Effects of Sea Water Canals on Fresh Water Resources: An Example from Big Pine Key, Florida

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Abstract

Management of the limited fresh water resources on small oceanic islands has become critical with increasing population and development in coastal areas. Canals, dredged for waterfront property and boat access, penetrate water bearing material and accelerate the natural discharge from fresh water lenses. Big Pine Key, located in the southern portion of the Florida Keys, is a heterogeneous, two-layer island with several canal networks. The island is approximately 3 km wide and 10 km long. The upper hydrostratigraphic unit (Miami Oolite Limestone) has a hydraulic conductivity of 100 meters per day (m/day). The lower unit (Key Largo Limestone) has a hydraulic conductivity of 1200 m/day.

To quantify the effects of canals on the fresh water lens of Big Pine Key, a numerical model was developed using the Dupuit and Ghyben-Herzberg assumptions. The thickness of the fresh water lens is sensitive to the location of the boundary between the upper and lower hydrostratigraphic layers. A simulation of present-day Big Pine Key, including canals, compared with predevelopment conditions shows that the total volume of the lens has decreased by 20% in response to the dredging of canals. As dredging of canals will certainly continue in the future, the numerical model was also used to investigate the types of canals that are most detrimental to a fresh water lens. For an island 3 km wide and 10 km long, a canal that penetrates 2 km lengthwise into the island reduces the volume of the fresh water lens by 6.5%. For the same island dimensions, a canal that penetrates 2 km through the midsection of the island reduces the volume of the fresh water lens by 7.1%. Several short canals, with a combined total length of 2 km decrease the volume of the fresh water lens by 4.0%. The deeper the penetration of the canal into the lens, the greater the influence of the canal. Therefore, several short canals are preferred over one long canal because shorter canals have less of an effect on the total volume of the fresh water lens. Canals also focus ground water discharge. The three configurations of 2000 m long canals each discharge 13 to 15% of the total recharge to the island.

Introduction

Fresh water resources on small oceanic islands are limited. The management of available fresh water has become critical with increasing population and development in coastal areas. The fresh water lenses are usually small, and often irregular in extent and thickness (Vacher 1988; Ayers and Vacher 1986; Kauahikaua 1987; Stewart 1988). It is not uncommon for islands to have several small, isolated lenses (Chidley and Lloyd 1977; Hanson 1980; Wightman 1990). If an island does contain a fresh water lens, its small size and proximity to the land surface make it susceptible to contamination. Extensive coastal development, such as dredging of boat canals, can adversely affect the quality and availability of fresh water. Canals penetrate water bearing material and increase natural discharge from fresh water lenses allowing salt water to move farther inland (Beaudoin 1990).

Big Pine Key is located in the Florida Keys, approximately 60 km (40 miles) northeast of Key West (Figure 1). The island is one of several of the larger Florida Keys that have fresh water lenses. Although approximately 50% of the island is part of the Key Deer National Wildlife Refuge, many boat canals have been dredged to create waterfront property and boat access for housing developments. The island has two fresh water lenses, the thicknesses of which are strongly controlled by the vertical position of the geologic contact between the Miami Oolite and Key Largo Limestones (Hanson 1980). The thicknesses of the two lenses have been characterized at three different times during the development of Big Pine Key. In 1976, Hanson (1980) drilled 22 shallow wells and measured chloride concentrations with depth. In his report, he presents the geometry of two sizeable fresh water lenses. In 1987, Wightman (1990) conducted a geophysical study of the fresh water lenses at Big Pine Key (Wightman's study is summarized in Vacher et al. 1992). Results from his study show that the lenses, especially the southeastern lens, have decreased in size when compared to the fresh water lenses described by Hanson (1980). Wightman attributed the decrease in lens volume to stresses that were introduced during the time between the two studies: dredging of boat canals, and an increase in the amount of ground water withdrawn from the lens for nurseries and domestic uses. In 1989, Beaudoin (1990) used surface geophysics to further delineate the northern fresh water lens in the vicinity of canals.

The purpose of this study is to quantify the effects that canals have on the extent and size of fresh water lenses. Canal effects at Big Pine Key were evaluated using a numerical model, developed

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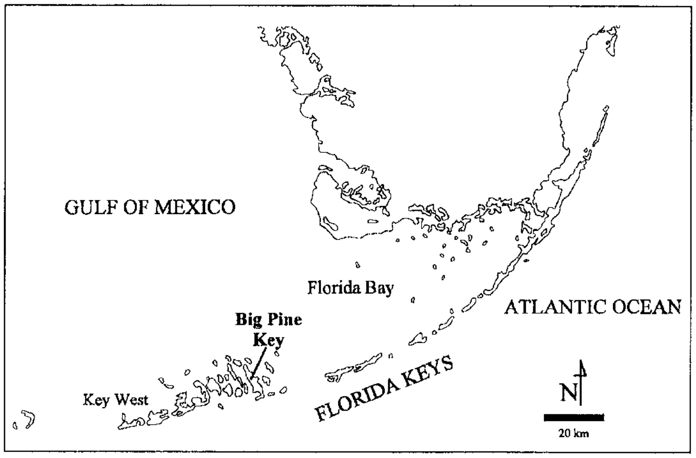

Figure 1. Map of the Florida Keys showing the location of Big Pine Key.

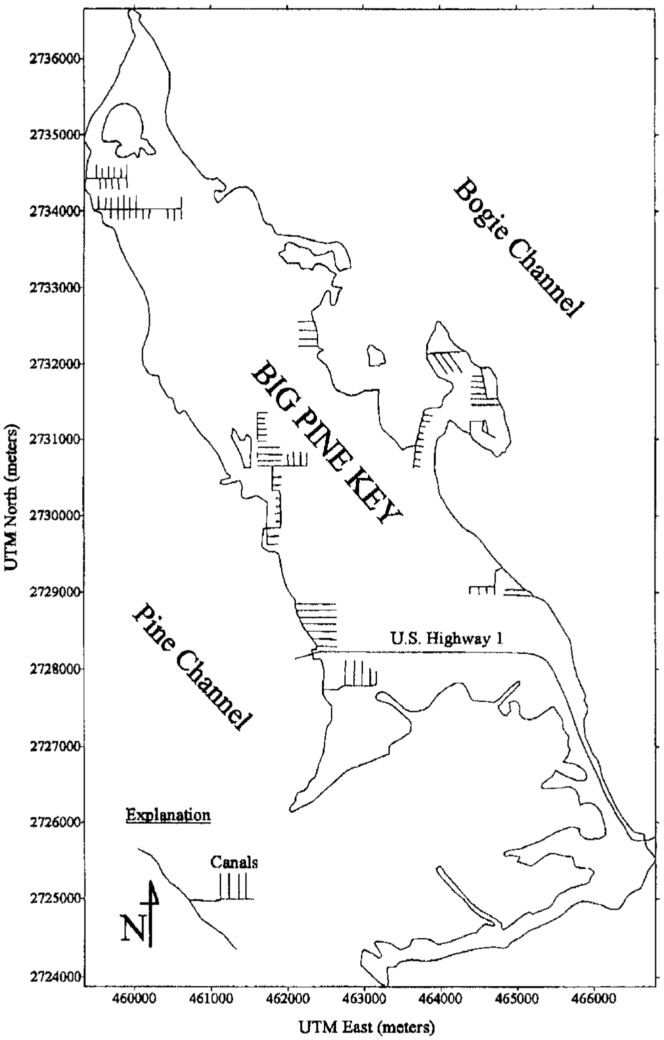

Figure 2. Map of Big Pine Key showing the location and number of dredged canals.

from the flow equation derived by Fetter (1972). This approach incorporates the assumptions of Dupuit and Ghyben and Herzberg and assumes that the fresh water/sea water interface is a sharp boundary. Big Pine Key was simulated with canals and without canals to illustrate, in a comparative sense, the effects canals have on the fresh water lens. In addition, several other canal geometries were simulated to determine the types of canals that have the greatest effect on the volume of a fresh water lens.

General Geology and Hydrogeology of Big Pine Key

Setting

Big Pine Key is the largest of the lower Florida Keys (Figure 2). It is approximately 10 km long and 2 to 3 km wide. The maximum surface elevations, measured from the National Geodetic Vertical Datum (NGVD), are 1.5 to 2.0 m. The island supports one of the most diverse assemblages of vegetation and wildlife in the Keys. The vegetation consists of pineland in areas of relatively higher elevation, with buttonwood and mangrove stands along the coastline (Carlson 1989). The island is home to several endangered species of mammals and reptiles including the Key deer, whose population is less than 300.

The southeastern half of the island has been heavily developed, while the Key Deer National Refuge, located on the northwestern half of the island, has had limited development. The island has a permanent population of about 3400. The influx of tourists during the winter increases the population to about 5000 (LaPointe and O'Connell 1989). This annual increase in population corresponds with the dry season and adds further stress to the fresh water resources.

The Florida Keys Aqueduct Authority provides most of the potable water used on the island via a pipeline from the Miami area. Supplemental water sources include shallow wells and rain cisterns. Hanson (1980) reports that approximately 150 private and commercial wells, the majority of which are in the southeastern half of the island, tap the fresh water lenses. Not suitable for potable use, this ground water is primarily used for private lawn and commercial nursery irrigation. The South Florida Water Management District, which has jurisdiction over Big Pine Key, does not hold any consumptive use permits or any other records of wells on the island. Records of the actual volume of fresh water pumped from the lenses are not kept.

It has been a common practice in the Keys to create waterfront property and boat access by dredging networks of canals along island shorelines. There are approximately 10.5 km of canals dredged into Big Pine Key (Figure 2). Approximately 6.3 km of those canals are in the northern half of the island. The depths of these canals range from 2.5 to 6 m. These canals intersect the fresh water lenses and cause accelerated discharge. Residents have observed fresh water discharging from the sides of the canals during low tides.

Geology

The Florida Keys form a 400 km chain of carbonate islands that stretch from Miami southwest to the Dry Tortugas. From Miami to just east of Big Pine Key, the islands are formed by reefal units and are long and narrow with a northeast-southwest orientation (Upper Keys). From Big Pine Key to the west, the islands are formed from oolite shoals. They become more closely spaced and change to a northwest-southeast orientation (Lower Keys). Big Pine Key is of particular interest because the contact between the upper Pleistocene Miami Oolite and Key Largo Limestones is at the surface (Hoffmeister and Multer 1968). The island was formed by an oolite shoal (Miami Oolite Limestone) overlying a coral reef platform (Key Largo Limestone). The contact between the two units is irregular but generally dips gently to the north (Hoffmeister and Multer 1968; Perkins 1977; Coniglio and Harrison 1983). This

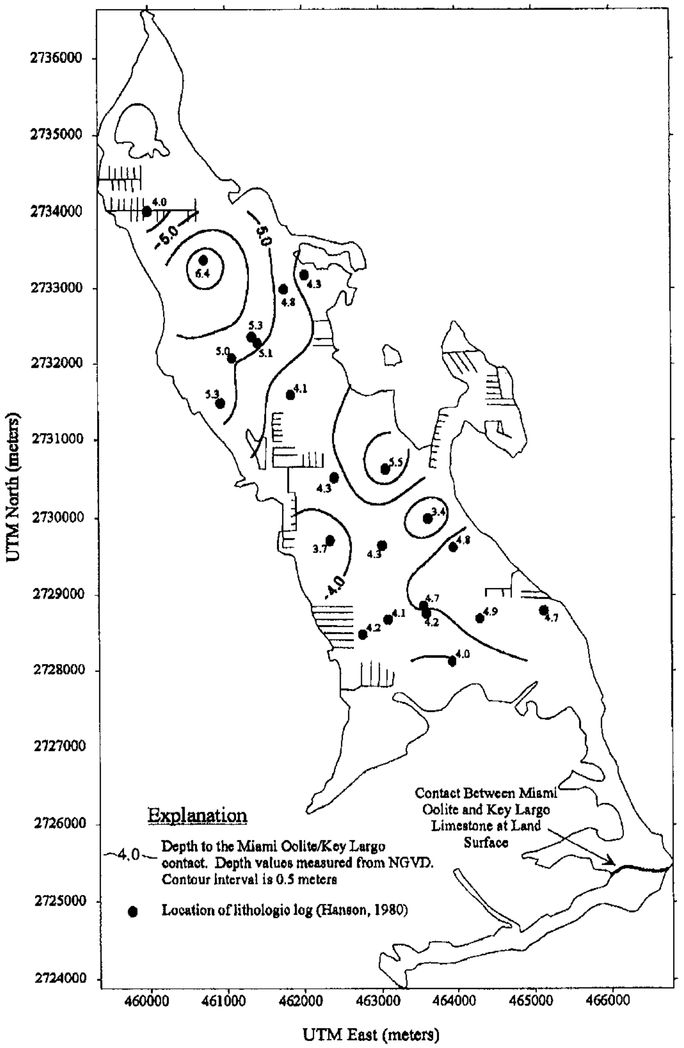

Figure 3. Contour map of the depth to the geologic contact between the Miami Oolite and Key Largo Limestone Limestones. Depths are measured relative to sea level. Contour interval is 0.5 m.

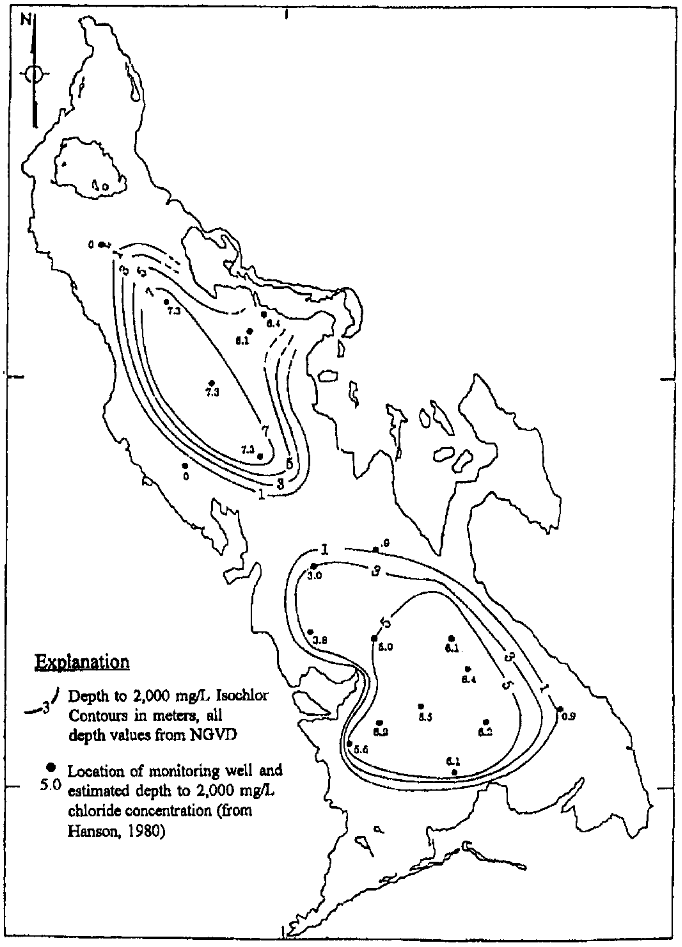

Figure 4. Contours of depth to the 2000 mg/L isochlor. From Hanson (1980).

contact intersects land surface on Big Pine Key, south of where U.S. Highway 1 enters the east side of the island. On the main part of Big Pine Key, the contact between the two limestone units ranges in depth from 3.4 to 6.4 m below sea level (Figure 3).

Hydrogeology

Several of the larger Florida Keys support lenses of fresh ground water. Hanson (1980) and Wightman (1990) documented the presence of two discrete fresh water lenses on Big Pine Key that persist throughout the dry season. During Hanson's study, 22 uncased monitoring wells were drilled and the ground water was tested for chloride concentrations at 1.5 m depth intervals over a period of a year (June 1976 through April 1977). Contours of depth to the 2000 miligrams per liter (mg/L) isochlor illustrate the presence of two fresh water lenses (Figure 4). The maximum measured thicknesses for the northwestern and southeastern lenses are 7.3 m and 6.5 m, respectively. The wells were plugged and abandoned at the end of the study. Water quality data indicate that chloride concentrations increase significantly just below the Miami Oolite/Key Largo Limestone contact. The thickness of the transition zone in Hanson's wells varies between 1.5 and 3.5 m.

The study by Wightman (1990) used surface geophysical techniques to map the fresh water lenses during the wet and dry seasons of 1987. Contours of depth to the sea water interface for March 1987 (Figure 5) and August 1987 (Figure 6) indicate the presence of two separate fresh water lenses. These lenses are similar in shape to the lens mapped by Hanson. Wightman concluded that the maximum depth of the lenses remains the same during both seasons, but the areal extent of these lenses changes in response to seasonal variations in recharge.

Rainfall on Big Pine Key averages 1 m a year with 75 to 85% occurring during the wet season from May through October. Approximately 0.75 m of this rainfall (75%) is lost through evaporation or transpiration from plants. The remaining 0.25 m represents the sole natural source of recharge to the Key (Wightman 1990; Hanson 1980). Discharge of water supplied by the aqueduct from septic tanks is another, unquantified, source of recharge.

Hanson (1980) collected field data during 1976 and 1977. Rainfall on Big Pine Key for those years was 1.19 m and 1.17 m, respectively. Rainfall data are not available after 1977 for Big Pine Key. Rainfall data, however, are recorded on Key West, which is about 18 km to the west. In 1987, the year the Wightman (1990) data were collected, the Key West station recorded 1.24 m of rainfall.

Fresh water from the lenses naturally discharges at the shoreline. There are also culturally induced discharges which include approximately 150 private and commercial wells, mosquito ditches, and canals. Most of the large capacity wells are in the southern lens. Since the fresh water lenses essentially float on the more dense sea

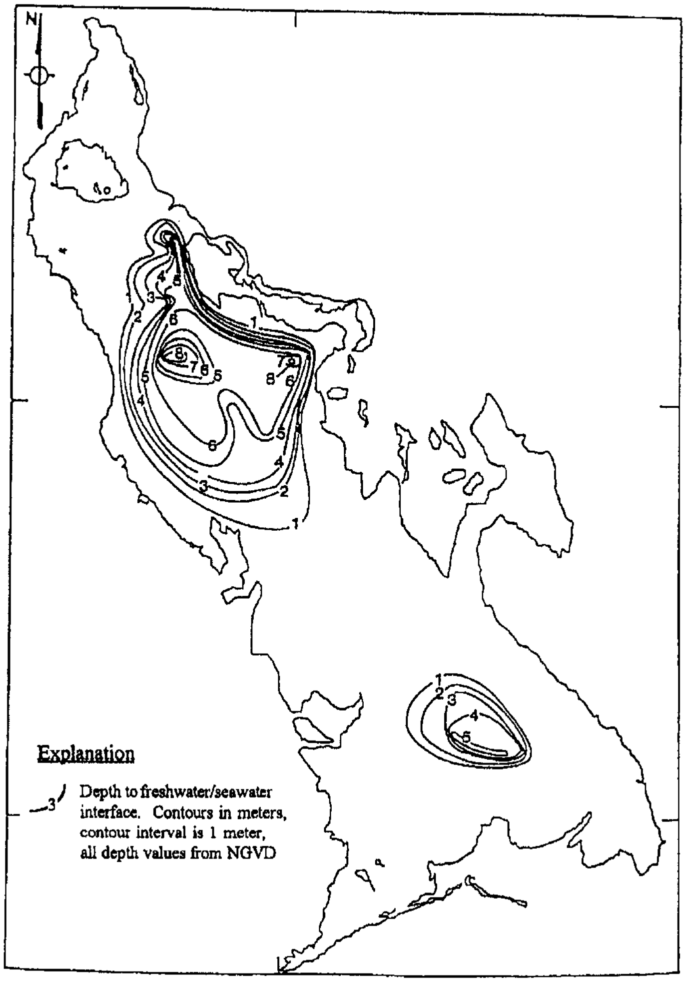

Figure 5. Contours of depth to the fresh water/sea water interface for March 1987. From Wightman (1990).

water, tides influence water levels and discharge. Water levels in monitoring wells on the island vary up to 30 cm per day (cm/day). LaPointe et al. (1990) measured the velocity of ground water flow in wells near a canal and found that tides and short-term increases in hydraulic head from rain events increase flow rates. Variation in the flow rate due to tides and rain events was quantified by establishing a basal flow rate. They defined the basal flow rate as the mean ground water flow rate calculated during one tidal cycle. Low tides doubled ground water flow rates while recharge events increased flow by up to six times the basal flow rate. Maximum flows were found to have a lag time of seven to nine hours after the recharge event before returning to basal flow rates.

The most significant control on the geometry of the Big Pine Key lenses is the hydrogeologic properties of the limestone units. Wightman (1990) calculated ranges of hydraulic conductivities for the Miami (upper) and Key Largo (lower) Limestones to be 100 to 140 m/day and 1200 to 1600 m/day, respectively, for recharge values of 0.2 to 0.3 meters per year (m/yr). This results in a 12:1 ratio of the lower-layer hydraulic conductivity (K_2) to the upper-layer hydraulic conductivity (K_1). The result of a low-permeability unit stratigraphically overlying a higher permeability unit is the truncation of the lower part of the fresh water lens (Vacher 1988). The Miami Oolite/Key Largo Limestone contact strongly controls the lower boundary of the lens and places the transition zone in the upper part of the Key Largo Limestone.

A rise in the Miami Oolite/Key Largo Limestone contact and a decrease in island elevation and width near the island's center contribute to the division of the ground water into two distinct lenses. A textural change in the Miami Oolite Limestone at the island's center from karstified to a smooth, laminated crust has been observed. This "tighter" texture may also contribute to a decrease in the lens thickness by impeding recharge (Hanson 1980).

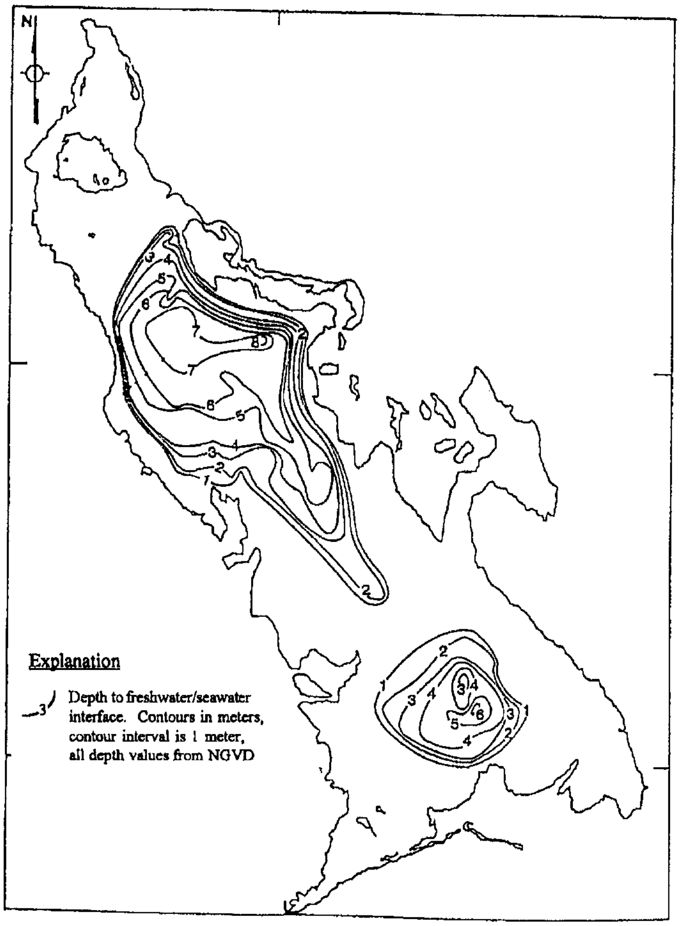

Figure 6. Contours of depth to the fresh water/sea water interface for August 1987. From Wightman (1990).

Theoretical Background

Fresh Water Lenses

Hydrogeologists have long been concerned with the dynamics of fresh water lenses primarily because they provide a source of potable water for island communities. An island surrounded by sea water may develop a thin lens of fresh water that floats on the underlying sea water if the island is large enough, has the proper hydraulic characteristics, and receives enough recharge. The interface between fresh water and sea water is commonly thought of as a sharp boundary; however, in most cases the boundary is not a sharp interface but rather a transition zone which gradually changes from fresh to saline water.

The classic problem of locating the position of the interface was addressed by Ghyben and Herzberg around the turn of the 20th century. By assuming that the lens is in static equilibrium with sea water, they determined that the depth to the interface, z, is described by the following equation:

$$z = \frac{\rho_f}{\rho_s - \rho_f} h_f \qquad (1)$$

where ρ_f is the density of fresh water; ρ_s is the density of sea water, and h is the elevation of the water table. Using densities of 1.000 grams per cubic centimeter (g/cm^3) and 1.025 g/cm^3 for fresh water and sea water, respectively, the interface equation reduces to:

$$z = 40h \tag{2}$$

Strictly speaking, the Ghyben-Herzberg principle is not entirely valid because the assumption of static equilibrium is an oversimplification. Treatment of dynamic fresh water/sea water interfaces is addressed by Hubbert (1940).

Governing Equation

The derivation of the steady-state flow equation for a fresh water lens is presented by Fetter (1972). His derivation is based on the assumptions of Dupuit, and Ghyben and Herzberg (DGH). The Dupuit assumption limits the problem to two dimensions by assuming vertical equipotentials and horizontal flowpaths. Therefore, there is no flow in the vertical direction. The Ghyben-Herzberg assumption simply states that for a density contrast of 0.025 g/cm^3, the depth to the fresh water/sea water interface is 40 times the fresh water head value. The general governing equation for an island lens according to Fetter (1972) is:

$$\frac{\partial^2 h}{\partial x^2} + \frac{\partial^2 h}{\partial y^2} = \frac{-2R}{K(\alpha + 1)} \tag{3}$$

where R is recharge; h is the elevation of head above sea level; α is the density of fresh water divided by the density difference between fresh water and sea water; and K is the hydraulic conductivity of the island.

Analytical Solution

Vacher (1988) developed the analytical solution for a fresh water lens in an infinite strip island. His solution is based on DGH assumptions. While Vacher (1988) presented several variations with respect to hydrogeologic conditions, the solution to the two-layer island is most relevant to this study. The analytical solution is derived for a two-dimensional cross section (Figure 7) by combining the continuity equation,

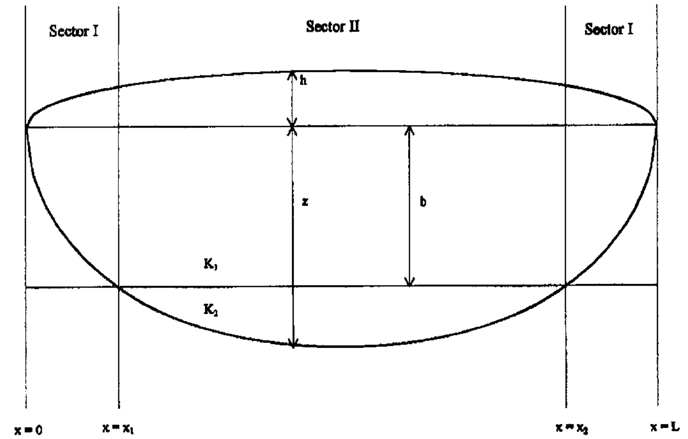

Figure 7. Cross section showing the general shape of a fresh water lens. The variables shown on the cross section are used to formulate the equation which describes ground water flow in the island; h is the elevation of the water table above sea level; z is the depth from sea level to the bottom of the fresh water lens; b is the thickness of the upper hydrostratigraphic unit; and K_1 and K_2 are the hydraulic conductivity values of the upper and lower hydrostratigraphic units, respectively. Sector I represents the portion of the island where the fresh water lens is located entirely in the upper unit. Sector II represents the portion of the island where the fresh water lens occurs in both the upper and lower units. x_1 and x_2 represent the locations where the boundary of the fresh water lens intersects the K_1/K_2 boundary. L is the width of an island with infinite length.

$$Q = -R\left(\frac{L}{2} - x\right) \tag{4}$$

where L is defined as the width of the island, and Q is the volumetric flow rate per unit width, with a form of Darcy's law that contains DGH assumptions. There are two different forms of Darcy's law—one for Sector I and another for Sector II (Figure 7). In the domain of Sector I, the entire fresh water lens is in the upper layer. Darcy's law for Sector I is:

$$Q = -K_1(\alpha + 1)h\frac{dh}{dx} \tag{5}$$

Combining Equations 4 and 5 results in:

$$R\left(\frac{L}{2} - x\right) = K_1(\alpha + 1)h\frac{dh}{dx} \tag{6}$$

The solution for head in Sector I is found by isolating the x and h variables on separate sides of Equation 6 and then integrating both sides subject to the boundary condition, at x = 0, h = 0. The resulting equation for h in Sector I is:

$$h_I = \sqrt{\frac{R}{K_1(\alpha + 1)}(Lx - x^2)} \tag{7}$$

The boundaries between Sector I and Sector II are located at x_1 and x_2 with corresponding heads of h_1 and h_2, respectively. At these locations, z = b, or with the GH assumption, $(\alpha+1)h = b$. By substituting Equation 7 into $(\alpha+1)h = b$ for h we can solve for x_1 or x_2. The solution for x_1 or x_2 is:

$$x_1,x_2 = \sqrt{\frac{-b^2K_1(\alpha + 1)}{R\alpha^2}} + \frac{L^2}{4} + \frac{L}{2} \tag{8}$$

The heads, h_1 and h_2, are found by substituting Equation 8 into Equation 7 for x. Note that Equation 7 has two roots. This is because the fresh water/sea water interface crosses the K_1/K_2 boundary at two different points along the x axis, x_1 and x_2 (Figure 7).

The solution for head in Sector II is found by using the same methodology as for Sector I. Darcy's law for flow in Sector II requires summing the fluxes in the upper and lower K units. Therefore, the equation for Darcy's law in Sector II is:

$$Q = -K_1(h + b)\frac{dh}{dx} - K_2(\alpha h - b)\frac{dh}{dx} \tag{9}$$

Again, by combining Equation 9 with the continuity equation, isolating the x and h variables, and then integrating both sides subject to the boundary condition, at $x = x_1$, $h = h_1$, an expression for h_{II} is found. The general equation for Sector II is:

$$R[L(x - x_I) - (x^2 - x_I^2)] = 2b(K_1 - K_2)(h_{II} - h_I) + (K_1 + K_2a)(h^2_{II} - h_I^2) \qquad (10)$$

This equation can be solved analytically by completing the square, or it can be solved numerically with either a spreadsheet or simple program.

Numerical Solution

The main limitation to solving the governing equation (Equation 3) numerically is that coarse discretization of the island can cause significant errors in the solution. To avoid this problem, the finite-difference grid must be fine enough to minimize discretization errors. For finely discretized model domains, another problem exists: simulation time can be prohibitively long. The benefits of using a numerical solution, however, far outweigh the drawbacks. A numerical solution provides the ability to simulate two-dimensional flow with an irregularly shaped coastline, and spatially variable recharge and hydraulic conductivity. Hence, it is possible to closely simulate the dimensions of Big Pine Key.

For a heterogenous, two-layered island, Fetter (1972) derived a weighted expression for K_{avg} that is based upon the vertical portion of each layer that is in the fresh water lens. Inspection of Figure 7 verifies that K_{avg} can be defined as:

$$K_{avg} = \frac{K_1(h + b) + K_2(z - b)}{(h + z)} \qquad (11)$$

where K_1 is the first-layer hydraulic conductivity; K_2 is the second-layer conductivity; h is the head above sea level; z is the depth below sea level to the interface; and b is the depth to the contact between layers. Equation 11 is necessary only if $z > b$. If $z \leq b$, the entire lens is within the upper layer, and the average hydraulic conductivity is equal to K_1.

Methods

Finite-Difference Approximation

In this study, a slightly different governing equation from that derived by Fetter (1972; Equation 3) is used. By using the DGH assumptions, hydraulic conductivity is heterogeneous because K_{avg} is a function of a head. Accordingly, we use the following form of the governing equation which allows for anisotropy and heterogeneity in hydraulic conductivity,

$$\frac{\delta}{\delta x}\left[K_x h \frac{\delta h}{\delta x}\right] + \frac{\delta}{\delta y}\left[K_y h \frac{\delta h}{\delta y}\right] = \frac{-R}{(\alpha + 1)} \qquad (12)$$

as the governing equation for our flow model. The finite-difference approximation for Equation 12 is written as:

$$h_0 = \left[\frac{\sum_{i=1}^{4} K_{i0} h_i^2 + \frac{2Ra^2}{(a + 1)}}{\sum_{i=1}^{4} K_{i0}}\right]^{1/2} \qquad (13)$$

where h_0 is the head value for the current cell; h_i is the head at cell i (refer to Figure 8 for stencil notation); and K_{i0} is the harmonic mean of the K_{avg} hydraulic conductivity values in cells i and 0, calculated using:

$$K_{i0} = \frac{2K_iK_0}{K_i + K_0} \qquad (14)$$

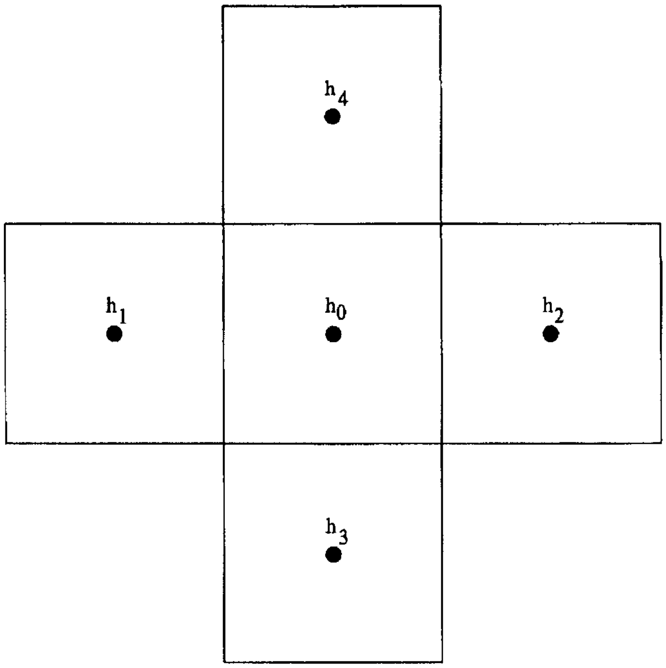

Figure 8. Stencil used to formulate the finite-difference solution to the flow equation.

During one iteration, Equations 11 and 13 are solved at each cell, and Equation 14 is solved for the four surrounding cells. Head values from the previous iteration are used as estimates of head to calculate K_{avg}. The convergence criterion is met when the head difference between two successive iterations is less than 1×10^{-6} m at each node. Using a simple Gauss-Seidel iteration scheme, the total number of iterations required for convergence ranges between 10 and 10,000, depending on how closely the initial head estimates match the solution.

Code Verification

The numerical code was validated against Vacher's (1988) analytical solution. The island dimensions used to validate the code are 3000 by 10,000 m. The depth to the boundary between K_1 and K_2 is held constant at 5 m. Recharge is held constant at 10 cm/yr. K_2 is a constant 1000 m/day. To ensure that the numerical solution matches the analytical solution, several different hydraulic conductivity ratios, using different values of K_1, are simulated. As a result, the depth to the interface can be compared in both Sectors I and II, as defined by the analytical solution. The analytical solution is valid for infinite-strip islands only (one-dimensional flow), therefore, geometry of the numerical model is chosen so that this type of flow system is produced.

Calculated interface depths from the numerical model were compared with the analytical solution. To ensure the validity of the comparison, interface depths from the model were taken from the region where one-dimensional flow exists. This region is located

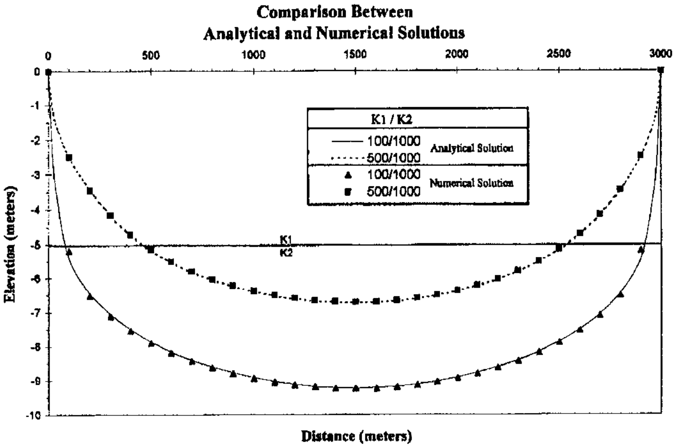

Figure 9. Cross section of a fresh water lens comparing the numerical solution to the analytical solution.

along the shorter axis of the rectangular island. The depths to the fresh water/sea water interface calculated by the numerical model closely match depths to the interface that are calculated with the analytical solution (Figure 9). For K_1/K_2 ratios equal to 500/1000 (1:2) and 100/1000 (1:10), depths compare well in both Sectors I and II.

Modeling Strategy

Two different island geometries were used to investigate the effects of canals on fresh water lenses. In the Big Pine Key simulations, the model geometry closely matches the geometry of Big Pine Key, and is intended to simulate ground water flow at Big Pine Key. This model geometry was used to investigate the effects of existing canals on the fresh water lens at Big Pine Key. In the second case, a simple rectangular island geometry was used to investigate, in general, the influence of canal placement and length on a fresh water lens in an oceanic island.

Big Pine Key Simulations

The principal objective of the Big Pine Key simulations is to develop a steady-state, numerical flow model of Big Pine Key that matches the fresh water lens configuration described by Hanson (1980), Wightman (1990), and Beaudoin (1990), and to then run the model without simulating canals to determine how canals affect the volume and shape of the fresh water lenses. Once a calibrated model is available, the hydrogeologic influence of the high hydraulic conductivity of the Key Largo Limestone can be assessed by setting the Key Largo Limestone hydraulic conductivity to the same value as the overlying Miami Oolite Limestone. This single-layer case is representative of many islands, including Key West. Three simulations were run:

1. Big Pine Key with existing canals
2. Big Pine Key without existing canals
3. Big Pine Key with existing canals, and $K_2 = K_1$

Simulations of Various Canal Positions

The goal of this step is to investigate how canal position and length affect the volume and flow patterns of a fresh water lens. Instead of using the exact dimensions of Big Pine Key, a generalized rectangular island is used for these simulations. Results from these numerical simulations are used to make recommendations for limiting the adverse effects of canals on oceanic islands with fresh water lenses. Four simulations were used:

1. No canals (baseline case)
2. 2000 m canal bisecting long axis of island
3. 2000 m canal bisecting short axis of island
4. Four 500 m canals placed on each side of island

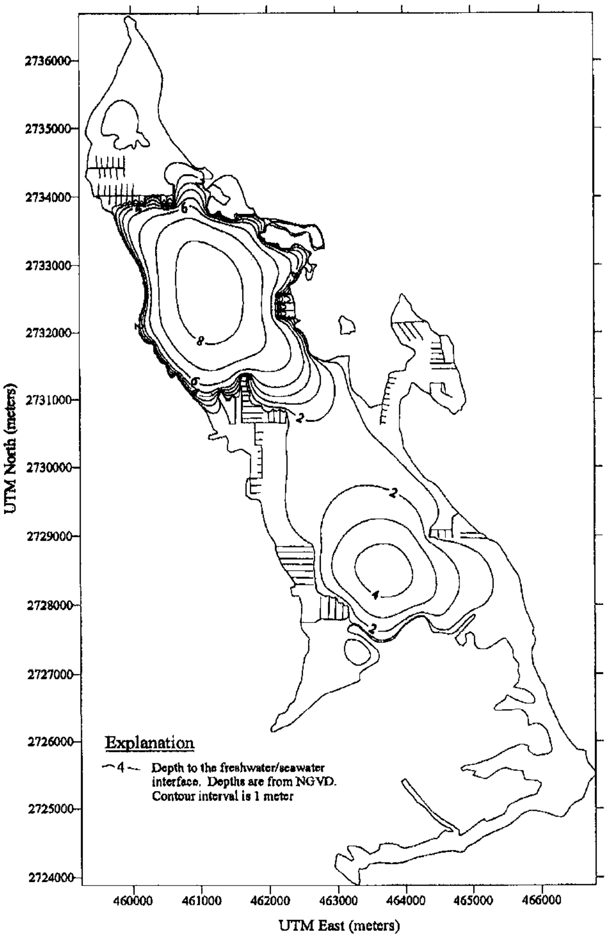

Figure 10. Results from the numerical simulation of Big Pine Key with canals. Contours represent depth to the fresh water/sea water interface. Contour interval is 1 m.

Development of the Big Pine Key Model

For the Big Pine Key simulations, the finite-difference grid consists of 426 rows by 272 columns. The origin of the grid, in the lower left corner, is located at Universal Transverse Mercator (UTM) Zone 17 coordinate (x = 459,235; y = 2,726,054). Each cell in the grid is 25 m by 25 m. A fixed head boundary condition (Dirichlet) surrounds Big Pine Key. All ocean cells, including those with canals, have heads fixed at at an elevation of 0 m. All other cells are active ground water flow cells.

A geographic information system (GIS) was used to construct a regularly spaced lattice representing the top of the Key Largo Limestone. The lattice was created by kriging data points from an earlier study (Hanson 1980). Bilinear interpolation of the lattice was used to assign values of depth to the Key Largo Limestone to each model cell. The GIS was also used to assign recharge values to each cell using a recharge zone map. Two recharge zones were selected based on location of fresh water lenses, and contours of elevation from a 7½ topographic map with a contour interval of 5 feet. Values

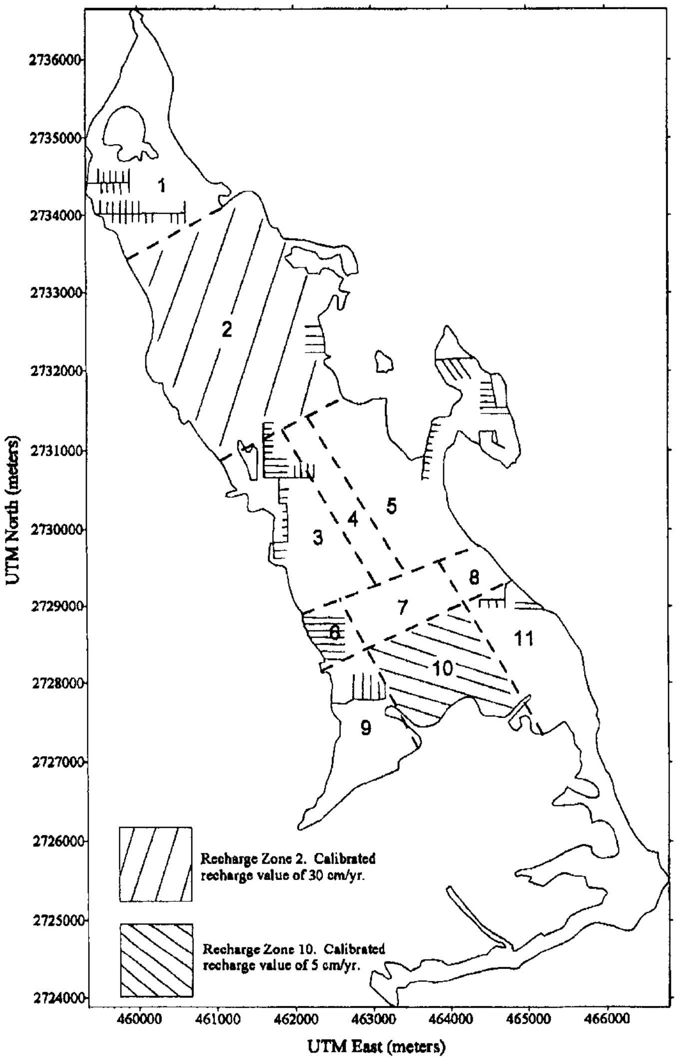

Figure 11. Map showing the initial recharge zones that were used to calibrate the Big Pine Key model. Recharge was only assigned to zones 2 and 10 during the final calibration run.

of recharge for each zone were adjusted until model results matched the general lens geometry of Hanson (1980; Figure 4) and Wightman (1990; Figures 5 and 6).

Simulation of Canals

The island geometry used to investigate the affects of various canal positions is a rectangular island 3 km by 10 km. Each cell in the model is 25 m by 25 m. The resulting finite-difference grid contains 121 rows and 401 columns. The outer rows and columns have the heads fixed at 0 m to represent sea level. In each case, the island contains an upper and lower layer. The upper and lower layers have hydraulic conductivity values of 100 and 1000 m/day, respectively. The contact between the two layers is located 5 m below sea level. Recharge is evenly distributed across the island. A recharge value of 10 cm/yr was selected for these simulations.

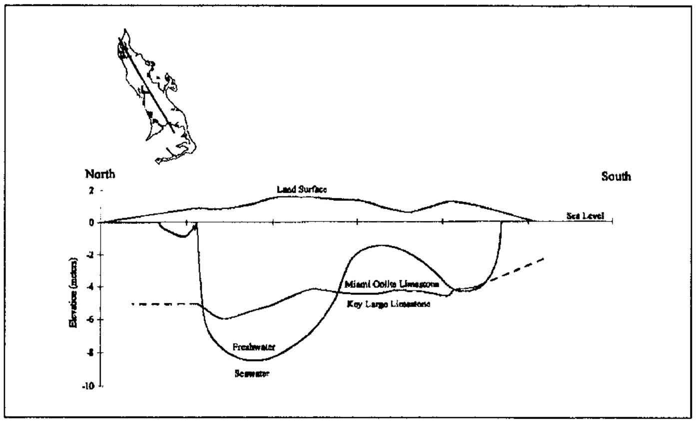

Figure 12. Cross section through Big Pine Key. Data for the position of the fresh water/sea water interface was taken from the calibrated model run of Big Pine Key with canals. Each tick along the horizontal axis is 2 km. Dashed lines indicate where the contact between the Miami Oolite and Key Largo Limestones is inferred. Vertical exaggeration is approximately 500.

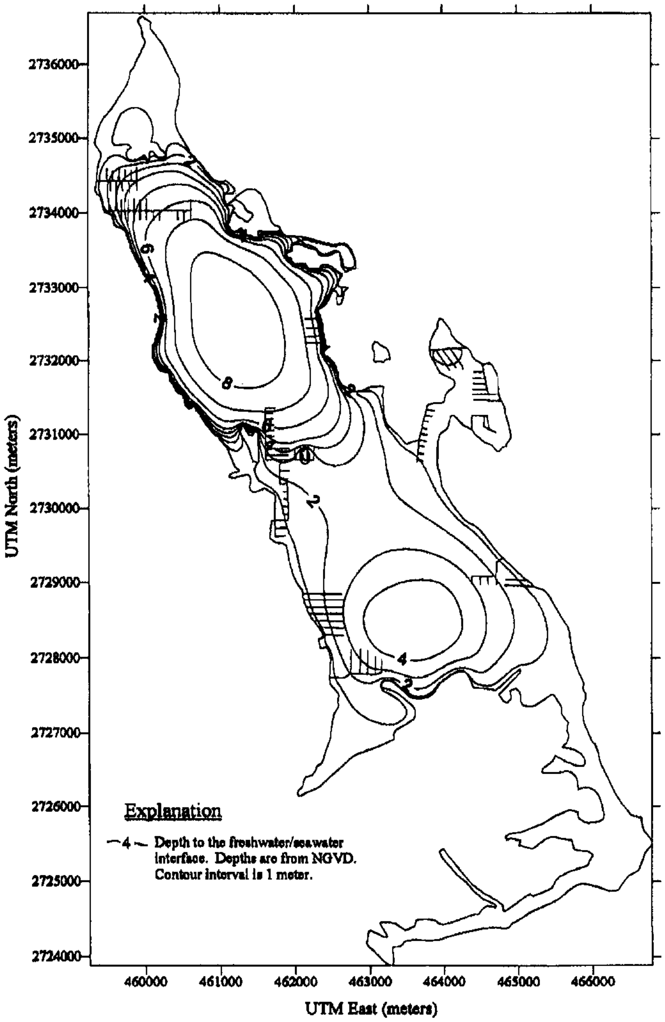

Figure 13. Results from the numerical simulation of Big Pine Key with canals removed. Contours represent depth to the fresh water/sea water interface. Contour interval is 1 m.

Results

Big Pine Key Simulations

Simulation of Big Pine Key with canals results in two fresh water lenses (Figure 10). The larger lens on the northwest portion of the island has a maximum depth below sea level of 8.8 m, whereas the smaller lens to the southeast has a maximum depth of 4.6 m. To calibrate the Big Pine Key model, the island was separated into 11 different recharge zones (Figure 11). The calibrated recharge values for the northwest (zone 2) and southeast (zone 10)

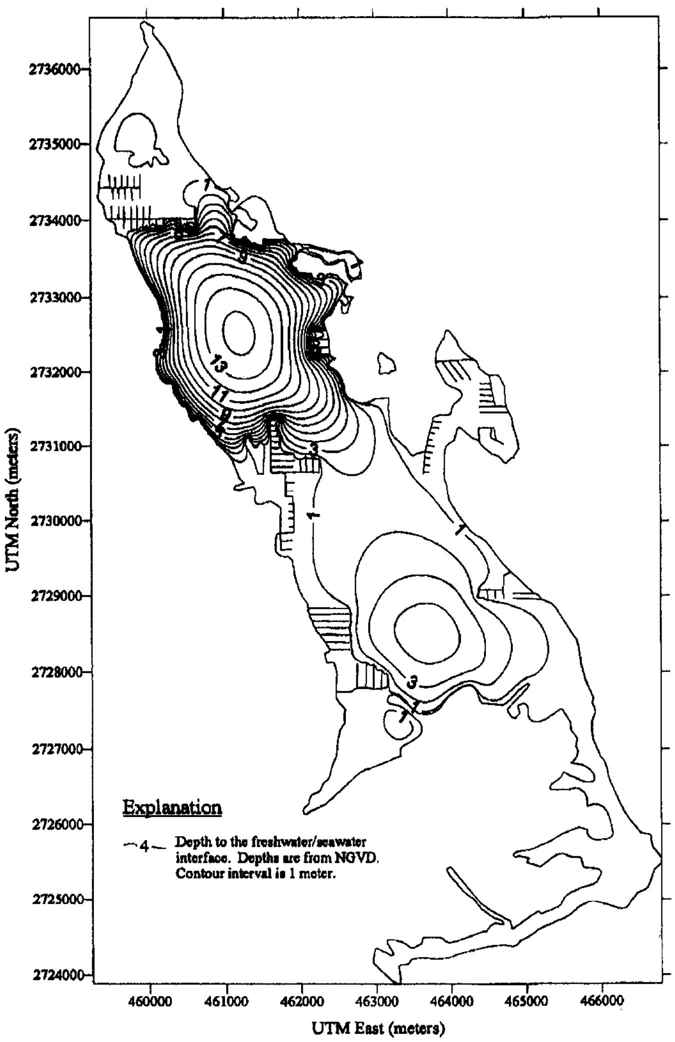

Figure 14. Results from the numerical simulation of Big Pine Key as a homogenous island. The boundary between the Miami Oolite and Key Largo Limestones has been removed to show the effect of the boundary on the size of the fresh water lens. Contour interval is 1 m.

portions of the island are 30 and 5 cm/yr, respectively. All other zones have no recharge in the calibrated model. The simulated lenses roughly match those mapped by Wightman (1990; Figures 5 and 6). Contours of depth for the northwest lens become more closely spaced towards the coast. Contours of depth are evenly spaced for the southwest lens. For both lenses, the 1 m contour closely parallels either the coast or the nearest canal, depending on location. The total volume of the fresh water–saturated portion of the island is 2.4×10^6 m^3.

Results from the Big Pine Key simulation can also be shown in cross section (Figure 12). The thickness of the northern lens is greatest where the Miami Oolite/Key Largo contact is lowest in elevation. The region between the northern and southern lenses corresponds with a depression in land surface elevation. Calibration of the model indicates that the recharge value in this region is zero. To the north, where the cross section intersects a canal (Figure 12), the boundary between fresh water and sea water is diverted upward.

Results from the simulation of Big Pine without canals are shown in Figure 13. Without canals, the lenses are bound only by the coast. As a result, both lenses cover a larger surface area of the island, but the maximum depths of both lenses do not change from the simulation of Big Pine Key with canals (8.8 m and 4.6 m for northwest and southeast, respectively). The volume of the fresh water–saturated portion of the island without canals is 3.1×10^6 m^3. This is about a 20% decrease in the total volume of the lens as a result of canal construction.

If the Key Largo Limestone unit was not present at Big Pine Key, or the contact between the Miami Oolite and Key Largo Limestone was tens of meters deeper, model results indicate that the volume of the fresh water–saturated portion of the island would be 3.0×10^6 m^3 with canals. Therefore, the presence of the highly permeable Key Largo Limestone potentially reduces the volume of the lens by 20%. Without the Key Largo Limestone, the northwestern lens would potentially have a maximum depth of 14.5 m (Figure 14). The southeastern lens would not change because the lower portion of this lens is not intersected by the Miami Oolite/Key Largo Limestone contact.

Simulation of Canals

Three variations of canal length and placement were simulated to determine how these factors influence the effects of canals on oceanic islands. Three separate canal simulations are compared with a baseline case (Figure 15a). The maximum reduction in lens volume is caused by the canal which bisects the long axis of the island (Figure 15b). This canal placement and length reduces the lens volume by 7%, and discharges 14% of the total recharge to the island. Placing a single, 2000 m long canal at the end of the island reduces the lens volume by about 6% and discharges about 13% of the total recharge (Figure 15c). Dividing the 2000 m canal length into four 500 m segments at the ends and middle of the island results in a lens volume reduction of about 4%, but the four canals discharge an aggregate 15% of the total recharge to the island (Figure 15d).

Discussion

The principal controls on the volume and configuration of the fresh water lenses on Big Pine Key are the depth to the contact between the lower permeability Miami Oolite and the higher permeability Key Largo Limestone, land surface elevation, and variation in recharge rates. The northern lens intersects the Miami Oolite/Key Largo Limestone contact (Figure 12). The elevation of this geologic contact controls the maximum lens thickness as the high permeability of the Key Largo Limestone (1000 m/day) truncates the bottom of the lens.

The southern lens barely intersects the Miami Oolite/Key Largo Limestone contact. Land surface elevation, a lower recharge rate, and the shoreline configuration appear to be the principal factors which limit the thickness of the southern lens. The more indurated surface of the limestone in the southern part of Big Pine Key appears to reduce recharge to the southern lens, as suggested by Hanson (1980). The calibrated recharge rates used in this study are 5 cm/yr for the southern lens, and 30 cm/yr for the northern lens.

The large difference in calibrated recharge rates between the two lenses may be due in part to direct withdrawals of ground water in the southern lens which are not explicitly simulated. These withdrawals reduce the thickness and extent of the lens. Calibrating the model by adjusting recharge means that the reduction in lens volume is accounted for by reducing the calibrated recharge values. In effect, part of the apparent difference in recharge between the northern and southern lenses may be because the lower apparent recharge rate in the southern lens, where most ground water withdrawals occur, is actually a net recharge rate, which includes the effects of pumping.

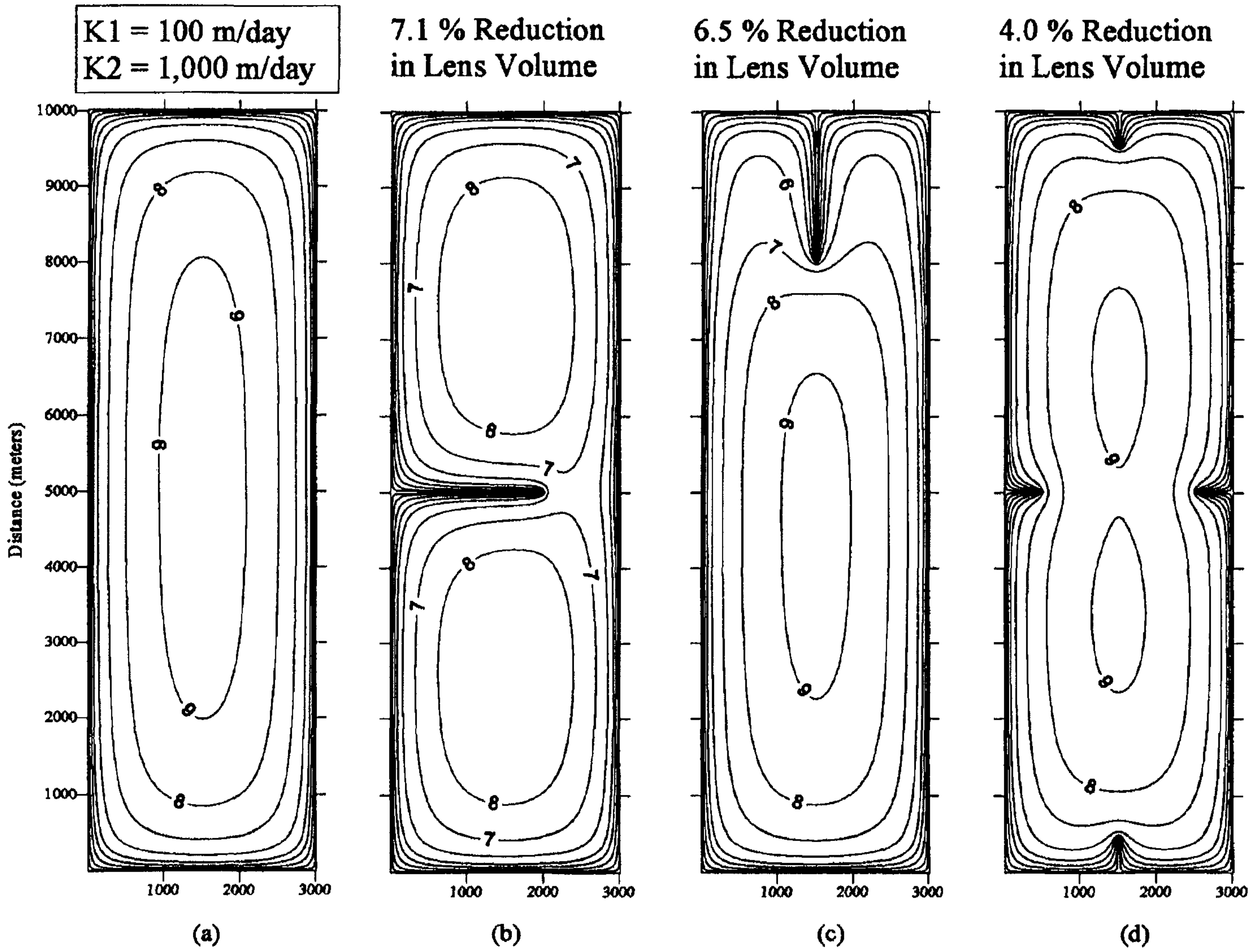

Figure 15. Results from the numerical simulation of various canal positions. Contours represent depth to the fresh water/sea water interface. In each case, the island is 10,000 by 3000 m. K_1 and K_2 are set at 100 and 1000 m/day, respectively. (a) Baseline simulation of island without canals. (b) Simulation of island with one 2000 m canal bisecting the island. (c) Simulation of one 2000 m canal bisecting the island lengthwise. (d) Simulation of island with four canals that total in length to 2000 m. The percent reduction for cases (b), (c), and (d) are calculated by comparing the simulated lens volume to the lens volume of baseline case (a).

Comparison of the volume of the fresh water lenses with and without canals suggests that the canals constructed on Big Pine Key have significantly reduced the volume of fresh water in the lenses. Comparison of simulations with and without canals suggests that the canals on Big Pine Key have reduced the volume of the fresh water lenses by about 20%. If Big Pine Key was comprised entirely of Miami Oolite Limestone, the effect of the canals would be greater, as the maximum thickness of the northern lens is already limited by the depth to the Key Largo Limestone contact, reducing the apparent effect of the canals.

Canals affect the entire lens by reducing the total volume of the lens. Canals at the ends of long, narrow islands and short canals have the smallest effect on lens volume. The fresh water flux into the canals, however, seems to be influenced principally by the total length of canals, rather than canal placement. All three canal length/placement scenarios have similar fresh water fluxes into the canals, about 13 to 14% of the total recharge flux, but differ significantly in reduction of lens volume, from 4 to 7%.

Canals tend to concentrate ground water discharge, as noted for embayments in the Door Peninsula, Wisconsin (Cherkauer and McKereghan 1991). Focusing of discharge can lead to concentrations of contaminants, especially nutrients, from septic tanks. In Figure 15b, a single canal perpendicular to the long axis of the island reduces the lens volume by 7%, and concentrates 14% of the total recharge to the island in the canal. As dredge and fill canals on Big Pine Key are normally lined with homes with septic tanks, the flow field effect of the canals is to collect and focus ground water discharge that has been affected by the effluent from the septic tanks. LaPointe et al. (1990) noted substantial increases in nutrients in ground water near septic tanks on Big Pine Key. On Big Pine Key, then, the effects of the canals are to significantly decrease the volume of the fresh water lens, and to focus discharge of ground water possibly contaminated by sewage. This may lead to eutrophication as a result of restricted circulation in the canals.

Conclusions

The principal controls on the current configurations of the northern and southern fresh water lenses on Big Pine Key are geologic, topographic, hydrologic, and anthropogenic. The thickness of the northern lens is determined by the depth to the Miami Oolite/Key Largo Limestone contact, and the lens extends to the effective shoreline. The thickness of the southern lens is restricted by lower land surface elevations and a lower net recharge rate.

Sea level canals can significantly reduce the volume of the fresh water lens on an oceanic island. The effects extend throughout the entire lens, but are greatest near the canals. The volume of fresh ground water on Big Pine Key has been reduced at least 20% by the construction of canals. Canals decrease the available fresh water in the lenses and may focus the discharge of nutrients and contaminants from septic tank effluent into surface water.

The effects of canals on lens volume depend principally on the relative penetration of the canal into the island and the canal position. Canals which laterally bisect long, rectilinear islands cause a somewhat greater reduction in lens volume than canals at the ends of the island.

Clearly, sea level canals can significantly affect ground water quality and quantity on small oceanic islands. An assessment of the effects of proposed dredge and fill or navigational canals on fresh water resources should be made prior to canal approval or construction.

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References

Ayers, J., and H.L. Vacher. 1986. Hydrogeology of an atoll island: A conceptual model from a detailed study of a Micronesian example. *Ground Water* 24, no. 2: 185-198.

Beaudoin, C.M. 1990. Effects of dredge and fill canals on freshwater resources of a small oceanic island, Big Pine Key, Florida. M.S. thesis, Geology Department, University of South Florida-Tampa.

Carlson, P.C. 1989. Effects of burning in the rockland pine community of the Key Deer National Wildlife Refuge, Florida Keys. M.S. thesis, University of Florida-Gainesville.

Cherkauer, D.S., and P.F. McKereghan. 1991. Ground-water discharge to lakes: Focusing in embayments. *Ground Water* 29, no. 1: 72-80.

Chidley, T.R., and J.W. Lloyd. 1977. A mathematical study of freshwater lenses. *Ground Water* 15, no. 3: 215-222.

Coniglio, M., and R.S. Harrison. 1983. Facies and diagenesis of Late Pleistocene carbonates from Big Pine Key, Florida. *Bulletin of Canadian Petroleum Geology* 31 no. 3: 135-147.

Fetter, C.W. Jr. 1972. Position of the saline water interface beneath oceanic islands. *Water Resources Research* 8, no. 5: 1307-1315.

Hanson, C.F. 1980. Water resources of Big Pine Key, Florida. USGS Open-File Report 80-447.

Hoffmeister, J.E., and H.G. Multer. 1968. Geology and origin of the Florida Keys. *Geological Society of America, Bulletin* 79, no. 11: 1487-1502.

Hubbert, M.K. 1940. The theory of ground-water motion. *Journal of Geology* 48, no. 8: 785-944.

Kauahikaua, J. 1987. Description of a fresh-water lens at Laura Island, Majuro Atoll, Republic of the Marshall Islands, using electromagnetic profiling. USGS Open-File Report 87-582.

LaPointe, B.E., and J.D. O'Connell. 1989. The effects of on-site sewage disposal systems on nutrient relations of groundwaters and nearshore surface waters of the Florida Keys. Technical Report, Monroe County Planning Department, Stock Island, Florida.

LaPointe, B.E., J.D. O'Connell, and G.S. Garrett. 1990. Nutrient couplings between on-site sewage disposal systems, groundwaters, and nearshore surface waters of the Florida Keys. *Biogeochemistry* 10, no. 3: 289-307.

Perkins, R.D. 1977. Depositional framework of Pleistocene rocks in South Florida. In *Quaternary Sedimentation in South Florida,* Memoir 147, ed. P. Enos and R.D. Perkins, 131-198. Boulder, Colorado: Geological Society of America.

Stewart, M.T. 1988. Electromagnetic mapping of freshwater lenses on small oceanic islands. *Ground Water* 26, no. 2: 191-198.

Vacher, H.L. 1988. Dupuit-Ghyben-Herzberg analysis of strip-island lenses. *Geological Society of America, Bulletin* 100, no. 4: 580-591.

Vacher, H.L., M.J. Wightman, and M.T. Stewart. 1992. Hydrology of meteoric diagenesis: Effect of Pleistocene stratigraphy on the Ghyben-Herzberg lens of Big Pine Key, FL. In *Quaternary Coasts of the United States: Marine and Lacustrine Systems,* Special Publication 48, eds. Fletcher and Wehmiller, 213-19. Tulsa, Oklahoma: SEPM.

Wightman, M.J. 1990. Geophysical analysis and mathematical modeling of freshwater lenses on Big Pine Key, Florida. M.S. thesis, Geology Department, University of South Florida-Tampa.