# PROCEEDINGS OF THE 15$^{TH}$ SYMPOSIUM ON THE GEOLOGY OF THE BAHAMAS AND OTHER CARBONATE REGIONS

**Edited by**
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Gerace Research Center
San Salvador, Bahamas
2012

Front Cover: *Porites* colony encrusted by red algae in waters of San Salvador, Bahamas; see paper by Fowler and Griffing., p. 41. Photograph by Pascal Kindler, 2011.

Back Cover:. Dr. Jörn Geister, Naturhistorisches Museum Bern, Keynote Speaker for the 15th Symposium and author of "Keynote Address – Time-Traveling in a Caribbean Coral Reef (San Andres Island, Western Caribbean, Colombia)", this volume , p. vii. Photograph by Joan Mylroie.

Press: A & A Printing



**ISBN 978-0-935909-93-7**

# WATER-QUALITY MONITORING OF SAN SALVADORIAN INLAND LAKES

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## ABSTRACT

This study aimed to produce high-resolution water quality datasets for nine inland lakes on San Salvador Island. Temperature, salinity, dissolved oxygen, pH, reactive phosphate, nitrate, nitrite, ammonia, and dissolved carbon species were measured monthly over a 22-month period. Crescent, Moon Rock, Oyster, and Mermaid ponds were classified as marine ponds, while Reckley Hill, Osprey, Little, and Salt ponds were classified as hypersaline ponds. The degree of ocean connectivity was found to be a driver for both salinity and dissolved organic carbon concentration within the lakes. Nutrient levels were generally low for all marine and hypersaline lakes, with the exception of elevated ammonia concentrations in Little Lake. Fresh Lake is a unique system that experiences widely ranging salinity levels and elevated nutrient concentrations. As such, Fresh Lake provides an opportunity for further study of anthropogenic impacts.

## INTRODUCTION

The inland lakes of San Salvador Island are the focus of a variety of geological and biological research projects conducted at the Gerace Research Centre. Geologists study the physical hydrology and water chemistry of the ponds (Davis and Johnson, 1989; Winter, 1993; Button et al., 2007; Moore and Martin, 2008), while biologists investigate their oysters, stromatolites, algal mats, and community ecology (Dakoski and Bain, 1984; Mann and Hoffman, 1984; Elliot, 1992; Edwards, 2001; Whitelaw, 2001; Cole et al., 2007; Lanterman et al., 2007; Cole et al., 2009; Dutke et al., 2009; Erdman et al., 2009; Swanson et al., 2009). There is also paleontological research focused on ostracode assemblages and coring for paleoclimate reconstruction (Sanger and Teeter, 1982; McCabe and Niemi, 2008; Park et al., 2008; Park and Trubee, 2008; Niemi et al., 2010; Sipahioglu et al., 2010). However, in spite of this vast degree of scientific inquiry, many researchers are restricted to visiting and sampling their field sites on a limited basis, often without repeat samples at a regular high temporal resolution. Sampling at only annual or biannual intervals may inhibit a researcher's ability to make accurate conclusions and interpretations concerning environmental conditions within the lakes and ponds. Further, monitoring equipment designed to remain *in situ* for extended researcher absences is often cost prohibitive, not to mention prone to malfunction in the harsh inland lake environments.

Utilizing the equipment of the Analytical Laboratory at the Gerace Research Centre, this study aimed to develop high-resolution nutrient and water-quality datasets for several of San Salvador's inland lakes. These data provide insight into the seasonal and annual fluctuations of these parameters, highlight any potential relationships between parameters, as well as allow for the preliminary assessment of anthropogenic impacts. The datasets will also prove useful to other researchers interested in relating the various chemical properties to their own work within the ponds and lakes.

## METHODS

Sites included in this study were chosen for their physiochemical and geographic diversity, accessibility, and levels of previous academic interest. Samples and data were collected approximately monthly for the 22-month period between October 2008 and July 2010 at Reckley

Hill Settlement Pond, Crescent Pond, Moon Rock Pond, Oyster Pond, Osprey Lake, Salt Pond, Mermaid Pond, and Little Lake (Figure 1). Fresh Lake was added to the study in September 2009, and was therefore only sampled for an 11-month period. A man-made causeway bisects Fresh Lake, so monthly samples we taken from both the northern and southern portions on either side of the causeway.

Basic water quality parameters were measured in situ at each site. Temperature, salinity, and conductivity measurements were collected with a YSI 30 Meter, and dissolved oxygen measurements were collected with a YSI 55 Meter.

In the lab, surface water grab samples from each site were analyzed for a suite of chemical parameters. Total reactive phosphate (TRP), nitrate, nitrite, and ammonia were analyzed with a Hach DR 2700 Spectrophotometer, using Hach Methods 8048, 10020, 10019, and 10023, respectively.Total dissolved carbon (TDC), total dissolved inorganic carbon (TDIC), and total dissolved organic carbon (TDOC) were analyzed with a Shimadzu TOC-5050A Total Organic Carbon Analyzer, and pH was measured with a Hanna Bench pH Meter Model pH210.

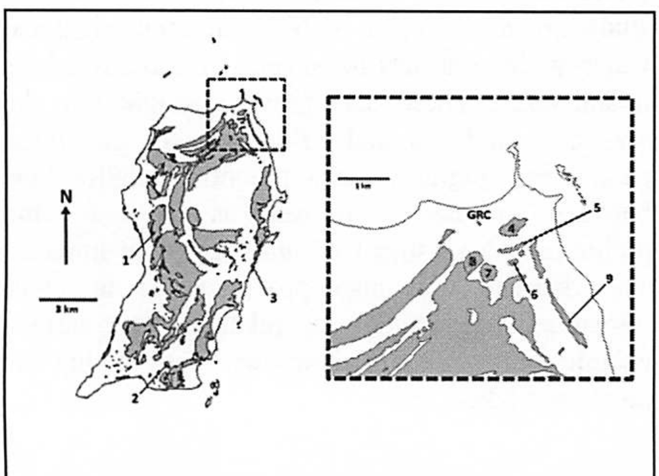


*Figure 1. San Salvador inland lake water-quality sampling locations: (1) Little Lake, (2) Mermaid Pond, (3) Salt Pond, (4) Reckley Hill Pond, (5) Crescent Pond, (6) Moon Rock Pond, (7) Oyster Pond, (8) Osprey Lake, and (9) Fresh Lake (adapted from McGee et al., 2010).*

RESULTS AND DISCUSSION

It is important to note that no tropical storms or hurricanes passed over the island of San Salvador during the course of this study. Hence, the data presented here represent a non-hurricane-influenced record of water quality within the ponds and lakes.

Certain water-quality parameters exhibit trends that are to be expected. For instance, the temperatures of all ponds display a predictable seasonal variability, with warmer temperatures during the summer months and cooler temperatures during the winter months (Figure 2). Salinity, nutrients, and dissolved carbon also exhibit trends that are discussed below. Parameters that did not produce discernable trends include dissolved oxygen and pH. Due to the potential for high variability among these two parameters, the sampling protocol for this study may not have been extensive enough to capture subtleties in their temporal and spatial distributions.

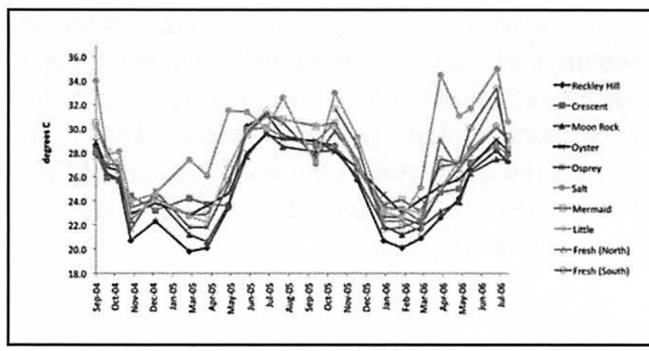


*Figure 2. Water temperature observations for San Salvador's inland lakes during the period of study. Note the seasonal variability with higher temperature in summer and lower in winter.*

Salinity-Based Pond Classification

By examining salinity trends, the ponds (with the exception of Fresh Lake) can be classified as marine or hypersaline bodies (Figure 3 and Table 1). The current discussion will focus on the marine and hypersaline ponds, while Fresh Lake will be further discussed separately.

Marine ponds are those that exhibit near ocean-like salinity (approximately 34-37 ppt)

*Table 1. Average monthly salinity and %TDOC for marine and hypersaline ponds on San Salvador.*

| | Salinity (ppt) Average | Salinity (ppt) SD | %TOC Average | %TOC SD |
|---|---|---|---|---|
| **Marine** | | | | |
| Crescent | 35.5 | 2.4 | 3.86 | 4.95 |
| Moon Rock | 35.4 | 1.8 | 2.82 | 4.16 |
| Oyster | 37.1 | 1.3 | 2.16 | 3.43 |
| Mermaid | 34.5 | 2.4 | 7.34 | 5.91 |
| **Hypersaline** | | | | |
| Reckley Hill | 41.4 | 9.0 | 26.30 | 6.30 |
| Osprey | 52.1 | 6.0 | 44.79 | 8.98 |
| Little | 43.0 | 3.9 | 28.03 | 3.82 |
| Salt | 112.2 | 76.6 | 71.73 | 9.14 |

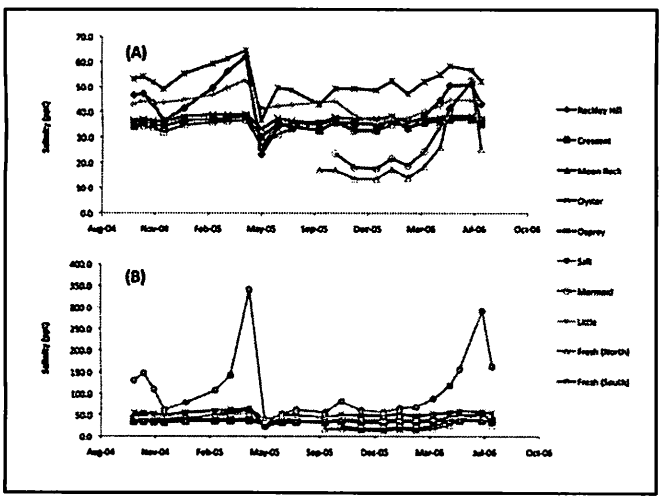


*Figure 3. (A) Observed pond salinities, excluding Salt Pond. (B) Observed pond salinities, including Salt Pond. A major rain event occurred on May 19, 2009.*

throughout the year. The ponds classified as marine by this study include Crescent, Moon Rock, Oyster, and Mermaid ponds. Their relatively constant, marine salinities are likely controlled by a strong connection to the ocean (usually through an underground conduit) and continuous tidal flushing. This interpretation is supported by previous studies that have determined that Crescent, Moon Rock, Oyster, and Mermaid ponds each contain tidally active conduits (Edwards et al., 1990; Godfrey et al., 1994; Crump and Gamble, 2006; Button et al., 2007).

Hypersaline ponds are those that exhibit higher-than-ocean salinities with more monthly variability throughout the year.The ponds classified as hypersaline by this study include Reckley Hill, Osprey, Little, and Salt. Their higher salinity levels and increased variability indicate that these ponds likely have a lower degree of ocean connectivity and are more influenced by evaporation. This interpretation is supported by previous findings that have determined that Reckley Hill, Little, and Osprey ponds include barely tidal or seasonably variable conduits that are insufficient to maintain marine conditions (Davis and Johnson, 1989; Edwards et al., 1990; McGee et al., 2010). Further, personal observations show that Salt Pond does not contain a conduit and is highly controlled by evaporation and rainfall.

Figure 3 further demonstrates that the salinities of both marine and hypersaline ponds are affected by rainfall events. Increased rainfall runoff into the ponds, such as that which occurred after a heavy storm on May 19, 2009, serves to dilute the pond water and lower salinity. For marine ponds this appears to be a short-term effect that is subsequently counteracted by tidal flushing, while hypersaline ponds generally take longer to return to previous salinity levels as a result of evaporative-controlled conditions.

## Nutrient Levels and Cycles

The nutrient data indicate that average monthly nutrient levels are low in both the saline and hypersaline ponds (Table 2).This is likely due to the absence of significant human development surrounding these ponds, the relatively nutrient-depleted soils that exist on the island, and the connectivity of the ponds to the open ocean. The lack of significant nutrient sources combined with various degrees of tidal flushing limit the build-up of nutrients within the ponds.

One exception to the relatively low nutrient levels is the ammonia concentration within Little Lake. While the rest of the ponds exhibit a virtual absence of ammonia, Little Lake has an average monthly ammonia concentration of 0.18 mg/L. Over the course of the entire study, monthly ammonia concentrations ranged from 0.0 mg/L to 0.6 mg/L. These levels are somewhat alarming considering that ammonia begins to have detrimental effects on the health of fish and other marine organisms at concentrations of 0.2 mg/L (Lang et al., 1987). These levels may be a result of Little Lake's

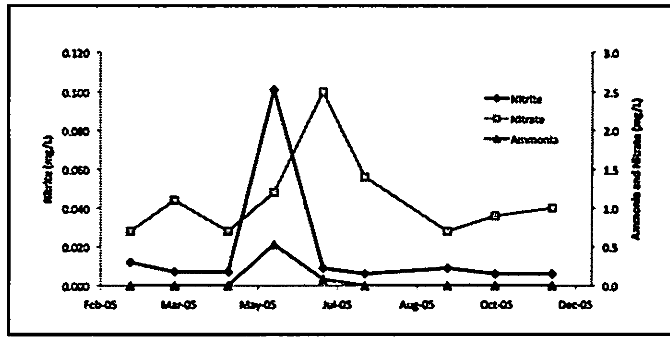


*Figure 4. Rainfall event signatures of ammonia, nitrite, and nitrate within Salt Pond, San Salvador.*

proximity to Cockburn Town, one of the island's main settlements, where increased human impact may be contributing to increased ammonia concentration. Potential sources of ammonia in the Cockburn Town area include mismanaged human and livestock waste and biomass burning. It is unlikely that fertilizer application is a source of ammonia in this instance, because the surrounding area is not under intense cultivation. However, the Bahamian Department of Environmental Health has been observed spraying for mosquitoes along the shores of Little Lake, so pesticide application is another possible source.

Despite the generally low-average nutrient levels in the remaining ponds, a rain-event signal for ammonia, nitrite, and nitrate is apparent. For the

*Table 2. Average monthly nutrient concentrations for marine and hypersaline ponds on San Salvador.*

| | TRP mg/L PO4 | Nitrate mg/L NO3-N | Nitrite mg/L NO2-N | Ammonia mg/L NH3-N |
|---|---|---|---|---|
| **Marine** | | | | |
| Crescent | 0.07 | 0.7 | 0.006 | 0.00 |
| Moon Rock | 0.09 | 0.7 | 0.004 | 0.00 |
| Oyster | 0.08 | 0.9 | 0.005 | 0.00 |
| Mermaid | 0.13 | 0.7 | 0.010 | 0.00 |
| **Hypersaline** | | | | |
| Reckley Hill | 0.11 | 0.8 | 0.006 | 0.00 |
| Osprey | 0.09 | 0.8 | 0.006 | 0.00 |
| Little | 0.07 | 0.7 | 0.012 | 0.18 |
| Salt | 0.10 | 1.0 | 0.015 | 0.00 |

sake of clarity, Figure 4 demonstrates this relationship for Salt Pond only, however similar relationships can also be observed in the data for Reckley Hill, Crescent, Oyster, Osprey, and Mermaid ponds. Immediately following a major rain event on May 19, 2009, there was a dramatic increase in both ammonia and nitrite concentrations in these ponds. This indicates that rainwater runoff is acting as a significant source of nitrogenous compounds to these ponds. A month later, while ammonia and nitrite concentrations have returned to relatively normal levels, these ponds experienced a significant increase in nitrate concentrations. This pattern is likely the result of nitrification within the oxygenated surface waters, during which nitrifying bacteria oxidize the runoff-supplied ammonia and nitrite to nitrate. The subsequent return of nitrate to pre-rainfall levels likely indicates the reduction of nitrate to gaseous species via denitrification in the suboxic conditions of the lower water column.

## Dissolved Carbon Regression Analysis

Table 1 indicates that the distribution of percent of dissolved total organic carbon (%TDOC) mimics the salinity classification of the ponds. Marine ponds exhibit low %TDOC values, while the hypersaline ponds exhibit much higher %TDOC values. This finding prompted a regression analysis

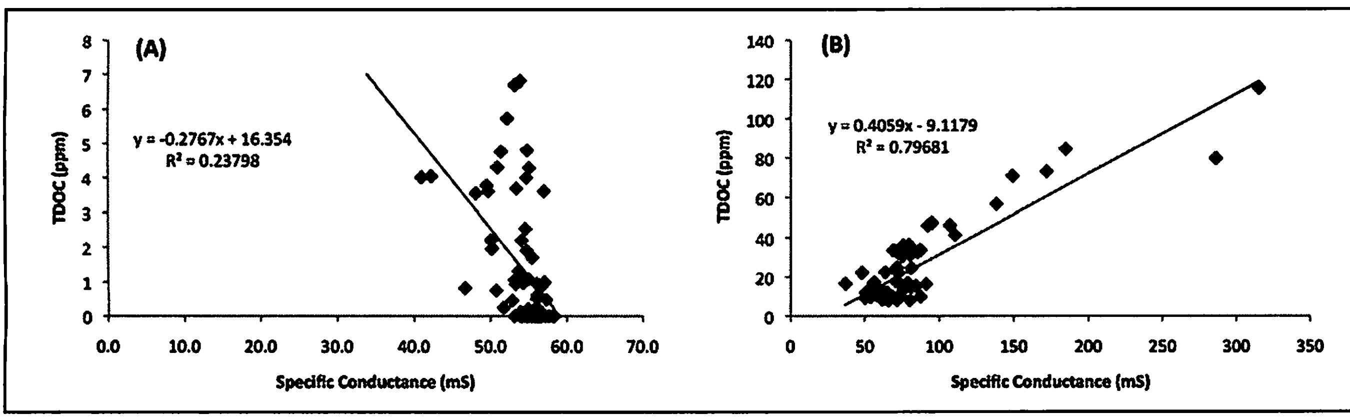


*Figure 5. (A) Regression of TDOC concentration and specific conductivity for marine ponds, San Salvador ($R^2$=0.2380). (B) Regression of TDOC concentration and specific conductivity for hypersaline ponds, San Salvador ($R^2$= 0.7968).*

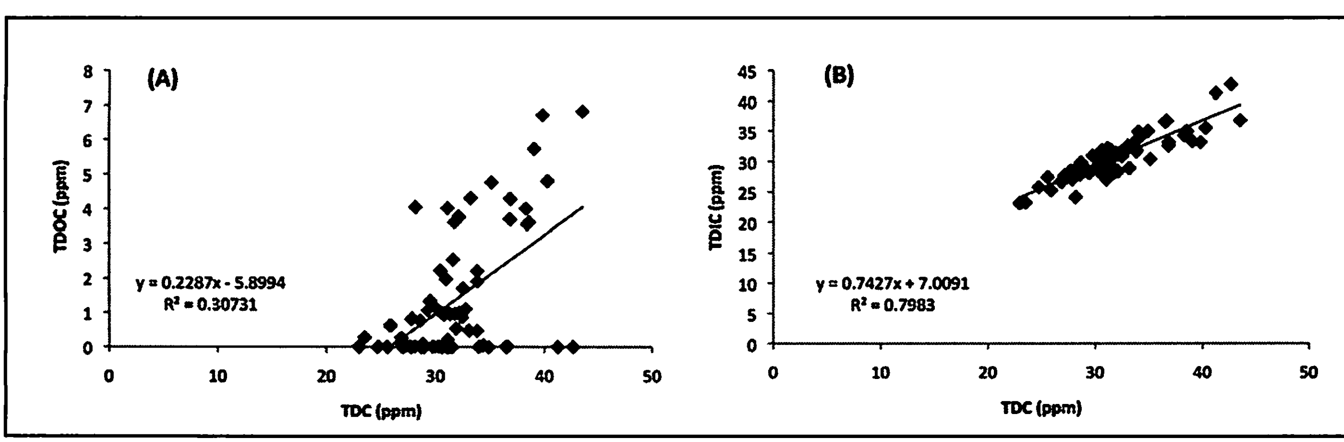


*Figure 6. (A) Regression of TDOC concentration and TDC concentration for marine ponds, San Salvador ($R^2$=0.3073). (B) Regression of TDIC concentration and TDC concentration for marine ponds, San Salvador ($R^2$= 0.7983).*

of the salinity and dissolved carbon data. For the regressions, specific conductivity values were used in lieu of salinity values as they correct for differences in pond-surface temperature

Results of the regression analysis indicate that there is not a statistically significant relationship between TDOC concentration and specific conductivity in the marine ponds (Figure 5A). However, a relatively strong relationship exists for the same two parameters in the hypersaline ponds (Figure 5B). In hypersaline ponds, as specific conductivity increases, so does TDOC concentration within the water column. This relationship highlights a common driver for the two parameters, the degree of tidal flushing and overall connectivity with the open ocean. Restricted ocean connectivity in hypersaline ponds not only contributes to their elevated salinities, but also to the concentration of dissolved organic carbon within the system. Storm-water runoff carries dissolved organic carbon of terrigenous origin into the ponds, where in the absence of tidal flushing the TDOC concentrations increase, allowing algae, cyanobacteria, and other microbes to visibly flourish (McGee et al., 2010).

Additional evidence for the connectivity driver of TDOC concentration can be found by examining the relationships between TDOC and TDC, as well as TDIC and TDC for both the marine and hypersaline ponds. In marine ponds, there is a stronger relationship between TDIC and TDC than between TDOC and TDC (Figure 6). This suggests that the total dissolved carbon in marine ponds is dominated by the inorganic component, likely as a result of carbonate dissolution and strong tidal flushing of runoff. Alternatively, in hypersaline ponds, there is a stronger relationship between TDOC and TDC than between TDIC and TDC (Figure 7). Hence, total dissolved carbon in hypersaline ponds is dominated by the organic component, again as a result of the lesser degree of tidal flushing and more evaporation -dominated conditions of the hypersaline ponds.

## Fresh Lake: A Unique Environment

Fresh Lake is a unique environment among San Salvador's inland water bodies. As its name implies, during parts of the year it experiences salinities that are among the lowest (freshest) on the island. However, as an almost completely rainfall and evaporation driven system (as evidenced by its tendency to completely dry out during severe drought conditions), there are periods when Fresh Lake salinity increases to hypersaline levels (Figure 3A). During this study period, the salinity of Fresh Lake ranged from approximately 13 to 42 ppt.

Located immediately adjacent and downhill of a densely populated portion of the United Estates settlement, Fresh Lake exhibits the greatest amount of human impact with regards to nutrient levels (Table 3). Concentrations of TRP, nitrate, and nitrite are higher in Fresh Lake than in any of the other ponds examined in this study. Fresh Lake also has higher levels of ammonia than the other ponds, with the exception of Little Lake. Potential sources of these nutrients include human and livestock waste, detergent runoff, biomass burning, and pesticide application. Nitrate and nitrite levels within Fresh Lake are still well below the U.S. EPA maximum contaminant levels of 10 mg/L and 1 mg/L, respectively (Sawyer et al., 2003). However, these preliminary findings still suggest that Fresh Lake is an ideal location for further study and monitoring of anthropogenic impacts on San Salvador's inland lakes.

Despite the fact that Fresh Lake exhibits less-than and/or near-marine salinities a majority of the time, it behaves more like the hypersaline ponds with regards to dissolved carbon dynamics. Table 3 displays the %TDOC data for Fresh Lake, which fall within the range of %TDOC levels of the hypersaline lakes presented in Table 1. Further, there is a relatively strong relationship between TDOC concentration and specific conductivity in Fresh Lake, even at less-than and near-marine conductivities (Figure 8). Initially, this may seem counterintuitive considering that this same relationship exists only for the hypersaline ponds (and not the marine ponds) included in the study. However, it does suggest that, in this unique system, the lack of ocean connectivity and tidal flushing is again driving both TDOC concentrations and salinity, even at less-than and near-marine salinities.

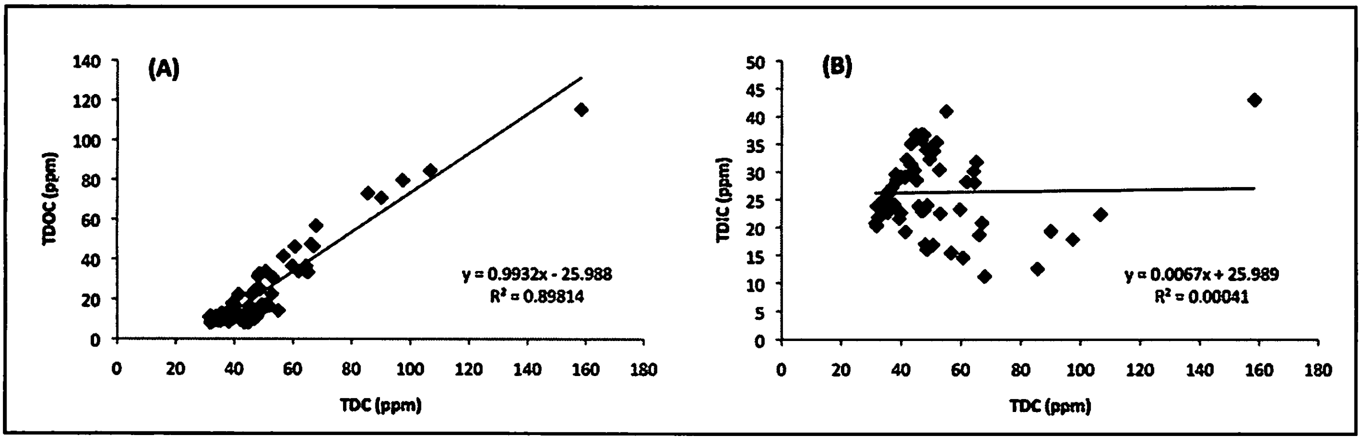


*Figure 7. (A) Regression of TDOC concentration and TDC concentration for hypersaline ponds, San Salvador ($R^2$=0.8981). (B) Regression of TDIC concentration and TDC concentration for hypersaline ponds, San Salvador ($R^2$ =0.0004).*

*Table 3. Average monthly nutrient concentrations and %TDOC for Fresh Lake, San Salvador. The North and South portions of the lake are separated by a manmade causeway.*

| | TRP mg/L PO4 | Nitrate mg/L NO3-N | Nitrite mg/L NO2-N | Ammonia mg/L NH3-N | %TDOC |
|---|---|---|---|---|---|
| **Fresh Lake** | | | | | |
| North | 0.23 | 1.2 | 0.019 | 0.02 | 58.93 |
| South | 0.22 | 1.3 | 0.029 | 0.03 | 61.99 |

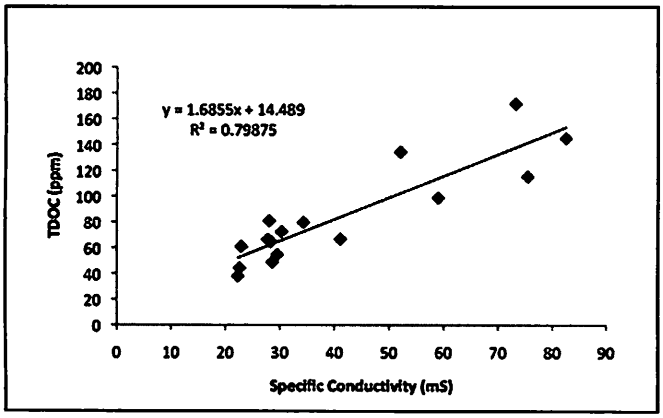


*Figure 8. Regression of TDOC concentration and specific conductivity for Fresh Lake, San Salvador (data set includes observations from both the North and South sections of the pond) ($R^2$= 0.7988).*

## CONCLUSIONS

Crescent Pond, Moon Rock Pond, Oyster Pond, and Mermaid Pond are classified as marine ponds. They experience a high degree of ocean connectivity as evidenced by their year-round near-ocean salinity levels. Dissolved carbon distributions within these ponds are dominated by inorganic carbonate dissolution.

Reckley Hill Pond, Osprey Pond, Salt Pond, and Little Lake are classified as hypersaline ponds. They experience a lesser degree of ocean connectivity and are more evaporation-dominated systems as evidenced by elevated and seasonably variable salinities. Dissolved carbon distributions in these ponds are dominated by the accumulation of organic carbon derived from surface runoff.

With the exception of elevated ammonia concentrations in Little Lake, both the marine and hypersaline ponds exhibit low-nutrient levels. However, nutrient runoff signals can be observed after significant rainfall events.

Fresh Lake is a unique inland water environment. It experiences salinities ranging from "fresh" to hypersaline and has elevated nutrient levels as the result of nearby human development. It behaves most similarly to the hypersaline ponds with regards to dissolved carbon dynamics.

## ACKNOWLEDGMENTS

The author would like to thank the Gerace Research Centre and The College of The Bahamas for their generous support of the Analytical Laboratory and this project, and special thanks to Tom Rothfus and Zipper for their field assistance.

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