PROCEEDINGS
OF THE FOURTH SYMPOSIUM
ON THE GEOLOGY OF THE BAHAMAS

Editor

John E. Mylroie

Production Editor

Donald T. Gerace

Sponsored by the Bahamian Field Station

June 17 - 22, 1988

ISBN 0-935909-31-1

Printed by Don Heuer in the U.S.A.

KARST HYDROLOGY OF SAN SALVADOR

R. Laurence Davis
New Hampshire Department of Environmental Services
Groundwater Protection Bureau
6 Hazen Drive, Box 95
Concord, New Hampshire 03301

Calvin R. Johnson, Jr.
Department of Geology
Indiana University
Bloomington, Indiana 47405

ABSTRACT

San Salvador is a typical carbonate platform island in the eastern Bahamas. Its major features include arcuate, consolidated dune ridges up to 40 meters high, and shallow, hypersaline lakes. These occupy the low areas between the dunes and cover a substantial portion of the island's interior. The subsurface contains large numbers of caves, conduits and vertical shafts. Despite the nearly 120 cm of annual rainfall, there is no flowing surface water. The ground water system is poorly defined and fresh water lenses are discontinuous and sporadic. Data collected during two years of field work has led to the construction of a general model of the island's hydrologic regime.

The system consists of six elements: 1) Precipitation; 2) Evapotranspiration; 3) Ground Water; 4) Inland Lakes; 5) Conduits and Blue Holes; and 6) Ocean tides.

Investigations included an examination of rock and water geochemistry, rock permeability, and physical hydrology. Over 430 water samples and 16 rock samples were analyzed. Ca^{++}/Mg^{++} and Mg^{++}/Cl^{-} ratios were used to trace water sources. Water chemistry was used to pinpoint the locations of conduits and seeps on the inland lakes. Ground water elevations were mapped in several locations and conduit flows were measured. Pump and laboratory tests were performed in order to estimate rock permeabilities. Tide gauges were used to measure ocean tides and water level fluctuations in caves and in the hypersaline inland lakes. This field data was used to construct the general model.

Groundwater in the interior of the island is found in discontinuous, isolated, fresh water lenses beneath the consolidated carbonate dunes. The lenses, which are fed by infiltrating rain water, drain into the hypersaline lakes where the water evaporates. Near the coast there are similar lenses, but these are disrupted in many places by flow through caves and conduits. Some of the interior lakes are connected to the sea by conduits, but most appear to be fed directly by ground water seeps and precipitation. The height of the tides varies considerably from day to day. The elevation of many of the inland lakes is above that of the lower high-tides. Therefore, conduit flow into them only occurs during the higher high-tides. At these times, the flow is especially vigorous and can contribute to the disruption of the fresh water lenses in the vicinity of the conduit. The rock has relatively low primary permeability and the direct influence of ocean tides on the fresh water lenses near the shore appears to be small. This model can be used to locate new freshwater resources for San Salvador and other similar islands. It may also be useful in examining the paleohydrology of the island and its impact on cave formation.

INTRODUCTION

Since January, 1987, we have been conducting research on the hydrology of San Salvador. Investigations have included water sampling and chemical analysis, electrical resistivity measurements, exploration, dye tracing, surveying, and current and tidal fluctuation measurements. Based on the field work, a preliminary model of the island's hydrologic system has been constructed. This paper examines both the data and the model.

BACKGROUND

Geography

San Salvador is located in the eastern Bahamas, approximately 600 km east of Miami (Fig. 1).

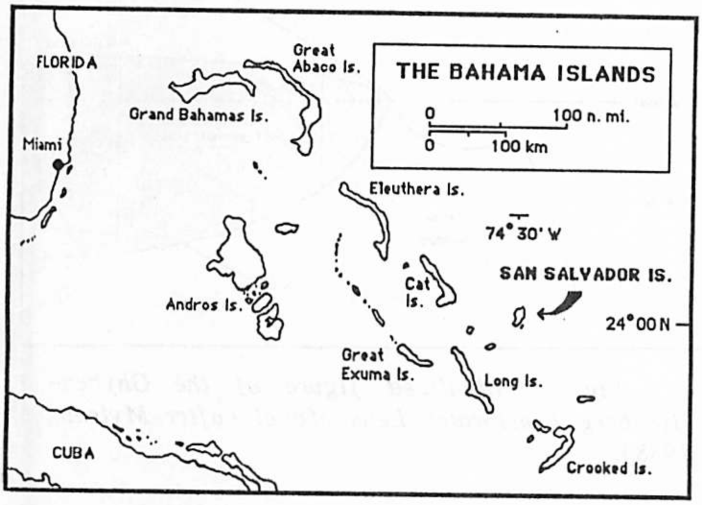

Fig. 1. Map of the Caribbean area showing the location of San Salvador, Bahamas (after Adams, 1983).

The island is part of the Bahamas platform, although it is separated from the main part of the platform by deep ocean water. The open North Atlantic Ocean lies to the east.

The island is approximately 14 kilometers North to South and 8 kilometers East to West. Major settlements are located at Cockburntown, United Estates, North Victoria Hill, and Long Bay. The CCFL Field Station is located at Grahams Harbor in the northeastern portion of the island. There is a group of vacation homes located in the Columbus Landings Subdivision along the southern coast of the island at Sandy Point and Sandy Hook (Fig. 2).

The topography of the island is dominated by consolidated carbonate dune ridges. These rise to elevations of over 40 meters above sea level, but most are in the 10-20 meter range. The low areas between the dune ridges are occupied by hypersaline lakes. Most of the lakes are about 1 to 2 meters deep and have no direct surface connection to the ocean. Many of the lakes, however, are interconnected either naturally or by man-made canals that were constructed as part of an intra-island transportation system dating from the early 1800's.

Off-shore there is a shelf, 0.5 to 25 kilometers wide, where water depths reach 15 meters. It is bordered by a fringing reef. The shelf ends with a sharp break in slope and the ocean floor plunges to a depth of over 2000 meters forming a feature known as the "wall".

The rock beneath the island contains many small caves and conduits. The caves are mostly dry and seem to be located about 2 meters above present sea level. The conduits transport water between the ocean and the inland lakes. Flooded cave openings have been observed along the wall at depths of more than 100 meters (Mylroie, 1988).

Geology

The geology of the island is similar to that found on other carbonate platforms. The rock is

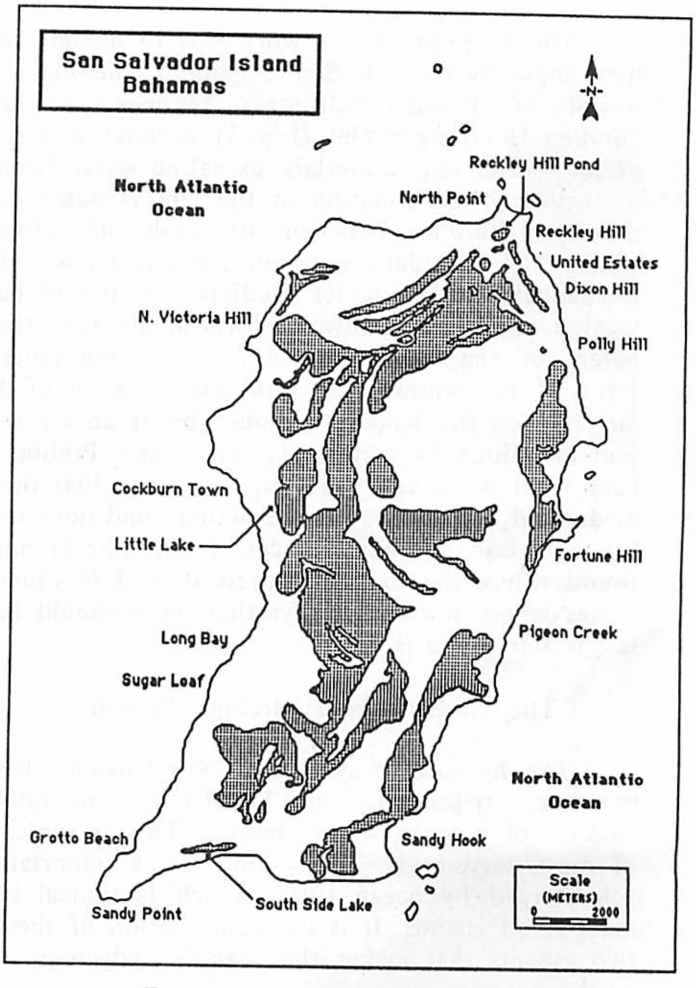

Fig. 2. Map of San Salvador Island.

no older than Pleistocene, and it is entirely carbonates (Carew and Mylroie, 1985). There are three major rock types: eolianites, beachrock, and reef rock (Adams, 1983). Eolianites make up the carbonate dune ridges found almost everywhere on the island. They also occur in the subsurface. These cross-stratified rocks consist of ooliths and bioclasts. They are often very porous and have distinct bedding planes.

Beachrock occurs on modern beaches where it is found in large tabular masses. It also may cap older rocks near the shore. The rock consists of cemented shell fragments and ooliths. It is usually porous and poorly cemented, and the units tend to be rather thin (less than 1 meter).

The final major rock type is reef rock, which is found at several localities along the shore and in the interior. This rock consists of fossilized reef materials; corals, molluscs, sponges, algae, etc. Its occurrence is spotty and the units tend to be thick and massive (Adams, 1983).

ISLAND HYDROLOGY

The purpose of our work was to model the hydrologic system on San Salvador. The classic model of island hydrologic regimes is the Ghyben-Herzberg model, (Fig. 3). It shows a fresh ground water lens underlain by saline water from the ocean. The formation of the lens is due to a density difference between the fresh and saline water. The boundary between them is known as the halocline. The model predicts that it will be located at a depth below sea level of 40 times the height of the freshwater table above sea level. Thus, if the water table is at an elevation of 1 meter, then the halocline should be at an elevation of minus 40 meters (Fetter, 1980). Preliminary field work and sampling suggested that this model did not always fit the actual conditions on San Salvador. In many places, freshwater is not found where the model predicts it, and in other places where the model says that there should be freshwater, there is none.

The San Salvador Hydrologic System

The hydrologic system on San Salvador has two very striking aspects. The first is the total absence of surface water streams. This is typical of most karst areas. The second is the important role played by ocean tides, which is typical of most small islands. It is the combination of these two aspects that makes the island's hydrology so complex.

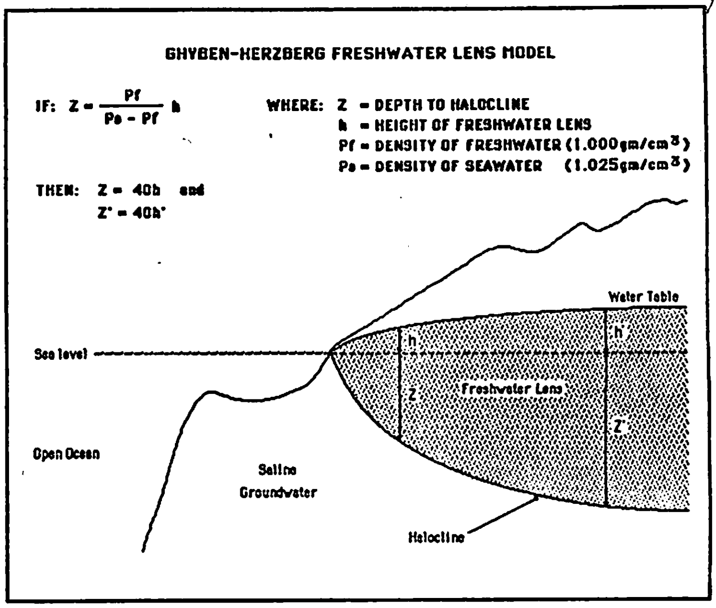

Fig. 3. Idealized figure of the Ghyben-Herzberg Freshwater Lens Model (after Mylroie, 1988).

The system has six elements. These are shown in Table 1 and are discussed individually in the following paragraphs.

Precipitation
Evapotranspiration
Ground Water
Inland Lakes
Conduits and Blue Holes
Ocean (Tides)

Table 1: The Elements of the San Salvador Hydrologic System

Precipitation

Precipitation on San Salvador averages between 1000 and 1250 mm per year. The majority of it occurs during the rainy season which lasts from late May to January (Sealy, 1985).

Evaporation

Potential evaporation averages between 1250 and 1375 mm per year (Sealy, 1985). Because this exceeds annual precipitation, there is a yearly deficit. During the rainy season, however, precipitation exceeds potential evaporation, so there is a temporary surplus of freshwater. During the dry season, potential evaporation is greater than precipitation, so that conditions then, are arid. The seasonal alternation of surplus and deficit conditions means that large variations are possible in the water chemistry of the inland lakes and ground water.

Ground Water

Ground water on the island may be fresh or brackish. The distribution of fresh ground waters is one of the issues that our work attempted to address. Unfortunately, ground water is accessible only at wells and at a few widely scattered caves and banana holes in the interior. The wells are located predominantly along the coast. The lack of data from the island's interior means that its ground water system is difficult to study. For the most part, water table elevations at accessible locations, are less than 1 meter above sea level.

Inland Lakes

Inland lakes are located in the low areas between the dune ridges. They cover a large percentage of the interior of the island. Depths range from less than 1 meter to almost 3, with most being 1 to 2 meters deep. The salinity of water in the lakes can be slightly lower than sea water, to more than 4 times that of sea water. This varies with the seasons and from lake to lake.

Conduits and Blue Holes

In several places on the island, there are vertical holes that connect, via conduits, directly to the ocean. These are known as blue holes. Other conduits connect some of the lakes to the ocean, or carry fresh ground water to the lakes or the sea.

Ocean

Hydrologically, the most important aspect of the ocean is the tides. These range from 0.3 to 1 meter, depending on lunar phases, the season, and the time of day. It is important to note that there may be a difference of more than 0.5 meters between the heights of the two high tides on a given day.

FIELD AND LABORATORY INVESTIGATIONS

Field work was conducted during six trips to the island, encompassing more than 90 days. We looked at each of the six components of the hydrologic system, and performed investigations involving water sampling, drilling, topographic leveling, flow measurements, exploration, tide measurements, rock chemistry analysis, electrical resistivity and dye tracing. Chemical analyses were performed with a Hach Digital Titrator using standard methods. Conductivity and pH were measured with the appropriate equipment.

Rock Chemistry

We examined a total of 16 rock samples. An attempt was made to sample all of the various rock types from a number of different places around the island ("+" symbols-Fig. 4). Locations were also chosen to reflect a variety of hydrogeologic conditions. For example, samples were taken from parts of the island that have never been below sea level. Some were taken in places such as Lighthouse Cave, where they are covered by sea water at every high tide. Others were

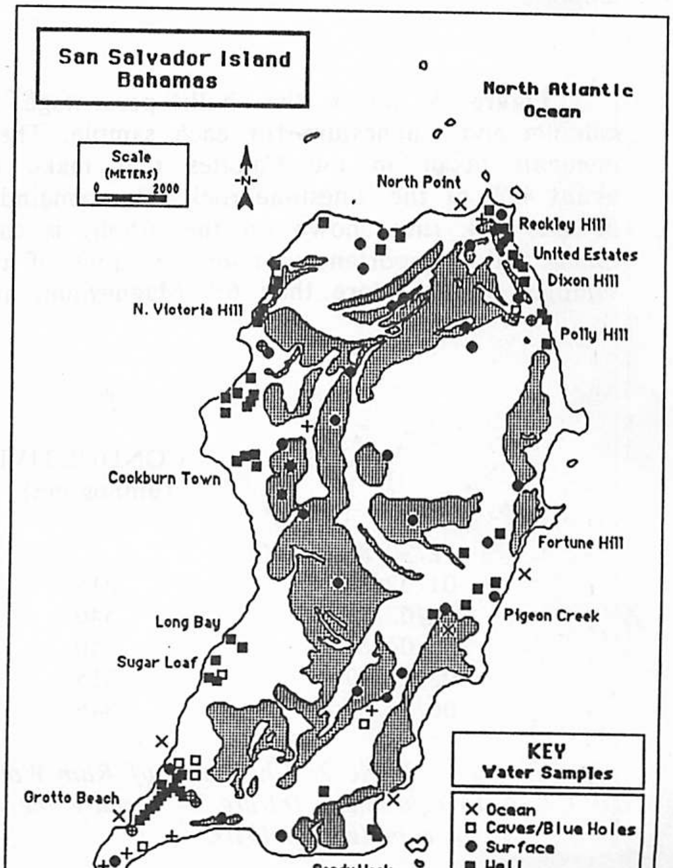

Fig. 4. Map of water sampling, rock sampling, and drilling locations.

taken from localities which are dry now, but which may have been submerged in the geologic past.

The rock chemistry was determined by dissolving a known quantity of powdered sample in hydrochloric acid and then analyzing the resulting solution.

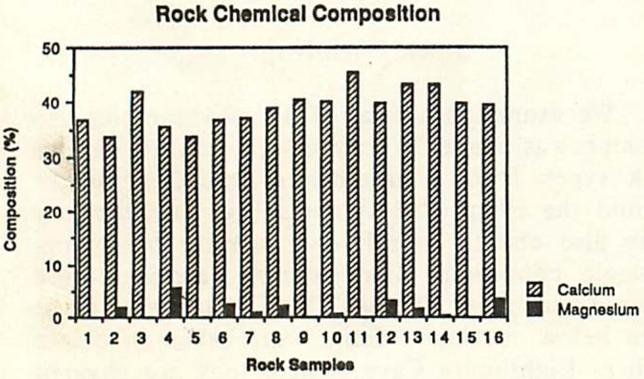

Fig. 5. Graph of chemical composition of rock samples.

Figure 5 shows the bulk percentage of calcium and magnesium for each sample. These elements occur in the Calcites that make up about 45% of the limestone rock. The remainder of the rock (not shown on the graph) is carbonate. It is important to note that none of the samples contain more than 6% Magnesium, and that several contain virtually none. Magnesium/calcium ratios range from 0.00 to 0.16 (Sample 4). Ground water derived only from precipitation which has percolated through the rock, should reflect these same magnesium/calcium ratios.

Precipitation

Precipitation was measured with a recording rain gauge, and water samples were collected for chemical analysis. Rain water was found to contain about 30 mg/l chlorides, about 12 mg/l calcium and virtually no magnesium (Table 2).

Water Chemistry

Figure 4 also shows the locations of water samples taken for analysis. In all, there were over 430, from approximately 150 different locations. Many of these were taken at wells, shown by solid squares. Others were taken as grab samples in the lakes, and some at casual surface ponds. Three lakes, Little Lake, Reckley Hill Pond, and South Side Lake, were sampled systematically. All lake samples and other samples of surface waters are shown by solid circles. Ocean water samples are shown by crosses. Samples from inside caves and conduits are shown by open squares.

Most of the water samples were analyzed for conductivity and pH plus chloride, calcium, magnesium and bicarbonate ion concentrations. Studies by other workers have shown that, with the exception of sodium (from sea water), and nitrates

DATE	CONDUCTIVITY (umhos/cm)	Cl^- (mg/l)	Ca^{++} (mg/l)	Mg^{++} (mg/l)	pH
12/30/86		17	39	3	-
01/02/87	215	26	30	1	-
01/02/87	540	44	54	3	-
01/04/87	240	22	20	3	-
05/22/87	315	59	-	-	7.85
06/14/87	346	54.8	12	-	7.3

Table 2: Chemistry of Rain Water. Dashes indicate data that is missing due to equipment failure or because the small volume of the samples did not allow for complete analysis.

(from sewage), these are the only ions of any importance in the water (Davis, 1975; Quarrier, 1975; Touchette, 1975; Countryman and Poole, 1981).

We found that Mg/Ca and Mg/Cl ratios were good indicators of the source of ground water (Johnson and Davis, 1987). As stated before, ground water with Mg/Ca ratios of less than 0.16 originates from precipitation that has flowed through the rock. Water from the ocean will have Mg, Cl, and Ca ions present. The Mg/Ca ratio of sea water is about 3.65, and therefore, ground water with ratios above 0.16 will be a mixture of water derived from both the ocean and precipitation. Mg/Cl ratios can also be used to discriminate between precipitation and ocean sources. Ocean water has a ratio of about 0.1. Fresh waters have generally higher ratios. We used a combination of these two ratios to determine the amount of seawater/freshwater mixing in any given sample.

Rock Permeability

Cores taken from the 16 rock samples (discussed under "rock chemistry") were tested for permeability using a constant-head permeameter. Based on published data for porous and oolitic limestones, values of permeability were expected to fall into the 10^{-6} to 10^{-4} centimeters/second range (Davis and DeWiest, 1966).

Actual values, however, were between 10^{-9} and 10^{-5} cm/sec with most lower than 10^{-6}. Hence, the rocks were considerably less permeable than expected.

Other Tests

Five wells were drilled and sampled with an auger-type drill rig provided by the Bahamian Government. Three were located at Sandy Point, one at North Victoria Hill, and one in United Estates at Dixon Hill (Figure 4).

Because of the small differences in well and ground water elevations on the island, careful topographic control was needed in order to interpret flow regimes. Leveling was done at Sandy Point, N. Victoria Hill, United Estates and on the east side near Fortune Hill. Leveling was also done to establish the elevations of Reckley Hill Pond (See Figure 2 for locations).

Tide gauges were installed on the ocean and at several locations inland. The timing and height of the tides were found to be irregular. In addition, some unexpected patterns were observed. For example, in Lighthouse Cave, far inland, the tidal range is greater (sometimes by as much as 1/2 m) than that in the ocean, whereas in Reckley Hill Pond, only 400 meters from the coast, the tidal range is just a few centimeters.

Pump tests were performed on some of the wells at Sandy Point. Drawdowns of almost 0.5 meters were found at pumping rates of only 1 liter/minute. This suggests that the permeability of the rock is significantly less than might be expected based on the nature of the rock. These conclusions are supported by laboratory tests on the rocks (see the previous sections).

Dye tracing was attempted in order to locate the ocean outlets for some of the conduits feeding the inland lakes, but the results proved inconclusive. Conduit flow was measured at Reckley Hill Pond, and electrical resistivity tests were conducted at United Estates, North Victoria Hill, and Sandy Point.

Work of Others

Scientific work provided by other researchers was invaluable to the success of this study. Gerhard Kunze of the University of Akron, supplied information on resistivity studies conducted at Sandy Point and Sandy Hook (Kunze and Burke, 1984; Kunze and Weir, 1987). James Teeter, also from the University of Akron shared information on the limnology of the inland lakes. John Winter of Molloy College, guided us to many sites in the island's interior and provided historical information on water sources on the island. Finally, John Mylroie of Mississippi State University and James Carew of the College of Charleston, supplied us with unpublished maps of caves and helped with information on Pleistocene sea levels, rock ages, etc.

RESULTS

The large amount of data that was collected helped us to gain an understanding of the nature of San Salvador's ground water, inland lakes, and conduits. The data obtained from each of these systems will be discussed separately in the sections that follow.

Ground Water

Chemical analyses of water samples, pump tests, permeability measurements, and topographic

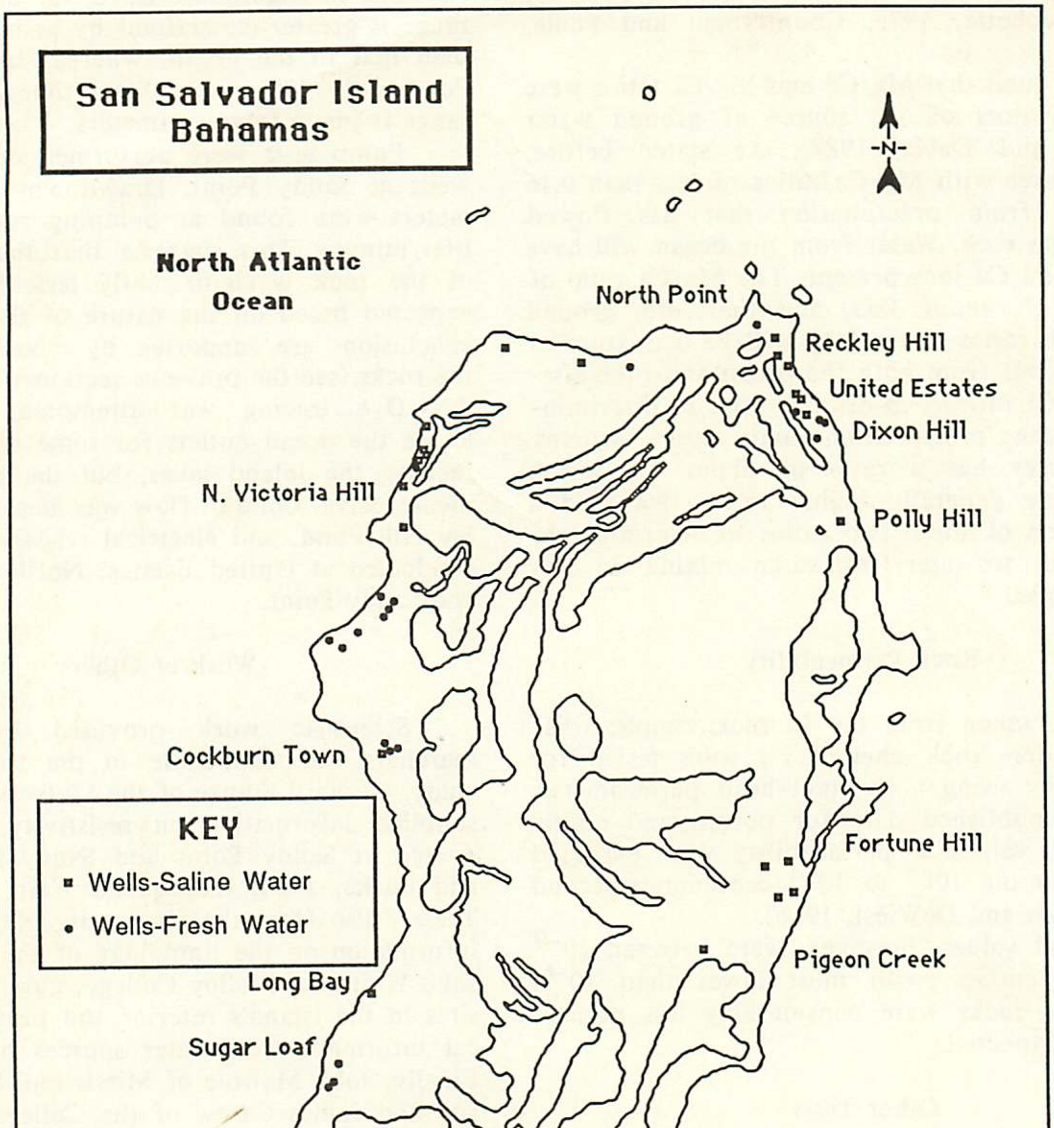

Fig. 6. Map of saline and freshwater well locations on San Salvador.

control were combined to produce insights into the nature of the ground water system.

Based on chemical analyses, Mg/Ca and Mg/Cl ratios were used to estimate the amount of mixing of saline and fresh ground waters. Figure 6 shows the chemical nature (fresh or saline) of the ground water in all of the wells that were sampled. It was found that some wells very near the coast had Mg/Ca ratios less than 0.16 and Mg/Cl ratios greater than 0.1, indicating that the ground water was derived only from precipitation. Other ratios indicated the addition of considerable amounts of saline water. Inland, most wells had fresh ground water, but in a few there was mixing. In general, mixing appeared to be related to the presence of conduits carrying sea water into and out of the inland lakes and caves.

Pump and laboratory tests have indicated that rock permeability is low. Work by Vascher (1988) suggests that under these conditions, water tables should be relatively high and freshwater lenses should be relatively thick. Resistivity work by Kunze and Burke, (1984); and Kunze and Weir (1987) supports the existence of these thick lenses. Low permeabilities would also account for the fact that freshwater lenses can exist very close to the coast, despite the potentially disruptive influence of the tides.

Drilling and resistivity work carried out during this study, however, suggest that in many areas, water tables are not as high and lenses are not as thick as expected. Furthermore, at Sandy Point, a small amount of pumping (<1 liter/min) produces salt-water intrusion, again suggesting relatively thin lenses.

In an attempt to resolve this apparent conflict, further work was done in the Sandy point area. A combination of water chemistry, pumping information, and topographic control was used to gain a more detailed understanding of the local ground water regime. Figure 7 shows the results of studies in this area. Note that in this figure, English units are used in order to conform to the topographic map of the island published by the Bahamian Government. The highest water table elevations are found under the topographic ridge. They are, however, only 1.5 (0.45m) feet above sea level. Based on this, the Ghyben-Herzberg model predicts a 60 foot (18m) thick freshwater lens. Resistivity (Kunze and Weir, 1987) and drilling suggest that a lens as thick as 35 feet (10.75m) does exist in some areas. This is well

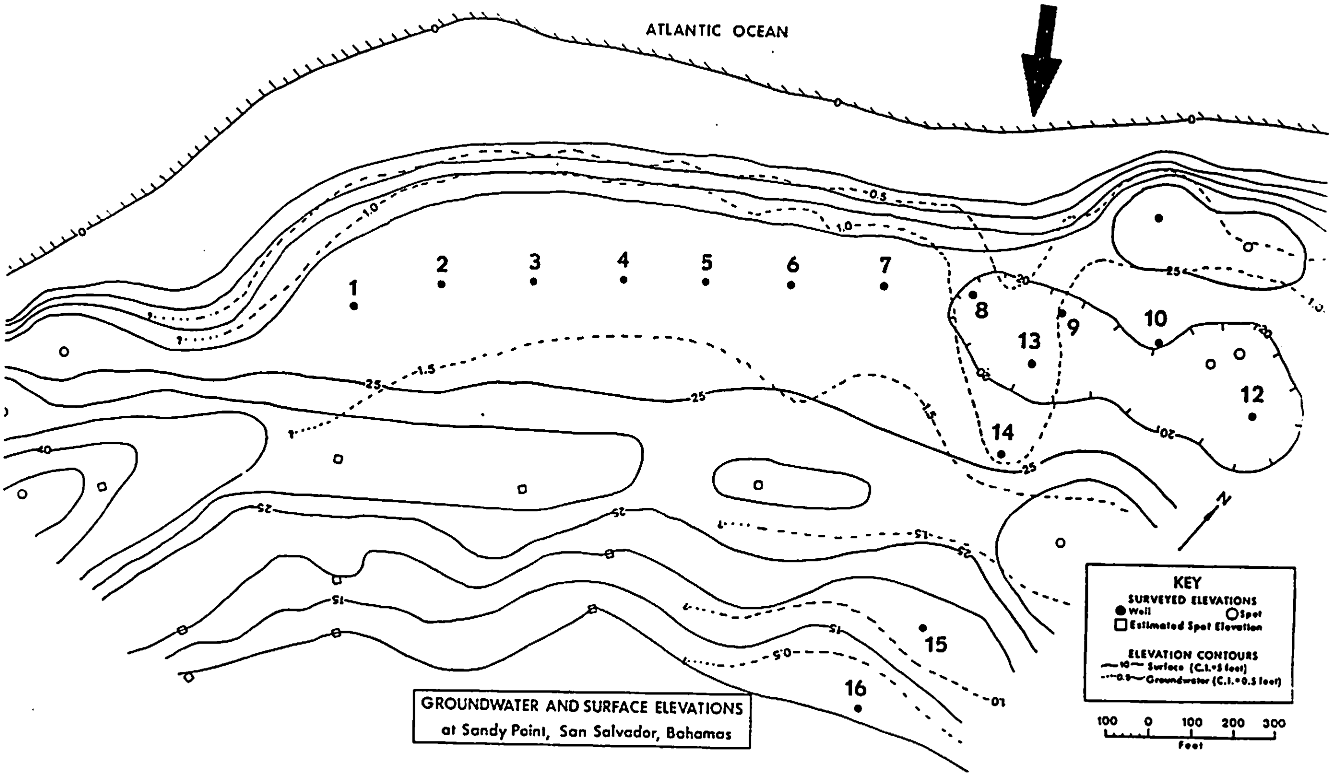

Fig. 7. Map showing surface and ground water topography at the Sandy Point well field.

Location	Number of Samples	Cl^- mg/l	Ca^{++} mg/l	Mg^{++} mg/l	Mg/Ca	pH
SP #8	8	246	104	15	0.14	7.61
SP #9	5	38	97	3	0.03	7.53
SP #10	4	145	73	7	0.10	7.79
SP #12	5	22	62	3	0.05	7.95
SP #13	6	145	96	10	0.10	7.56
SP #14	4	604	116	41	0.34	7.60
Ocean	9	20508	479	1714	3.63	8.35

Table 3: Water Chemistry (average values) of the Wells Near the Sandy Point Ground Water "Channel".

within the error range of the data.

Of particular interest, is the area on the map marked by an arrow (Figure 7). Here the contours indicate a ground water "channel". All of these wells not only have lower than expected water table elevations, but they also show higher than expected mixing of sea water (Table 3). It is important to note that none of these wells have ever been pumped, nor is there any indication that pumping in nearby wells has affected them. Consequently, this seems to be a natural phenomena. Vasher (1988) discusses what might happen to freshwater lenses and water tables under varying conditions of permeability. He states that a high permeability "basement" results in lower water tables and hence, thinner freshwater lenses. Nearby, at Grotto Beach, a conduit carrying freshwater out to the ocean has been found. If such a conduit were located beneath the ground water "channel" shown on Figure 7, then the permeability of the rocks should be very high. This would result in lower water tables, such as those shown on the map. In addition, at high tides, sea water would flow along the conduit and into the rock where it would mix with the fresh ground water. This would account for the relatively high chloride concentrations in wells 10, 13 and 14.

Topographic control and water analyses performed in the United Estates area suggests that a ground water "channel" may also exist here. Its location is directly over the inferred path of a conduit that connects Reckley Hill Pond to the sea. Careful measurements of water table elevations may reveal other locations where this phenomena is present.

Conclusions

In summary, the ground water results demonstrate that the Ghyben-Herzberg model is applicable in areas that are under the ridges and far from any conduits. In these locations, fresh water lenses, of some thickness, are found. In addition, the existence of low permeabilities in the rocks over most of the island, means that, in these areas, the direct influence of the ocean and tides on the ground water system is limited. Consequently, fresh water lenses can, and do, occur very close to the shore.

Conversely, where conduits and areas of high permeability are present, they exert a strong influence on ground water chemistry and flow. In these areas, fresh water lenses may be entirely absent, and, if they are present, they will be thinner than predicted by the Ghyben-Herzberg model. The water in the lenses will also be brackish due to the tide-driven mixing of fresh and sea waters within the permeable zones.

Inland Lakes

Information provided by John Winter (Personal Communication), and continued exploration, revealed the presence of many freshwater seeps along the shores of the inland lakes. The water coming from these seeps is considerably fresher and cooler than that in the adjacent lake (Table 4). These seeps always seem to be associated with a highly karstified type of rock, that is called moon rock locally. A similar feature is found in caves world-wide. It is the result of mixing corrosion. This occurs when two solutions, saturated at different calcium ion concentrations, mix. The resulting mixture, paradoxically, is unsaturated and hence, aggressive (White, 1988). This aggressive water dissolves the rock where the two solutions come into contact, producing "spongework" and other highly karstified features. This same phenomena would occur where the Ca-

Location	Cl^- mg/l	Ca^{++} mg/l	Mg^{++} mg/l	Mg/Ca	pH	Temperature °C
Duck Pond Seeps (samp.1)	15020	344	1233	3.58	8.31	24
Duck Pond Seeps (samp.2)	15440	408	1382	3.39	7.81	24
Duck Pond Surface	77800	1408	6431	4.57	7.95	30
Granny Lake Seep	5680	282	474	1.68	6.73	
Granny Lake Surface	20850	584	1636	2.80	7.34	
S. Side Lake Seeps	9700	493	627	1.27	7.30	
S. Side Lake Surface	139700	536	17378	32.42	7.25	
Ocean	20507	479	1714	3.63	8.35	

Table 4: Water Chemistry of Seeps and Surface Water at Several Lakes

saturated water from the seeps mixes with the lake water, which is saturated at a different Ca concentration. The mixing would result in the formation of moon rock.

In some locations, moon rock is present, even though there are no discernible seeps. These may be areas where seeps existed once but are now no longer active.

Our study of the lakes revealed two general types. The first is very muddy and contains substantial colonies of blue-green algae. These often appear red due to nutrient deprivation. The salinity of the lakes ranges from 36 to 90 parts per thousand (ocean salinity is 35 ppt), and water temperatures are usually very high (exceeding 30° C). Conduits are not associated with this type of lake.

The second type of lake is clear, and salinities are similar to those of ocean water (Table 5). Water temperature also resembles that of ocean water. Conduits are always found associated with these lakes. Both types of lakes may or may not have seeps and moon rock.

It is likely that the first type of lake receives water from three sources: direct precipitation, seeps, and saline ground water flow. During the dry season, evaporation concentrates the salts in these lakes and they may become highly saline. During the wet season, direct precipitation becomes important and salinities drop, sometimes below that of sea water (Countryman and Poole, 1981). A comparison of the water chemistry of South Side Lake during the dry season (June) and during the wet season (January) illustrates this point well. In June, the chloride concentration was over 139,000 mg/l. In January, it averaged only 36,000 mg/l (see Table 5). Ocean water chloride concentration is about 20,000 mg/l. We have named this type of lake "seep-fed".

The second type of lake receives water from the same sources as the seep-fed lakes, but in addition, it receives a "slug" of sea water through the conduit during most high tides. We have named this type of lake "conduit-fed". The water chemistry in conduit-fed lakes is close to that of sea water and it remains fairly constant throughout the year. For example, the average chloride concentration in Reckley Hill Pond during the dry season is about 30,000 mg/l, while it is about 21,000 mg/l during the wet season. The fact that concentrations are higher than sea water indicates that evaporation can play a role in the water chemistry of these lakes, but it is not nearly as important as it is for the seep-fed lakes.

Three lakes, Little Lake, South Side Lake, and Reckley Hill Pond (see Figure 2), were sampled systematically during January, 1988. Little Lake is medium sized (~300 hectares), conduit-fed, and there are several freshwater seeps. Its depth averages about 2 meters. South Side Lake is small (~18 hectares) and seep-fed. It also has several freshwater seeps. It averages less than 1 meter in depth. Reckley Hill Pond is small (~14 hectares) and conduit-fed. There are no freshwater seeps. It averages about 1.25 meters in depth.

Little Lake

Forty-two samples were taken from the northern three-quarters of Little Lake during a six hour period on 8 January 1988. The tide was low. Figure 8 shows the locations of the samples, indicated by closed circles, and chloride ion

Location	Number of Samples	Type	Cl^- mg/l	Ca^{++} mg/l	Mg^{++} mg/l	Mg/Ca	pH
		Averages By Lake					
Miller's Pond	1	C	31200	748	2756	3.68	8.65
Reckley Hill Pond	89	C	21457	484	1729	3.57	8.12
Little Lake	46	C	25721	588	2134	3.63	8.36
S. Granny Lake	1	C	20850	584	1636	2.80	7.34
Pond N of Quarry E	1	C	24340	608	2709	4.46	
Clear Lake	1	C	21840	456	1780	3.90	7.85
N Little Lake @N End	1	S	40350	848	3266	3.85	8.38
Storr's Lake @Narrows	1	S	44100	1028	3787	3.68	8.38
Pond - Bridge (Dixon Hill)	1	S	47080	560	3660	6.54	
Duck Pond Surf	1	S	77800	1408	6431	4.57	7.95
Great Lake	6	S	40741	839	3326	3.99	7.98
Stout's Lake	2	S	44600	908	3434	3.78	
Sm. Pond W of Stout's	1	S	42220	624	3289	5.27	
S Side Lake/June	1	S	139700	536	17378	32.42	7.25
South Side Lake (January)	34	S	36622	820	2774	3.39	8.16
		Averages By Type					
Conduit-fed	139		22957	522	1877	3.59	8.20
Seep-fed	48		41043	828	3311	4.23	8.13
Ocean	9		20508	479	1714	3.63	8.35

Table 5: Average Water Chemistry in Inland Lakes. "C" in types column indicates conduit-fed, "S" indicates seep-fed.

concentrations, contoured at a 250 mg/l interval. Of particular interest is the area of low chloride ion concentration surrounding point 23 in the central portion of the lake. This is known to be the location of the conduit which feeds the lake. At times of high tide, water can be observed "boiling up" here (Winter, Personal Communication). The lake is about 2 meters deep at this point, but the conduit is not visible due to turbidity. Nevertheless, the water chemistry clearly shows the presence of this conduit, even though the tide was not flowing in at the time of the sampling.

Two other points of interest are number 5 (east-central part of the lake) and number 18 (west-central). Moon rock is present at both of these locations. The water chemistry at point 5 suggests the presence of a seep, and a small amount of water was observed flowing from the rock. The water chemistry at point 18 does not suggest a seep. However, the lake is deep (1.5 meters) here and, on the day that sampling was carried out, there was a brisk northeast wind. This would promote mixing, which could, at the scale of our sampling grid, mask the effect of a freshwater seep.

A final point of interest is number 29, located in the northwest corner of the lake. Here the chloride concentration is relatively high. The most likely explanation for this is the presence of the Cockburntown Dump along the shore between points 29 and 30. The northeast wind/ might be pushing water, bearing leachate, from the dump into the vicinity of point 29. Again, the density of the sampling grid did not permit confirmation of this hypothesis.

South Side Lake

Thirty-four samples were taken from South Side Lake over a three hour period on 4 January 1988. The wind was calm. Sample locations are shown by solid circles on Figure 9. Chloride ion concentrations are contoured at a 500 mg/l interval.

Seeps and moon rock are located on the northeast shore of the lake near points 17, 19, and 21. These are clearly shown by the chloride contours. Other areas of interest include the west end of the lake, which has high chloride concentrations. The lake is very shallow (less than

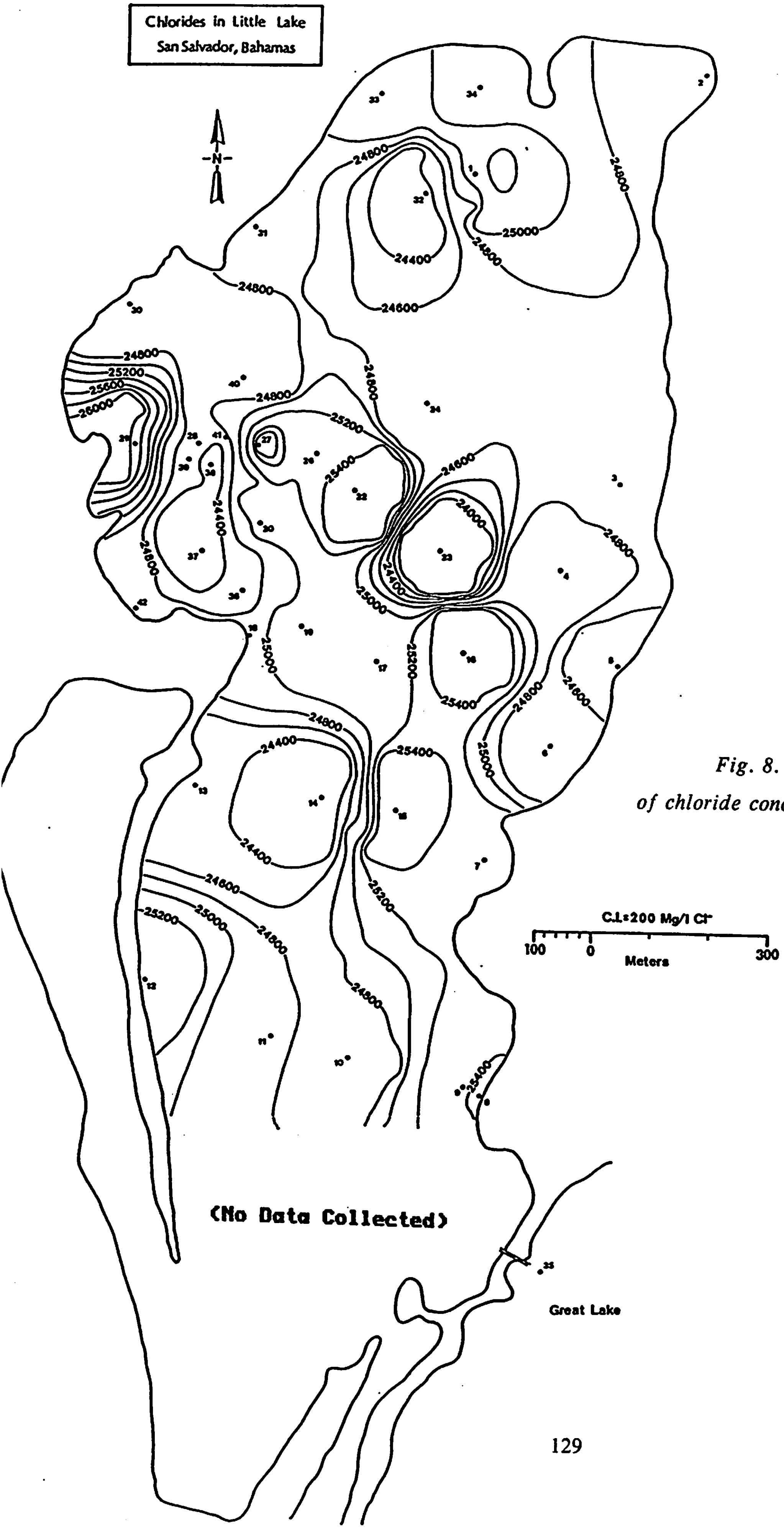

Fig. 8. Sampling locations and contours of chloride concentrations, Little Lake.

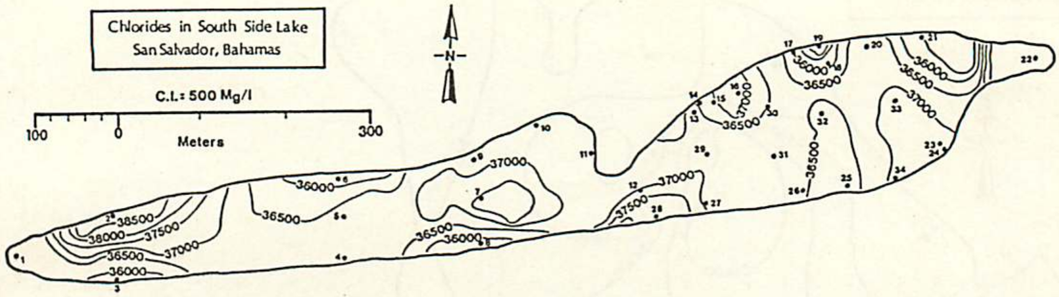

Fig. 9. Sampling locations and contours of chloride concentrations, South Side Lake.

0.3 m) and water temperatures are 1-2° C higher than in the deeper parts of the lake. Hence, the higher concentrations are probably caused by increased evaporation. The higher concentrations near points 13, 14, 15, and 16 (north shore) are probably also due to shallow water and higher temperatures.

Chloride concentrations are very high relative to both ocean water and the water in the other two lakes (Table 5). This is true even though the January samples were taken at the end of a very wet Autumn. Sampling done in June, 1987, showed chloride concentrations as high as 132,000 mg/l.

Reckley Hill Pond

Thirty-nine samples were taken from Reckley Hill Pond on 10 January 1988. Their locations are shown by solid circles on Figure 10. Samples were collected over a three hour period. High tide occurred while the sampling was being conducted, so water was flowing into the lake from the conduit during the entire time. On the figure, pH has been contoured at an interval of 0.04 pH units. It was not possible to contour chlorides, since the concentrations in the lake water were very close to that coming in through the conduit.

The contours show a plume of water, with lower pH, flowing from the conduit in the SE corner of the lake. It spreads out towards the

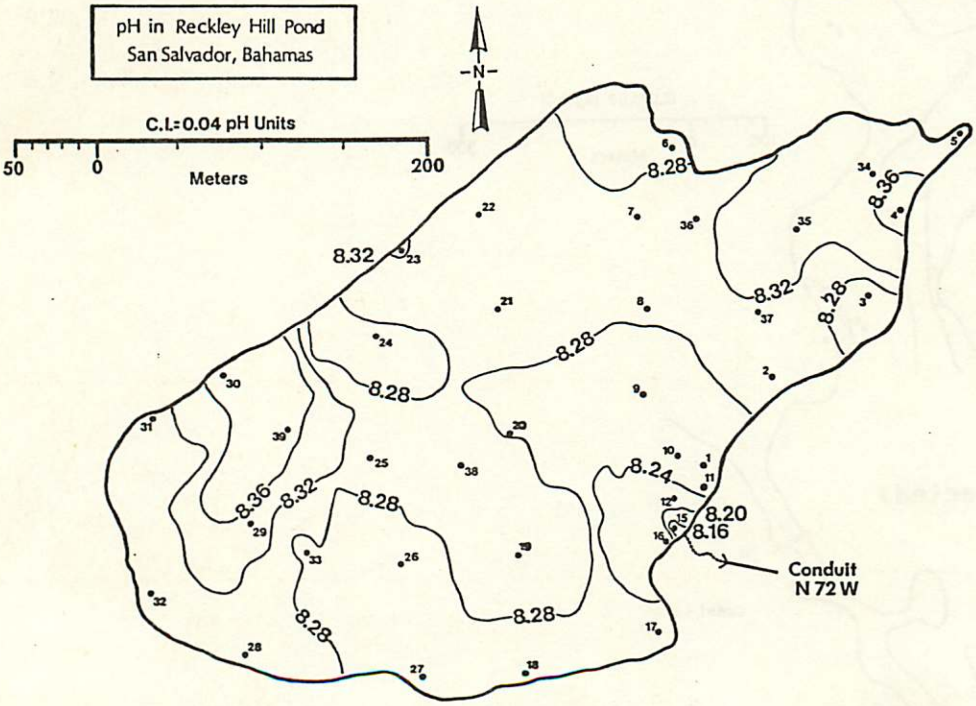

Fig. 10. Sampling locations and contours of pH, Reckley Hill Settlement Pond.

center of the lake for almost 100 meters. No seeps or moon rock were found along the lake shore, and the water chemistry also did not show any areas of incoming fresh water.

Conclusions

Based on these observations, we conclude that the influence of conduits and seeps can be seen in the water chemistry of most lakes. The nature of the water sources controls the lake's chemical condition. Those fed only by seeps, precipitation, and saline ground water (such as South Side Lake) are strongly influenced by evaporation, which results in high and variable salinities. During the wet season the salinities may be twice that of ocean water. During dry seasons, they may be as much as 6 times as high. Under these conditions, seeps are particularly noticeable when water chemistry is contoured. The difference in the calcium concentrations between the lake and the seep waters allows for mixing solution and the formation of moon rock.

In those fed by conduits, such as Reckley Hill Pond and Little Lake, waters are mixed, resulting in salinities that are relatively constant through out the year. Seeps are not as obvious under these conditions, although water chemistry differences between the lake and seep waters are still large enough to produce mixing corrosion and the formation of moon rock.

Conduits and Tides

Extensive studies of conduit flow were performed at Reckley Hill Pond. The conduit appears as an opening in the limestone at the foot of a ridge. A rectangular channel approximately 60 centimeters square, leads through the mangroves to the pond, which is approximately 25 meters away. The tides force water in and out of the conduit. Flow measurements and water chemistry were studied at the conduit on three separate occasions: June, 1987 (for 12 hours), December, 1987 (for 13 hours) and January, 1988 (for 7 hours). The results of these measurements are shown in Figures 11A and B. Figure 11A shows flow on 10 June 1987. Combined flows on December 31, 1987 and January 11, 1988, are shown on Figure 11B giving an idea of what a complete tidal cycle might look like. On both figures, positive discharges indicate flow into the lake (tide coming in) and negative discharges indicate flow out of the lake (tide going out).

Since flow is clearly driven by the tides, we expected that water would flow into the pond for 6 hours and out for 6 hours of each 12 hour tidal cycle. However, during the first observation period, on 10 June 1987, water flowed in for only 4 hours and out for 8 (Figure 11A). During the second observation period, water flowed out during the entire time that data was being collected (13 hours). During the third observation, on 11 January, 1988, water flowed in for 3 hours and out for 9 (Figure 11B). Careful measurement of the pond's elevation, and an examination of tide tables and our own records, provided an explanation (Figure 12). The elevation of the pond is about 70 cm above mean low tide. This is higher

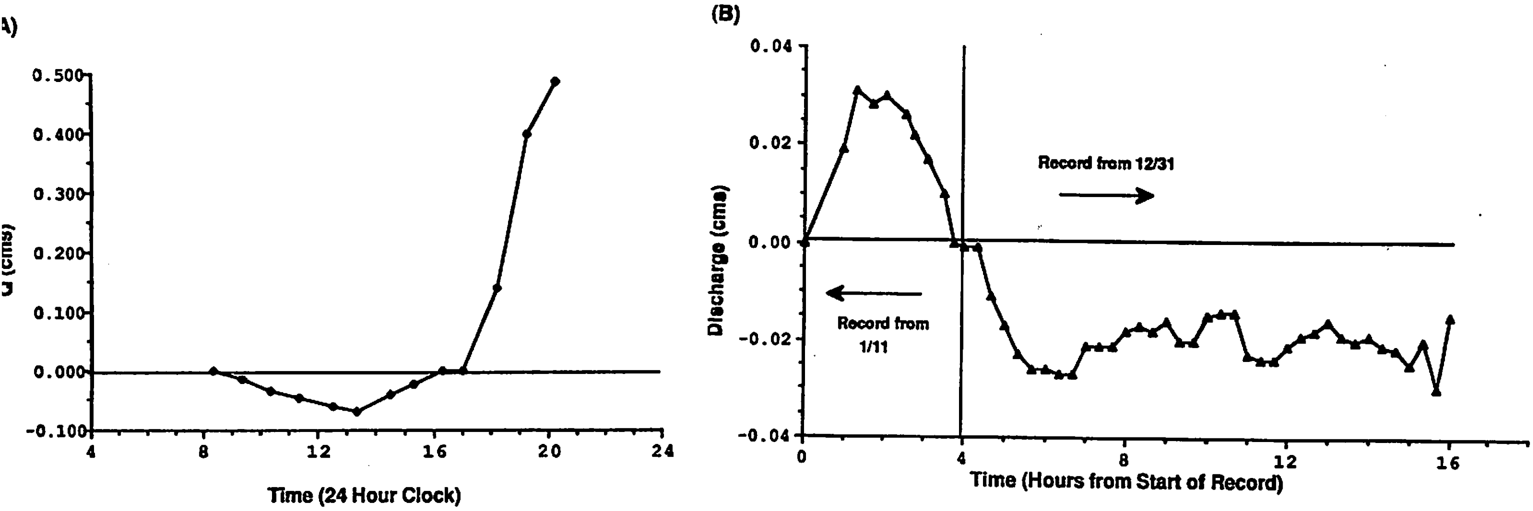

Fig. 11. Hydrographs for Reckley Hill Settlement Pond. (A) 10 June 1987 (B) 31 December 1987 and 11 January 1988.

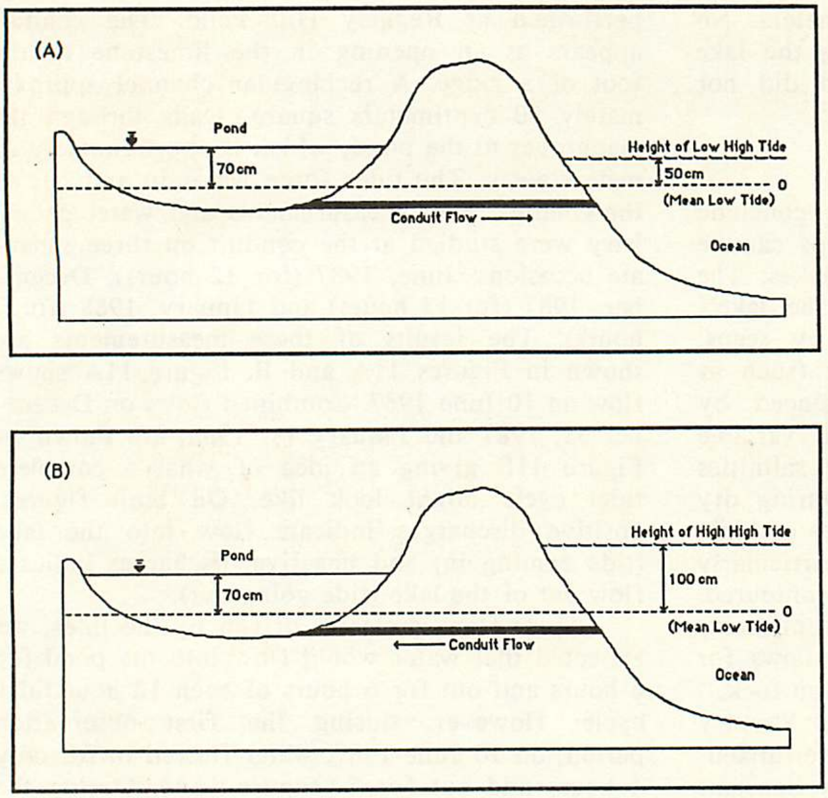

Fig. 12. General model of tidal fluctuations and conduit flow. (Based on conditions at Reckley Hill Settlement Pond).

than the elevation of many high tides. At times of low high-tide, the elevation of the water in the ocean never reaches the surface of the pond. Consequently, water will flow out during the entire tidal cycle. At times of higher high-tides, water will only flow into the pond during that part of the cycle when the tide is higher than the pond's elevation. High tides on June 10 were very high (~1.1m). Those on December 31 were much lower (~0.70m), and those on January 11 were low (~0.90m), but were about 20 cm higher than on December 31.

Mass balance calculations were carried out to see if the water coming into the pond balanced that going out. Water enters the pond through the conduit at relatively high discharges (see Figure 11). This means that even though the duration of incoming flow may be short, the volume is fairly large. Outgoing discharges are considerably smaller. In fact, on 10 June, the volume of water coming into the pond was larger than that flowing out (by about 2 times). The difference can be accounted for by evaporation (Davis, et. al., 1988). Conduits at other ponds appear to behave in a similar fashion (Teeter, Winter, and Gerace, Personal Communication), although direct observations will have to be made to confirm this.

When the water does flow into the pond, the flow is very forceful and turbulent. This would promote mixing in the ground water zone adjacent to the conduit, and may produce the kind of ground water "channel" and chemistry features that were observed at Sandy Point.

CONCLUSIONS

Based on the field work, we have been able to reach some preliminary conclusions about the nature of the hydrologic system on San Salvador. Figure 13 shows how the elements of our model interact. Freshwater lenses of varying thicknesses exist under the dune ridges both along the coast and in the interior. If there are no conduits running under the ridges, then the ground water will be fresh and potable. Where conduits cross the ground water zones, the quality of the water is diminished. Salt water from the ocean mixes with the fresh ground water producing brackish water, and water tables in these areas are usually lower.

The water in the inland lakes is supplied by

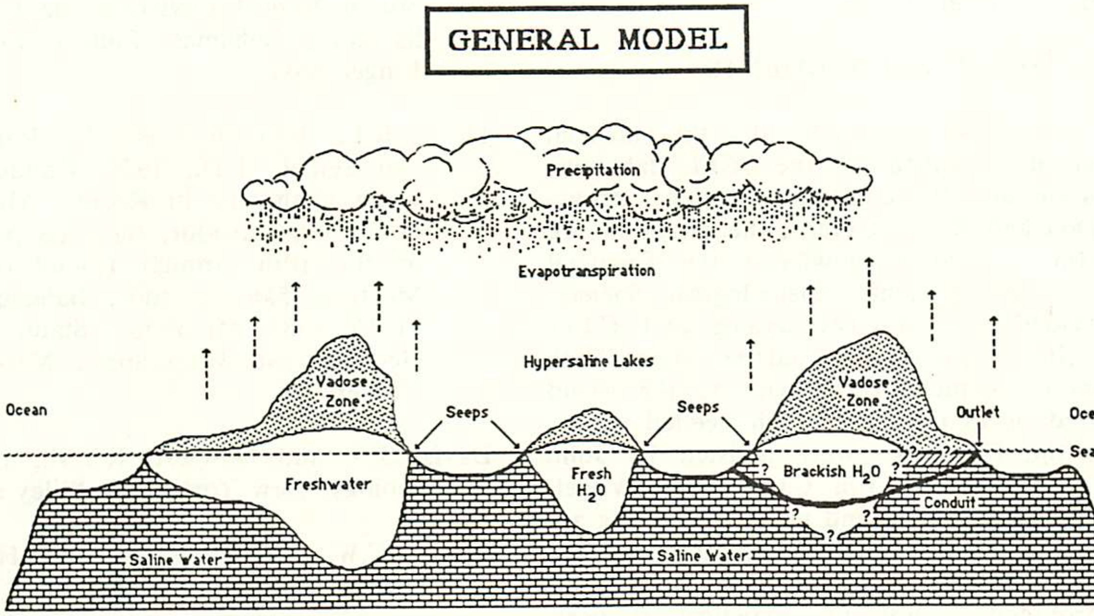

Fig. 13. General model of the hydrologic system on San Salvador.

precipitation, seeps from the lenses in the dunes, saline ground water infiltration, or conduits. Those lakes that have conduits, maintain a salinity that is close to sea water throughout the year. These lakes are also clear and free of algae.

Lakes that are not fed primarily by conduits are dominated by evaporation. During the rainy season, the water may be brackish, but during the dry season, the water is hypersaline. These lakes are muddy and full of algae. In either case, the locations of seeps and conduits can be determined by a systematic chemical analysis of the lake water.

Flow in the conduits is controlled by tides and lake elevations. Most of the lakes are higher than low high-tides, and water will flow into them only at higher high-tides. During the dry season, overall lake levels are lower, so inflow should be more sustained than during the rainy season.

Future Work

This preliminary model could be made more specific by conducting a variety of other field tests. Important ones might include: 1) deep holes drilled on the ridges, especially in the interior, 2) the examination of the coast north of Grotto Beach to see if there really is a conduit located where the ground water map suggests, and 3) an analysis of the ground water topography at other locations to see if it matches that at Sandy Point, and if it reflects the presence of known conduits. Also, other lakes should be systematically sampled, so that the locations of seeps and conduits can be mapped.

Implications

There are many important implications of our work. We have already used the model to locate one potential water source at N. Victoria Hill Settlement and it may be possible to locate others. The model can also be used to help with management of the water supply. More water sources may, in turn, bring some development to the island, providing new jobs for the residents. Pumping, however, must be done with great care, since the permeability of the rocks is low and the possibility for salt water intrusion is high.

This preliminary understanding of the hydrologic regime could also lead to speculation on how the system looked at higher and lower sea level stands. Were there more or less conduits? Was there a greater or lesser quantity of freshwater? Were freshwater lenses more continuous than they are today and did they conform more closely to the Ghyben-Herzberg model? The answers to these questions can lead to an understanding of the origin of the island's caves and karst, and, by extension, the origin of caves and karst on other similar islands world-wide. They may also provide important indicators as to how caves and conduits can be used to determine the history of

Pleistocene sea level changes.

ACKNOWLEDGEMENTS

We would like to acknowledge the financial and logistical assistance of the CCFL Bahamian Field Station and the continuous support provided by Don and Kathy Gerace, the directors. We would also like to acknowledge the financial support of the National Speleological Society, who provided us with two grants and C.I.D. Landfill, Incorporated of Chaffee, New York whose grants financed three trips to the island and allowed us to purchase much needed equipment. In the field, we were assisted by John Winter, John Mylroie, Jim Carew, Pete Vogel, John Rapp, Todd Seibel, and many others. We are grateful to them for their time and interest. Clifford Fernander of the Bahamas Ministry of Works provided equipment, logistical support, transportation and encouragement. Finally, we would like to thank the people of San Salvador for their warm welcome and their willingness to share their knowledge and ideas with us.

REFERENCES CITED

Adams, R.W., 1983, General guide to the geological features of San Salvador, in Gerace, D.T., ed. Field Guide to the Geology of San Salvador. 3rd ed. San Salvador, Bahamas: CCFL Bahamian Field Station.

Carew, J.L. and Mylroie, J.E., 1985, The Pleistocene and Holocene stratigraphy of San Salvador Island, Bahamas with reference to marine and terrestrial lithofacies at French Bay, in Curran, H.A., ed. Pleistocene and Holocene Carbonate Environments on San Salvador Island, Bahamas, Geological Society of America Annual Meeting (Orlando, Florida) Guidebook for Field Trips #2. Fort Lauderdale: CCFL Bahamian Field Station, pp. 11-61.

Countryman, K. and Poole, M., 1981, Physical and chemical characteristics of Merrill's Pond, San Salvador Island, Bahamas, Unpublished Paper, Elmira, N.Y.: Elmira College Dept. of Geology, (on file at CCFL Bahamian Field Station, San Salvador, Bahamas).

Davis, M.R., 1975, Iron in wells, in College Center of the Finger Lakes, Island Environmental Studies Report-Environmental Chemistry, San Salvador, Bahamas: College Center of the Finger Lakes.

Davis, R.L., Johnson, C.R., Jr., Rapp, J.C., Jr., and Seibel, T.D., 1988, Conduit flow and water chemistry in Reckley Hill Settlement Pond, San Salvador, Bahamas (abs), Program of the 10th Annual Friend of the Karst Meeting, San Salvador, Bahamas, February 11-15, 1988. Mississippi State, Ms: Dept. of Geology and Geography, Mississippi State University.

Davis, S,N. and DeWiest, R.J.M., 1966, Hydrogeology, New York: John Wiley and Sons.

Fetter, C.W., Jr., 1980, Applied Hydrogeology, Columbus: Charles E. Merrill.

Gerace, D.T., Director, CCFL Bahamian Field Station. Personal Communication.

Johnson, C.R., Jr. and Davis, R.L., 1987, The use of Ca^{++} and Mg^{++} ions as indicators of groundwater mixing on San Salvador, Bahamas, Abstracts with Programs Annual meeting, Southeast Section-Geological Society of America, Norfolk, VA Pg. 91.

Kunze, A.W.G. and Burke, J.C., 1984, A resistivity survey of Sandy Point, San Salvador, Bahamas, in Teeter, J.W., ed. Proceedings of the 2nd Symposium on the Geology of the Bahamas. June 16-20, 1984. San Salvador, Bahamas: CCFL Bahamian Field Station, pp. 97-112.

Kunze, A.W.G. and Weir, W.G., 1987, Geoelectrical ground-water survey of the Sandy Hook Area, San Salvador, Bahamas, in Curran, H.A., ed. Proceedings of the 3rd Symposium on the Geology of the Bahamas, June 6-10, 1986, Fort Lauderdale: CCFL Bahamian Field Station. pp. 81-89

Mylroie, J.E., 1988, Karst of San Salvador, in Mylroie, J.E., ed. Field Guide to the Karst Geology of San Salvador Island, Bahamas. Mississippi State, MS: Dept. of Geology and Geography, Mississippi State University.

Quarrier, N., 1975, Sulfate in pond and well water, in College Center of the Finger

Lakes, Island Environmental Studies Report-Environmental Chemistry, San Salvador, Bahamas: College Center of the Finger Lakes.

Sealey, N.E., 1985, Bahamian Landscapes: London Collins Caribbean.

Teeter, J.W., University of Akron, Department of Geology. Personal Communication.

Touchette, N., 1975, Nitrates in well water, in College Center of the Finger Lakes, Island Environmental Studies Report-Environmental Chemistry. San Salvador, Bahamas: College Center of the Finger Lakes.

White, W.B., 1988, Geomorphology and Hydrology of Karst Terrains. New York: Oxford University Press.

Winter, J.D., Molloy College, Division of Social Sciences. Personal Communication.