GROUNDWATER SEEPAGE INTO THE INDIAN RIVER LAGOON AT PORT ST. LUCIE

Ashok Pandit and Clovis Clovis El-Khazen

Department of Civil Engineering, Florida Institute of Technology, Melbourne, FL 32901

Abstract: *A finite element program, GROSEEP, was developed to estimate the groundwater seepage from the surficial aquifer into Indian River lagoon along a selected cross-section in Port St. Lucie, Florida. The model is a general purpose model and can be used at other cross-sections. Model results using a single layer indicate that groundwater seepage could be an important freshwater source into the lagoon. Sensitivity analysis using a three–layer model predicted that among other parameters the presence of windows in the clay layers could significantly affect seepage rates into the lagoon.*

Estuaries are areas where sea water is measurably diluted with freshwater from land drainage. One of the most important characteristics of an estuary is its effectiveness as a habitat for marine species. Since species tolerances for salinity vary, it is possible for salinity to be too high or too low for specific species at certain times of the year. Gunter, Ballard, and Venkataramaiah (1973) found that dilution of salt water by excess fresh water or vice versa can have a definite and sometimes drastic effect on the flora and fauna of the affected area. The Indian River lagoon, a semi-enclosed area where freshwater mixes with saltwater, can be defined as an estuary or as a lagoon. It extends 155 miles from Volusia to Palm Beach County and is approximately 227 square miles in area. The width and depth of the lagoon vary between 0.5 to five miles and three to ten feet, respectively. Circulation and flushing of Indian River lagoon are greatly influenced by freshwater inflows. Principal freshwater sources are natural streams, rainfall, direct land runoff, a number of wastewater treatment plants and groundwater.

Glatzel (1986) estimated annual values for inputs due to precipitation, controlled discharge (through canals), anthropogenic flows, and non-point runoff to be 32.0, 49.0, 26.0 and 13.0 billions of cubic feet, respectively. Glatzel also noted that groundwater input from the surficial aquifer could not be estimated because of lack of sufficient data. South Florida Water Management District (SFWMD, 1987) concluded that only groundwater could account for a relatively constant, background flow of freshwater into the St. Lucie Estuary. Annual seepage was estimated to be between 60 and 600 ft^3 per foot of shoreline. Gu, Iricanin and Trefry (1987), reported that in samples taken from Eau Gallie Harbor interstitial water chlorinity decreased linearly from 10700 ppm to 3500 ppm over a length of a core approximately 11.8 inches long. This decrease suggested that groundwater may be seeping through the sediments. The results of these studies, indicating that groundwater flow could be a major freshwater input into the lagoon, lead to the present research study.

Indian River lagoon has two watersheds: a natural watershed formed by natural topographic highs on both sides of the lagoon, and a more extensive watershed drained by several canals that link the mainland and the barrier islands to the lagoon. The boundaries of the natural watershed are generally considered to be the Atlantic Coastal Ridge on the mainland and the high ridge in the barrier islands east of the lagoon. Since water table elevations usually conform to the natural topography, the groundwater divide in the surficial aquifer is considered to be along these ridge lines. The direction of regional groundwater flow in the surficial aquifer, within the confines of the groundwater divides on either side of the lagoon, is perpendicular to the lagoon (Toth, 1987). Thus, the surficial aquifer can provide a continuous flow of groundwater into the lagoon and act as a non-point source.

METHODS—Groundwater seepages can be estimated by solving partial differential equations that describe the conservation of fluid mass during flow through a porous medium. A detailed description of these equations is provided by Pinder and Gray (1977). The equations are solved by using numerical methods such as the finite difference or the finite element methods. Eyre (1985) simulated the flow of groundwater and the effects of future groundwater development by using a two-dimensional finite element model. Attia and co-workers (1986) used a two-dimensional finite element model to simulate groundwater flows in the aquifer underlying the Nile Valley of Egypt. A general purpose Galerkin two-dimensional finite element model developed by Pandit (1982) was also used to predict steady and unsteady groundwater flow rates below an impervious dam. The results from this model were quite close to analytical results. In this study, a finite element model GROSEEP (Groundwater Seepage) was developed to quantify the non-point groundwater flow into the lagoon. GROSEEP is a modified version of the model developed by Pandit (1982).

DESCRIPTION OF SELECTED SITE AND LITHOLOGY—The subsurface system in central coastal Florida consists of a surficial aquifer and the confined Floridan Aquifer, separated by the relatively impermeable Hawthorn Formation. Groundwater levels in the surficial aquifer, along the groundwater flow direction, are required to operate the finite element model, GROSEEP. A section on the southern end of St. Lucie County was selected for this study after assessment of all available data (Fig. 1). This section was selected mainly because of the existence of five wells, STL 173, STL 174, STL 175, STL 176, and STL 177, which were located along the direction of regional groundwater flow. Three additional two inch diameter PVC pipe shallow monitoring wells, IRL 1 (Indian River Lagoon 1) through IRL 3, were installed by the authors on the barrier island to determine the location of the water-table-divide on the east side of the lagoon. Well IRL 4 was installed on the mainland to pinpoint the location of the water table on the west side of the lagoon. An added advantage in using this cross-section was that groundwater elevation in wells STL 175 and STL 176 had been measured by a water stage recorder from March 1975 to October 1978 by the USGS and these data were available for analysis. The average monthly groundwater elevations in STL 176 for 1975 and 1976 are shown in Table 1.

TABLE 1. Average monthly groundwater elevation in STL 176 groundwater elevations (ft.) (above MSL)

Year	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.
1976	11.8	11.5	11.3	11.4	11.5	12.5	12.1	11.9	12.6	13.4	13.5	13.3
1977	13.3	13.2	12.9	12.3	11.6	11.8	11.1	10.7	12.7	12.6	12.9	13.6

TABLE 2. Seepage values for h2 = 0.5 ft., d1[a] = 30.0 ft., d2[a] = 10.0 ft., d3[a] = 120.0 ft., SS = 0

Case No.	h1 (ft.)	KH1[b] (ft./day)	KH2[b] (ft./day)	KH3[b] (ft./day)	KV1[b] (ft./day)	KV2[b] (ft./day)	KV3[a] (ft./day)	Seepage (ft.3/day-ft.[c])
1	15.00	50.00	0.05	4.15	50.00	0.05	0.27	21
2	15.00	50.00	0.05	14.15	50.00	0.05	0.27	13
3	15.00	50.00	0.05	4.15	10.00	0.05	0.28	20
4	15.00	10.00	0.05	14.15	10.00	0.05	0.28	13
5	15.00	50.00	0.05	4.15	0.10	0.05	0.86	14
6	15.00	10.00	0.05	14.15	0.10	0.05	0.86	10
7	9.00	50.00	0.05	4.15	50.00	0.05	0.27	13
8	9.00	10.00	0.05	14.15	50.00	0.05	0.27	9
9	9.00	50.00	0.05	4.15	10.00	0.05	0.28	12
10	9.00	10.00	0.05	14.15	10.00	0.05	0.28	9
11	9.00	50.00	0.05	4.15	0.10	0.05	0.86	8
12	9.00	10.00	0.05	14.15	0.10	0.05	0.86	7
13	15.00	50.00	0.005	4.15	50.00	0.05	0.27	21
14	15.00	10.00	0.005	4.15	50.00	0.05	0.27	13
15	15.00	10.00	0.005	4.15	50.00	0.005	0.27	6

[a] d1, d2, and d3 are the thicknesses of the sand, clay, and sand and shell layers, respectively

[b] KH1, KV1 are the horizontal and vertical hydraulic conductivity of the sand layer
KH2, KV2 are the horizontal and vertical hydraulic conductivity of the clay layer
KH3, KV3 are the horizontal and vertical hydraulic conductivity of the sand and shell layer per foot of lagoon shoreline

[c] per foot of lagoon shoreline

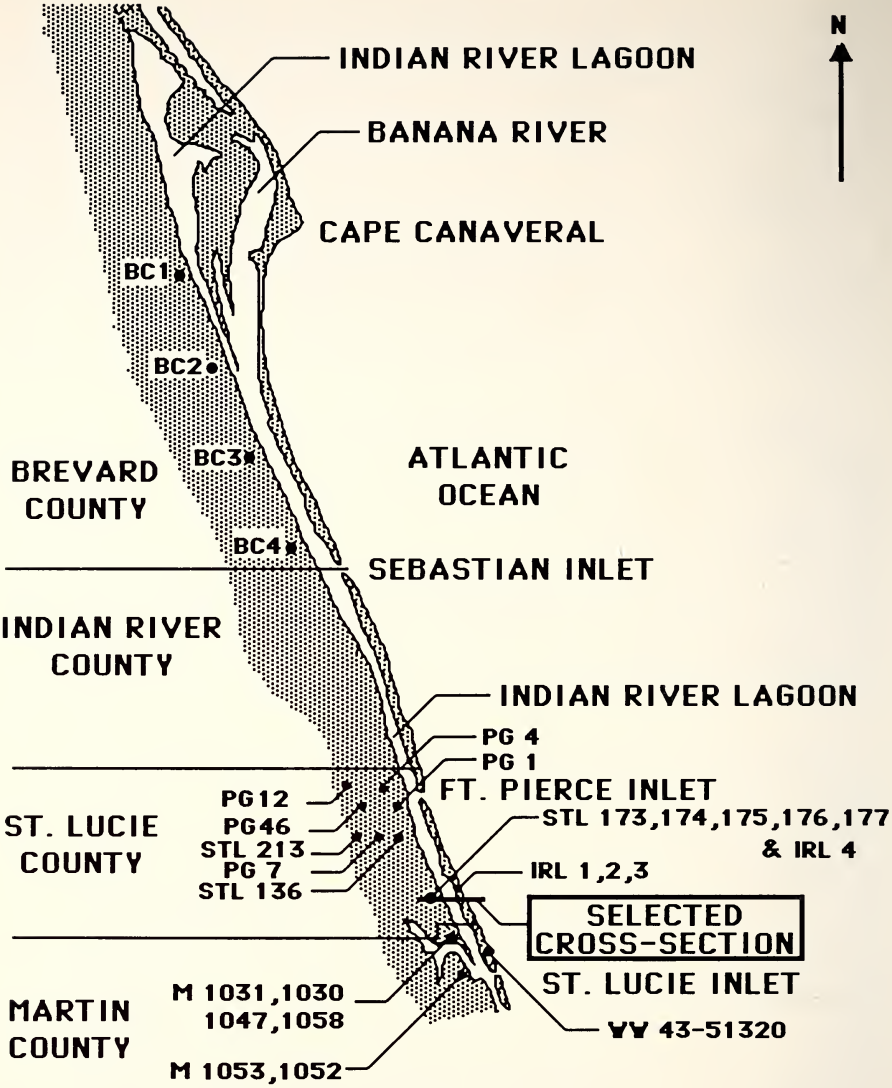

FIG. 1. Location and nomenclature of shallow wells at selected cross-section and other shallow wells along Indian River lagoon, Florida.

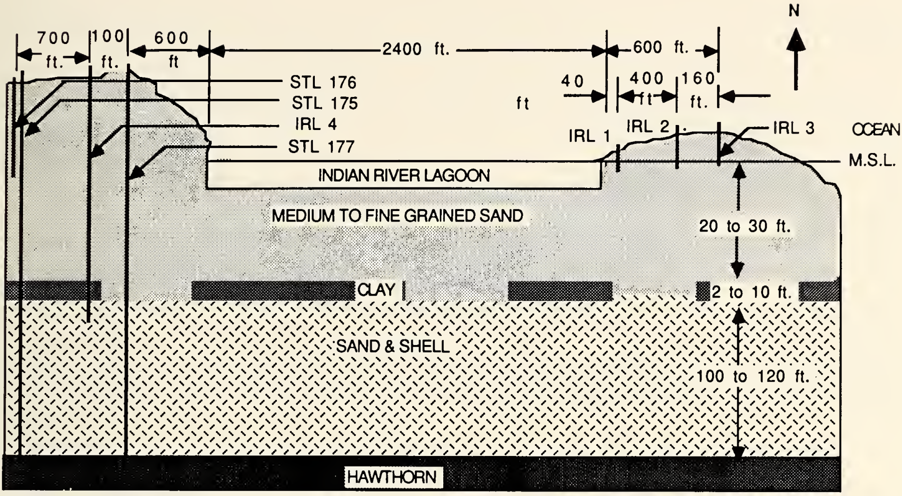

Fig. 2. Description of idealized cross-section and well location.

The natural watershed on the west side of the lagoon is very narrow in the Port St. Lucie area due to the presence of some local hills up to 40 feet high (Fig. 2). Groundwater elevation measurements indicated that although the topographic high exists at the location of well STL 177 the groundwater divide exists at the location of well STL 176. Based on the lithology at the location of STL 175, STL 176, STL 177, reported by Miller (1979) and the lithology at the new wells, IRL 1, IRL 2, IRL 3, and IRL 4 installed by the authors, the hydrogeologic cross-section was idealized for modeling purposes (Fig. 2). The surficial aquifer has a medium to fine grained sand layer, a clay layer, and a sand and shell layer. The medium to fine grained sand layer extends to a depth of approximately 20 to 30 feet from the MSL (mean sea level). It usually consists of some combination of fine-to-medium tan sand, fine-to-medium dark brown sand, medium-grained dark brown sand, gray silty sand, and yellowish or orange silty sand. The lithologic section of STL 175 reported by Miller (1979) shows the presence of a clay layer at a depth of 30 feet to 37 feet from the MSL. Discussion with local drillers indicated that the thickness of the clay layer is usually within two to ten feet and varies considerably within a short distance. The fact that the lithologic description of STL 177 (Miller 1979) does not report the presence of a clay layer supports this observation. It is possible that the clay layer was too thin to be located by split spoon samples at this location. The sand and shell layer has a thickness of about 100 feet to 120 feet and connects the clay layer to the Hawthorn Formation. The percentage of shells in the sand and shell layer increases from about 75 percent to 90 percent with increasing depth. The distance between STL 175 and STL 176 is 13 feet.

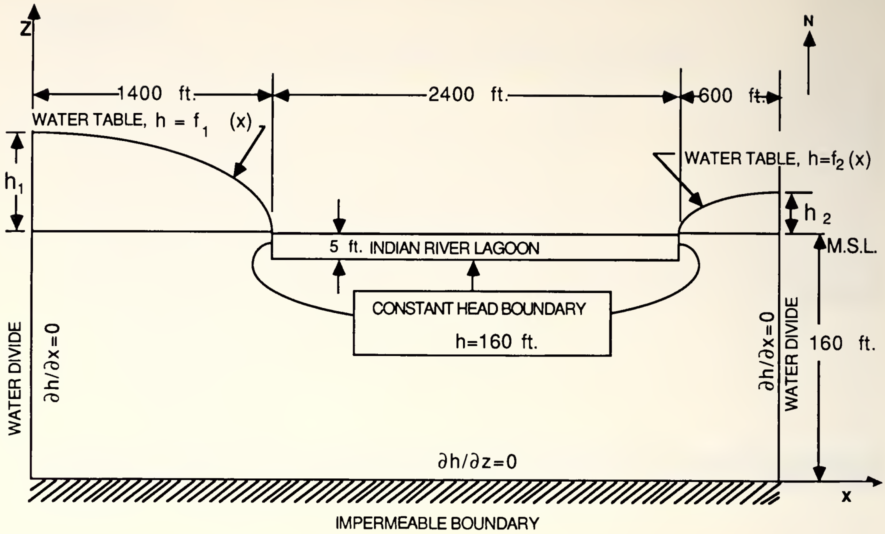

FIG. 3. Region size and boundary conditions assuming water-table-divide in the barrier island.

RESULTS AND DISCUSSION—The partial differential equation that describes unsteady groundwater flow in a homogeneous but anisotropic medium is:

$$K_{xx}(\partial^2h/\partial x^2) + K_{zz}(\partial^2h/\partial z^2) = S_s\partial h/\partial t \qquad (1)$$

in which K_{xx}, K_{zz} (L/T) are the hydraulic conductivities of the aquifer in the x and z directions, respectively; h(L) is the freshwater hydraulic head; $S_s(L^{-1})$ is the specific storage of the aquifer; t is time; and x, z are the spatial coordinates.

There are two ways to idealize the cross-section shown in Fig. 2. One way would be to bound the cross-section between the water table divides at the mainland and the barrier island. Groundwater measurements indicated that the water-table divide in the barrier island is approximately at the location of well IRL 3. The boundary conditions for the idealized cross-section between the water table divides (Fig. 3) are based on the following assumptions: 1) The shallow aquifer extends up to the Hawthorn Formation which is 160 feet below MSL. 2) A water divide exists at the location of well STL 176 in the mainland and at the location of well IRL 3 in the barrier island. 3) The Hawthorn Formation is impermeable. 4) The water level in Indian River lagoon is at mean sea level. 5) The lagoon has an average uniform depth of five feet at the selected cross section. 6) The density of the lagoon water is the same as the density of the freshwater. The boundary conditions for this idealized cross-section can be mathematically stated as follows:

$$\partial h/\partial x(0, z, t) = 0 \tag{2}$$
$$h(0,160,t) = h_1 + 160 \tag{3}$$
$$h(x, 160, t) = f_1(x) + 160 \qquad (0 \leq x \leq 1400) \tag{4}$$
$$h(1400, z, t) = 160.0 \qquad (155 \leq z \leq 160) \tag{5}$$
$$h(x, 155, t) = 160.0 \qquad (1400 \leq x \leq 3800) \tag{6}$$
$$h(3800, z, t) = 160.0 \qquad (155 \leq z \leq 160) \tag{7}$$
$$h(x,160, t) = f_2(x) + 160 \qquad (3800 < x < 4400) \tag{8}$$
$$h(4400, 160, t) = h_2 + 160 \tag{9}$$
$$\partial h/\partial x(4400, z, t) = 0 \tag{10}$$
$$\partial h/\partial z(x, 0, t) = 0 \tag{11}$$

In equations (3) and (9), h_1 and h_2 are the aquifer thicknesses above MSL in wells STL 176 and IRL 3, respectively. In equations (4) and (8) f_1 and f_2 represent the functions used to determine the water table elevations above MSL.

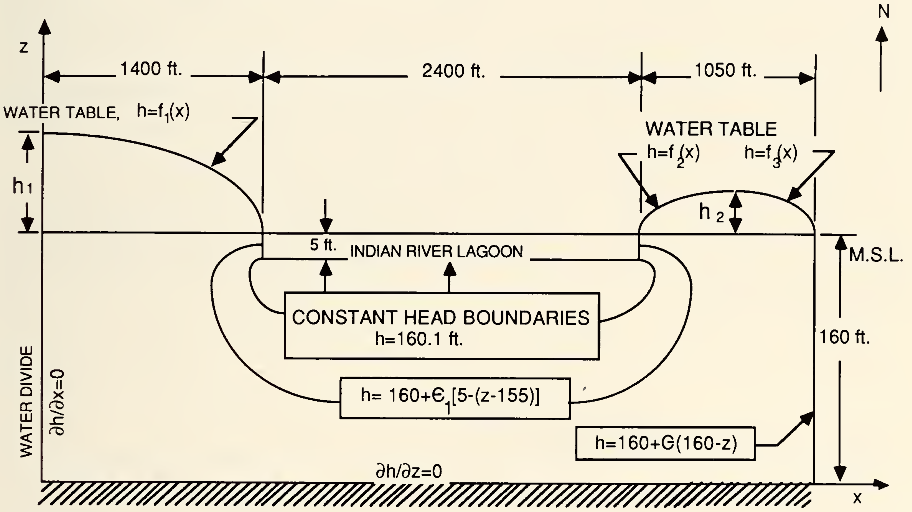

FIG. 4. Region size and boundary conditions with region extended to the Atlantic Ocean.

A second way of idealizing the cross-section would be to bound the region from the water-table-divide on the mainland to the ocean as shown in Fig. 4. The boundary conditions for this idealized cross-section are based on the same assumptions stated earlier with two exceptions: 1. The right boundary of the previous idealization (which was the water-table-divide on the barrier island) has been replaced by the ocean boundary. This ocean boundary represents a sharp interface between the fresh water and sea water. Similarly, the boundaries separating the lagoon from the aquifer are also sharp interface boundaries because they separate the saline lagoon water from the fresh water in the aquifer. 2. The densities of the sea water and lagoon water are no longer assumed to be equal to the density of fresh water. Therefore, the mathematical description of the boundary conditions for this idealization is the same as the previous description with the following exceptions:

$$h(1400, z, t) = 160 + E_1[5-(z-155)] \qquad (155 \leq z \leq 160) \tag{12}$$

$$h(x, 155, t) = 160.1 \qquad (1400 \leq x \leq 3800) \tag{13}$$

$$h(3800, z, t) = 160 + E_1[5-(z-155)] \qquad (155 \leq z \leq 160) \tag{14}$$

$$h(x, 160, t) = f_3(x) \qquad (4400 \leq x \leq 4850) \tag{15}$$

$$h(4850, z, t) = 160 + E(160-z) \tag{16}$$

In which:

$$E = (R_s-R_f)/R_f, \tag{17}$$

$$E_1 = (R_1-R_f)/R_f, \tag{18}$$

f_3 is the function used to define the water table elevation on the barrier island (Fig. 4), and R_s, R_1 and R_f are the respective densities of the sea water, lagoon water, and fresh water. The values of E and E1 were computed to be 1.025 and 1.02, respectively. Note that the hydraulic head prescribed in Equation (13) is 160.1 ft (instead of 160.0 ft prescribed in Equation (7) because the pressure head produced by 5 ft of lagoon water is equivalent to the head produced by 5.1 ft of fresh water. Note that the boundary conditions at the vertical boundaries separating the lagoon and the aquifer have also been redefined in equations (12) and (14) because of the density differences between the lagoon and fresh water. Similarly, the presence of heavier ocean water leads to the boundary condition defined in equation (16).

Finite Element Mesh: The idealized cross-section between the water-table-divide and the ocean was discretized by the finite element mesh shown in Figure 5. A similar mesh was used for the idealized cross-section between the water-table-divides.

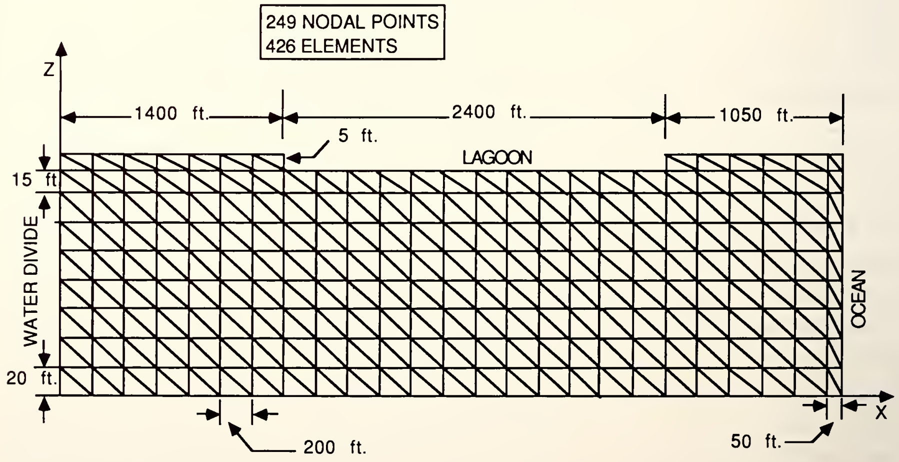

FIG. 5. Finite element mesh used for the idealized cross-section between the water-table-divide and the ocean.

Estimated Groundwater Seepage Using Single-Layer Model: The boundary conditions described by equations (2) through (11) were used to estimate monthly groundwater seepages for 1976 and 1977. The value of h_1 (Eq. 2) was selected to be equal to the average monthly groundwater elevation in STL 176 (Table 1). The values of h_2 (Eq. 9) were not known for this period. A value of 0.5 feet was selected for h_2 based on recent measurements. Sensitivity analysis indicated that the main seepage was from the mainland and that changes in values of h_2 did not significantly alter the total seepage. The functions f_1 and f_2 used to obtain the water-table configurations are parabolic. Function f_1 was derived using the water-table elevations in the lagoon, STL 176 and IRL 4. Function f_2 was derived using the water-table elevations in IRL 1, IRL 2 and IRL 3. Since the initial hydraulic head distribution was unknown, the initial conditions were simulated as follows: equation (2) was solved for $S_s = 0$ and $h_1 = 12.2$ feet (the measured mean monthly groundwater elevation in December, 1975) and the nodal hydraulic heads were calculated. These calculated values were used as initial conditions for solving equation (1) for the period between January, 1976, and December, 1977. The average values of K_{xx} and K_{zz} were estimated to be 12.5 and 0.25 ft./day. (El-Khazen, 1988) and are close to those estimated by Nealon and co-workers (1986).

The annual seepages from the mainland for 1976 and 1977 were calculated to be 1438 ft^3 and 1625 ft^3 per foot of lagoon shoreline, respectively. The annual seepage from the barrier island in 1976 and 1977 was estimated to be 80 ft^3 per foot of lagoon shoreline. If the groundwater seepage into the lagoon, all along the shoreline, is the same as that estimated at Port St. Lucie, then the annual seepage into the lagoon from the mainland (assuming a shoreline of 155 miles) would be 1.2 billion cubic feet in 1976 and 1.33 billion cubic feet in 1977.

Estimated Groundwater Seepage Using Three-Layer Model: Groundwater seepages using a three-layer model were obtained by solving equation (1) and using the boundary conditions described by equations (2) through (5), equation (11) and equations (13) through (18). Sensitivity analyses were conducted to determine the effect of soil permeabilities, groundwater elevations, layer thicknesses and window locations in the clay layers on seepage rates. The physical parameters as well as the calculated seepages (per foot of lagoon shoreline) are shown in Tables 2 through 4. It can be observed from the values presented in Table 2 that the seepage entering the lagoon is affected to a large extent by K_{H1} (the horizontal hydraulic conductivity of the top sand layer) h_1 (the groundwater elevation at the water table divide in the mainland), d2 (the thickness of the clay layer) and KV2 (the vertical hydraulic conductivity of the clay layer).

Comparisons of the seepage values shown in Table 3 indicate that a thicker clay layer causes reduced seepage. Comparisons of the seepage values in Table 4 indicate that the presence of windows in the clay layer increases the seepage (see Fig. 2 for location identification). Results also indicate that a clay window at location B significantly changes the seepage entering the la-

Table 3. Seepage values for $h_1 = 15.0$ ft., $h_2 = 0.5$ ft.

Case No.	dl (ft.)	d2 (ft.)	d3 (ft./day)	KH1 (ft./day)	KH2 (ft./day)	KH3 (ft./day)	KV1 (ft./day)	KV2 (ft./day)	KV3 (ft./day)	Seepage (ft.^3/day-ft.[a])
1	30.0	10.0	120.0	50.00	0.05	4.15	50.00	0.05	0.27	21
2	30.0	10.0	120.0	10.00	0.05	14.15	50.00	0.05	0.27	13
16	20.0	20.0	120.0	50.00	0.05	4.15	50.00	0.05	0.27	17
17	20.0	20.0	120.0	10.00	0.05	14.15	50.00	0.05	0.27	11
18	30.0	20.0	110.0	50.00	0.05	4.15	50.00	0.05	0.27	20
19	30.0	20.0	110.0	10.00	0.05	14.15	50.00	0.05	0.27	11

[a]per foot of lagoon shoreline

Table 4. Seepage values for hl = 15.0 ft., h2 = 0.5 ft., dl = 30.0 ft., d2 = 10.0 ft., d3 = 120.0 ft

Case	Clay Window Location	KH1 (ft./day)	KH2 (ft./day)	KH3 (ft./day)	KV1 (ft./day)	KV2 (ft./day)	KV3 (ft./day)	Seepage (ft.^3/day = ft.[a])
1	N/A	50.00	0.05	4.15	50.00	0.05	0.27	21
2	N/A	10.00	0.05	14.15	50.00	0.05	0.27	13
20	A	50.00	0.05	4.15	50.00	0.05	0.27	21
21	A	10.00	0.05	14.15	50.00	0.05	0.27	14
22	B	50.00	0.05	4.15	50.00	0.05	0.27	28
23	B	10.00	0.05	14.15	50.00	0.05	0.27	16
24	C	50.00	0.05	4.15	50.00	0.05	0.27	21
25	C	10.00	0.05	14.15	50.00	0.05	0.27	13
26	A,B,C	50.00	0.05	4.15	50.00	0.05	0.27	28
27	A,B,C	10.00	0.05	14.15	50.00	0.05	0.27	17

[a]per foot of lagoon shoreline

goon while clay windows at locations A and C do not.

Summary and Conclusions—The model, GROSEEP, can be used to predict groundwater seepages. Seepages calculated using a single layer model indicate that groundwater could be an important freshwater source into the lagoon. Sensitivity analyses using the three-layer model indicates that an effort should be made to determine the location of windows in the clay layer and the depth of the clay layer more precisely. The vertical hydraulic conductivity of the clay layer and the horizontal conductivity of the sand layer also significantly influence seepage into the lagoon.

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