

NOAA Coral Reef Conservation Grant – Final Report  
**Groundwater pollution and its impact on Bermuda's reefs and inshore waters**

Submission Date: May 29, 2008

Project Award Number: NA06NOS4630085

Project Period: October 1, 2006 - March 31, 2008

**Thomas M. Iliffe**

Texas A&M University at Galveston

Department of Marine Biology

**Project Goals:** The goal of this project was to locate karstic tidal springs along the coastline of Bermuda and determine the flux and environmental impact of groundwater nutrients and other pollutants on Bermuda coral reef and seagrass communities.

**Implementation Strategy:**

1. Survey Bermuda's coastline for tidal springs; record their GPS locations
2. Determine flow volumes into and out of springs over complete tidal cycles
3. Periodically analyze samples of discharge for water to calculate nutrient or other pollution fluxes
4. Obtain vertical water quality profiles along transects from the ocean into the interior of Bermuda's caves
5. Determine reef and seagrass health at sites close to discharge.
6. Correlate groundwater quality with overlying land use practices.
7. Identify groundwater threats and consult with local resource managers toward development of best management practices.
8. Involve high school students and the general public in the field and lab research
9. Prepare a documentary film and interactive educational website on the interrelationships between groundwater quality and coral reef and seagrass health

**Summary of research accomplishments:**

During this 18 month project, the PI participated in four, 2-week field trips to Bermuda during October 2006, March 2007, June 2007 and January 2008. In addition, two of the PI's graduate students spent two months in Bermuda during summer 2007 to conduct research related to this project. The objective of our first trip in Oct. 2006 was to assess field sites and gather preliminary data using electronic water quality monitoring sondes. This trip was carried out in collaboration with the Cambrian Foundation, and with support from the Bermuda Government. During this trip, educational outreach activities included a public seminar held at the Bermuda Underwater Exploration Institute (BUEI) and a Human ROV demonstration where secondary school students were able to ask questions and observe a diver in real time while he was swimming through an underwater cave. During the March 2007 trip, we obtained current velocity measurements from both new and previously visited sites. At each site, acoustic Doppler current meters were used to determine flow rates and volumes, while water samples were collected for nutrient analysis. During the October 2006 trip, hydrological data was collected from ten cave springs in Bermuda including four located along Harrington Sound, four on Castle Harbour, and two on the North Shore (Fig. 1). In March, we returned to six of the same caves, while adding an additional cave spring in the western part of the island.

Texas A&M (TAMU) Wildlife and Fisheries Masters students Jenipher Cate and Bridget Maloney spent two months (June and July 2007) in Bermuda conducting field research related to this project and to be used as their thesis research. This trip was part of a summer internship for the students at the Bermuda Aquarium sponsored by the Bermuda Zoological Society, the Bermuda Biodiversity Project and the Bermuda Department of Conservation Services. While in Bermuda, Jenipher and Bridget were assisted by TAMU-Galveston undergrads Kim Janusaitis and Elizabeth Foster, Arizona State University undergrad Gabrielle Cashdollar and TAMU-Galveston staff member Brendan Maloney. Local assistance was provided by Bermudian scientists Dr. Anne Glasspool, Jack Ward, Dr. Sara Manuel, Dr. Kathryn Coates, Lisa Greene, Dr. Thaddeus Murdock, Mandy Shailer and Matthew Hammond of the Bermuda Aquarium, Museum, and Zoo, in addition to Bermudian cave divers Gil Nolan and Leon Kemp. The PI, Dr. Thomas Iliffe, and TAMU Oceanography Ph.D. student Pak Leung also spent 10 days in Bermuda at the end of June to assist with field studies. In particular, Iliffe and Leung coordinated programming and placement of a new Nortek Vector acoustic Doppler velocimeter purchased with funds from an NSF grant to the PI.

During June and July 2007, 14 coastal karstic springs were investigated (Fig. 1). Nine of these caves line the western side of Castle Harbour and extend from North Shore to Tucker's Town Bay. One additional cave is situated on the North Shore, while the remaining four are along the shoreline of Harrington Sound. Study sites were chosen based on a number of factors including presence of seagrass, coral, degree of land development near the site, volume of water coming out of the spring and size of the entrance to the submerged cave. All sites had seagrass present except Burchall's Cove, Kim's Spring, Tucker's Town Dock Cave, Tucker's Town Bay Cave and Gazebo Cave. The only site lacking coral within 30 m of the entrance was Kim's Spring.

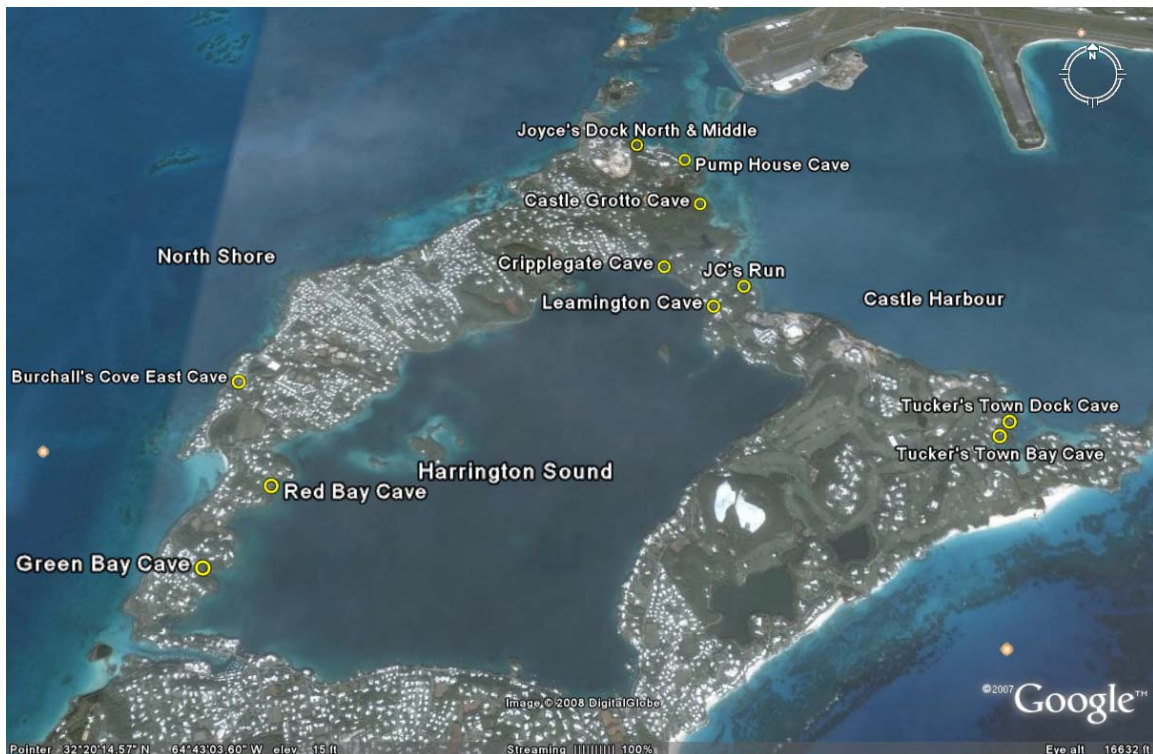


Figure 1: Coastal spring study sites in Bermuda

A final 10-day trip to Bermuda took place in January 2008 to finish field work and to present preliminary results of the project to a forum attended by representatives on various government agencies. Participants on this trip include three Texas A&M Wildlife and Fisheries Masters students working in my lab (Jenipher Cate, Bridget Maloney and Terrence Tysall) and underwater photographer and cave diver Tamara Thomsen of the Wisconsin Historical Society. Local assistance during this trip was provided by Bermudian scientists Dr. Anne Glasspool, Jack Ward, Dr. Sara Manuel, and Dr. Kathryn Coates of the Bermuda Aquarium, Museum, and Zoo, as well as by Bermudian cave divers Gil Nolan and Leon Kemp.

During this last trip, nine cave dives were conducted in Green Bay, Red Bay, Joyce's Dock, Deep Blue, Blue Grotto, Tucker's Town, and Tucker's Town Bay Caves. Projects on these dives included sonde and current meter placements in Blue Grotto, Green Bay, and Joyce's Dock Middle Caves. In addition, water samples for nutrient analysis were collected at 30 minute intervals over the course of complete outflows from Joyce's Dock Middle and North, Tucker's Town Bay, and Green Bay Caves.

Underwater and surface photo-documentation was a major objective of the trip. An on-line photo album of the caves and research activities is available at: <http://picasaweb.google.com/tamarathomsen/Bermuda2008> Coastal springs that were photographed included Joyce's Dock Middle and North, Castle Grotto, Burchall's Cove, Tucker's Town Bay, Green Bay, Red Bay, and Leamington Caves. Sonde and current meter placement was photographed at all three locations including Blue Grotto, Green Bay, and Joyce's Dock Middle Caves. Eighteen inland cave pools were also photographed, several with composite panoramic views. These inland cave pools are being concurrently investigated by TAMU graduate student Bridget Maloney for her M.S. thesis research. The focus of her study is to investigate relationship between cave pool water quality, especially elevated nutrient levels, and the composition and abundance of marine macroalgae inhabiting these partially illuminated entrance pools. The project involved in-situ nutrient addition and productivity experiments and biodiversity surveys aimed at determining if selected macroalgae species can serve as bioindicators of water quality and environmental health. This data provides support and supplementary information on the more inland sections of Bermuda's cave systems.

Underwater photography was used in Green Bay, Red Bay, Deep Blue, and Tucker's Town to illustrate characteristic features of Bermuda's submerged caves systems. Human impact on the caves was documented with photos of rusting oil barrels in Bitumen Cave, oil slicks at Tucker's Town Bay Cave, construction and golf courses at Tucker's Point Resort, and huge piles of trash amid rare cave ferns in Sears Cave.

On the morning of January 14<sup>th</sup> 2008, a Bermuda Cave and Karst workshop and forum was organized by Dr. Annie Glasspool at the Bermuda Aquarium, Museum, and Zoo. Invited participants included representatives of the Bermuda Ministry of the Environment, the Department of Conservation Services (including Director and higher level staff), the Department of Planning (including the Director and higher level staff), Bermuda Zoological Society, Bermuda National Trust, the Bermuda government's Marine and Terrestrial Conservation Officers, and the Bermuda government Hydrologist. The format for this meeting consisted of the showing of a 10 minute documentary film on Bermuda's caves entitled *Bermuda High*, oral presentations by Dr. Iliffe and TAMU graduate students Jenipher Cate and Bridget Maloney, followed by open discussion and exchange of information and ideas between all participants. Discussion topics included:

- Legislation and policy
  - Review/strengthen current legislation concerning caves (especially land use and sewage treatment)
  - Synchronize Planning Statement and Planning Act with regard to caves
  - Cessation of quarrying activities
  - Alternative solution to “deep sealed” boreholes
  - Lack of sensitivity amongst judiciary when considering environmental infractions
  - Potential and benefit for having caves listed under RAMSAR Convention
  - Need to license researchers and recreational cave divers
  - Need to consider system of compensation for land owners ensuring protection of caves on their property
  - Need to better understand land owner boundaries with regard to underlying caves
- Information sharing
  - Need to ensure centralized and secure location for data storage and information retrieval
  - Integration of cave data into GIS layers
  - Point contact person to facilitate sharing of information
- Conservation Action
  - Cave restoration projects
  - Educational outreach and public awareness
  - Endangered species and biodiversity hotspots
  - Habitat management
  - Cave exploration and mapping
  - Need for ecological and environmental research
  - Need for ongoing environmental and biodiversity monitoring

### **Methods:**

The first phase of this project was to locate coastal springs along Castle Harbour, North Shore, and Harrington Sound. This was done by snorkeling during the appropriate time of the tide, when cold, clear water would be flowing out of the cave. Another visual indication of a coastal spring was the growth of green algae *Caulerpa* or the presence of larger numbers of fish. Sometimes, the submerged spring entrances were large enough for a diver to enter, while others consisted of small holes or cracks on coastal rock faces.

For the October 2006 trip, data was evaluated from two similar electronic water quality analysis sondes: a YSI 600XLM and a TROLL 9500. They were both programmed to log data on depth, temperature, salinity, dissolved oxygen, and pH at a frequency of once per minute. In addition, the YSI sonde also recorded ORP, while the TROLL measured turbidity. The use of two instruments allowed us to cover more sites and to compare the two instruments. Cave springs were selected based on previous knowledge of location, significance of the cave and available access. Due to the geometry of Bermuda’s inshore waters, caves on Harrington Sound exhibit an outflow of cave water during a rising tide, while those along Castle Harbour and the North Shore have cave water outflowing on a falling tide. Sondes were secured in midwater on a line running from the ceiling to the floor, approximately 10 to 50 m inside the cave from the entrance. This was to prevent tampering with the instruments by swimmers and to ensure that the water flowing past the instruments was cave water and not a mixture of cave and outside water. As Bermuda tides are semi diurnal, sondes were left inside the caves for a minimum of twenty-

four hours to obtain two full cycles of high and low tides. The instruments were then removed and the data was downloaded to a laptop.

During the March 2007 trip, only the YSI sonde (Fig. 2) was used, programmed to collect data at a frequency of once every two minutes, while moorings were extended to a minimum of 36 hours to allow for collection of additional data over a number of tidal cycles.



Figure 2: YSI Sonde moored in Gazebo Cave

Nortek Aquadopp and Velocimeter current meters were used to measure velocity profiles in the caves. Each consists of internal data logger and 3 transducers that utilize the reflection of transmitted sound energy to resolve water currents. Aquadopp is an ADCP (Acoustic Doppler Current Profiler) which operates at 1 MHz frequency and measures velocity profiles at intervals throughout the water column. Velocimeter (Fig. 3) is a single point current meter that collects high resolution velocity data from a single point, 16 cm above its sensor head. Data sets collected from the Aquadopp and Velocimeter are slightly different. The Aquadopp was used to measure vertical current profiles in larger cave passages, while the Velocimeter was employed for point measurements in narrow cave passages. Divers placed the velocimeter facing into the cave, typically 5 to 80 m back from the entrance, at a point where the cave passage narrowed down and current velocities were higher. High resolution data from single point current meter is also useful for turbulence and mixing processes investigations.



Figure 3: Nortek Vector Velocimeter mounted on a PVC deployment pod and weighted in place

In order to calculate the volume of water passing in and out of the spring, a cross section of the cave passage was surveyed and sketched at the location where the Vector was deployed. Distances to the cave walls or ceiling were measured at 0, 45, 90, 135, and 180 degrees angles from the base of the instrument across the cave passage. A photograph of the cave walls was taken to aid in producing a scale drawing of the cross section.

Temperature profiles were measured with a string of Onset thermistors deployed along a 3 m line attached to the cave ceiling and floor; hence a thermistor string. Each thermistor sensor was separated by 0.25 m. This thermistor string provided information on the stratification and temperature variation in the water column with respect to time.

Water samples were collected at the end of the outflow, one day after the instruments had been placed in their respective caves, but while the instruments were still recording. All water samples were obtained via snorkeling or diving at the entrance of the cave at a depth of 5 m. Three samples were taken from each site including a sample collected three hours after the start of outflow near its midpoint; and another sample from near the end of the cave outflow; and a control consisted of ocean water in the area where the cave was located, but far enough away that mixing with cave water should not have occurred. The samples were frozen for later analysis for nitrate, nitrite, ammonia, silica, urea, and phosphate. Water samples were shipped frozen to the Geochemical and Environmental Research Group (GERG) in College Station, Texas for nutrient analysis. Cave tides were compared with reference open ocean data from Bermuda's official tide station on the Esso pier.

*Escherichia coli* and *Enterococcus* levels in spring outflows were measured at the King Edward VII Memorial Hospital using membrane filtration. These bacteria are components of the normal intestinal flora of both humans and animals and are commonly used as indicators of fecal contamination arising either from cesspit seepage or wastewater injection wells.

Sea grass cover and abundance were measured using protocols developed by the Bermuda Conservation Services Department for their Sea grass Project Monitoring Plan in order to produce comparable data between the two projects. At each site with sea grass, ten random 0.5 m<sup>2</sup> quadrats were laid along a 50 m transect line (Fig. 4). Cover and abundance was estimated using a preformatted data sheet used by Conservation Services. The Sonde was used to collect basic water parameter data for each site. A water sample was also taken to measure nitrate, nitrite, phosphate, ammonium, silica, and urea concentrations.



Figure 4: Quadrat in healthy seagrass bed at Red Bay Cove

Lastly, coral population density was surveyed using the Atlantic and Gulf Rapid Reef Assessment (AGRRA) surveying protocol used by Conservation Services. This survey involved random placement of ten 25 cm<sup>2</sup> quadrats along a 10 m transect line. Photos of each quadrat were taken to input into the population density program PRIMER 6 (Plymouth Routines In Multivariate Ecological Research). This utilizes an extensive array of univariate, graphical and multivariate routines for analyzing the species/sample abundance (or biomass) matrices that arise in biological monitoring of environmental impact.

## Preliminary Results:

Coastal spring caves in Bermuda exhibit reversing tidal currents generated by the hydrological imbalance between tides in enclosed water bodies as opposed to the open sea. Tides in Harrington Sound are out of phase with those in the open ocean by a two and a half hour delay. In the springs found along Harrington Sound, outflow of cave water occurs during a rising tide as currents exit the caves, transporting water to the Sound. Tidal exchange in springs found along the coastline of Castle Harbour and the North Shore behave in the opposite manner, with the outflow of cave water occurring on the falling tide. On a rising tide, springs along the North Shore and Castle Harbour act as siphons (inflow of water into the cave), while those inside Harrington Sound are springs. Thus, a hypothetical cave connecting either the North Shore or Castle Harbour to Harrington Sound would simultaneously have a siphon at one end and a spring at the other.

Sonde data were imported into Microsoft Excel, with parameters plotted individually as a function of time in comparison to tidal (depth) fluctuations. In general, outflowing cave water was lower in salinity, dissolved oxygen and pH than inflowing sea water (Fig. 4). Cave and open water temperatures fluctuated seasonally such that outflowing cave water tended to be relatively cooler in summer and warmer in winter than inflowing sea water.

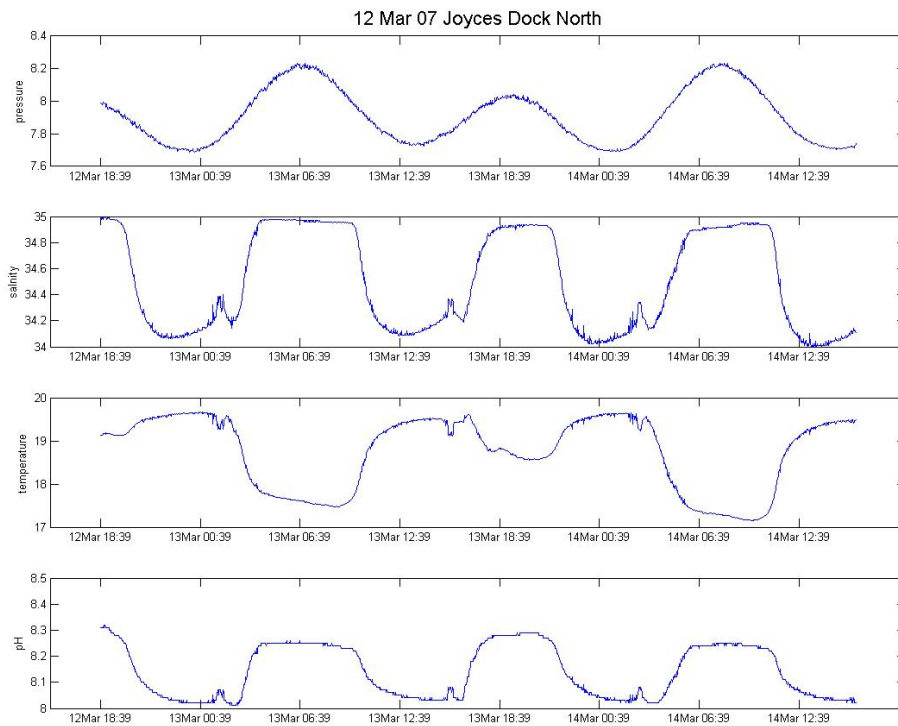


Figure 4: Plots of depth, salinity, temperature and pH at Joyce's Dock North Cave, 12-14 March 2007. In this cave, outflow of cave water occurs on a falling tide. At this time of year, outflowing cave water has decreased salinity and pH and increased temperature relative to surrounding sea water.

Data sets from the Thermistors were plotted using MetLab to show the tidal variations in cave temperature as color changes. Well defined color changes correspond to inflow of ocean water and outflow of cave water. For example in Figure 5 from Joyce’s Dock Middle Cave, water temperatures are vertically well stratified during inflow (colder sea water) and outflow (warmer cave water).

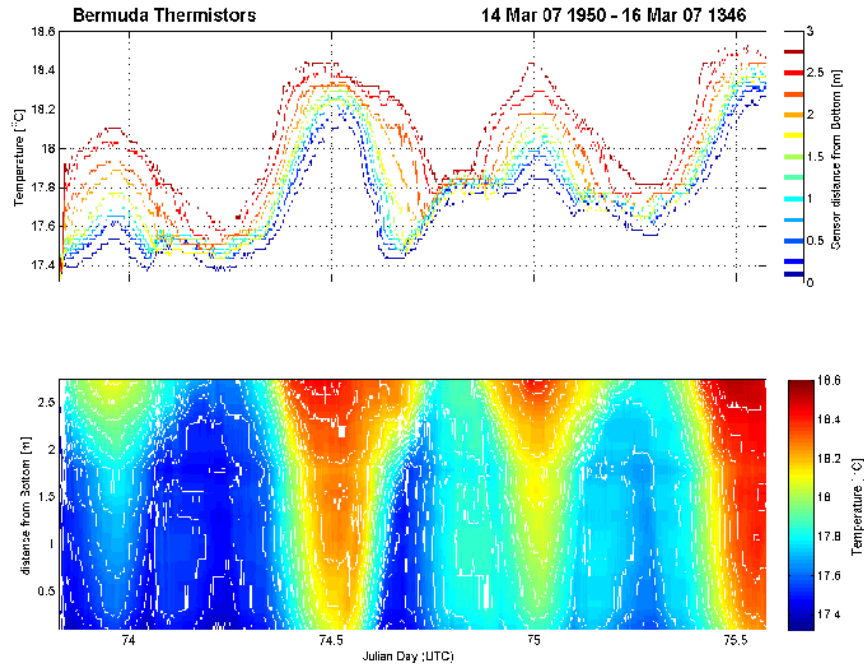


Figure 5: Thermistor chain data for Joyce’s Dock Middle Cave, 14-16 March 2007. Note that denser, cooler water (blue) flows along the cave floor, while less dense, warmer water (red) is on the ceiling.

Aquadopp and Velocimeter data were also plotted using MetLab to illustrate variation in direction and speed of currents at locations near the cave entrance. Aquadopp is used to measure vertical current profiles. Velocity (top) and direction (bottom) data collected with the Aquadopp (Figure 6) are depicted by color changes as a function of water depth (vertical axis) and time (horizontal axis). Data obtained from the Velocimeter (Figure 7a & b) depicts current direction in each of three axes (top), while pressure changes (middle) illustrate the tidal variation. Flow direction speed histograms indicate relative changes between inflow and outflow. In a straight passage, these should be 180° from one another, while divergence could be caused by instrument placement at a bend in the passage or deflection off obstructions.



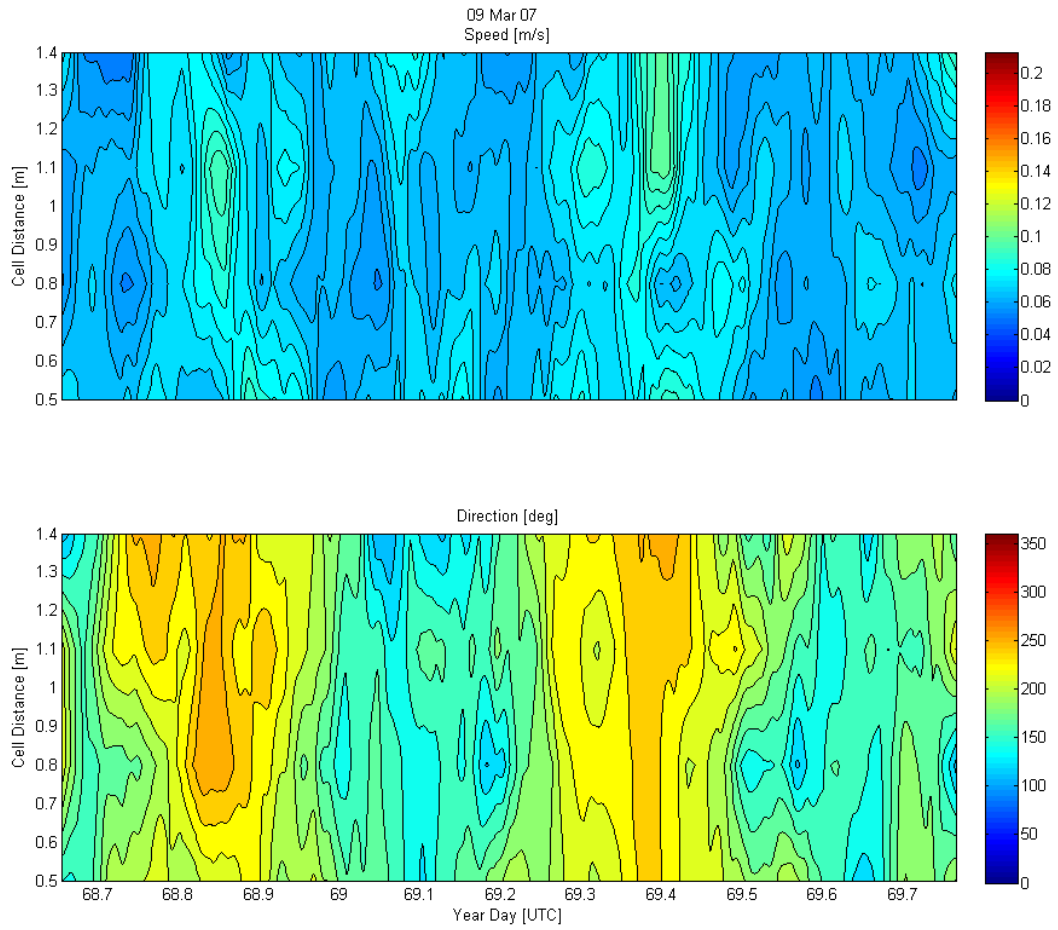


Figure 6: Aquadopp velocity (top) and direction (bottom) data from Burchall's Cove Cave are depicted by color changes as a function of water depth (vertical axis) and time (horizontal axis).

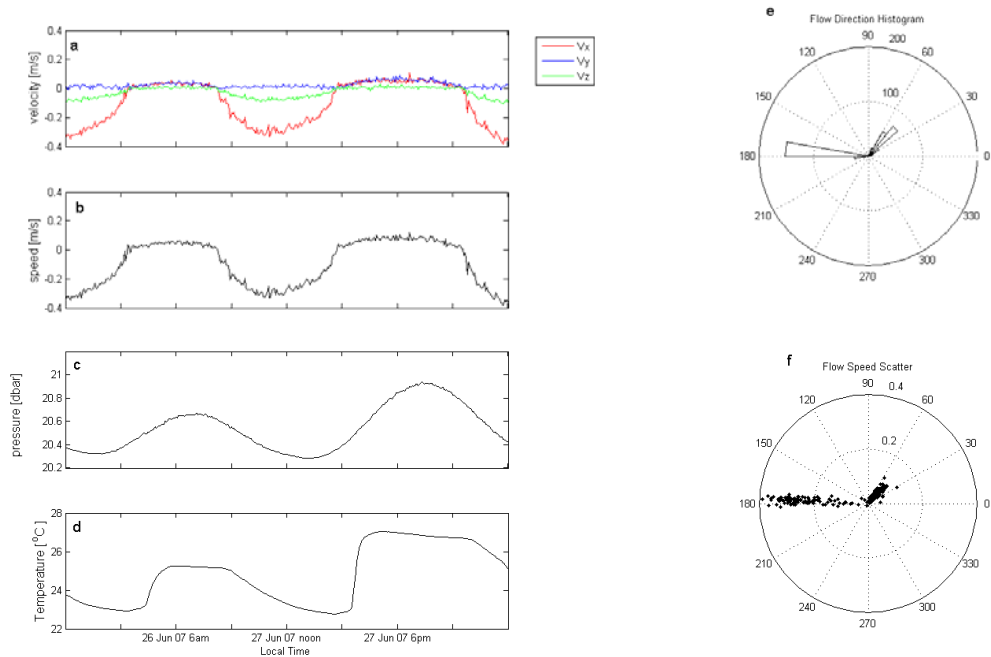


Figure 7a: Velocimeter data from Joyce's Dock North Cave on Castle Harbour, 26-27 June 2007. This cave is unusual in that water flows out of the cave but not in.

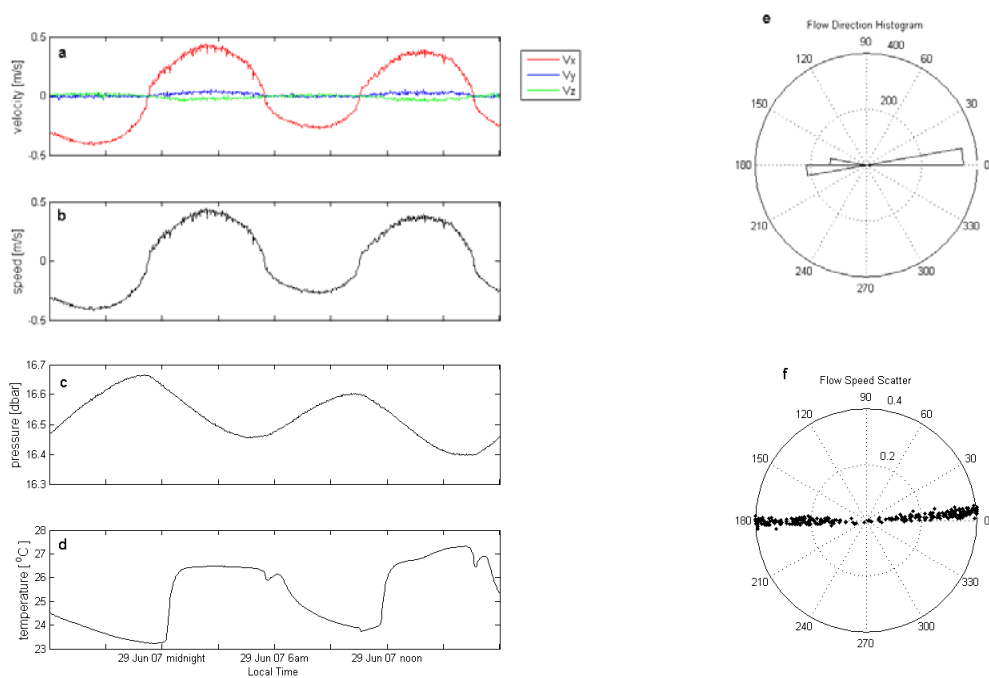


Figure 7b: Velocimeter data from Red Bay Cave on Harrington Sound, 28-29 June 2007. This cave shows more typical mass balance between inflow and outflow.

Cross sectional drawings of the cave passage at the site where the current meter was placed were digitally rendered using Adobe Illustrator and Adobe Photoshop to aid in the calculating the cross sectional area that is needed to determine the volume of water transported during each phase of the tidal cycle. For example, a cross section of Joyce’s Dock North Cave at the point where the Vector meter was installed is illustrated in Figure 8. The dashed lines are points at which measurements were taken and the numbers indicate the respective distances. The instrument was set 30 m back from the entrance where the passage leveled off at 20 m depth. The Vector actually takes measurements at a point 27 cm above the cave floor, indicated by a pink dot in Fig. 8.

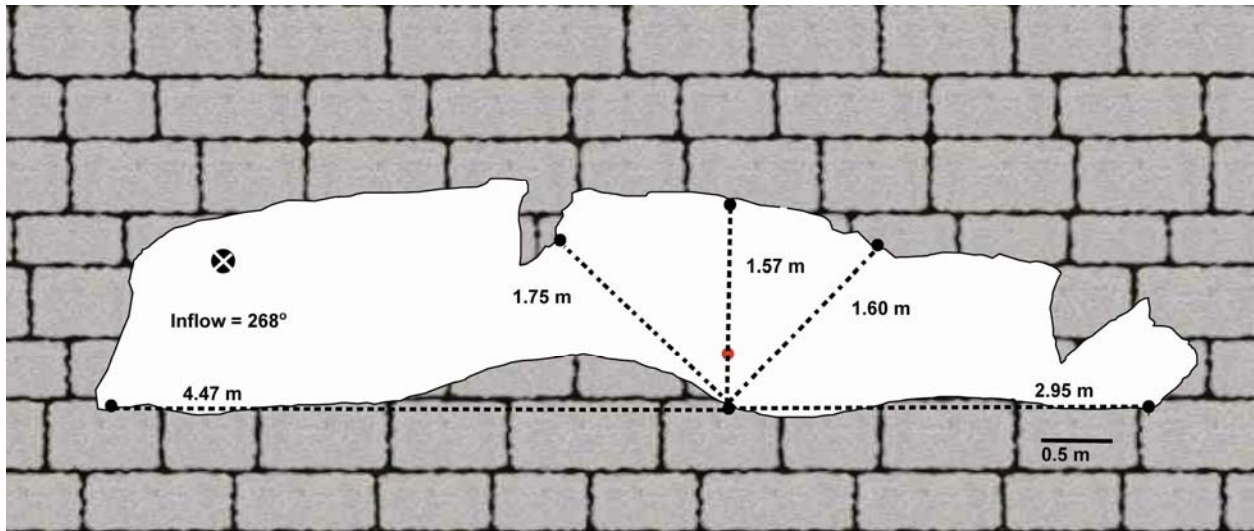


Figure 8. Cross section of Joyce’s Dock North Cave passage at the site where the Vector current meter was placed. The solid black line depicts the edges of the cave wall, white void is open passage, and bricked background is limestone bedrock. The red dot is the point at which measurements were taken, while the circle with an X in it represents the inflow compass bearing (268°) into the page.

Water flow through a single conduit cave passage is similar to flow through a pipe. Therefore, a pipe network approach was used to predict the discharge volume, based upon the Hagen-Poiseuille law. In this model, flow through a pipe creates friction along the perimeter, decreasing energy of flow along the sides. The only water movement is in the direction of the conduit. Velocity then becomes a function of distance from the side of the conduit. Bermuda cave cross-sections are not circular and therefore have to be simplified using the best fitting cross-sectional shape to represent the dominant flow features. Most Bermuda caves can best be fitted to a rectangular shape. As shown in Figure 9a, a cross sectional drawing of Cripplegate Cave demonstrates how rectangular duct shape is a good estimate for the cave passage. Figure 9b is a contour plot of velocity changes in Cripplegate Cave using the rectangular duct approximation. Current is strongest in the center and weakens towards the sides due to friction.

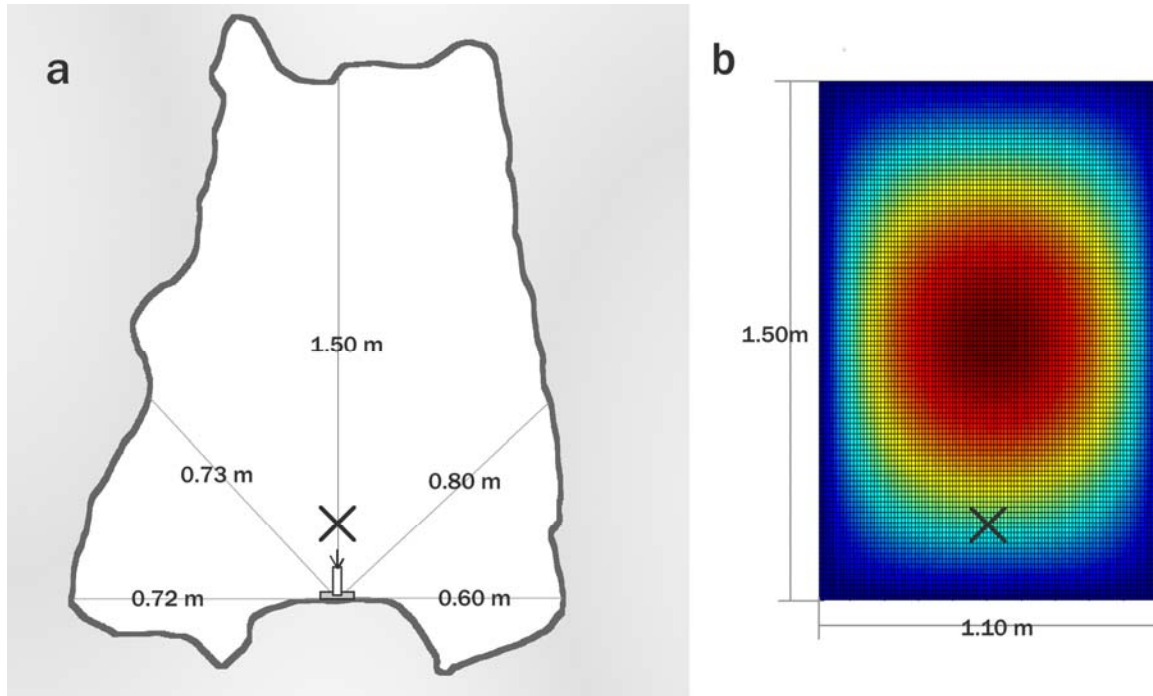


Figure 9: Cross section view of Cripplegate Cave (a) and rectangular grid (b) showing relative current velocities ranging from slower speeds near the walls (blue) to highest speed in the center of the passage (red).

Flow rate can be determined by numerically calculating the velocity at all points within the cross sectional grid and taking the sum. This will yield flow rate with cross sectional dimension over time. Volume is estimated by scaling the flow rate to an appropriate time scale based on the sampling period. Green Bay Cave (Table 1) has the largest flow volume due to its large cross-sectional area (25.5 m<sup>2</sup>). The imbalance of flow volumes suggests there are alternate exit / entry points for water within those cave systems.

Table 1. Summary of flow flux properties in each study site.

Cave Sites	Sample Date	Cross Sectional Area m <sup>2</sup>	Inflow Volume 1000 m <sup>3</sup>	Outflow Volume 1000 m <sup>3</sup>	Avg. Inflow m/s	Avg. Outflow m/s	Max Velocity m/s
Green Bay Cave	Jun-07	25.50	1960	1150	0.10	0.07	1.50
Red Bay Cave	Jun-07	10.20	68	60	0.28	0.26	0.50
Leamington Cave	Jun-07	7.10	28	42	0.16	0.24	0.25
Cripplegate Cave	Jun-07	0.60	1.0	0.4	0.13	0.06	0.40
Joyce's Dock North Cave	Jun-07	10.80	11	51	0.05	0.23	0.40
Castle Grotto Cave	Jun-07	1.00	20	23	0.93	1.06	0.50
Tucker's Town Dock Cave	Jun-07	1.80	6.7	6.1	0.25	0.20	0.40
Tucker's Town Bay Cave	Jun-07	4.10	57	55	0.64	0.62	0.75
Burchall's Cove East Cave	Jun-07	13.10	98	70	0.10	0.08	0.25

Positive tests were obtained for both *Enterococcus* and *E. coli* in water samples from several springs (Table 2). Springs located in lesser developed areas tend to have a lower concentration of *Enterococcus* and *E. coli* bacteria than those located in areas with a higher population density. The highest concentration was found in Green Bay Cave where *E. coli* values of 31/100 ml and *Enterococcus* of 23/100 ml.

**Table 2:** *E. coli* and *Enterococcus* counts for Bermuda cave springs

<b>Cave</b>	<b><i>E. coli</i> /100ml</b>	<b><i>Enterococcus</i> /100 ml</b>
Joyce's Dock North	<1	<1
Joyce's Dock Middle	<1	19
Pump House	<1	<1
Castle Grotto	<1	5
Kim's Spring	5	21
JC's Run	<1	8
Gazebo Cave	<1	2
Tucker's Town Dock	1	17
Tucker's Town Bay Cave	<1	<1
Cripple Gate	<1	<1
Leamington Cave/ Spring*	2/1	34/12
Red Bay Cave	3	1
Green Bay Cave	31	23
Burchall's Cove East	< 1	3

\* Leamington Cave water sample was taken from the main pool inside of the cave (land access) at 2 meters depth; Leamington Spring sample was taken at the spring entrance on Harrington Sound

A total of 31 water samples from 14 tidal springs in Bermuda were analyzed for nutrient concentrations and compared with open water samples collected from Harrington Sound, Castle Harbour and the North Shore of Bermuda. Initial examination indicates that spring outflow is generally higher in nitrate, while comparable to open water in ammonium, silicate, phosphate and nitrite (Table 3). All cave outflow water samples contained higher dissolved inorganic nitrogen (DIN) concentrations than their corresponding regional control (Table 3). Phosphate values are considerably lower than nitrogen and in general, comparable with the control values. This may be due to selective adhesion of phosphate to limestone bedrock or sediments.

**Table 3.** Mean nutrient concentrations of phosphate and DIN from June 2007. Also shown is the mean percentage each form of nitrogen contributes to the total DIN for each cave.

Cave Sites	HPO <sub>4</sub> <sup>=</sup> (μM)	DIN (μM)	%NO <sub>3</sub> <sup>-</sup>	%NO <sub>2</sub> <sup>-</sup>	%NH <sub>4</sub> <sup>+</sup>
Green Bay Cave	0.37	7.00	68.5	3.5	28.0
Red Bay Cave	0.41	6.74	58.7	3.5	37.8
Cripplegate Cave	0.49	8.56	44.6	4.9	50.5
Leamington Cave	0.28	5.74	29.0	7.0	64.0
Joyce's Dock North Cave	0.30	6.30	90.2	3.0	6.8
Joyce's Dock Middle Cave	0.38	9.97	69.6	4.0	26.4
Pump House Cave	0.51	6.77	56.9	5.9	37.2
Castle Grotto Cave	0.45	6.37	71.1	4.0	24.9
JC's Run	0.45	4.78	66.4	5.2	28.4
Tucker's Town Dock Cave	0.43	22.54	95.3	0.8	3.9
Tucker's Town Bay Cave	0.40	19.97	94.3	1.6	4.1
Burchall's Cove East Cave	1.01	12.81	46.2	2.6	51.2
Harrington Sound Control	0.52	4.52	29.77	4.37	65.85
Castle Harbor Control	0.31	4.33	24.25	6.02	69.73
Tucker's Town Bay Control	0.77	17.89	64.75	1.38	33.90
North Shore Control	0.32	2.81	31.61	6.73	61.86

Density, frequency and abundance of three species of sea grass - *Thalassia testudinum*, *Syringodium filiforme* and *Halodule wrightii* - were determined on a percent scale in the vicinity of eight tidal springs in Bermuda (Table 4). Only two of these sites had all three sea grass species, while five other tidal springs had no sea grass within 100 m. The three sites with the highest DIN values, Tucker's Town Dock and Bay Caves and Burchall's Cove Cave, were among the sites that lacked sea grass.

**Table 4.** Sea grass density (d), frequency (f) and abundance (a) near tidal springs

Cave spring	<i>Thalassia testudinum</i>			<i>Syringodium filiforme</i>			<i>Halodule wrightii</i>		
	d (%)	f (%)	a (%)	d (%)	f (%)	a (%)	d (%)	f (%)	a (%)
Green Bay Cave	36	70	51	10	20	50			
Red Bay				44	90	49	61	100	61
Leamington Cave	9	30	30	18	40	45	70	30	23
Cripple Gate Cave	25	70	36	34	60	57	7	50	52
Joyce's Dock Cave				18	40	45	14	50	28
Pump House Cave	23	80	29	66	100	66			
Castle Grotto Cave				26	100	26	48	100	48
JC's Run	76	100	76						

Water samples for nutrient analysis were taken every 30 minutes over an outflow at Green Bay Cave, Joyce's Dock North and Middle Caves, and Tucker's Town Bay Cave. Nutrient concentrations were observed to increase in general throughout an outflow (Figure 10). Towards the end of the sampling, Joyce's Dock Middle nutrient values began to decrease, possible as current direction changed. If the sampling period had been extended to include the beginning of the inflow, this should occur in other springs as well.

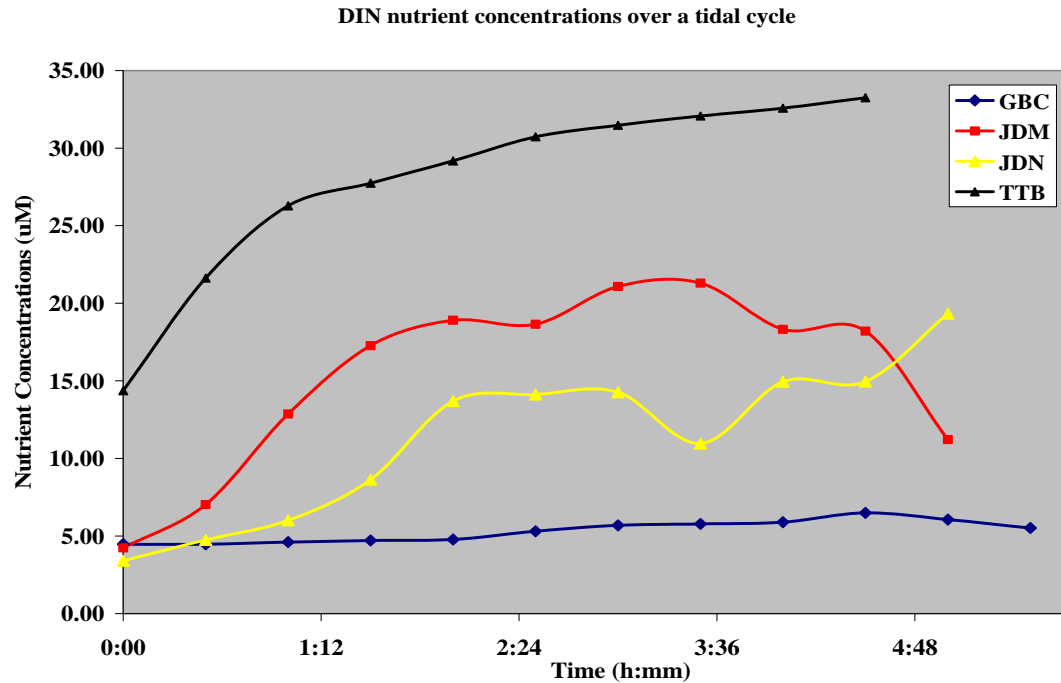


Figure 10: DIN concentrations over a six hour outflow from Joyce’s Dock North and Middle, Green Bay Cave, and Tucker’s Town Bay Cave taken in January 2008.

Finally, a one month deployment of both current meter and CTD was carried out in Jan-Feb 2008 at Green Bay Cave (Fig. 11). This deployment included the low point for seasonal water temperature (Fig. 12) and provided an opportunity to examine tidal fluctuation in relation to currents over a complete lunar cycle.

**Conclusions:**

Coastal cave springs in Bermuda facilitate tidal exchange of marine waters between partially enclosed inshore bays and sounds and the open ocean. They are parts of highly integrated but as yet not fully explored subterranean networks of cave passages serving as hydrological conduits. As evidenced by lower salinity, water outflowing from tidal springs has significant freshwater input, likely including cesspit seepage. The presence of fecal coliforms and elevated nitrate levels in spring outflow supports the contention that terrestrial pollutants contaminate the underlying groundwater and are transported through underwater caves to the coastline. The absence of sea grass in those bays with the highest nitrate concentration is suggestive of a link between pollution levels and health of marine ecosystems. Longer term monitoring of water flow and pollutant concentrations in coastal springs, coupled with investigations of sea grass abundance and diversity, is needed to confirm a linkage between the two. The Bermuda Government is aware of these potential problems and is seeking means to mitigate or eliminate environmental disturbances.

Two resulting publications are now in preparation. An article on groundwater hydrology and tidal flow through Bermuda’s caves will be submitted to the International Journal of Speleology, while a paper on pollutant levels in springs and sea grass health will be submitted to Marine Ecology Progress Series.

One month depth & temperature plots for Green Bay Cave

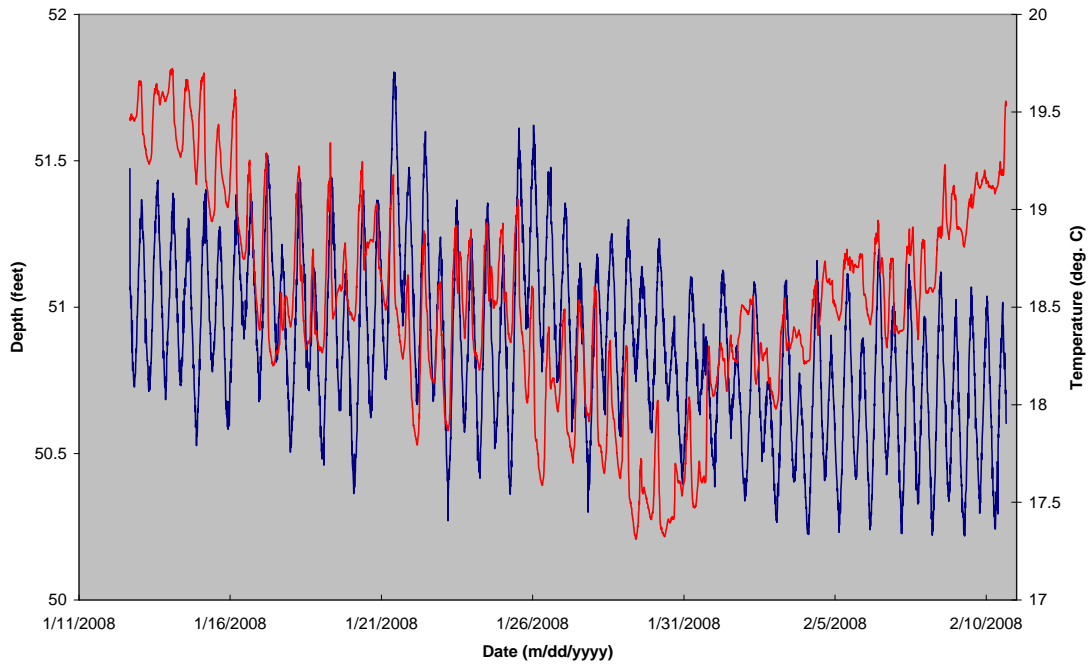


Figure 11: One month CTD record of depth/tides (blue line) and temperature (red line) variations in Green Bay Cave entrance passage. Seasonal low water temperature of 17.3°C occurred on 29 January 2008. Sample interval programmed for 10 minutes.

One week depth & temperature plots for Green Bay Cave

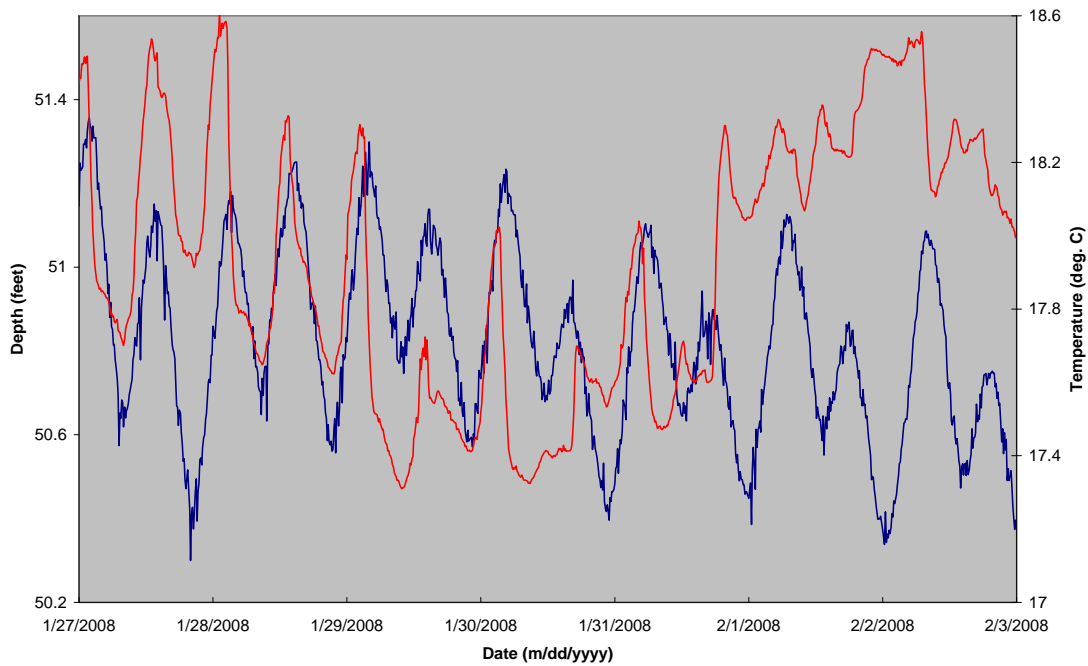


Figure 12: One week CTD record of depth/tides (blue line) and temperature (red line) variations in Green Bay Cave entrance passage (higher resolution view of data from previous figure). Seasonal low water temperature of 17.3°C occurred on 29 January 2008. Sample interval programmed for 10 minutes.



**Coastal Spring Photographs (all photos by Tamara Thomsen):**



Joyce's Dock Middle Cave



Joyce's Dock North Cave (note strong outflow)



Castle Grotto Cave



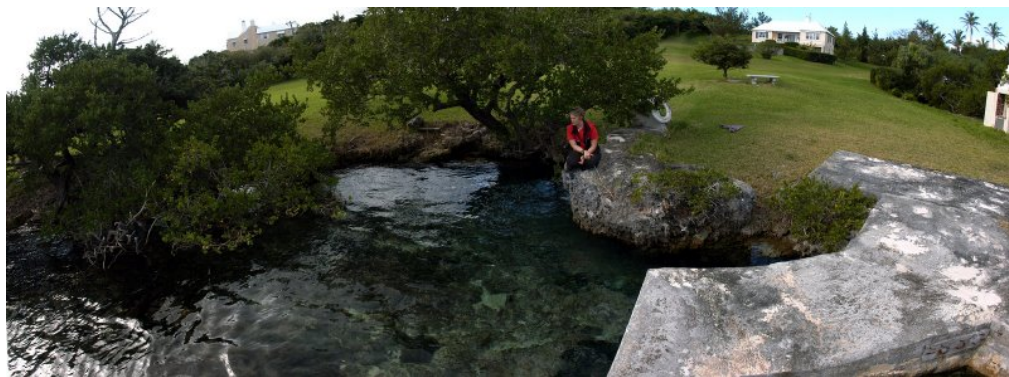
Burchall's Cove (cave under boat ramp at right)



Tucker's Town Bay (cave under far shore)



Green Bay (cave under cliff in rear center)



Red Bay Cave (entrance under rock outcrop at center)



Leamington Cave pool w/ conn. to coastal spring

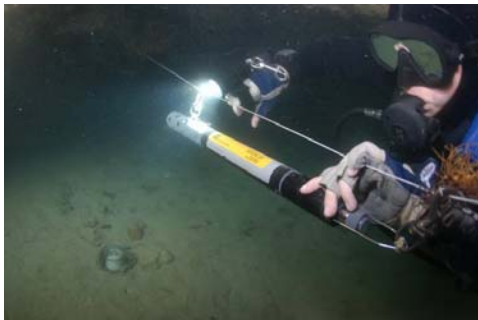
**Instrument Placement:**



Sonde on rt. in Joyce's Middle (note trash)



Blue Grotto placement

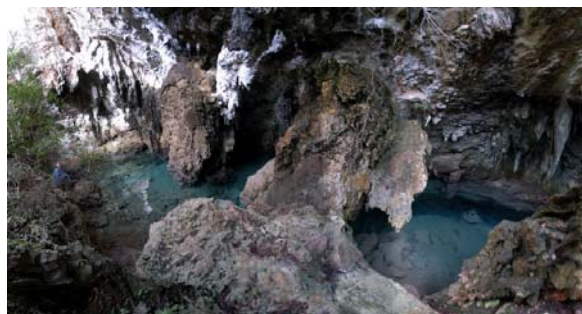


Sonde secured in Tucker's Town Dock Cave

**Inland Cave Pools:**



Angel Pool



Walsingham South Cave Pool



Walsingham North Cave Pool



Cliff Pool entrance to Green Bay Cave



Causeway Cave



Grenadier Pool



Emerald Sink



Palm Cave

**Underwater Cave Photographs:**



Breakdown in Green Bay Cave



Vine Cave entrance light



Green algae in Deep Blue Pool



Deep Blue *Agaricia*, crustose coralline, red algae



Stalagmite in Green Bay Cave



Stain line on stalactites in Green Bay



Cliff Pool entrance (Green Bay Cave)



Sponges in high flow Red Bay Cave passage

### **Human Impact on Bermuda Caves:**



Rusting oil barrels in Bitumen Cave



Excavation for new resort and golf course



Trash and rare ferns in Sears Cave



Oil slick on water surface in Tucker's Town Bay



Panorama of massive dumping amid endemic cave ferns in Sears Cave