HYDROCLIMATIC ANALYSIS OF A CARBONATE ISLAND POND THROUGH THE DEVELOPMENT OF A HYDROLOGIC LANDSCAPE UNIT MODEL

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Abstract: The purpose of this study is to develop a methodology that allows for an estimate of the hydroclimatic influence on an inland pond system on San Salvador, Bahamas. The methodology utilizes the Hydrologic Landscape Unit (HLU) model, a new conceptual model that offers hydrologists and water-resource managers more flexibility in representing the components of the unique and complex hydrologic systems of small carbonate islands. For this case study, a linear regression model was developed to empirically assess the HLU. This analysis separates tidal and climatic impacts on water levels of the pond and indicates that astronomical tides dominate, explaining 65% of the variance in pond water-level observations. Further, clusters of days with positive and negative outliers identified in the linear regression analysis were compared to precipitation events to determine response of water levels to climatic inputs. More than 78% of the days with positive outliers were associated with precipitation events and 83% of the days with negative outliers in Crescent Pond were explained by a lack of precipitation, signifying cumulative evaporation effects. Thus, while tidal variation is the principle forcing mechanism for Crescent Pond water-level variability, significant interaction between the atmosphere and the pond surface can be identified with this methodology at the daily to weekly time scale. Such a tool can be used by hydrologists and water-resource managers on small carbonate islands to assess the degree of freshwater input into inland water bodies and the appropriate time scale for potential freshwater harvest. [Key words: carbonate islands, hydroclimatology, pond systems, Caribbean.]

INTRODUCTION

The hydrology, particularly the hydroclimatology, of small carbonate islands is poorly understood. Reasons for this poor understanding include a lack of quality climatic data to define inputs and parameters of hydrologic systems (Granger, 1985; Kodama and Businger, 1998), inappropriate assumptions of homogeneous physical characteristics and processes (e.g., rainfall and weather patterns) on small carbonate islands (Gamble, 2004), a poor understanding of island geology (Vacher and Quinn, 1997), and improper application of traditional hydrologic models such as the Ghyben-Herzberg freshwater lens (Vacher, 1988). One potential tool for the assessment and modeling of hydroclimatic systems on small carbonate islands is

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the Hydrologic Landscape Unit (HLU) model (Gamble, 2004). The HLU is a conceptual model that defines a hydrologic system as a fundamental physiographic unit where landform, geology, and climate interact as a complete system of runoff (surplus), groundwater flux, and atmospheric flux (Winter, 2001). Such a model is particularly useful and appropriate for locations such as small islands, due to the flexibility in identification of inputs and parameters of these unique, "nontraditional" hydrologic systems. As compared to "traditional" watershed systems, small carbonate islands have no surface streams, and water tables are strongly influenced by tides and experience intense evaporation. Thus "traditional" hydrologic models are not appropriate for these areas.

The purpose of this study is to develop a methodology that utilizes the HLU model and offers an estimate of the hydroclimatic influence on an inland pond system on San Salvador, a small carbonate island in the Bahamas. This pond system is analogous to other poorly understood hydrologic systems on carbonate islands across the Caribbean and Pacific, and the results of this study are expected to offer information and a methodology useful to hydrologists and water-resource managers in these regions. Such knowledge can potentially assist in the incorporation of natural climatic variability into strategies of water-resource management, the greatest challenge to sustainable development in small island states (Nurse et al., 1998). In addition, this methodology has been developed to utilize minimal computer and software resources. Such a methodology can be implemented with relatively inexpensive field equipment and readily available spreadsheet software. Through such an approach, hydrologists and water-resource managers on small island states of the Caribbean and Pacific can complete initial assessment of hydrologic systems without a commitment of extensive resources. Such a minimal requirement in infrastructure is a clear advantage in a region with a history of inadequate financial resources for environmental management (Leatherman and Beller-Simms, 1997).

REGIONAL OVERVIEW AND STUDY AREA

The Bahamian Archipelago (Fig. 1) is recognized as one of the great carbonate provinces of the world (Carew and Mylroie, 1997). The archipelago trends southeast from Little Bahama Island to Great Inagua Island and spans 6° of latitude. Annual precipitation and temperature variability decrease from north to south along the archipelago. Climate patterns on the northern islands are linked to those of the southeastern United States, averaging 1300 mm/yr precipitation, while the southern islands are tropical dry, receiving ~750 mm/yr precipitation (Shaklee, 1996). Islands receiving less than 1100 mm/yr of precipitation possess isolated and scattered freshwater resources due to net annual losses of water from their hydrological system via evaporation (Cant and Weech, 1986; Whitaker and Smart, 1997).

San Salvador is a small "out-island" or "family-island" (an island with a small rural population in the nation's preiphery outside of Nassau) of the Bahamian archipelago located approximately 600 km east-southeast of Miami, Florida (Sealey, 1990; Fig. 1). The island is 155 km^2 in area and represents one of the small isolated carbonate platforms common to the southeastern Bahamas. The climate of San Salvador has been classified as the Köeppen Aw (Tropical Savannah) climate type,

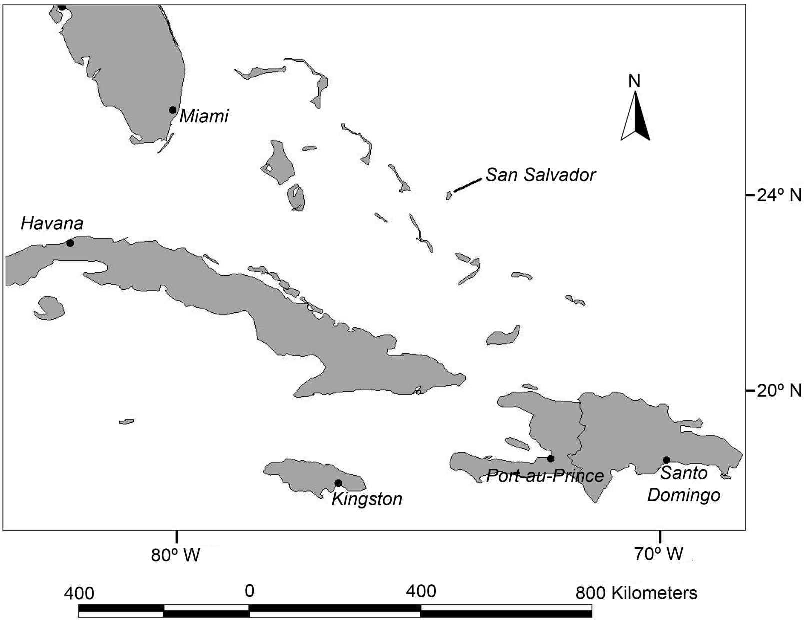

Fig. 1. Location of San Salvador Island, Bahamas.

which is characterized by dry winters and constant temperatures (Shaklee, 1996). The average monthly temperatures range between 22° and 28°C, with July and August as the high-sun period. The mean annual precipitation is 1007 mm with 40% of that precipitation falling during a three-month period (Sept.–Nov.) in the Atlantic hurricane season and another 20% accounted for in late spring/early summer (May and June). Annual precipitation is highly variable and can range from half to double the mean in any given year.

Five major landforms can be found on San Salvador, but three—dune ridge complexes (21% of island area), shallow surface water (22% of island area), and low plains (49% of island area)—dominate the island surface area (Wilson et al., 1995). The occurrence of surface-water bodies on this island, and across the Bahamas, is controlled by the structural geology (Vacher and Mylroie, 1990). These water bodies were formed as oölitic eolianite topography became inundated by sea-level rise. Two categories of surface-water bodies exist on these islands—lakes with limited exchange to groundwater and lakes with open exchange to groundwater or marine sinks through a conduit (Davis and Johnson, 1988). It is hypothesized that lakes with limited groundwater exchange are dominated by variability introduced through climatic inputs and parameters, whereas water bodies with open exchanges have variability that mimics tidal fluctuations (Davis and Johnson, 1988). Of the two types of surface-water bodies, lakes with open exchange are the least understood components of the Bahamian hydrologic landscape, particularly in terms of the degree to which climatic variability is superimposed on astronomical tidal variations.

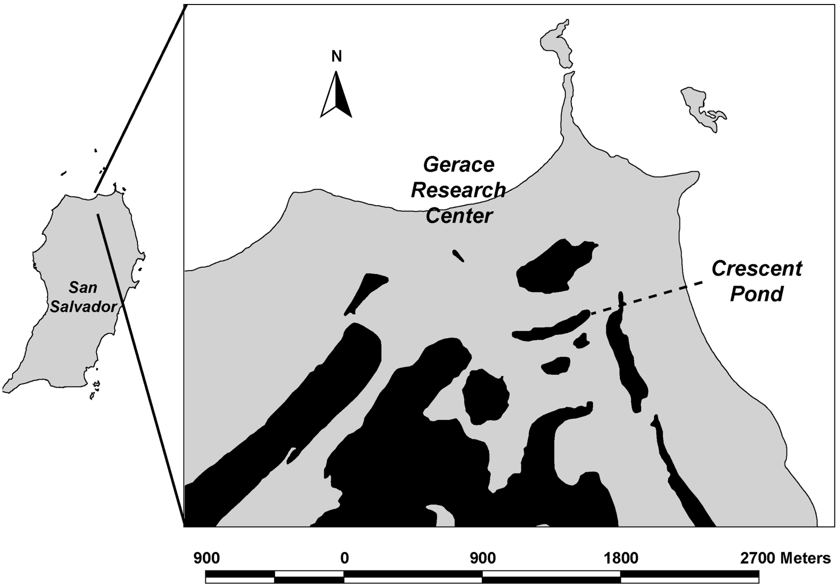

Fig. 2. Location of the study site, Crescent Pond, on San Salvador Island. The grey shaded area represents land and black shaded areas represent inland water bodies (Robinson and Davis, 1999).

The focus of this study, Crescent Pond, is an inland pond that exchanges significant amounts of water via a conduit, or lake drain, between the pond and a marine source/sink (Mylroie, Carew, and Vacher, 1995; Fig. 2). Surface streams are not present in the Crescent Pond drainage basin, but seeps have been identified along the shoreline. Given the small number and size of these seeps, the overall contribution of these features to pond water-level fluctuation has been characterized as minimal (Davis and Johnson, 1988). Previous research has indicated that water levels in this pond fluctuate in semi-diurnal patterns due to tidal influence, but variability in pond level associated with hydroclimatic processes has yet to be studied or quantified (Davis and Johnson, 1988). The pond is approximately 90 m long and 35 m wide and reaches a depth of 3 m. It represents a landform common to the Bahamian archipelago and many other Caribbean and Pacfic small island states.

THE HLU FRAMEWORK: CONCEPTUAL DEVELOPMENT

Previous research of San Salvador has identified six hydrological landscape components (Davis and Johnson, 1988). The first and dominant component is the astronomical tide. Tidal oscillations control the halocline position, mechanical forces that mix fresh and salt water, and base level head changes that result in horizontal flow through conduits (Mylroie, Carew, and Vacher, 1995). San Salvador experiences a mixed semidiurnal microtidal regime where the astronomical tides range from 0.3 m to 1 m (Davis and Johnson, 1988).

The second and third components of the hydrologic landscape, evaporation and precipitation, represent climatic inputs and outputs to and from the hydrologic landscape. For this study area, the annual potential evaporation ranges between 1250 and 1375 mm/yr (Sealey, 1994). Precipitation is the dominant source of freshwater for the hydrologic landscape and ranges 500 to 2000 mm/yr on San Salvador.

Groundwater, the fourth component of the hydrologic landscape, ranges from fresh to hypersaline (>90 psu). Conventional theory suggests that the thickness of the freshwater lens is 40 times the height of the fresh water above sea level due to the difference in the density of fresh and saline water (Davis and Johnson, 1988; Erdman et al., 1996; Vacher, 1997; Fetter, 2001). Accordingly, for every unit above sea level that freshwater exists, 40 units of freshwater should be below sea level, assuming a homogeneous matrix and no mixing. On San Salvador, the freshwater lens deviates from this ideal geometry due to variability in porosity and permeability, conduit locations, proximity of surface water, aquifer flow, coastline configurations, depositional structures, and freshwater input (Vacher and Wallis, 1992; Bukowski et al., 1998). The major controls of freshwater lens geometry for an island such as San Salvador have been identified as climate regime and hydrological properties of the island's lithology, underscoring the importance of understanding the hydroclimatic aspects of these systems (Vacher, 1988).

Inland lakes, the fifth component of the San Salvador hydrologic landscape, are structural features of the landscape (Vacher and Mylroie, 1990). These water bodies are up to 3 meters deep and develop in topographic lows between parallel dune ridges. Eogenetic karst features modify the drainage areas, resulting in the absence of surface streams while retaining runoff pathways. Inland lakes exchange water through direct flux driven by atmospheric processes, indirect input from seeps and infiltration, and conduit flow, or some combination of the three. Accordingly inland lakes have been classified into two types—those with open exchange with groundwater or marine sources and those with limited exchange with groundwater or marine sources (Davis and Johnson, 1988). Lakes with open exchange maintain nearly constant brackish to marine salinities (25–35 psu), have clear water, and temperatures similar to the ocean. Lakes with limited connections have salinities that exceed 90 psu during the year, brownish to reddish murky water, temperatures in excess of 30°C, and support colonies of cyanobacteria (Neumann et al., 1988; Pinckney et al., 1995).

Conduits and blue holes are the final components of the San Salvador hydrological landscape. Blue holes result from vertical karst development and are treated as a special case due to the complex history of formation (Mylroie, Carew, and Moore, 1995). Conduits are horizontally developed karstic pathways that have been recognized as being efficient transmitters of tidal signals and groundwater flow beneath the island's landscape (Kunze and Quick, 1994).

A conceptual HLU of the Crescent Pond landscape can be constructed through a systematic combination of these six hydrologic landscape components (Fig. 3). The land-surface form is represented by the surface water and surrounding topographic depression. The HLU geology is represented by groundwater interaction, including water maintained by the aquifer matrix, as well as any structural geologic features that affect flow (i.e., conduits and catchment epikarst). In addition, the HLU geology component represents astronomical tides through groundwater table and conduit flux. The HLU climate portion is represented by two fluxes: precipitation and

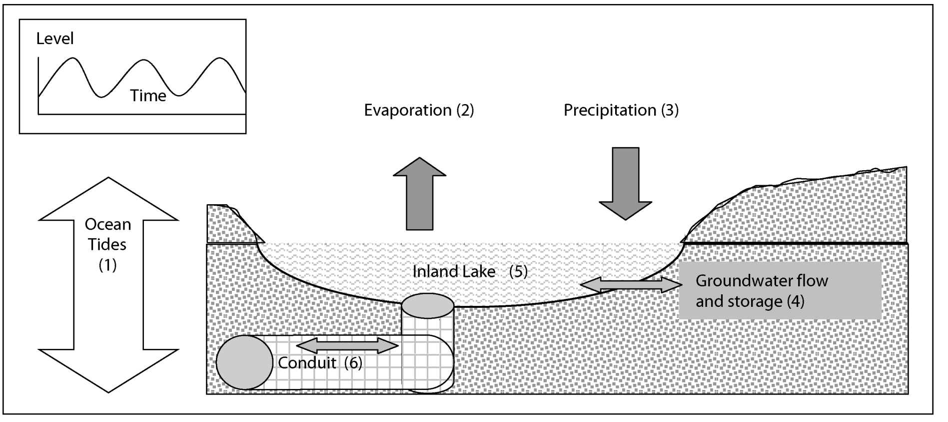

Fig. 3. Schematic drawing of the San Salvador Hydrologic Landscape Unit model including the six components: astronomical tides, evaporation, precipitation, groundwater, inland lakes, and conduits.

evaporation. Further, this HLU can be applied specifically to Crescent Pond by utilizing the following assumptions that characterize the interaction of the three components as a whole at this specific location. These assumptions were constructed through a combination of information from available literature and direct observation of the inland lake during field research completed from 1997 to 2005. (1) Crescent Pond maintains an open exchange with a marine source through a conduit in the center of the pond. (2) Input of water to Crescent Pond occurs discretely as precipitation events and continuously as conduit flux. (3) Precipitation is quickly routed to Crescent Pond as a combination of catchment area runoff, surface infiltration, and seep flow. (4) Evaporative flux occurs with variable intensity from both the land and water surfaces of the Crescent Pond/watershed. (5) Hydrostatic pressures produced by astronomical tides drive conduit exchange between Crescent Pond and the marine sink. (6) Crescent Pond's volume is in dynamic equilibrium with the surrounding environment and hydrologic conditions.

Based on these assumptions, the authors hypothesize that tidal patterns should effectively propagate through the conduit and dominate Crescent Pond water levels. Further, imprinted over these primary tidal signals will be secondary responses to climate events indicating freshwater input from non-tidal conduit–derived sources.

THE HLU FRAMEWORK: EMPIRICAL ASSESSMENT

An empirical assessment of the HLU model can be performed through a linear regression analysis of predicted tide levels for San Salvador and Crescent Pond water levels. Specifically, estimates of tide levels for San Salvador were used as the independent variable in the regression analysis, with hourly observations of Crescent Pond water levels as the dependent variable. Because San Salvador does not have a tidal observation system, tidal predictions for Settlement Point, Grand Bahama, as provided at the NOAA National Ocean Service Center for Operational Oceanographic Products and Services website (http://co-ops.nos.noaa.gov), were used as estimates for San Salvador tides. The Settlement Point tide predictions were deemed an accurate estimate of San Salvador tides because the authors monitored tidal levels in Graham's Harbour, San Salvador, for a short period of time and these observations correlated best with Settlement Point as compared to the other Bahamian tidal prediction locations. In addition, residents of San Salvador and researchers at the College of the Bahamas' Gerace Research Station on San Salvador concurred that Settlement Point is the best available predictor of tides for San Salvador.

Water levels for Crescent Pond were recorded at hourly intervals with a Global Water Level wl 14 data logger at the research site for four time periods (1/6/01–3/2/01, 3/13/01–5/12/01, 8/9/01–10/12/01, and 10/27/01–12/29/01), producing 5096 hourly observations. This instrument utilizes a transducer to measure the pressure of a water column. With calibration, the water-column height is determined as a function of pressure. The data were downloaded using Ezlevel™ software, supplied by the manufacturer, and a field laptop. A continuous record could not be recorded due to the need for removal of the equipment for periodic maintenance and calibration.

Initial examination of the data indicated that the peaks of each tidal phase in Crescent Pond occurred 2.5–3 hours after peaks in the tidal estimates for San Salvador. Such differences in timing of astronomical tidal phases and pond water levels have been reported in previous research on inland ponds, with the lags explained by a difference in elevation of the pond water surface and higher high and lower high tide and the resistance to water flow in conduits (Davis and Johnson, 1988). Correlation coefficients were calculated to determine the degree of association between the San Salvador tidal estimates and Crescent Pond water levels over a range of lag intervals (–1 hr to +4 hr.). The highest correlation value (r = .86, remaining lags r = .1 to .5) indicated that Crescent Pond's tide variations occurred at a three-hour lag after the estimates of San Salvador's tidal cycle.

Further, the tidal range in Crescent Pond was found to be 30% less than the San Salvador tidal estimate range. Thus, in order to normalize for the differences in physical measurements of astronomical and pond tidal range, each of the time series was normalized by transforming raw data into z-scores (observation minus the mean divided by the standard deviation). Z-scores have been commonly used in statistical analysis of climatic and hydrologic data to standardize for different sample variance. For example, Hirschboeck (1987) and Gamble and Meentemeyer (1997) used z-scores to standardize stream discharge data, allowing for comparison between watersheds. Jones et al. (2003) also indicated that atmospheric pressure measurements are to be standardized before use in the calculation of the North Atlantic Oscillation Index, in order to avoid domination by the northern node in analysis due to its greater variability. The linear regression completed in this analysis used z-scores of the Settle Point predicted tide time series as the independent variable and z-scores of a three-hour lagged Crescent Pond water level as the dependent variable (Fig. 4).

Upon completion of the regression analysis, any variation from the linear model (i.e., high positive or negative residuals) was considered to represent non–tidal-induced water-level variation. Residuals in excess of one standard deviation of the

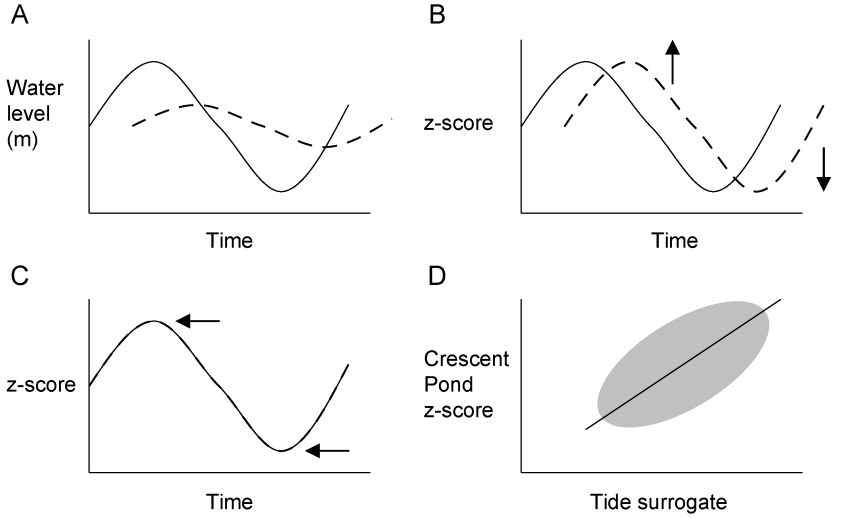

Fig. 4. Data normalization steps required before regression analysis. (A) The raw data, with the solid line representing the Settlement Point predicted tide data and the dotted line representing the water levels observed in Crescent Pond. (B) The normalization of the estimated tide and Crescent Pond water-level data (*z*-score) to compensate for the differences in raw data range. (C) The three-hour forward shift of Crescent Pond water levels with respect to the estimated San Salvador tide data. (D) The regression between Crescent Pond value and tide data.

mean residual value were classified as outliers. Standard deviation was used to identify the outliers because it offers a conservative approximation of the greatest deviation from the model and can also serve as an indicator of the appropriateness of the linear model as a predictive model. If the residuals are not normally distributed (32% of all residuals are greater than one standard deviation from the mean), a basic assumption of the linear model is not met and the model may not be appropriate as a predictive tool. This inappropriateness may be deemed as a negative in prediction. However, such a finding can be useful in that it provides evidence that other factors beyond hydroclimatic processes are influencing pond water level, assisting in the construction of a more appropriate model. In the case of Crescent Pond, a non-normal distribution of residuals could suggest that another process, such as groundwater addition to the pond, may be impacting pond water levels.

To assist in interpretation of outlier occurrence in terms of the physical processes of Crescent Pond HLU, the outliers were then aggregated by continuous occurrence across two or more tidal cycles into days of outlier occurrence. Such an aggregating of outliers was necessary since rainfall data were only available in the form of daily totals. By aggregating the outliers into days of occurrence, the hourly water-level data become compatible with the rainfall period of observation. The days containing outliers were then classified into one of four possible Hydrologic Response Types that were defined by the occurrence of precipitation or evaporation during a 24-hour period (Fig. 5). Hydrologic Response Type I represents the occurrence of a cluster of positive outliers in conjunction with a rain event(s). Hydrologic Response

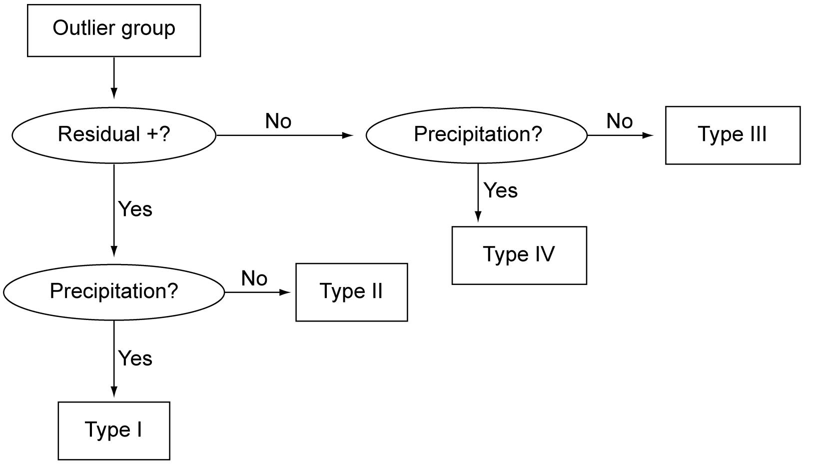

Fig. 5. The Hydrologic Response Type classification decision tree.

Type II represents a cluster of positive outliers that occurs in the absence of a rain event(s). Hydrologic Response Types III and IV are responses represented by clusters of negative outliers; Type III occurs with no rain events and Type IV occurs in conjunction with a rain event(s).

Hydrologic Response Types I and III represent the direct relationships between Crescent Pond water levels and climatic processes. That is to say, during and after precipitation events, increased water levels should occur in Crescent Pond (Type I). Conversely, during lengthy periods without precipitation, decreased water levels are expected in Crescent Pond (Type III). Hydrologic Response Types II and IV represent less direct relationships between Crescent Pond water levels and components of the HLU. Type IV represents precipitation events, but this model assumes that water levels are always in equilibrium with input and output values. Thus, if conduit exchange does not "reset" the cumulative effects of climate with each change of the tide cycle, the landscape will respond over longer climatic scale periods (weeks, months, or seasons) as opposed to the 24-hour period of classification used in this study. For instance, during the dry season, small daily evaporation values can contribute to larger long-term deficits in the San Salvador hydrologic landscape. So precipitation would not necessarily create positive residuals in such a drought period; rather the rain may reduce the negative value of an outlier during a dry period, allowing for the occurrence of precipitation and negative residuals at the same time (Type IV).

Hydrologic Response Type II (positive outliers in the absence of rain), the authors believe, is the result of some other interactions not accounted for in this assessment of the conceptual HLU. Such interaction and processes may include other atmospheric interactions (i.e., wind causing changes in pond water level), seasonal climate trends, or structural features of the Crescent Pond groundwater interface that are not accurately modeled by the linear regression techniques or the data utilized in this analysis.

Table 1. Regression Results for Linear Model of Normalized Crescent Pond Water Levels and Tidal Estimates for San Salvador, Bahamas[a]

Sample	Dates of observation	Regression model	r^2 value
1	01/06–03/02/2001	$Y = .8608x$	.7409
2	03/13–05/12/2001	$Y = .7722x$	.5963
3	08/09–10/12/2001	$Y = .8378x$	.7018
4	10/27–12/29/2001	$Y = .7922x$	.6276

[a]All regressions significant at the 95% confidence interval.

Table 2. The Frequency of Positive and Negative Residuals Occurrence During Flood and Ebb Tide in Crescent Pond

	Flood tide	Ebb tide
Positive residual frequency	403	286
Negative residual frequency	153	606

RESULTS AND DISCUSSION

Linear regression model analysis indicates that estimates of San Salvador's tides corrected for a three-hour lag explain 59% to 74% of the variance in Crescent Pond water levels for the four data collection periods (Table 1). It should be noted the observation periods with the lowest r^2 values were the periods that experienced the heaviest rain (3/13/01–5/12/01, $r^2 = .60$ and 10/27/01–12/29/01 $r^2 = .62$) and thus represent the times when a linear model of tide and pond levels is expected to perform most poorly. The four linear regression models indicate that 26% (or 1498) of the residuals vary more than one standard deviation from the residual mean and are labeled outliers. The 26% is lower than the expected 32% with normally distributed residuals. This discrepancy indicates that this linear model is not appropriate for predictive purposes. However, because the difference is not large (only 6%), the linear model can still be used for descriptive purposes with the caveat that attempts at prediction of Crescent Pond water level require a model that incorporates a greater number of physical processes.

Positive outliers were found to occur predominantly during flood tides of the semi-diurnal pattern; where negative outliers were found predominantly on ebb tides, especially the lowest low tide phase of a given day (Table 2). When positive outliers occurred during ebb tide, they most often occurred during the highest low tide of a given day (Fig. 6). Clusters of positive outliers occur more frequently (15 times) than negative outliers (12 times). The former averaged 3.7 tide cycles and clusters of negative outliers averaged 6.9 tidal cycles (Table 3).

A total of 163 days during the study period had a series of outliers across two or more tidal cycles. The classification of these days into Hydrologic Response Types yielded 49 days with positive outliers and precipitation (Type I), 24 days with positive outliers and no precipitation (Type II), 41 days with negative outliers and no precipitation (Type III), and 47 days with negative outliers during precipitation

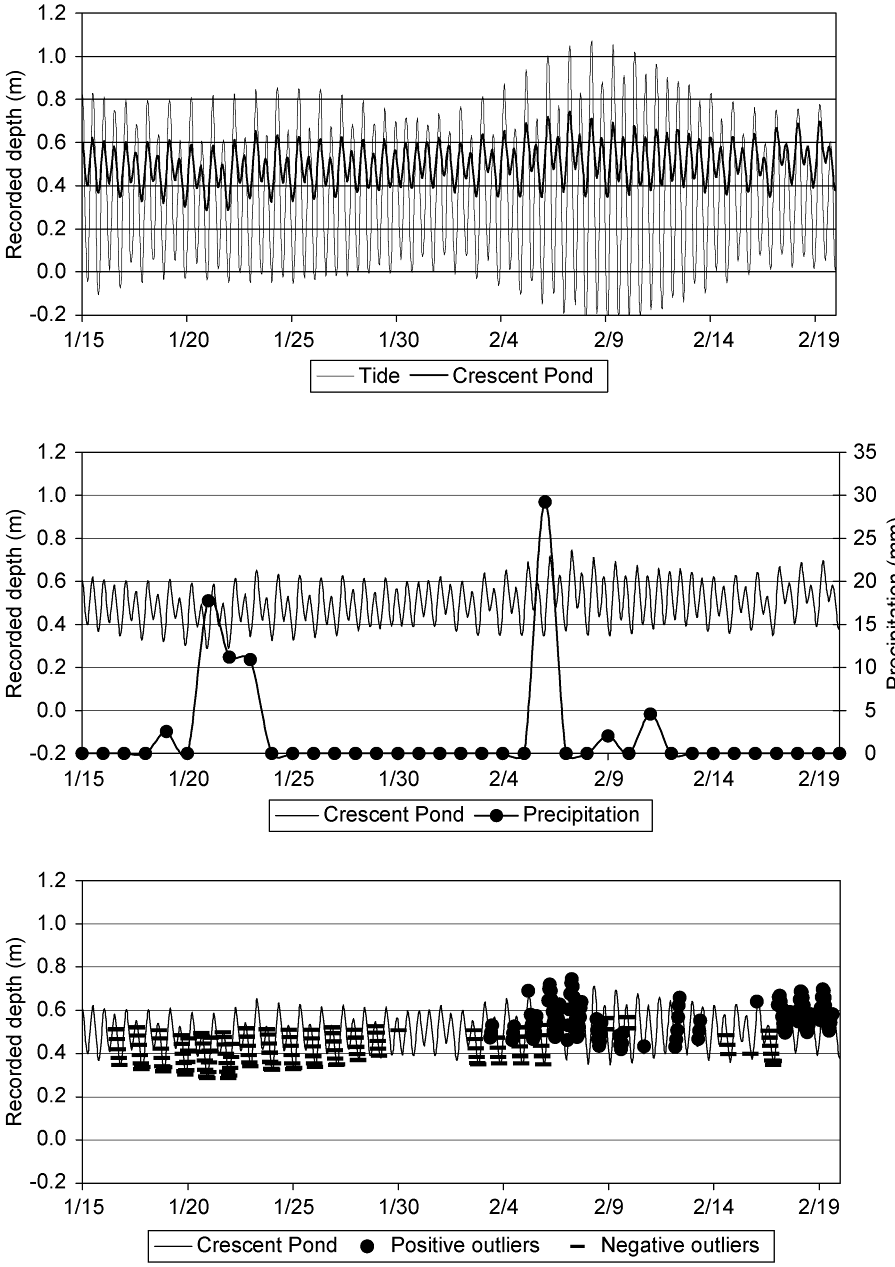

Fig. 6. Example of time series of estimated San Salvador tides, Crescent Pond water levels, precipitation amounts, positive residuals, and negative residuals.

events (Type IV; Table 4, Fig. 7). In all instances except one, outlier days are clustered together, representing a string or cluster of a specific Hydrologic Response Type. A total of 26 clusters were represented in the study period, with the overall

Table 3. The Frequency Outlier Clusters and the Average Tidal Length of Each Cluster

	Frequency	Average tidal cycle duration
Positive outlier clusters	15	3.7
Negative outlier clusters	12	6.9

Table 4. Descriptive Statistics of Outlier Days by Hydrologic Response Type

	Number of outlier days	Number of outlier day clusters	Average outlier day cluster length	Maximum outlier day cluster length	Minimum outlier day cluster length
Hydrologic Response Type I	49	10	4.9	9	2
Hydrologic Response Type II	24	3	8.0	12	3
Hydrologic Response Type III	41	6	6.8	17	1
Hydrologic Response Type IV	47	7	6.7	14	2

average length of a cluster being 6.7 days, the maximum length 17 days, and the minimum length one day. A frequency analysis indicates 69% of the clusters were a week or shorter, 27% are between one and two weeks in duration, and 4% were longer than two weeks. Thus, it can be reasonably assumed that any direct hydro-climatic influence on Crescent Pond will manifest itself on a daily to weekly time scale.

In terms of each Hydrologic Response Type, the longest average outlier day clusters occurred with Type II responses, with 8.0 days, followed by Type IV, Type III, and Type I (7.0, 6.8, and 4.9, respectively). The greatest range in outlier day clusters occurs with the Type II response, with a 16-day range (maximum 17 days and minimum 1 day), followed by Types IV, II, and I (clusters average 4.9 days with a maximum of 12 and a minimum of 2 days). There seems to be no clear pattern in difference of outlier day cluster duration and variance in terms of positive (Types I and II) versus negative outliers (Types III and IV) and wet (Types I and IV) versus dry outliers (Types II and III). However, given the small number of clusters, 26, and days without observations in January, April, May, June, August, and September, such an interpretation may not be physically accurate.

Closer examination of the Hydrologic Response Type IV clusters indicates that four Type IV clusters change from large negative outliers to smaller negative outliers. These four clusters include 39 of the 47 Type IV days and occurred on 1/16–1/24, 8/10–8/19, 11/18–11/20, and 11/26–12/7. In the first two clusters, negative outliers are distributed on rising and falling tide conditions and precipitation occurs midway through the cluster, at which time the outliers become less negative. The decrease in negative values takes place within one tidal cycle and then a new pattern is established with negative residuals occurring preferentially on falling low-low tide. In the last two clusters of Type IV outliers, negative residuals occur during the lowest ebb tide and precipitation occurs at the end of the cluster interval. After the precipitation event, and within one tidal cycle, the negative residuals are no

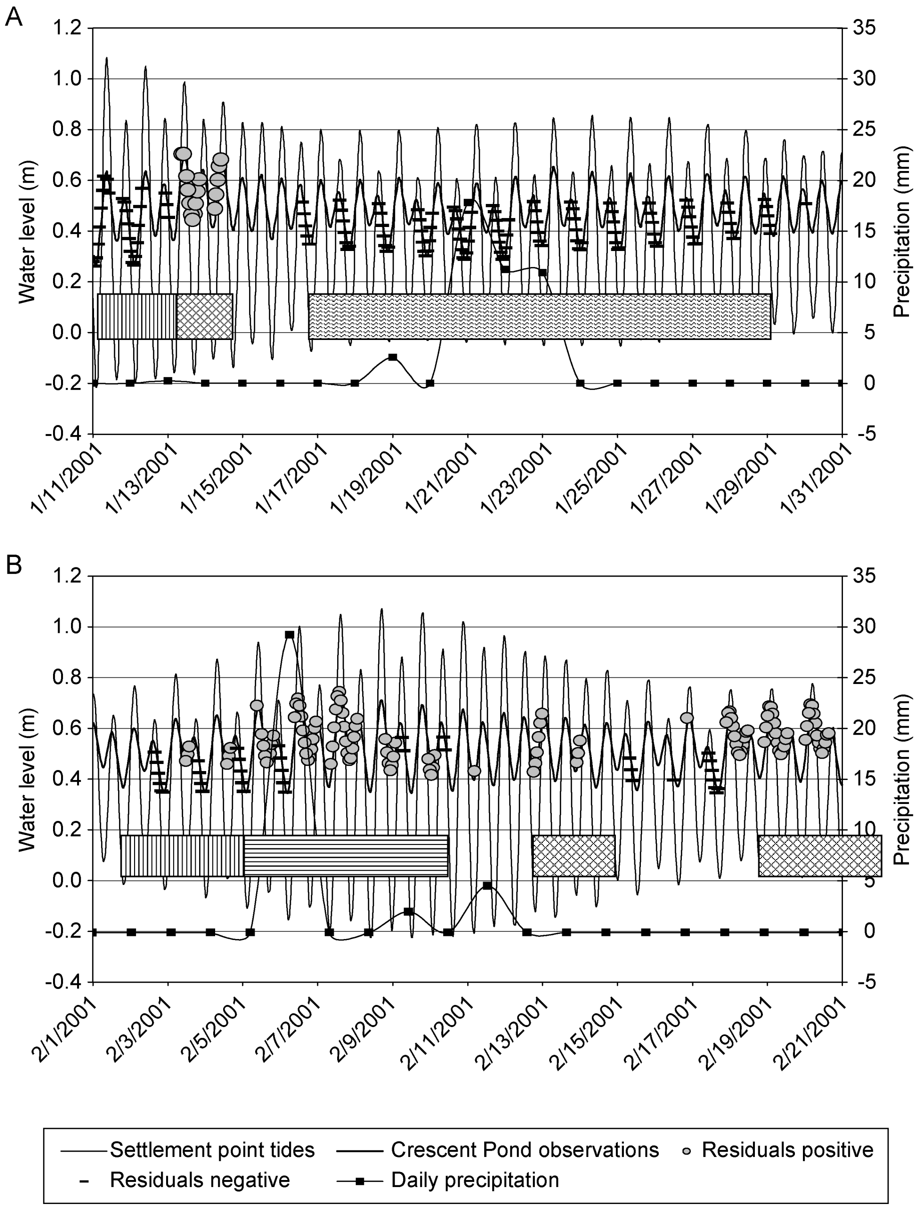

Fig. 7. Crescent Pond water-level record for (A) January or (B) February 2001 with Hydrologic Response Type. Boxes represent Type I (horizontal), II (cross hatches), III (wave), and IV (vertical) hydrologic responses as determined by the residual analysis.

longer present. In both cases, the water level of Crescent Pond changed from below predicted values before the rain to values that were "more normal" after the rain.

Such patterns indicate that outliers in Hydrologic Response Type IV represent the same processes as Response Type I (the increase of water level due to a precipitation event); thus these four clusters of Response Type IV outlier days can be combined with Type I to represent an increase in Crescent Pond water level due to net water addition through precipitation. The combination of these Type I and IV clusters results in 88 outlier days (49 Type I and 39 Type IV) being associated with net water addition by precipitation or 78% of outlier days linked to precipitation. This reclassification also increases to 83% the percentage of days with negative outliers (Type III and the remaining Type IV outliers) that can be explained by evaporative water loss.

Based on this quantitative assessment of the Crescent Pond HLU, the authors hypothesize that beyond tidal influences, the water levels of the Crescent Pond are affected to the greatest extent by input from precipitation and extraction through evaporation. Net additions of water to the landscape occur during precipitation events and result in water levels that are higher than predicted by astronomical tides. For a short time after precipitation events (daily to weekly time scales), the addition of water to the landscape via surplus and infiltration within the catchment area produces short, frequent, positive outlier clusters. Net losses of water from the landscape occur mainly through evaporation. The lengthy intervals between precipitation events contribute to drought conditions, allowing small daily losses of water to accumulate up to the monthly time scale, and create lower water levels in Crescent Pond, or the less frequent, longer, negative outlier clusters in this model.

This hydroclimatic variability is imprinted over Crescent Pond water-level variation caused by continuous adjustment to the ubiquitous forcing of astronomical tides. This underscores the dominance of the well-developed open connection between the pond and a marine source/sink. However, the balanced distribution of positive residuals with respect to tidal stage (58% during flood, 42% during ebb tide) suggests that the processes producing positive responses are independent of the tide. This result is corroborated by the continuity of positive residual patterns throughout tidal phases as compared to the intermittency displayed by negative residuals. Negative residual occurrence is not an equal distribution with respect to tidal stage (20% during flood, 80% during ebb tide) and suggests that tidal processes may compound this "negative" response.

CONCLUSIONS

For this study, a HLU was proposed as a qualitative model to assess the hydroclimatology of Crescent Pond on San Salvador, Bahamas. This model was empirically assessed through an attempt to separate tidal and climatic impacts on water levels of the pond with a linear regression model. Astronomical tides dominated water levels in the pond, explaining approximately 65% of the variance in water-level observations during the study period. Days with positive and negative outliers identified through the linear regression analysis were compared to precipitation events to determine the response of the water levels to climatic inputs. Each outlier day was classified as one of four possible climatic response types. Response Types I and III represent direct relationships between precipitation and water levels. Types II and IV demonstrate relationships between evaporation and water levels. Type IV responses were reevaluated because of their association with precipitation events;

four clusters of outlier days indicated the presence of interactions similar to Type I, and were reclassified as such.

When positive outliers were identified for a given day (Types I and IV) in Crescent Pond, more than 78% of these days were associated with precipitation events. When Crescent Pond experienced negative outliers (Types II and III), 83% of the days were explained by lack of precipitation, signifying cumulative evaporation effects. Thus, while tidal fluctuation is the dominant mode of variation in the Crescent Pond HLU components, it appears that atmospheric interactions imprinted over astronomical tidal variation may be a significant source of variability in Crescent Pond on a daily to weekly time scale.

Future directions in this research will include the accommodation of more physical processes in the empirical assessment through multiple regression or other multivariate models and techniques. This model may also be applied to other landscape features on the island, such as lakes without a conduit or groundwater exchange. In this respect, it is possible to build a larger landscape model from smaller specific units. Further, responses identified in this study may be catalogued and compared to responses created by extreme events such as hurricanes, record amounts of rainfall, or long droughts. Such information can be used by water-resource managers on small carbonate islands to assess variation in water availability on weekly and daily time scales, allowing for more efficient, sustainable water-resource development.

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