AN ENVIRONMENTAL ASSESSMENT OF BERMUDA'S CAVES

A Thesis

by

DARCY ANN GIBBONS

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

December 2003

Major Subject: Wildlife and Fisheries Sciences

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ABSTRACT

An Environmental Assessment of Bermuda's Caves. (December 2003)

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Dr. Stephen E. Davis, III

The current environmental status of the majority of Bermuda's one hundred sixty-six known caves was investigated. This survey replicated a historical cave study performed in 1983, wherein each was analyzed for positive and negative features. Statistical analysis of the data showed a significant difference between the historical and current survey ratings, with an overall decrease in environmental status.

A water quality study was performed on twenty different caves with sea level pools in various locations around the island. Nitrate, nitrite, ammonia, and phosphate levels were measured from varying depths in these caves. Fifteen of these caves were also tested for the presence of fecal bacterial contamination. High nitrate levels were discovered in some of the caves, particularly in surface samples. Additionally, bacterial contamination was detected in some caves. No obvious relationship between cave size or location and contamination existed for any of the pollutants sampled.

Three separate caves from this group were dived and analyzed using a Hydrolab Sonde 3 Multiprobe Logger to acquire *in situ* water column data including depth, temperature, pH, salinity, and dissolved oxygen. Each cave studied had its own unique trends in hydrology at varying depths in the water column.

A later water sampling study with a randomized experimental design was created and caves were divided into four classes based on size and location. Surface and subsurface samples were gathered from twelve randomly selected caves, three from each class. Each sample was analyzed for nitrate, nitrite, and ammonia concentrations. The results were analyzed using multiple analysis of variance statistics. A significant difference between the nitrate concentrations in the surface and subsurface water samples was discovered. None of the other comparisons were statistically significant.

To represent the data visually, a Bermuda Cave and Karst Information System (BeCKIS) was created using the environmental survey data and water quality information. Some of the maps generated highlighted regions where negative environmental impacts on caves were concentrated geographically, thus demonstrating how this geographic information system could be used as a conservation tool.

DEDICATION

To Andrew

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I want to thank everyone who helped out during the different phases of this thesis research project. First, thank you Dr. Iliffe for introducing me to the world of caving in Bermuda, and to the country and people of Bermuda. I will forever have fond memories of living and working in Bermuda thanks to the opportunity I had to travel back and forth to the island many times during the course of my data collection. I would also like to thank Dr. Herbert and Dr. Davis for their help throughout the writing and editing of this thesis.

My research project would not have been the same without the tremendous support, patience and field assistance from Andrew Mello, President of the Bermuda Cave Diving Association. Thank you for volunteering many hours of your time in the field to assist during the data collection phase of this project, and specifically for carrying out the cave diving that was required in order to gather the data I needed from deeper sections of the submerged cave passages. I am also indebted to the help given by my fellow interns at the Bermuda Aquarium, Museum and Zoo (BAMZ). Thank you so much Rebecca, Jonny and Matt for your help in the heat of the summer and in the downpours of December and March. I am most grateful for the technical support and advice on the GIS aspects of my project from Joe Furbert, and to Heather DeSilva who assisted me in securing permission to access many of the caves that are located on private property in Bermuda. Other employees of the BAMZ who helped out during my research trips include Dr. Wolfgang Sterrer, Dr. Annie Glasspool, and Judy Clee. Gil Nolan, coordinator of the Bermuda Cave and Karst Information System (BeCKIS), was also extremely helpful during the beginning phase of this thesis project in Bermuda, when the BeCKIS team gathered to help discuss ideas regarding the specific focus of my research.

I would not have been able to complete my research without the internship granted to me during the summer of 2002 by the BAMZ, nor without the generous grant that I was awarded by the Cave Conservancy, which allowed me to obtain the data collected during two additional research trips to the island. Last but not least, I want to acknowledge all my family members, especially my father, for tremendous editing assistance, and my close friends, Aphroditi, Candice, Lara and Holly, who provided support and advice about my project.

TABLE OF CONTENTS

Page
ABSTRACT iii
DEDICATION v
ACKNOWLEDGMENTS vi
TABLE OF CONTENTS viii
LIST OF TABLES x
LIST OF FIGURES xi
INTRODUCTION 1
BACKGROUND 6
  Purpose 6
  Hypotheses 6
  Description of study site 7
  General introduction to threats 8
  Geology 9
    Construction/Quarrying 15
  Hydrology 18
    General cave hydrology 18
    Cave adapted fauna 20
    Vulnerability of karst topography to groundwater pollution 21
    Freshwater storage tanks and sewage 22
    Bermuda’s freshwater lenses 23
    Excess nitrates in groundwater 24
    Various examples of nitrate contamination 27
    Use of Enterococcus as a contaminant indicator 29
  Tourism and anthropogenic impacts on caves 32
  Bermuda Cave and Karst Information System (BeCKIS) 33
MATERIALS AND METHODS 35
  Comprehensive environmental cave survey 35
  Preliminary water quality sampling 39
  Characterization of water column chemistry 43
  Diving safety and protocol 45
  Setup of water quality sampling ANOVA experiment 45

Page

RESULTS.......... 50

Comprehensive environmental survey: 1983 and 2002 compared 50
Comparison of surveys.......... 52
Contingency table analysis of environmental survey 1983 vs. 2002 58
Discussion of highlighted caves.......... 59
Preliminary water sampling 64
Hydrolab data 73
Water quality sampling – analysis of variance.......... 82
GIS data.......... 86

SUMMARY AND CONCLUSIONS.......... 99

Cave environmental survey.......... 99
Dumping/Littering.......... 100
Water pollution.......... 100
Vandalism.......... 101
Quarrying/Construction.......... 102
Water quality analysis 105
Hydrolab data logging.......... 109
GIS analysis.......... 110
Recommendations for future research.......... 110

REFERENCES 113

APPENDIX 118

VITA 137

LIST OF TABLES

Table Page

1 Description of positive feature rating methodology...37

2 Description of negative feature rating methodology..38

3 Categorization of caves chosen for water sampling in December 2002
(* denotes that a cave dive was used for water sampling) 42

4 Parameter specifications for the Hydrolab DataSonde 3 Multiprobe 44

5 Caves randomly selected for water sampling analysis of variance
experiment 48

6 Contingency tables for each negative category with observed
and expected values..58

7 Chi-squared values for negative environmental ratings from 1983 versus
2002 contingency tables...59

8 Preliminary cave water quality sampling December 2002.......................................65

9 Mean nitrate and ammonia concentrations in randomly sampled caves..................83

10 Descriptive statistics of water quality data...84

11 Analysis of variance of water quality data...85

LIST OF FIGURES

Figure Page

1 Map of Bermuda. 1

2 Fossilized bird bones in Jane's Cave with Bermudian coin for scale 3

3 Old wooden torch in Jane's Cave 4

4 Map of cave locations. 7

5 Major types of rock formations in Bermuda, created by The Ministry of Works and Engineering of the Bermuda Government. 12

6 Drapery speleothems in Shop Cave. 14

7 Stalactites in Kitson Cave. 15

8 Photo of Wilkinson Quarry. 16

9 Vertical water sampler (Aquatic research webpage). 48

10 Breakdown of caves with improved, worsened, and identical ratings in each negative category between 1983 and 2002. 53

11 Breakdown of vandalism ratings in 1983 and 2002 (1 = least endangered, 5 = most endangered). 54

12 Breakdown of dumping and littering ratings in 1983 and 2002 (1 = least endangered, 5 = most endangered). 55

13 Breakdown of water pollution ratings in 1983 and 2002 (1 = least endangered, 5 = most endangered). 56

14 Breakdown of ratings for quarrying and construction in 1983 and 2002 (1 = least endangered, 5 = most endangered). 57

15 Trash that still remains under the overhang in Sear's Cave. 63

16 Nitrate concentrations at increasing depth in Tucker's Town Cave. 69

17 Cliff Pool nitrate data at increasing depth. 70

Page

18 Straw Market Cave nitrate data at increasing depth. 70

19 Temperature versus depth in Tucker's Town Cave (0-17 m). 73

20 Salinity versus depth in Tucker's Town Cave (0-17 m). 74

21 pH versus depth in Tucker's Town Cave (0-17 m). 74

22 Dissolved oxygen versus depth in Tucker's Town Cave (0-17 m). 75

23 Temperature versus depth in Straw Market Cave (0-6 m, 6-19 m). 76

24 Salinity versus depth in Straw Market Cave (0-6 m, 6-19 m). 77

25 pH versus depth in Straw Market Cave (0-6 m, 6-19 m). 77

26 Dissolved oxygen versus depth in Straw Market Cave (0-6 m, 6-19 m). 78

27 Temperature versus depth in Cliff Pool (0-17.8 m). 80

28 Salinity versus depth in Cliff Pool (0-17.8 m). 80

29 pH versus depth in Cliff Pool (0-17.8 m) 81

30 Dissolved oxygen versus depth in Cliff Pool (0-17.8 m). 81

31 Geographical distribution of caves compared in 1983 and 2002 survey. 87

32 Map of vandalism ratings for the 1983 survey (1 = least endangered, 5 = most endangered) 88

33 Map of vandalism ratings for the 2002 survey (1 = least endangered, 5 = most endangered) 89

34 Map of dumping ratings for the 1983 survey (1 = least endangered, 5 = most endangered). 91

35 Map of dumping ratings for the 2002 survey (1 = least endangered, 5 = most endangered). 92

36 Map of water pollution ratings for the 1983 survey (1 = least endangered, 5 = most endangered). 93

Page

37 Map of water pollution ratings for the 2002 survey (1 = least endangered, 5 = most endangered). 94

38 Map of quarrying ratings for the 1983 survey (1 = least endangered, 5 = most endangered). 96

39 Map of quarrying ratings for the 1983 survey (1 = least endangered, 5 = most endangered). 97

40 Cave locations that were compared in the two surveys and locations of caves that have been destroyed since the 1983 study with the Walsingham rock formation displayed. 98

INTRODUCTION

Bermuda is a small and isolated island located in the Atlantic Ocean, at 32º N latitude and 64º W longitude (Figure 1). Despite its size, Bermuda has a higher concentration of caves per unit area than any other country in the world (Iliffe personal communication). These caves are unique in that they have well-preserved and beautiful speleothems (e.g. stalactites and stalagmites), both in air-filled rooms and underwater passages. A variety of tiny rare cave adapted invertebrates, most of which are endemic to Bermuda thus far, have been discovered in Bermudian caves.

Figure 1. Map of Bermuda.

This thesis follows the style and format of Limnology and Oceanography.

The caves in Bermuda not only hold intrinsic value due to their natural beauty and unique cave adapted fauna, some of which are considered “living fossils,” but also represent an important historical resource. Since the time when Bermuda was originally discovered, there have been a number of accounts recorded of early explorers investigating and seeking refuge in the caves on the island. For example, the first reference to Bermuda’s caves was in 1624, by Captain John Smith, who wrote about his voyages to Bermuda, stating that in some places there were “verye strange, darke and cumbersome caues” (Smith 1624).

One of the more well-known caves on the island, Admiral’s Cave, holds historical significance, as it received its name from Sir Admiral David Milne, who in 1819 removed a large stalagmite from the cave and brought it to a museum in Edinburgh, Scotland. Forty-four years later, the Admiral’s son returned to Bermuda, determined that 33.3 cm^3 of stalagmitic material had been deposited onto the stump of the remaining stalagmite, and thereby calculated that the speleothem was 600,000 years old, assuming constant deposition (Milne-Home 1866). To this day, the stump of the old stalagmite still sits in the cave.

Some caves also contain relicts which evidence events that occurred much earlier in the history of the cave. For example, some caves on the island contain fossilized bird skeletons, some of which are believed to be cahow bird bones, revealing a time in Bermuda’s history when the currently endangered cahow population was much larger (Figure 2).

Figure 2. Fossilized bird bones in Jane’s Cave with Bermudian coin for scale.

Another feature in the caves that shows the presence of earlier explorers includes black soot on the ceilings of some of the caves, which was deposited by either wooden torches or kerosene lamps before the time of batteries and flashlights. In one particular cave, Jane’s Cave, located next to a fairway on the Castle Harbour golf course, an extremely old wooden torch was discovered cemented by calcite to a slab of flowstone that was located a considerable distance into the cave (Figure 3). This relict revealed how, prior to the days when more reliable light sources became an essential part of caving, early explorers were not deterred and ventured deep into some of the more complex and physically challenging caves.

Figure 3. Old wooden torch in Jane's Cave.

Because of the beauty of the island and its high standard of living, Bermuda has become a densely populated island, and a popular tourist destination. Beautiful beaches and marine activities increase the lure of the island to tourists. The average income is quite high and unemployment is extremely low, partially explaining the fast rate of population growth. In fact, the population has almost doubled from approximately 37,000 in 1950 to about 65,000 in 2003, creating areas of high housing density on the island and explaining why the government must maintain strict immigration laws (CIA World Factbook).

A rapid pace of development persists which continues to reduce the amount of open space. Therefore, regardless of where a cave is located on the island, it is most likely to be in close proximity to some type of human environment and is therefore vulnerable to a variety of anthropogenic impacts that can lead to the deterioration of cave habitat.

BACKGROUND

Purpose

The primary purpose of this study was to characterize the environmental status of each cave in Bermuda, in order to compare its current condition to that documented in 1983 by Iliffe's comprehensive survey (1983). Because little is known about overall characteristics of water quality in Bermuda's caves, a secondary purpose was to measure nitrates, phosphates, and the level of fecal bacterial contamination in the water of a number of randomly selected caves. Ultimately, the data on caves and cave water quality that was generated by this study was entered into the Bermuda Cave and Karst Information System (BeCKIS) in the form of a geographic information system (GIS) database in order to show various characteristics of each cave on map layouts. This database was donated to the Bermuda Biodiversity Project (BBP) of the Bermuda Aquarium, Museum and Zoo. These data are intended for use in conservation efforts to protect endangered caves and cave fauna.

Hypotheses

The data collected during this study was used to test the following null hypotheses:

Ho: The current environmental status of the caves is not significantly different from that recorded in the 1983 survey.

Ho: The nitrate, nitrite, ammonia, and phosphate concentrations in each cave will not exhibit any significant differences regardless of: a) the depth from which the sample was removed; b) the distance of the cave from a potential polluting source (>40 m or <40 m), or; c) the size of the cave/underwater system (>100 m long or <100 m long).

Description of study site

While the entire island of Bermuda was considered the study site for this research project, the majority of the caves studied were situated between Harrington Sound and Castle Harbour in the Walsingham rock formation (Figure 4).

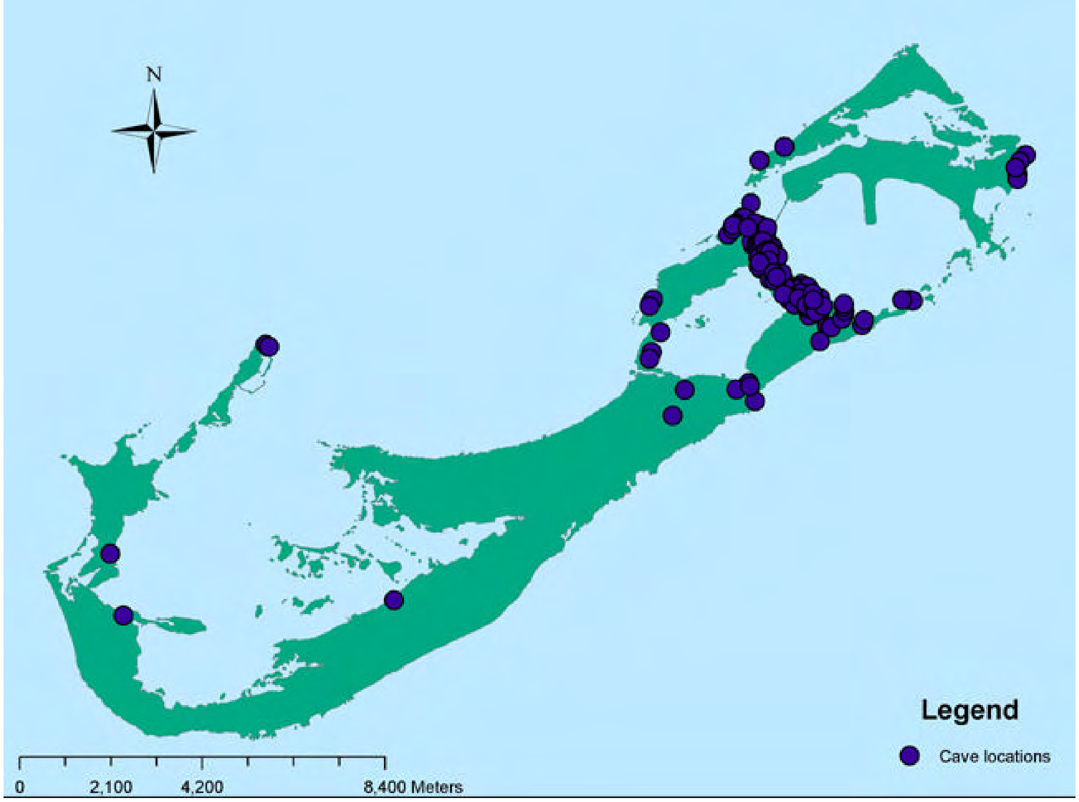


Figure 4. Map of cave locations.

During the time of the original cave survey in the early 1980s, the island's population was approximately 54,050. Although legislation enacted by the Planning Department has mandated that the preservation of open space and natural environment take precedence over other planning considerations, only 10% of the total land in Bermuda remains as natural woodland or forest (Proctor and Fleming 1999). A total of 33% of the land in Bermuda remains as open space (Anderson et al. 2001).

At the time of the original Bermuda cave survey in 1983, a total of 179 caves were known. There are a multitude of dry caves, some of which are connected to one another by diveable underwater systems. Moreover, groundwater also has the potential to travel through tiny cracks and crevices, and could hydrologically link a number of seemingly unconnected caves together underground. These narrow connections, however, are too small for cave divers to explore.

Though there are currently 166 known caves on the island, Iliffe estimates that it is likely that only about half of the total caves have been discovered (personal communication). Often entrances to the caves are concealed by vegetation, and some caves are entirely underground and have no opening to the surface. Therefore, it is not unusual in Bermuda for construction workers digging out the foundation for a new home, or quarry workers mining limestone from the stepped walls of a quarry, to open entrances into caves that would have been inaccessible for exploration and study.

General introduction to threats

Throughout the history of Bermuda, a variety of human impacts have threatened the island's cave resources. In particular, four major threats to Bermuda caves include:

filling for construction projects and limestone quarrying activities, water pollution, dumping of wastes and littering, and vandalism of speleothems and other cave deposits (Iliffe 1979). Thompson and Foster (1986) identified three principle water pollution risks including solid waste disposal, oil spillage and disposal, and unsewered sanitation. Another considerable source of water pollution on the island stems from elevated levels of nutrients in groundwater due to fertilizer runoff from golf courses and small agricultural plots.

The following background description of Bermuda's caves includes a discussion of: geology, cave hydrology, groundwater, cave biology, and environmental threats within each of these subject areas. A history of protective cave legislation enacted in Bermuda is included in the Appendix.

Geology

The island of Bermuda originally formed as a mid-ocean carbonate seamount approximately 60 million years ago (Iliffe et al. 1983). Later in the island's geologic history, about 30 million years ago, a second phase of volcanism occurred. During the early Pleistocene period, the volcanic platform was eroded by wave action to its current average depth of ~75 m below present sea level. The limestone which caps the island are principally eolianites (i.e., wind blown sand cemented into rock) that were deposited during interglacial high stands of the Pleistocene sea level (Iliffe et al. 1983).

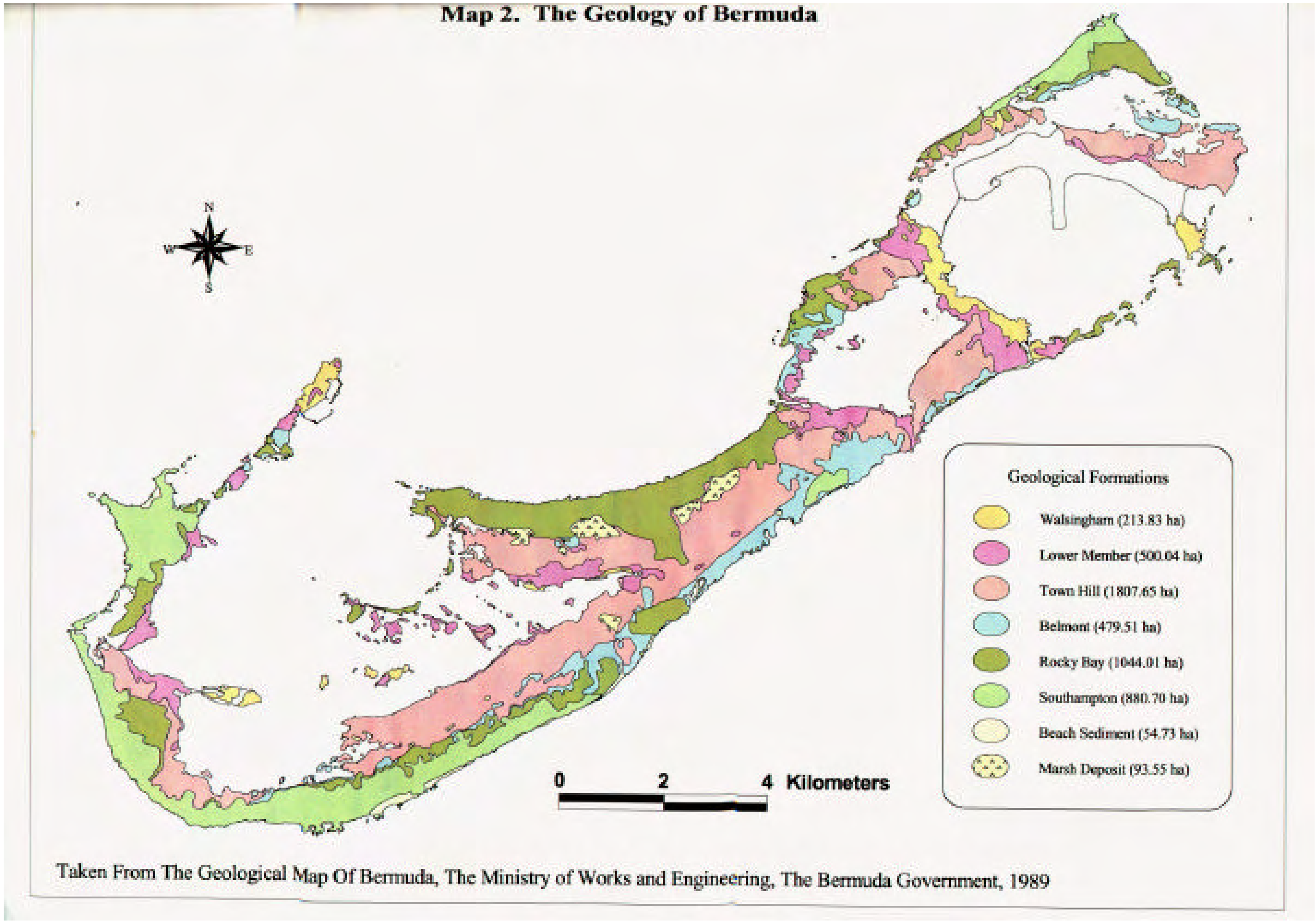
The rocks are made up of sand and calcium carbonate shells of organisms that over time were washed up and blown into dunes, which became cemented and compacted into large carbonate masses, a process known as carbonate diagenesis.

Diagenesis describes the process of compaction, cementation, dissolution, and replacement of limestone deposits, which results in consolidated rocks with a porosity no more than 15% (Ford and Williams 1989). It is possible to witness this wind-blown carbonate formation process, evidenced by exposed rock outcroppings, on nearly any beach or shoreline in Bermuda, as visible stratification layers, or bedding planes, are cemented on top of one another at a 30-45º angle. A bedding plane is produced by some change in sedimentation, represented by varying grain size, or the introduction of clay by a storm or flood (Ford and Williams 1989). Such bedding planes are also present in a number of the cave systems; angular layers of differently colored deposition are noticeable along the sides of some of the passages.

Bermuda is considered karst terrain, meaning an area of limestone or other highly soluble rock in which the landforms are of primarily solutional origin. Furthermore, the drainage is wholly underground in solutionally enlarged cracks, fissures, and conduits (caves) (Drew and Hötzl 1999). Bermuda fits this description quite aptly as there are no surface rivers, lakes, or streams, and all rainwater rapidly percolates downward through the unsaturated vadose zone and into the saturated phreatic zone of groundwater below the water table. The surficial zone of karst in Bermuda is irregularly pitted with dissolution channels and networks of great complexity through the first few meters of rock. The surface is either fully exposed or covered with a thin layer of soil and weathered material (Mylroie et al. 1995).

The most widely accepted theory of cave formation in Bermuda holds that caves were formed during glacial low stands. During times when sea level was lower over the past 1-2 million years, the island was approximately 13 times larger than it is currently, and a large fresh groundwater body—necessary for cave formation—was present. The limestone-basalt contact was located within the vadose zone and water was channeled by the irregularities of the basalt surface, and followed the downstream pathways (Mylroie et al. 1995). The island's volcanic "basement" is located, on average, at a depth of –30 m. Thus, the fact that cave divers have been able to penetrate down to a maximum depth of 24 m in the underwater caves lends support to the theory of solutional formation at the limestone-basalt interface.

The formation of caves in Bermuda, however, was confined to the Walsingham rock geological formation. This formation is the oldest and hardest of the carbonate rocks that comprise Bermuda, and therefore the most porous and most weathered of the five different formations: Walsingham, Town Hill, Belmont, Rocky Bay, and Southampton, in descending order (Vacher 1978). For this reason, caves are only found where there are Walsingham rock outcroppings in several isolated locations on the island. The highest concentration of caves is found in the Walsingham rock that is exposed between Harrington Sound and Castle Harbour on the northeast region of the island (Figure 5). Other more isolated caves are found in regions where there are smaller Walsingham outcroppings on other parts of the island. Later, when post-glacial



Taken From The Geological Map Of Bermuda, The Ministry of Works and Engineering, The Bermuda Government, 1989

Figure 5. Major types of rock formations in Bermuda, created by The Ministry of Works and Engineering of the Bermuda Government (Walsingham rock formation in yellow).

sea levels rose, seawater replaced the freshwater in the caves. Because seawater is typically saturated with calcium, submerged speleothems remained unaltered even after many thousands of years.

On the whole, Bermuda has a positive water budget; precipitation exceeds evapotranspiration. Groundwater flows both downwards and outwards towards the sea. Therefore, during the many glacial periods and sea level changes, topographic depressions, located inland between elevated areas on the periphery of the island where eolian deposition occurred, expanded and deepened through dissolution by CO_2-enriched acidic freshwater contained in the basin which percolated down and out through the porous limestone (Mylroie and Carew 1995). Thus, interdune enlargement through dissolution continuously modified the original topography of Bermuda.

The collapse that occurred when sea level fell at the start of glacial periods explains the large amount of breakdown and irregular chambers and fissure entrances characteristic of many of Bermuda's caves (Iliffe 1994). Thus, the caves that are present today on the island are most likely only a fraction of the size of the original massive solutional voids carved out by freshwater early in Bermuda's geologic history (Iliffe personal communication). The large chambers became highly unstable when sea level fell and their ceilings collapsed into hollow voids. Thus, the caves that remain today are most likely the voids located around the periphery of the centrally collapsed ceiling. A number of sinkholes do in fact exist in Bermuda today, and it is not unusual to discover caves on the edges of the central collapsed areas.

Like the caves themselves, the speleothems within the caves also formed slowly over many thousands of years, and thus can be considered nonrenewable resources (Iliffe 1979). Some of the speleothems from the collapse caves in Bermuda have been studied and were found to be at least 200,000 years old (Harmon et al. 1983). Thus, while caves can recover from certain impacts, the effects of vandalism of speleothems or the elimination of caves through quarrying are permanent in terms of the lifetime of our present society. Gamble (1981) asserts that intentional disturbance to the surface or subsurface portion of a cave is normally of a long-term nature and is usually irreversible. Figures 6 and 7 represent speleothem decoration in two separate caves in Bermuda.

Figure 6. Drapery speleothems in Shop Cave.

Figure 7. Stalactites in Kitson Cave.

Construction/Quarrying

One major threat to the internal speleothems and overall geological structure and hydrology of caves is the destruction of habitat that results from construction activities and limestone quarrying. A number of small quarries have been in operation at various times in locations on the island far from the Walsingham rock outcroppings. Material extracted from these quarries can be used, depending on the quality, as stone block and slate, or for concrete block production. It is softer than the Walsingham formation material and thus does not require the use of dynamite blasting. The hard crystalline sandstone in the Walsingham formation, in contrast, can only be quarried by blasting (Department of Planning 1988). Two major quarries are situated in the Walsingham rock formation: the Wilkinson quarry, a privately owned quarry (Figure 8), and the Public Works Department (P.W.D.) Quarry, run by the government. Though the P.W.D. quarry has not been quarrying actively for the past four years and is currently not in operation, there is still considerable rock on the property left to extract (Tankard personal communication). The material removed from these quarries is used to provide hard aggregate for concrete and asphalt (Department of Planning 1988).

Figure 8. Photo of Wilkinson Quarry.

Throughout the course of the respective operations in these quarries, a number of caves have been destroyed, including Government Quarry Cave, one of the largest and most well decorated on the island. Additionally, twelve of the thirteen remaining caves at the P.W.D. quarry that existed in 1983 have been destroyed. As sensitivity towards the cave environment was not truly introduced in any significant way into Bermuda legislation until the 1980s, countless unknown other caves on the two quarry properties were most likely destroyed. As the supply of material from these quarries is finite, it is clear that Bermuda will eventually have to rely on imported materials, as the Planning Department has asserted that there is no alternate location that could provide this particular type of hard aggregate without serious environmental damage. Furthermore, there are few large areas of land that remain undeveloped or environmentally unprotected where large scale quarrying could even be considered (Department of Planning 1988).

Quarrying away large volumes of rock in karst topography not only completely destroys caves, but it can also disrupt or alter groundwater flow paths and may alter the quantity of water flowing through the karst system. Removing rock cover lessens the buffering zone between potential surface contamination and reduces the capacity for the contaminants to be absorbed, or somewhat filtered, before entering the groundwater, and the water in the cave systems. The quarry, in essence, acts as a sinkhole, which can rapidly carry surface water to the ground water system (Hess and Slattery 1997). In fact, studies have shown that downstream groundwater in one karst system in Turkey experienced microbiological pollution from rapid infiltration of surface runoff through a quarry containing animal waste (Hess and Slattery 1997).

The development of new houses and golf courses can also be a threat to cave habitat. Sometimes new caves are discovered when leveling out the land for the foundation of a house or the fairway for a golf course. Unless the proper governmental conservation officers are notified in time, it is unlikely that such a cave would be preserved, as there has been little environmental sensitivity towards caves in Bermuda's development history, despite the detailed protective legislation enacted over the past fifteen years, and the threat of steep fines if damaged or destroyed.

Hydrology

General cave hydrology

Bermuda's cave waters are classified as anchialine environments. Stock et al. (1986) defined the term anchialine to include: "a habitat that has bodies of haline waters, usually with a restricted exposure to open air, always with more or less extensive subterranean connections to the sea, and showing noticeable marine as well as terrestrial influences." Anchialine environments are unique, as they typically have a scarcity of food, and are completely dark with no photosynthetic organisms. The pools in Bermuda's anchialine caves typically have no surface connection to the sea, are brackish to fully marine, and fluctuate with the tides. While some pools are fully marine throughout the water column, other pools exhibit stratification of water layers and contain a thin surface layer (0.5-2 m) of brackish water (0-25 ppt salinity) overlying nearly fully marine seawater (25-35 ppt salinity) (Iliffe 2000). The salt-water portion begins at about 2 m depths and extends downward to 25 m in the deepest cave pools and submarine portions of caves. The water column in these pools is quite stable because there is no wind or wave induced mixing to disturb the stratification of the less dense, brackish water on top of the higher density seawater. The interface between the brackish and salt water is known as the halocline—a distinct transition line between the two water bodies. Divers can, at certain times, distinguish this transition zone, because it tends to be a hazy and distorted layer of water.

Like salinity, temperature also increases with depth in cave water. It is thought that the temperature increase may be the result of the seamount's geothermal gradient, which creates warmer water at greater depths (Iliffe 2000). While temperature varies in the cave water depending on proximity of the underwater system to the coast, inland caves remain fairly constant at approximately 20-20.5ºC at the surface to 22.2ºC at depth year-round. The pH of water in limestone and dolomite terrains typically falls between 6.5 and 8.9 (Ford and Williams 1989). The water in Bermuda's caves is consistent with this finding and ranges between 6.5-9.0.

The water within many of Bermuda's caves is often crystal clear, especially in pools located far inside the larger caves. Several contributing factors explain the unusual clarity of the cave water. There is an absence of wind and wave induced mixing in caves, resulting in a highly stratified water column, and there is a reduced time and amplitude in tidal oscillation as compared to open water tides (Iliffe 1995). Furthermore, no photosynthetic phytoplankton is present, which means that there are low food supplies, which naturally lowers the overall biomass within cave water. In contrast to the dark parts of underwater cave systems, pools that are open to the outside environment and that are illuminated by sunlight support the growth of phytoplankton and algae, which by their presence cause reduced visibility.

Because most cave pools in Bermuda are not exposed to sunlight, there is an absence of photosynthesis and, therefore, low dissolved oxygen (DO) levels. While at the surface gas exchange with the atmosphere causes oxygen levels to be close to saturation (90%), a sharp drop in DO occurs at the halocline. DO levels remain fairly constant in deeper waters, though there are some oxygen sags in regions of fluctuating water exchange. DO levels of at least 55% saturation (3.75 mg 0_2/l H_20) were recorded in a study of seven normal cave systems (Iliffe et al. 1984). Although deeper waters have a low DO saturation level, values in normal caves still fall within the 2.0-8.0 mg/l "oxic" range in Sket's (1996) classification of DO levels in low-oxygen regimes, such as anchialine environments.

Cave adapted fauna

Iliffe et al. (1984) estimated that approximately 30% of cave species are endemic to Bermuda. Given their limited numbers and isolated geographical distribution, many Bermuda cave species are especially vulnerable to negative environmental impacts. In fact, 25 endemic, stygobitic species from Bermuda currently are classified as critically endangered on the IUCN Red List (IUCN 2000). Another important reason to concentrate on the protection of cave species is that they hold value as "indicator species" in karst areas, and their decline can warn us of the declining health of specific groundwater and karst systems (Elliott 2000), whether the cause is anthropogenic or natural in origin.

Anoxic conditions in cave water can result from anthropogenic activities (such as unlined land fills, dumping of wastes into caves, deep well injection, and cesspit seepages) or natural processes (the buildup of decaying organic matter that washes into caves from outside locations). Only microorganisms that can tolerate these polluted conditions can survive, and it is difficult to reverse the effects of the contamination.

Vulnerability of karst topography to groundwater pollution

For a number of reasons, karst topography tends to increase the vulnerability of the underlying groundwater because of its complex characteristics and irregular networking. With this topography, there is little or no soil cover, which leads to poor filtration and rapid infiltration. High flow velocities allow transit times that may be too short for microorganisms to die off, especially in shallow groundwater systems. Large numbers of interconnected fissures can result in pollution inputs from the surface to large areas of subsurface groundwater (Drew and Hötzl 1999). These vulnerabilities are quite applicable to the karst topography of Bermuda, as the island's rock formations vary in age and permeability. While some formations may act as a sponge, removing contaminants from percolating groundwater, others may act as a gutter, channeling pollutants down water into the phreatic zone (Sterrer and Barnes 1982).

Quarries are, however, not the only source of altered groundwater flow in Bermuda. Construction of new housing developments can alter the surface topography and remove soil and natural vegetation that once provided somewhat of a filter for percolating rainwater. Another potential negative result of surface changes includes an increase or reduction in the amount of recharge flowing along pathways, conduits, fissures, and eventually to the phreatic, or saturated zone of groundwater. Altered recharge volume can affect the rate of speleothem growth and development process, as calcite cannot be deposited in the absence of recharge (Hardwick and Gunn 1993). For example, a decrease in recharge following the change of vegetation cover from pasture to pine forest is known to have led to the desiccation and "fossilization" of speleothems in underlying caves (Hardwick and Gunn 1993).

Freshwater storage tanks and sewage

As indicated previously, there are no freshwater lakes, rivers or reservoirs in Bermuda. Consequently, freshwater has been a precious commodity throughout the island's history. The major source of freshwater for use within households has been collecting precipitation using specially designed stepped roof and hillside catchments, which direct rainwater into large storage tanks (Simmons et al. 1985). The larger catchments are privately owned and are used to supply businesses with water, or for selling to homeowners whose tanks have run dry during times of drought.

The government has sole control over access to wells that tap into the groundwater lenses. Water that it sells to individuals and businesses from these wells must be purified. Over the years, the individual daily consumption of freshwater has increased from 30 liters per day per person in the mid-1940s to 100 liters per day per person currently with the introduction of dishwashers and washing machines, and up to 450 liters per day per person for tourists (Vacher and Rowe 1997).

Practically all of Bermuda's domestic waste is disposed of via unlined subsurface cesspits that, in order to avoid emptying, are specifically designed to promote seepage into the limestone bedrock (Simmons et al. 1985). Waste materials from houses, including both gray water from showers, sinks, dishwashers, and washing machines, and black water from toilets, are piped into the cesspits. Raw sewage flows directly from the house drains into the cesspit and the larger solids settle to the bottom while the liquid portion seeps out through the sides (Brandes 1977). However, separation of the solids from the liquids is not very efficient, which is why cesspits only work in either coarse or highly fissured surrounding rock (Miller 1980).

While the majority of homes have cesspits connected to them, newer housing and development regulations have improved somewhat, as properties that are developed with a known cave nearby or somewhere on the property have to comply with more stringent regulations which mandate the construction of proper septic tanks which filter wastes better than unlined cesspits (Rowe personal communication).

Bermuda's freshwater lenses

Five major freshwater underground lenses have been identified in Bermuda; they are not safe, however, to use as potable water supplies unless the water is purified. These buoyant water nuclei are supplied by freshwater percolation through soils, and are technically named Ghyben-Herzberg lenses (Todd 1959). The largest lens, the Devonshire lens, is located centrally on the island; it has been estimated that 27% of the freshwater recharge comes from cesspit tank effluent, while another 2% comes from sewage plant input. Thus, it has been only used as a source of water for cleaning and flushing toilets, but not as drinking water (Simmons et al. 1985). Private residents must obtain special governmental permission to use their well as a source of drinking water.

In areas of the island with higher housing density, cesspit effluents become even more problematic and concentrated. Dense housing development leads to a higher total land area that is covered by roof catchments. This results in a greater volume of precipitation being channeled past the soil cover and all the way to the water table, as it is first stored in water storage tanks, and then used in daily household activities (showering, flushing the toilet, and washing dishes), and ultimately passes through the household cesspit en route to the water table. This increases the volume of groundwater recharge, as more rural areas would have a higher rate of evapotranspiration of water back into the atmosphere (Simmons et al. 1985). Thus, not only is the volume of water transported into the overall groundwater system increased as housing development continues, but a large majority of the water being added to the groundwater is that which is slowly leaching out of cesspits.

Excess nitrates in groundwater

Few comprehensive studies have been conducted on the quality of Bermuda's cave water, primarily because it is such a difficult environment to access and evaluate. Helpful parallels can be drawn between Bermuda's freshwater lenses and the water in caves because they both exhibit stratification of buoyant freshwater on top of denser saltwater. Moreover, the lenses can be used as a guide in designing experiments to test for water pollution in caves. Many of the studies of the freshwater lenses highlighted the exorbitant levels of nitrates (NO_3^-) present. For example, a comprehensive study of the

Devonshire lens exhibited a range of nitrate from only 1 µM to over 2300 µM nitrate (0.062 mg/l to 142.6 mg/l). The average concentration was 46.4 mg/l, which slightly exceeds the EPA drinking water standard for nitrate of 45 mg/l (Simmons et al. 1985). More recent data shows that the average level of nitrate, from groundwater tests of the lenses across the island, ranges from 40 mg/l to 56 mg/l (Simmons 2003).

Nitrate is not an initial component of domestic sewage because most of the nitrogen is tied up as organic-N or ammonium (NH_4^+). Microorganisms in soil rapidly degrade these former species, however, to nitrate and water, in the aerated, or aerobic zone (Simmons et al. 1985). Simmons et al. (1985) state that phosphates are also present in cesspit leachates, though in a lesser concentration (N:P ratio 9:1), since phosphates are removed efficiently from the percolating wastes through the process of adsorption onto calcium carbonate (Freeman and Rowell 1981). Nitrification of cesspit materials, therefore, results in pollution of the groundwater lenses by nitrate.

Nitrates have long been considered an indication of sewage pollution, and pose a danger in drinking water when levels exceed 45 mg/l, as long-term consumption can lead to a birth defect in children called “blue baby syndrome,” or methemoglobinemia (EPA 2002-Draft). Nitrates have been shown to be a good “tracer” for sewage in Bermuda, in particular, as measuring nitrate levels in groundwater correlates well with the amount and distribution of contamination by sewage (Rowe 2002). Though nitrates continue to be a contaminant in Bermuda, the problem is not unusual. Price (1996) asserts that for many decades, there have been individual wells in Britain and many other countries where nitrate levels in the groundwater have exceeded 50 mg/l or even 100 mg/l. More recently, a survey by the US EPA (2002-Draft) found that 41 states considered nitrate to represent a significant threat to the quality of their groundwater. Nitrate was the most frequently reported contaminant in the survey (Price 1996).

Another important factor that contributes to periodic higher levels of contamination of both groundwater lenses and cave water is the presence of pollutants in soils and the unsaturated zone for long periods of time. During times of high precipitation, increased levels of contamination can be flushed down into cave waters. In fact, the time lag between nitrate release from the soil and arrival in the saturated zone could take hours to decades (Drew and Hötzl 1999). A long-term study in Bermuda illustrated this trend, as data measurements showed peaked nitrate concentrations during and immediately after the drought years of 1989, 1990, and 1991. Excess nitrates were flushed into the groundwater lenses following the drought years, as this pollutant had been continually concentrated in the soil during the lengthy dry spells (Rowe 2002).

While nitrate is a concern if excess amounts are present in drinking water, such as the water from wells that tap into the groundwater lenses, cave water is too salty to use as a source of drinking water. Thus, the main concern related to the presence of excess nitrogen species in cave water is their ecological impact on cave ecosystems. As noted previously, when leaching cesspit materials filter through the unsaturated zone, rapid nitrification occurs so that nitrate is the primary species that reaches the groundwater as opposed to ammonia or nitrite. Crunkilton (1985) asserts that the presence of nitrate in cave water is nontoxic to cave organisms by itself. However, excess organic material, in the form of nitrate, could foreseeably become more problematic in a situation where dissolved oxygen levels in a cave system dropped.

While nitrate is not harmful by itself, the introduction of high levels of ammonia to a groundwater system could be much more detrimental. For example, if a cesspit were constructed directly along a transport conduit that carried water directly down into a cave pool, there might not be sufficient soil cover in order for nitrification to occur prior to the point when the ammonia reached the water. Subsequently, nitrification could occur in the cave water and a continued removal of DO from the cave water during the conversion of ammonia to nitrate could lessen the overall dissolved oxygen concentration in the water, negatively impacting vulnerable aquatic cave species.

Various examples of nitrate contamination

Nitrification is not implausible as demonstrated by an incident that occurred in November 1981, when an estimated 80,000 liters of liquid ammonia nitrate and urea fertilizer was spilled at a pipeline break near Dry Fork Creek, Missouri. For nine days following the spill, dissolved oxygen in a spring connected to this spill site underground, dropped to less than 1 mg/l, and ammonia and nitrate-nitrogen concentrations were elevated for over 38 days. This accident resulted in the death of more than 38,000 fish, and rare cave adapted crayfish, cave fish, amphipods, isopods, and gastropods (Crunkilton 1985). Water quality measurements showed excess levels of ammonia in the spring water; the ammonia was eventually converted to nitrate.

During the nitrification process in the Missouri spring, the available dissolved oxygen was consumed and no longer available to the organisms that needed it to survive.

While ammonia is a natural product of decomposition, it is rarely measured in aquatic systems at concentrations above 0.1 mg/l. The levels measured in the spring for the period following the pipeline leak far exceeded this concentration (Crunkilton 1985). It is interesting to note that the affected spring, Maramec Spring, was located 21 km away from the spill site, which again demonstrates that the ecological impacts of pollution that is introduced into karst topography can occur far from the source of the pollution.

Another study of nitrates involved the measurement of geochemical data from unconfined sand aquifers beneath two operating domestic septic systems. While septic systems differ from the more rudimentary cesspits that are typically constructed in Bermuda, the findings of this study are nonetheless useful in understanding the transport and fate of leaching waste materials. Similar to the studies of the fate of cesspit leachates in the groundwater lenses that have been performed, this study demonstrated that the septic-tank effluent underwent aerobic oxidation in the undersaturated zone, with the conversion of NH_4^+ to NO_3^-. Interestingly, the effluents were found to flow in distinct downward plumes through the undersaturated zones, and then primarily laterally in the ground-water zones (Wilhelm et al. 1996). However, the ultimate fate of the constituents of the septic effluent was dependent on the chemical conditions of the unsaturated zone—through which it was filtered—at two different sites that were examined. At one site, anaerobic conditions existed close to the plume of the effluents, and the nitrate was ultimately reduced. At the other site, the NO_3^- released from the effluent was detected as far as 100 m away from the plume (Wilhelm et al. 1996). Therefore, it is clear that when aerobic conditions are present in the vadose zone, there is a high potential for NO_3^- persistence in the groundwater at distances far from the source of contamination. This study is quite applicable to the transport of contaminants in Bermuda groundwater as the nature of karst is complex, as noted previously. Sterrer and Barnes (1982) state that since it is almost impossible to predict the flow path of effluents from a given cesspit, contamination could be discovered far from the original source.

Use of Enterococcus as a contaminant indicator

Simmons et al. (1985) assert that high levels of nitrogenous compounds also serve as a good indicator for sewage pollution and that they are most likely accompanied by a multitude of additional water contaminants. While there are a great many potential pathogens in sewage water, it would be difficult and time consuming to test for each and every contaminant. In the past, tests of the safety of recreational water relied on the measurement of fecal coliform levels. However, the EPA and other agencies have recently begun to switch to a more reliable testing method based on results from comparative tests using both fecal coliform bacteria and *Enterococcus* as indicators of pathogens. Thus, the most current method used for testing the safety of recreational saltwater is the detection of a bacterial indicator species, *Enterococcus*. While these organisms do not usually cause illness directly, compared to fecal coliform levels, they have demonstrated characteristics that make them better indicators of the presence harmful pathogens in bodies of water (EPA 2002-Draft).

Unlike the historical indicator species that was widely used to detect fecal contamination, i.e., fecal coliform bacteria, which can originate from a variety of sources, *Enterococcus* is found primarily in the intestinal tract of warm-blooded animals.

Therefore, fecal coliform bacteria are not as accurate an indicator of fecal contamination as *Enterococcus*. Moreover, E*nterococcus* is also resistant to harsh environmental factors, including saline environments, which enhance their viability in marine waters (Kane personal communication). Species within this genus are facultative anaerobic bacteria and they can survive with or without oxygen, and they can obtain oxygen form nitrate, sulfate, carbon dioxide, and other inorganic compounds when molecular oxygen is not present (Boyd 2000).

One study of the survival, transport, and dissemination of fecal coliform as compared with enterococci in a karstic aquifer confirmed a much higher persistence and better resistance of the latter in water and soil (Personné et al. 1998). A more recent study highlighted the vulnerability of karst to bacterial contamination, and affirmed that there tends to be extreme temporal variability in bacterial concentrations in groundwater and suggested event-based monitoring of the bacterial composition, such as following a period of heavy rain (Mahler et al. 2000).

The current EPA recommendations state that measured *Enterococcus* in marine water should not exceed a geometric mean of 35/100 ml, where at least five samples are gathered over a thirty-day period. If only an individual sample is tested, the level ought not exceed 104/100 ml for a designated beach area, 158/100 ml for moderate full body contact, 276/100 ml for lightly used full body contact, and 501/100 ml for infrequently used full body contact (EPA 1986 ambient water quality standards).

Though cave water is not used as a source of drinking water in Bermuda, it is considered recreational water since many of the underwater systems are regularly explored by cave divers and some of the cave pools are used by locals as swimming holes. Consequently, it is important to monitor cave water for the presence of fecal contamination, as those who recreate in the caves are exposed to potential pathogens. These pathogens can result in health problems through accidental ingestion of the contaminated water, or when the pathogenic microorganisms come into contact with small breaks and tears in the skin or ruptures in delicate membranes in the ear or nose which can result from diving into the water (EPA 2002-draft). While the most common effect of exposure to these microorganisms is illness of the gastrointestinal tract, respiratory illness could also result (EPA 2002-draft).

Detection of *Enterococcus* is a fairly new parameter used to test for fecal contamination. Therefore, past studies of Bermuda groundwater generally relied on fecal coliform counts to determine the extent of contamination. One such study determined that the fecal pollution risk was associated with the degree of limestone cementation and karstification, and with the thickness of the strata making up the unsaturated zone. In other words, where the thickness of the unsaturated zone is limited, groundwater is much more vulnerable to microbiological pollution. The study asserted that percolation through more than a few meters of unsaturated Paget limestone was effective in eliminating fecal bacteria (Thompson and Foster 1986).

Another more general study described the survival and transport of pathogenic bacteria and viruses in groundwater in relation to the type of rock in which the groundwater was flowing. Matthess and Pekdeger (1981) declare that the transport and propagation of pollutants in fissured and karstic aquifers is much faster than in porous aquifers such as sand or clay. The transport time in sand or clay ranges from <1 m per day to a few meters per day, whereas it is approximately 26 m per day in karstic aquifers. The larger paths and fissures in karstic topography allow a better transport of microorganisms, as they are less subject to adsorption to underground particles through this type of transport (Matthess and Pekdeger 1981). Coliform bacteria transport in karst, in particular, were studied using model calculations, and were found to be able to travel more than 1 km away from the source.

Tourism and anthropogenic impacts on caves

Another major impact on caves that can dramatically alter their internal environment includes the effects of human visitors, whether cave explorers or tourists. Unfortunately, the simple act of visitation by people often results in deterioration of the cave resource (Huppert et al. 1993). There are many caves in Bermuda that are particularly beautiful and large, and well adorned with speleothem decoration. These caves are historically important to Bermuda. At least seven have been commercially shown to tourist groups at one time or another over the last one hundred years. It is important that such show caves be used in order to educate locals and tourists alike about the uniqueness and fragility of the cave ecosystem.

Many tourist caves around the world, however, have suffered negative impacts of continual tourism (Huppert et al. 1993). Sometimes, excess amounts of carbon dioxide from human respiration, for example, can build up in caves. Too much carbon dioxide can cause the carbonate speleothems to begin dissolving, and to disintegrate gradually. Once gone, they are impossible to recreate. Furthermore, large groups of people in caves alter the internal environment by changing the temperature and humidity, which can in turn affect the rate of speleothem deposition.

Other problems in tourist cave systems result from a lack of understanding of how to evaluate the carrying capacity of the cave in order to monitor properly the conduct of the visitors in each group (Huppert et al. 1993). Because of this, certain disrespectful visitors are tempted by the beautiful formations and vandalize the cave in order to be able to take home a “souvenir”. Other tourists who are not properly trained or guided as on how to maneuver within the cave may accidentally break off speleothems. Other visitors are tempted to touch speleothems, unaware that their body oils can impede the further development of growing speleothems (Huppert et al. 1993). Clearly, it is extremely important to ensure that there is proper management of tourist caves so that they can be preserved for many generations to enjoy.

Cave scientists too ought to be aware of their potential impacts on cave ecosystems and should try to minimize visitation for the purposes of study and exploration of non-tourist caves and should maneuver carefully within caves to preserve the natural integrity of the environment. It is also a responsibility of these scientists not to reveal the location of particularly vulnerable or delicate caves so that potential irreparable damage by misguided individuals does not occur.

Bermuda Cave and Karst Information System (BeCKIS)

In 1997, the Bermuda Aquarium, Museum and Zoo initiated the Bermuda Biodiversity Project (BBP), a long-term research effort aimed at environmental data collection. Thus far, terrestrial and marine inventory data and aerial photographs have been entered into the BBP GIS database. A component database, known as the Bermuda Cave and Karst Information System (BeCKIS), is the location where all of the data gathered during this study will be stored and illustrated. The creation of the BeCKIS database will allow for a variety of data sources, including cave maps, species distribution, hydrographic parameters, etc., to be integrated and visualized through the creation of maps. In the future, it will be helpful in resource management decision-making.

MATERIALS AND METHODS

Comprehensive environmental cave survey

The environmental survey of the majority of Bermuda’s caves was performed during a three-month field investigation in the summer of 2002. This survey set out to replicate the 1983 survey performed by Dr. Thomas Iliffe using the same data categories. Caves were located using coordinates recorded by Dr. Iliffe during the original survey. A compass bearing was determined from a known landmark on the topographic map and then used to navigate to the cave’s entrance in the field.

Some of the caves were never located, as vegetation in some areas had become extremely dense since the time of the original survey. Other caves were not located because the map coordinates had been estimated in the original survey, making it difficult to find them during the relatively short duration of the field work. Certain caves could not be assessed because they were located on private property and landowners would not grant permission to investigate them. Lastly, some of the underwater marine caves were not investigated, as time did not permit the researcher to send divers into each underwater cave to gather information on its status.

Positive and negative features were recorded in each of the caves that were explored. In keeping with the setup of the 1983 survey, the following descriptive categories were recorded:

- map number (number of topographic quadrangle map)
- parish (name of the parish in which the cave is located)

- number (arbitrary number assigned to each cave)
- cave name
- coordinate (GPS reading at entrance)
- number of entrances to the cave
- elevation at the entrance
- SL = whether or not the cave reaches sea level (Y/N)
- CD = whether the cave has potential for cave diving (0-5 rating scale)

The following positive aspects were assessed on a scale from one to five, with five being the most positive rating possible (sometimes ratings such as 1.5 or 2.5 were used to describe the current positive or negative features because the qualities in a few caves fell in between the whole number values):

- B (biological rating)
- F (formations = speleothems)
- S (size of the cave)
- U (uniqueness of undefined positive features)
- H (historical rating)

The following table (1) outlines the rating system for each positive category.

Table 1. Description of positive feature rating methodology.

Rating	Biology	Formations	Size	Uniqueness	Historical Rating
1	No underwater portion, lack of cave adapted salt water fauna	Few to no speleothems present in cave	Less than 4 m in length, no major underwater sections	Small single room, no adjoining passages or rooms	Little historical significance to Bermuda
2	Small isolated pool (<20 m long), no significant fauna yet collected	A few smaller speleothems, low overall presence of cave deposits (30% coverage)	Less than 20 m in length, a few small rooms, tunnels to explore	Some complexity to cave, a few tunnels, layers in cave	Some historical significance to Bermuda
3	Medium sized (<50 m long), possibly diveable pool with known cave adapted fauna	A good amount of speleothems (~30% coverage), some large and significant	Less than 150 m in length, more complex cave with side passages and separate room	More complexity in layering and passages in cave, possibly other highly unique features in cave	Holds considerable historical value, such as unique internal relicts
4	Large diveable pool (total size unknown) with complex tunnels, significant, rare cave fauna continually observed	Approximately 75% coverage by speleothems, with a high number that are large and/or unique to the cave	Less than 300 m in length, with considerable side passages, and large cavernous rooms	Highly individualized structure to cave, large amount of unusual speleothems	Cave contains historical relicts (fossilized bird bones), was explored by early inhabitants
5	Large pool with many connecting passages, with leads to be explored, significant rare, possibly endangered species present	Majority of cave is well adorned with large and unique speleothems	Total size greater than 300 m, with many leads left to be explored, huge rooms and high complexity of side passages, and a large submerged portion	Extremely distinctive features within cave, shape of cave unparalleled by any other on the island	Major documentation surrounding cave throughout Bermuda's history, a number of unique relicts within cave

The following negative aspects were also assessed on a scale from one to five (Table 2), with five being the most endangered or worst threat:

- V (threat to the cave from vandalism)
- D (threat to the cave from dumping and littering)
- P (threat to the cave from water pollution)
- Q (threat to the cave from quarrying and/or construction)

Table 2. Description of negative feature rating methodology.

Rating	Vandalism	Dumping	Pollution	Quarrying/Construction
1	Little to no damage to internal features	Little to no trash dumped inside cave	Located >500 m away from any potential polluting source, no visible water pollution	Little to no threat of being damaged or destroyed
2	Some intentional breakage of speleothems, or a minor amount of other damage (graffiti)	Some trash in cave, mostly small objects	Located >200 m away from a potential point source	Small threat of being damaged or destroyed
3	Approximately 50% speleothems broken, graffiti in several places in cave	A mixture of small and large discarded items within cave	Located between 50-200 m to a potential point source, some visible trash in water	Considerable threat of damage to speleothems/overall structure by nearby quarrying/construction
4	Approximately 75% speleothems broken, graffiti in many places in cave	A lot of trash covering a significant portion of cave	Located between 10-50 m to a potential point source, a lot of trash seen in water, mild hydrogen sulfide odor in water when disturbed	High potential of portions or entire cave being destroyed by quarrying or development or
5	Almost all speleothems damaged, and/or graffiti all over cave	Entire cave used as a dump for trash	Most of cave pool/underwater passage full of trash, strong hydrogen sulfide odor in water when disturbed	High possibility that the entire cave will shortly be destroyed

Digital photos were taken at each cave entrance to provide visual information on its condition and inside to document internal features. Though GPS locations were recorded at each cave entrance, they are not included in data tables within this study so as to protect the fragile nature of Bermuda's caves. They were incorporated into the BeCKIS geographic information system, and will be available to cave scientists and explorers, as necessary. To enable future cave researchers to learn more about a certain cave or isolate a particular type of cave to study prior to going into the field, a short narrative description of each cave was written based on the data and notes collected in the field. This set of descriptions was also incorporated into the BeCKIS geographic information system.

All of the data gathered from this survey and the data gathered in the 1983 study were entered into spreadsheet format so that they could be incorporated into a GIS data layer; ArcGIS 8.3 GIS Software created by ESRI was used to create the data layer. Various layers were then created based on various data categories, e.g. vandalism and water pollution, making it possible to visualize changes in individual cave status over the past 20 years and areas where certain impacts are more or less concentrated.

Preliminary water quality sampling

The quality of the cave water is much less well understood than that in the freshwater lenses, and there have not yet been any comprehensive studies of cave water. A localized cave water quality study was conducted to investigate the effects of a massive dumping event in a cave at the Government Quarry where trash was used to fill a cave pool in order to prevent loss of overlying rock (Iliffe et al. 1984). However, aside from the 1984 study of the caves near Government Quarry, this study represents the first broad survey of water quality from varied types of caves across the island.

Based on literature that deals with Bermuda groundwater pollution, the main sources of pollution that have been identified are inorganic and organic contamination leached from cesspits, and nitrogen and phosphorus inputs from agricultural fertilizers (Jickells et al. 1988). Consequently, the following parameters were selected for this study: nitrate, nitrite, ammonia, phosphate, and *Enterococcus* bacteria. This preliminary study was not designed to generate data that could be analyzed statistically, but rather to create a general understanding of cave water chemistry across the island. Therefore, the samples collected at varying depths were not replicated, and the caves that were sampled were not selected randomly.

A total of twenty diverse caves were selected for water sampling in December 2002. Seven were located close to the shore (<100 m away), thirteen were inland (>100 m away), nine were large with extensive underwater passages (>100 m long), eleven were small with rather isolated anchialine pools (<100 m long), and lastly, nine were close to potential polluting sources (<40 m away) (e.g. homes, buildings, and agricultural plots) while eleven were located in nature preserve areas (>40 m away) (Table 3).

Surface and subsurface samples (ranging from 2-5 m) were gathered from these caves and analyzed for each of the nitrogen species and phosphate. Surface water samples were collected using sterilized 125 ml Nalgene plastic bottles. Subsurface samples were gathered using a 5 m pole constructed with a screw clamp at the end onto which a sterilized 125 ml Nalgene bottle was attached. The pole was submerged into the water and was lowered to the deepest part of the pool. A string connected to a rubber bung lodged in the opening of the bottle was pulled upwards, allowing water to flood the bottle. Subsequently, the pole was quickly raised out of the water in order to minimize water exchange, and then the bottle was removed and securely sealed.

There was considerable difficulty in accessing the pools in some of the caves; two to three hours were required to collect certain samples. Because bacterial sampling must be performed within at most 6 hours post collection, not every cave was analyzed for bacterial contamination. All samples were placed on ice and returned to the laboratory prior to sampling. For each of the other parameters, it was acceptable, based on the sampling protocol, to test within 24 hours of collecting the sample provided that it had been chilled.

More detailed sampling was performed at several of the caves where there were extensive underwater passages and pools, and where it was possible to conduct a cave dive. In these caves, samples were obtained from the following depths: surface, 1 m, 3 m, 10 m, 20 m (or maximum bottom depth) in order to characterize how pollutant concentration changes within the water column. Nalgene bottles filled with sterilized water (to prevent implosion at depth) were used. Once the individual sampling depths were reached, the diver would purge the sterilized water out of the bottle using the purge valve on his regulator, and then allow cave water to flow into the bottle. After the dive, each of these samples was placed on ice and returned to the laboratory, where it was analyzed for salinity, the nitrogen species, phosphate, and *Enterococcus* bacteria.

Table 3. Categorization of caves chosen for water sampling in December 2002 (* denotes that a cave dive was used for water sampling).

Cave Name	Nature Preserve	Residential Property	Commercial Property	Government Property	National Park	Entrance Proximity to Coastline (>, < 100 m)
Admiral’s			X			>100 m
Olivewood	X					>100 m
Cow	X					>100 m
Cordial		X				>100 m
Shop				X		>100 m
Fort Scaur				X	X	<100 m
Tucker’s Town*						>100 m
Church		X	X			>100 m
Causeway	X					>100 m
Coffee		X				<100 m
Walsingham	X					>100 m
Swizzle						>100 m
Chalk		X				<100 m
Cliff Pool*		X				<100 m
Fern Sink	X					>100 m
Cherry Pit	X					>100 m
Roadside	X					>100 m
Shrimp	X					<100 m
Canyon	X					<100 m
Straw Market*	X					<100 m

The nitrogen species and phosphate were tested using HACH water quality test kits. The cadmium reduction method with a color disc was used for both nitrate and nitrite, the salicylate method with a color cube was used for ammonia, and the ascorbic acid method with a color disc was used for phosphate. These tests follow the procedures set forth in the Standard Methods for the Examination of Water and Wastewater (Clesceri et al. 1999). Salinity was measured using a portable refractometer. *Enterococcus* bacteria levels were measured using enumeration materials designed by

IDEXX laboratories. The IDEXX enumeration powder packets were mixed with 99 ml of distilled sterilized water, and 1 ml of the cave water sample. Next, the mixture was poured into IDEXX enumeration trays that were sealed and then incubated for 24 hours at 41ºC. A 365 nm UV light was then used to count the number of fluorescing wells in the tray and the MPN table provided by IDEXX was used to calculate the MPN for each sample. All of these sampling kits recommended procedures that conform to procedures set forth in the Standard Methods for the Examination of Water and Wastewater (Clesceri et al. 1999).

Characterization of water column chemistry

A Hydrolab Data Sonde 3 Multiprobe Logger (DS3) was used to collect data about the cave water chemistry. It was employed during cave dives in caves with more extensive underwater passages and pools during the December 2002 field period. Water column profiles for the following parameters were collected:

- depth
- temperature
- salinity
- pH
- dissolved oxygen

Each time that the DS3 was to be deployed in the field, it was cleaned and calibrated for data collection according to the instructions provided by the Hydrolab® Corporation. Fully charged batteries were placed in the DS3; each probe was programmed to the desired optional criteria. Table 4 provides information about the various parameters that the DS3 measures and its expected performance.

Table 4. Parameter specifications for the Hydrolab DataSonde 3 Multiprobe. This information is courtesy of Hydrolab® Corporation.

Parameter	**Sensor**	**Range**	**Accuracy**	**Resolution**	**Calibration**
Depth (m)	strain gauge transducer	0 to 100 m	±0.45 m	0.1 m	set to zero in air
Temperature (ºC)	Thermistor	-5 to 50ºC	±0.15ºC	0.01ºC	None
pH (units)	glass pH; low ionic strength reference electrode	0 to 14 units	±0.02 units	0.01 unit	pH 7 buffer plus one slope buffer pH 10
Dissolved Oxygen (mg/l)	Polarographic one mil Teflon™	0 to 20 mg/l	±0.2 mg/l	0.01 mg/l	saturated air
Salinity (ppt)	Calculated from specific conductance	0 to 70 psu	±0.2 psu	0.1 psu	Uses calibration from specific conductance

Only when the divers were ready to begin their dive was the start and stop time of the logging run programmed into the DS3. It is normally too difficult to predict beforehand how long it will take to carry all of the diving equipment through the jungle and into a cave and the amount of time needed for divers to assemble and get into all of their gear. During each dive in which the DS3 was used, the diver would hold the instrument out in front of his body so that it would log data from undisturbed water. Following the dive, the data logged and stored in the DS3 memory was downloaded into an Excel spreadsheet and subsequently each parameter was graphed with respect to depth.

Diving safety and protocol

All of the diving that was carried out for water sample collection using the DS3 followed the training and equipment standards developed by the National Speleological Society – Cave Diving Section (NSS – CDS) and the National Association of Cave Diving (NACD). Furthermore, diving standards set forth by the American Academy of Underwater Sciences (AAUS) were followed.

Setup of water quality sampling ANOVA experiment

After examining the data from the preliminary water sampling in December 2002, a much better understanding of cave water chemistry was gained. The results from this study facilitated the design of a proper randomized multi-way analysis of variance experiment so that hypotheses about cave water chemistry could be formulated and tested. This experiment was conducted during one week of research in the field in March 2003.

Based on the average ranges of pollutant concentrations recorded during the initial water quality sampling, test kits with ranges that were more appropriate to the observed values in the preliminary testing were selected. Secondly, water test strips were chosen rather than the original water test kits from the HACH laboratories, as the strips could be used immediately in the field to quantify data. Though the resolution was small with the original test kits (ex: nitrate, 0-10 ppt range, 0.02 interval) and while the concentration increments were greater using the test strips (ex: nitrate 0, 2, 5, 10, 20, 50 ppt), it was still possible to distinguish between samples that merely contained background levels (<1.7 mg/l nitrate) of pollutants as opposed to abnormal amounts of contamination. For a more precise and detailed study of cave water chemistry, however, a higher resolution would most likely be preferred.

The original December 2002 study helped guide this multi-way analysis of variance experimental design, as the data gathered was congruent with the findings of other studies that focused on phosphorus contamination in Bermuda groundwater—the level of phosphorus was extremely low, and mostly nonexistent in cave water (<1.0 mg/l). While studies have consistently shown that limestone is highly efficient at removing phosphorus in the vadose zone prior to the time when it reaches the water table, in high concentrations it is not completely removed (Simmons et al. 1985). Therefore, phosphorus was not included as one of the parameters in this experimental design.

Lastly, a trend of rapidly decreasing pollutant levels concomitant with increasing depth was observed in the preliminary sampling period. This finding prompted further study and comparisons of surface and depth pollutant concentrations in cave water.

While the initial December 2002 study did elucidate many trends about cave water chemistry, several questions were left unanswered which prompted the design of this completely randomized multi-way analysis of variance experiment. For example, it was not clear whether the size of the cave or whether the proximity of the cave to a potential polluting source had an impact on the pollutant levels. Thus, all of the known caves with any sort of anchialine pool, lake, or extensive underwater passage (48 total) were divided into four categories (Appendix A-1).

The categories were as follows:

- big cave (>100 m in length), < 40 m away from potential polluting source (e.g., building with attached cesspit, agricultural plot)
- big cave (>100 m in length), > 40 m away from a potential polluting source
- small cave (<100 m in length), < 40 m away from a potential polluting source
- small cave (<100 m in length), > 40 m away from a potential polluting source

Next a total of twelve caves were sampled, though not equal numbers from each category due to the difficulty of obtaining permission to sample some of the caves that were randomly selected, shown in Table 5. Surface and subsurface samples, between 1-2 m were collected at each cave, two-three replicates per depth. Depth samples were collected using a vertical student water sampler, designed by Aquatic Research Instruments®, so as to more accurately record the depth from which samples were collected and ensure that the samples collected were representative of the depth sampled (Figure 9). The sampler was rinsed with distilled water in between each deployment.

Table 5. Caves randomly selected for water sampling analysis of variance experiment.

Size	**Small (<100 m in length)**	**Large (>100 m in length)**
Far from a potential polluting source (>40 m)	Coral Cave Walsingham Sink Bush Cave	Walsingham Cave Tucker's Town Cave
Close to a potential polluting source (<40 m)	Swizzle Cave Leaning Tower Cave Palm Pit	9th Hole Cave Admiral's Cave (pools 1 and 2) Straw Market

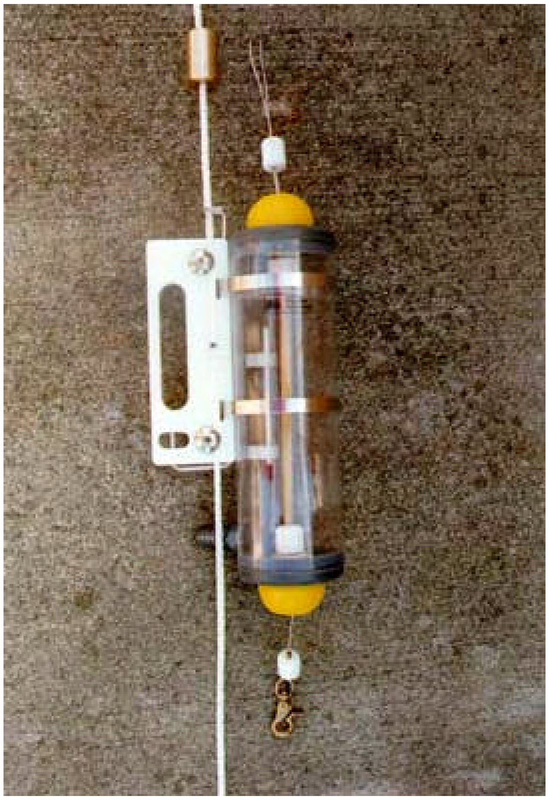


Figure 9. Vertical water sampler (Aquatic research webpage).

Water test strips were used to test each sample for ammonia, nitrite, nitrate, and pH, and a portable refractometer was used for salinity. As this field sampling period only lasted one week, it was not possible to incorporate bacterial contamination sampling into this particular experiment due to time restrictions. Once the sampling was completed, the data was analyzed statistically for significant interactions using SPSS software, with a multiple analysis of variance design.

RESULTS

Comprehensive environmental survey: 1983 and 2002 compared

Although the goal of this study was to reevaluate each cave included in the original survey, this was not possible. Several factors, as mentioned earlier, prevented a complete analysis: the shorter field study period (3 months vs. 2 years), the lack of land owner permission, and the difficultly in locating some caves. Despite these difficulties, the majority of the caves originally evaluated in 1983 were relocated and reevaluated in 2002 (111 out of 168) so that comparisons could be made between the two data sets. Furthermore, contingency tables using Chi-square statistics were used to determine if there was a statistically significant difference between the data sets. A geographical analysis of the two data sets was performed using ArcGIS 8.3 GIS software, and is presented in a later section.

In 2002, a total of 111 caves were analyzed, as compared with 168 caves in 1983. A total of 179 caves with individual entrances were identified in the 1983 survey, though some caves were grouped together into one overall rating because they were connected by underground tunnels, which explains why there were only 168 separate ratings. In the current study, these caves were evaluated separately because individual entrances of a large cave system that are connected by submerged tunnels can experience vastly different levels of environmental degradation based on location. Seven caves of the 111 analyzed in the current study were newly discovered since the original survey. Ratings for each cave visited in 1983 and 2002 are presented in Appendix A, while descriptions of the caves analyzed in 2002 are presented in the Bermuda Cave and Karst Information System GIS.

A total of seventy of the caves evaluated in 2002 could be compared with those studied in 1983. Of the 111 cave sites located in 2002, twenty represented caves that were destroyed since 1983, seven were new and therefore lacked historical data for comparison, and fourteen caves could not be compared because they are primarily submerged and it was not possible to conduct cave diving evaluations in the limited field period available in 2002. Overall, a total of 166 caves are currently known to exist on the island (179 original-20 destroyed+7 newly discovered). Thus, this analysis on the general environmental status and health of Bermuda's caves was based on a comparison of seventy caves that were analyzed both in 1983 and 2002.

A general comparison of the negative ratings will be discussed here in order to illustrate changes over the twenty-year period between the two surveys. Positive features in the caves were also recorded. The differences, however, were far less indicative of overall environmental health, as these various categories described features that do not have the potential for dramatic change over only twenty years. For example, speleothems (one of the positive categories) in a cave form over thousands and to tens of thousands of years. Consequently, it would be impractical to analyze differences of these positive characteristics, as they could not have changed dramatically over the past twenty years. Furthermore, two other positive categories—size and uniqueness—would most likely not have changed at all over the past twenty years in any of the caves, as a major geological event would have been necessary to change the size of a cave or its overall shape and uniqueness. Therefore, the discussion that follows will focus primarily on changes in the negative categories between the two data sets.

Perhaps the most striking finding was the fact that a total of twenty caves included in the original survey had been destroyed due to limestone quarrying (12), construction activities (6), or by natural weather events (2). This number does not include a number of other caves—unknown at the time of the original survey—that were also destroyed in the past twenty years.

Comparison of surveys

Of the caves that still exist, the seventy that were compared for improvements and degradations, the overall trend shows a worsened environmental status from the time of the original survey in all four categories: vandalism, dumping and littering, water pollution, and threat from quarrying/construction. In all categories, the ratings reflected a higher threat rate in 2002 compared to 1983 (Figure 10).

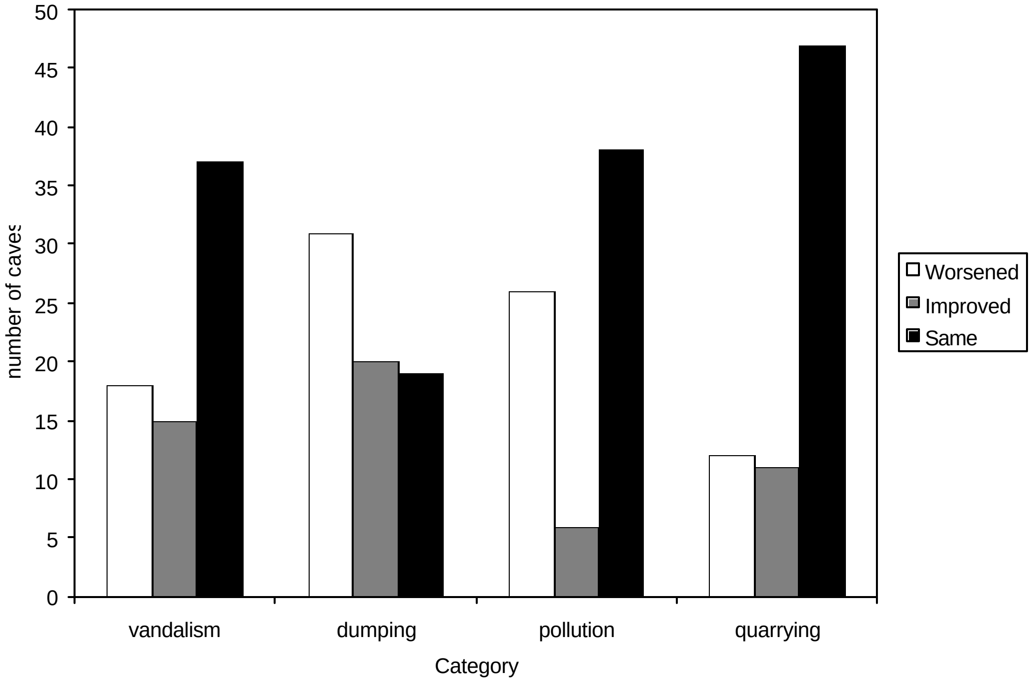


Figure 10. Breakdown of caves with improved, worsened, and identical ratings in each negative category between 1983 and 2002.

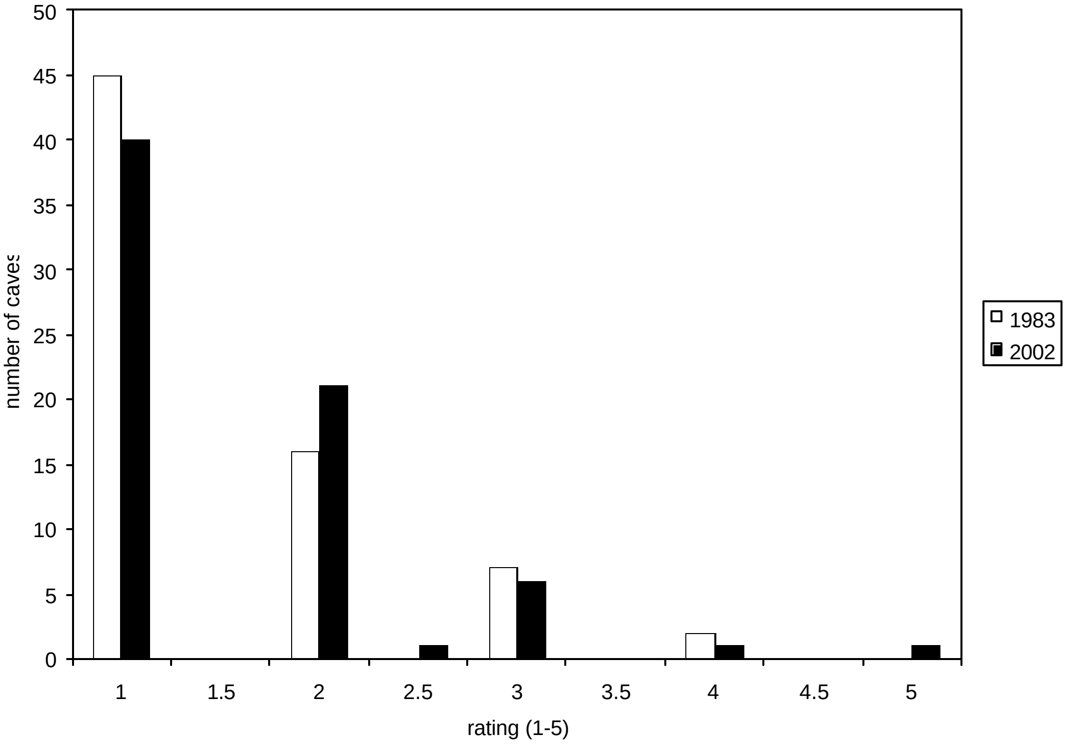


Figure 11. Breakdown of vandalism ratings in 1983 and 2002 (1 = least endangered, 5 = most endangered).

More specifically, in the vandalism category, five caves were increased from a "1" rating to a higher, more impacted status (Figure 11).

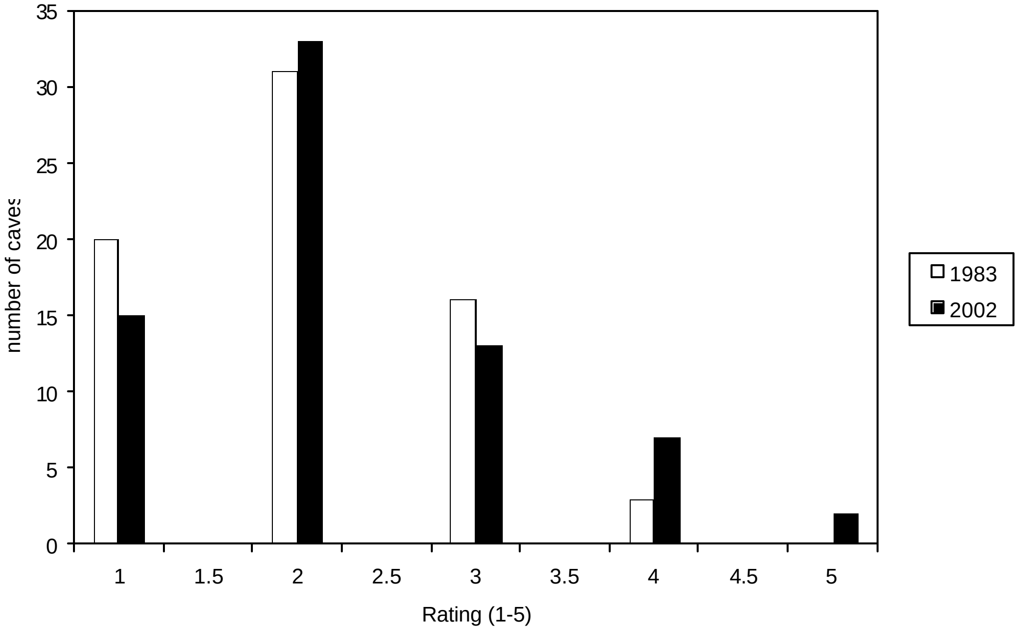


Figure 12. Breakdown of dumping and littering ratings in 1983 and 2002 (1 = least endangered, 5 = most endangered).

In the dumping and littering category, seven caves were assigned a “4” rating as compared to only three in 1983, and two caves—Admiral’s Cave and the New Quarry Cave—were assigned a “5” rating, the highest impact possible, while none were at this level in 1983 (Figure 12).

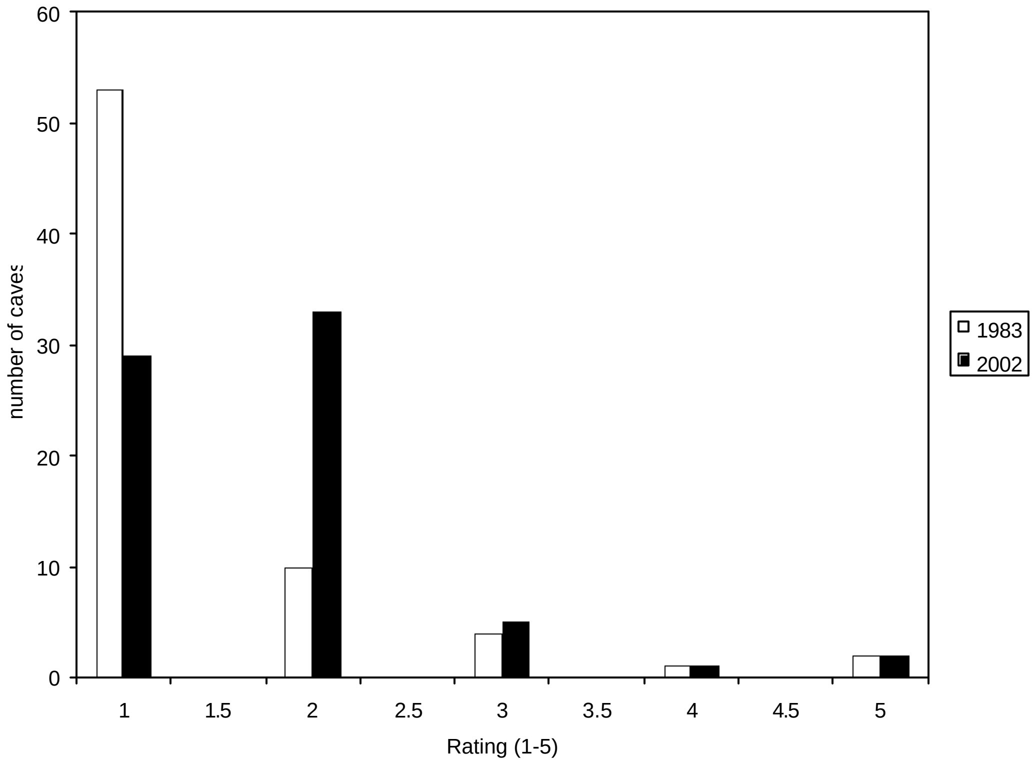


Figure 13. Breakdown of water pollution ratings in 1983 and 2002 (1 = least endangered, 5 = most endangered).

In the water pollution category, a total of twenty-four caves were increased from the “1” rating to a higher rating, demonstrating how this category had the most marked changes of any of the negative impacts (Figure 13).

In the quarrying and construction category, there were not any major differences in the paired comparisons between the two surveys (Figure 14). This finding is slightly misleading however, and it is important to point out that the most threatened caves from the original survey are clearly not a part of the comparison, as twelve of these caves were indeed destroyed since the time of the original survey.

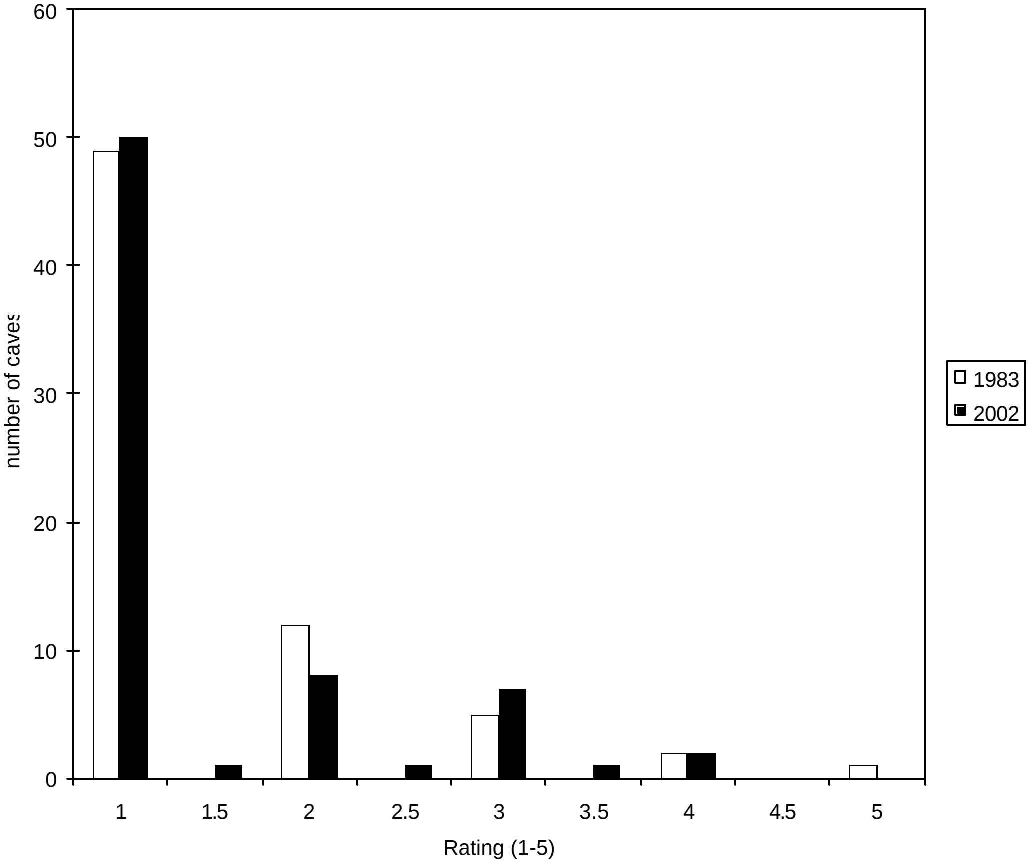


Figure 14. Breakdown of ratings for quarrying and construction in 1983 and 2002 (1 = least endangered, 5 = most endangered).

Contingency table analysis of environmental survey 1983 vs. 2002

These percentage comparisons are further supported through the use of Chi-Square statistical analysis using contingency tables. The observed vs. expected values for the ratings are displayed in the following table (Table 6).

Table 6. Contingency tables for each negative category with observed and expected values.

Category	**Year**	**Sum "1" Rating**	**Sum "2" Rating**	**Sum "3" Rating**	**Sum "4" Rating**	**Sum "5" Rating**
Vandalism						
Observed	sum ratings	1	2	3	4	5
	1983	45	16	7	2	0
	2002	40	21	6	1	1
Expected	sum ratings	1	2	3	4	5
	1983	30.5	13	4.67	1.1	0.35
	2002	30.5	13	4.67	1.1	0.35
Dumping						
Observed	sum ratings	1	2	3	4	5
	1983	20	31	16	3	0
	2002	15	33	13	7	2
Expected	sum ratings	1	2	3	4	5
	1983	12.5	32	10	3.57	0.7
	2002	12.5	32	10	3.57	0.7
Pollution						
Observed	sum ratings	1	2	3	4	5
	1983	53	10	4	1	2
	2002	29	33	5	1	2
Expected	sum ratings	1	2	3	4	5
	1983	29	15	3.2	0.7	5
	2002	29	15	3.2	0.7	5
Quarrying						
Observed	sum ratings	1	2	3	4	5
	1983	49	12	5	2	1
	2002	50	8	7	2	0
Expected	sum ratings	1	2	3	4	5
	1983	36.8	7.35	4.4	1.47	0.36
	2002	36.8	7.35	4.4	1.47	0.36

The observed data in all four categories was significantly different when compared to the expected data ($p = 0.05$, $df = 4$). This supported the fact that the 1983 data was independent of the 2002 data, and cave ratings were not the same in both surveys. These statistical results, which demonstrate a difference in the two surveys, support the earlier discussion, which indicated that the ratings tended to worsen in each category from 1983 to 2002. The following table shows the chi-square values for the four categories and the corresponding p values (Table 7).

Table 7. Chi-squared values for negative environmental ratings from 1983 versus 2002 contingency tables.

Category	**X^2 critical**	**X^2**	**p value**
Vandalism	9.488	22.44	$p < 0.001$
Dumping	9.488	16.04	$p < 0.01$
Pollution	9.488	48.19	$p < 0.001$
Quarrying	9.488	16.017	$p < 0.01$

Discussion of highlighted caves

Aside from the overall comparisons, there were several caves that stood out from the data set, as they had either dramatically improved or worsened over the twenty-year period. For example, Fort Scaur Cave, a rather isolated cave in Sandy's Parish, located on the Fort Scaur National Park grounds, experienced a significant amount of dumping and littering, as it was originally rated at a "1" level and now is rated at level "4". When the cave was explored, a substantial amount of dumped trash including old kitchen appliances, rusty old bikes, and piles of old clothes were discovered. Moreover, spray-painted graffiti was observed on some of the walls of the caves and in a number of places, a sharp object was used to scratch messages into the flowstone deposits. Unfortunately, it appears that this cave has been used as a "hangout" and trashed by those who discovered it.

Another cave that has changed significantly since the time of the original survey is Admiral's Cave, located in woodland near the Swizzle Inn in Hamilton Parish. While this large cave is historic and well known among locals, it has suffered from several negative impacts recently. The cave was upgraded from a "1" rating in 1983 for water pollution to a "5" in 2002. Several of the pools in the cave have been badly polluted and emit a hydrogen sulfide, or rotten egg odor when disturbed. The pools have become anoxic below the first few feet of water and would be potentially hazardous to dive. Moreover, it is unknown how drastic the effects of this pollution have been on the cave adapted organisms that inhabit the pools of this cave. Because the staff quarters to the Grotto Bay Hotel are located directly above part of this cave, the cesspit connected to the building is a likely source of the pollution.

In addition to the water pollution, Admiral's Cave is also endangered by the nearby Wilkinson Quarry. The cave was rated at a "1" threat level in 1983 from construction and quarrying, but has been upgraded to a "3" level. Dynamite blasting at the nearby quarry threatens delicate formations within Admiral's Cave, as the vibrations have the potential to crack and destroy internal formations. Also, since the 1983 survey, the quarry has dramatically expanded and encroached upon the outer boundaries of the cave passages, increasing the threat from blasting and digging operations. This threatens the stability of the cave since all of the known passages of Admiral's Cave were formed by massive collapse and only a relatively thin span of ceiling rock exists over the largest chambers.

Both Shrimp Cave and Canyon Cave, located close to Tom Moore's Tavern in Blue Hole Hill Park, have a worsened water pollution rating. These two caves were originally rated a "1" for water pollution originally, and both were increased to a "3" rating. Because these caves are located on a nature preserve and are seemingly protected from negative impacts, it was surprising to discover high levels of bacterial contamination in their pools. The pools in each cave were tested for *Enterococcus* during December 2002. Shrimp Cave had a one-time reading of 74 MPN per 100 ml, and Canyon Cave had a one-time reading of 51 MPN per 100 ml. These caves are both located approximately 20 m away from several animal pens located on the periphery of the nature preserve which could be a potential source of the contamination. Because they are also approximately 35 m away from Tom Moore's Tavern, the cesspit connected to the restaurant is another potential source.

One cave that has changed for the better is Cordial Cave, located in the backyard of a private residence between Harrington Sound and Castle Harbour. Previous owners had used the cave as a dumping ground for trash and yard debris over the years, so that it was extremely polluted. The cave has been downgraded, however, from a "3" rating for dumping and littering in 1983 to a "1". By assigning their gardener the task of cleaning it up, the most recent owners have dramatically improved its status. Presently, there is no longer any trash or debris in the cave, and the entrance has been tastefully landscaped with ferns and other plants. What was once a trashed and ugly cave is now a beautiful grotto.

Another cave that has been improved significantly since the original survey is Sear’s Cave, a 15 m diameter sinkhole located in Smith’s Parish (Figure 15). This cave is rather isolated from the majority of the caves that are located in the Walsingham rock formation in Hamilton Parish. Nevertheless, it is particularly vulnerable and merits protection, as it contains the largest population of the endangered Bermuda cave fern on the island. It is located behind a residential area, and for years it was used as a trash dump. Eventually, huge piles of trash built up in the cave, including cans, bottles, discarded appliances and yard and lawn debris. The cave was considered to be dangerous to residents who lived nearby, as it was such a large and deep pit, that they worried about children accidentally falling into the cave. Currently, the cave has a much better status, as both the cave and surrounding area were purchased by the Audobon Society. The group used large construction machinery to extract large piles of trash.

Figure 15. Trash that still remains under the overhang in Sear's Cave.

While a great deal of the trash was removed, it was difficult to clean it all out because the lip of the cave is undercut on two sides, making it difficult to access that area of the sinkhole. After the majority of the trash was extracted, a tall fence was installed around the entrance to the cave to prevent further dumping and to keep trespassers from entering the cave. Originally, this cave was rated a "4" for dumping and littering and is now rated a "2". Thus, despite the poor environmental health of this cave in the past, current efforts dramatically improved the status of its habitat.

Preliminary water sampling

In order to gather data on pollution levels from a variety of caves, a preliminary sampling series was designed to test the water at varying depths in caves both large and small (>, <100 m), inland and in close proximity to the shore (>, <40 m), and in caves located in various parts of the island. Nitrate, nitrite, ammonia, phosphate, and *Enterococcus* bacteria were selected as parameters to be assessed within the selected caves. A total of twenty caves were examined over the month-long testing period in December 2002. Some caves were found to have high levels of pollution while others had little to no detectable pollutants. Table 8 shows the results of the water quality tests.

Table 8. Preliminary cave water quality sampling December 2002.

Cave Name	Depth (m)	Salinity (ppt)	Nitrate (mg/l)	Nitrite-nitrogen (mg/l)	Ammonia (mg/l)	Phosphate (mg/l)	MPN *Enterococcus*
Admiral's Cave							
North Pool	1.5	28	ns	ns	ns	ns	0
White Room pool	0.3	25	4.4	0	0.1	0	0
Pool 1	0	10	68.2	0.23	0.4	0.08	0
Pool 1	3	32	0	0	0	0.02	0
Pool 2	0	21	6.6	0.13	0.1	0.02	0
Pool 2	3.3	35	0.53	0	0.1	0	0
Olivewood Cave							
	0	24	0.35	0	0.1	0	31
	2.1	34	0	0	0.1	0	ns
Cow Cave							
	0	35	0	0	0	0	0
	3	35	0	0	0.1	0	ns
Cordial Cave							
Pool 1	0	35	0	0	0	0	ns
	1	35	0	0	0.1	0	ns
	1.5	35	0.04	0.03	0.1	0	ns
Pool 2	0	35	ns	ns	ns	ns	10
	0	35	ns	ns	ns	ns	0
Shop Cave							
	0	7	19.67	0.23	0.3	0.06	0
	1.8	25	0.97	0.03	0.1	0.06	0
Fort Scaur Cave							
	0	22	2.2	0	0.1	0	ns
	1.2	25	1.1	0	0.3	0	0
Tucker's Town Cave							
	0	24	88	0.03	0.1	0.02	20
	1	28	6.6	0	0.1	0	0
	3	29	2.42	0	0.1	0	0
	10	33	1.32	0	0.1	0	0
	20	34	0.44	0	0	0	0
Church Cave							
	0 (1)	17	7.92	0.03	0.2	0.06	0
	0 (2)	ns	ns	ns	ns	ns	0
	3	27	3.3	0.02	0.3	0.04	ns
Causeway Cave							
	0	35	0.22	0	0.1	0	0

Table 8. Continued.

Cave Name	Depth (m)	Salinity (ppt)	Nitrate (mg/l)	Nitrite - nitrogen (mg/l)	Ammonia (mg/l)	Phosphate (mg/l)	MPN *Enterococcus*
Coffee Cave							
	0	22	4.4	0	0.3	0.08	20
Walsingham Cave							
	0	35	0.22	0	0	0.04	0
Swizzle Cave							
	0	24	2.2	0.04	0.3	0	ns
Chalk Cave							
	0	25	4.53	0.03	0.3	0.1	ns
Cliff Pool							
	0	15	68.2	0.03	0.1	0.04	63
	1	33	0.53	0.03	0.05	0	0
	3	35	0.26	0.03	0.05	0	0
	10	36	0	0	0	0	0
	20	36	0	0	0	0	0
Fern Sink							
	0	25	0.66	0.03	0.1	0.04	20
Cherry Pit							
	0	35	0.22	0	0.3	0.04	ns
Roadside Cave							
	0	18	1.49	0	0.1	0	ns
Shrimp Cave							
	0	34	0.53	0	0	0	51
	1.8	35	0	0	0	0	ns
Canyon Cave							
	0	31	0.66	0	0.1	0.02	74
	3	36	0.22	0	0	0.08	ns
Straw Market Cave							
	0	21	1.32	0	0.1	0.02	0
	1	36	0.22	0	0.1	0	0
	3	35	0.13	0	0.1	0	0
	10	ns	0	0	0.1	0	0
	20	35	0	0	0	0	0

Of the three nitrogen species, nitrate had the highest readings, ranging from 0-88 mg/l. Furthermore, the highest readings for nitrate were recorded in surface water, and tapered off to lower readings at depth. For example, in Admiral’s Cave, the pool 1 surface reading was 68.2 mg/l and 0 mg/l at 3 m. In pool 2, the surface nitrate reading was 6.6 mg/l and 0.53 mg/l at 3.3 m. Some other caves that also had high nitrate readings included Shop Cave, with 19.66 mg/l at the surface and 0.96 mg/l at 1.8 m. Church Cave had a nitrate level of 7.92 mg/l at the surface, and again had a lower level of 3.3 mg/l at a depth of 3 m. Two additional caves with high nitrates, in which only surface measurements were recorded, were Coffee Cave with 4.4 mg/l at the surface, and Chalk Cave with 4.53 mg/l at the surface.

Three caves from this group with large, diveable underwater sections were sampled more extensively: Tucker's Town Cave, Cliff Pool and Straw Market Cave. Cave diving made it possible to gather a broader spectrum of samples at deeper depths in these systems. Tucker's Town Cave is different from Cliff Pool and Straw Market Cave, as the underwater segment does not directly connect to the shore-water through a diveable passage. It is a more self-contained water body. The cave is located in a wooded area beside Tucker's Town Road in a residential area. The entrance is approximately 4 m wide and 6 m tall, and immediately descends on a steep vertical 8 m drop to the main chamber. Periodically, vegetative debris from the surrounding jungle falls down into the cave and eventually into the lake. The main room consists of a small dry sandy area, which is surrounded by a large, deep tidal cave lake. The central area of this lake has a steeply slanting underwater descent with a bottom depth of approximately 17 m. The deepest area leads down through a short tunnel, which opens into another large underwater room in the back of the cave. These two underwater environments are the total extent of the diveable section of this cave, though considerable tidal fluxes in the cave lake show that the cave is connected through cracks and fissures to sea water.

In contrast, both Cliff Pool and Straw Market Cave have large openings to open water bodies—the Atlantic Ocean and Harrington Sound, respectively. The entrance to Cliff Pool is situated in the back yard of a private residence off North Shore Road, at the bottom of a 7 m tall limestone cliff face. This 15 m long by 6 m wide pool is open to the outside environment, and is illuminated by sunlight most of the day. The main entrance descent consists of a wide tunnel that leads into the rest of the cave, which consists of a maze of complex tunnels branching off in many directions. Some are wide and others are rather narrow. This cave connects underwater to Green Bay Cave, with a marine entrance that connects the cave directly to the Atlantic Ocean.

Straw Market Cave is located on the periphery of Tom Moore's Jungle, within 5 m of the back yard of a private residence that borders the nature preserve. The cave consists of a small dry section, which is surrounded by the main pool that leads into the submerged portion of the cave. A short tunnel leads from this section to the main underwater circular loop that connects the cave underwater to four separate entrances, one of which connects the cave directly to Harrington Sound.

These three caves all demonstrated the hydrological trend seen in other caves, of higher nitrate concentrations in surface water, which decreased dramatically as depth increased. Tucker's Town Cave, for example, had a nitrate reading of 88 mg/l at the surface and a 0.44 mg/l concentration at 20 m (Figure 16).

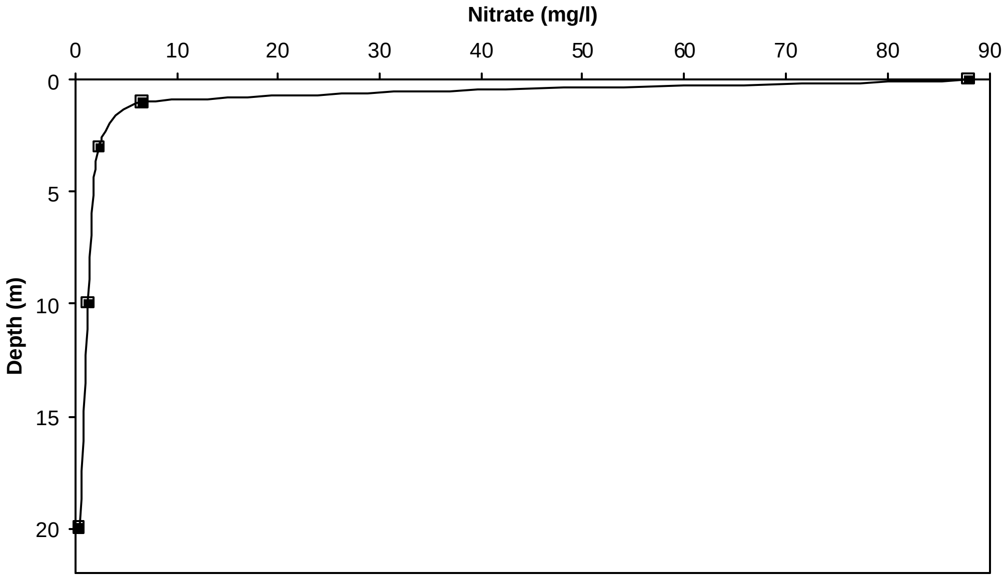


Figure 16. Nitrate concentrations at increasing depth in Tucker's Town Cave.

Similarly, Cliff Pool had a high reading of 68.2 mg/l at the surface and lower readings at depth—0.264 mg/l at 3 m, and 0 mg/l at 20 m (Figure 17). Straw Market Cave also demonstrated the same trend, the nitrate readings in this system were, however, much lower at the surface—1.32 mg/l, and decreased to 0 mg/l at 20 m (Figure 18).

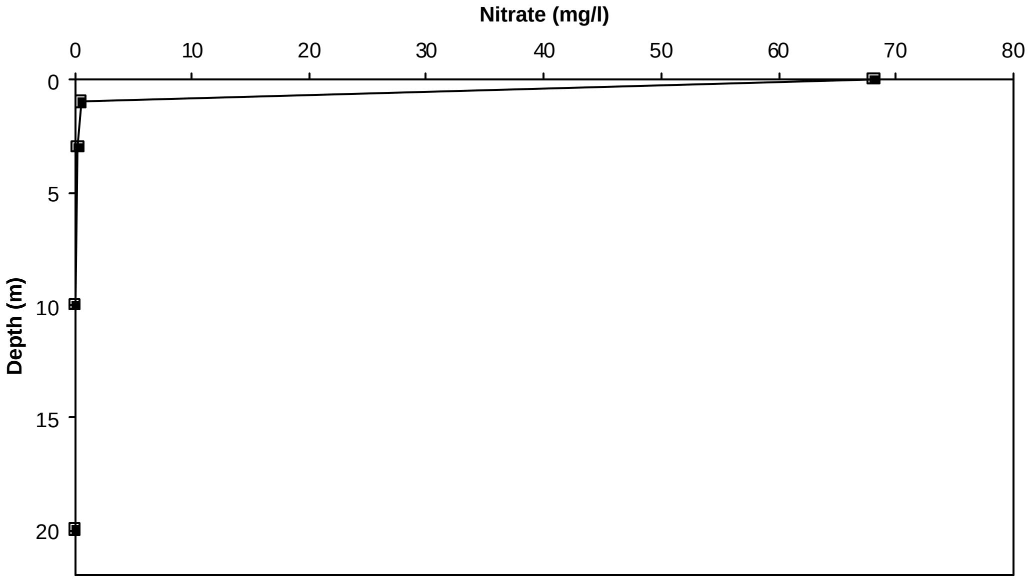


Figure 17. Cliff Pool nitrate data at increasing depth.

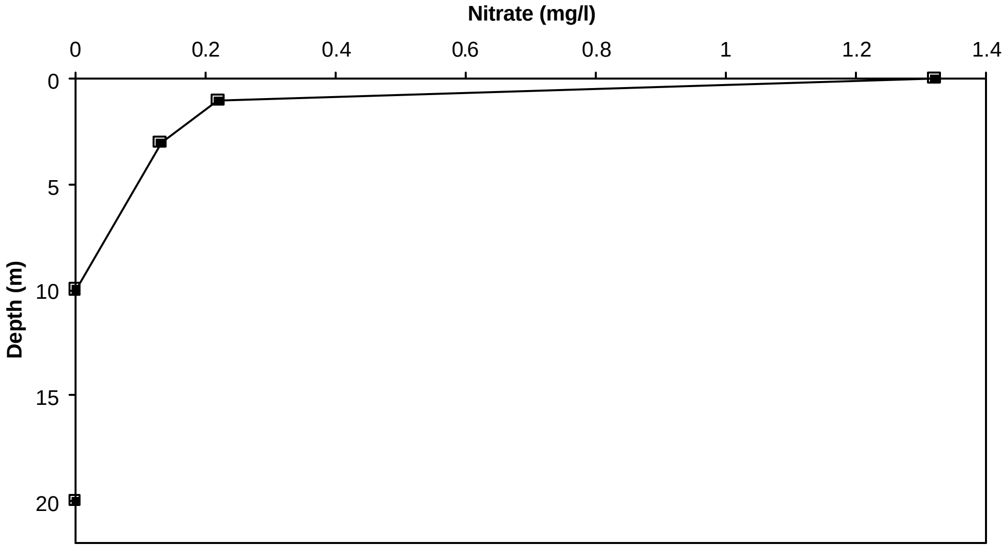


Figure 18. Straw Market Cave nitrate data at increasing depth.

All caves sampled in this preliminary testing series demonstrated a general trend of higher levels of nitrite, ammonia, and phosphate at the surface, rapidly dropping off immediately beneath. All of these parameters were much less striking than the nitrate levels. For example, the range of readings for nitrite was 0-0.23 mg/l. The highest reading of 0.23 mg/l was recorded in the surface sample of pool 1 in Admiral's Cave and in the surface sample from Shop Cave. Both caves had a depth sample reading of 0 mg/l. All the other caves sampled had negligible amounts of nitrite, if any.

The ammonia readings from most caves were also negligible, ranging from 0-0.4 mg/l. In several caves, the readings decreased, as was the case with the other parameters, with depth. For example, the highest reading of 0.4 mg/l was recorded in the surface water of pool 1 in Admiral's Cave, and dropped to 0 mg/l at 3 m. Similarly, the level of ammonia in Shop Cave at the surface was 0.3 mg/l and 0.1 mg/l at 1.8 m. Unlike the other parameters, the readings for ammonia increased with depth in two of the caves sampled. In Church Cave, the level was 0.2 mg/l at the surface and 0.3 mg/l at 3 m. Similarly, in Fort Scaur Cave, the reading was 0.1 mg/l at the surface and 0.3 mg/l at 1.2 m. All of the remaining caves sampled contained little to no ammonia.

Phosphate was similar to nitrite and ammonia in that the readings were negligible in most of the caves. The levels of phosphate ranged from only 0-0.08 mg/l. Most of the caves, however, had no detectable phosphate. Based on these findings, phosphate was eliminated from subsequent water quality testing experiments, as the variety of caves selected for the preliminary sampling demonstrated that this parameter was not a significant pollutant.

Because the *Enterococcus* samples were one-time readings, and not gathered several times during an established testing period, the results were compared to the EPA's recommended one-time reading scale in order to determine the level of contamination. The EPA recommended a one-time most probable number (MPN) reading of 158 per 100 ml water for moderate use full body contact. This is the type of exposure one would expect in cave water, as caves are occasionally used as swimming holes, and also, periodically, by local cave divers. While not essential, it would have been even more definitive to test the safety of the water five times over a thirty-day period. The geometric mean level of bacterial contamination could be assessed and compared to the EPA recreational recommended limit of 35 MPN per 100 ml. Time did not permit, however, for a more extensive sampling protocol.

None of the samples tested for *Enterococcus* exceeded the EPA recommended limit of 158 MPN per 100 ml of water for moderate use full body contact. Based on this finding, all of the underwater cave systems sampled appear to be safe for recreation. However, several of the samples had rather high levels of contamination, and, if tested over a thirty-day period, might consistently remain high and thereby average out to a level that would exceed the 35 MPN per 100 ml geometric mean. For example, the highest level recorded was 74 MPN per 100 ml in the surface sample from Canyon Cave. Next highest was Cliff Pool, with 63 MPN per 100 ml in the surface sample. Shrimp Cave also had a high level of 51 MPN per 100 ml in the surface sample. Of the three caves that were dived for sampling at 0, 1, 3, 10 and 20 m, two of the caves had contamination at the surface: Cliff Pool, as already mentioned, with 63 MPN per 100 ml and Tucker's Town with 20 MPN per 100 ml. However, none of the depth samples in any of the three caves that were dived had any *Enterococcus* contamination.

Hydrolab data

Hydrolab water quality profiles were recorded in the three cave systems that were dived: Tucker's Town Cave, Cliff Pool, and Straw Market Cave. The vertical profiles provided information regarding how the following parameters—temperature, salinity, pH and dissolved oxygen—behaved at different depths.

The steep vertical descent in main large pool in Tucker's Town Cave was profiled vertically from the surface to 17 m in December 2002. The following figures (19-22) show the results for temperature, salinity, pH and dissolved oxygen.

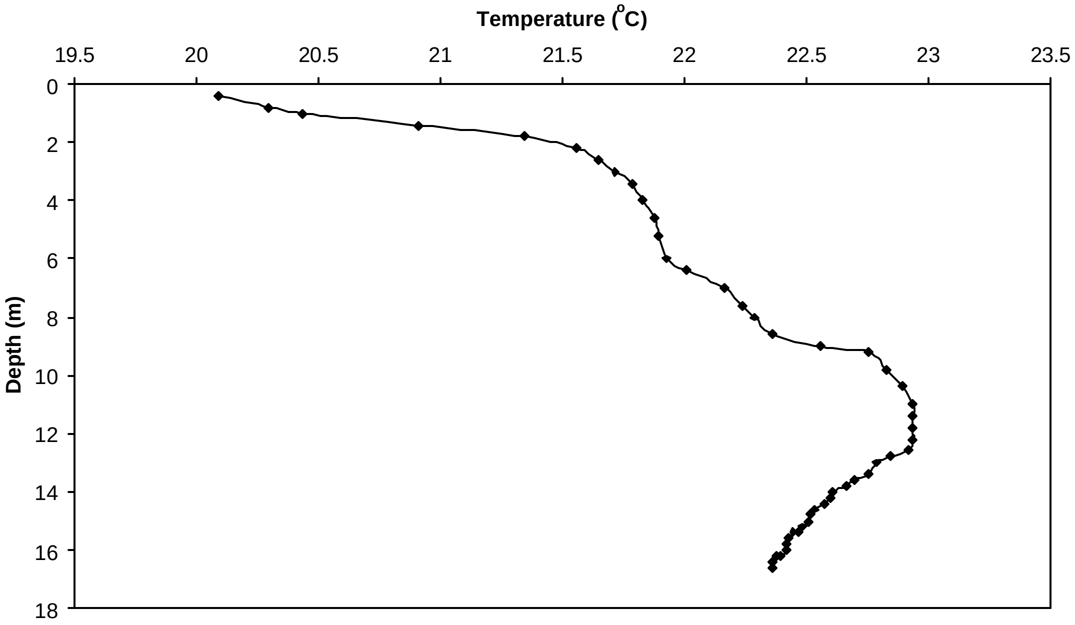


Figure 19. Temperature versus depth in Tucker's Town Cave (0-17 m).

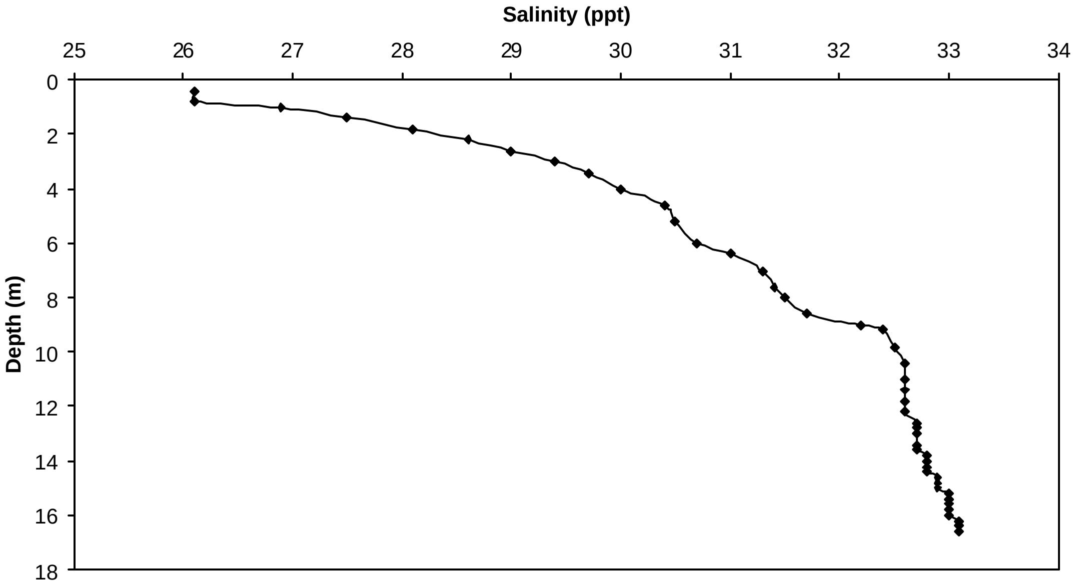


Figure 20. Salinity versus depth in Tucker’s Town Cave (0-17 m).

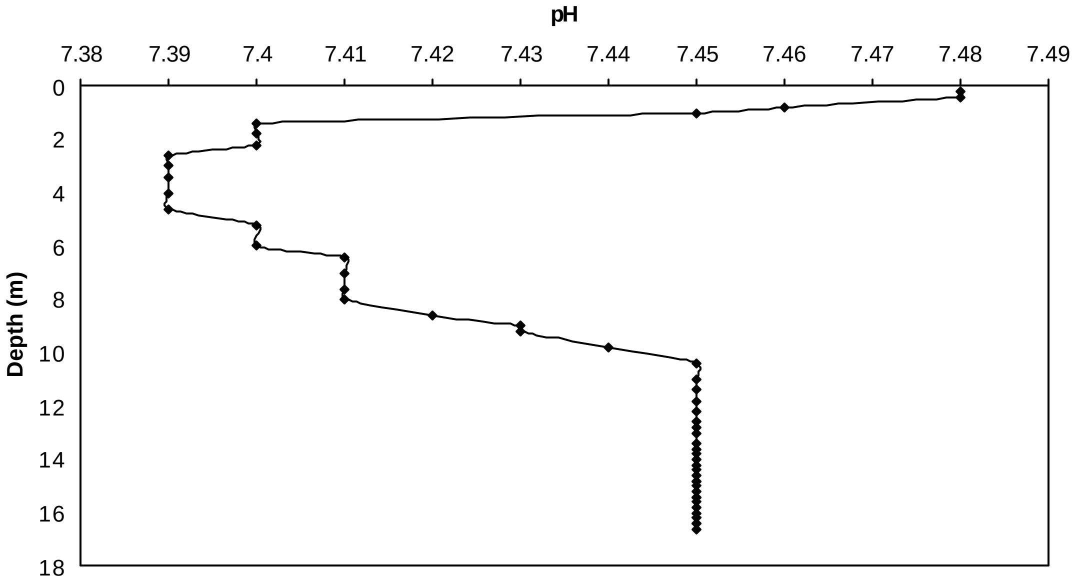


Figure 21. pH versus depth in Tucker’s Town Cave (0-17 m).

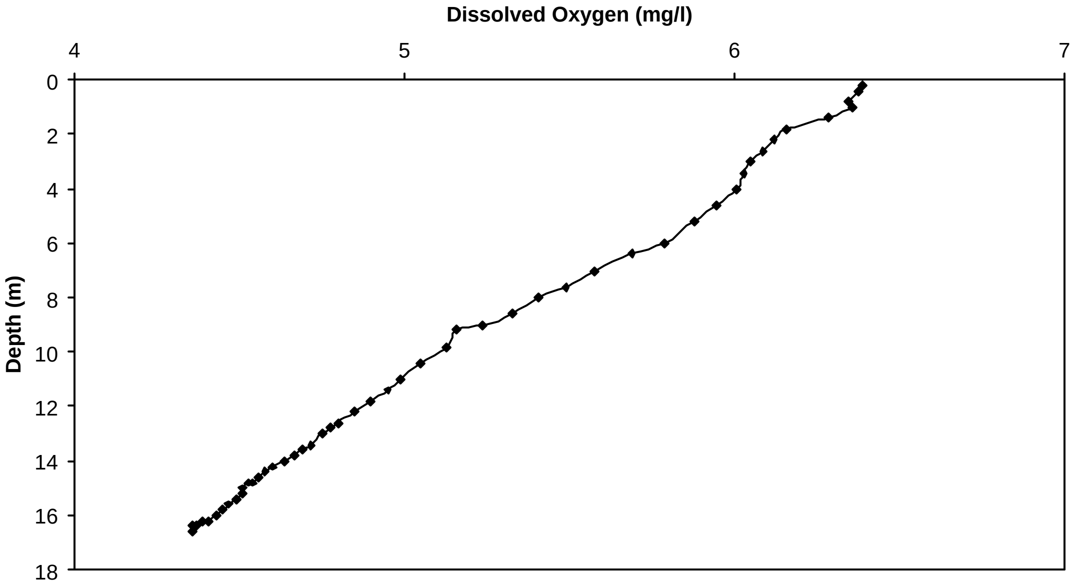


Figure 22. Dissolved oxygen versus depth in Tucker's Town Cave (0-17 m).

These figures depict certain noticeable trends in the water chemistry of Tucker's Town Cave. First, the temperature started out cooler at the surface at ~20ºC, increased to 23ºC at 12 m, and then again got colder as depth increased. The salinity similarly increased with depth from 26 ppt at the surface, to 33 ppt at 10 m. Dissimilarly, the pH started at 7.48 at the surface and rapidly decreased to 7.39 at 2 m and then began to increase again at 5 m, and reached 7.45 at 17 m. Lastly, dissolved oxygen generally decreased as depth increased, from 6.5 mg/l at the surface down to 4.3 mg/l at 17 m.

The next four figures (23-26) demonstrate the behavior of temperature, salinity, pH and dissolved oxygen at various depths in Straw Market Cave. When the Hydrolab was deployed in this cave, two separate profiles were recorded. Therefore, these four figures depict the hydrology of the first profile, in the main entrance pool heading down the main tunnel towards the circular loop, from 0-6 m, and the hydrology of the second profile, a descent in one section of the main loop of the underwater system, from 6-19 m.

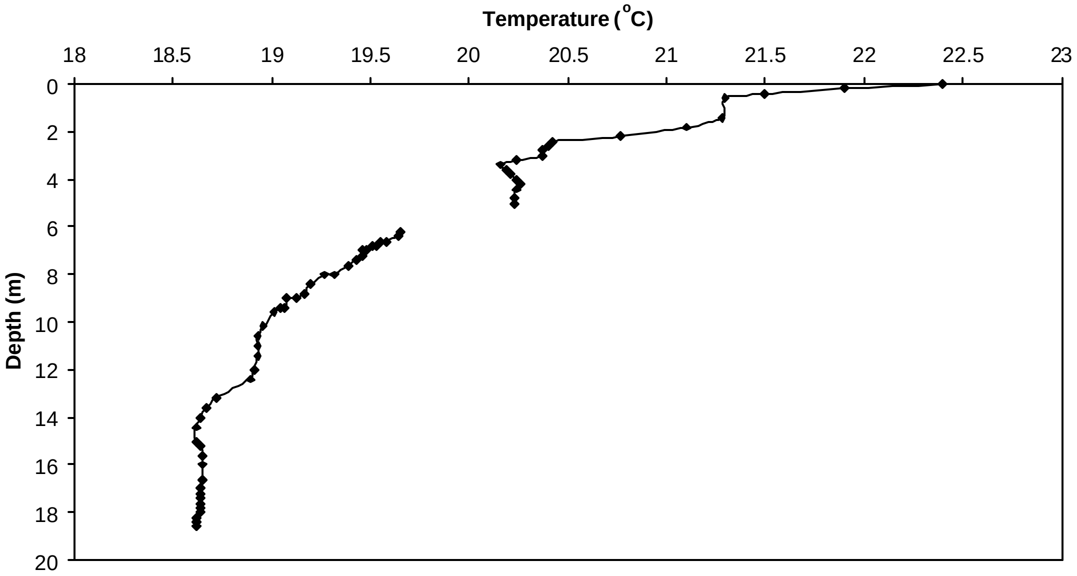


Figure 23. Temperature versus depth in Straw Market Cave (0-6 m, 6-19 m).

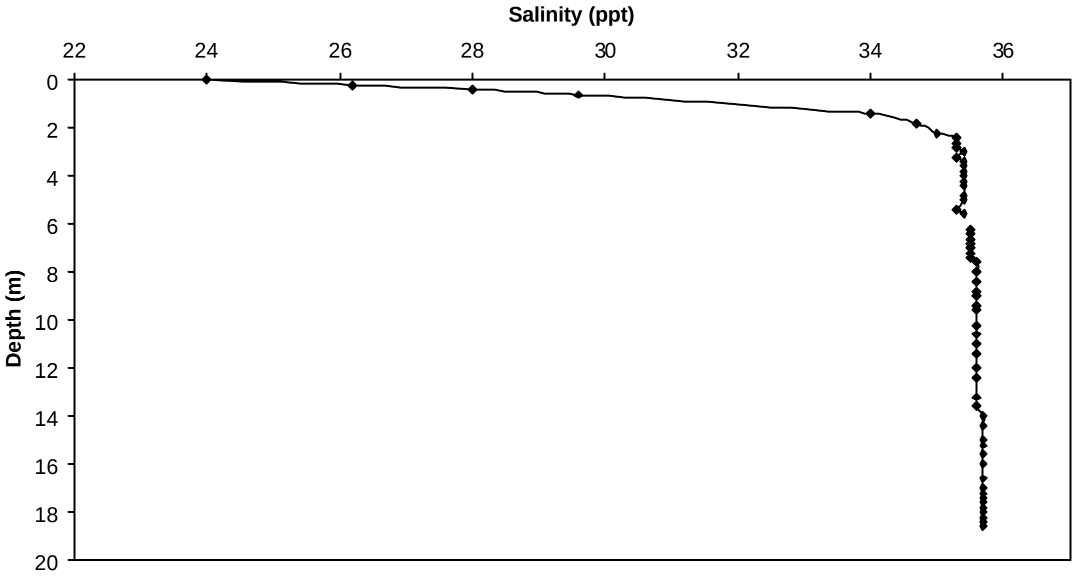


Figure 24. Salinity versus depth in Straw Market Cave (0-6 m, 6-19 m).

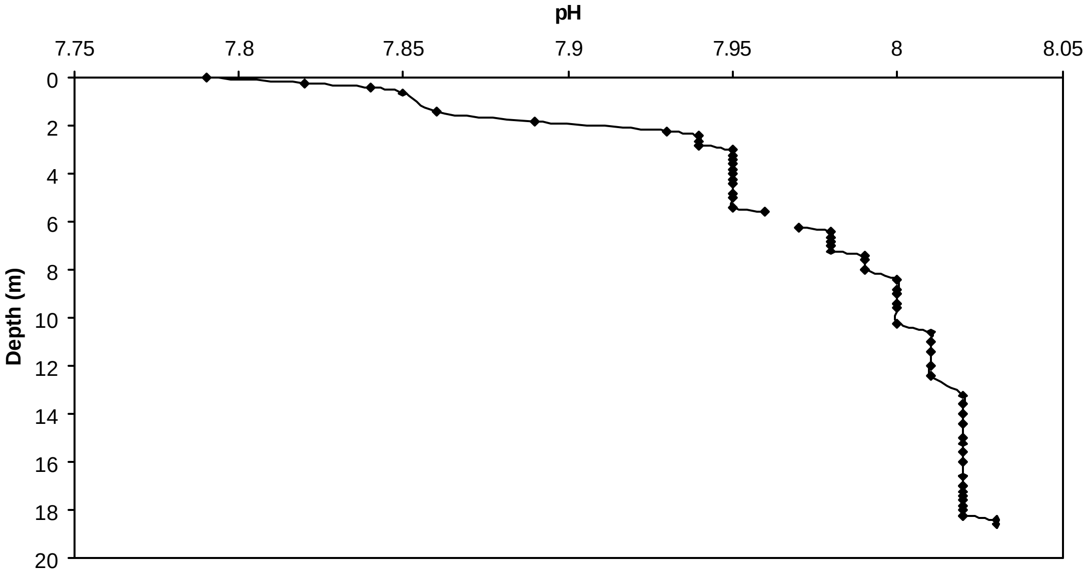


Figure 25. pH versus depth in Straw Market Cave (0-6 m, 6-19 m).

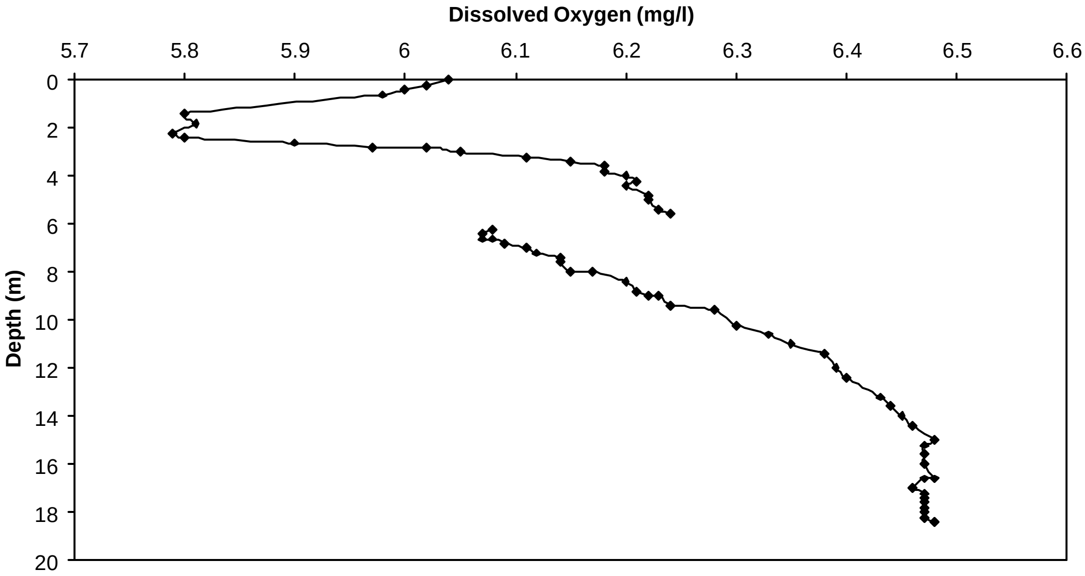


Figure 26. Dissolved oxygen versus depth in Straw Market Cave (0-6 m, 6-19 m).

These four figures demonstrate some definitive trends in the water chemistry of Straw Market Cave. Unlike Tucker's Town Cave, temperature gradually decreased with depth from 22.4ºC at the surface to 20.3ºC at 5 m. In the second descent, temperature continued to decrease with depth from 19.68ºC at 6 m to 18.6ºC at 19 m. Salinity quickly increased with depth from 24 ppt at the surface to 35 ppt at 3 m and remained at that level until 6 m. Salinity continued to increase, as it had in the first profile, from 35.5 ppt at 6 m to 35.7 at 19 m. pH increased from 7.8 at the surface to 7.95 at 3 m and remained constant down to 6 m. pH then increased from 7.97 at 6 m to 8.03 at 19 m.

Dissolved oxygen (DO) behaved quite differently as compared to the results from Tucker's Town Cave. A measurement of 6.04 mg/l was recorded at the surface, decreasing to 5.8 mg/l at 2 m and then increasing again to 6.25 mg/l at 6 m. DO continued to increase with depth in the second profile, from 6.07 mg/l at 6.5 m to 6.47 mg/l at 15 m. This trend was the opposite of what was observed in Tucker's Town Cave. Perhaps a stronger tidal flux between the cave water and sea water from Harrington Sound brings along more DO into this system as compared to the less turbulent water exchange that occurs in Tucker's Town Cave.

The next four figures (27-30) display how the same four parameters—temperature, salinity, pH, and dissolved oxygen—behaved as depth increased in Cliff Pool. The data were collected from the main entrance pool of the cave down into the first main tunnel from 0-17.8 m.

These graphs illustrate the trends in hydrology in Cliff Pool. Temperature increased rapidly from 17.5ºC at the surface to 24.3ºC at 3 m, and then decreased again, moving gradually back down to 19.7ºC at 17.8 m. Salinity also increased rapidly in the surface layer of water from 16.5 ppt at the surface to 35 ppt at 4 m and remained constant down to 17.8 m. pH moved in the opposite direction of temperature and salinity in the surface layer and started off at 7.82 at the surface, rapidly decreased to 7.51 at 2 m, then gradually increased to 7.99 at 17.8 m. Dissolved oxygen behaved erratically as the general trend of readings changed direction twice during the vertical profile. It gradually increased between the surface and 1 m from 7.2 mg/l to 7.8 mg/l, then decreased rapidly to 3.0 mg/l at 5 m and began increasing again slowly to 5.9 mg/l at 17.8 m.

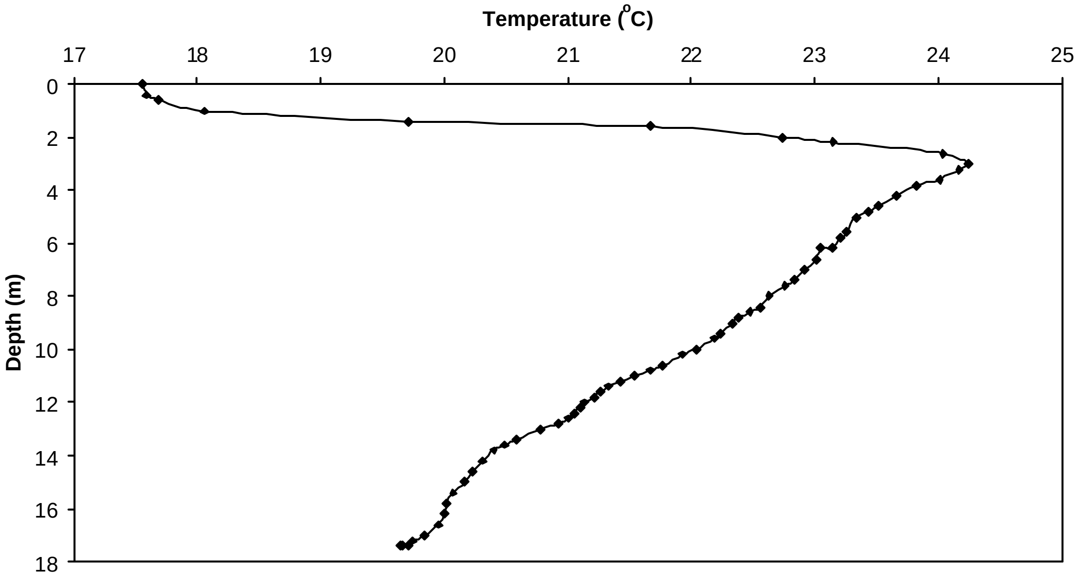


Figure 27. Temperature versus depth in Cliff Pool (0-17.8 m).

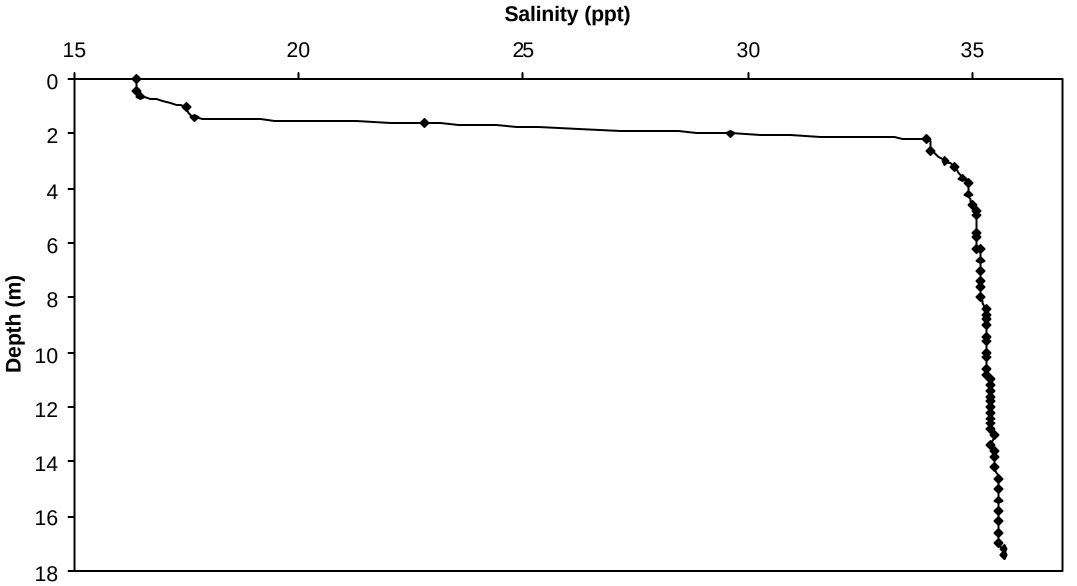


Figure 28. Salinity versus depth in Cliff Pool (0-17.8 m).

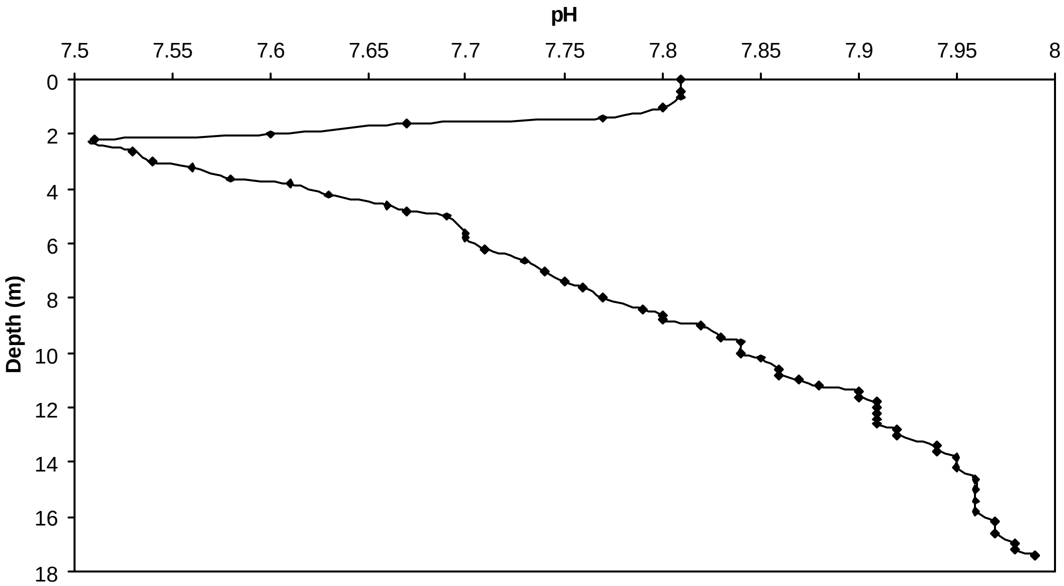


Figure 29. pH versus depth in Cliff Pool (0-17.8 m)

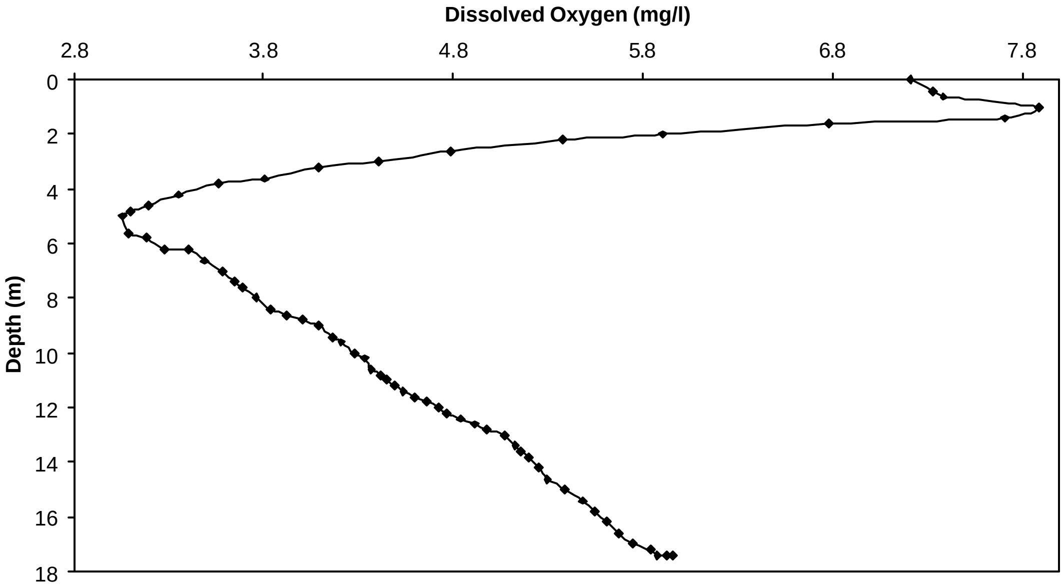


Figure 30. Dissolved oxygen versus depth in Cliff Pool (0-17.8 m).

Water quality sampling – analysis of variance

In March 2003, nitrate, nitrite, and ammonia concentrations were measured in surface and subsurface samples from twelve randomly selected caves, each from one of four classes based on size and location. The pollutant data was analyzed using a multiple analysis of variance design. The following table includes the averaged concentrations of nitrate and ammonia from the samples collected in the experiment (Table 9). Nitrite data was excluded because it was only detected in one cave at a very negligible concentration. The nitrate data was normalized using a log transformation $\ln(x + 1)$ because $\ln 0$ does not exist. In order to perform the analysis of variance, cave classes were assigned numbers 1-4: big and close to a potential polluting source (1), big and far (3), small and close (4), small and far (2). Surface and subsurface samples were also coded: surface (0) and subsurface (1). A confidence interval of $p = 0.05$ was used.

Table 9. Mean nitrate and ammonia concentrations in randomly sampled caves.

Cave Name	**Size in length (m)**	**Distance from Potential Source (m)**	**Class**	**Depth**	**N**	**Mean NO_3^- (mg/l)**	**Mean NH_3 (mg/l)**
9th Hole Cave	>100 m	<40 m	1	1	2	2.2	0
9th Hole Cave	>100 m	<40 m	1	0	3	3.04	0.1
Admiral's Cave (pool 1)	>100 m	<40 m	1	1	3	0	0.41
Admiral's Cave (pool 1)	>100 m	<40 m	1	0	3	5.3	0.25
Admiral's Cave (pool 2)	>100 m	<40 m	1	1	2	0	0.3
Admiral's Cave (pool 2)	>100 m	<40 m	1	0	2	3.3	0.3
Straw Market Cave	>100 m	<40 m	1	1	3	1.39	0
Straw Market Cave	>100 m	<40 m	1	0	3	2.48	0.15
Bush Cave	<100 m	>40 m	2	1	3	2.08	0.3
Bush Cave	<100 m	>40 m	2	0	3	2.3	0.15
Coral Cave	<100 m	>40 m	2	1	3	0	0
Coral Cave	<100 m	>40 m	2	0	3	0	0
Walsingham Sink	<100 m	>40 m	2	1	2	1.39	0.3
Walsingham Sink	<100 m	>40 m	2	0	3	1.39	0
Tucker's Town Cave	>100 m	>40 m	3	1	2	1.95	0.3
Tucker's Town Cave	>100 m	>40 m	3	0	3	4.22	0.15
Walsingham Cave	>100 m	>40 m	3	1	3	0	0.3
Walsingham Cave	>100 m	>40 m	3	0	3	2.2	0
Leaning Tower Cave	<100 m	<40 m	4	1	3	1.61	0
Leaning Tower Cave	<100 m	<40 m	4	0	3	1.95	0.05
Palm Pit	<100 m	<40 m	4	1	3	0	0.1
Palm Pit	<100 m	<40 m	4	0	3	1.39	0.1
Swizzle Cave	<100 m	<40 m	4	1	2	2.2	0.31
Swizzle Cave	<100 m	<40 m	4	0	3	2.4	0.2

First, descriptive statistics of the data were generated using SPSS statistics software. The following table demonstrates these data including the mean values, the standard deviation, and the sample sizes (Table 10).

Table 10. Descriptive statistics of water quality data.

	Depth	**Class**	**Mean**	**Std. Dev**	**N**
Nitrate	0	1	3.5321	1.22	4
		2	1.2296	1.15	3
		3	3.2084	1.42	2
		4	1.91	0.5	3
		Total	2.497	1.37	12
	1	1	0.8959	1.08	4
		2	1.1552	1.05	3
		3	0.973	1.37	2
		4	1.2689	1.13	3
		Total	1.0668	0.97	12
	Total	1	2.214	1.77	8
		2	1.1924	0.99	6
		3	2.0907	1.72	4
		4	1.5895	0.86	6
		Total	1.7819	1.37	24
Ammonia	0	1	0.2	0.09	4
		2	0.05	0.08	3
		3	0.075	0.1	2
		4	0.1167	0.07	3
		Total	0.1208	0.09	12
	1	1	0.1775	0.2	4
		2	0.2	0.17	3
		3	0.3	0	2
		4	0.1367	0.15	3
		Total	0.1933	0.15	12
	Total	1	0.1888	0.15	8
		2	0.125	0.14	6
		3	0.1875	0.14	4
		4	0.1267	0.11	6
		Total	0.1571	0.13	24

These mean concentration data sorted by depth and class were analyzed using a two-way analysis of variance statistical setup. The depth and class categories were compared individually with pollutant concentrations, and the depth and class categories were then crossed and compared to pollutant concentrations to determine which interactions were significant. The outcome showed that only the depth category variance analysis for nitrate had a statistically significant interaction of $p = .009$, with $F = 8.798$ (critical $F_{1,16} = 4.49$). Therefore, of all the categories only the interaction between surface and depth nitrate concentrations was statistically significant. Neither the class, nor the depth crossed with class interaction was statistically significant for nitrate or ammonia (Table 11).

Table 11. Analysis of variance of water quality data.

Source	**Dependent Variables**	**Type III SS**	**Df**	**MS**	**F**	**Sig.**	**Observed Power**
Depth	nitrate	11.018	1	11.018	8.798	0.009	0.795
	ammonia	4.90E-02	1	4.90E-02	2.569	1.29E-01	0.326
Class	nitrate	4.182	3	1.394	1.113	0.373	0.244
	ammonia	2.35E-02	3	7.82E-03	0.41	7.48E-01	0.114
Depth*Class	nitrate	7.249	3	2.416	1.93	0.166	0.405
	ammonia	5.45E-02	3	1.82E-02	0.952	4.39E-01	0.213
Error	nitrate	20.036	16	1.252			
	ammonia	3.05E-01	16	1.91E-02			
Total	nitrate	119.946	24				
	ammonia	1.01E+00	24				

GIS data

Bermuda cave maps were created using ESRI 8.3 ArcGIS software, in order to show the geographical distribution of categorical data gathered in both the 1983 and 2002 survey. The seventy caves that were compared in the two surveys were plotted (Figure 31). It is clear from this map that the majority of the caves are located in the Walsingham outcropping between Harrington Sound and Castle Harbour. Therefore, this region was selected as the focus region when map layouts were created for comparison between the geographical trends in the four negative categories in 1983 and 2002. In each negative category, ratings (1-5) were assigned different shapes and colors to indicate the varied levels of environmental threat. Figure 32 and 33 display the results of the vandalism ratings in 1983 and 2002.

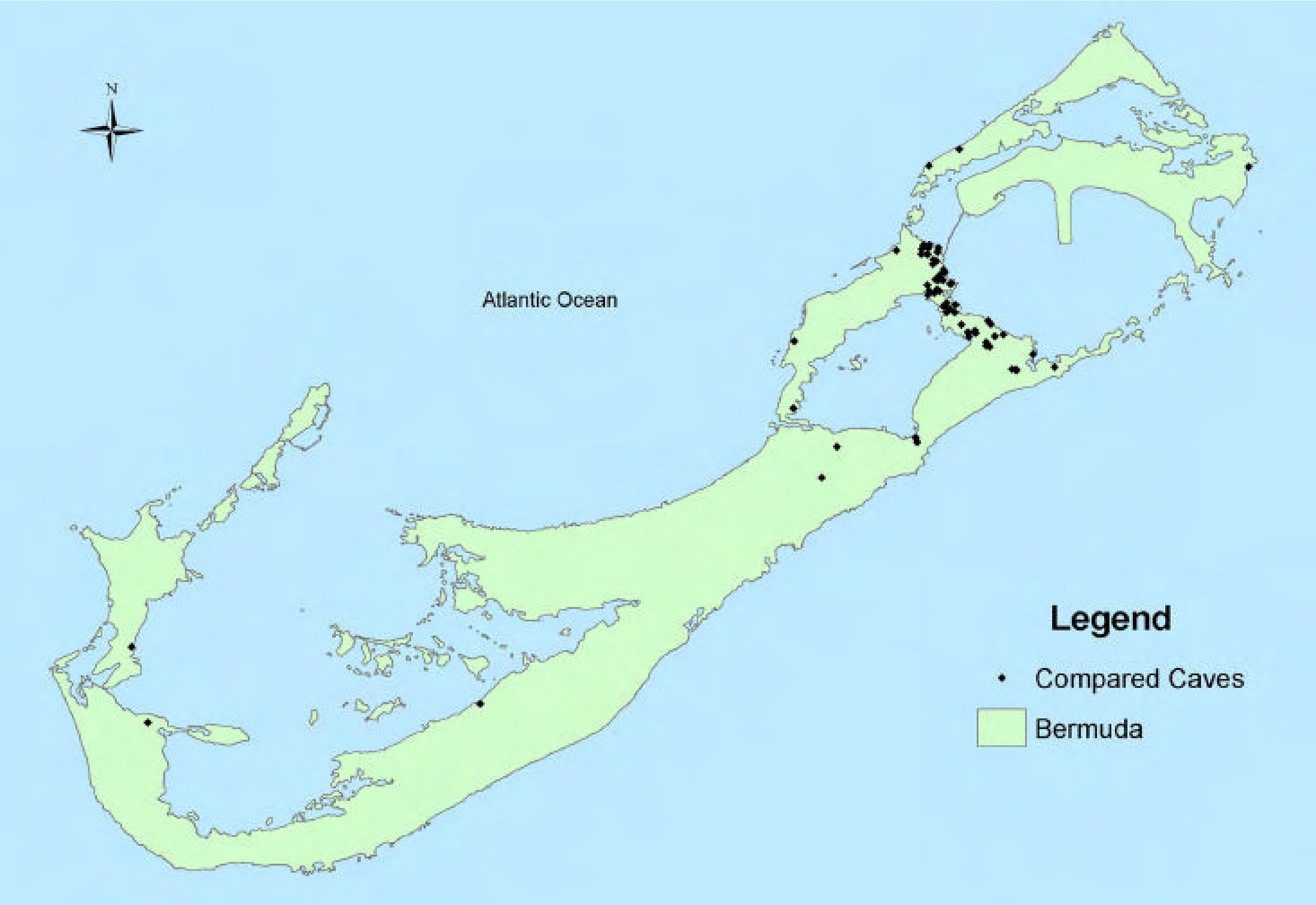


Figure 31. Geographical distribution of caves compared in 1983 and 2002 survey.

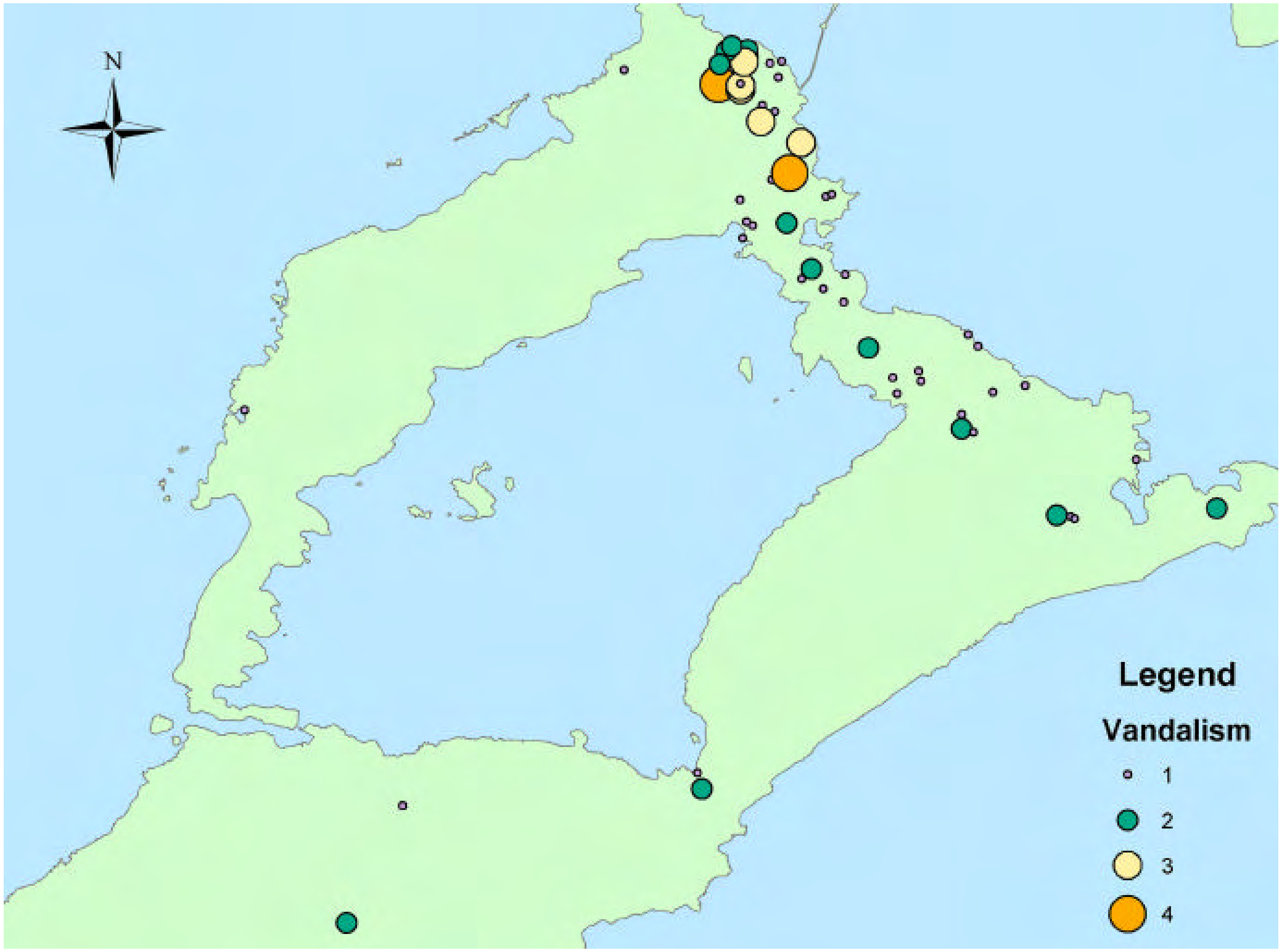


Figure 32. Map of vandalism ratings for the 1983 survey (1 = least endangered, 5 = most endangered).

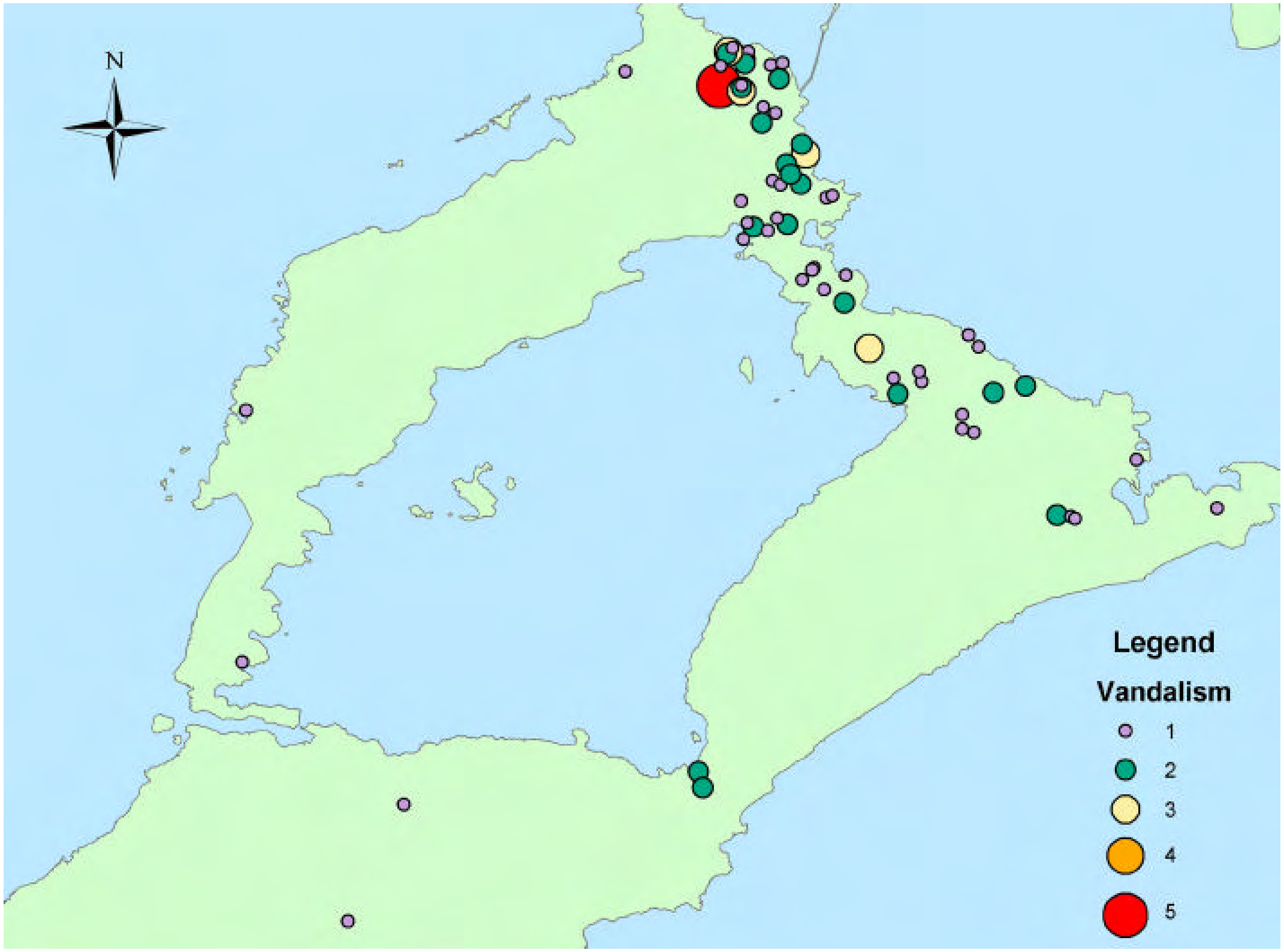


Figure 33. Map of vandalism ratings for the 2002 survey (1 = least endangered, 5 = most endangered).

Figures 32 and 33 illustrate how vandalism used to be more concentrated in the northern area of the Walsingham rock outcropping in 1983 and became more spread out in the 2002 survey throughout the region. Perhaps as the population has increased, more and more people are discovering cave locations in the Walsingham region and causing damage to the internal formations. There was also one cave that was elevated to a “5” rating, whereas no caves in this area were rated at the most endangered level in 1983. The next two figures (34-35) demonstrate the geographical relationships within the dumping ratings in 1983 and 2002. These two maps show how a number of the caves rated a “3” in 1983 were elevated to a “4” or “5” in 2002. Apparently, littering in these caves has only continued to worsen over the twenty years between the two studies. The next two maps demonstrate the changes in geographic relationships between caves threatened by water pollution (Figures 36, 37).

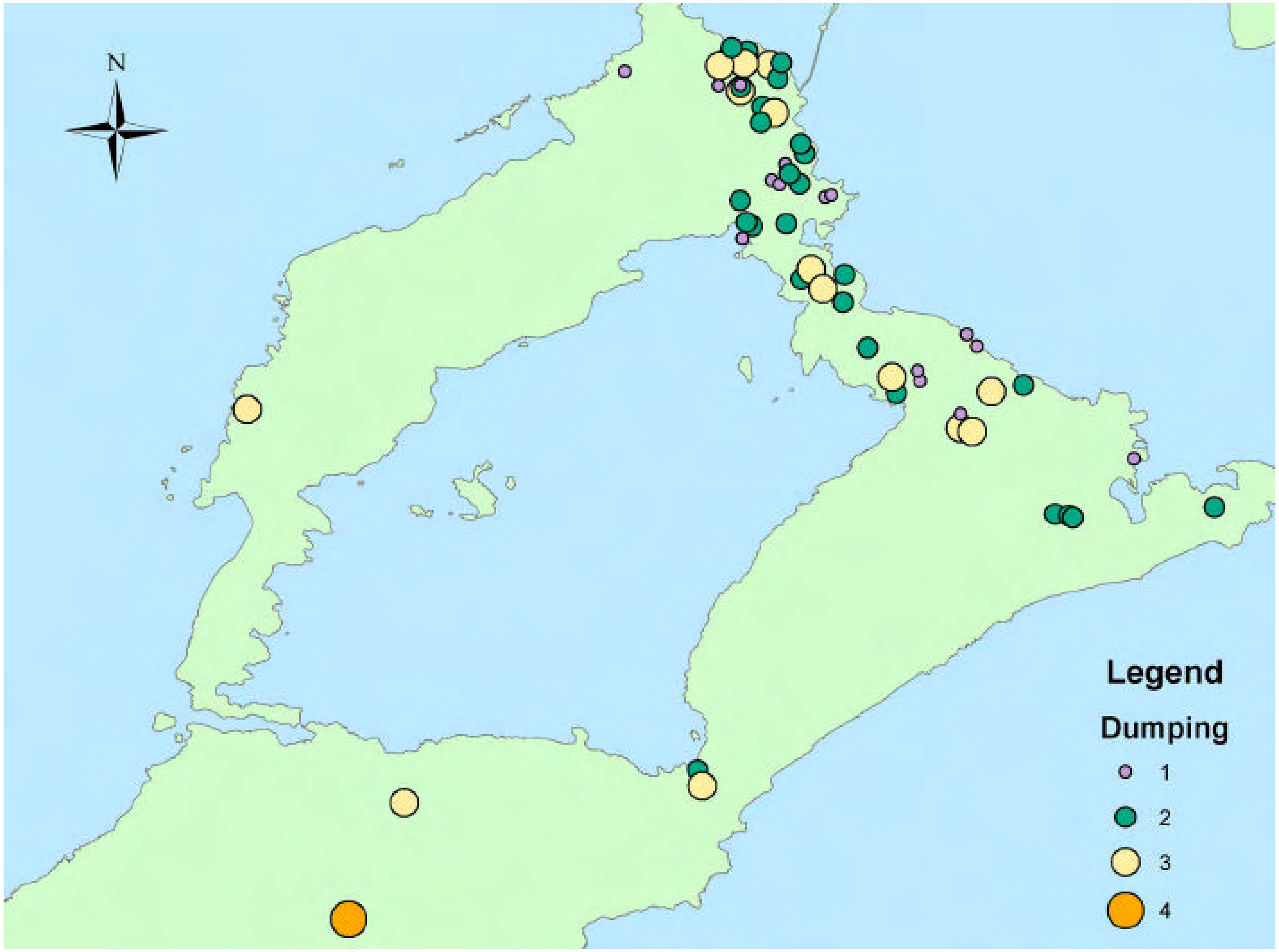


Figure 34. Map of dumping ratings for the 1983 survey (1 = least endangered, 5 = most endangered).

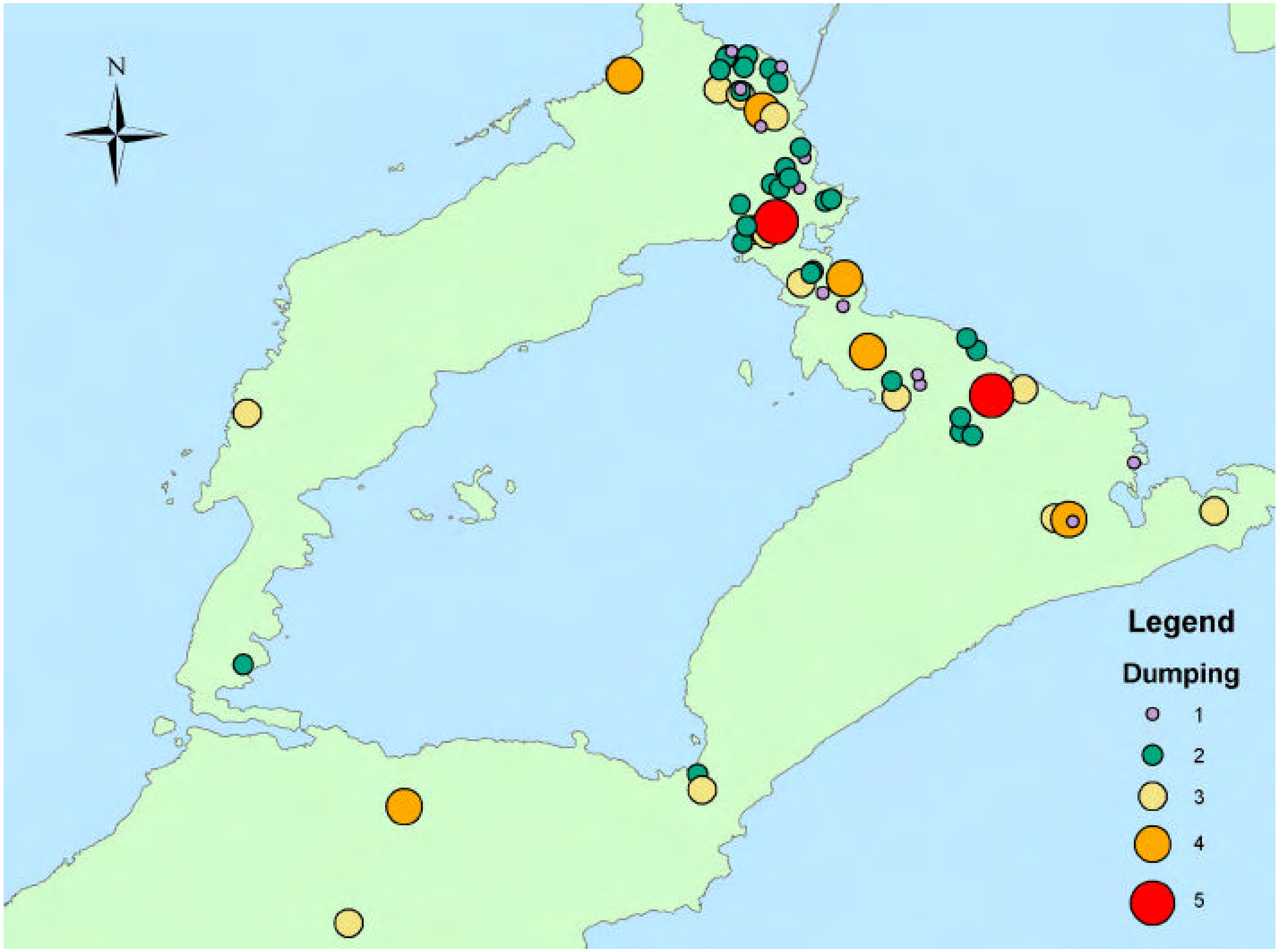


Figure 35. Map of dumping ratings for the 2002 survey (1 = least endangered, 5 = most endangered).

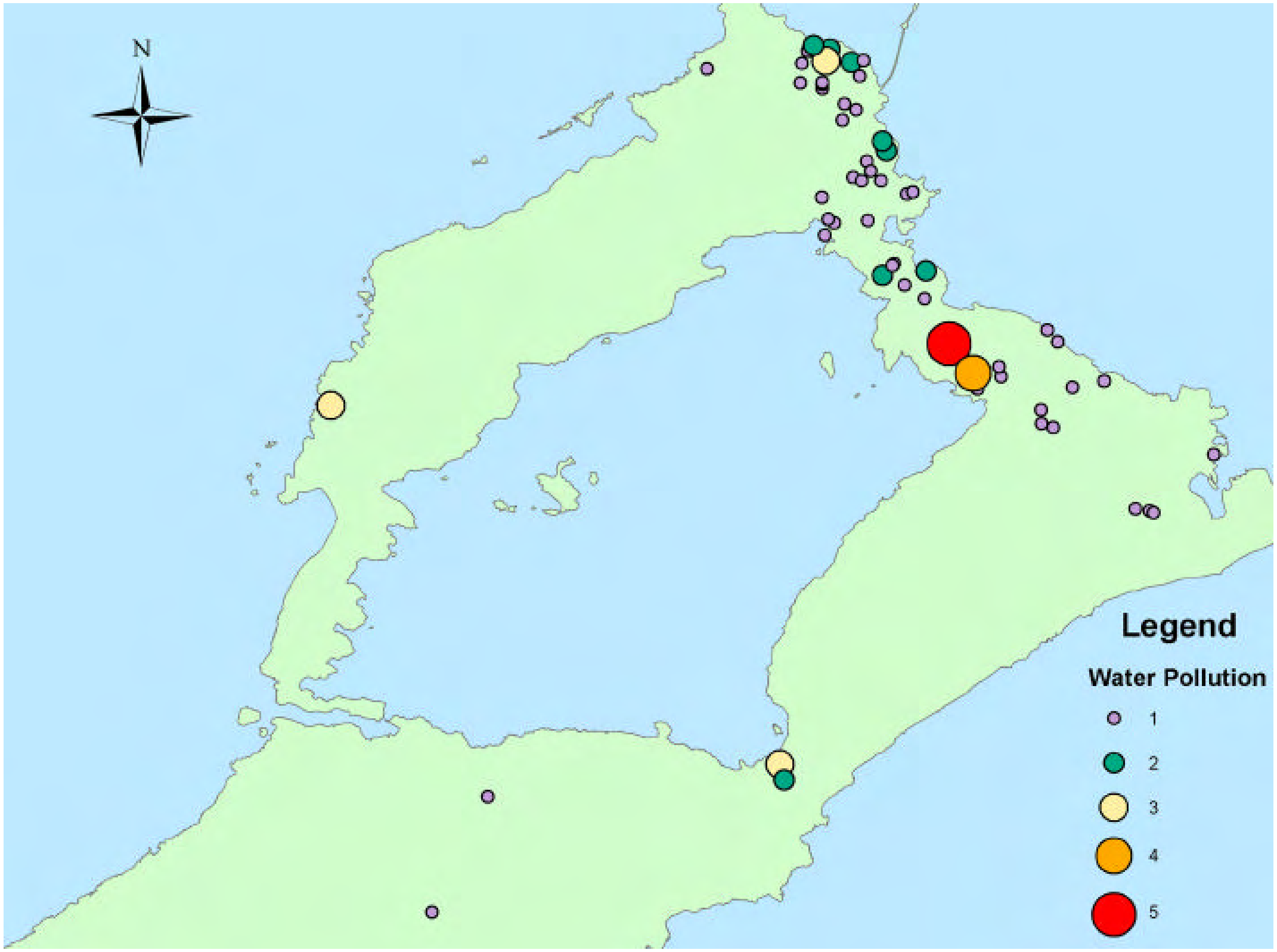


Figure 36. Map of water pollution ratings for the 1983 survey (1 = least endangered, 5 = most endangered).

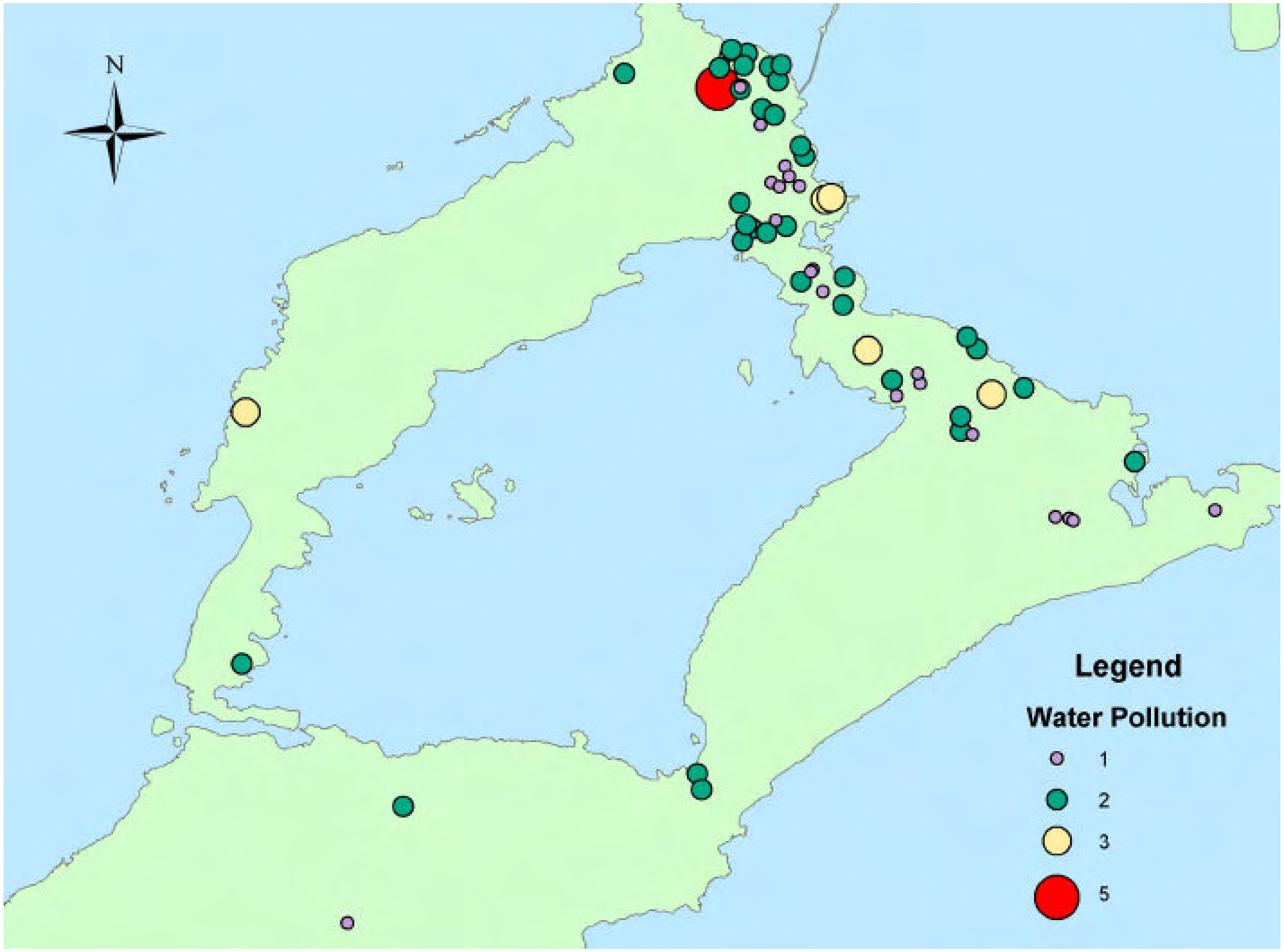


Figure 37. Map of water pollution ratings for the 2002 survey (1 = least endangered, 5 = most endangered).

Figures 38 and 39 display the differences in quarrying/construction in 1983 and 2002. There are several caves rated at higher levels throughout the Walsingham region when compared to their ratings in 1983. This map demonstrates how new housing developments are encroaching on cave habitat, and how continued quarrying in the Wilkinson quarry in particular is threatening nearby caves in the northern section of the Walsingham region. Figure 40 illustrates cave locations that were compared between the two studies, and includes locations of caves that have been destroyed since that time. Twelve of these caves were destroyed by quarrying, six by housing development, and two coastal caves that were destroyed by a hurricane. It is clear from how clustered many of the destroyed caves are how one quarry can have a dramatic impact on cave habitat.

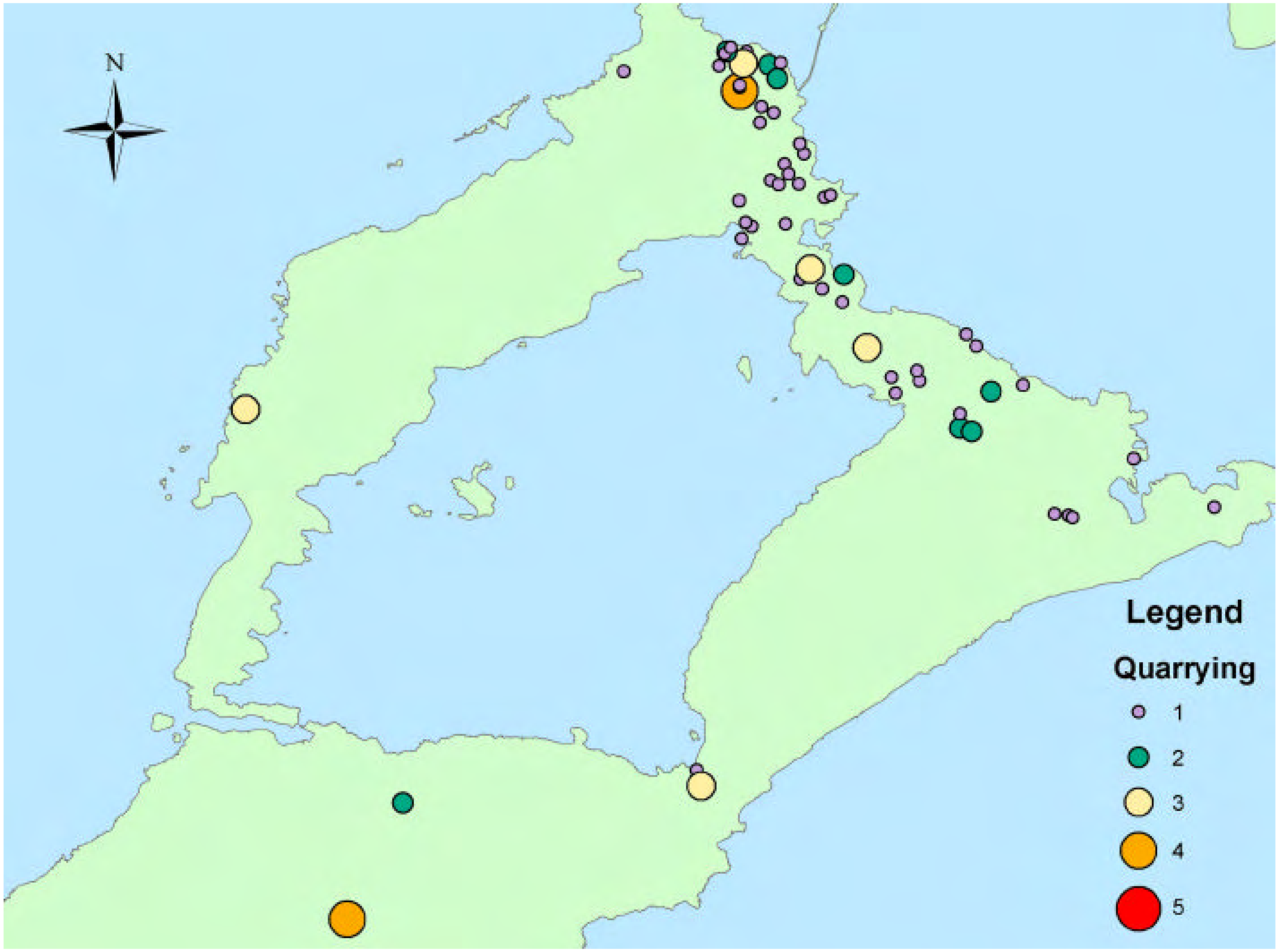


Figure 38. Map of quarrying ratings for the 1983 survey (1 = least endangered, 5 = most endangered).

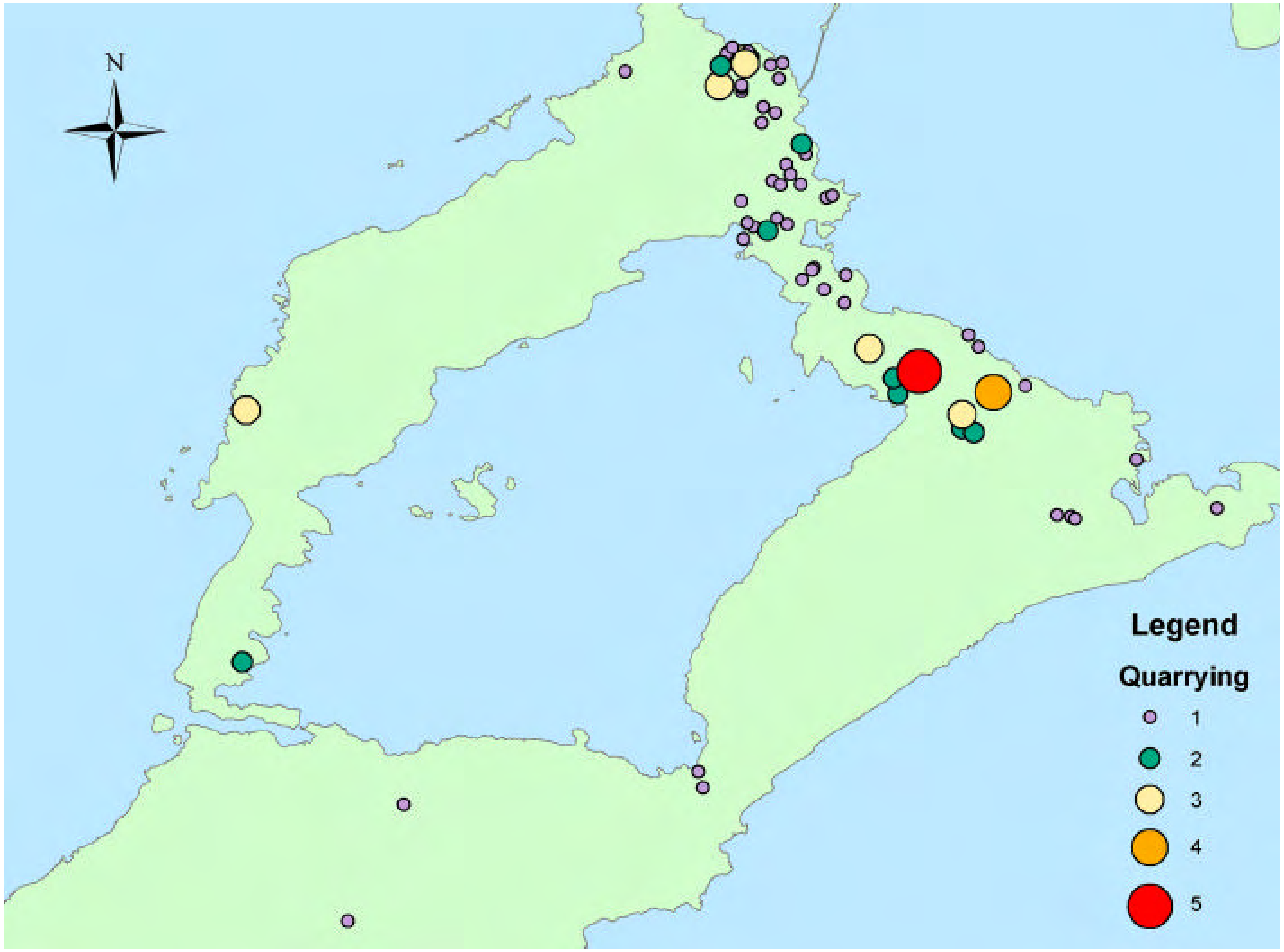


Figure 39. Map of quarrying ratings for the 1983 survey (1 = least endangered, 5 = most endangered).

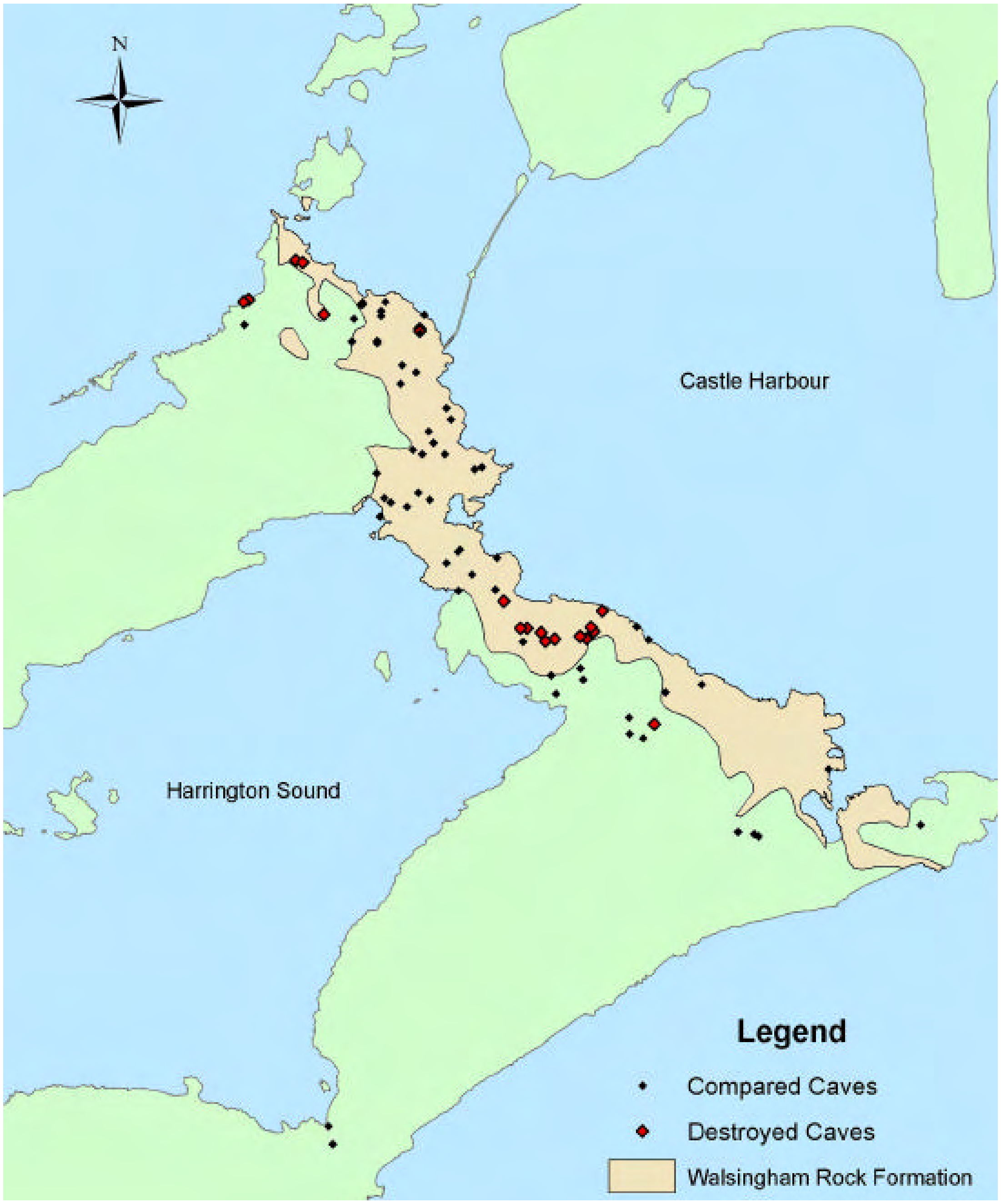


Figure 40. Cave locations that were compared in the two surveys and locations of caves that have been destroyed since the 1983 study with the Walsingham rock formation displayed.

SUMMARY AND CONCLUSIONS

This study utilized three methods to investigate the present day environmental health of Bermuda's caves: a categorical survey of visual environmental quality, experimental analysis of water quality, and the incorporation of these data sets into a GIS database known as the Bermuda Cave and Karst Information System (BeCKIS). Each independent part of this research study revealed different information about Bermuda's caves.

Cave environmental survey

Chi-square statistical analysis for each of these categories demonstrated a significant difference between the expected and observed data with $p < 0.001$ for vandalism and water pollution, and $p < 0.01$ for dumping and quarrying/construction (df = 4, $X^2_{crit} = 9.49$). These statistical tests show that the null hypothesis, that there is no difference in the current and historical environmental status, can be rejected since $p < 0.05$. Though the Chi-square analysis showed that there was a difference in the two data sets, it did not indicate whether the overall environmental status of the caves had improved or declined. Therefore, to show improvement or deterioration, an average negative rating was calculated for each of the 70 caves based on the four negative categories in the two surveys. The 1983 average values were compared to the 2002 averaged values, and the data showed that 14 caves improved in environmental quality, 30 caves declined and 26 caves remained the same. Furthermore, when each individual negative category (i.e., vandalism, dumping, water pollution and quarrying/construction) was analyzed, more caves were rated at a higher endangered level than a lesser endangered level in each category.

Dumping/Littering

Dumping and littering continues to be a significant problem. Of the four negative categories, dumping and littering had the most ratings that indicated a greater level of threat in the current study compared to the findings of the 1983 study: 31 caves had declined, 20 improved, and 19 stayed the same. There was an average rating of 2.02 in 1983 and 2.27 in 2002, which further substantiated a decline in the environmental status. Caves, especially those with vertical pit-like entrances, are vulnerable to littering because they appear to provide a natural repository for trash. However, many caves in Bermuda could be restored to their natural state by a mere half-day cleanup with a small volunteer group. Some of the larger caves, especially underwater ones, would require a much greater effort. Two caves mentioned in the results section—Cordial Cave and Sear's Cave—serve as examples of instances where cleanups have drastically improved the environmental health and appearance of a cave.

Water pollution

The visual survey of water pollution was supplemented by chemically and physically profiling the cave water column. Survey ratings were based primarily on the proximity of the cave to potential pollution sources, e.g., buildings or houses, which have cesspits attached, and to the presence of noticeable contamination, such as abnormal turbidity or hydrogen sulfide odor. The survey was limited by its observational nature, while the further studies of water chemistry allowed for an improved assessment of the trends in water quality and chemistry.

This category had the second highest number of worsened cave ratings: 26 had declined, 6 improved, and 38 remained the same. The survey ratings in this category changed from an average of 1.41 in 1983 to 1.75 in 2002, indicating an overall decline in health. The number of more endangered caves increased mostly because development plans are in place for construction of new homes and buildings in close proximity to a number of caves, which thereby threatens the water quality due to cesspits that will be attached to these structures. In particular, a number of villas and a small shopping strip will be constructed in the near future on the Bermuda Properties land, located in and around the Castle Harbour golf course. Also, a new hotel and staff quarters will be constructed where the old Castle Harbour Marriott was located. These construction plans involve regions of high cave density.

Vandalism

Of the four categories, vandalism had the third highest number of cave ratings that had dropped to a lower rating: 18 had declined, 15 improved, and 37 stayed the same. In 1983, there was an average rating of 1.51 and 1.59 in 2002. Intentional destruction and vandalism of speleothems and other cave formations is irreversible. This is true not only of Bermuda's caves, but of caves throughout the world. Tourists and amateur explorers may be tempted by the beauty of the speleothems to break them off in order to take a "souvenir" home. During a visit to a impressively decorated and newly discovered cave on the Wilkinson Quarry property in Bermuda, one quarry employee admitted that he and his co-workers had intentionally broken off and collected the most beautiful speleothems they could find in this cave. The fact that speleothems are nonrenewable resources was supported by a recent dating study. A small, already broken stalagmite from a Bermuda cave was recently collected by a scientist visiting Bermuda, to enable him to investigate whether stalagmites may be used as a tool to study climate change over many thousands of years. Isotopic dating of the specimen revealed that it had begun to form at least 50,000 years ago (Keigwin personal communication). This evidence demonstrates how damaged or destroyed speleothems will not be replaced for many millennia.

Clearly, there is a need for better dissemination of information about the cave environment among Bermudians so that this irreplaceable resource is not lost due to ignorance. Since public education is a lengthy process, a more immediate solution would involve the installation of gates at cave entrances (Hunt and Stitt 1981). If cave gates were placed on entrances of some of the more vulnerable caves, their environmental status could definitely be improved. Although the addition of a gate to a cave clearly is an alteration of the natural environment, the protective benefits may greatly outweigh the aesthetic and visual losses. Fortunately, many cave entrances are naturally camouflaged by thick undergrowth, while others are generally inaccessible due to their location on private property.

Quarrying/Construction

Quarrying has had a dramatically negative impact on cave environmental status over the past twenty years as evidenced by the destruction, through blasting and quarrying, of twelve caves representing 7% of Bermuda’s known caves. Very likely, a number of other caves that were not known at the time of the 1983 survey were also destroyed, particularly in the Wilkinson Quarry. Of the four negative categories studied, quarrying/construction had the least number of caves with a higher level of threat in 2002 compared to 1983: 12 had declined to a worse threat level, 11 had improved, and 47 had remained the same. Since 1983, however, the average rating increased from 1.44 to 1.46. These numbers are slightly misleading as they exclude ratings of the twelve caves that were destroyed by quarrying, which, therefore, could not be rated in the current study.

Bermuda’s two existing quarries in karst terrain—Wilkinson and Government Quarries—pose a major threat to cave habitat. A large and extremely well-decorated cave, for example, was discovered during blasting operations at Wilkinson Quarry in November 2001. Government officials first became aware of the existence of the new cave when a quarry worker—drinking at a local pub—displayed a stalagmite that he removed from the cave earlier that day. Blasting in the quarry has shattered meter thick deposits of flowstone within the cave and caused several large blocks of rock to collapse from the cave ceiling. Though the Planning Department has now mandated that no blasting may occur within 18 m of the entrance of this cave, it is extremely difficult to enforce this ruling, as the quarry is privately owned and continual monitoring of operations is not feasible (Madeiros personal communication).

Admiral’s Cave, one of the largest and most historically significant caves on the island, is located directly adjacent to the Wilkinson Quarry. Although no blasting is allowed within 18 m of the cave entrance it, like the newly discovered cave on the quarry grounds, can still be negatively affected by vibrations from more distant blasting. Fragile soda straw stalactites are highly vulnerable to such disturbances, and even slight vibrations could easily destroy them. Furthermore, some underground passages within Admiral's Cave trend toward the quarry and thus could be situated much closer to the blasting site than the prescribed 18 m entrance buffer zone. A neighboring house located several hundred meters from the quarry has had windows broken by blasting, and exterior damage from chunks of rock that have been flung outwards and collided with the house. Given that the house is located much further from the quarry than the cave, it still has experienced considerable damage, and thus it is apparent that the 18 m buffer zone is a rather inadequate protective measure.

Another fact that weakens the argument for the necessity of local quarrying is that the costs of importing limestone are highly comparable to the costs of extracting it locally. Wilkinson Quarry, for example, retailed hard aggregate at about $30 per cubic yard, while a local asphalt company retailed imported hard aggregate to the general public at about $36 per cubic yard, and to bulk purchasers at about $33 per cubic yard (Department of Planning 1988). Thus, it is difficult to justify the continuation of local quarrying operations from an economic standpoint. Furthermore, the approximately 124 jobs that would be lost if quarrying operations were discontinued could be made up by new positions for dock and/or shipping crew and transport workers for increased hard aggregate importing (Department of Planning 1988). Taking into account the economic and environmental considerations, it would be more practical to discontinue local quarrying and shift over to importing concrete and asphalt materials.

In addition to quarrying, construction of new homes in Walsingham rock outcroppings on the island poses a significant threat to caves. It is suspected that a number of caves uncovered during residential construction, particularly on the land between Harrington Sound and Castle Harbour, were quickly destroyed or filled in before news of their discovery reached government conservation officials. This threat will continue to persist as long as development continues in the Walsingham rock formation.

Difficulties associated with adequately protecting Bermuda's caves appear to result from lack of the enforcement rather than from a need for new cave protection legislation. Even though clear laws and regulations have been enacted to prevent destruction of cave habitat, no individual or government agency has been designated to enforce them. In addition, the political process is designed such that ministerial power can override the Planning Department's recommendations regarding the prevention of development/destruction of cave habitat, thus weakening or completing negating cave protection legislation.

Water quality analysis

Since the initial water sampling series was not performed randomly, only general observations could be derived from the data. Elevated concentrations of nitrate and ammonia were observed in some caves, while high levels of *Enterococcus* bacterial contamination appeared in others. Moreover, a clear correlation between depth and pollutant levels was apparent, with higher concentrations of pollutants at the surface of cave pools than in subsurface waters. It was not possible to determine whether the proximity of a cave to a house or building (with an attached cesspit representing a potential source of water pollution) affected the pollutant levels in the water column. While some caves directly adjacent to or under buildings had low levels of pollutants, a few relatively remote caves in a nature preserve (Shrimp Cave and Canyon Cave) had surprisingly high levels of bacterial contamination. Therefore, further studies are necessary in order to better understand the trends observed in the first sampling series.

While no relationship between cave location and the presence or absence of bacterial contamination in the cave water was detected, bacterial contamination was evident only in surface water samples, never in subsurface samples. Perhaps the slow turnover rate in cave water bodies and the low amount of vertical mixing, given the absence of wind and wave induced mixing, explains this trend. Another factor could be the presence of unfavorable conditions deeper in cave waters that prevent the survival of *Enterococcus* bacteria. Time constraints during the second sampling period did not allow for further study to examine the depth trend.

A multiple analysis of variance experiment using random sampling attempted to distinguish whether factors including depth, proximity to a house or building, and size of a cave had an impact on pollutant (nitrate, nitrite, ammonia) concentrations in the water column. Of the three factors (depth, location, size) and three pollutants that were selected, the only interaction that resulted in a statistically significant correlation was nitrate concentrations and depth with $F = 8.798$, $p = 0.009$ (critical $F_{1,16} = 4.49$).

Based on this result, the null hypothesis, that there is no difference between nitrate concentrations at surface and subsurface measurements, was rejected. This finding supported the initial observation made during the first sampling period, that pollutants seemed more highly concentrated at the surface of cave pools than in subsurface samples. Perhaps pollution entering the cave pools from the overlying vadose zone remains at the surface of the water table due to slow vertical mixing, and spreads horizontally rather than vertically once it reaches the water table. This finding supports the Ghyben-Herzberg principle of the presence of a convex brackish water table underneath carbonate islands, where water trends first downwards in the vadose zone and then outwards at the water table as it seeks a region of less hydrostatic pressure (Todd 1959). If the flow is outwards towards the edge of the island once percolating freshwater reaches the water table, there is limited vertical mixing, and explains why low pollutant concentrations were characteristic of subsurface samples in this study.

Another potential explanation for lower nitrate levels in subsurface waters could be the presence of facultative bacteria that metabolize nitrate, using it as an energy source. On a positive note, the highest pollutant concentrations were consistently found in surface waters. Since most stygobitic invertebrates live in deeper, fully marine cave waters (> 7 m), they are removed from direct contact with the highest levels of pollutants. However, if the pollutants from above alter the water chemistry such that the effects are magnified downwards into the water column, clearly the organisms below would be impacted. This characteristic was, in fact, observed in a study of cave water chemistry in Government Quarry Cave and a number of nearby caves (Iliffe et al. 1984).

Further studies are necessary to better understand the biogeochemistry of Bermuda's cave water. Whatever the explanation for varying concentration levels compared to depth, the observed stratification of nitrate in cave waters, mirrors the findings of previous studies that measured nitrate levels at various depths in the groundwater of Bermuda's freshwater lenses (Simmons et al. 1985).

The manova statistics in this study did not support the hypothesis that there is no relationship between ammonia concentrations and depth, nor the hypothesis that there is no relationship between cave class and pollutant concentrations in cave water. Therefore, these hypotheses could not be rejected. The inability to reject these hypotheses does not necessarily mean that these factors would never have a significant impact on pollutant concentrations. In fact, several of the p values generated in the manova statistical analysis were relatively close to the alpha value (0.05), suggesting that there may be a significant interaction between the following factors: depth and ammonia concentrations (p = 0.129) and depth and class (1, 2, 3, 4) for nitrate (p = 0.166). The manipulation of experimental design in future studies may allow for a significant finding. Perhaps the experimental size was not large enough, testing could have been done at different times during the year, or sampling could have been performed in conjunction with weather events (i.e., droughts, storms, light rain).

On the other hand, further experimentation could confirm these conclusions that cave location or size has little effect on pollutant concentrations, and that groundwater hydrology on carbonate islands is complex by nature. Prior studies of contaminant transport demonstrate that water pollution can travel for long distances in groundwater, and reappear far away from the source (Crunkilton 1985). The results of this study suggest that pollutants spread horizontally once reaching the water table. In order to test new hypotheses regarding the fate of water pollution in Bermuda, a dye tracer could be dispensed into potential polluting sources (e.g., a household toilet), located near a region of high cave density.

Surface water samples could then be collected from every known cave pool and water filled collapse area, such as those found in the Walsingham rock formation, and then tested for the presence of the dye. It would be necessary to test the water in these pools immediately after the dye was dispensed, and thereafter on a regular basis as both the dispersal pattern and timing of groundwater in karst can be highly variable. This may better help to determine the complexities of contaminant transport and dispersion which are influenced by the irregular directionality of groundwater flow as tidal fluxes filter in and out of caves, and by the periodic downward input of water from the vadose zone.

Hydrolab data logging

Vertical profiling of cave water quality was conducted in three separate caves: Tucker’s Town Cave, Cliff Pool, and Straw Market Cave. Variations in these water column profiles demonstrate that each cave had its own unique hydrology trends, as temperature, pH, and dissolved oxygen changed quite differently with depth in each cave. Perhaps factors such as the relative distance of each cave from the shoreline and the amount of water exchange with the ocean influence the hydrology of cave water at different depths. Varying microbiological features in different tunnels and passages within these caves could also alter these parameters. The only factor that seemed to behave similarly in all three caves was salinity, which increased with depth from brackish to seawater. It would be interesting to perform data logging runs in these caves throughout the year in order to observe how much the parameters change over time.

GIS analysis

The map layouts created using the data from the cave environmental surveys in 1983 and 2002 demonstrate how GIS can be used to visually represent the results. The map layouts included are an example how the software was used, however, a number of other layouts could be created to represent the data differently. For example, other layers could be added to demonstrate, for example the relationship between cave locations and population density. This GIS database could also be used as a conservation tool. The proximity of caves with the highest formation rating—which corresponds to the highest amount of speleothem decoration—to the existing quarries on the island could be plotted, in order to represent those caves that would be most vulnerable to speleothem breakage and deterioration caused by quarrying activities. The database could also be used to identify caves that have continually suffered from vandalism, and indicate which caves may benefit the most by the installation of cave gates to protect them in the future from even more vandalism.

Recommendations for future research

There were a number of findings produced by the various experiments performed in this thesis project that raised further questions about the environmental status and hydrology of Bermuda’s caves. Future studies would be beneficial in order to better understand questions raised by this research. The list that follows presents several ideas for future studies:

1. Finish the current survey of Bermuda's caves by investigating every single cave that was studied in 1983, in order to allow for a full comparison between data from the two studies.
2. Increase the sample size of caves, and replicate the cave water pollution experiment designed in this experiment, testing for nitrates and *Enterococci* bacteria, to better assess whether cave location and size impact the level of water pollution, and use random sampling of caves to allow for statistically based conclusions.
3. Study the biogeochemistry of cave water by sampling for a variety of facultative and anaerobic bacteria in the water column in order to better explain the changes in pollutant concentrations at different depths.
4. Carry out Hydrolab data logging runs, through the use of cave diving, in select caves throughout the year, to compare hydrology trends over time and seasonal changes.
5. Gather Hydrolab profiles from the specific underwater tunnels of caves in which cave adapted invertebrates have been noticed repeatedly on dives, in order to better understand the water chemistry that is beneficial and supportive of life in cave water.

6. Perform dye tracing experiments to determine the length of time in takes for cesspit wastewater to travel into cave water, and distance that it can travel away from the source.
7. Conduct additional water quality experiments to detect the potential wide array of groundwater pollutants that could be found in cave water.

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APPENDIX

Discussion of Bermuda cave legislation

The earliest specific mention of cave protection in Bermuda legislation was contained in the Development and Planning Act of 1974. This Act came after earlier legislation in 1965, which created a Planning Department and created various categories of land and zoning- including public and private open space. The 1974 legislation designated caves as protected areas, as they were considered a type of land that possessed natural features of environmental value (Development and Planning Act 1974 Section 28). A 1983 amendment to the Development and Planning Act of 1974 created "overlay zoning" and environmental conservation areas, citing that the preservation of open space and the natural environment takes precedence over other planning considerations.

Later, regulations were created in 1988 to carry out the intent of the Bermuda National Parks Act of 1986, which more specifically detailed how the cave resource ought to be protected, and how vandals ought to be punished. Part 3 contains regulations that pertain to prohibited conduct in open spaces, and line F reads: "No person shall in any protected area remove, deface, damage or destroy any structure, archaeological artefact, treasure, buried relics, cave formations or mineral deposit…" (15 July 1988 Department of Planning). Anyone who disobeys this regulation is subject to the punishment described in section 27 and 28 of the Act. Paragraph 28 reads: (1) Where a person commits an offence against this Act or any regulations made thereunder: Punishment on summary conviction: in respect of each offence imprisonment for 3 months or a fine of $1,000 or both such imprisonment and fine and, in the case of a second or subsequent conviction imprisonment for 6 months or a fine of $2,000 or both such imprisonment and fine; and in the case of a continuing offence a further fine of $200 for every day during which the offence continues. A person found guilty of an offence against this Act or any regulations made thereunder may, if there has been damage done to a protected area and the court thinks fit, be ordered to pay, in addition to any penalty for which he is liable for the offence, a sum not exceeding the cost of the damage done to the protected area, as assessed by the court (National Parks Act of 1986).

The most recent regulations regarding cave protection include those that have been enacted by the Planning Department and those contained in the Bermuda 1992 Plan, which had the purpose of regulating the development and use of land in Bermuda until the year 2000 (Section 1.1). Caves fall under the designation, "protection area", and the development plan states that, "extreme care must be taken with the siting and density of development and with the disposal of sewage to ensure cave entrances and underlying cave systems are properly protected" (BP 1992 Section 12). The Planning Board also has the power to require an individual applying for a development permit on land with cave habitat to submit a detailed cave survey to enable the Board to assess the potential impact of a development proposal (section 12). Thus, according to these regulations established by the Planning Department, caves are afforded quite stringent protection on the island.

A loophole exists in the legislative process, however, that makes it possible for individuals to sidestep legislation that aims to protect Bermuda's cave resources.

Although the Planning Board can recommend that a development proposal be turned down if cave habitat would suffer, the Minister of the Environment can override recommendations and decisions of the Planning Board, thereby allowing development to proceed. Thus, regulations can be ignored if the Minister decides to override a Planning Board decision.

Table A-1. Comprehensive group of forty-eight caves with known underwater pools and tunnels, from which twelve (italicized) were selected for MANOVA water quality analysis.

	Large Cave (>100 m)	Small Cave (<100 m)
Close to potential polluting source (<40 m)	Cave House	Cathedral Cave
	Admiral's Cave	Island Cave (Prospero's)
	Wonderland Cave	Grenadier Pool
	Crystal Cave	Shrimp Cave
	Shop Cave	Canyon Cave
	Emerald Sink	**Leaning Tower Cave**
	Jane's Cave	Cordial Cave
	Ninth Hole	Staff Quarter's Cave
	Church Cave	Christie's Cave
	Bitumen Pitch	Chalk Cave
	Cliff Pool	**Swizzle Cave**
	Straw Market	**Palm Pit**
	Deepdene	
Far from potential polluting source (>40 m)	Fort Scaur Cave	Fern Sink
	Sibley's Cave	Causeway Cave
	Walsingham Cave	**Bush Cave**
	Deep Blue	Whiskey Cave
	Waterloo Cave	Coffee Cave
	Tucker's Town Cave	Calabash Sink
	Leamington Cave*	Bee Pit
		Coral Cave
		Cow Cave
		Dead Horse
		Olivewood Cave
		Cherry Pit
		Roadside Cave
		Walsingham Sink
		Palm Cave
		Boiler Room Cave

* Leamington Cave could not be sampled, as it was not possible to obtain permission to access this cave during the study period.

Table A-2. 1983 comprehensive cave environmental survey.

	Cave Name	Parish	# of Entrances	Elevation (ft)	SL	CD	+	B	F	S	U	H	-	V	D	P	Q
1	Small Fish Pond	Sandy's	1	20	Y	2	4	3	2	3	4	5	3	1	4	2	2
2	Neptune's	Sandy's	1	10	Y	1	2	2	1	1	2	3	2	1	1	2	1
3	Fort Scaur	Sandy's	1	65	Y	2	3	2	2	3	4	3	4	1	4	2	2
4	Bassett's	Sandy's	1	40	Y	2	5	3	3	4	5	5	5	1	4	5	5
5	Rocky Cox	Devonshire	1	20	Y	2	4	3	3	2	4	1	3	2	3	1	2
6	Cave House	Warwick	1	30	Y	1	4	2	4	3	4	2	2	3	2	1	1
7	Moving Sands	Paget	1	5	Y	1	1	1	1	1	1	1	5	1	1	1	5
8	Cemetary	St. George's	3	35	Y	0	3	2	2	2	3	2	2	1	2	1	1
9	Goon	St. George's	1	45	N		2	1	2	1	2	1	2	2	2	1	1
10	Great Head Sea	St. George's	1	45	Y	0	3	2	1	2	4	2	1	1	1	1	1
11	Coney Island	St. George's	1	5	Y	2	3	2	1	2	3	2	2	1	2	2	2
12	Skinner's	St. George's	1	25	n		3	2	2	2	3	2	2	2	2	1	1
13	Store Room	St. George's	2	30	n		2	2	2	2	2	2	2	2	2	1	1
14	Fresh Water	St. George's	1	20	n		4	3	2	2	4	5	2	2	2	1	1
15	SOFAR	St. George's	1	10	n		1	2	2	1	1	1	1	1	1	1	1
16	Trash	St. George's	1	20	n		1	2	2	1	1	1	4	1	4	1	1
17	Admiral's	Hamilton	2	90	y	3	5	4	5	5	5	5	3	4	1	1	0
18	Cricket	Hamilton	1	35	n		1	1	2	1	1	2	5	2	5	4	3
19	Convovulus	Hamilton	2	55	y	0	4	1	3	3	5	4	3	3	3	1	4
20	Sibleys	Hamilton	1	65	y	2	5	4	5	5	5	4	2	3	2	1	1
21	Cathedral	Hamilton	2	30	y	1	5	3	4	4	4	5	2	3	1	2	1
22	Hog Hole	Hamilton	1	15	y	2	3	2	2	1	2	4	2	2	2	2	1
23	Grotto Sign	Hamilton	1	35	y	3	4	3	3	2	4	1	3	1	3	2	2
24	Island	Hamilton	2	35	y	3	4	3	4	3	4	5	3	3	3	3	3
25	Nap	Hamilton	1	40	n		2	1	2	2	1	1	1	1	1	1	1
26	Y	Hamilton	1	35	n		2	1	2	1	1	2	2	2	1	1	2
27	Z	Hamilton	1	35	y	1	3	2	2	3	3	1	2	2	1	1	1
28	Bush	Hamilton	1	75	y	3	3	3	3	3	4	1	3	2	3	1	1
29	Pipe	Hamilton	1	15	y	3	3	3	2	2	3	1	5	1	3	4	5
30	Bandana	Hamilton	1	20	y	0	2	2	2	1	2	1	2	1	2	1	2

Table A-2. Continued.

	Cave Name	Parish	# of Entrances	Elevation (ft)	SL	CD	+	B	F	S	U	H	-	V	D	P	Q
31	Cordwood	Hamilton	1	20	y	1	3	3	3	2	3	1	4	4	4	2	3
32	Blue Grotto	Hamilton	1	10	y	4	4	4	2	2	4	4	2	1	2	2	1
33	Crystal Pit	Hamilton	1	50	y	1	4	3	4	3	3	3	2	2	3	1	2
34	Wonderland	Hamilton	2	70	y	3	5	4	5	4	5	5	2	3	2	1	1
35	Crystal	Hamilton	4	110	y	5	5	5	5	5	5	5	3	4	2	2	2
36	Fern Sink	Hamilton	same														
37	Castle Grotto	Hamilton	4	10	y	3	4	5	3	3	4	4	2	3	2	2	1
38	Palmetto	Hamilton	1	90	n		4	1	4	3	4	1	2	3	2	1	1
39	Causeway	Hamilton	1	35	y	2	4	3	5	2	5	2	3	2	1	4	1
42	Corridor	Hamilton	1	100	n		3	1	2	2	4	1	3	4	1	2	2
43	Mussel	Hamilton	1	105	n		2	1	2	1	2	1	1	1	2	1	1
44	Grotto Bay Jungle	Hamilton	1	30	y	1	2	3	3	2	2	1	2	1	2	1	1
45	Dead Cedar	Hamilton	1	20	y	0	2	2	3	2	2	1	4	1	5	2	2
46	Coffee	Hamilton	1	10	y	3	3	4	3	3	2	1	1	1	2	1	1
47	Whiskey	Hamilton	1	5	y	2	3	3	2	2	2	1	2	1	3	1	1
48	Grenadier	Hamilton	1	5	y	2	3	3	2	2	3	3	1	1	1	1	1
49	Joyce's Dock #1	Hamilton	1	5	y	3	3	3	3	2	4	3	2	2	2	2	1
50	Joyce's Dock #2	Hamilton	1	5	y	3	3	3	2	2	4	2	2	1	2	1	1
51	Lobster Pot	Hamilton	1	5	y	3	3	3	2	2	4	1	2	1	2	1	1
52	Bayou	Hamilton	1	0	y	2	2	3	1	1	2	1	2	1	2	1	1
53	Low Tide	Hamilton	1	5	y	2	3	3	2	2	3	1	2	1	2	1	1
54	Railway East	Hamilton	3	30	n		3	1	3	2	4	3	4	2	4	2	3
55	Railway West	Hamilton	1	30	n		3	1	3	2	4	3	2	2	2	1	1
56	Quarry	Hamilton	1	40	n		3	1	2	3	3	1	5	1	1	1	5
57	Blue Hole Hill	Hamilton	2	90	N		3	1	4	3	3	1	3	3	2	1	1
58	Agave	Hamilton	1	15	y	2	3	3	3	1	3	1	3	1	3	3	2
59	Government Quarry	Hamilton	3	20	y	5	5	4	5	5	5	3	5	4	5	5	5
60	Calabash Sink	Hamilton	2	10	y	3	4	4	2	2	3	5	2	1	2	1	1

Table A-2. Continued.

	Cave Name	Parish	# of Entrances	Elevation (ft)	SL	CD	+	B	F	S	U	H	-	V	D	P	Q
61	Bathtub		same														
62	Bee Pit	Hamilton	2	25	y	2	3	3	2	2	3	1	1	1	1	1	1
63	Belly Scratcher	Hamilton	1	15	y	0	2	1	2	1	2	1	1	1	1	1	1
64	Blasted	Hamilton	1	10	y	0	2	1	2	1	1	1	5	1	1	3	5
65	Cat	Hamilton	1	20	n		1	1	1	1	1	1	1	1	1	1	1
66	Cherry Orchard	Hamilton	3	45	n		3	1	2	1	3	3	2	3	2	1	1
67	Clay	Hamilton	1	5	y	0	2	2	1	1	2	1	1	1	1	1	1
68	Close Call	Hamilton	1	75	n		1	1	2	1	1	1	4	1	1	1	4
69	Close Encounters	Hamilton	1	15	n		1	1	1	1	1	1	1	1	1	1	1
70	Coral	Hamilton	4	10	y	3	5	5	1	3	4	1	1	1	1	1	1
71	Walsingham Pond	Hamilton															
72	Cow	Hamilton	2	20	y	3	4	4	3	2	4	1	1	1	1	1	1
74	Walsingham	Hamilton	4	30	y	5	5	5	5	5	5	5	4	3	2	1	1
75	Deep Blue	Hamilton	same														
76	Dead Horse	Hamilton	same														
77	Vine 1	Hamilton	same														
78	Vine 2	Hamilton	same														
80	Finch	Hamilton	1	35	n		2	2	1	1	1	1	5	1	1	1	5
81	Gone	Hamilton	1	25	y	0	2	2	1	1	1	1	5	1	1	4	5
82	Halfmoon	Hamilton	1	25	y	1	2	2	2	2	2	1	5	1	4	5	4
83	Harbour	Hamilton	2	5	y	2	4	4	1	2	3	4	2	1	2	1	1
84	Mangrove	Hamilton	1	5	y	0	1	2	1	1	1	1	1	1	1	1	1
85	Olivewood	Hamilton	1	40	y	3	4	3	4	3	4	1	1	1	1	1	1
86	Cherry Pit	Hamilton	5	25	y	3	4	4	4	3	4	1	2	2	2	1	1
87	Pool Pit	Hamilton	1	10	y	2	3	3	1	1	2	1	1	1	1	1	1
88	Roadside	Hamilton	1	10	y	2	3	4	2	2	2	1	1	1	2	1	1
89	Shop	Hamilton	1	55	y	3	5	3	5	3	3	2	5	2	2	5	3
90	Siphon	Hamilton	1	10	y	0	1	1	1	1	2	1	1	1	1	1	1

Table A-2. Continued.

	Cave Name	Parish	# of Entrances	Elevation (ft)	SL	CD	+	B	F	S	U	H	-	V	D	P	Q
91	Spider	Hamilton	2	25	y	2	3	3	2	2	3	1	2	1	1	1	3
92	Stone Bowl	Hamilton	1	20	n		1	1	1	1	1	1	1	1	1	1	1
93	Subway	Hamilton	1	30	n		4	1	3	2	3	4	3	4	2	1	1
94	Triangle	Hamilton	1	20	n		1	1	1	1	1	1	1	1	1	1	1
95	Twin Domes	Hamilton	2	20	n		2	1	1	2	2	1	1	1	1	1	1
96	U-Turn	Hamilton	1	15	n		1	1	1	1	1	1	1	1	1	1	1
97	Waterloo	Hamilton	1	80	y	2	4	3	5	3	3	1	1	1	2	1	1
98	Wilson's	Hamilton	1	90	n		2	1	1	1	2	1	5	1	1	1	5
99	Dynamite	Hamilton	1	40	y	2	4	3	4	3	3	1	5	1	1	4	5
100	Shearwater	Hamilton	3	30	y	1	3	2	3	2	3	1	4	1	1	4	4
101	Hidden Cove	Hamilton	1	5	y	3	4	4	3	3	5	2	2	1	1	3	1
102	Emerald Sink	Hamilton	1	30	y	3	5	4	3	3	5	3	2	1	2	2	1
103	Leamington	Hamilton	3	60	y	3	5	4	5	4	5	5	3	2	4	2	1
104	Dandelion	Hamilton	1	15	y	1	2	2	2	2	2	1	1	1	1	1	1
105	Trema Tree	Hamilton	1	40	n		1	1	1	1	1	1	1	1	1	1	1
106	Walsingham Sink	Hamilton	3	45	y	3	5	5	3	3	3	2	2	2	2	1	1
107	Shrimp	Hamilton	2	10	y	3	4	4	2	2	3	1	1	1	1	1	1
108	Canyon	Hamilton	1	15	y	3	4	4	2	2	3	1	1	1	1	1	1
109	Point	Hamilton	1	10	y	1	2	2	2	1	2	1	1	1	2	1	1
110	Palm	Hamilton	5	15	y	5	5	5	4	5	5	1	2	1	2	1	1
111	Cripplegate	Hamilton	same														
112	Myrtle Bank	Hamilton	same														
113	Sailor's Choice	Hamilton	same														
114	Straw Market	Hamilton	same														
115	Angel	Hamilton	1	5	y	2	4	4	1	2	5	3	1	1	1	1	1
116	Stream Passage	Hamilton	3	15	y	2	4	4	3	2	4	1	1	1	1	1	1
117	Rat Trap	Hamilton	1	10	n		2	2	2	2	1	1	1	1	1	1	2
119	Little River	Hamilton	1	5	y	2	3	3	3	2	3	1	1	1	2	1	1
120	Swimming Pool	Hamilton	1	-5	y	3	3	3	1	1	3	1	1	1	1	1	1

Table A-2. Continued.

	Cave Name	Parish	# of Entrances	Elevation (ft)	SL	CD	+	B	F	S	U	H	-	V	D	P	Q
121	Gusher	Hamilton	1	0	y	1	3	3	1	1	3	1	1	1	1	1	1
122	White Stonewall	Hamilton	1	5	y	2	2	3	2	2	2	1	1	1	1	1	1
123	Valley	Hamilton	1	10	y	2	3	3	2	2	2	1	1	1	1	1	1
124	Double Pond	Hamilton	1	5	y	1	2	3	2	1	2	1	1	1	1	1	1
125	Three Rivers	Hamilton	1	20	y	1	3	3	3	2	3	1	1	1	1	1	1
126	Hidden Sink	Hamilton	1	15	y	2	3	3	3	2	3	1	1	1	1	1	1
127	Walsingham Lodge	Hamilton	1	20	y	3	3	3	3	2	3	1	4	1	4	1	1
128	Second Pool	Hamilton	1	-5	y	3	3	3	1	1	3	1	1	1	1	1	1
129	Palm Pit	Hamilton	1	10	y	1	2	2	2	2	3	1	1	1	2	1	1
130	Secret Entrance	Hamilton	1	25	n		1	1	1	1	2	1	1	1	1	1	1
131	Natural Trap	Hamilton	1	20	y	1	2	2	2	2	2	1	3	2	3	1	3
132	Cordial	Hamilton	1	50	y	3	3	3	3	3	3	1	2	1	3	1	1
133	Red Bay	Hamilton	1	0	y	4	4	3	1	1	4	1	1	1	1	1	1
134	Burchall Cove North	Hamilton	2	-20	y	4	4	4	3	4	4	1	3	1	3	3	3
135	Davis Pond	Hamilton	same														
136	Burchall Cove South	Hamilton	1	-25	y	3	4	4	2	2	4	1	4	1	3	3	4
137	Staff Quarters	Hamilton/St. George's	2	45	y	2	3	3	2	2	3	3	5	1	2	5	2
138	Cedar Stump	Hamilton/St. George's	1	35	n		2	1	2	1	2	1	2	1	2	1	1
139	Disappointment	Hamilton/St. George's	1	65	n		2	1	1	1	2	1	1	1	1	1	1
140	Runoff	Hamilton/St. George's	1	20	n		1	1	1	1	1	1	2	1	2	3	1
141	Boiler Room	Hamilton/St. George's	1	50	y	2	3	3	2	2	3	1	4	1	3	4	1
142	Walkway	Hamilton/St. George's	1	110	n	1	1	1	1	1	1	1	1	1			
143	Wingate's	Hamilton/St. George's	1	145	n		4	2	3	3	4	1	1	1	1	1	1
144	Creeping Fern	Hamilton/St. George's	1	145	n		1	1	2	1	1	1	1	1	1	1	1
145	Shark Hole	Hamilton/St. George's	1	10	y	0	4	3	3	3	4	4	3	3	2	2	2
146	Devil's Sinkhole	Hamilton/St. George's	1	60	n		4	2	2	2	4	1	1	1	2	1	2
147	West Boundary	Hamilton/St. George's	1	35	n		2	1	2	2	2	1	1	1	2	1	1
148	Jane's	Hamilton/St. George's	2	90	y	4	5	4	5	5	5	3	3	2	3	1	2
149	Ninth Hole	Hamilton/St. George's	1	70	y	2	3	3	3	3	3	1	3	1	3	1	2

Table A-2. Continued.

	Cave Name	Parish	# of Entrances	Elevation (ft)	SL	CD	+	B	F	S	U	H	-	V	D	P	Q
150	Zephyr	Hamilton/St. George's	1	70	y	?	3	3	4	3	3	1	2	1	2	1	2
151	Paynter's	Hamilton/St. George's	1	85	n		2	1	1	1	2	1	1	1	1	1	1
152	Paynter's Hill	Hamilton/St. George's	1	95	?		3	1	3	3	3	1	1	1	1	1	1
153	Tucker's Town	Hamilton/St. George's	2	65	y		5	5	4	4	5	4	2	2	2	1	1
154	Church	Hamilton/St. George's	3	135	y	4	5	4	3	4	5	5	3	2	3	1	2
155	Arch	Hamilton/St. George's	1	70	n	3	1	2	3	3	1	1	1	1	1	1	1
156	Buttonwood	Hamilton/St. George's	1	-5	y	3	3	3	1	1	3	1	1	1	1	1	1
158	Hilltop	Hamilton/St. George's	1	160	n		4	1	3	3	4	1	1	1	1	1	1
159	Dump	Hamilton/St. George's	1	70	n		3	1	3	3	3	1	4	1	4	1	1
160	Elevator	Hamilton/St. George's	1	10	y	1	2	1	2	1	1	1	3	3	2	1	2
161	Bitumen Pitch	Hamilton/St. George's	1	80	y	4	4	4	5	3	4	2	2	1	3	1	2
162	MOC	Hamilton/St. George's	1	70	n		3	1	3	3	2	1	2	2	2	1	1
163	Moonmilk	Hamilton/St. George's	1	90	y	?	3	3	3	3	3	1	2	1	2	1	1
164	Landslide	Hamilton/St. George's	1	90	?		3	3	3	2	3	1	2	1	2	1	1
165	Tucker's Town Bay	Hamilton/St. George's	1	0	y	4	4	4	2	2	4	1	1	1	1	1	1
166	Round House	Hamilton/St. George's	1	-10	y	3	4	3	2	2	4	1	2	1	1	1	2
167	Swan Cove	Hamilton/St. George's	1	0	y	1	2	2	1	1	2	1	1	1	1	1	1
168	Tuckahoe	Hamilton/St. George's	1	0	y	2	3	2	1	1	3	1	1	1	1	1	1
169	Cable Bay	Hamilton/St. George's	1	0	y	0	2	2	2	1	2	1	1	1	1	1	1
170	Castle Point	St. George's	2	5	n		3	1	1	1	3	1	2	1	2	1	1
171	Howard Bay	St. George's	2	5	n		3	1	1	1	3	1	2	1	2	1	1
172	"sea cave"	St. George's	1	0	y	0	2	1	1	2	2	1	1	1	1	1	1
173	Green Bay	Hamilton	2	15	y	5	5	5	5	5	5	3	2	1	2	2	2
174	Cliff Pool	Hamilton	same														
175	Southdown	St. George's	1	75	y	1	4	3	2	2	4	1	1	1	1	1	1
176	Deepdene	Smith's	1	90	y	2	3	2	2	3	4	1	2	1	3	1	2
177	Sear's	Smith's	1	150	n		4	4	3	2	4	4	4	2	4	1	4
178	Devil's Hole	Smith's	1	5	y	2	5	3	2	2	5	5	3	1	2	3	1
179	Gravell Bay	Smith's	1	0	y	0	1	1	1	1	1	1	1	1	1	1	1

Table A-2. Continued

	Cave Name	Parish	# of Entrances	Elevation (ft)	SL	CD	+	B	F	S	U	H	-	V	D	P	Q
180	Sound Winds	Smith's	1	60	n		3	1	2	2	3	1	2	1	2	1	1
181	Chalk	Smith's	1	40	y	3	4	4	4	3	4	2	3	2	3	2	3

Table A-3. 2002 comprehensive cave environmental survey (italicized and bolded caves no longer exist).

	Cave Name	Parish	# of Entrances	Elevation (ft)	SL	CD	+	B	F	S	U	H	-	V	D	P	Q
1	Small Fish Pond	Sandy's	1	20	y												
2	Neptune's	Sandy's	1	10	y												
3	Fort Scaur	Sandy's	1	65	y												
4	Bassett's	Sandy's	1	40	y	0	5	1	2	4	5	5	5	2	5	5	3
5	Rocky Cox	Devonshire	1	20	y												
6	Cave House	Warwick	1	30	y	1	5	2	5	3	5	3	2	2	2	1	1
7	***Moving Sands***	***Paget***	***1***	***5***	***y***												
8	Cemetary	St. George's	3	35	y	2	2	2	2	3	3	2	3	2	3	1	1
9	Goon	St. George's	1	45	n	0	2	1	1	1	2	1	1	1	1	1	1
10	Great Head Sea	St. George's	1	45	y												
11	Coney Island	St. George's	1	5	y												
	entrance rating					2	3	2	1	3	2	1	3	1	3	2	1
12	Skinner's	St. George's	1	25	n	0	2	1	2	2	3	1	3	3	3	1	1
13	Store Room	St. George's	2	30	n												
14	Fresh Water	St. George's	1	20	n												
15	SOFAR	St. George's	1	10	n												
16	Trash	St. George's	1	20	n												
17	Admiral's	Hamilton	2	90	y	3	5	3	5	5	5	5	5	5	3	5	3
18	***Cricket***	***Hamilton***	***1***	***35***	***n***												
19	Convovulus	Hamilton	2	55	y	?	5	2	3	4	5	4	3	3	3	1	1
20	Sibleys	Hamilton	1	65	y	2	5	2	5	5	5	5	2	2	2	2	1
21	Cathedral	Hamilton	2	30	y	2	5	3	3	2	2	5	3	2	2	2	3
22	Hog Hole	Hamilton	1	15	y	2	2	2	2	2	2	2	2	1	2	2	1
23	Grotto Sign	Hamilton	1	35	y	2	2	2	2	2	1	2	2	1	2	2	1
24	Island (Prospero's)	Hamilton	2	35	y	2	5	2	3	3	3	5	3	2	2	2	3
25	Nap	Hamilton	1	40	n	0	1	1	1	1	1	1	1	1	2	1	1
26	Y	Hamilton	1	35	n	0	2	1	2	2	2	2	3	3	2	1	1
27	Z	Hamilton	1	35	y	2	3	2	3	3	2.5	1	2	2	2	1	1
28	Bush	Hamilton	1	75	y	3	4	2	4	3	3	2	2	1	2	2	2

Table A-3. Continued.

	Cave Name	Parish	# of Entrances	Elevation (ft)	SL	CD	+	B	F	S	U	H	-	V	D	P	Q
30	Bandana	Hamilton	1	20	y	2	2	2	2.5	2	2	1	2	2.5	2	1	1.5
31	***Cordwood***	***Hamilton***	***1***	***20***	***y***												
32	Blue Grotto	Hamilton	1	10	y	4	5	2	2	3	3	5	3	3	1	2	1
33	Crystal Pit	Hamilton	1	50	y												
34	Wonderland	Hamilton	2	70	y												
35	Crystal	Hamilton	4	110	y												
36	Fern Sink	Hamilton	1	?	y	3	5	5	1	2	3	5	2	1	2	2	1
37	Castle Grotto	Hamilton	4	10	y	4	5	2	3	3	2	5	2	2	2	2	2
38	Palmetto	Hamilton	1	90	n												
39	Causeway	Hamilton	1	35	y												
	entrance rating				y	3	5	3	2	2	5	2	2	1	1	2	1
40	Blue Hole	Hamilton	1	0	y												
41	Bedding Plane	Hamilton	1	75	n	0	2	1	2	1	1	1	1	1	1	1	1
42	Corridor	Hamilton	1	100	n												
43	Mussel	Hamilton	1	105	n												
44	***Grotto Bay Jungle***	***Hamilton***	***1***	***30***	***y***												
45	***Dead Cedar***	***Hamilton***	***1***	***20***	***y***												
46	Coffee	Hamilton	1	10	y	3	2	2	2	2	2	2	4	1	4	2	1
47	Whiskey	Hamilton	1	5	y	2	2	2	2	1	1	1	3	1	3	2	1
48	Grenadier	Hamilton	1	5	y	1	5	5	2	3	3	3	4	1	4	2	1
49	Joyce's Dock #1	Hamilton	1	5	y	3	4	3	2	3	4	1	2	1	1	2	1
50	Joyce's Dock #2	Hamilton	1	5	y	3	3	3	2	2	4	1	2	1	1	2	1
51	Lobster Pot	Hamilton	1	5	y	2	3	2	2	3	3	1	2	1	1	2	1
52	Bayou	Hamilton	1	0	y												
53	Low Tide	Hamilton	1	5	y												
54	***Railway East***	***Hamilton***	***3***	***30***	***n***												
55	***Railway West***	***Hamilton***	***1***	***30***	***n***												
56	***Quarry***	***Hamilton***	***1***	***40***	***n***												
57	Blue Hole Hill	*Hamilton*	1	90	n	0	2	1	2	2	2	1	1	2	1	1	1

Table A-3. Continued.

	Cave Name	Parish	# of Entrances	Elevation (ft)	SL	CD	+	B	F	S	U	H	-	V	D	P	Q
58	Agave	Hamilton	1	15	y	2.5	3	3	2	2	3	1	4	1	4	2	1
59	***Government Quarry***	***Hamilton***	***?***	***20***	***?***												
60	Calabash Sink	Hamilton	2	10	y	2	4	4	2	1	1	5	2	2	1	1	1
61	Bathtub	Hamilton		10	y	2	4	4	2	1	1	5	2	2	1	1	1
62	Bee Pit	Hamilton	2	25	y	2	3	2	2	2	3	1	2	1	2	1	1
63	Belly Scratcher	Hamilton	1	15	y												
64	***Blasted***	***Hamilton***	***1***	***10***	***y***												
65	Cat	Hamilton	1	20	n												
66	Cherry Orchard	Hamilton	3	45	n												
67	Clay	Hamilton	1	5	y												
68	***Close Call***	***Hamilton***	***1***	***75***	***n***												
69	Close Encounters	Hamilton	1	15	n												
70	Coral	Hamilton	4	10	y												
71	Walsingham Pond	Hamilton															
72	Cow	Hamilton	2	20	y	3	3	2	2	3	3	2	2	2	2	1	1
73	Dead End Sink	Hamilton	1	85	n	0											
74	Walsingham	Hamilton	4	30	y												
	entrance rating				y	5	5	5	3	3	4	5	2	2	1	2	1
75	Deep Blue	Hamilton	same														
	entrance rating					5	5	3	2	3	3	5	2	2	2	2	1
76	Dead Horse	Hamilton	same														
	entrance rating					2	5	5	1	2	2	5	2	1	2	2	1
77	Vine 1	Hamilton	same														
78	Vine 2	Hamilton	same														
79	***Dusty***	***Hamilton***	***1***	***55***	***n***												
80	***Finch***	***Hamilton***	***1***	***35***	***n***												
81	***Gone***	***Hamilton***	***1***	***25***	***y***												
82	***Halfmoon***	***Hamilton***	***1***	***25***	***y***												
83	Harbour	Hamilton	2	5	y												

Table A-3. Continued.

	Cave Name	Parish	# of Entrances	Elevation (ft)	SL	CD	+	B	F	S	U	H	-	V	D	P	Q
84	Mangrove	Hamilton	1	5	y												
85	Olivewood	Hamilton	1	40	y	2	4	2	4	3	4	1	2	1	2	1	1
86	Cherry Pit	Hamilton	5	25	y	5	4	4	2	2	2	1	2	2	1	2	1
	entrance rating					5	4	4	2	2	2	1	2	2	1	2	1
87	Pool Pit	Hamilton	1	10	y												
88	Roadside	Hamilton	1	10	y	2	3	3	2	2	2	1	2	1	2	2	1
89	Shop	Hamilton	1	55	y	3	5	2	5	4	3	3	4	3	4	4	3.5
90	Siphon	Hamilton	1	10	y												
91	***Spider***	***Hamilton***	***2***	***25***	***y***												
92	Stone Bowl	Hamilton	1	20	n												
93	Subway	Hamilton	1	30	n	0	4	1	2	2	2	4	2	2	2	1	1
94	Triangle	Hamilton	1	20	n												
95	Twin Domes	Hamilton	2	20	n												
96	U-Turn	Hamilton	1	15	n												
97	Waterloo	Hamilton	1	80	y	2	4	2	5	4	5	2	2	2	1	2	1
98	***Wilson's***	***Hamilton***	***1***	***90***	***n***												
99	***Dynamite***	***Hamilton***	***1***	***40***	***y***												
100	***Shearwater***	***Hamilton***	***3***	***30***	***y***												
101	Hidden Cove	Hamilton	1	5	y												
	entrance rating					3	3	2	2	3	3	1	2	1	1	2	1
102	Emerald Sink	Hamilton	1	30	y	3	3	2	2	3.5	4	2	3	1	3	2	1
103	Leamington	Hamilton	3	60	y												
104	Dandelion	Hamilton	1	15	y												
105	Trema Tree	Hamilton	1	40	n												
106	Walsingham Sink	Hamilton	3	45	y												
	entrance rating					2	5	5	2	2	3	2	2	1	1	2	1
107	Shrimp	Hamilton	2	10	y	1	2	2	2	1	2	1	3	1	2	3	1
108	Canyon	Hamilton	1	15	y	3	2	2	1	1	2	1	3	1	2	3	1
109	Point	Hamilton	1	10	y												

Table A-3. Continued.

Cave Name	Parish	# of Entrances	Elevation (ft)	SL	CD	+	B	F	S	U	H	-	V	D	P	Q
110 Palm	Hamilton	5	15	y	2	5	5	3	2	2	1	3	2	3	2	1
entrance rating																
111 Cripplegate	Hamilton															
112 Myrtle Bank	Hamilton															
113 Sailor's Choice	Hamilton	1	10	y	5	2	2	1	2	2	1	3	1	3	2	2.5
114 Straw Market	Hamilton	1	5	y	5	5	4	4	5	5	1	4	1	5	1	1
entrance rating						3	2	2	2	3	1	2	1	2	1	2
115 Angel	Hamilton	1	5	y												
116 Stream Passage	Hamilton	3	15	y												
117 Rat Trap	Hamilton	1	10	n	0	2	2	2	1	2	1	1	1	2	1	1
118 Leaning Tower	Hamilton	1	10	y												
entrance rating					3	4	3	2	3	4	1	2	1	2	2	1
119 Little River	Hamilton	1	5	y												
120 Swimming Pool	Hamilton	1	-5	y	3	3	3	2	1	3	1	1	1	2	2	1
121 Gusher	Hamilton	1	0	y	1	2	2	1	2	2	1	1	1	2	2	1
122 White Stonewall	Hamilton	1	5	y												
123 Valley	Hamilton	1	10	y												
124 Double Pond	Hamilton	1	5	y	2	3	3	1	1	2	1	2	1	2	2	1
125 Three Rivers	Hamilton	1	20	y												
126 Hidden Sink	Hamilton	1	15	y												
127 Walsingham Lodge	Hamilton	1	20	y												
128 Second Pool	Hamilton	1	-5	y												
129 Palm Pit	Hamilton	1	10	y	4	2	2	2	2	1	1	2	1	2	2	1
130 Secret Entrance	Hamilton	1	25	n												
131 Natural Trap	Hamilton	1	20	y	1	2	2	2	2	2	1	2	1	2	1	1
132 Cordial	Hamilton	1	50	y	3	3	3	3	3	3	1	1	1	1	1	1
133 Red Bay	Hamilton	1	0	y												
134 Burchall Cove North	Hamilton	2	-20	y	3	5	5	3	4	4	1	3	1	3	3	3
135 Davis Pond	Hamilton															

Table A-3. Continued

Cave Name	Parish	# of Entrances	Elevation (ft)	SL	CD	+	B	F	S	U	H	-	V	D	P	Q
136 Burchall Cove South	Hamilton	1	-25	y												
137 Staff Quarters	Hamilton/St. George's	2	45	y												
138 Cedar Stump	Hamilton/St. George's	1	35	n	0	3	1	2	1	3	1	3	2	3	1	2
139 Disappointment	Hamilton/St. George's	1	65	n												
140 Runoff	Hamilton/St. George's	1	20	n												
141 Boiler Room	Hamilton/St. George's	1	50	y	2	2	2	2	2	3	2	2	1	2	2	2
142 Walkway	Hamilton/St. George's	1	110	n	0	1	1	1	1	1	1	1	1	1	1	2.5
143 Wingate's	Hamilton/St. George's	1	145	n	1	5	4	3	4	3	1	3.5	1	1	1	5
144 Creeping Fern	Hamilton/St. George's	1	145	n												
145 Shark Hole	Hamilton/St. George's	1	10	y												
146 Devil's Sinkhole	Hamilton/St. George's	1	60	n												
147 West Boundary	Hamilton/St. George's	1	35	n												
148 Jane's	Hamilton/St. George's	2	90	y	3	5	4	4	5	3	2	2	1	2	2	2
149 Ninth Hole	Hamilton/St. George's	1	70	y	2	3	2	2	3	2	1	2	1	2	1	2
150 Zephyr	***Hamilton/St. George's***	***1***	***70***	***y***												
151 Paynter's	Hamilton/St. George's	1	85	n												
152 Paynter's Hill	Hamilton/St. George's	1	95	?	0	3	1	2	3	3	1	3	1	2	2	3
153 Tucker's Town	Hamilton/St. George's	2	65	y	3	5	5	5	3	5	2	3	1	3	1	1
154 Church	Hamilton/St. George's	3	135	y	5	5	3	3	4	5	5	3	3	2	3	4
155 Arch	Hamilton/St. George's	1	70	n												
156 Buttonwood	Hamilton/St. George's	1	-5	y	3	2	3	1	1	2	1	1	1	1	2	1
157 Christie's	Hamilton/St. George's	1	20	y	3	3	2	3	2	3	1	3	2	3	2	1
158 Hilltop	***Hamilton/St. George's***	***1***	***160***	***n***												
159 Dump	***Hamilton/St. George's***	***1***	***70***	***n***												
160 Elevator	Hamilton/St. George's	1	10	y												
161 Bitumen Pitch	Hamilton/St. George's	1	80	y	4	5	2	3	3	3	5	5	2	5	3	4
162 MOC	Hamilton/St. George's	1	70	?	1	3	1	3	3	2	1	3	2	3	1	1
163 Moonmilk	Hamilton/St. George's	1	90	y	?	3	1	3	3	3	1	4	1	4	1	1
164 Landslide	Hamilton/St. George's	1	90	?	?	3	1	2	3	2	1	1	1	1	1	1

Table A-3. Continued

Cave Name	Parish	# of Entrances	Elevation (ft)	SL	CD	+	B	F	S	U	H	-	V	D	P	Q
165 Tucker's Town Bay	Hamilton/St. George's															
166 Round House	Hamilton/St. George's	1	-10	y												
167 Swan Cove	Hamilton/St. George's	1	0	y												
168 Tuckahoe	Hamilton/St. George's	1	0	y												
169 Cable Bay	Hamilton/St. George's	1	0	y												
170 Castle Point	St. George's	2	5	n												
171 Howard Bay	St. George's	2	5	n												
172 "sea cave"	St. George's	1	0	y												
173 Green Bay	Hamilton	2	15	y												
174 Cliff Pool	Hamilton			y	5	5	5	5	5	5	3	2	1	2	2	2
175 Southdown	St. George's	1	75	y												
176 Deepdene	Smith's	1	90	y	2	4	2	2	4	4	2	4	1	4	2	1
177 Sear's	Smith's	1	150	n	0	4	2	2	4	4	2	3	1	2	1	1
178 Devil's Hole	Smith's	1	5	y	2	5	5	2	3	5	5	2	2	2	2	1
179 Gravell Bay	Smith's	1	0	y												
180 Sound Winds	Smith's	1	60	n												
181 Chalk	Smith's	1	40	y	3	3	3	3	2	3	1	3	2	3	2	1
182 New Quarry Cave	Hamilton	1	?	y	3	5	5	5	3	5	5	5	5	1	2	5
183 Swizzle	Hamilton	1	?	y	1	3	1	3	2	2	3	5	2	5	1	1
185 Behind Cemetary	St. George's	1	?	n	0	2	1	1	1	2	1	3	1	3	1	1
188 Andrew's cave	St. George's	1	?	n	0	5	2	3.5	3	5	2	2	2	1	1	1
189 Grotto Heights	Hamilton	1	?	n	0	4	1	4	2.5	4	1	3	3	1	1	1
191 Darcy's Grotto	Hamilton	1	?	y	2	3	2	2	2.5	3	2.5	2	2	1	1	3

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- Research Assistant: Bahamas cave exploration, cave species collection, and water quality monitoring. Caribbean Marine Research Center: Lee Stocking Island, Bahamas. January 2003
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