A Hydrogeologic Model of Samana Cay, Bahamas, and Its Implications for the Columbus Landfall Question

by José J. Valdés[a]

Abstract

Samana Cay, Bahamas, is a leading candidate among the sites proposed as the first landfall of Columbus in the New World. One main point of contention against this identification is that Samana lacks a feature matching the *laguna* observed by Columbus in the middle of his landfall island. However, this argument has failed to consider the paleogeographic aspects of the problem. A hydrogeologic computer model suggests the existence of a sizable surface-water feature in the medial interior of Samana Cay under conditions theorized to have been present when Columbus arrived in the Bahamas. This feature may correspond to the *laguna* described by Columbus.

Introduction

The identity of Christopher Columbus's first New World landfall, known to the Lucayan Indians as *Guanahani* and christened by him *San Salvador*, has remained enigmatic for most of the past 500 years. Samana Cay (also known as Atwood Cay), an island in the central Bahamas (Figure 1), was initially proposed in 1882 by G. V. Fox as the first landfall. More recent work, especially by Judge (1986), has established Samana Cay as one of the leading candidates in the landfall debate (Dor-Ner and Scheller, 1991; Keegan, 1992a).

One main issue of the debate has been the identification of the feature on *Guanahani/San Salvador* that Columbus described in his onboard log as "a very large *laguna* in the middle" of the island (from the Dunn and Kelley, 1989 transcription) (Valdés, 1994). The most favored interpretation of this description is that, when observed by Columbus, *Guanahani/San Salvador* possessed a pond or lake in its central interior. The fact that Samana Cay (Figure 2) is devoid of any surface-water body meeting Columbus's description has been a principal point of contention regarding this proposed landfall (Obregón, 1987; Taviani, 1987; Barreiro-Meiro, 1987).

However, comparisons between the current features of the island and those described by Columbus presume that conditions have remained unchanged during the past 500 years. Paleogeographic analysis (Valdés, 1994) suggests that significant climatic and environmental changes have occurred in the Bahamas during the past 500 years. In particular, it is likely that precipitation and sea level were higher during aboriginal times on the islands.

A numerical computer model has been created to evaluate the effects of such conditions on the hydrologic system of Samana Cay. Prior to discussing the model, the necessary hydrogeologic and hydroclimatic considerations and assumptions will be examined.

Hydrogeologic Setting

Fresh ground water in an oceanic island aquifer takes the form of a lens floating on the denser saline water that underlies and surrounds the island. Surface-water bodies may occur where the water table is at a higher elevation than the land surface.

No specific hydrogeologic data exist for Samana Cay except for the general observation that "[g]ood water can be obtained by digging wells" (USNHO, 1917, p. 143), although a well in the island's seasonal settlement has been tested at 2,070 ppm chloride (Sealey, 1991). However, the hydrogeology of the Bahama islands is basically similar and consists of a principal aquifer, the Lucayan Limestone formation, and minor localized aquifers in shallow unconsolidated sands of lower permeability (Cant and Weech, 1986; Cant, 1988; Little et al., 1977). The base of the Lucayan Limestone tends to represent the maximum thickness to which the fresh-water lens can develop, as deeper units are too cavernous to prevent fresh and saline waters from freely intermixing (Cant and Weech, 1986). The thickness of the Lucayan at Samana Cay is not known, but, based on data from Cant and Weech (1986) for neighboring islands, it is likely in the range of 83 to 116 ft.

The permeability of the limestone is very high and accounts for the lack of rivers, streams, and significant runoff on the islands (Tarbox, 1987; Little et al., 1977). Data for Great Exuma (Wallis and Vacher, 1990), Mayaguana, and San Salvador (Watling) Island (Klein et al., 1958) suggest that 165 to 330 ft/d is a representative range of values for the hydraulic conductivity of the limestone aquifer.

Topographic data for Samana Cay are available from maps published at scales of 1/10,000 (10-ft contour interval) (DLS, 1971) and 1/25,000 (20-ft contour interval) (DLS, 1972). The

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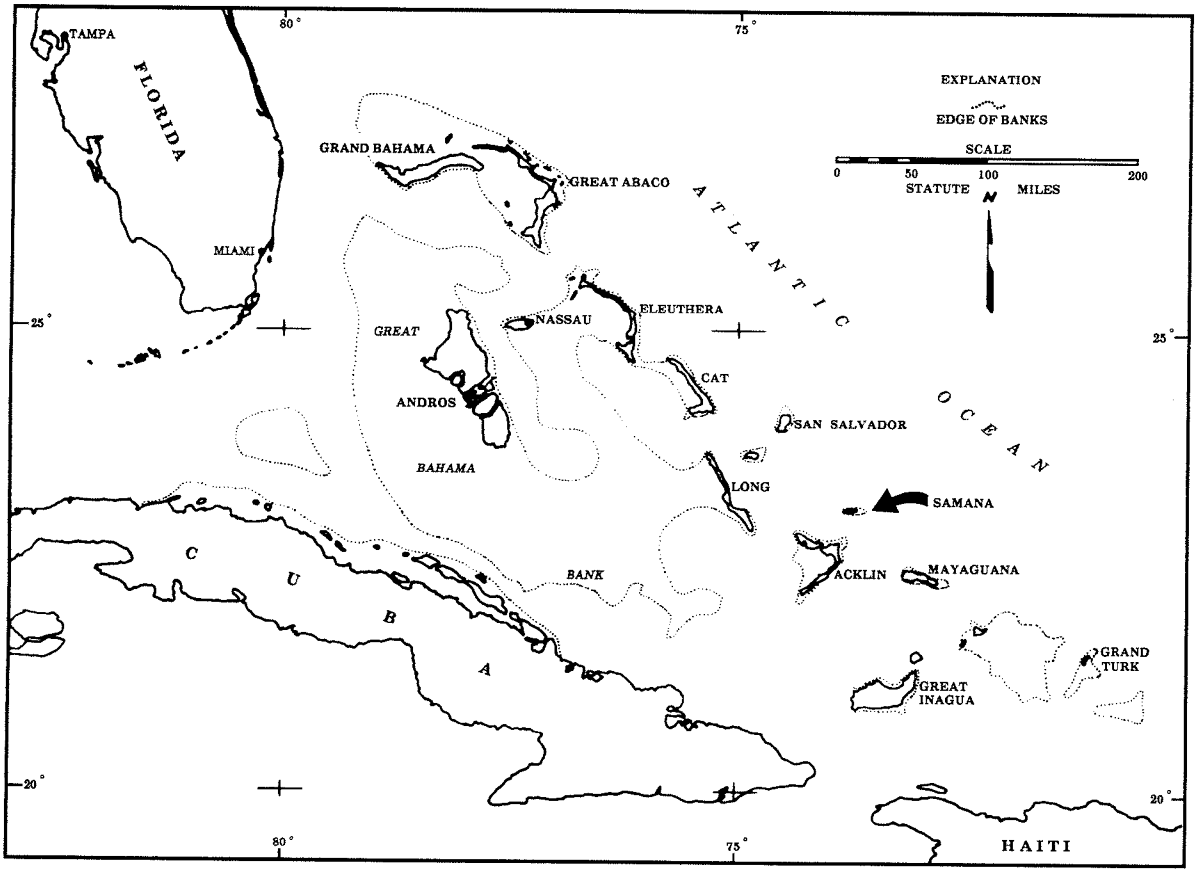

Fig. 1. The Bahama Archipelago. Samana Cay, rather than the island named San Salvador by the Bahamian goverment in 1926, may be the true Columbus landfall.

control-point and contour elevations shown on these maps were utilized to draw the closed contours with an altitude value of 5 ft above mean sea level shown in Figure 2. Inside the basinal areas enclosed by these contours are the lowest elevations in the interior of the island, ranging down to 1 ft above mean sea level. It is within these areas that inland surface exposures of the water table would be likely to occur if water levels were sufficiently high.

An important hydrogeologic consideration is that sea level in the Bahamas 500 years ago appears to have been 1.7 ft higher than at present (Lind, 1969a, b; Valdés, 1994). This condition would result in an upward shift of the fresh-water lens and the water table by an equal amount.

Rainfall and Evapotranspiration

Present Conditions

Mean annual rainfall for Samana Cay is estimated to be about 37 in./yr. This estimate is based on inverse-distance weighted averages of rainfall for neighboring islands (Little et al., 1977) and agrees with the isohyetal map of the Bahamas presented by Keegan (1992b, p. 29).

Fig. 2. Map of the physical features of Samana Cay. The dashed lines represent +5-ft elevation contours enclosing inland basinal areas.

Potential evapotranspiration (PET) for Samana Cay has been estimated using the Thornthwaite method (Dunne and Leopold, 1978, pp. 136-138) and monthly inverse-distance weighted averages of temperature for neighboring islands (Ministry of Education, 1985, p. 36). The PET value thus calculated is 57.5 in./yr.

Several ponds occur around the periphery of the island (Figure 2). These seem to correspond to the Bahamian salt ponds described by Little et al. (1977) and probably represent coastal topographic depressions where surface exposures of the water table occur. Assuming full potential evapotranspiration in these ponds, comparison of the PET and rainfall values indicates that there is a recharge deficit of -20.5 in./yr in the areas occupied by them.

Due to the small field capacity of Bahamian soils, actual evapotranspiration (ET) from soil-covered areas of the islands is expected to be significantly less than PET (Wallis and Vacher, 1990). Theoretical quantitative estimation of ET is difficult because this parameter is partly a function of available water, plant cover, and solar radiation. However, the relation of these factors to rainfall indicates that an underlying relation exists between ET and rainfall. Extending the work of Giusti (1978) in this area, Figure 3 was prepared using data from the region of the American tropics/subtropics. The ET and rainfall data used for this plot were derived from water budget studies at the different locations indicated. The curvilinear relationship shown has a coefficient of determination of 0.77 and is described by the equation

$$ET = P/(0.01246P + 0.6615) \qquad (1)$$

where ET and P are annual evapotranspiration and precipitation in inches, respectively. Based on this equation, a value of 78% is predicted for the ratio of ET to P given 50 in. of annual rainfall, which compares favorably with the value of 75% for ET/P cited by Little et al. (1977, p. 35) for Bahamian islands with this much precipitation.

Given 37 in. of mean annual ranfall for Samana Cay, an ET value of 33 in./yr is obtained from equation (1). The portion of rainfall not lost to evapotranspiration, amounting to 4 in./yr, rapidly sinks into the permeable limestone where, upon reaching the water table, it recharges the aquifer.

Past Conditions

Inferences regarding conditions during aboriginal times suggest that rainfall may have been at least 55 in./yr (Valdês, 1994). Based on equation (1), the amount of annual aquifer recharge resulting from 55 in./yr of rainfall is estimated to be 14 in.

Numerical Hydrogeologic Model

As derived by Fetter (1972), the equation describing steady-state ground-water flow in an island is expressed in two dimensions (x and y) as

$$\frac{\delta^2 h^2}{\delta x^2} + \frac{\delta^2 h^2}{\delta y^2} = \frac{-2R}{K\left(1 + \dfrac{\rho_f}{\rho_s - \rho_f}\right)} \qquad (2)$$

where h is the fresh-water hydraulic head (i.e., the elevation of the water table above mean sea level); R is the recharge to the aquifer; K is the hydraulic conductivity; ρ_s is the density of saline water; and ρ_f is the density of fresh water.

Equation (1) may be approximated by the difference equation

$$\tfrac{1}{4}[h^2(x + n, y) + h^2(x - n, y) + h^2(x, y + n) + h^2(x, y - n)] - \tfrac{1}{4}n^2\left(\frac{-2R}{K\dfrac{\rho_f}{\rho_s - \rho_f}}\right) = h^2(x, y) \qquad (3)$$

where n is the spacing between nodal points on an x-y grid, and the other parameters are as previously defined. As indicated by this equation, the elevation of the water table increases as K decreases and R increases.

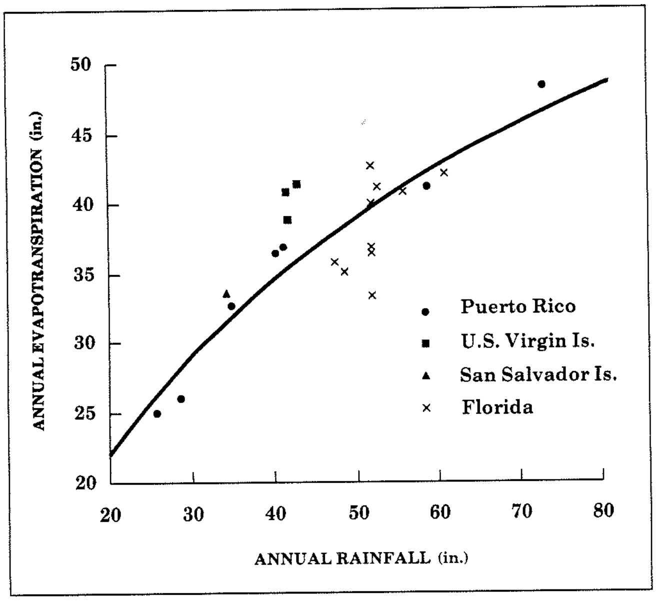

Fig. 3. Annual evapotranspiration (ET) as a function of annual rainfall. The ET and rainfall data plotted were derived from regional water budget studies (Puerto Rico: Giusti, 1978; Florida: Jones et al., 1984; Virgin Is.: Goméz-Goméz and Heisel, 1980; San Salvador Is., Bahamas: Balcerzak et al., 1990).

Equation (3) was applied in a computer spreadsheet program, using the general techniques outlined by Stewart (1986), to develop a numerical hydrogeologic model of Samana Cay. A value of n equal to 1558 ft was used in creating the model grid. Mean sea level along the coastline of the island was taken as a constant head boundary where $h = 0$. The generally accepted value of 40 for $\rho_f / \rho_s - \rho_f$ (Fetter, 1972) was used in the model.

Model outputs are in terms of water-table elevations in feet above present-day mean sea level to allow direct comparison with the topographic map coverage available for Samana Cay. Superimposed on the output water-table maps are the 5-ft contours delineating the lowest inland basinal areas.

Simulations of Current Conditions

Simulations of current water-table elevations on the island were made using respective hydraulic conductivity values of 165 and 330 ft/d. A recharge value of -20.5 in./yr was used for the coastal pond areas and 4 in./yr for the rest of the island. The simulated average annual water levels resulting under the two hydraulic conductivity scenarios are shown in Figures 4A and 4B. As follows from equation (3), the resulting water levels are higher in the lower hydraulic conductivity scenario. However, in neither scenario is the water table close to or above the land surface within extensive expanses of the inland basinal region. Although lack of water-level data prevents calibration of the model, these results are in agreement with the observation that no significant surface-water features exist in the interior of Samana Cay under average current conditions.

Simulations of Theorized Past Conditions

Simulations of past conditions are intended to approximate the effects of higher recharge resulting from increased precipitation. The simulation scenarios represent baseline cases with no areal excesses of PET over ET as estimated from Figure 3. An upward shift of the water table of 1.7 ft due to a higher sea level must also be taken into account. Hydraulic conductivity values of 165 and 330 ft/d were again considered.

Base runs were made using a uniform recharge rate of 14 in./yr resulting from 55 in. of annual rainfall. Model results indicate that, for $K = 165$ ft/d, the average annual water levels rise to and above an elevation of +5 ft in the eastern part of the basinal region (Figure 4C). With the same recharge rate of 14 in./yr but with $K = 330$ ft/d, the water table reaches an average annual elevation of +4 to +4.5 ft within this area (Figure 4D).

With $K = 330$ ft/d, it was determined by trial-and-error runs that a recharge rate of 20 in./yr (corresponding to 64 in. of annual rainfall) causes the water table to reach an average annual elevation of +5 ft in the east-central part of the basinal region and over +4 ft in most of the rest (Figure 4E). This result is exactly equivalent to that obtained with $K = 165$ ft/d and $R = 10$ in./yr (corresponding to 48 in. of annual rainfall).

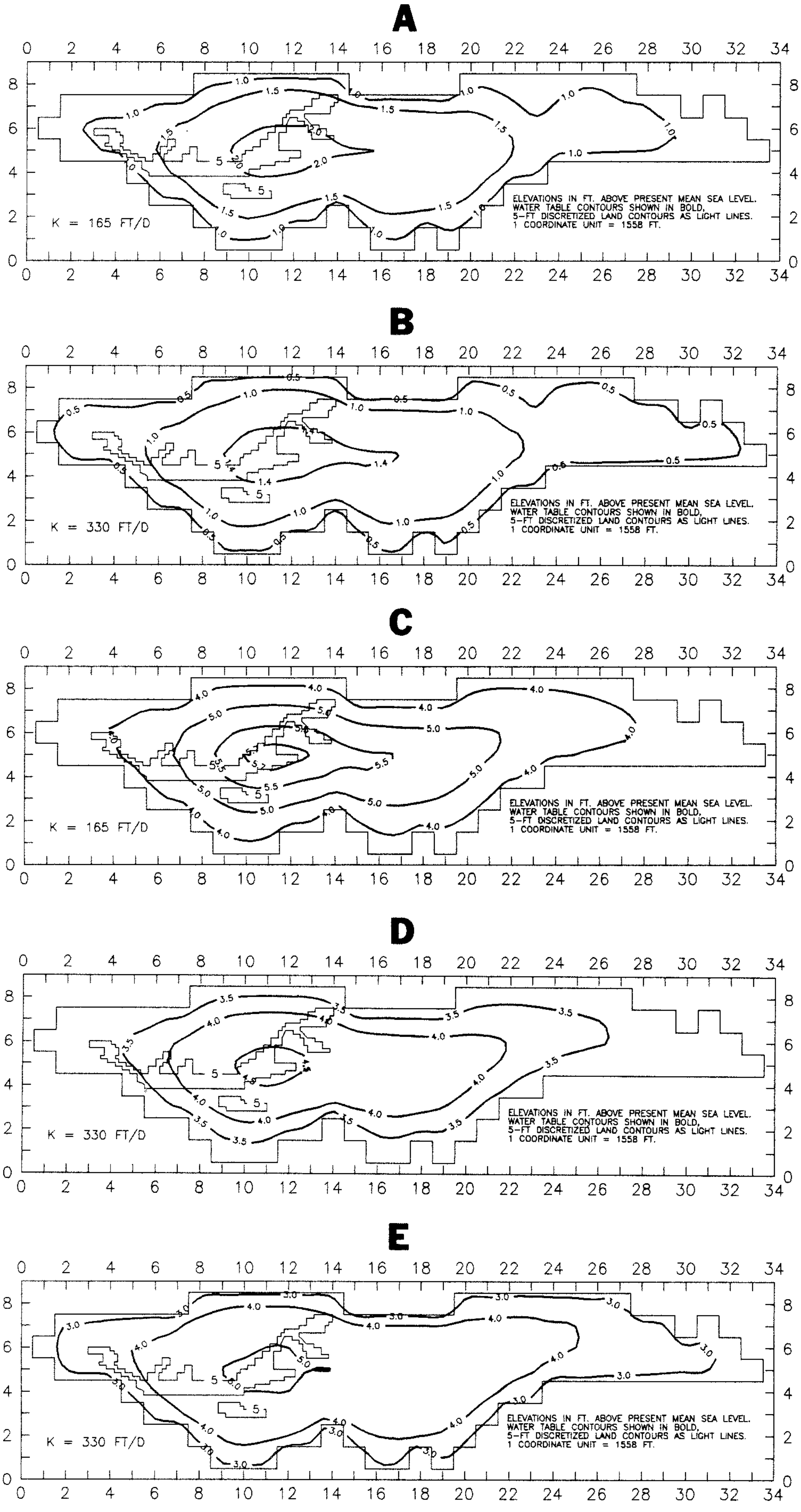

Fig. 4. Simulated average annual water-table elevations under different scenarios. Hydraulic conductivity (K) as indicated on figures. A & B: Estimated current recharge of -20.5 in./yr for coastal pond areas and 4 in./yr for the rest of the island. C-E: Uniform recharge rates of 14 in./yr (C & D) and 20 in./yr (E).

Based on the Ghyben-Herzberg relationship (Tarbox, 1987), the maximum water-table elevations indicated by these simulations (taking into account the 1.7-ft sea level difference) correspond to a fresh-water lens extending 110 to 158 ft below present mean sea level. By contrast, the base of the Lucayan Limestone, below which the fresh-water lens would tend to be truncated, is ostensibly located some 69 to 106 ft below present mean sea level (Cant and Weech, 1986). It is thus evident that the latter parameter places an upper bound on the results of the simulations. With the base of the fresh-water lens located at the base of the Lucayan, the Ghyben-Herzberg relationship indicates that the maximum water-table elevations (allowing for sea level 1.7-ft higher than present) would be in the range of +3.5 to +4.4 ft. As elevations within the basinal region range from +1 to +5 ft, the area would have been characterized by a very shallow water table and zones of standing water. Such a region would be prone to flooding during the rainy season. The month of October, when Columbus arrived on the islands, is normally one of the wettest months in the Bahamas (Ministry of Education, 1985, p. 36; Little et al., 1977). That rainy weather was actually prevalent on the islands in October of 1492 is indicated by numerous entries in Columbus's log (Dunn and Kelley, 1989).

Conclusions

A numerical hydrogeologic computer model suggests the existence of a sizable surface-water feature in the medial interior of Samana Cay under conditions of higher sea level and rainfall theorized to have been present upon Columbus's arrival in the Bahamas. This feature may correspond to the *laguna* described by Columbus as characterizing the landfall island of *Guanahani/ San Salvador.*

Geologic coring and analysis of the sediments and rocks within the region delineated by the model simulations may provide evidence of the former existence of the inferred feature.

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