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Article

Analytical Model of Salt Budget in the Upper Indian River Lagoon, Florida USA

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Abstract : Effect of freshwater discharge on the long-term salt balance in the Northern and Central Indian River Lagoon (IRL) is successfully simulated by a new analytical solution to a water balance-based one-dimensional salt conservation equation. Sensitivity tests show that the salinity levels drop abruptly even during the dry season (November to May) due to the high surface runoff discharge caused by tropical storms, depressions, and passage of cold fronts. Increasing surface runoff and direct precipitation has risen by ten times, lowering the salinity level down to 12 psu in the Northern Central zone, and to 17 psu in the Northern zone. However, the salinity level in the Southern Central zone has decreased to 25 psu. High sensitivity of the Northern Central zone to freshwater discharge can be partially explained by a rapid urbanization in this zone. During the dry season, less sensitivity of the Southern Central zone to the increased surface runoff is attributed to the proximity of the zone to the Sebastian Inlet and a strong diffusion condition possibly resulting from the seawater intrusion to the surficial aquifer at the Vero Beach. During the wet season, however, the whole study area is highly sensitive to freshwater discharge due to the weak diffusion conditions. High sensitivity of the IRL to the given diffusion conditions guarantees that the freshwater release occurs during strong wind conditions, achieving both flood control in the drainage basin and a proper salinity regime in the IRL.

Key words : salt budget, diffusion coefficient, sensitivity test, urbanization, lagoon

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1. Introduction

The Indian River Lagoon (IRL) is one of the most productive lagoon ecosystems along the east coast of Florida having an average depth of about 1.4 m, a narrow width of about 2 to 4 km, and an elongated length of about 195 km (Fig. 1). The commercial shellfish (oyster and hard clam) fishery in the IRL is an important income resource in the state of Florida. However, for flood control and irrigation in the watershed, large freshwater discharges from canals, creeks, rivers, and non-point sources, such as stormwater runoff and groundwater discharge, can cause harm to the shellfish and ecosystem.

Since the maintenance of a proper salinity regime in the lagoon is critically important to the IRL ecosystem, the study of salt balance is required to assist in the management of the ecosystem and water quality in the IRL (Barile and Rathjen 1986; Esteves and Marshall 1992; Smith 1993; Rao 1987; Provancha *et al.* 1992; Zarillo and Surak 1994).

However, few studies of the long-term salt balance in combination with the long-term water balance have been applied in the IRL. To investigate anthropogenic influences of increased freshwater discharge from the greatly expanded watershed, a newly developed analytical model is applied in the IRL. The main goal in this work is to quantify the effect of freshwater on the salinity distribution at the seasonal (wet and dry) and annual time scales in the IRL. The influence of a large volume of groundwater from the surficial aquifer to the salinity regime can also be examined by the sensitivity tests.

The climate of the IRL is transitional between the temperate and subtropical climates, since the IRL is closely adjacent to the Atlantic Ocean and Gulf Stream passes offshore throughout the entire length of the IRL.

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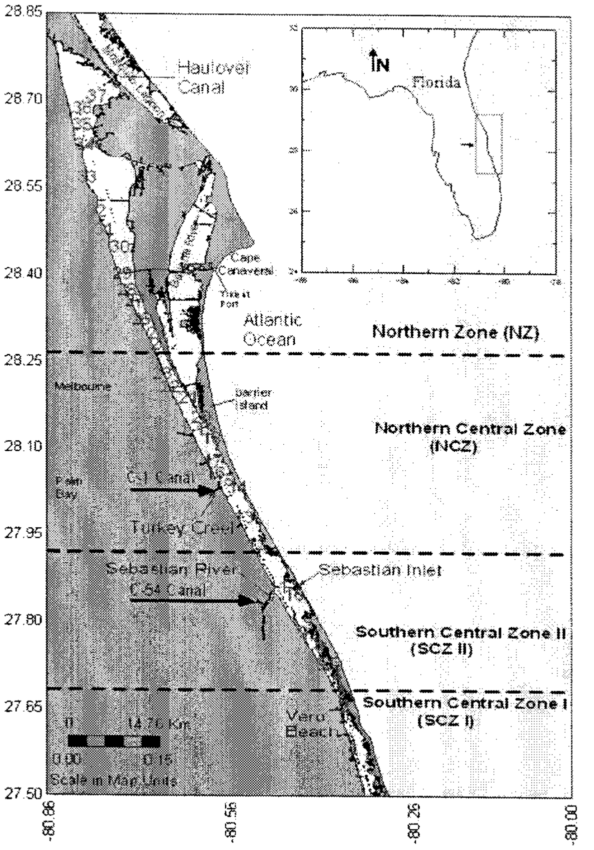

Fig. 1. Location of the study area. Arabic number (1 to 37) denotes salinity measuring stations.

The summer months (June to October) are warm, humid and rainy, and winters are relatively mild with occasional freezes due to the cold front passage. The cold fronts occasionally stall over the northern part of the IRL. Thirty year long data (1951-1980) from National Oceanic Atmospheric Administration (NOAA) shows mean annual air temperatures ranging from 22.1°C to 22.7°C. Summer mean air temperatures of 27.2°C-27.8°C are relatively uniform throughout the IRL. The lowest air temperatures of 15.7°C-18.2°C occur in January (Rao 1987; Kim 2001).

This study area has two distinctive seasons, a wet season from June to October and a dry season from November to May. Severe storms usually occur in the winter and spring seasons. In late September and early October, slow-moving or stalled frontal systems occasionally produce heavy rainfall of 25.4 to 50.8 cm within a week. More than 50 percent of the total rainfall is attributed to the thunderstorms that occur at an average of 75 days each year. The tropical depressions, tropical storms, and hurricanes during the summer and fall season produce substantial rainfall in the IRL basin (Rao 1987; Knowles 1995).

Annual mean pan evaporation for 1992-1998 is 173 cm at Vero Beach. Multiplying the pan evaporation coefficient of 0.80 given by Glatzel (1986) gives a potential evaporation rate of about 138 cm for the IRL, which approximately equals the annual rainfall over the IRL (Kim 2003). However, in the closed water body, the role of evaporation could be important in the salt budget. Mosquito Lagoon and Banana River show high salinity levels even during the rainy summer, since they have small surface runoff and limited exchange with the ocean (Provancha *et al.* 1992). For the stagnant waters in the closed basin, the higher air temperature in summer enables the evaporation to accumulate enough to eventually exceed precipitation levels (Glatzel 1986; Kim 2001).

Wind speed and direction vary seasonally, with southerly and southeasterly winds during the wet season, and northerly and northwesterly winds during the dry season. Annually, easterly winds from the Atlantic Ocean is predominate (Glatzel 1986). During the summer season, southerly-southeasterly winds are found predominant in the case of daily land-sea breezes. In the dry winter season, the stronger winds result from the passage of cold fronts in intervals of about 5 days (Henry *et al.* 1994; Zarillo and Surak 1994).

Carter and Okubo (1965) executed a dye release experiment in the northern IRL, Mosquito Lagoon, and Banana River and found that the surface current speed was about 4.5%. The intensity of turbulent mixing in the northern IRL was found to be smaller than in Mosquito Lagoon and Banana River. No reason was found. However, this may be partially explained by the accumulated evaporation effect on the closed water bodies (Glatzel 1986) in combination with the strong lateral seawater intrusion into the Mosquito Lagoon and southern region of the Banana River (Toth 1987). Dill (1974) compared the steady-state solution for current velocity with the current and wind measurements in the northern IRL, Mosquito Lagoon, and Banana River, and found that the circulation in these shallow lagoons was governed by wind stress and its associated water elevation. The current speed was found to be 0.28-1.80% of the wind speed. Peter (1996) showed the current speed in the NCZ was 2.5 ± 0.7% of the surface wind speed measured at a tower 10 m above ground at Melbourne Airport. Usually, although wind-driven currents are highly complicated in pattern, the current speed is expected to be around the order of 3% of the wind speed (Csanady 1982).

The offshore tidal range of semi-diurnal tide (M_2) is 0.99 m. The spring tidal range at the mouth of the Sebastian

Inlet is 0.78 m with a mean range of 0.43 m. Since the shallow depth of the IRL damps the tide at some distance from the inlet, the principal M_2 has an amplitude of only 0 to 5 cm in the northern IRL. The tidal currents are strong only near the inlets and peter out within a few kilometers of the inlets. The minimum tidal currents occur primarily north of Turkey Creek and near the narrow zone at Vero Beach. They are located about 12 km north and south of the Sebastian Inlet, respectively. Due to the narrow opening of the Sebastian Inlet, most of tidal signals are filtered. The tidal excursion is on the order of 1.6-3.2 km at the Sebastian Inlet. The tidal excursion length can be much shorter at neap tide. Below the Sebastian Inlet, a southward net flow of the order of 1-2 cm/sec was suggested by averaging the tidal current (Smith 1987, 1990).

Several numerical models have been applied to simulate the salinity structure, tide and wind-driven circulation. A lagoon-wide one-dimensional model by Sheng, *et al.* (1990) suggested that it would take about 30 days for the freshwater and seawater to reach a salinity equilibrium in the tidally affected regions. Under conditions of high winds and tidal effect, it takes only about 5 to 10 days to reach a steady state in the salinity regime. A three-dimensional model by Sheng *et al.* (1993), Zarillo and Surak (1994), and Smith (1989, 1993) provided an understanding of some dynamics in certain areas of the IRL. However, none of them can explain the various types of pressure exerted on the IRL, particularly the effect of groundwater seepage on the salinity regime.

2. Model equation and solution

The one-dimensional salt conservation equation with the precipitation, evaporation, surface runoff, and groundwater discharge can be stated as (Kim 2001) by extending that derived by Officer (1976):

$$\frac{d^2s}{dx^2} - \frac{(Bx+u_0)}{K_x}\frac{ds}{dx} - \frac{B}{K_x}s = \frac{w_g s_g}{hK_x} \tag{1}$$

where x is the longitudinal coordinate, K_x longitudinal eddy dispersion coefficient, w_g groundwater discharge, s_g groundwater salinity, and u_0 is the constant. The constant B in the equation (1) is determined by

$$B = \frac{P}{h} - \frac{E}{h} + \frac{w_g}{h} + \frac{R}{b} \tag{2}$$

where P is precipitation, E evaporation, R surface runoff, h depth, and b width.

The general solution to equation (1) is given by Kim (2001)

$$s(x) = \left(C_4 - C_2\sqrt{\frac{\pi}{2C}}e^{\frac{D^2}{2C}}\left(1 + erf\left(\frac{D}{\sqrt{2C}}\right)\right.\right.$$
$$\left.\left.\left. -erf\left(\frac{Cs+D}{\sqrt{2C}}\right)\right)\right)e^{\frac{Cx^2}{2}+Dx} + \frac{w_g s_g}{hB} \tag{3}$$

where $C=B/K_x$, $D=u_o/K_x$, and $erf(x)$ is an error function, defined by

$$erf(x) = \frac{2}{\sqrt{\pi}}\int_0^x e^{-t^2}dt = \frac{2}{\sqrt{\pi}}\left(x - \frac{x^3}{1!3} + \frac{x^5}{2!5} - \frac{x^7}{3!7} + \ldots\right) \tag{4}$$

The constants C_4 and C_2 are determined by the assigned boundary conditions.

Boundary conditions $s(x=0)=s_0$ at one end of a certain segment and $s(x=L)=s_L$ at the other end of the given segment provide a final closed-form solution,

$$s(x) = \left(s_0 - \frac{w_g s_g}{hB} - C_2\sqrt{\frac{\pi}{2C}}e^{\frac{D^2}{2C}}\left(erf\left(\frac{D}{\sqrt{2C}}\right)\right.\right.$$
$$\left.\left.\left. - erf\left(\frac{Cx+D}{\sqrt{2C}}\right)\right)\right)e^{\frac{Cx^2}{2}+Dx} + \frac{w_g s_g}{hB} \tag{5}$$

where

$$C_2 = \frac{s_0 e^{\frac{CL^2}{2}+DL} - s_L - \frac{w_g s_g}{hB}\left(e^{\frac{CL^2}{2}+DL} - 1\right)}{\sqrt{\frac{\pi}{2C}}e^{\frac{(CL+D)^2}{2C}}\left(erf\left(\frac{D}{\sqrt{2C}}\right) - erf\left(\frac{CL+d}{\sqrt{2c}}\right)\right)} \tag{6}$$

3. Applications

The salinity data have been measured by civilian volunteers weekly and bi-weekly using a salinity titration test kit. The measured data were gathered and summarized by Marine Resources Council of East Florida (MRC 2000). The salinity measuring stations between 1992 and 2000 are seen in Fig. 1.

The analytical solution (5) is now ready to evaluate the monthly, seasonal, and annual salinity distribution as a function of longitudinal distance. To apply the analytical solution to the IRL, the study area is divided into four segments, Northern Zone (NZ), Northern Central Zone (NCZ), Southern Central Zone I (SCZ I), and Southern Central Zone II (SCZ II), since each zone shows a distinctive longitudinal salinity feature. Salinity station 1 is taken as the origin ($x = 0$), and a positive x-direction is aligned to the north.

Table 1. The values of each parameter used to calibrate the analytical model.

Month	SCZ I and SCZ II						NCZ						NZ					
	V_P	V_R	V_G	V_E	V_O	u_0	V_P	V_R	V_G	V_E	V_O	u_0	V_P	V_R	V_G	V_E	V_O	u_0
	($\times 10^6$ m^3/sec)					(cm/sec)	($\times 10^6$ m^3/sec)					(cm/sec)	($\times 10^6$ m^3/sec)					(cm/sec)
1	7	27	78	−5	−106	−1.4	8	19	112	−6	−131	−1.4	13	9	230	−13	−237	−1.8
2	6	28	82	−6	−111	−1.5	7	14	80	−8	−94	−1.0	14	8	202	−17	−210	−1.6
3	8	36	104	−9	−138	−1.9	8	22	126	−11	−144	−1.5	18	11	289	−24	−292	−2.2
4	7	23	67	−11	−83	−1.1	7	14	82	−13	−87	−0.9	18	7	190	−28	−180	−1.4
5	6	18	52	−13	−65	−0.9	6	10	61	−15	−64	−0.7	15	3	77	−33	−67	−0.5
6	13	41	100	−12	−146	−2.0	13	24	100	−14	−127	−1.3	26	10	264	−30	−280	−2.1
7	10	34	82	−12	−103	−1.4	13	31	130	−14	−147	−1.6	32	10	270	−31	−255	−1.9
8	12	48	117	−10	−160	−2.1	17	31	132	−12	−158	−1.7	31	13	348	−27	−344	−2.6
9	12	60	145	−10	−202	−2.7	18	41	174	−12	−216	−2.3	31	12	323	−27	−326	−2.5
10	11	77	186	−7	−277	−3.7	14	56	234	−8	−307	−3.2	37	16	440	−18	−502	−3.8
11	5	44	128	−6	−177	−2.4	4	31	183	−8	−218	−2.3	9	12	313	−17	−334	−2.5
12	4	29	84	−5	−115	−1.5	4	13	76	−6	−92	−1.0	9	9	245	−13	−260	−2.0
Wet	12	52	126	−10	−178	−2.4	15	37	154	−12	−191	−2.0	32	12	329	−26	−341	−2.6
Dry	6	29	85	−8	−114	−1.5	6	18	103	−10	−119	−1.2	14	8	221	−21	−226	−1.7
Annual	8	39	102	−9	−140	−1.9	10	26	124	−11	−149	−1.6	21	10	266	−23	−274	−2.1

V_P = Precipitation at the lagoon surface
V_R = Total surface runoff from the watershed to the IRL
V_G = Groundwater seepage into the IRL
V_E = Evaporation from the lagoon surface
V_O = Net water transport from the lagoon

Substituting all calculated parameters into the analytical solution (5) and adjusting the eddy dispersion coefficient K_x gives an axial salinity distribution. Using the water balance budget previously calculated by Kim (2003), Knowles (1995), and Swazenski *et al.* (2001), all parameters for the simulation are summarized in Table 1. The groundwater is assumed to be freshwater of 1 psu for all simulations, since the groundwater salinity data have not been published.

The relative error (RE) is defined as the difference between the analytically calculated salinity values (s_c) and the measured salinity data (s_m) with the number of data points N,

$$RE = \sum_{i=1}^{N} \frac{|s_{c,i} - s_{m,i}|}{s_{m,i}} \times 100 \qquad (7)$$

Calibration runs continued, until the RE reaches the level of less than 10%. To examine the average distribution of the error, root mean squared error (RME) was also calculated by (Tuma 1987)

$$RME = \sqrt{\frac{1}{N}\sum_{i=1}^{N} (s_{c,i} - s_{m,i})^2} \qquad (8)$$

After completing the calibration within 10% RE, sensitivity tests by adjusting each parameter up or down, were executed to identify the degree of contribution for each parameter.

Wet Season Simulation (Fig. 2)

More freshwater discharge is expected to decrease the

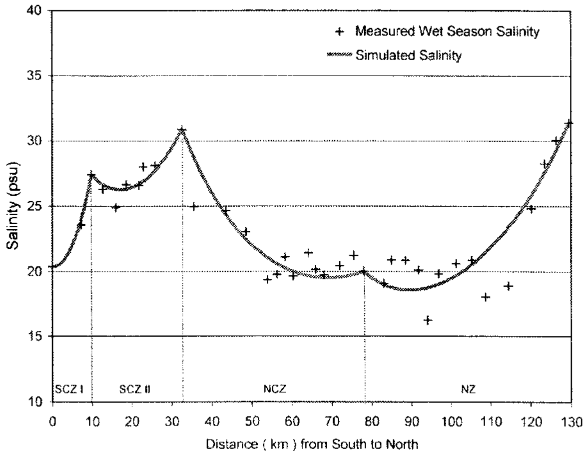

Fig. 2. Simulation of the measured wet season salinity.

Table 2. Summary of the calibrated diffusion coefficients and relative error.

	K_x (10^6 cm^2/sec)				RE	Accuracy	RME
Month	SCZ I	SCZ II	NCZ	NZ	(%)	(%)	(psu)
1	0.70	5.00	0.20	0.60	5	95	1.60
2	0.30	5.00	0.17	0.70	5	95	1.64
3	0.30	7.00	0.30	5.00	5	95	2.04
4	0.30	2.00	0.25	1.00	8	92	2.43
5	1.00	0.30	0.60	0.15	5	95	1.88
6	2.00	4.00	0.80	0.25	4	96	1.37
7	0.15	0.41	0.47	0.35	5	95	1.92
8	0.80	0.60	0.70	1.00	8	92	2.18
9	0.50	5.00	0.70	0.45	7	93	2.48
10	0.35	7.00	0.42	0.70	5	95	1.44
11	0.25	0.50	0.38	1.20	7	93	2.19
12	1.50	6.00	0.18	0.80	9	91	2.18
Annual	0.30	1.20	0.40	0.65	4	96	1.24
Wet season	0.30	0.70	0.65	0.50	4	96	1.49
Dry season	0.30	3.00	0.29	0.90	4	96	1.22

salinity levels except for the NCZ. Wet season salinity was simulated up to 96% accuracy with 1.49 psu of RME. The simulated salinity minimum of 18 psu occurred in the NZ. The calibration coefficient, K_x, ranges from 0.30 × 10^6 cm^2/sec at SCZ I to 0.70 × 10^6 cm^2/sec at SCZ II (Table 2).

Dry Season Simulation (Fig. 3)

Relatively small amounts of surface runoff discharge are expected to increase the overall salinity levels in the IRL during the dry season except for the NCZ. The dry season salinity was simulated with an accuracy of 96% and with an RME = 1.22 psu. The calibrated, K_x ranges from 0.30 × 10^6 cm^2/sec at SCZ I to 3.00 × 10^6 cm^2/sec at SCZ II (Table 2). The diffusion coefficient of 3.00 × 10^6 cm^2/sec at SCZ II decreased to 0.70 × 10^6 cm^2/sec during the wet season. In the NZ, the diffusion coefficient of 0.90 × 10^6 cm^2/sec also decreased to 0.50 × 10^6 cm^2/sec in the wet season. However, the dry season coefficient of 0.29 × 10^6 cm^2/sec in the NCZ increased to 0.65 × 10^6 cm^2/sec due to the slightly high salinity level by about 2 psu in the NCZ.

Annual Simulation (Fig. 4)

This scenario simulates the salinity regime on an average annual basis. The simulated salinity is nearly symmetric in the NCZ and NZ. Annually, a high salinity of 30 psu was found to occur at SCZ II and the uppermost region of the NZ. The lowest annual salinity of about 18

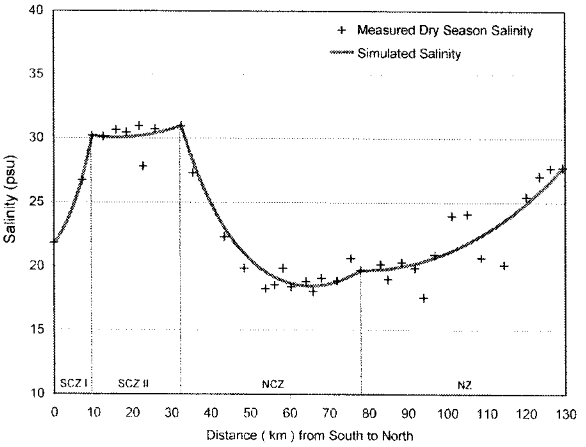

Fig. 3. Simulation of the measured dry season salinity.

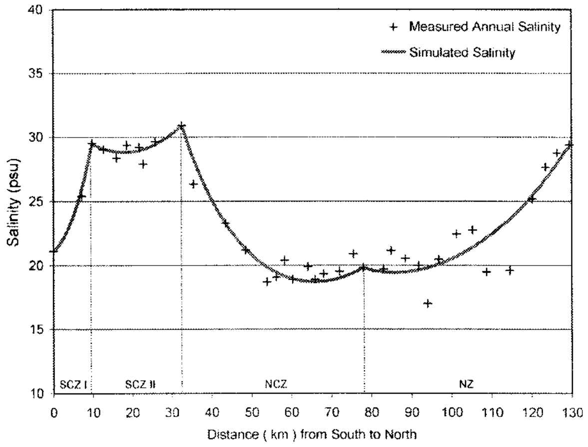

Fig. 4. Simulation of annual salinity.

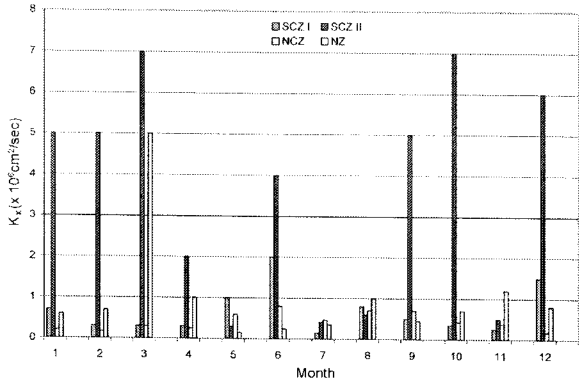

Fig. 5. Spatial and temporal variation of diffusion coefficients for each zone.

psu occurred between 60 to 100 km. The calibrated diffusion coefficients in the SCZ I, NCZ, and NZ are below 2 × 10^6 cm^2/sec except for March. The high diffusion coefficients occurred in the SCZ II due to the highest salinity levels measured (Fig. 5).

4. Sensitivity tests

Using the calibrated diffusion coefficients with an accuracy of 96%, three sensitivity tests for each parameter were executed. Fixed boundary conditions were used for every sensitivity test.

Sensitivity Test : V_R, $V_P = 0$ and $20\ V_R$, V_P

Even during the dry and cold season, eventual high precipitation by storms or stalled cold fronts may cause low salinity levels for a few days to a month. A periodic release of freshwater from the C-1 canal through Turkey Creek causes harm to the IRL ecosystem. Since the discharge from C-54 canal results in a great impact on the IRL ecosystem during hurricanes and tropical storms, St. Johns River Water Management District (SJRWMD) is taking steps to reduce the discharge from the C-1 canal and C-54 canal.

The sensitivity tests for minimum and maximum V_R, V_P were executed seasonally and annually. The completely eliminated surface runoff and precipitation increased the salinity slightly over the whole study area. However, surface runoff and precipitation increased by ten to twenty times, causing the salinity to drop to 13 psu to 9 psu in the NCZ for the wet season (Fig. 6). For the dry season, the NCZ is as sensitive as the wet season. However, the remaining zones are less sensitive to the increased freshwater. Even with the maximum surface water and precipitation, SCZ II remained at 27 psu and SCZ I and NZ maintained 17 psu (Fig. 7). All sensitivity tests for in Figs. 6, 7, and 8 showed that NCZ is the most sensitive to the surface

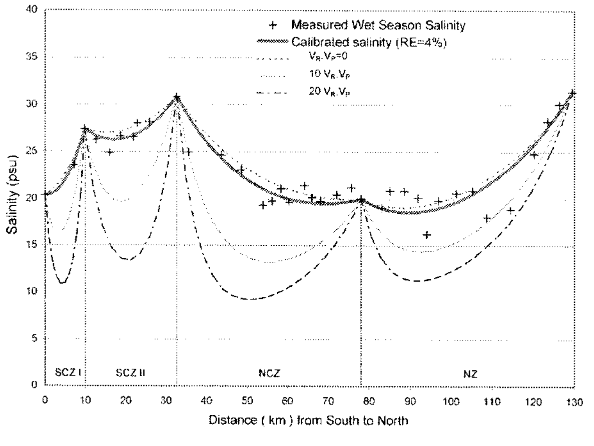

Fig. 6. Sensitivity tests for minimum and maximum V_R and V_P in the wet season.

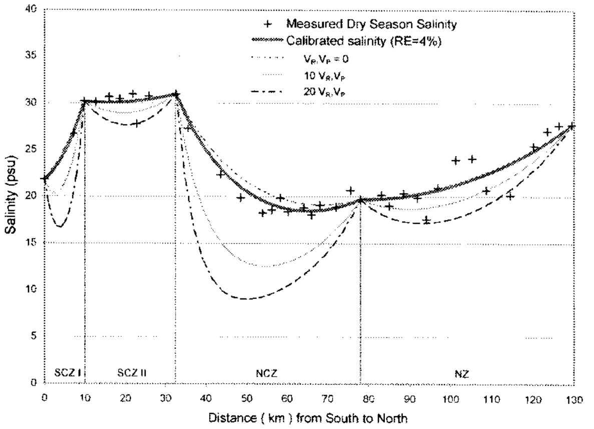

Fig. 7. Sensitivity tests for minimum and maximum V_R and V_P in the dry season.

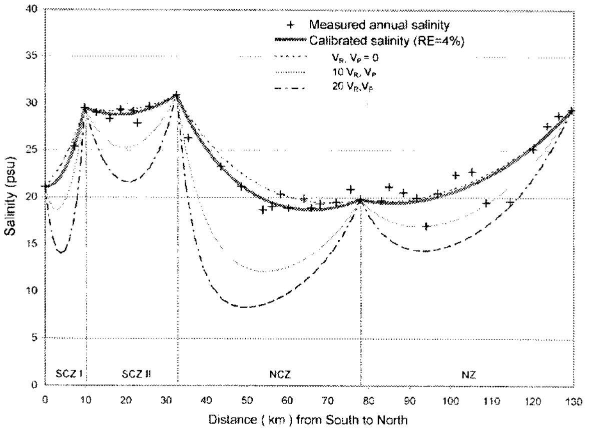

Fig. 8. Sensitivity tests for minimum and maximum V_R and V_P on an annual basis.

runoff in the study area. This means that NCZ has the largest surface runoff due to the artificially expanded drainage basin occurring as a result of urbanization.

Sensitivity Test : $w_g = 0$ and $10\ w_g$

Sensitivity tests for minimum and maximum groundwater discharge with groundwater salinity of 1 psu were executed seasonally (Figs. 9 and 10), and annually (Fig. 11). Since the calibrations were executed for the high groundwater discharge, the sensitivity test for zero groundwater seepage showed that the salinity increased rapidly to the maximum level. Whereas the NCZ is the most sensitive to the fresh groundwater seepage in the dry season and annual sensitivity tests, the NZ is significantly more sensitive than the NCZ in the wet season. This interesting feature can be explained by the fact that the NZ has a smaller drainage basin; therefore, most of the freshwater during the wet season comes from groundwater not from the surface runoff.

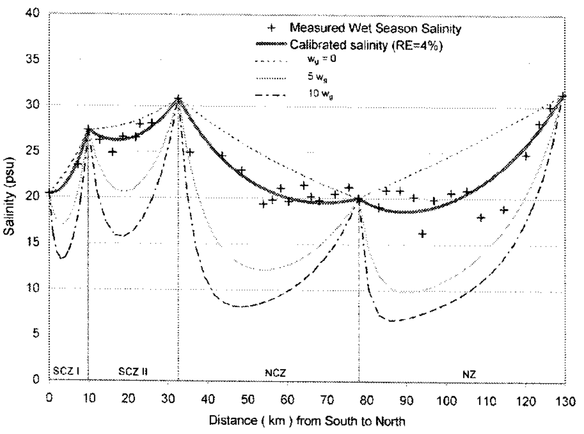

Fig. 9. Sensitivity test for minimum and maximum w_g in the wet season.

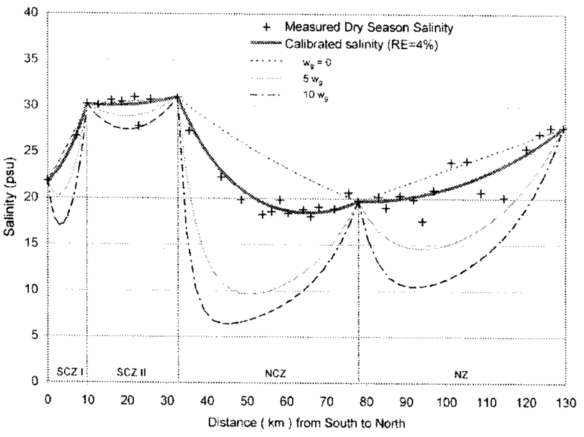

Fig. 10. Sensitivity tests for minimum and maximum w_g in the dry season.

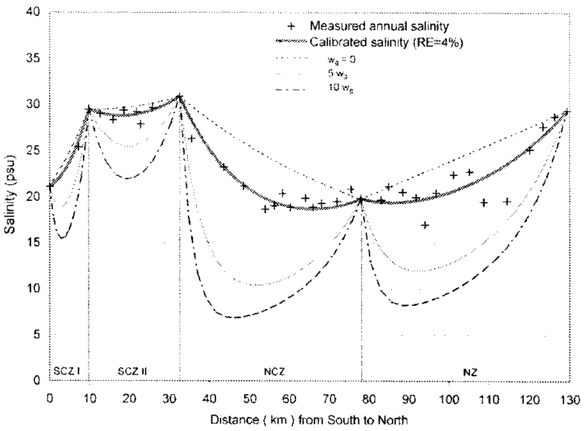

Fig. 11. Sensitivity tests for minimum and maximum w_g on an annual basis.

Sensitivity Test : $K_x = 10^5$ cm²/sec and $K_x = 10^7$ cm²/sec

The whole study area proves to be highly sensitive to the diffusion coefficients. This feature agrees well with actual dynamics in the IRL, and also validates the derived one-dimensional model in this work. A low diffusion coefficient of 10^5 cm²/sec caused the salinity to be lower than 10 psu during the wet season (Fig. 12) and to be about 11 psu during the dry season (Fig. 13). The reduced effect of diffusion by weak wind conditions and neap tides may result in significantly lower salinity over the whole area. For the annual condition of the high diffusion, the whole study area reached the maximum salinity level (Fig. 14). Freshwater release from the drainage basin for flood control purposes is recommended during strong wind conditions. Particularly, strong southerly winds are

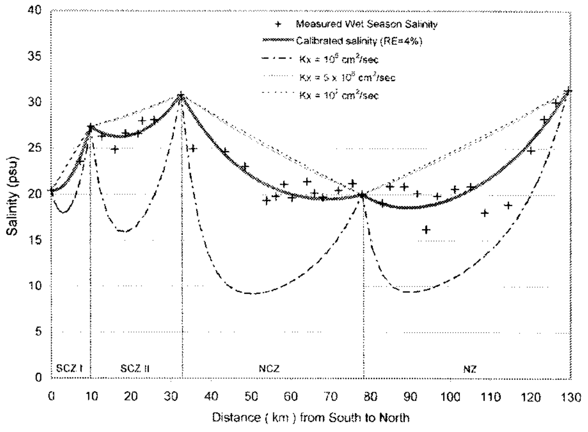

Fig. 12. Sensitivity tests for minimum and maximum K_x in the wet season.

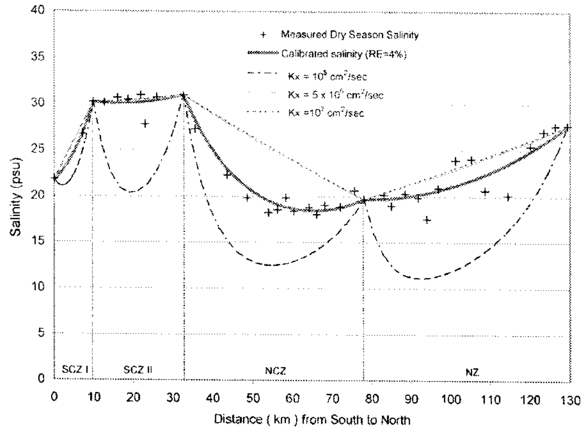

Fig. 13. Sensitivity tests for minimum and maximum K_x in the dry season.

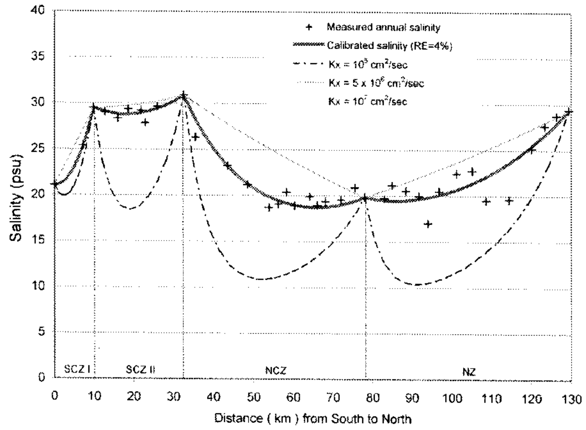

Fig. 14. Sensitivity tests for minimum and maximum K_x on an annual basis.

preferable for flood control and the maintenance of proper salinity levels.

5. Discussion

In order to quantify the effect of freshwater on the salinity distribution at the seasonal (wet and dry), and annual time scales in the IRL, the magnitude of each controlling parameter for the salinity regime needs to be estimated. The salinity in the IRL was successfully simulated by applying a newly-developed solution piecewise to the four-segmented zones. Data analysis and simulations showed that each zone had distinctive salinity features according to their location with respect to the inlets, the land use pattern in the watershed, and the surficial aquifer characteristics.

Whereas the Northern Central zone is affected by strong freshwater, resulting in small salt diffusivity of order of 0.29×10^6 cm^2/sec for the dry season and of 0.65×10^6 cm^2/sec for the wet season, the Southern Central zone is controlled by high diffusivity of the order of 3×10^6 cm^2/sec for the dry season and of 0.7×10^6 cm^2/sec for the wet season. However, salinity drops rapidly to about 22 psu in the region of the Southern Central IRL farthest from Sebastian Inlet. The high freshwater discharge during the wet season decreases the diffusion coefficients for the dry season except for the Northern Central zone.

SCZ Even with the highest surface runoff, salinity in SCZ II remained high at about 30 psu annually due to the proximity to the Sebastian Inlet, resulting in the high diffusion condition. The high chloride concentration of more than 20,000 mg/*l* in the Vero Beach area may partially explain the high annual salinity condition (Toth 1988). To be sure that the very high saline groundwater is really discharged into the IRL, the concentration of the sampled water from the seepage meters should be examined. The salinity at the SCZ I is about 22 psu due to the remoteness from the Sebastian Inlet.

NCZ This zone has the second largest freshwater discharge, which is mostly composed of gaged discharges (77%). In combination with the cold front passages at 3 to 5 day cycles (Henry *et al.* 1994; Zarillo and Surak 1994), the highly urbanized area of this zone allowed the freshwater to be discharged to the IRL even after October to the next April, resulting in lower dry season salinity by 2 psu. The lowest annual salinity of about 18 psu occurred in the NCZ and lower region of the NZ. If the annual salinity levels are low enough to harm the IRL ecosystem, strategies to maintain a certain level of salinity should be provided.

Based on the sensitivity tests, flood-controlling freshwater discharge might be suggested for days of high wind conditions in the spring tide, even though the excessive surface runoff masks the wind mixing on the long-term time scale. The sensitivity tests showed that completely eliminating surface runoff increased the salinity level slightly due to the high fresh groundwater discharged into the IRL. To increase the reliability of the model sensitivity, more accurate measurement of the groundwater seepage is required, since the limited existing data and high variability of groundwater seepage may result in overestimating the total amount of discharged groundwater into the IRL.

Since this zone is considered the most sensitive to surface runoff, which agrees well with the data analysis, the present plan by SJRWMD to redirect the surface runoff to the west during the wet season is appropriate, unless another seawater source is provided. In addition, the increasing water borne pollutants from the urban area are highly concerned even with fairly short flushing time.

NZ This region has the lowest freshwater discharge due to the smallest drainage basin. Although the boundaries of the watershed are poorly defined, most of the freshwater comes from the ungaged discharge (95%). The Haulover Canal provides salt to the NZ from April to September, resulting in high salinity during the wet season in the vicinity of the Haulover Canal. The effect of the accumulated evaporation on poor flushing in this zone is considered the second factor in controlling salinity in the NZ. Annually, the net flow in the Haulover Canal is found to be directed toward the Mosquito Lagoon, which controls the water budget in combination with the local wind conditions.

The analytical solution used in this study can be used to investigate the effect of modified surface runoff and groundwater discharge on the salinity regime in the IRL. Due to its fast calculation and expandability to other areas in the IRL, the one-dimensional analytical model is expected to serve as a salinity management tool in combination with water resource management tools.

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