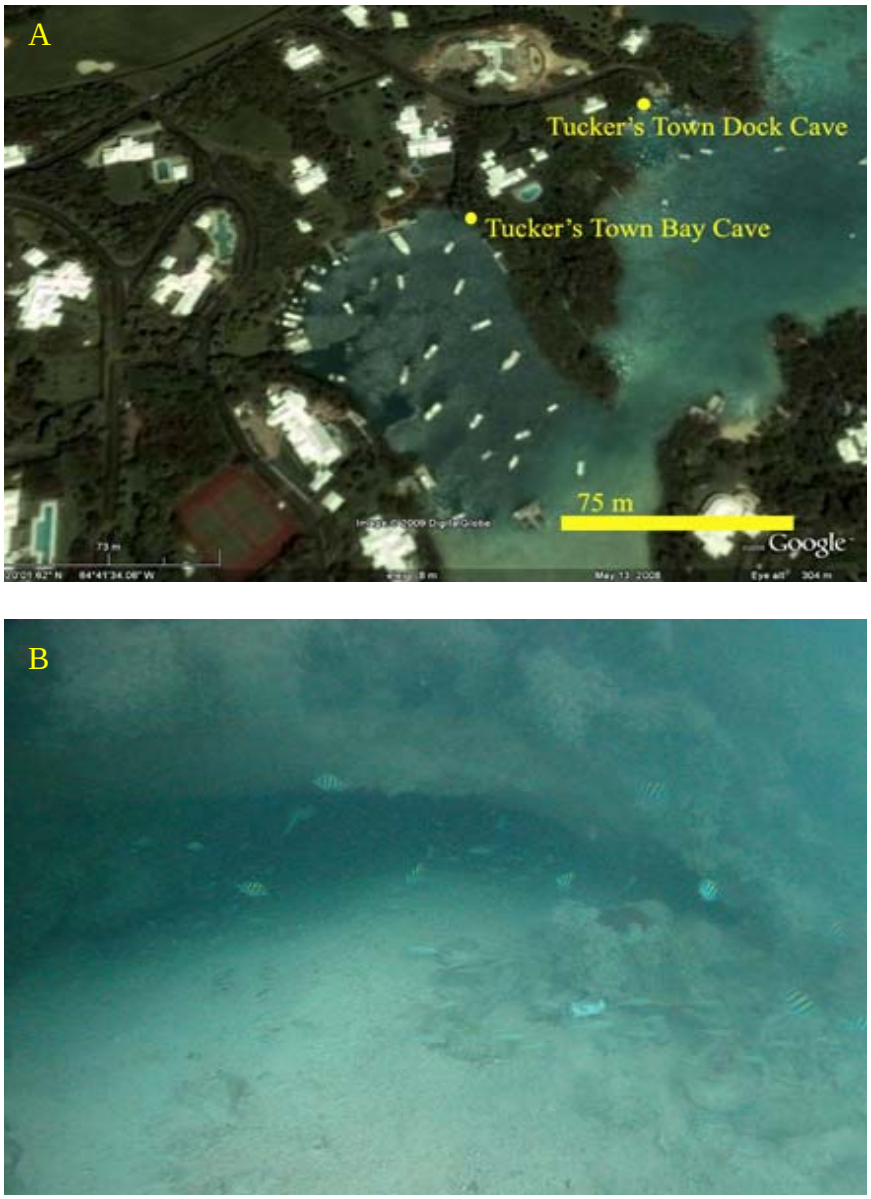


Fig. 19. Tucker's Town Caves. A) Google Earth view of TTD and TTB. Note the golf course on the upper left hand corner of this photograph. B) Schooling fish at entrance of TTD during an outflow.

Fig. 20. Inland entrance of TTB. This second entrance was 20 m into the cave opening up to a wooden deck with lawn chairs on it. Note the film on the surface of the water has an oil-like sheen to it (Photo taken by Tamara Thomsen).

BURCHALL'S COVE EAST CAVE (BCE), North Shore

BCE was a large natural sinkhole on the North Shore of Bermuda (Fig. 21A). This bay was used as an active marina that had a quarried out channel to the open sea. BCE was located under a boat ramp on the northeastern side of the cove at a depth of 7 m (Fig. 21B). The bottom inside the cave ranged from coarse sand in areas of strong currents near the entrance to silt in wide interior tunnel. The cave entrance extends for about 100 m to the northeast, under the main highway before coming up to the surface in an inland karst pool, Davis Pond. The cavern zone was littered with a sunken boat, trash, wires, batteries, etc, that have been sucked into the cave by inflowing tides. Trash was also found throughout the cave itself. There was no seagrass inside the up to 10 m deep cove. Another cave was located at the southwestern edge of the cove, but appears to be a separate cave system. The cove was typically crowded with boats, with private homes located on all sides. Adjacent to Davis Pond is a large supermarket and several smaller businesses.

Fig. 21. Burchall's Cove East Cave. A) Aerial view of BCE using Google Earth. Davis Pond is marked with an 'x'. B) BCE situated at the end of the boat ramp just below the red X. (Photo taken by Tamara Thomsen).

Project Logistics

This project consisted of four research expeditions over a span of 15 months (October 2006, March 2007, June-July 2007 and January 2008). Each trip lasted two weeks, except for a two month trip during June and July 2007. Seagrass surveys were conducted in June-July 2007. Environmental parameters were measured during each trip, and water samples were taken in June-July 2007 and January 2008. Differences in sampling and location between the four trips were based on availability of instruments and collaboration with Bermuda Conservation Services. Control sites for water samples were selected in Harington Sound, Castle Harbour, Tucker's Town Bay, and North Shore at a location more than 100 m from shore and 200 m from a cave entrance.

CHAPTER II

CAVE SPRING TIDAL CURRENTS

Introduction

Cave and groundwater quality can be used as indicators of the overall environmental health of Bermuda. When groundwater quality deteriorates, conditions of the island's subterranean and nearshore ecosystems and freshwater lenses are threatened. The Bermuda Cave and Karst Information System (BECKIS), a multidisciplinary research program coordinated through the Bermuda Biodiversity Project of the Bermuda Aquarium, Museum & Zoo, was formed to concentrate efforts on investigating Bermuda's underground wilderness. This study was an extension of BECKIS to further our understanding of cave and groundwater processes.

Studies on open water tidal fluctuations and cycles have been conducted by scientists from the Bermuda Biological Station (Morris et al. 1977, von Bodungen et al. 1982), although cave spring flow velocity and quantity in Bermuda have never been documented. The nearly enclosed Harrington Sound averaged a 20 cm tidal range, with only 50 percent of the water entering from Flatt's Inlet (Morris et al. 1977). The rest of the in/outflow was believed to travel through caves, cracks, and fissures along the coastline. Determining the mass transport of water entering/exiting the cave systems would help scientists understand sources, transport, and residence times of Bermuda's inshore waters.

Materials and Methods

Study Sites

Coastal springs were identified along Castle Harbour, North Shore, and Harrington Sound by swimming around the coastline during the proper time of the tide, when cold, clear water should be flowing out of the cave (Fig. 22). Other visual indicators of coastal springs include the presence the green algae, *Caulerpa*, or large numbers of fish. Sites were classified as regions based on inshore water bodies (e.g. Harrington Sound, Castle Harbour, North Shore, and Tucker's Town Bay) where they

were located. Four caves were on Harrington Sound (GBC, RBC, LMC, CRP), three on Castle Harbor (JDN, JDM, CGC), two on Tucker's Town Bay (TTD, TTB), and one on the North Shore (BCE). Each study sites had one known entrance to the inshore waters, exhibited reversing flow with tidal change, and connected to networks of cave passages trending inland.

Fig. 22. Joyce's Dock North Cave entrance during an outflow. The arrows point to *Caulerpa* growing outside cave entrance (photo by Tamara Thomsen).

Instrumentation

Instruments to measure the currents and water quality parameters were placed into the caves by a certified SCUBA diver following the training and equipment recommendations of the National Speleological Society – Cave Diving Section (NSS-CDS) and the National Association of Cave Diving (NACD). In addition, diving standards set forth by the American Academy of Underwater Sciences (AAUS) were followed. Spring flow speed and direction were measured using an Acoustic Doppler Velocimeter (ADV; Nortek Vector, accuracy 0.5% of measured value ±1 mm s^{-1},

maximum sampling rate 64 Hz) which provides accurate three dimensional information on tidal cycles. This instrument also measured temperature, and pressure (tidal water depth) at a single point. These data are necessary to understand the cyclically changing cave environment. The ADV measures speed and direction of currents using the principle of Doppler shift by emitting a sequence of high frequency sound pulses that scatter off of moving particles in the water. The frequency of the return signal from the moving particles to the sensor is then used to determine the relative current speed. Signal strength also provides an indirect observation of the turbidity. A pressure sensor mounted onto the ADV records data using a silicon piezoresistive sensor. The ADV was manually placed at a central location in a smaller diameter section of the cave passage to assure capture of flow geometry as accurately as possible. The transducer was mounted on a PVC stand with the measuring point located at 0.27 meters above the cave floor (Fig. 23). During the Bermuda measurement campaign, the ADV sampled velocity, temperature, and pressure in 240 second intervals for at least 48 hours in each cave.

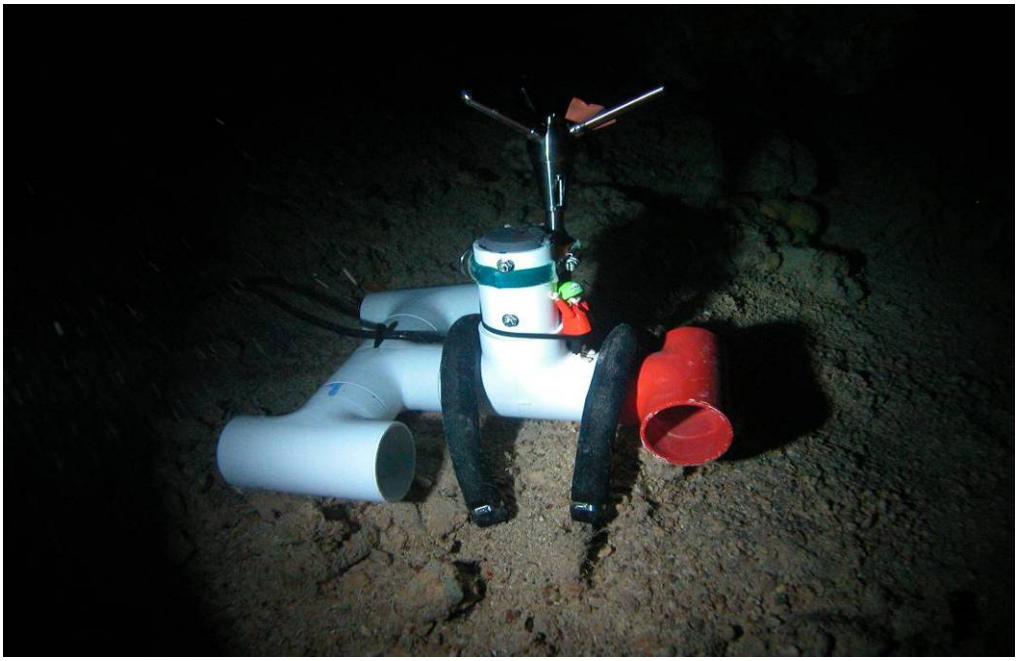


Fig. 23. Acoustic Doppler Velocimeter deployed into Red Bay Cave. Red section of the pod is oriented into the cave.

Divers measured and sketched cave passage cross-sections where the ADV was deployed. Distances from wall to the base of the current meter were measured in a clockwise fashion at 45 degree increments using a measuring tape. The cross-sectional sketches of the caves were digitally rendered and used for calculating the cross-section geometry of the cave flows.

The ADV was placed on a level floor and secured with weight to keep it from shifting during the collection period. Each cave placement was individually selected based on the configuration of the conduit. ADV placements from June 2007 through January 2008 are described in Table 2. Measurements were analyzed by Pak Tao Leung at Texas A&M University at Galveston using Matlab version 7.1.

Table 2. Depth and distance into the cave for the ADV mooring of individual deployments.

Cave	Deployment	Depth (m)	Distance in cave (m)	Comments
GBC	June 2007	16	50	
RBC	June 2007	16	90	
LMC	June 2007	2	6	Room filled with plastic debris
CRP	June 2007	1	3	
JDN	June 2007	8	45	
JDM	January 2008	6	16	Placed cave side of boulder
CGC	June 2007	1	3	
TTD	June 2007	1.8	6	
TTB	June 2007	2	3	Placed just at entrance
	January 2008	2	30	Placed beyond entrance before passage undercuts
BCE	June 2007	14	75	

Cave flow through a single conduit was similar to flow through a pipe. Therefore, a pipe network approach was used to predict the discharge volume of groundwater (Wicks 2005). This method assumes the surrounding bedrock was

impermeable. Water flow was measured at the cave entrance, in the narrowest portion of the tunnel so that all water moving in and out passed the ADV. The pipe approach was based upon the Hagen-Poiseuille law (Poiseuille 1840, Wicks 2005). Flow through a pipe created friction along the perimeter, decreasing energy of flow along the sides. Assuming the only water movement was in the direction of the conduit, velocity then becomes a function of distance from the side of the conduit. At this point, flow was fully developed, and reached its maximum potential.

The pipe network approach was based on the assumption that the conduit is circular. Since Bermuda cave cross-sections were not circular and therefore had to be simplified using the best fitting cross-sectional shape to represent the dominant flow features, this approach was modified through calculation and manipulation. Most caves in Bermuda excluding a few that are semi-elliptical, were fitted with a rectangular shape. As shown in Fig. 24A, a cross sectional drawing of CRP demonstrates how rectangular duct shape was a good estimate for the cave passage. Fig. 24B is a contour plot of velocity changes in Cripplegate Cave using the rectangular duct approximation. Current was strongest in the center and weakened towards the sides due to friction.

Flow rate was also be calculated numerically by measuring all points along a cross sectional grid and taking the sum. This yielded flow rate with cross sectional dimension over time (Fig. 24C). Volume was estimated by scaling the flow rate to an appropriate time scale based on the sampling period.

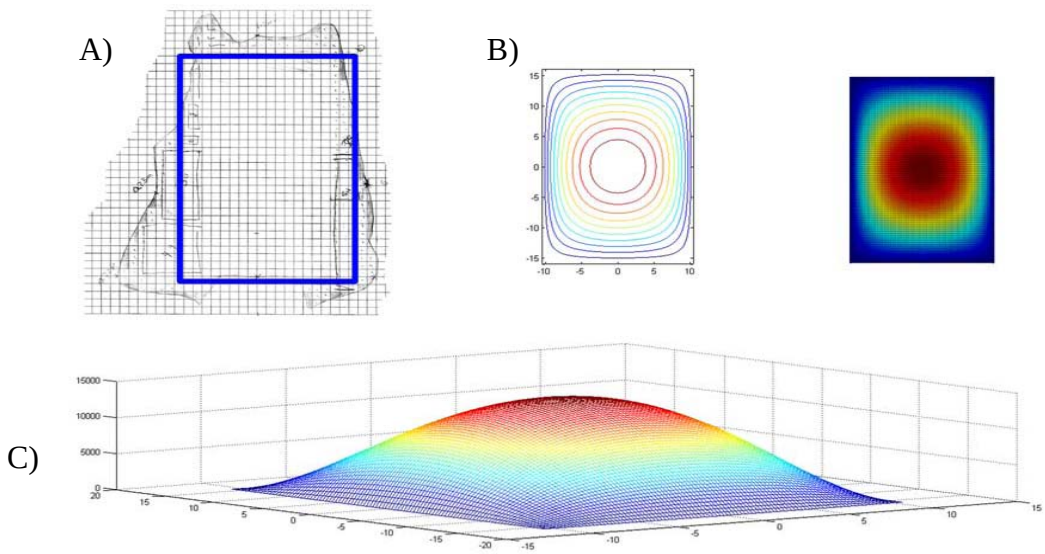


Fig. 24. Cave data analysis. A) Sketch of Cripplegate Cave. The blue outline is the proposed rectangular outline approximation for the cave. B) Two contour plots of the velocity distribution. Warm color corresponds to high velocity and cold color represents low velocity. C) Three dimensional plot of the velocity distribution.

Results

Semi-diurnal tidal currents were measured over a 24 to 48 hour periods. North Shore and Castle Harbour caves were in synchrony with open ocean tides, demonstrating similar ranges. Caves measured on Harrington Sound were out of phase with the open ocean tides by 2 to 3 hours and produced smaller ranges. Pressure measurements from BCE were compared with National Oceanic and Atmospheric Administration (NOAA) tidal data from Ferry Reach Esso Pier for that day (Fig. 25). Cave tides reached their peak height approximately the same time as the NOAA data. Fig. 26 represents tidal flux from RBC and CRP compared to the NOAA tidal gauge. Both are in Harrington Sound and display one fourth (0.2 m) of the range as the open ocean tides (0.8 m).

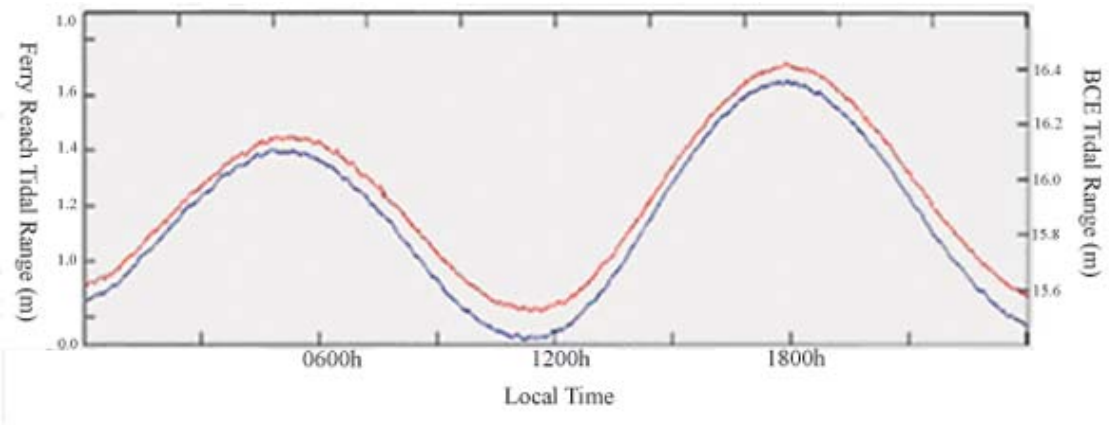


Fig. 25. Pressure measurements from ADV at Burchall's Cove East Cave and Ferry Reach. Cave data (red line) was compared to Ferry Reach NOAA tidal gauge data at the same period (blue line). The two gauges are at different depths, though, notice the amplitude and frequency are similar.

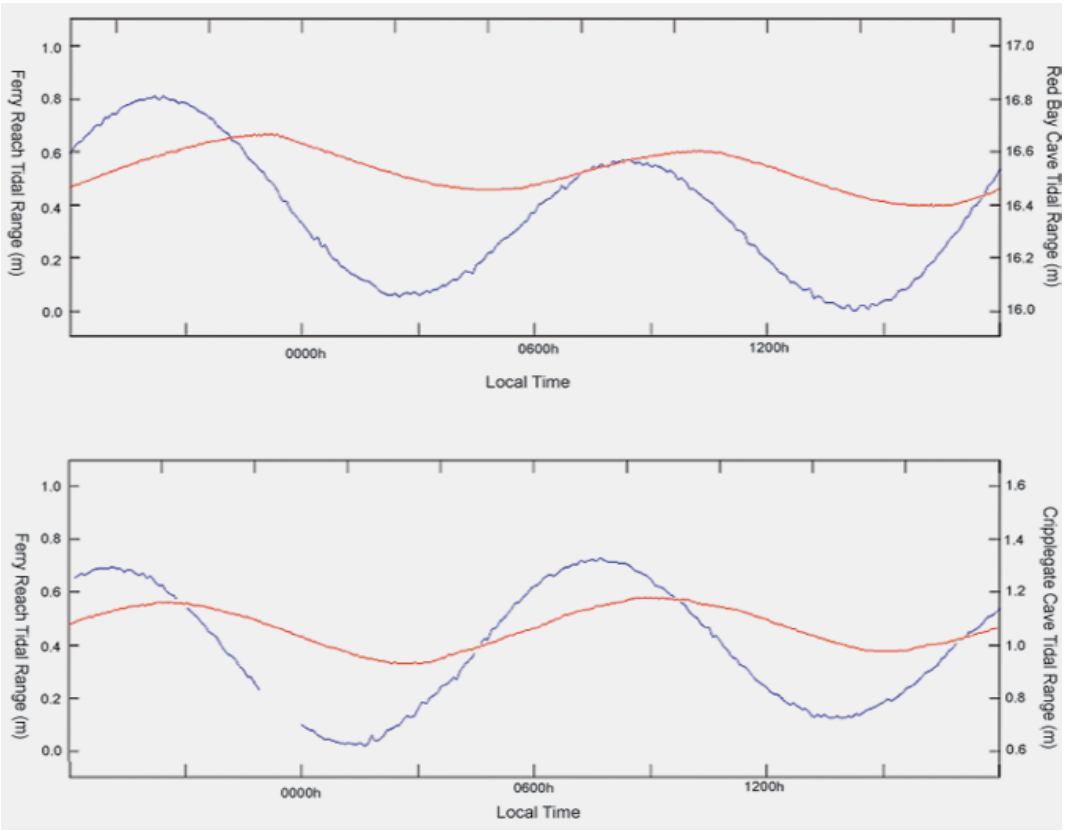


Fig. 26. Pressure measurements from Harrington Sound caves compared to Ferry Reach tidal gauge. Cave data (red lines) is compared to the Ferry Reach NOAA tidal gauge (blue lines) at the same period (blue line). Notice the amplitude is reduced to by 75 % in the caves and delayed by 2:45 hours. Pressure gauge was mounted on ADV.

ADV flow data collected from each cave were analyzed with respect to flow direction. This allowed for a better understanding of changing physical properties such as temperature. The ADV data from JDN and RBC were summarized in Figs. 27 and 28. Since the instrument was placed with the positive X axis facing into the cave, a positive Vx indicated current velocity of inflow from open water into the cave and a negative value indicated current velocity of the outflow (from the cave into open water). Lateral water movement, Vy and Vz, was observed in some cases, but this was minimal and had little effect on the main flow. Current direction is depicted by the histogram plot.

Discharge was calculated using velocity along the cross sectional plot. Given the semidiurnal nature of Bermuda tides, two outflows and two inflows occurred during a 24 hour period. Tidal volumes over a 24 hour period and maximum velocities are listed in Table 3. Four of the nine caves exhibited a 1:1 (rounded values from Table 3) inflow-to-outflow ratio. GBC had the largest measured area, and also contained outflow volumes 16 times higher than the next largest cave measured (BCE). CRP, with the smallest measured cave area, had the lowest in and outflow volume.

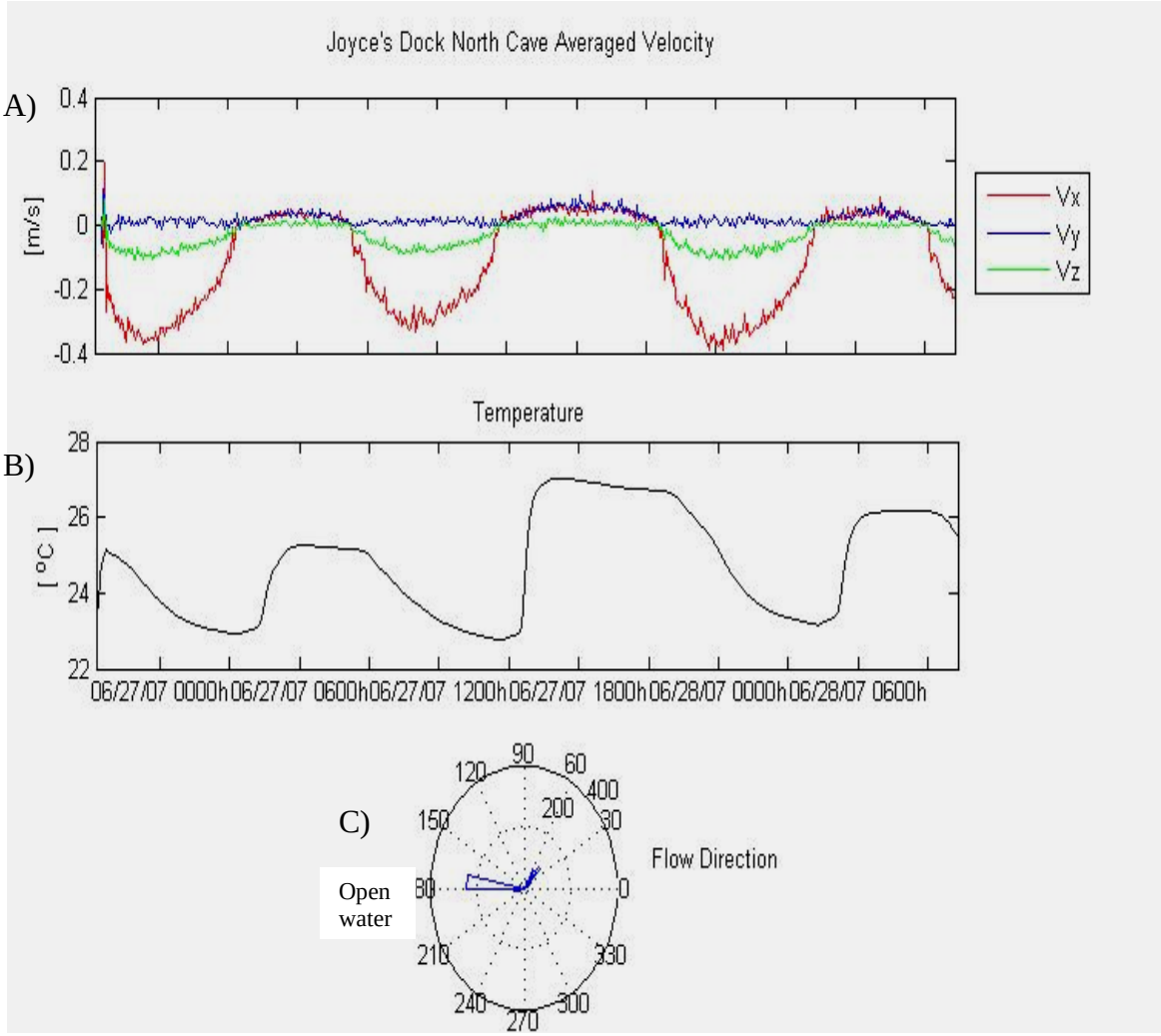


Fig. 27. Summary of hydrographical data collected in Joyce Dock North Cave. This includes A) flow velocity, B) temperature, and C) flow direction (June 2007). Note inflow (55 degrees) and outflow (80-85 degrees) were not in opposition. In JDN, there is a 30 degree difference between current in and out flows due to bends in the cave contour (the cave tunnel is not straight and water has to flow around a curved wall.

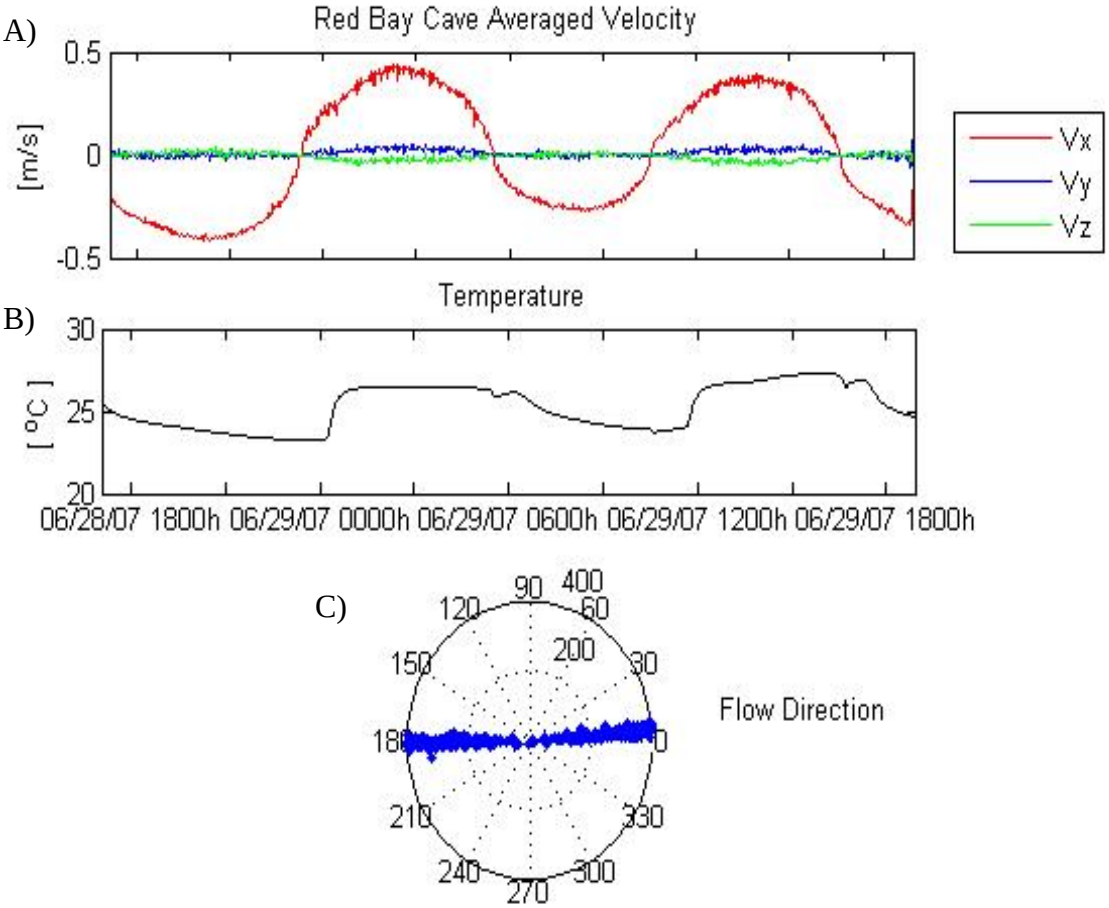


Fig. 28. Summary of hydrographical data collected in Red Bay Cave. This includes A) flow velocity, B) temperature, and C) flow direction (June 2007). Zero degrees on the compass indicates the interior of the cave, and 180 degrees is in the direction of the exit (ocean). Flow direction in RBC is 180 degrees opposite for in and out flows showing that the flow of water was in a straight line (there were no bends in the tunnel).

Table 3. Summary of discharge and flow data from each study site, June 2007. Note the amount of water is not always a 1:1 ration between in and outflows.

Cave Sites	Cross Sectional Area	Current Inflow Volume	Current Outflow Volume	In : Out Flow Ratio	Max Velocity
units	m^2	1000 m^3 /day	1000 m^3 /day	Out : In	m/s
GBC	25.5	1960	1150	1.7 : 1.0	1.5
RBC	10.2	68	60	1.1 : 1.0	0.5
LMC	7.1	28	42	1.0 : 1.5	0.25
CRP	0.6	1	0.4	1.0 : 2.5	0.4
JDN	10.8	11	51	1.0 : 4.6	0.4
CAS	1	20	23	1.0 : 1.1	0.5
TTD	1.8	6.7	6.1	1.1 : 1.0	0.4
TTB	4.1	57	55	1.03 : 1.0	0.75
BCE	13.1	98	70	1.4 : 1.0	0.25

Discussion

Harrington Sound's delayed tide and reduced range was a result of the restricted nature of Flatt's Inlet (25 m^2) and the limestone permeability dissipating tidal flow (Fig. 29) (Morris et al. 1977). Flatt's Inlet was the only channel connecting the ocean to Harrington Sound which caused tides in Harrington Sound to lag an average of 2:45 hours behind the NOAA ocean tidal gauge. Flatt's Inlet acted as an amplitude filter reducing tidal amplitude. Caves along Harrington Sound responded to imbalanced water levels between Harrington Sound and the open ocean. This gradient caused caves on one side to inflow, while the opposite side outflows, or "springs".

Conduit size is not the only factor that influenced the transport of water through caves. GBC and BCE had the largest flow volumes and cross sectional areas, while CRP (Table 3) had the smallest flow volume to cross sectional area. However, the remaining caves did not follow this pattern.

Fig. 29. Flatt's Inlet. A restricted narrow channel connecting Harrington Sound to the North Shore. This restriction created a delay in the tidal cycle (-2:45 hours) and acted as a filter of Harrington Sound's tidal range.

A smaller opening should create a restriction for water movement and, depending on the overall amount of force acting on the water, could cause the same volume of water to move through a smaller opening by increasing its velocity. Therefore, a larger conduit may not have the highest volumes of water movement in or out when compared to a smaller one.

The amount of water movement between caves and open waters could also be influenced by geographical factors such as multiple cave entrances or interior connections to large bodies of water. Many of the caves exhibited an unbalanced inflow to outflow ratio (GBC, CRP, LMC, JDN, and BCE). In order for this to occur, the gradient that facilitated water movement must have been lower at another location to draw water away from the original source. An alternate entry point would modify this gradient depending on the location. If the additional opening were connected to the same body of water (e.g. Harrington Sound) then flow would diffuse equally between the two entrances allowing for a lower volume of water output into the open water through the original opening, and exhibiting higher inflow volumes during the next tidal cycle.

A connection to an alternate body of water (e.g. an inland pool, the North Shore, or Harrington Sound) would allow for differences between in and outflow volumes. All the groundwater in Bermuda is influenced tidally. This is true even for inland ponds (Iliffe 2000). Some tides in Bermuda (e.g., Harrington Sound, inland pools) are out of sync from the open ocean due to time delays and geographical barriers (Iliffe 2000, Morris et al. 1977). If a cave were connected to an alternate body of water, with a different tidal cycle, there could be a change in the overall water gradient. Therefore, the volume and force of water moving would be different between in and outflow values.

Spring or neap tide changes tidal ranges, thus affecting the overall volume exiting the caves. Though no caves were sampled during a new or full moon, there might have been some gradient changes due to this factor. Tidal ranges at Esso Pier increased an average of 0.5 m from spring to neap tide. This effect was trivial to the current study but would prove an important factor if sampled for longer periods of time (>1 month).

The flux magnitude and water volume of individual caves was dependent on the geometry of the cave. Small caves tend to have higher velocities than larger ones with the same amount of force acting upon flow. However, larger caves exhibit higher volume outputs than smaller ones due to the increased conduit sizes. The imbalance between inflow and outflow volumes suggests that there are multiple cave entrances or water sources connected to a particular cave network. This is not a new concept. Iliffe (2000) described coastal caves to have a complete exchange of water from tidal currents, though the main entrances may not have been the only water source. Iliffe et al. (1984) noted changes in water clarity and chemistry in cave pools when nearby caves (previously not thought to be connected) were being used as a dumping ground. With the ADV, it might be possible to find those connections that are otherwise inaccessible to divers, using current flow measurements.

Conclusion

Bermuda cave springs are important the Bermuda nearshore ecosystem as a whole. They are the connection between land and sea and have the potential to transport

millions of litters of water into the open bays every six hours. Each cave sampled in this study proved to be highly influenced by ocean tides. Therefore, outflowing tides could be timed almost to the minute. However, due to their individual characteristics, such as geometry, location, and the matrixes of tunnels, these caves were unique in comparison to each other.

Understanding water movement and transport through these highly interconnected tunnels can give an insight on residence times and pollution transport from the groundwater to the open bays. Longer sampling should be conducted to fully understand flow volumes as these could be a crucial piece of the environmental food web.

CHAPTER III

WATER QUALITY

Introduction

Cesspit seepage in Bermuda was not a new occurrence. Iliffe (2000) believed sewage contamination to be the source of elevated nutrients in inland cave pools. Also, in a study from 1982, cesspits were seen as the primary source for groundwater contamination in Bermuda (Sterrer & Barnes 1982). Sterrer and Barnes (1982) stated sewage input into cesspits accounted 3.59 million liters per day when the population was 54,800 inhabitants (NationMaster 2009). Sewage typically contains 0.6% nitrogen, which equates to 5×10^8 M (molar) cesspit nitrogen flux per year (Simmons & Lyons 1994). Given a current population 66,532 residences (CIA world Factbook 2008), there would be an expected 21% increase in sewage input possibly yielding 4.43 million liters per day (based on an mean value of 66.6 liters of sewage produced/ person/ day). The question then becomes how much sewage is contained within the limestone, or leaked into the nearshore environment?

Population growth near aquifers such as those in Florida, the Florida Keys, and Texas has been linked to elevated groundwater nutrient concentrations (Lapointe et al. 1990, Hudak 2000, Finkl & Chartier 2003). This threatens endangered endemic cave species, creates non-potable water, and introduces large quantities of nutrients into connecting ecosystems leading to other problems such as eutrophication.

An additional problem associated with anthropogenic nutrients is the shift in primary producers and the alteration of the food web of the effected ecosystem (McGlathery 1995, Deegan et al. 2002). In the late 1970's, a bloom of the green alga *Cladophora prolifera* occurred throughout most of the inshore waters in Bermuda (von Bodungen et al. 1982, Thomas 2004). The use of cesspits as an onsite sewage disposal system led to nitrate contamination of groundwater that, when carried through groundwater discharge, resulted in an elevated nutrient flux and a bloom of *Cladophora* (Simmons et al. 1985). The bloom lasted for three years and produced mats up to one meter in thickness (Barnes & von Bodungen 1978, von Bodungen et al. 1982, Thomas

2004). As a result, oxygen levels became used up due to bacterial decomposition, leaving several bays depleted of their formerly abundant fauna and flora (Thomas 2004). The bloom still appears for short time spans in the summer months (Thomas 2004). This algae bloom represented one of the most dramatic changes to the Bermuda marine environment in 30 years (Von Bodungen et al. 1982).

Bermuda has a subtropical climate. The Gulf Stream current creates two main seasons that are based on the average amounts of rainfall (The Bermuda Turtle Project 2009, turtle.org/bermuda/environment.htm). The wet winter season (November through April) receives a total average of 15 cm of rain, while the dryer summer season (May through October) can have a total of 10 cm of rain (Morris et al. 1977). The offshore sea surface temperature in Bermuda varies seasonally between 18 to 28°C due to sea surface heating and stratification (Morris et al. 1977). Since surface run-off through the limestone can carry land contaminates into the groundwater system, karst springs, such as those in Florida, have been found to contain higher amounts of nitrogen and phosphorus during wetter seasons (Lapointe et al. 1990).

Water quality measurements including dissolved inorganic nitrogen (DIN), $HPO_4^{=}$, temperature, salinity, pH, and dissolved oxygen were undertaken in June-July 2007 and January 2008 for each of the tidal springs from Chapter I. Increased concentrations of nutrients, such as nitrogen and phosphorus, between tidal springs could result from anthropogenic sources such as sewage seepage. Since the complete extent of most caves in Bermuda is unknown, a direct link from a cesspit to a cave cannot be determined from the study sites. However, if a cave is located under permanent structures, such as houses and hotels, then there is a greater possibility for increased levels of nutrients in cave waters. The water quality information from this chapter can be used as a baseline for future cave studies relating to developmental and housing issues.

Purpose

The objective of this study was to describe characteristics of submarine cave springs in Bermuda. This portion also attempted to determine if similar nutrient levels

were found in all cave springs. Providing all caves contained the same amounts of nutrients (DIN and $HPO_4^{=}$), then surface development did not have an effect on nutrient contamination in the groundwater supply. If this was not the case, region-specific processes (e.g. the level of surface development) may have played an integral role in regulating nutrient concentrations in cave water.

To address this, water samples were collected from caves at several times during outflowing tidal cycle to assess nutrient content. Additional sampling of bacterial levels of *Escherichia coli* and *Enterococcus* spp. was conducted to determine whether the source of pollution was derived from domestic waste. Since Bermuda has no native mammals, it is reasonable that any *E. coli* or *Enterococcus* spp. originated from a domestic source. These measurements were not designed to detect contamination from a known source (point source); rather they would determine if sewage contamination was present in cave waters and whether there is a need for further study.

Materials and Methods

Study sites for environmental parameters were the same as those surveyed in Chapter II. Nutrient water sampling was conducted in all caves during the June 2007 and January 2008 sampling periods. Fecal coliforms *E. coli* and *Enterococcus* spp. were measured in June 2007.

The level of surface development near each cave entrance and the known/presumed span of the cave systems were determined using areal photographs obtained by Google Earth. Each photograph was taken from an elevation ranging between 375 and 400 m. All structures within the cave area were counted and used to assess potential threats due to surface development if cave nutrient levels were differing from each other.

Instrumentation

Environmental parameters including water depth, salinity, temperature, dissolved oxygen, and pH were measured using a YSI 600XLM multi parameter water quality

monitor (Sonde) (Fig. 20). The instrument was calibrated prior to each deployment. The Sonde was moored inside cave entrances near the ADV for 48 hours and programmed to sample every four minutes. In the first field period in October 2006, the Sonde was moored for a minimum of 24 hours. Due to the semi-diurnal nature of tides in Bermuda, subsequent sampling for two full days facilitated examination and comparison of data from multiple tidal cycles. Sampling was completed during the neap tidal phase, within two days of a spring phase. After retrieval, Sonde measurements from the springs were examined using Microsoft Excel 2003, with parameters plotted individually as a function of time in comparison to tidal (depth) fluctuations. Reversal of water direction was interpreted by abrupt changes in salinity, temperature and dissolved oxygen where out flowing water from deep within the cave interior is suddenly replaced by inflowing open sea water.

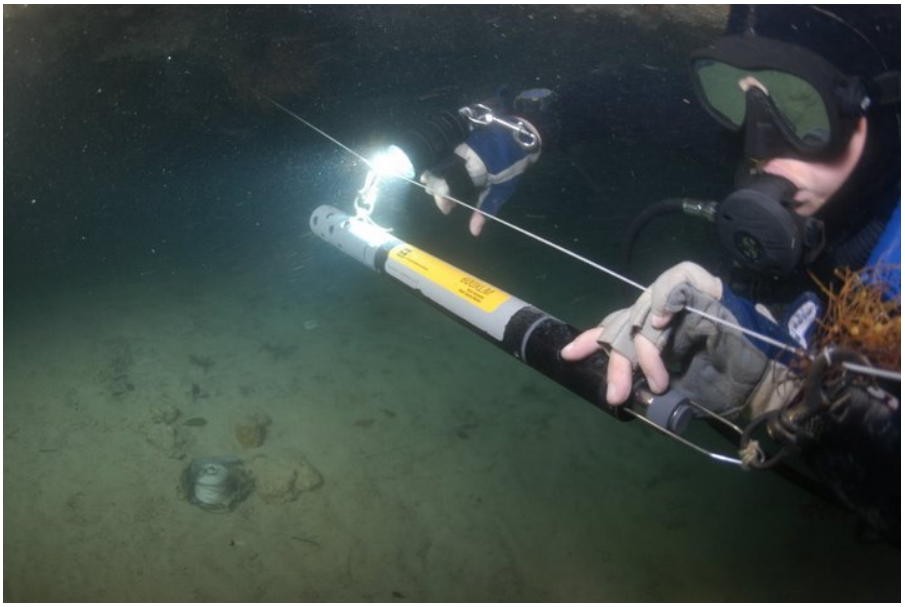


Fig. 30. YSI Sonde. This was moored with sensor pointing into Tuckers Town Bay Cave (photo by Tamara Thomsen).

Nutrient Sampling

Two subsurface water samples were collected by divers at the mouth of each cave using 50 ml sterile plastic vials – the first, at the midpoint of the tidal outflow and the second, near the end of tidal outflow when water from deepest within the cave was emerging. In January 2008, a series of samples was also taken every half hour over an entire outflow period to examine variation in nutrient concentration over a tidal cycle. Control samples of sea water were obtained from open water where the influence of cave water should have been minimal (>150 m seaward). Samples were immediately frozen and kept in the dark until analyzed by the Geochemical and Environmental Research Group (GERG) laboratory at Texas A&M University in College Station using a Technicon Autoanalyzer (detection limits in µM: NO_3^- - 0.089, $HPO_4^=$ - 0.0241, NH_4^+ - 0.0326, NO_2^- - 0.00947) (Armstrong et al. 1967).

Additional water samples were collected in 100 ml sterile vials and measured for *E. coli* and *Enterococcus* spp. levels using a modified *Enterococci* Method (Method 1600) and the original *E. coli* Method (Method 1103.1) (USEPA 2000). Samples were kept on ice in a dark cooler until analyzed (within an hour) by the Bermuda Department of Health at the King Edward VII Memorial Hospital using the membrane filtration method (USEPA 2000).

Results

Environmental Parameters

Cave water temperature demonstrated seasonal variation. As seen in Table 4, temperatures ranged from 17.3^{o}C in March 2006, 21.0^{o}C in June 2007, 29.8^{o}C in October 2007, and 21.2^{o}C in January 2008. Water exiting caves in Harrington Sound was cooler than the nearshore water in October and January and warmer in March and June. Castle Harbour and the North Shore cave waters were cooler in October and warmer for the rest of the sampling. Caves in Tucker's Town exhibited cooler water January and March, but warmer water in June and October. Salinity and pH decreased

during outflows for all study sites. TTD showed increased DO values during an outflow in March 2007, where all other caves decreased.

Salinity and pH remained fairly consistent throughout the sampling period. Highest mean salinity values were seen in TTD, which was also higher than mean ocean salinity (Morris et al. 1977) (possibly a result of improper calibration as this was the first location the instrument was used). DO values were variable ranging from 39 (CRP) to 95 (JDM) percent saturation.

Table 4. Mean environmental parameters from cave springs between October 2006 and January 2008. Values represent the mean outflow and inflow environmental parameters recorded during sampling with the YSI SONDE in the four field seasons. Outflow values are given first followed by inflow. Numbers with an * represent the standard deviation from the difference between out and inflows.

n = 9	GBC	RBC	CRP	LMC	JDN	JDM	CAS	TTD	TTB	BCE
	(out: in)									
Temperature (^{0}C)	20.2 : 21.3	23.8: 24.7	26.1: 29.1	25.2: 27.0	21.8: 19.37	23.2: 22.7.0	24.7: 27.7	23.2: 24.0	21.7: 22.1	22.2: 24.7
	*1.37	*2.29	*0.59	*0.08	*2.33	*2.79	*0.74	*1.21	*2.0	*1.89
Salinity (ppt)	34.7 : 34.9	34.9: 35.1	34.9: 34.1	34.6: 34.8	34.9: 35.5	35.4: 36.2	34.9: 35.2	36.5: 37.5	34.3: 35.0	34.4: 34.8
	*0.03	*0.03	*0.05	*0.01	*0.56	*0.28	*0.03	*0.10	*0.14	*0.52
pH	8.1: 8.2	8.1: 8.2	8.2 : 8.3	8.1: 8.3	8.0 :8.2	7.9: 8.1	8.2: 8.3	7.9: 8.2	7.9: 8.1	8.0: 8.3
	*0.06	*0.03	*0.02	*0.03	*0.02	*0.04	*0.04	*0.02	*0.05	*0.06
DO (% saturation)	78 : 97	69 : 75	39 : 58	77: 103	75: 109	95: 116	63: 90	85: 114	64: 90	68: 87
	*0.65	*1.85	*0.27	*0.42	0.43	*1.58	*0.47	*1.65	*0.74	*0.89

Nutrients

Cave water contained higher DIN concentrations than their regional controls (Table 5). Mean DIN for Harrington Sound control (4.52 µM) was less than the mean DIN for Harrington Sound caves which ranged from 5.74 µM at LMC to 8.56 µM at CRP. For individual samples, GBC had the highest DIN concentration (9.85 µM) and LMC contained the lowest (3.28 µM). Castle Harbour control (4.33 µM) was also less

than mean cave DIN concentrations compared to all caves on Castle Harbour. Caves in Tucker's Town averaged higher DIN levels than their respective control. TTD and TTB contained 22.94 and 19.97 µM while the control water sample was 17.89 µM. TTD had the highest mean DIN concentrations of all caves sampled (22.94 µM). BCE on the North Shore had 4.5 times more DIN than the North Shore control (12.81 µM compared to 2.81 µM). Ranges in Table 4 coincided with the timing of the sample collection in each cave. Minimum values were from samples taken during the middle of an outflow, and maximum values were from the end of an outflow.

$HPO_4^{=}$ concentrations were considerably lower than nitrogen (Table 5). With a mean concentration of 1.10 µM, BCE had higher $HPO_4^{=}$ levels. Harrington Sound and Tucker's Town caves had lower concentrations than their controls, while JDN was the only Castle Harbour cave with lower $HPO_4^{=}$ levels than the control. Cave nutrient values were 10 to 36.7 times higher than the open ocean, Sargasso Sea (0.02 – 0.16 µM) and Harrington Sound concentrations (0.03 – 0.05 µM) (Morris et al. 1977). The Harrington Control sample (0.52 µM) taken during this study was 10 times higher than the 1977 values (Morris et al. 1977) Samples collected by Morris et al (1977) from Jew's Bay (0.95 µM), near a hotel and a cooling outfall, were similar to levels found at BCE.

Ratio of N:P in water samples provide an indication of nutrient availability (Carruthers et al. 2005). Cave water N:P ratios, ranged from 23.9 (CRP) to 110.4 (TTB) (Table 5). The mean N:P ratio for all caves is 50.5, which was higher than all control samples except Tucker's Town.

Nitrogen was the dominant nutrient found in cave water, specifically NO_3^- (Fig. 31). NO_2^- is combined with NO_3^- (NO_x) because it comprised less than 10% of overall DIN in cave and control samples and was not considered to be of overriding significance. Excluding the Tucker's Town control sample, controls had more NH_4^+ than NO_x. NO_x was the dominant DIN component in cave water except in CRP, LMC, and BCE, which had elevated percentages of NH_4^+ relative to NO_x. LMC nutrient concentrations were similar to the open water control, where there are higher amounts of NH_4^+ than NO_x.

Table 5. Mean nutrient concentrations of $HPO_4^{=}$ and DIN from June 2007. DIN and $HPO_4^{=}$ values represent mean percentages (n=3) and range (in parentheses). Mean ratio of total dissolved nitrogen to phosphorus (N:P) calculated as the average of Total Nitrogen: Total Phosphorus ratios for each sample.
( ) represents the range; * n=1 due to vial damage during shipping.

n = 3	$HPO_4^{=}$ (µM) (range)	DIN (µM) (range)	N:P (molar)
GBC	0.37 (0.31-0.45)	7 (3.83-9.85)	41.8
RBC	0.41 (0.34-0.41)	6.74 (4.45-8.26)	40.3
CRP	0.49 (0.47-0.51)	8.56 (8.23-8.88)	23.9
LMC	0.28 (0.26-0.29)	5.74 (3.28-8.21)	61.1
JDN	0.3 (0.3)*	6.3 -6.3	41
JDM	0.38 (0.33-0.42)	9.97 (4.90-15.05)	58
CAS	0.45 (0.44-0.45)	6.37 (4.96-7.79)	31.3
TTD	0.43 (0.38-0.47)	22.54 (17.48-27.59)	118.7
TTB	0.4 (0.36-0.45)	19.97 (16.78-25.98)	110.4
BCE	1.01 (0.88-1.14)	12.81 (9.98-15.63)	28
Castle Harbour Control	0.31	4.07	30.6
North Shore Control	0.32	2.62	19.2
Harrington Sound Control	0.52	4.32	19.3
Tucker's Town Control	0.77	17.64	51.4

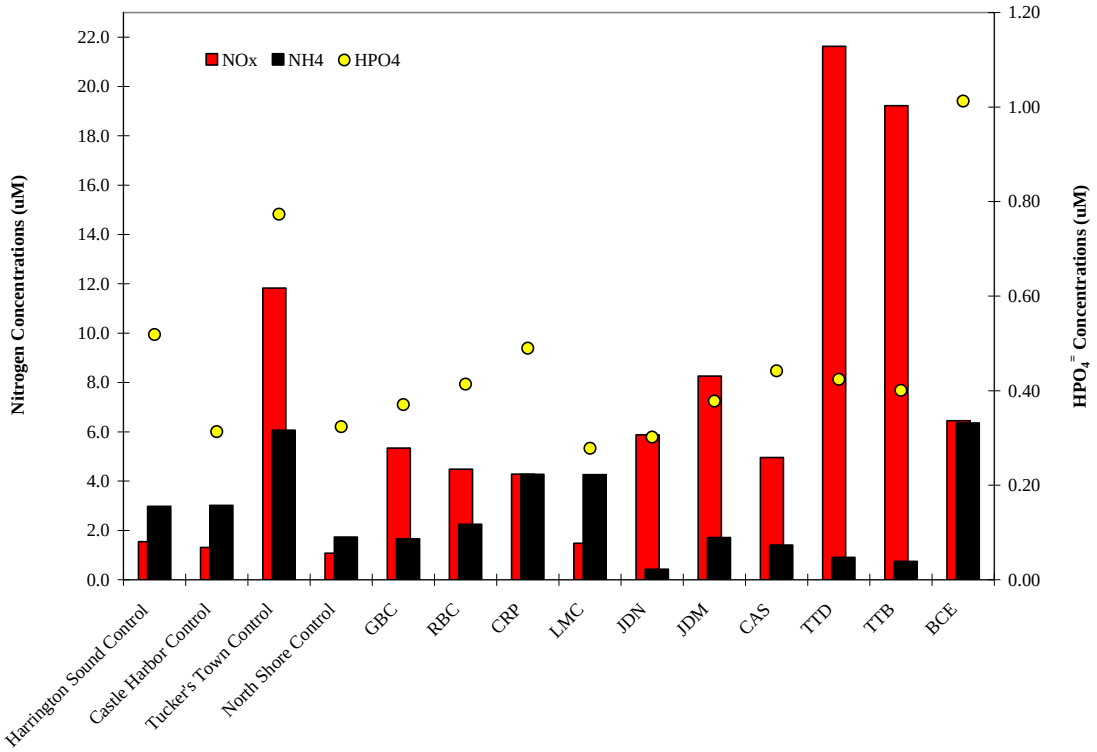


Fig. 31. Mean nutrient concentrations from cave water, June 2007. Shown are mean concentrations of $HPO_4^{=}$, NH_4^{+}, and NO_x. Note the higher concentrations of NOx in cave water as compared to the open bays. Mean $HPO_4^{=}$ concentrations were < 1.0 µM in all locations except BCE (1.01 µM).

The trend for nutrient concentrations was to increase during the outflowing tide, with the higher values being observed at the end of the tidal cycle. Water samples were taken every 30 minutes throughout an outflow in January 2008 at GBC, JDN and JDM, and TTB. Towards the end of the sampling period, JDM nutrient values decreased, which should have happened with the other caves if the sampling period had been extended, as seen in Fig. 32. TTB DIN (ranged from 14.36-33.25 µM) was the greatest of all caves from June 2007 and January 2008. Compared to the other locations, GBC was the only cave that did not have higher mean DIN values from June 2007 to January 2008.

Fecal Coliforms

Fecal coliforms measured during June 2007 (Table 6) were all within acceptable EPA limits for recreational swimming water (< 104 colonies/100ml water) (USEPA 2000). *Escherichia coli* and *Enterococcus* bacteria concentrations were measured using colonies/100 ml of water (CFU). GBC had the highest *E. coli* levels. Larger amounts of *Enterococcus* spp. were found in LMC, GBC, JDM, and TTD.

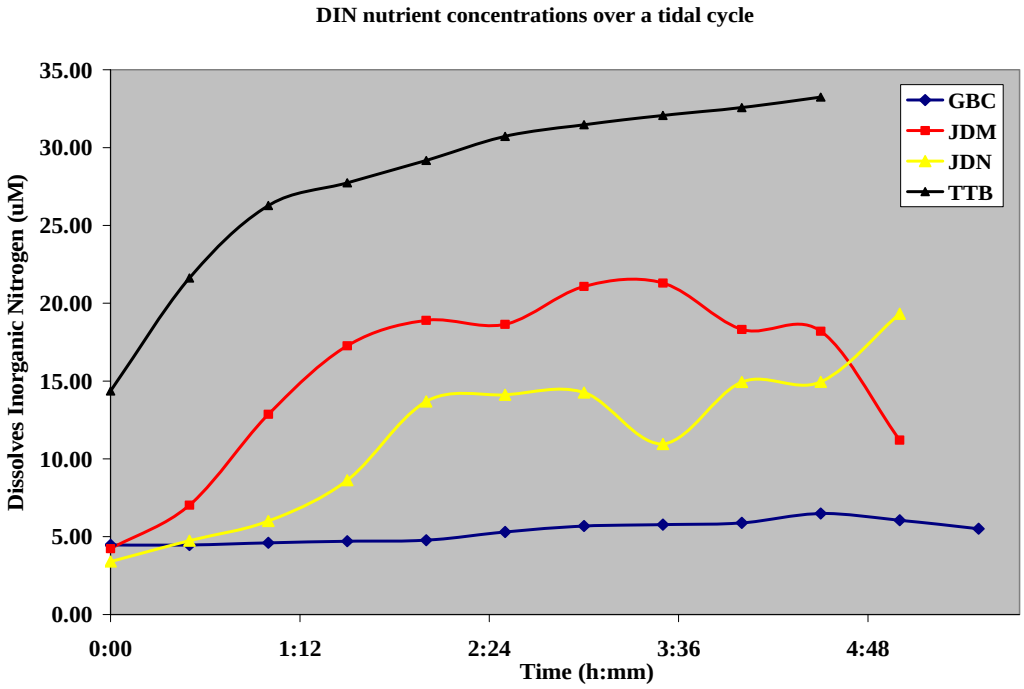


Fig. 32. DIN concentrations over a five hour outflow. Samples were from Joyce's Dock North and Middle, Green Bay Cave, and Tucker's Town Bay Cave taken in January 2008.

Table 6. Coliform bacterial concentrations from each spring in June 2007. Samples were collected at cave entrances (1-2 m depth) at the end of the outflow.

Cave Sites	*E. coli* (/100ml)	*Enterococcus* (/100ml)
GBC	31	23
RBC	3	1
CRP	<1	<1
LMC	2	34
JDN	<1	<1
JDM	<1	19
CGC	<1	5
TTD	<1	17
TTB	<1	<1
BCE	<1	3

Discussion

Once the tide turned from an inflowing to an outflowing tide, several events took place within an underwater cave. First, a reversal of water direction created by a gradient change began to push water out of the cave. That water, represented by Table 4 (inflow), first showed ocean characteristics such as higher salinity (~35 ppt), DO (> 3.8 mg), pH (~8.2) and temperature similar to the nearshore waters. Nutrient levels were also that of the nearshore environment, containing lower DIN and variable $HPO_4^{=}$ as compared to cave water (Fig. 31). Towards the end of the ~6 hour tidal outflow, the water began to exhibit more cave-like qualities (e.g., decreased salinity, DO, pH, and a change in temperature). Nutrient concentrations increased (higher DIN and variable $HPO_4^{=}$). Coliform bacterial were also more prevalent within cave water, though variable between caves.

Cave waters were generally similar. Environmental parameters and nutrients typically changed together, though this does not mean they were related to each other. From previous literature, Bermuda cave water has possessed certain qualities during an outflowing tide such as decreased salinity, pH, and DO, and increased temperatures (Iliffe et al 1983, Gibbons 2002). NO_x found in groundwater have ranged from 14 to 242 µM (Iliffe et al. 1983) in confined pools and 16 to > 400 µM in wells (Rowe 2002). To date, there has been no published data regarding nutrients in Bermuda caves springs. Bacterial sampling from 1997 detected *E. coli* levels between 1 and > 490 CFU's and *Enterococcus* spp. from 2 to > 620 CFU's in caves with and without an open water connection (Gibbons 2002). Those with a direct link to the open water contained fewer colonies than those without. This study set out to characterize caves with a direct connection to the open ocean which would allow for a better understanding of the link between inland processes and the nearshore environment.

Environmental Parameters

Cave water salinity, DO, pH, and temperature were within expected levels based on previous studies, while only temperature exhibited clear seasonal variation. Waters of

the shallow Bermuda Platform showed greater extremes of heating and cooling than the surrounding ocean waters, allowing relatively cooler cave water in the summer and warmer water in the winter. Warmer outflows could be due to the island's geothermal gradient which would heat the deeper water within the bedrock (Iliffe 2000). Seasonal variations were not evident from salinity, DO, and pH.

Decreased salinities could be explained by dilution as a consequence of rainwater infiltration through the karstic limestone bedrock. The relatively high salinity values from ground and open water reflected a great amount of mixing between the two bodies (Morris et al. 1977). Water entering cesspits was primarily fresh from toilets, showers, washing machines, dishwashers, etc. The lowest salinity concentrations from this study were 33.9 ppt (TTD) though this was obtained during the wet season when there were several storms during the sampling period. However, over a longer time frame, consistently lower salinity levels could be attributed to either daily input from cesspits and/or a release from long term recharge storage within the bedrock.

Lower DO concentrations in cave water were due, in part, to a lack of photosynthetic oxygen production in the lightless cave habitat. pH was slightly basic (above 8.0), possibly due to the biological reduction of sulfate into sulfide by bacterial decomposition (Harris 1997). The drop in pH was associated with lower salinity values. At the end of an outflowing tide, water exiting caves would be purely from a groundwater source as the ocean water (from the previously inflowing tide) had been flushed out.

Nutrients

The increased nutrient levels, specifically DIN, provided evidence that submarine tidal springs were a source of nutrients to the nearshore waters. Nutrients can be introduced into the groundwater via several paths (e.g. sewage, fertilizers, rain water run-off). Iliffe et al. (1984) described polluted and unpolluted inland caves in Bermuda. Polluted caves from this 1984 study showed obvious signs of trash in cave pools and discoloration near the surface. Iliffe et al. (1984) found that nitrogen levels were inversely related to depth and temperature; as temperature increased at deeper depths,

especially beneath a halocline. Though these caves were inland and lacked a strong tidal current, these findings provided insight to historical nutrient levels of groundwater in Bermuda. Compared to that report, all nutrients sampled during this study (cave and inshore waters) were higher in both DIN and $HPO_4^{=}$ than the 1984 inshore waters and unpolluted cave water, but on the lower end of polluted cave water concentrations, especially NO_2^-. Control samples from this study more resembled nutrients levels from the 1984 groundwater samples (that were three times higher than 1984 inshore values).

Cave springs behave in similar fashion as rivers and estuaries. Rivers typically flush more nitrogen during winter or wetter months, while collecting and transporting nutrients into bays and oceans (Rimmeline et al. 1998). River nitrogen input into the Arcachon Bay, France, was 90% of the total DIN inputs for the bay (Rimmeline et al. 1998). This is similar to findings of groundwaters in Jamaica (D'Elia et al. 1981) and Guam (Marsh 1997). Cave water contained higher concentrations of NO_x, while control samples were dominant in NH_4^+, which was the most prevalent form of DIN in Bermuda's nearshore environment (von Bodungen et al. 1982). Increased nearshore NH_4^+ in Bermuda was partially the result of a thermocline that maintained a steady NH_4^+ concentration with little flux (von Bodungen et al. 1982). Cave springs increased water mixing and resulted in a high turnover rate of nitrogen into NO_x, thus accounting for the shift in the forms of the dominant nitrogen species between the ground and nearshore waters. Before reaching the groundwater supply, terrestrial water passed through layers of soil and limestone where nitrification in the subsurface zones yielded higher NO_3^- concentrations in cave water. NO_3^- concentrations were inversely related to the oxygen concentration (Naqvi & Gattuso 2006). Higher NO_3^- was typically found in waters with lower dissolved oxygen levels. Observed NO_3^- levels (Fig. 32) were typically highest at the end of an outflow, while DO levels (Table 4) were the lowest at the same point.

Phosphorus removal by a carbonate substrate could account for high N:P ratios (mean value of 50.5) and low concentrations of $HPO_4^{=}$, as compared to the nearshore waters (as seen in Table 6) (Lapointe et al. 1990, Simmons & Lyons 1994, Cable et al. 2002). Soluble reactive phosphorus combined with calcium carbonate to produce

calcium phosphate or apatite (Lapointe et al. 1990). The adsorption of $HPO_4^{=}$ by limestone would allow nitrogen to be more mobile and add to the elevated N:P ratios in cave water, when compared to the nearshore waters. In unpolluted open ocean water, the ratio of utilization of N:P by phytoplankton is around 16:1 (Mosely & Aalbersberg 2003). Since the observed N:P ratio was above 20, cave waters were enriched with nitrogen relative to phosphorus, indicating that phosphorus was a limiting nutrient in cave water (Mosely & Aalbersberg 2003). Morris et al. (1977) also reported low $HPO_4^{=}$ values (< 2 µM) in the inshore waters, especially Harrington Sound. $HPO_4^{=}$ concentrations in this study were < 1.5 µM, similar to findings by Simmons and Lyons (1994) of 0.1 to 4 µM and Morris et al. (1977).

At the time of this project, there were increased levels of nutrients in cave waters. Nutrient addition could be from a number of sources, including waste water seepage and fertilizers. Some sites, such as JDN, JDM, TTD, and TTB, have a higher probability of fertilizer run-off or increased levels of sewage into the groundwater than others. These four sites are located on two resorts with manicured lawns. Tucker's Town also has two golf courses. Fertilizers could be a source of the higher nitrogen in Tucker's Town given the nutrient levels at the latter two caves, 16.8 – 27.6 µM DIN. Though not all locations were in close proximity to hotels and golf courses, each was at risk of possible cesspit leakage. Due to the nature of cave springs, nutrients were washed out of the system into the nearshore environment where there was ample time to mix with the open water. The continual back and forth movement of cave water from inflow to outflow may not allow for an accurate measure of nutrient loading into the open waters.

Fecal Coliforms

In 1994, cesspit seepage was the primary form of nitrogen input to the groundwater in highly populated areas of Bermuda (Simmons & Lyons 1994). Since the TTD cave system had 17 CFU of *Enterococcus* spp., this suggests some sewage contamination of the ground and cave water was occurring. However, fewer

E*scherichia coli* were present in this sample than *Enterococcus* spp. The latter is a heartier bacterium, originating from human feces.

The higher *Escherichia coli* and *Enterococcus* spp. levels at GBC may be indicative of a closer link to cesspit leakage. GBC has been mapped for more than 2.5 km and extends towards the North Shore, passing under houses, roads, and businesses. There was only one other entrance into the system, an inland sinkhole at Cliff Pool, linked to the GBC entrance by submerged passages. Coliform bacteria samples taken at the same time as the GBC samples, revealed *E. coli* and *Enterococcus* spp. levels > 200 CFU (personal communication, Bridget Maloney). Cliff Pool could be acting as a karst window into the cave system allowing surface runoff to be more directly channeled into the cave. Without detailed water quality surveys of the entire cave system, the sewage sources may never be determined. However, within the cave system, fecal coliforms exceeded the EPA standards for swimming water, which is an indication of sewage pollution.

Conclusion

Environmental parameters of cave water behaved similarly throughout this study, though each cave presented qualities that made them a unique entity. There was a presence of waste water contamination in several caves based on higher nutrient concentration and the presence of fecal bacteria, especially *Enterococcus* spp. in cave water. Nutrients could have originated from several sources (e.g. fertilizes, surface water run-off, cesspit, or additional organic mater). However the presence of the *Enterococcus* spp. bacteria in cave water suggested some level of human fecal contamination. This was most likely from sewage seepage because each cave was located near a housing unit or residential area (as noted in Chapter I).

This study did not find nutrient levels equivalent to those in direct contact with sewage outfalls, as in the Florida Keys (Lapointe et al. 1990) or from contaminated wells in the middle of Bermuda (Simmons & Lyons 1994). However, it did put into prospective that caves are a pathway for point-source pollution to enter the inshore

waters. Tucker's Town area was a prime example that the nutrient source may or may not be located directly over the known path of the cave, but still exported elevated nutrients into the open bays. Porous limestone can disperse contaminated water through the many tunnels that are believed to be crossing under the island.

Nutrient and bacterial analysis was a snapshot of conditions throughout an entire cave system at one place and time. For example, land-locked cave pools sampled along Castle Harbor and Harrington Sound showed higher levels of bacteria than coastal springs. GBC System is the longest known cave in Bermuda at 2.5 km in length and the amount of water being flushed through this system is 1.15×10^6 liters per tidal outflow (Chapter II). It was impossible to capture the whole picture in a few samples without knowing the internal environment of each cave system and the nature of the water mixing from inflow to outflow. The data presented were an initial baseline, or starting point for future analysis. Nutrient and fecal coliform sampling should be conducted over a longer span of time, months to years, to obtain a better understanding of Bermuda's groundwater.

CHAPTER IV

SEAGRASS ANALYSIS

Introduction

Human influences such as development, eutrophication, and toxic pollutants added to coastal environments are creating increasingly high amounts of stress on seagrass around the world (Cabaco et al. 2008). Seagrass is a marine flowering plant that grows in meadows, or beds. Seagrass are commonly found in shallow protected coastal areas. Seagrass utilize photosynthesis for respiration and thus require sufficient sunlight. Worldwide, there are 60 known species. Typical of tropical and subtropical areas in the Western Hemisphere, Bermuda only has four species: *Thalassia testudinum* and *Halophila decipiens*, from the family Hydrocharitaceae, and *Syringodium filiforme* and *Halodule wrightii* from the Cymodoceaceae family (Orth et al. 2006).

Seagrass beds are highly productive and diverse ecosystems inhabited by hundreds of species, especially free living microalgae, epiphytes, juvenile fish, nematodes, tube worms, and mollusk. Several species, including the green sea turtles (*Chelonia mydas*) and sea urchins, use the plant as a main part of their diet (Beck et al. 2001). Seagrass is also a key provider of organic carbon, sediment stabilization, nutrient cycling, wave reduction, shelter, and trophic transfers to nearby habitats (Orth et al. 2006). Natural threats to seagrass include storms, urchin over grazing, and desiccation. Anthropogenic disturbances, which include eutrophication, mechanical destruction of habitat, global warming, and over fishing, are the major reasons for the worldwide decline of seagrass (Orth et al. 2006).

Seagrass have developed distinctive morphological, physical, and ecological adaptations to maintain life in sub-aquatic habitats. These include epidermal chloroplast, underwater pollination, and marine dispersal (den Hartog 1970). Due to the need for extremely high light levels (25% incident radiation; Dennison et al. 1993), seagrass are responsive to changes in the environment, specifically water clarity. Seagrass and their associated micro and macro epiphytes maintain higher primary production capabilities than many cultured terrestrial ecosystems (Duarte & Chiscano 1999). Deep sea

ecosystems obtain a great portion of their organic matter from seagrass communities in the photic zone (Orth et al. 2006).

Coastal seagrass provides protection for organisms within their network of shoots and leafs. They also diffuse wave and current energy, thus decreasing wave action along the coastline. Seagrass habitats effectively filter sediments and nutrients, limiting their transport to the coastal ocean (Hemmings & Duarte 2000). Seagrass is critical to the overall survival of many other organisms and habitats. It is a nursery to economically important juvenile fish and shellfish (Beck et al. 2001). In the early 1930's, "eelgrass wasting disease" caused a wide scale die off of eelgrass throughout the North Atlantic Ocean (Rasmussen 1977) which also led to the collapse of scallop fisheries, a decline in waterfowl population, and the only known case of a marine gastropod extinction (Carlton et al. 1991).

Seagrass is an indicator of changes in the marine habitat, especially those from anthropogenic sources. The assessment of larger-scale trends is aided by seagrass's extensive distributions over tropical and temperate regions. Since seagrass live largely in shallow protected open waters near the coast, they are in the direct path of surface run-off, cave spring nutrients and sediment discharge, and therefore highly susceptible to these factors (Orth et al. 2006). Seagrass in Bermuda should be seen as important species and utilized as warning indicators for potential environmental threats.

Seagrass are generally hardy, living in habitats requiring constant adaptation. Seagrass have succeeded in evolving on a geological time scale; however, the rate of anthropogenic change occurring in the marine environment is exponential and may be too fast to allow the necessary time for adaptation (Orth et al. 2006). Nutrients in coastal runoff increase nitrogen and phosphorus inputs to the marine system. Seagrass, and other marine plants utilize both of these elements for their energy needs, but excessive amounts are harmful to their survival (Short & Wyllie-Echeverria 1996). Algae thrive on nitrogen and phosphorus, that if present in excess, creates algal blooms which lead to the loss of light and oxygen. Phototrophic organisms under the bloom can die from lower light levels. In turn, bacteria decomposing the dead matter will utilize vital oxygen

within the water column, depleting O_2 levels. (Orth et al. 2006). Low levels of light are the more damaging to seagrass, but low oxygen levels effects non photosynthetic seagrass associated species dependant upon seagrass beds (Orth et al. 2006).

Currently, Bermuda has a seagrass monitoring project under the supervision of the Department of Conservation Services. This is a long term study monitoring seagrass density and species composition from locations throughout the island (personal communication, K. Coates & S. Manuel).

The increase in human pressures has led to decreased biodiversity. An example of an area showing this trend in Bermuda is Tobacco Bay (Thomas 2004). Tobacco Bay was once a highly diverse ecosystem, contained lush seagrass and a large population of ghost crabs. The decline of seagrass and ghost crabs is believed to be a direct response to housing developments. Development of the bay led to increased numbers of bathers in the water. In the aftermath, this location was left sparse of the original fauna and flora (Thomas 2004). Also, In the 1970's, a mass algal bloom of the Common Pincushion (*Cladophora prolifera*) depleted oxygen in both the water column and sediment, killing many fauna and flora (Thomas 2004). The bloom was believed to have been a direct result of nutrient loading to the nearshore water. After three years, areas of Harrington Sound were left depleted of biota (von Bodungen et al. 1982).

Purpose

This chapter relates the presence of seagrass located near cave entrances to water nutrient quality. Differences in seagrass density near cave springs may indicate variation in nutrient concentrations between sites. There are other factors regulating seagrass growth, such as light availability, depth, salinity, disturbance of habitat, etc.; however nutrients plays a vital role to seagrass survival. Increased nutrient loads to the nearshore waters leads to eutrophication promoting the deterioration of water quality (Short & Wyllie-Echeverria 1996). The addition of nutrients has been shown to increase tissue growth and density (Fourqurean et al.1992). However, there are strong negative effects

once a threshold of nutrient concentration has been reached, resulting in a decline in growth and density, and increased epiphyte biomass (Hughes et al. 2004).

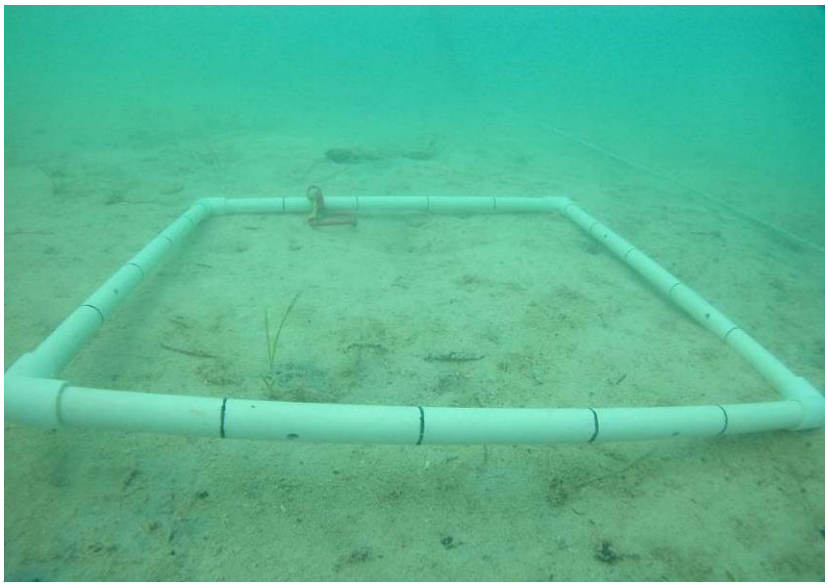
Materials and Methods

The ten caves investigated for flow volumes and water quality (Chapter II and III) were also surveyed for seagrass density within 100 m of their spring entrances between June and July 2007 using a transect-based approach. Sampling followed the seagrass monitoring protocol used by the Bermuda Conservation Service in their Permanent Seagrass Monitoring Project (personal communication, K. Coates & S. Manuel). At each cave spring, divers randomly placed ten 0.5 m^2 quadrats along a 50 m transect line running perpendicular to the coastline. These were surveyed for combined species density of Thalassia testudinum (*Tt), Syringodium filiforme (Sf), Halodule* wrightii (*Hw),* and *Halophila decipiens (Hd).* Seagrass percent cover was measured using a modified Braun-Blanquet (BB) abundance scale which assigned a numerical code to percent cover: 0.1 = one individual (Fig. 33A); 0.5 = few individuals, < 5% cover; 1 = many individuals, < 5% cover; 2 = 5-25% cover; 3 = 25-50% cover: 4 = 50-75% cover; and 5 = 75-100% cover (Fig. 33B). At each quadrat, depth, canopy height, sediment composition, visibility (visual assessment of water clarity), and presence of additional organisms was measured. Seagrass was collected when present for morphometry and stable isotope analysis following collection and preparation protocol of Duarte and Kirkman (2001). Stable isotope analysis was carried out at Florida International University.

Environmental parameters were measured using a YSI 600XLM multi parameter water quality monitor (Sonde). This instrument measured water depth, salinity, temperature, dissolved oxygen (DO), and pH at 4 second intervals. The Sonde was moored at the end of the transect line for the duration of the sampling (~30 minutes). Measurements were analyzed using the same method as in Chapter III. Nutrient samples were also taken following the same protocol as Chapter III.

Seagrass in the vicinity of cave spring outflows were measured for changes in overall and individual species density (*Tt*, *Sf*, *Hw*, and *Hd*). Density (D) was calculated by taking the sum of each quadrat BB score and dividing by the total number of quadrats giving a score between 0-5. Frequency (F), a measure of how often a species occurred within a seagrass bed, was calculated by taking the total number of species occurrences and dividing by the number of quadrats sampled per site. This yielded a score from 0 (no species occurrence) to 1 (100% occurrence).

Overall Mean density was compared to location using a Chi-Square test to determine similar seagrass coverage between sites. The relationship of environmental parameters and seagrass density was also calculated using a Pearson Correlation model. Since each transect was run from a point closest to the cave to a point 50 m away, the spatial density of individual species was measured using a linear regression. All tests were run using SPSS v. 16.0.

A) 

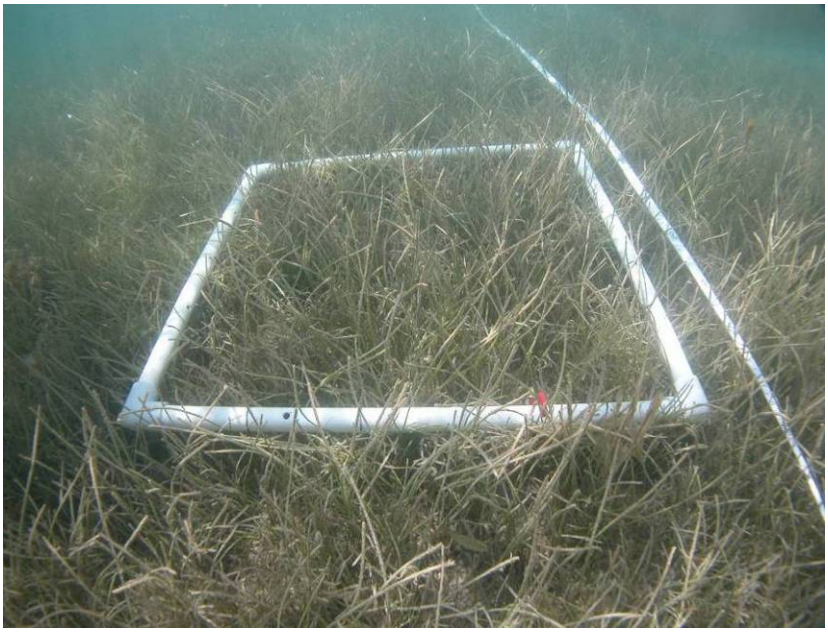
B) 

Fig. 33. Seagrass Surveys. A) single blade of *H. wrightii* in front of Joyce's Dock North Cave. B) 100% cover of *S. filiforme* outside of Red Bay Cave**.** Note the transect line along the right side of the quadrat.

Results

Surveys were conducted to identify characteristics of nearshore beds, specifically those located within 100 m of a cave spring. Only *Thalassia. testudinum*, *Syringodiu. filiforme*, and *Halodule wrightii* were encountered during this study, though *H. decipiens* was seen in similar surveys further offshore (personal communication, K. Coates & S. Manuel). All seagrass sites were covered with dense epiphytic calcareous algae commonly associated with seagrass.

Observations on seagrass beds were only recorded for sites with seagrass present. Mean values did not include zeros. Mean seagrass density between all sites ranged between 0.91 at JDM/JDN to 4.5 at RBC (BB scale) (Table 7). BCE, TTB, and TTD bays contained no seagrass. Table 6 illustrates sampling sites, species presence, and density of seagrass. Seagrass depths (mean 2.15 m) ranged from 1.21 m at CRP and RBC to 2.70 m at GBC. Canopy height (mean 24.2 cm) varied between 20 cm at GBC to 30 cm CRP. Bottom substrate was primarily sand, though the three locations without seagrass had muddy bottoms.

Species compositions from surveys were used to determine individual species density and frequency (as seen in Table 8). The following information pertains to only sites with the occurrence of seagrass and specific species. *Syringodium filiforme* was present at all sites, and *Halodule wrightii* was at all locations, excluding GBC. *Thalassia testudinum* was only seen near caves in Harrington Sound, except RBC.

Halodule wrightii had the highest mean density and frequency, followed by *Syringodium filiforme*, and then *Thalassia testudinum*. This was partially an effect of the level of occurrence of each species. Mean frequency values indicated that within the surveys, each species was observed between 57 and to 66 percent of the time.

Table 7. Seagrass survey sites in June 2007. This includes species make up, depth, location, and overall mean site seagrass density.

Site	Depth (m)	Species	Region	Mean Density BB scale
GBC	2.70	*Tt, Sf*	HS	1.30
RBC	1.21	*Sf, Hw*	HS	4.50
CRP	1.21	*Tt, Sf, Hw*	HS	1.15
LMC	1.52	*Tt, Sf, Hw*	HS	3.20
JDN	1.83	*Sf, Hw*	CH	0.91
JDM	1.83	*Sf, Hw*	CH	0.91
CAS	1.52	*Sf, Hw*	CH	2.30
TTD	12.00	X	TT	X
TTB	3.00	X	TT	X
BCE	6.70	X	NS	X

Tt = T. testudinum, *Sf = S. filiforme*, *Hw = H. wrightii*, *X* = no seagrass present
HS = Harrington Sound, CH= Castle Harbour, TT = Tucker's Town, NS = North Shore

Table 8. Mean and individual seagrass surveys for species composition. Species Density (D) and Frequency (F) were calculated within each site. Values are based on the BB scale used to during sampling. A site with no species present is marked with a (-). Values are based on the range given after each of D and F. *H. decipiens* was not found during the surveys.

Mean Values			*Tt*	*Sf*	*Hw*	*Hd*
	Density	(0-5)	1.17	1.25	1.56	-
	Frequency	(0-1)	0.57	0.58	0.66	-
Individual Values						
			Tt	*Sf*	*Hw*	
GBC	D		1.80	0.50	-	
	F		0.70	0.20	-	
RBC	D		-	2.20	3.05	
	F		-	0.90	1.00	
LMC	D		0.45	0.90	0.35	
	F		0.30	0.40	0.30	
CRP	D		1.25	1.70	1.30	
	F		0.70	0.60	0.50	
JDN/JDM	D		-	0.90	0.70	
	F		-	0.40	0.50	
CAS	D		-	1.30	2.40	
	F		-	1.00	1.00	
TTD	n/a					
TTB	n/a					
BCE	n/a					

Environmental parameters were similar between sampling sites. Temperature ranged from 24.20-27.48 °C (cooler temperatures occurred at deeper depths, GBC and BCE), salinity ranged from 33.52-35.00 ppt, and pH between 8.2-8.3. Lower salinity was attributed to the less saline cave water flow over the nearshore seagrass beds.

Plots of nutrient concentrations (Fig. 34) depicted levels of NO_x, NH_4^+, DIN, and $HPO_4^=$ associated with each cave. Of the seven caves with seagrass growth, $HPO_4^=$ levels were below 1.00 µM. When compared to cave nutrient levels (Chapter III, Table 5), NH_4^+ was the primary form of nitrogen in water sampled over the seagrass bed. Total nitrogen and phosphorus from seagrass samples are presented in Table 9. The molar N:P ratios were derived from total nitrogen and phosphorus values. Average N:P ratios for *Halodule wrightii* were the highest (32) and *Thalassia testudinum* were the lowest (26), though ratios ranged from 20 – 38 between each site.

A correlation of seagrass density to nutrients showed a negative relationship (Table 10), though this was not significant ($p > .05$). Also, density showed a larger negative correlation to depth and pH ($p < .05$).

Syringodium filiforme exhibited a spatial gradient within the nearshore sites, where quadrats contained different densities from the beginning to the end of the transect. *S. filiforme* was denser closer to cave entrances (shoreline), and declined within 50 m from the first measuring point (Fig. 35). Distance was factored against individual species density. *Thalassia testudinum* and *Halodule wrightii* exhibited variable densities, though *H. wrightii* was a more constant along the special gradient.

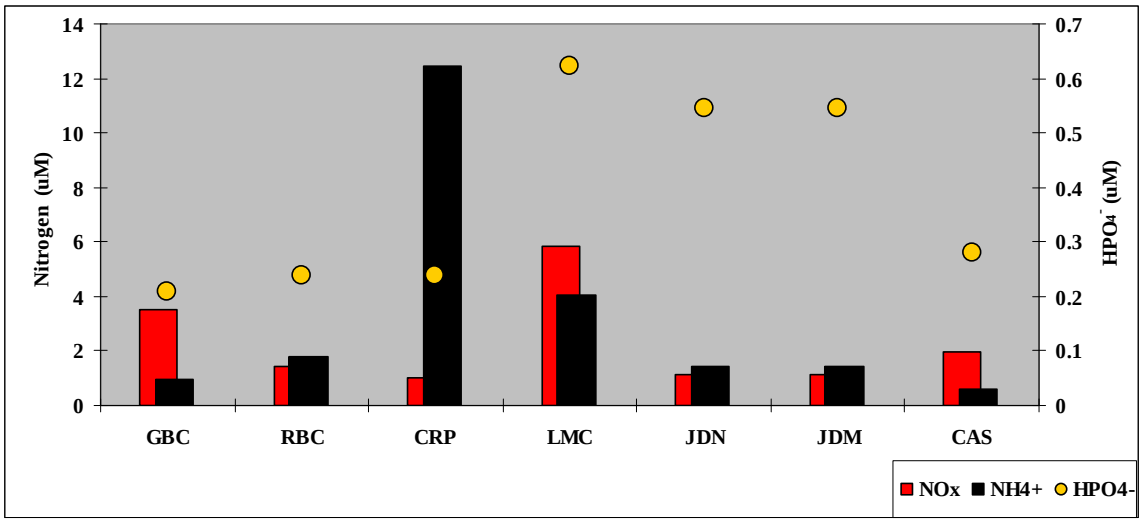


Fig. 34. Mean water nutrient concentrations from seagrass beds, June 2007. Mean NO_x and NH_4^+ concentrations from June 2007. These surface water (1-1.5 m depth) samples were taken at the time of the seagrass surveys. Mean HPO_4^- concentrations are also shown. Note there were higher concentrations of NH_4^+ than NO_x for most sites, which was different than cave water nutrient concentrations (Chapter III). Also, HPO_4^- was 3 times higher at LMC, JDM, and JDN.

Table 9. Seagrass total nitrogen and total phosphorus taken from leaf isotope analysis. Values represent mean concentrations (n = 3) and standard errors (in parentheses). Mean ratio of total dissolved nitrogen to phosphorus, N:P calculated as the mean of TN:TP ratios for each sample.

Site	Species	TN (%)	TP (%)	N:P molar
GBC	S. *filiforme*	3.0	0.22	31
	H. *wrightii*	2.9	0.23	29
RBC	T. *testudinum*	1.7	0.17	23
	S. *filiforme*	2.4	0.20	26
CRP	T. *testudinum*	2.6	0.22	26
	S. *filiforme*	2.8	0.19	32
	H. *wrightii*	2.6	0.22	26
LMC	T. *testudinum*	2.4	0.22	24
	S. *filiforme*	2.6	0.17	33
	H. *wrightii*	3.6	0.21	38
JDN & JDM	T. *testudinum*	2.8	0.20	31
	S. *filiforme*	2.4	0.18	30
CAS	S. *filiforme*	2.0	0.14	32
	H. wrightii	2.0	0.17	26
Mean	T. *testudinum*	2.69 (0.27)	0.196 (0.015)	26 (2.0)
	S. *filiforme*	2.50 (0.13)	0.20 (0.008)	28 (1.0)
	H. *wrightii*	2.37 (0.19)	0.183 (0.014)	32 (2.0)

Table 10. Pearson correlation of seagrass density to both environmental parameters and nutrient concentrations. A negative value indicates a negative correlation.

		Depth	Temp	Salinity	DO	pH	HPO_4^-	DIN
Density	Pearson Correlation	-.514**	.038	-.062	-.008	-.446**	.080	-.205
	Sig. (2-tailed)	.000	.773	.637	.950	.000	.545	.117
	N	60	60	60	60	60	60	60

**. Correlation significant at the 0.01 level (2-tailed).

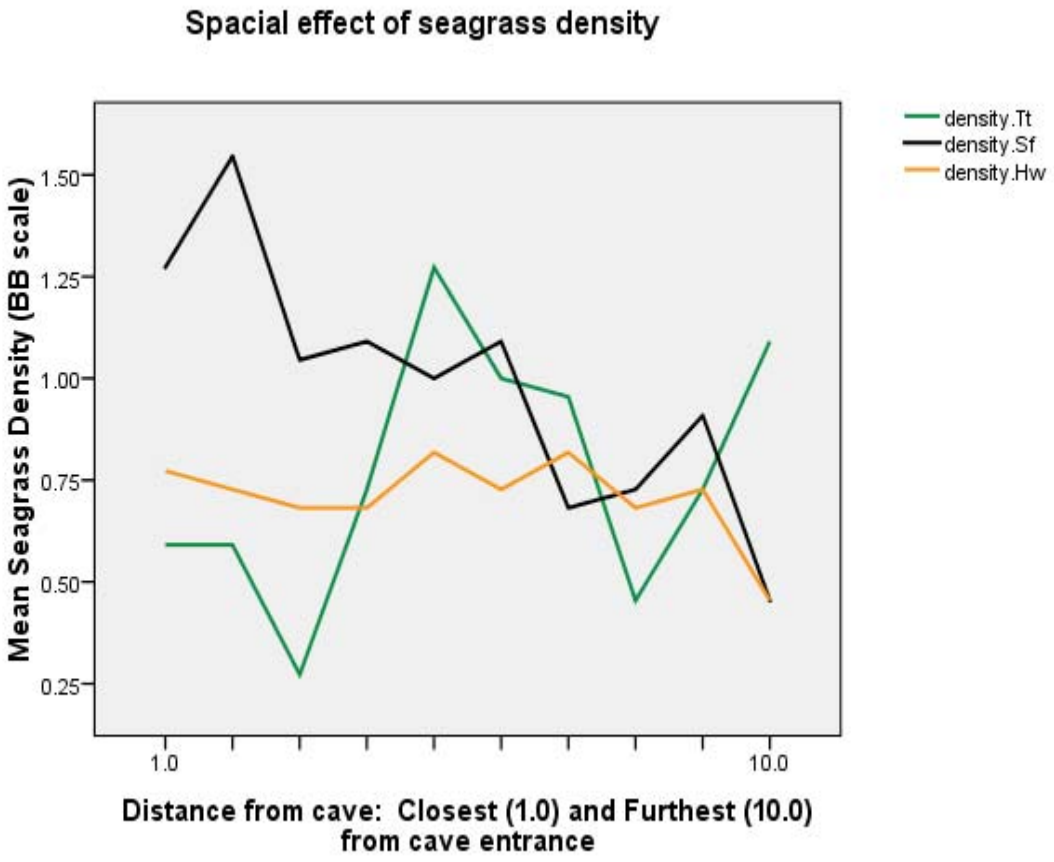


Fig. 35. Spatial gradient of seagrass density from cave entrances towards open water. Distance was measured from quadrats sampled along a 50 m transect line starting closest to cave entrance towards open water. Quadrat 1.0 was closest to cave entrance, and 10.0 was furthest away (within 150 m). Note density of *S. filiforme* decreases as the transect moves further away from the shore.
*Density.Tt = *T. Testudinum,* density.Sf = *S. filiforme, and* density.Hw = *H. wrightii.*

Discussion

Seagrass is an important nutrient sink on the ecosystem scale, but this is seasonally variable depending on the growth requirements of seagrass(McGlathery et al. 2004). Since only a small percentage of seagrass can be supported by nitrogen fixation within the sediment, most nutrients are adsorbed in the water column by the leaves and accumulated organic matter sedimented into the meadow (Welsh 2000). Therefore, the addition of external nutrients may lend to shifts in primary producer dominance, whether be it macroalgae, microalgae, or macrophytes (Sand-Jensen & Borum 1991). A seasonal shift could occur where microalgae enhance the production of phytoplankton by storing nutrients, and act as a nutrient pool. Once seagrass dies off, nutrients are released and the net effect is an elongation of a phytoplankton bloom beyond its normal nutrient limitation (Cerco & Seitzinger 1997). Negative effects of eutrophication include reduction of light attenuation, a decreased recruitment of shoots and rates of leaf appearance, and an increase in NH_4^+ concentrations (Hauxwell et al. 2000). However, *T. testudinum* may be resilient to low light attenuation by ephemeral shading because of an increased below ground biomass.

In general, seagrass meadows were patchy, with a relatively even species distribution within heterogeneous beds. There were four species of seagrass in Bermuda, although only three were encountered this study: *T. testudinum*, *S. filiforme*, and *H. wrightii*. *H. decipiens* was sparsely distributed in deeper water, characteristic of this species (Deis 2000; Murdoch et al. 2007; The Bermuda Government 2007). A higher mean density of seagrass in Harrington Sound than other regions, suggest that the enclosed, protected nature of the sound allowed for reduced wave and current action (as noted in Chapter II). Seagrass studied in Harrington Sound encountered less habitat destruction from boats, based on its close proximity and depth to shore. All three Harrington Sound caves were on private property, also restricting the level of human contact. This was evident when compared to seagrass from JDM and JDN, (average density of 0.91) which faced the highest level of direct human disturbance, being 10 m

offshore of a resort beach in 1.5 m depths where bathers wading in the water could tread on seagrass and by stirring up sediment, thus decreasing light availability.

Relative to nearshore waters, cave outflow flushed cooler, less saline water with lower pH levels onto seagrass beds in the nearshore environment. The close proximity of cave springs to seagrass beds suggests the potential for a direct impact of nutrients. Continuously changing conditions resulting from the tidal flux of water would require hearty species able to cope with the lower temperatures, salinities, the possibility of increased nutrients, and anything else transferred from within the subterranean system. This changing environment may be suitable for a mixture of species within a seagrass bed, not just a single species.

Both nearshore and offshore seagrass beds in Bermuda were comprised primarily of mixed species and comparable densities (personal communication, K. Coates and S. Manuel). This indicated nutrients from cave springs were not an immediate threat to nearshore populations. Offshore seagrass was located around the island, > 100 m from the shore, and exhibited similar densities and species composition as the nearshore locations (personal communication, K. Coates and S. Manuel).

Changes in species composition were attributed to increased depth and decreased light availability. *H. decepiens,* noted in one sample from the offshore study, was found primarily in deeper waters (Deis 2000; Murdoch et al. 2007; The Bermuda Government 2008) and was the rarest of the four seagrass species in Bermuda (Thomas 2004). *T. testudinum*, a slower growing species (Fourqurean et al. 2003), has been seen to be outcompeted by *H. wrightii* in waters of higher nutrient concentrations (Fourqurean et al. 1995). A study by Fourqurean et al (1995) noted an increase in the density and individual morphology of *T. testudinum* with the addition of nutrients, specifically nitrates. Fourqurean et al. (1995) also noted in the same study that with the addition of nutrients, *H. wrightii,* a fast growing seagrass with a higher nutrient requirement, can take over and eliminate *T. testudinum* from that area.

A study in Florida Bay observed changes in seagrass species from *T. testudinum* to a mixture of *H. wrightii* and *S. filiforme* (Fourqurean et al. 2003). These mixed

communities were associated with increased phosphorus concentrations and decreased light availability (Fourqurean et al. 2003). Due to the lack of nutrient data from the offshore sites over an extended period (10 years), this comparison could not be examined in Bermuda. However, it was a possible explanation for the changes in species composition and overall to the seagrass communities in Bermuda.

There was a correlation between seagrass presence and water quality. Seagrass have been shown to temporarily immobilize nutrients, thus influencing the physico-chemical environment (Pederson et al. 2004). Therefore, changes in the physical environment may stimulate the conservation of nutrients (Pederson et al. 2004). By doing this, seagrass can interfere with the benthic nutrient cycle, modifying oxygen levels, pH, and redox potentials. This would inevitably affect the solubility of chemical compounds changing nutrient adsorption to particles, nitrification, denitrification, and N-fixation (Wigand et al. 1997).

The dominant form of nitrogen in the nearshore waters was NH_4^+, as opposed to NO_x in cave waters. In the nitrogen cycle, NH_4^+ was either lost to the substrate or oxidized into NO_x. This then went through denitrification into N_2, or was absorbed by the marine food web. The dominant presence of NH_4^+ suggested utilization of NO_x by primary producers, mineralization in anoxic sediments, and/or bacterial reduction of NO_x into NH_4^+ (Risgaard-Peterson 2004). However, increased NO_x concentration at GRB and LMC may be due to direct seepage from a sewage source since these caves had the highest *Enterococcus* spp. levels (Ch III, Table 6).

N:P ratios of seagrass near cave outflows were 20-38, with an overall average of 29 and a species specific average N:P ratio for *H. wrightii* and *T. testudinum* of 31 and 26, as indicated by Table 8. Duarte (1990) explored percent nitrogen, phosphorus, and carbon in different seagrass species throughout the world, and found a median N:P ratio of 24, with specific ratios for *H. wrightii* and *T. testudinum* to be 37 and 25, respectively. Due to the variability of nutrient uptake from species between and within sites (McGlathery et al. 1992), the N:P ratios within this study (Table 9) were compared to the average concentrations found by Duarte (1990). This suggested that phosphorus,

not nitrogen, was the limiting nutrient in Bermuda inshore waters (Morris et al. 1977; von Bodungen et al. 1982; Simmons & Lyons 1994).

Tropical and subtropical seagrass communities tend to have higher denitrification rates than in temperate zones due to decreased levels of organic matter and bacterial oxygen demand (McGlathery et al. 2004). There was usually a higher phosphorus turn-over rate in subtropical carbonate systems compared to nitrogen where phosphorus was preferentially removed and affixed to the sediment (McGlathery et al. 2001; McGlathery et al. 2004). Jensen et al. (1998) found that of the total phosphorus affixed into the sediment, only 2% was loosely adsorbed and could be re-released into the porewater. The remaining 98% was more strongly adsorbed or permanently bound to the sediment as florapitite.

McGlathery (1995) noted seagrass density near groundwater seeps in Bailey's Bay, on the North Shore, was considerably less than seagrass farther from shore (200 m). Nutrient enrichment had a direct relationship to grazing on seagrass and was directly related to nutrient enrichment where seagrass in eutrophic waters contained higher epiphyte cover, and thus more nutrients (McGlathery 1995). In contrast, based on a linear regression, there was a general decrease in *S. filiforme* densities from quadrats further away (within 150 m) from cave entrance in the present study. This was the only species to exhibit this pattern in the nearshore environment suggesting *S. filiforme* thrived in nutrient rich, shallow waters (closer to cave entrances).

Seagrass growth may vary depending on a multitude of factors (geography, current, salinity, light, sediment, predation, etc.). Light conditions can determine species distribution. The relationship of seagrass to available light was found to be influenced by sediment conditions and water quality (Livingston et al. 1998). Short and Wyllie-Echeverria (1996) noted nutrient concentrations influenced light reduction and increased productive biomass, which effectively creates a cloud over seagrass blocking out light. Seagrass densities have been shown to decrease in eutrophic waters (DIN 5.0 µM) where nutrient enrichment had a significant effect on macroalgae cover, reducing available light (McGlathery 1995). Densely populated areas, coupled with cesspit use, enrich DIN

concentrations in water (Simmons et al. 1985). DIN levels from cave springs (0.67-26.23 µM) (Ch III, Table 5) were higher than those reported in Bailey's Bay (5.0 µM) by McGlathery (1995) and at a groundwater discharge system at Big Pine Key Florida (2.32 µM) (Tomasko & Lapointe 1991), suggesting nutrient enrichment into the nearshore waters from cave springs. However, a greater threat to seagrass beds was possibly increased surface run-off, specifically fertilizers. Fertilizers and more densely populated areas were thought to be the main reasons for high DIN concentrations in Tucker's Town as compared to other caves, such as CAS. Lower nutrient concentrations at CAS, coincided with denser seagrass beds and little surface development. Given the lower population densities near this cave, there was less opportunity for fertilizer or sewage run-off into the open bays.

Since 1962, Ward (1999) noted individual seagrass meadows in the nearshore waters have varied in size; some have declined, while others have grown. Murdoch et al. (2007) observed a decline in offshore seagrass habitats in Bermuda (at least 900 ha) between 1996 and 2004 (Murdoch et al. 2007). The exact reason for the mass decline was, to date, unknown. However, it coincided with reversal of the North Atlantic Oscillation in 1996 that caused a regional climate change (Murdoch et al. 2007). This loss was also thought to be a culmination of many factors such as cooler water temperatures in 1996 resulting in lower productivity, lower nutrient availability in the offshore region, and shorter day lengths in winter (Murdoch et al. 2007). Nearshore seagrass beds, which were "exposed to intense anthropogenic stresses", varied between 1996 and 2004, over the study period, but did not decline in overall density throughout Bermuda (Murdoch et al. 2007). Groundwater diluted rapidly once integrated into the open water. This was evident from nutrient samples taken along the groundwater seeps in Jews Bay and Bailey's Bay, Bermuda (Morris et al. 1977; McGlathery 1995). Seagrass near cave springs were not qualitatively measured by Ward (1999) or Murdoch et al. (2007), and therefore it can not be determined if nearshore seagrass were not being negatively affected.

Conclusion

Multiple parameters such as nutrient concentration and surface development interact to regulate seagrass growth and distribution. Additional factors included those linked to eutrophication, light availability, human impacts, climatic changes, temperature, wind, sediment conditions, salinity, and biological aspects such as disease and grazing. This study focused on regional distribution of seagrass in the nearshore waters, specifically those located near coastal cave springs. These springs were sampled for nutrient concentration during outflows to assess the correlation of cave nutrients to seagrass pattern and distribution. Seagrass was not found at locations with more than 12.5 µM DIN (TTD, TTB, BCE). Regions with higher DIN concentrations, the North Shore and Tucker's Town Bay, contained no seagrass within 100 m of a cave entrance. All caves in Harrington Sound had seagrass outside of the entrance, and the highest average densities.

Terrestrial development could also influence seagrass growth. Construction and land surface modifications (e.g., quarries, landscaping, etc.) change the ecosystems that are directly linked to the disturbed area. This could lead to surface run-off, increased turbidity, and cesspit leakage into the nearshore water.

Future studies on nearshore seagrass habitats are needed, especially those close to cave springs, to determine whether the primary influence on these organisms was nutrient addition. This study did not explore other factors influencing seagrass growth and density, such as turbidity, toxins, weather patterns, etc. A decline in seagrass can be due to many factors across the spatial and temporal scale (Orth et al. 2006). Species shift within a seagrass site may indicate disturbance. To identify these shifts, seagrass should be monitored seasonally over at least a three year period (Duarte & Kirkman 2001). Data within this study will provide a valuable starting point for future projects.

CHAPTER V

SUMMARY AND CONCLUSIONS

Summary

This investigation set forth to characterize the karstic and nearshore environments of Bermuda. Specifically, this study sought to describe the 1) behavior and periodicity of cave spring current velocity, direction, and flux magnitude; 2) water quality of submarine springs; and 3) nearshore marine seagrass bed density. The preceding chapters were subdivided into broad topics, though it should be noted that the subterranean environment and associated nearshore seagrass were interconnected ecosystems. One can exist without the other, though signature traces of cave outflows were recorded over seagrass beds. In order to draw conclusions regarding the interactions between these two environments, a summary of each chapter is provided:

Cave Spring Tidal Currents

Velocity and flux magnitude of cave springs were a function of the individual cave geometry, the tidal nature of the connecting body of water, and whether there were additional seeps to the open water. Tidal currents were the primary means for cave water exchange with the open water. Harrington Sound's delayed tide and reduced range was a result of the restricted nature of Flatt's Inlet (25 m^2) and the limestone permeability dissipating tidal flow through pores, cracks, and fissures. Caves along the Harrington Sound responded to imbalanced water levels between Harrington Sound and the open ocean. This gradient caused caves along the coastline of Harrington Sound to inflow, while those along the outer edge (Castle Harbour, Tucker's Town, and the North Shore) outflowed. Cave tidal spring volumes were not always a 1:1 ratio in/out, possibly the result of water flow through additional unknown openings within the cave system. Therefore, the behavior of caves spring direction was dependant upon the body of water to which it directly connected.

Water Quality

Environmental parameters and nutrient concentrations typically correlated, though they were not necessarily directly related. Outflowing cave springs sampled at the entrances had similar environmental characteristics such as decreasing salinity, DO, pH, and a change in temperature (variable with seasonal shifts). In general, the environmental parameters of cave water were consistent throughout this study, though each cave presented qualities that made them unique. Nutrient concentration (DIN and HPO_4^-) in cave outflows tended to increase towards the end of the outflow. This, coupled with the presence of fecal bacteria (*Enterococcus* spp.), indicative of sewage pollution, led to the conclusion that cave springs exhibited anthropogenic contamination, presumably from waste water. The level of pollution appeared to be minimal in most caves. Unfortunately, certain areas were considered at 'higher risk' than others given nutrient concentration, surrounding surface land development, and degree of fecal contamination. For example, caves in Tucker's Town had the highest observed nutrient concentrations both within cave waters and in the open bay. Onshore processes, such as fertilizer run-off and cesspit seepage from the two resorts with golf courses, and the many houses in the area were presumably the cause of nutrient additions to the cave systems, and consequently the nearshore bays. Other inland caves in this area could be linked through connecting subterranean tunnels which would aid in nutrient transport from a source further inland.

This data did not find nutrient levels equivalent to those in direct contact with sewage outfalls, as in the Florida Keys (Lapointe et al. 1990) or from contaminated wells in the middle of Bermuda (Simmons & Lyons 1994). However, it did put into prospective that caves were a pathway for point-source pollution to enter the inshore waters.

Seagrass Analysis

Seagrass need optimal conditions such as nutrient concentrations, light availability, and specific environmental parameters (pH, salinity, temperature, etc.) in

order to survive. Surveyed nearshore seagrass beds in Bermuda (within 100 m of coastal cave springs) were patchy, though comprised of an even distribution of three species: *T. testudinum*, *S. filiforme*, and *H. wrightii*. There was a range of densities from 0% cover (TTB, TTD, and BCE) to ~75% cover (RBC = 4.5 BB scale). Some locations seemed better suited for seagrass colonization and growth. Specifically, shallow, protected bays in Harrington Sound had the highest seagrass densities and species diversity among the study sites. Changes in species composition were attributed to increased depth, decreased light, nutrient availability, and possibly a multitude of additional factors not observed in this study (e.g., predation, currents, toxins, climate change, etc).

Increased nutrient concentrations in the nearshore waters were associated with lower seagrass densities. Nutrient input may be a function of location on the island, where the highest concentrations were found in densely populated areas (Simmons & Lyons 1994). Sites with DIN concentrations above 12.5 µM (TTB, TTD, and BCE) contained no seagrass within their bays. They also all had murky water (diving visibility < 3 m), highest density of moored boats, and the greatest amount of observed trash in their entrances. This association was not proven statistically, though the observation provides insight as to how anthropogenic influences may limit seagrass growth in this system.

There was a shift in dominant nitrogen species from ground water (NO_x) to open water (NH_4^+). Seagrass and associated primary producers were presumably utilizing/converting NO_x into NH_4^+. Therefore, the addition of external nutrients may lead to shifts in primary producer dominance (Sand-Jensen & Borum 1991). Nutrient loading from terrestrial development could influence seagrass growth through changes in landscape that allow increased surface run-off, turbidity, and potentially cesspit leakage. This would increase primary production in algae and phytoplankton, which decreases light availability.

Conclusion

The nature in which cave springs interconnected groundwater and nearshore seagrass ecosystems was subtle, but evident. Cave springs provided nutrients to the seagrass beds and in return, seagrass beds created oxygen as a byproduct that could be carried into caves via an inflowing tide (additional oxygen could also be from the atmospheric deposition).

Thus, groundwater, originating from the deep interior of caves was slightly less saline and with lower pH and DO values than seawater, flowed out from cave springs to the nearshore environments. Components commonly associated with sewage pollution (DIN, $HPO_4^{=}$, and fecal coliforms) were also found to be in higher concentrations in cave water. These pollutants most likely originated from surface processes leaching through bedrock and into cave water. Since cave springs, and all subterranean water in Bermuda were tidally influenced, any additional materials would make their way out of caves via cave springs within 18 month (recharge time for brackish groundwater as proposed by Rowe 2002). However, fecal coliforms like the *Enterococcus* spp. have a short life expectancy in marine water (< 1 to 4 days); therefore it was likely measured bacteria and accompanying nutrients were recently introduced into the cave ecosystem (Leiendecker 2007). The short transport time from cesspit to cave spring and exit to the nearshore environment raised further concern for areas with above normal nitrogen levels such as Tucker's Town.

There was a correlation between seagrass presence and a shift in nutrients from cave water, but like all ecosystems, there is a limit to the amount of any one parameter for optimal sustainability. Terrestrial processes such as sewage disposal, construction, and poor planning were the biggest issues concerning excess nutrient introduction to these ecosystems. Sewage input into the marine environment recorded in 1982 and 1994 accounted for an average 2.5-11 x 10^9 liters per year (Sterrer & Barnes 1982, Simmons & Lyons 1994). According to Simmons & Lyons (1994), groundwater flux to the nearshore environment was the major contributor to overall nitrogen (7.2 x 10^5 to 5.8 x 10^8 moles per year) from terrestrial sources. Bermuda caves are highly integrated

systems that have the potential to transport water, nutrients, pollution, and other substances to the open bays. Flow volumes were measured in an attempt to understand the forces of cave springs. Between 4 $x10^5$ to 1.96 $x10^9$ liters of nutrient-rich water were calculated to outflow during one daily cycle. With longer sampling periods (weeks to months) and more consecutive nutrient water sampling, a more accurate daily nutrient budget can be calculated for Bermuda marine ecosystems.

Previous records of seagrass decline were thought to be the result of anthropogenic stressors (Murdoch et al. 2007). Overall Bermuda has lost almost 900 ha of seagrass meadows within the nearshore and offshore environments (Murdoch et al. 2007). These declines coincided with regional climate change from the reversal of the North Atlantic Oscillation in 1996 (Murdoch et al. 2007) which caused low productivity, low nutrient availability in the offshore region, and shorter day lengths in winter (Murdoch et al. 2007).

Due to its close proximity, cave water has the ability to influences nearby seagrass meadows. Cave outflows, characterized by cooler, less saline, water with decreased pH levels was flushed out to the nearshore environment. However, there does seem to be a connection between location, nutrient concentrations, and seagrass density, although increased nutrients were measured at sites with the decreased (or absent) seagrass. Nutrients may not be the only factor limiting seagrass near some caves, as light, temperature, toxic pollutants, permanent moorings, sediment quality, etc. can influence seagrass growth (Orth et al. 2006). On a positive note, both nearshore and offshore seagrass beds were comprised primarily of mixed species and comparable densities (personal communication, K. Coates & S. Manuel), which indicated nutrients from cave springs were not an immediate threat to nearshore populations.

In the past decade, the worldwide decline of seagrass has led to the need for increased marine protected areas that include seagrass monitoring and restoration projects (Orth et al. 2006). In 2006, due to a 25% reduction in offshore seagrass coverage since 1997, Bermuda has created the Seagrass Monitoring Program designed to survey and assess the health of seagrass through yearly monitoring around the island

(personal communication, K. Coates & S. Manuel). There was no published data from the monitoring project, as it was only in its 3rd year of surveying. This study of nearshore seagrass habitats was in cooperation with Bermuda's Conservation Services to aid in planning decisions for future waste management and conservation efforts.

In closing, being one step ahead of ecosystem change is more important now than ever. Increased carbon dioxide emissions and sewage pollution can cause water to be more acidic. The low $HPO_4^{=}$ levels in cave water observed in this study was supportive of the theory that $HPO_4^{=}$ binds to the sediment and bedrock in the form of fluorapitite, virtually removing it from the nutrient web. However, dissolution of carbonates (limestone bedrock) by decreasing the pH would reintroduce $HPO_4^{=}$ into the marine environment. $HPO_4^{=}$ concentrations within this study were low (< 1.10 µM) and similar to past investigations by Simmons and Lyons (1994). Thus, the near shore marine environment in Bermuda seems to be phosphorus-limited and therefore may be sensitive to anthropogenic changes in phosphorus loading.

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