Vol. 25(1):75-87 | Ocean and Polar Research | March 2003

Article

Water Balance and Flushing Time in the Restricted Indian River Lagoon (IRL), Florida USA

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Abstract : The water balance calculation in the IRL shows that fresh groundwater discharge is the primary factor, with surface runoff from gaged and ungaged areas as the second freshwater contributor. Precipitation and evaporation are almost in balance for the entire IRL. Due to high freshwater discharge from groundwater, the annual net flow is outward from the IRL to the continental shelf of the Atlantic Ocean, resulting in a relatively short flushing time, denoted as $T_{0.5}$ (50% flushing time) and $T_{0.99}$ (99% flushing time). $T_{0.5}$ and $T_{0.99}$ without a tidal effect in the Northern IRL are 17 and 114 days, respectively, during the dry season. During the wet season, they are 10 and 65 days, respectively. Tidal flushing effects are considered in central IRL due to the proximity to Sebastian Inlet. In the Northern Central zone during dry season, $T_{0.5}$ and $T_{0.99}$ are 6 and 43 days, respectively and during the wet season 5 and 33 days. In the Southern Central zone they are 2 and 16 days for the dry season, 2 and 15 days for the wet season. High groundwater seepage into the IRL is considered to be a positive effect in maintaining relatively good water quality condition even with few narrow inlets.

Key words : water balance, flushing time, lagoon, surface water, ground water.

1. Introduction

A lagoon is an area of shallow water that is separated from the ocean by a series of barrier islands (Kjerfve and Magill, 1988). An estuary is a partially enclosed area of water that opens to the ocean and has freshwater inflows (Pritchard, 1967). Therefore, the IRL may be called a lagoon or a bar-built estuary. The IRL system lies between latitudes of 26°57'-29°03' and longitudes of 80°05'- 80°55' along the east coast of Florida where the narrow continental shelf produces 1 m of tidal range. The IRL is aligned parallel to the coast of the Atlantic Ocean having shallow depths of about 1 to 5 m, narrow width of about 2 to 4 km, and elongated length of about 195 km. The surface area of the IRL is about 714×10^6 m^2 with a volume of 1015×10^6 m^3, producing an averaged depth of about 1.4 m. Large volumes of freshwater are released from the watershed area of about 5000 km^2, of which 3000 km^2 has been added due to addition of draining from the Florida Canal systems (Glatzel, 1986).

Since the coastal lagoons, estuaries, or bays are composed by a relatively small water body or a series of water bodies having shallow, narrow, and axially elongated or bending features, they are inherently susceptible to the various forces from inland, atmosphere, and continental shelf. Due to the transitional location between the land and ocean, estuaries also serve as physical and chemical filters from land to ocean before entering the ocean, and vice versa. However, the natural buffering capacity can be severely reduced due to the excessive freshwater loading with various pollutants and nutrients through surface and subsurface runoff (Mee, 1978; Moore, 1996, 1999).

The point and non-point surface runoff discharges occur from river and natural and man-made watershed. Meteoric groundwater discharge from the surficial aquifer also provides the freshwater into the estuaries. In combination with atmospheric pressure, front system, and land-sea breeze, the precipitation and evaporation play an important

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role in governing the water and salt budget in the semi-closed bay and chocked lagoon. The processes in the continental shelf such as tide, wind wave, alongshore current, and long-term sea level variation from seasonal to geological time bands control the water and salt budget as well as water quality. Recently, the tide and wind wave-induced lateral seawater intrusion in combination with the terrestrial groundwater seepage were found to significantly contribute the chemical and geological features of the coastal water bodies and coastal aquifer systems (Li *et al.*, 1999; Swazenski *et al.*, 2001).

Segmentation of study area

For the water balance calculation, the study area is divided into three segmented zones, Northern zone (NZ), Northern Central Zone (NCZ) and Southern Central Zone (SCZ), which were initially defined by Knowles (1995), based on location along the IRL, aquatic habitats of the IRL, and the potential effects of drainage from each zone on the hydrologic nature of the IRL.

Northern Zone (NZ)

The NZ is hydraulically connected with Mosquito Lagoon by Haulover Canal, which is a man-made canal for navigational purpose excavated by the U.S. Army Corps of Engineers in 1854. The average depth of Haulover Canal is 4.5 m, and the length is 2000 m, and the width is 45 m. Although two basins, Big Flounder Creek basin and Addison Creek basin, are included in this zone, the boundary of the watershed is poorly defined, and there has been very little artificial expansion of the watershed in the NZ. The ungaged freshwater discharge primarily comes from the urbanized areas near to the IRL. Another main non-point source of freshwater discharge is from citrus groves in the Flounder Creek basin and in scattered areas on the east shore of the IRL. The overland flow from the U.S. 1 Highway is directed to the IRL along much of this basin. The ungaged area of 207.7 km^2 is about 19 times bigger than the gaged area of 10.9 km^2 (Knowles, 1995).

In the upper region above the Intra Coastal Waterway (ICW) at the Haulover Canal, which covers an area of about 48 km^2 having an average depth of 1.2 m, the groundwater was found to seasonally fluctuate with a seepage rate of 0.035 m/day during the dry season, and of 0.052 m/day during the wet season. The value of wet season is approximately 2 times greater than that of dry season, which means that the high precipitation may increase seepage flux (Swazenski *et al.*, 2001). Since the effect of tide in this zone is negligible due to the remoteness from the inlet, a relatively small amount of surface runoff allows winds to be dominant in controlling the circulation and mixing, resulting in a long flushing time. Due to the long flushing time in this zone, the accumulated effect of evaporation is expected to be higher than the other areas. These physical features of this zone are common in a chocked estuary, as defined by Kjerfve and Magill (1988).

Northern Central Zone (NCZ)

The NCZ is hydraulically connected to the Banana River near the Eau Gallie River. Since no flow measurements at the opening have been reported, exact volume transported is unknown. During the wet season, the Banana River shows salinity features of a negative estuary due to the exceeded evaporation over the freshwater discharge. Consequently, the water of the IRL is driven

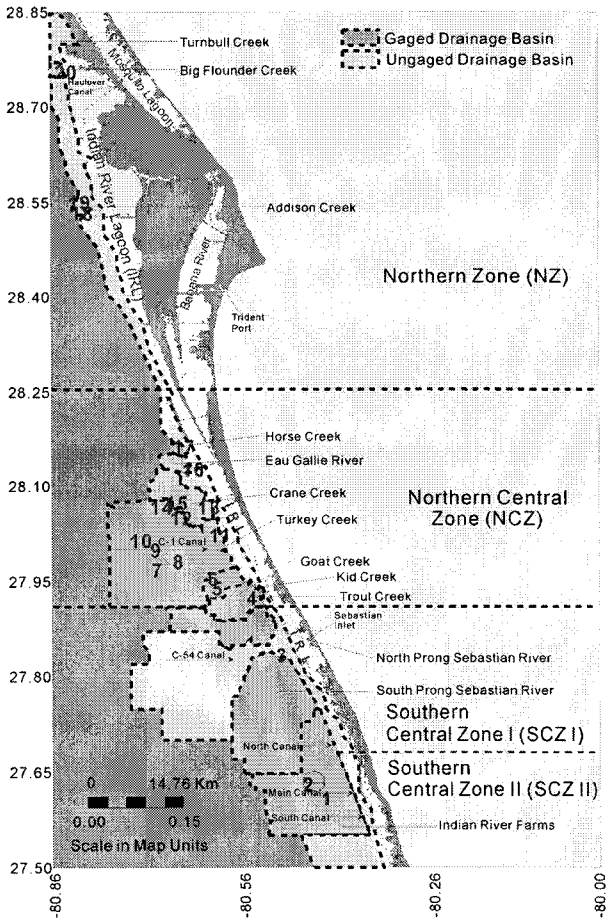

Fig. 1. Location of the study area. Arabic number (1 to 20) denotes precipitation measuring stations. ⊕ denotes evaporation station.

through the 152.4 m wide opening to the Banana River by wind and excessive evaporation.

Due to a narrow inlet of small cross-section and shallow depth of the IRL, the bottom friction rapidly dissipates the tidal energy with distance from the inlet. The ocean spring tide range of 1 m is reduced to 0.78 m at the mouth of the Sebastian Inlet and decreases to 0.3 m near the Sebastian River. The tidal range continuously decreases to 6 cm between the Crane Creek and Eau Gallie River, about 15 km from the Sebastian Inlet. Tide is absent further north from the Eau Gallie River. Much of this zone was found to have low tidal mixing (Smith, 1987, 1993).

This segment contains seven mainland basins between the Banana-IRL junction (latitude 28°15') and about 4.8 km north of Sebastian Inlet (latitude 27°52'): Horse Creek basin, Eau Gallie River basin, Crane Creek basin, Turkey Creek basin, Goat Creek basin, Kid Creek basin, and Trout Creek basin (Fig. 1). Turkey Creek receives discharges from the main C-1 canal, the minor C-82 canal, and non-point source discharges from the highly urbanized area. The C-1 canal, composed of C-1A, C-10, C-37, C-61, and C-69 canals, has a bi-directional flow. St. Johns River Water Management District (SJRWMD) has a plan to redirect some water to the west into upper St. Johns River Basin to reduce pollution loads and to protect commercial fishery (Adkins, 1998).

The highest freshwater discharge from the C-1 canal through Turkey Creek results in a salinity stratification, which is either ephemeral or persists for a few days, depending on turbulence intensity by winds, wind waves, and tides. A salinity reverse gradient is also occasionally developed due to the fresh groundwater in combination with evaporation. This unstable condition was observed to last for a short period of time. In spite of shallow depth and strong wind condition in the IRL, this short time persistence of reverse stratification implicitly suggests that the seepage rate of groundwater from the surficial aquifer is very high (Zarillo and Surak, 1994). The U.S.1 Highway, closely parallel to the IRL along much of this basin, drained the precipitation directly to the IRL as an overland flow. The gaged area of 404 km^2 is about 3.8 times bigger than the ungaged area of 106 km^2 (Knowles, 1995).

Southern Central Zone (SCZ I and SCZ II)

The man-made Sebastian Inlet is within this zone. It was first opened in 1886 at a former natural inlet location. It closed and reopened several times, and now is stabilized with jetties. The dimensions of Sebastian Inlet is about 3.4 m deep, 686 m long, and 180 m wide at the throat section (Springer, 1994). The mean tidal excursion distance was reported to be about 3 km at the Sebastian Inlet (Smith, 1987).

The gaged and ungaged areas of the SCZ are 475 km^2 and 348.3 km^2, respectively (Knowles, 1995). This zone consists of North Prong Sebastian River basin, South Prong Sebastian River basin, and Indian River Farm basin. The Sebastian River, the second largest inflow to the IRL, is composed with C-54 canal and Main canal (Fig. 1). They run closely parallel to each other. The C-54 canal, connected to the St. Johns River watershed like the C-1 canal, can have a bi-directional flow. Discharges from the two canals have a great impact on the IRL system during hurricanes and tropical storms. Occasionally, this confluent discharge is estimated to be about 50 percent of the total surface runoff to the IRL.

Using seepage meters in nearshore sediments (25 m from west shore of the IRL), located to the 62 km south from the Sebastian Inlet, Zimmermann *et al.* (1985) showed that a groundwater seepage rate through seagrass-associated sediments is 0.089 m/day, and 0.066 m/day at the seagrass -deficient sediments. The seepage rate was found to decrease dramatically with the increased distance from the shore, and to show an inverse correlation between the seepage rate and tidal height. Groundwater flow was reduced at high tide and increased at low tide. This inverse relationship was also noted in the IRL at Jensen Beach (latitude 27°15') by Belanger and Walker (1990). The tidal fluctuation was found to have a strong effect on those areas closest to the east shore of the IRL, but no effect on the west shore of the IRL.

2. Available data

Mean sea level of Atlantic Ocean has been measured at Trident Harbor (Fig. 1). The monthly averaged Mean sea level data from 1994 to 2000 were downloaded from http://www.co-ops.nos.noaa.gov/. Adkins (1998) summarized pan evaporation data of 1986 to 1995 measured at NOAA 9219 shown in the Fig. 1. The remaining data up to 1998 were supported from South Florida Water Management District (SFWMD). The rainfall data between 1989 and 2000 were collected from twenty measuring stations (Fig. 1). Twelve tributary basins were gaged in the three hydrologically divided zones. The gaged and ungaged basins in the Fig. 1 are listed in the Table 1. The gaged data were downloaded from http://water.usgs.gov/ak/nwis/monthly/.

Table 1. Drainage Area in each basin (Knowles, 1995).

Basin Name	Drainage Area (km^2)	
	Gaged	Ungaged
Southern Central Zone (SCZ)	**475.01**	**348.36**
Indian River Farms basin	199.69	
South Prong Sebastian River basin	201.50	
North Prong Sebastian River basin	78.82	
Northern Central Zone (NCZ)	**405.59**	**106.19**
Trout Creek basin	38.85	
Kid Creek basin	4.40	
Goat Creek basin	20.98	
Turkey Creek basin	271.95	
Crane Creek basin	48.43	
Eau Gallie River basin	14.76	
Horse Creek basin	6.22	
Northern Zone (NZ)	**10.88**	**207.72**
Addison Creek basin	6.22	
Big Flounder basin	4.66	

3. Methods

Defining the lagoon water balance

Calculations of lagoon water balance were provided by Glatzel (1986), Belanger and Walker (1990), Kjerfve *et al.* (1996). The net water balance in the IRL can be written:

$$\frac{dV}{dt} = V_P + V_E + V_G + V_R + V_O \quad (1)$$

The units of water balance are in L^3/T, where L is a length and T is time. The sign convention is positive for water gain and negative for water loss. The change in the lagoon water storage (dV/dt), where V is a lagoon volume, is positive when the volume increases. V_P is the precipitation to the lagoon surface, and is calculated as the product of rainfall rate and the lagoon surface area. V_E is the evaporation from the lagoon surface, and is calculated as the product of the directly measured evaporation rate and the lagoon surface area. V_G is the groundwater seepage into the lagoon (positive). Using the seepage meters, Swazenski *et al.* (2001) reported that the average groundwater seepage rate (w_g) was 0.052 m/day during the wet season, and 0.035 m/day during the dry season at the NZ of the IRL. The two values were applied to the whole study area, since they are the minimum values reported in this study area and are believed to be measured by reliable direct methods using seepage meters and isotope techniques. V_G is calculated as the product of the w_g and the lagoon bottom area. V_R is the total surface runoff from the watershed to the IRL, and is expressed as $V_R = V_D + V_U$. V_D is the gaged runoff from canals and rivers with respect to time. This will be determined by summing the total monthly flows from canal and river discharge records supplied by the USGS. V_U is the ungaged surface runoff. To estimate discharge for the ungaged basins, a Surface Runoff Intensity-to-Precipitation ratio (i/P ratio) should be first computed for each gaged basin using measured stream discharge and precipitation data. In case of the stream flow data that are missed in the gaged basin, the values of the missed stream flow data was extrapolated from nearby gaged basins. For any basins without rainfall gages, the precipitation was estimated by linearly interpolating the nearest precipitation data. A value of i/P ratio for the ungaged basin can be computed by averaging i/P ratios for the given number of gaged basins. Since the precipitation for the ungaged basin is already known, the value of discharge for the ungaged basin can be computed (Knowles, 1995). V_O is the net water transport from lagoon (inflow is positive) through the inlets. It is the residual water exchange between the inflow of ocean water and outflow of lagoon water on monthly or longer seasonal time scales. The change in storage (dV) can be determined by monthly mean ocean water level data, assuming that the lagoon water level would follow the mean ocean water level. On the monthly, seasonal, or annual time scale band, V_O can be determined from the calculation of dV/dt.

Flushing time

Due to the rapid increase of human population in the coastal areas, the water quality in the IRL is a very important issue. One of the most critical measures evaluating the water quality of coastal lagoon is a flushing time, a time scale for water exchange. Physically, since the water in the lagoon is never completely flushed, the flushing time only represents the time required to replace a certain percentage of the lagoon water volume. Widely used measure is a flushing half-life ($T_{0.5}$ in days), or 50% flushing time required to replace half of the lagoon water volume. Another is the 99% flushing time required to replace 99 percent of the lagoon water (Pritchard, 1960).

Since the flushing rate, denoted as k, represents the fraction of the lagoon water volume replaced each day by precipitation (V_P), groundwater seepage (V_G), surface runoff (V_R), inlet ocean exchange (V_0) and tidal exchange (V_T) through the inlet, but not by water loss due to the evaporation (V_E), it can be calculated as in 1/day (Kjerfve *et al.*, 1996):

$$k = \frac{V_P + V_G + V_R + V_O + V_T}{V} \quad (2)$$

where V is the volume of water in the lagoon. Since the dominant tide in the IRL is semidiurnal, the tidal exchange, V_T is calculated as in volume/day:

$$V_T = A_L \Delta h \frac{24}{12.42} \quad (3)$$

where A_L is the water-covered area of each segment lagoon. It changes very slightly between high and low tides due to the small tidal range in the IRL. The mean tidal range is Δh.

Once the constant rate k is known, $T_{0.5}$ and $T_{0.99}$ are calculated using a first-order kinetics formulated as (Pritchard, 1960):

$$\frac{dV}{dt} = -kV \quad (4)$$

The solution to this well-known separable equation with initial condition $V(0) = V_0$ is

$$V(t) = V_0 e^{-kt} \quad (5)$$

Both $V(T_{0.5}) = 0.5\ V_0$ and $V(T_{0.99}) = 0.99\ V_0$ respectively give

$$T_{0.5} = \frac{0.69}{k} \quad (6)$$

$$T_{0.99} = \frac{4.60}{k} \quad (7)$$

4. Results

Precipitation

Throughout the IRL there are two distinctive seasons, a wet season from June to October and a dry season from November to May (Fig. 2). The mean precipitation during the wet season ranges from 14.8 cm in October to 17.9 cm in September with mean values of 16.0 cm. The mean precipitation during the dry season ranges from 5.0 cm at December to 9.3 cm at March with mean value of 7.0 cm.

The Fig. 3 shows the seasonal and annual precipitation in the study area.

In contrast to the historical data, the upper region (Palm Bay) and lower region (Vero Beach) from the Sebastian Inlet area show the highest rainfall during the wet season. However, the Sebastian Inlet area shows the lowest rainfall. During the dry season, the highest rainfall occurs

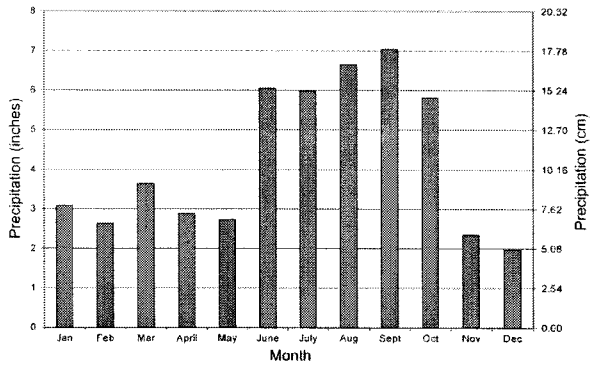

Fig. 2. Monthly mean precipitation distribution.

at the Vero Beach area. The annual distribution shows the highest rainfall at the Vero Beach and lowest rainfall at the Sebastian Inlet area.

The climate of the IRL is transitional between temperate and subtropical climates, since the IRL is closely adjacent to the Atlantic Ocean and the Gulf Stream passes offshore throughout the entire length of the IRL. The summer months 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 (Rao, 1987). During June to September, the frontal systems in the north and central Florida occurred with an average of a 10-day cycle. In the south Florida, the cold fronts occurred once per month for the same period. During the winter (October to May), north and central Florida has a 3 to 5-day cycle of front passage and south Florida a 5 to 7 frontal cycle (Henry *et al.*, 1994).

Evaporation

The monthly mean pan evaporation data for 1992-1998 at NOAA 9219 station at Vero Beach were used to calculate the lagoon evaporation by multiplying a mean correction factor of 0.80 suggested by Glatzel (1986). Using this pan evaporation coefficient of 0.80, the potential evaporation rate for the IRL is about 131.5 cm, which is approximately equal to the normal precipitation for the IRL. The potential evaporation ranges from 6.1 cm at December to 15.5 cm at May. Whereas the high precipitation occurred from June to October, the high evaporation occurred from March to September (Fig. 4).

Changs in Lagoon Volumes (dV)

The dV was estimated from monthly mean sea level (MSL) data measured at Trident Pier, Port Canaveral using

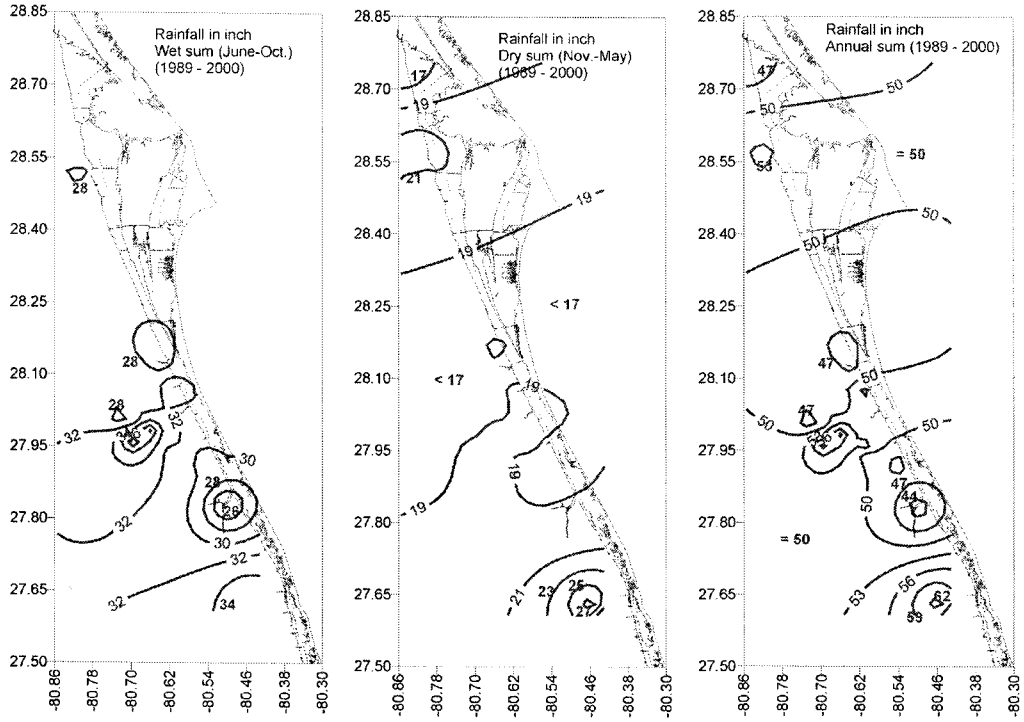

Fig. 3. Distribution of Precipitation during wet, dry season, and annual basis.

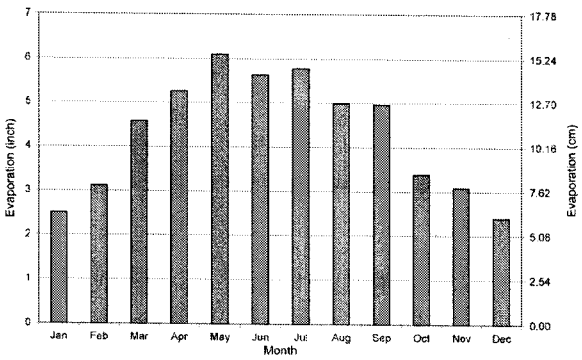

Fig. 4. Corrected monthly mean IRL evaporation at Vero Beach (NOAA index no.9219) for 1992-1998.

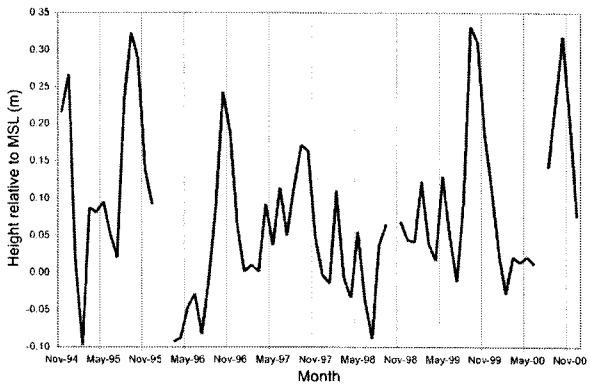

Fig. 5. Monthly Mean Sea Level (MSL) at Trident Pier, Port Canaveral for 11/1/1994-12/31/2000.

an assumption that the long-term lagoon water levels would follow the mean sea level variations. The seasonal MSL variation is found to be about 40 cm (Fig. 5). A maximum sea level rising occurs near October of each year, which may be due to the maximum thermal expansion accumulated by October. This feature is clearly shown in the Fig. 6. The sea level rapidly increases from August and reached the maximum in October. The sea level rapidly decreases after October and reaches the minimum in July.

Monthly surface runoff discharge

One of the primary objectives of this work is to estimate the total surface runoff discharge to the IRL. This was achieved by adding the measured stream discharge from each of the gaged basins to the estimated discharge from the remaining ungaged basins.

Gaged discharge

The highest discharges occur in October for all creeks, rivers, and canals. The monthly mean discharge at the

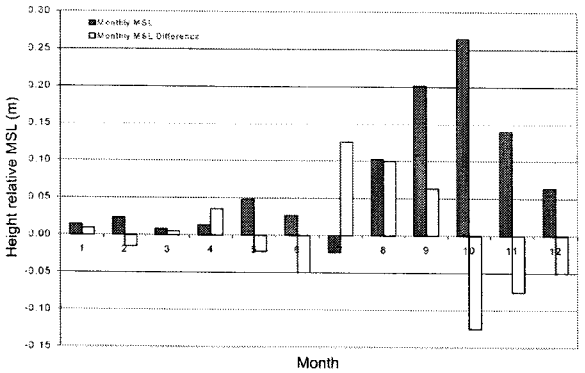

Fig. 6. Monthly IRL water level in meters and water level difference based on 7 year (1994-2000) MSL at Trident Pier, Port Canaveral.

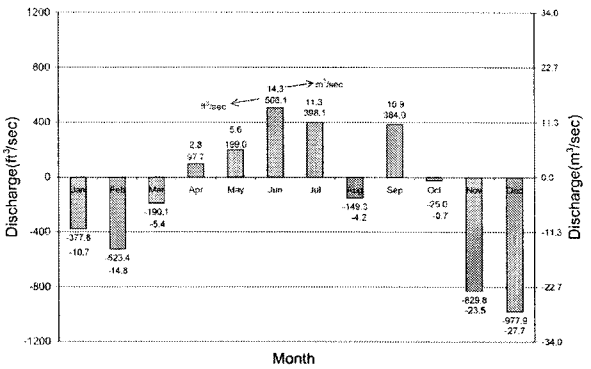

Fig. 8. Monthly discharge from Haulover Canal for 1996-2000.

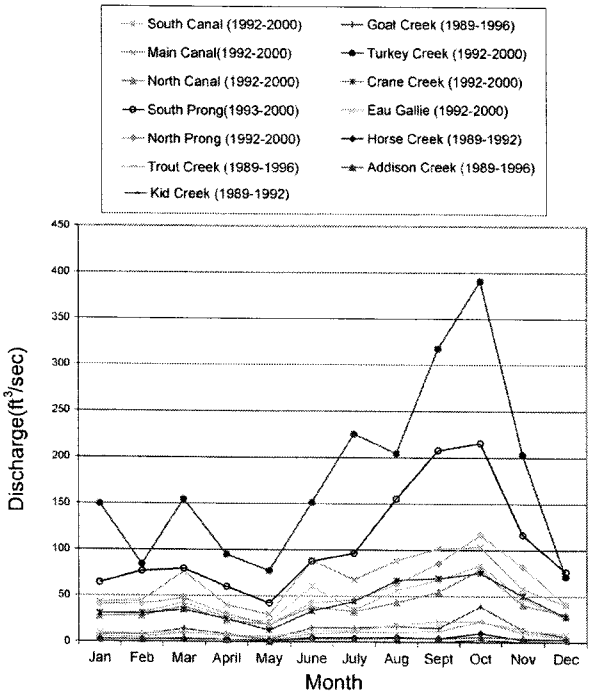

Fig. 7. Monthly gaged discharge for 1989-2000.

Turkey Creek ranges from 11.1 m^3/sec in October to 2.0 m^3/sec in May. The annual mean is 5.0 m^3/sec, which is the largest of all the gaged stations (Fig. 7). During 1992-2000, the combined annual mean discharge from North Prong and South Prong is about 4.6 m^3/sec, which is approximately equal to the annual mean discharge from the Turkey Creek. The combined annual mean discharge from North, Main, and South canals is about 4.2 m^3/sec, which is a nearly equal to the combined annual mean discharge of 4.6 m^3/sec from North and South Prongs.

Through the Haulover canal (Fig. 8), a water exchange occurs locally between the northern IRL and Mosquito Lagoon. From April to September, except for August, the highly saline water from he Mosquito Lagoon enters the northern IRL. Whereas the total inflow amount is 44.9 m^3/sec, which is the second largest annual discharge after the Turkey Creek (60.2 m^3/sec), the total outflow amount is -87.0 m^3/sec, resulting in the net outflow to the Mosquito Lagoon.

Ungaged discharge

Using the *i/P* ratio, the monthly, seasonal, and annual ungaged discharge can be calculated. The annual average of the *i/P* ratio for the Indian River basin was calculated to be 0.46, which was similar to the ratio for the Turkey Creek (0.44) and to the ratio for the Indian River Farms (0.43). The ratios range from 0.18 for the Trout Creek tributary basin to 0.78 for the Eau Gallie River tributary basin (Table 2). The high ratios during the dry season are considered to be due to the time lag between the precipitation and tributary discharge. Although, some of the basins release the surface water into the IRL immediately after the precipitation, most of the basins discharge the surface water with time lag (Knowles, 1995).

In the study area, a heavy precipitation usually occurs near the late wet season. During the study period, hurricane Floyd in mid-September and Irene at mid-October of 1999 contributed to substantial precipitation. Subsequently, the delayed surface water from the accumulated precipitation during the wet season is discharged into the IRL during the next dry season. The delayed surface runoff occurred particularly in the upper part of the highly urbanized NCZ; Horse Creek, Eau Gallie River, and Crane Creek. Each basin has higher *i/P* ratio of 0.68, 0.89, and 0.70,

Table 2. Calculation of annual ungaged discharge using *i/P* ratio.

Annual (365 days) 1992-2000 Drainage Basin	A_D Drainage Area (km^2)	P Precipitation (cm)	$r(=i/P)$ ratio	$i = Q/A_D$ Runoff intensity (cm)	Q Mean Discharge (m^3/s)
NZ	**218.6**	**120.16**	**0.45**	**53.5**	**3.7**
Big Flounder Creek	4.7	116.21	0.46	53.5	0.1
Addison Creek	6.2	124.11	0.43	53.5	0.1
Remaining ungaged	207.7	120.16	0.45	53.5	3.5
NCZ	**508.4**	**120.75**	**0.49**	**58.8**	**9.5**
Horse Creek	4.9	115.18	0.64	73.5	0.1
Eau Gallie River	12.4	116.74	0.78	91.6	0.4
Crane Creek	48.7	125.77	0.61	76.7	1.2
Turkey Creek	272.0	132.67	0.44	58.2	5.0
Goat Creek	23.6	119.71	0.43	51.9	0.4
Kid Creek	1.8	118.30	0.25	30.1	0.0
Trout Creek	38.9	116.89	0.18	21.5	0.3
Remaining ungaged	106.2	120.75	0.52	63.3	2.1
SCZ	**823.4**	**124.77**	**0.45**	**55.7**	**14.5**
Sebastian River:					
Northern Prong	73.8	113.05	0.59	66.3	1.6
South Prong	201.5	109.21	0.43	47.3	3.0
Indian River Farms	199.7	152.06	0.43	66.0	4.2
Remaining ungaged	348.4	124.77	0.42	52.4	5.8
Total					
Gaged	**888.1**	**121.66**	**0.47**	**57.8**	**16.3**
Ungaged	**662.3**	**120.61**	**0.46**	**54.5**	**11.4**
Indian River Basin	**1550.4**	**121.90**	**0.46**	**56.4**	**27.7**

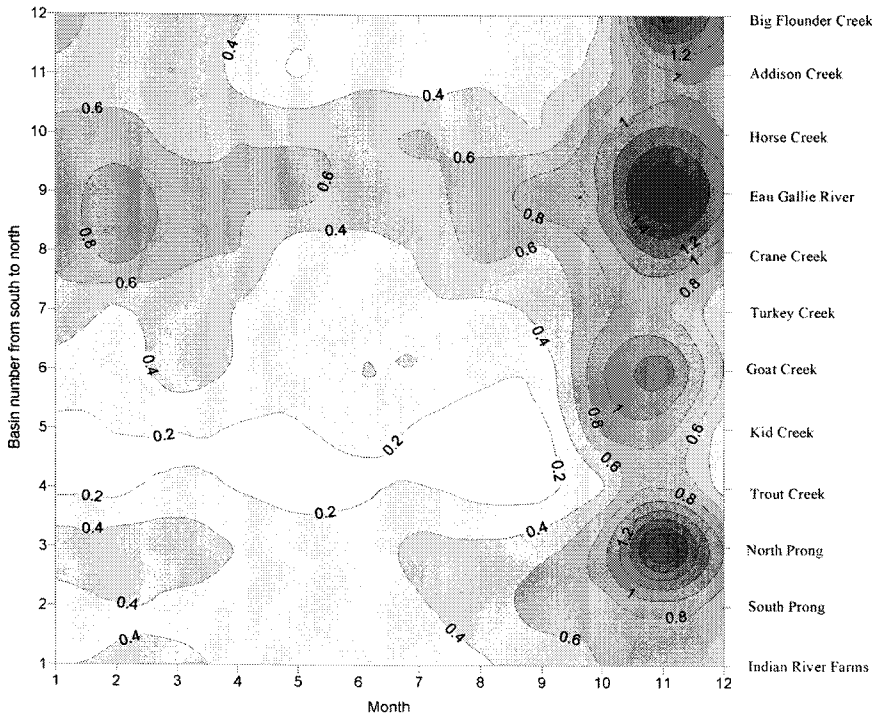

Fig. 9. Surface runoff intensity-to-Precipitation ratio (*i/P*) in the drainage basins.

respectively for the dry season. The highest ratios due to the over-surface runoff are found in November except for the Indian River Farms (Fig. 9).

Total surface runoff discharge

The total freshwater discharge from the surface runoff to the IRL averaged 37.6 m^3/sec during the wet season

Table 3. Seasonal freshwater discharge summary for the IRL drainage basin.

1992-2000	Discharge			Percentage of Discharge		
Drainage Basin	Annual (m^3/s)	Wet-Season (m^3/s)	Dry-Season (m^3/s)	Annual %	Wet-Season %	Dry-Season %
NZ	**3.7**	**4.5**	**3.2**	**13.4**	**11.9**	**15.3**
Big Flounder Creek	0.1	0.1	0.1	0.3	0.3	0.3
Addison Creek	0.1	0.1	0.1	0.4	0.3	0.4
Remaining ungaged	3.5	4.3	3.0	12.7	11.3	14.5
NCZ	**9.5**	**13.7**	**6.5**	**34.2**	**36.3**	**31.4**
Horse Creek	0.1	0.2	0.1	0.4	0.4	0.4
Eau Gallie River	0.4	0.5	0.3	1.3	1.3	1.3
Crane Creek	1.2	1.6	0.9	4.3	4.4	4.2
Turkey Creek	5.0	7.3	3.4	18.1	19.4	16.4
Goat Creek	0.4	0.6	0.3	1.4	1.5	1.2
Kid Creek	0.0	0.0	0.0	0.1	0.1	0.1
Trout Creek	0.3	0.4	0.2	1.0	1.0	0.9
Remaining ungaged	2.1	3.1	1.5	7.7	8.2	7.1
SCZ	**14.5**	**19.5**	**11.0**	**52.4**	**51.8**	**53.3**
Sebastian Creek:						
Northern Prong	1.6	2.0	1.2	5.6	5.3	5.9
South Prong	3.0	4.3	2.1	10.9	11.5	10.1
Indian River Farms	4.2	5.7	3.1	15.1	15.1	15.0
Remaining ungaged	5.8	7.5	4.6	20.9	19.9	22.2
Total						
Gaged	**16.3**	**22.8**	**11.6**	**58.7**	**60.6**	**56.2**
Ungaged	**11.4**	**14.8**	**9.1**	**41.3**	**39.4**	**43.8**
Indian River Basin	**27.7**	**37.6**	**20.7**	**100.0**	**100.0**	**100.0**

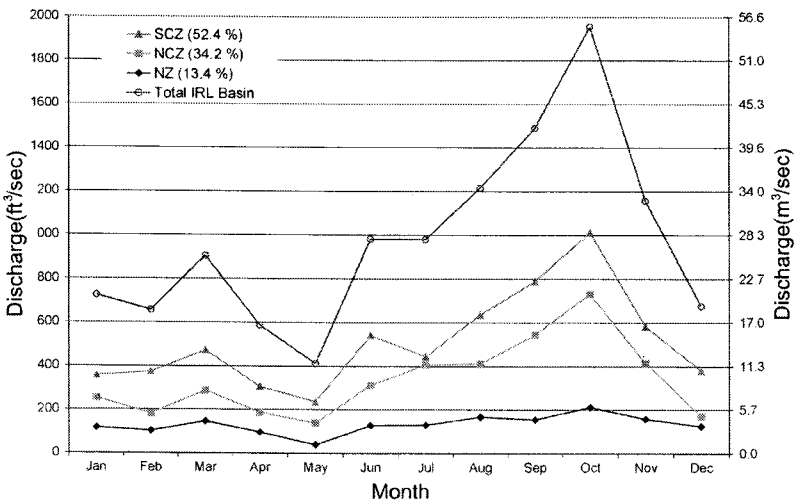

Fig. 10. Monthly surface runoff discharge into the IRL.

and 20.7 m^3/sec during the dry season (Table 3). Annual freshwater discharge to the IRL basin averaged 27.7 m^3/sec. The SCZ contributed the most freshwater at 14.5 m^3/sec (52.4%), the NCZ contributed 9.5 m^3/sec (34.2%), and the NZ contributed 130 m^3/sec (13.4%). The greatest gaged discharge is from the Turkey Creek (18.1%). The second largest discharge is from the Indian River Farms (15.1%), and the third is from South Prong (10.9%).

The SCZ has the largest ungaged discharge (20.9%), followed by the NZ (12.7%), and then NCZ (7.7%). Whereas the NCZ discharges much of the freshwater from the gaged basin (77%), the NZ discharges most of the freshwater from ungaged basin (94%). The SCZ contributed freshwater discharge from the ungaged basins (40%) and gaged basins (60%).

In the Fig. 10, the maximum surface runoff occurred in October, which coincided with the end of the wet season. The minimum surface runoff occurred in May, which coincided with the end of the dry season. On the annual and seasonal basis, the SCZ discharged most of the freshwater (52.4%), followed by NCZ (34.2%), and the NZ (13.4%).

Lagoon water balance

The long-term lagoon water budget for each of the three segments is summarized in Table 4, 5, and 6. The term V_G used for water balance was linearly interpolated to obtain the monthly values using an assumption that the V_G would follow the V_R on a long-term basis. While the terms V_G's in the SCZ and NCZ are two and five times greater than V_R's, the term V_G in the NZ is twenty six times greater than V_R, showing a dominant role of the groundwater in the water balance. The vertical and lateral totals in the water budget tables may not balance due to the rounding off used for integerizing the tables. The negative signs in the term, dV denote a decrease in the lagoon volume changes. The negative sign for V_E was assigned to denote the output. The annual $V_P + V_E$ is approximately equal to zero for all three tables. The net flow, V_O is directed from the IRL to the Mosquito Lagoon and the Atlantic Ocean through the Haulover canal and inlets. The volume exchange, V_T by the tide was calculated using the formulation (3). The mean tidal amplitude of semi-diurnal tide is 8.1 cm in the SCZ and 2.1 cm in the NCZ (Smith, 1987).

Flushing time

Using an assumption that the lagoon volume is completely replaced by the precipitation, groundwater discharge, surface runoff, ocean exchange through inlet, and tidal exchange defined by the formulation (3), the flushing rate, k in the last column in Table 4, 5, and 6 was expressed in 1/month. Using Pritchard's formulations (6) and (7) and converting the unit to a day, the flushing time for each zone was obtained and summarized in

Table 4. Water balance table for SCZ.

Month	Surface elevation		Elevation difference	Volume difference	Input			Output		Mean current from V_O			Flushing rate
	Final (F)	Initial (I)	$F-I$	dV	V_P	V_R	V_G	V_E	V_O	u_0		V_T	k
	cm	cm	m	10^6 m^3	10^6 m^3	10^6 m^3	10^6 m^3	10^6 m^3	10^6 m^3	m/month	cm/sec	10^6 m^3	1/month
1	2.320	1.400	0.009	1	7	27	78	−5	−106	−36913.2	−1.4	780	8.58
2	0.817	2.320	−0.015	−1	6	28	82	−6	−111	−38506.4	−1.5	704	8.00
3	1.333	0.817	0.005	0	8	36	104	−9	−138	−48051.8	−1.9	780	9.16
4	4.833	1.333	0.035	3	7	23	67	−11	−83	−28819.1	−1.1	754	8.03
5	2.667	4.833	−0.022	−2	6	18	52	−13	−65	−22532.6	−0.9	780	7.90
6	−2.280	2.667	−0.049	−4	13	41	100	−12	−146	−50849.8	−2.0	754	9.06
7	10.217	−2.280	0.125	10	10	34	82	−12	−103	−35806.4	−1.4	780	8.66
8	20.167	10.217	0.100	8	12	48	117	−10	−160	−55442.6	−2.1	780	9.60
9	26.460	20.167	0.063	5	12	60	145	−10	−202	−70172.1	−2.7	754	10.08
10	13.950	26.460	−0.125	−10	11	77	186	−7	−277	−96312.4	−3.7	780	11.44
11	6.383	13.950	−0.076	−6	5	44	128	−6	−177	−61437.2	−2.4	754	9.52
12	1.400	6.383	−0.050	−4	4	29	84	−5	−115	−40088.0	−1.5	780	8.69
Wet Mean	13.703	11.446	0.023	2	12	52	126	−10	−178	−61716.6	−2.4	770	9.77
Dry Mean	2.822	4.434	−0.016	−1	6	29	85	−8	−114	−39478.3	−1.5	762	8.55
Annual Mean	7.356	7.356	0.000	0	8	39	102	−9	−140	−48744.3	−1.9	765	9.06

Table 5. Water balance table for NCZ.

Month	Surface elevation		Elevation difference	Volume difference	Input			Output		Mean current from V_O			Flushing rate
	Final (F)	Initial (I)	$F-I$	dV	V_P	V_R	V_G	V_E	V_O	u_0		V_T	k
	cm	cm	m	10^6 m^3	10^6 m^3	10^6 m^3	10^6 m^3	10^6 m^3	10^6 m^3	m/month	cm/sec	10^6 m^3	1/month
1	2.320	1.400	0.009	1	8	19	114	−6	−134	−36535.6	−1.4	243	2.51
2	0.817	2.320	−0.015	−1	7	12	74	−8	−87	−23695.2	−0.9	220	2.29
3	1.333	0.817	0.005	1	8	22	129	−11	−147	−40084.7	−1.5	243	2.50
4	4.833	1.333	0.035	3	7	14	82	−13	−86	−23477.1	−0.9	235	2.37
5	2.667	4.833	−0.022	−2	6	10	62	−15	−65	−17734.4	−0.7	243	2.39
6	−2.280	2.667	−0.049	−5	13	23	98	−14	−124	−33900.0	−1.3	235	2.79
7	10.217	−2.280	0.125	12	13	31	131	−14	−149	−40592.5	−1.6	243	2.90
8	20.167	10.217	0.100	10	17	31	133	−12	−159	−43394.6	−1.7	243	2.91
9	26.460	20.167	0.063	6	18	40	171	−12	−211	−57408.7	−2.2	235	2.92
10	13.950	26.460	−0.125	−12	14	56	237	−8	−310	−84389.2	−3.3	243	3.11
11	6.383	13.950	−0.076	−7	4	30	181	−8	−215	−58595.5	−2.3	235	2.53
12	1.400	6.383	−0.050	−5	4	13	78	−6	−94	−25654.5	−1.0	243	2.47
Wet Mean	13.703	11.446	0.023	2	15	36	154	−12	−191	−51937.0	−2.0	240	2.92
Dry Mean	2.822	4.434	−0.016	−1	6	17	103	−10	−118	−32253.9	−1.2	237	2.44
Annual Mean	7.356	7.356	0.000	0	10	25	124	−11	−148	−40455.2	−1.6	238	2.64

Table 6. Water balance table for NZ.

Month	Surface elevation		Elevation difference	Volume difference	Input			Output		Mean current from V_O			Flushing rate
	Final (F)	Initial (I)	$F-I$	dV	V_P	V_R	V_G	V_E	V_O	u_0		V_T	k
	cm	cm	m	10^6 m^3	10^6 m^3	10^6 m^3	10^6 m^3	10^6 m^3	10^6 m^3	m/month	cm/sec	10^6 m^3	1/month
1	2.320	1.400	0.009	2	13	9	230	−13	−237	−46652.4	−1.8	143	2.00
2	0.817	2.320	−0.015	−3	14	8	202	−17	−210	−41256.2	−1.6	129	1.78
3	1.333	0.817	0.005	1	18	11	289	−24	−292	−57484.2	−2.2	143	2.38
4	4.833	1.333	0.035	7	18	7	190	−28	−180	−35496.1	−1.4	138	1.69
5	2.667	4.833	−0.022	−5	15	3	77	−33	−67	−13184.2	−0.5	143	0.96
6	−2.280	2.667	−0.049	−10	26	10	264	−30	−280	−55100.7	−2.1	138	2.28
7	10.217	−2.280	0.125	26	32	10	270	−31	−255	−50112.8	−1.9	143	2.25
8	20.167	10.217	0.100	21	31	13	348	−27	−344	−67625.3	−2.6	143	2.78
9	26.460	20.167	0.063	13	31	12	323	−27	−326	−64138.2	−2.5	138	2.63
10	13.950	26.460	−0.125	−26	37	16	440	−18	−502	−98650.4	−3.8	143	3.60
11	6.383	13.950	−0.076	−16	9	12	313	−17	−334	−65633.9	−2.5	138	2.55
12	1.400	6.383	−0.050	−10	9	9	245	−13	−260	−51106.0	−2.0	143	2.11
Wet Mean	13.703	11.446	0.023	5	32	12	329	−26	−341	−67125.5	−2.6	141	2.71
Dry Mean	2.822	4.434	−0.016	−3	14	8	221	−21	−226	−44401.8	−1.7	140	1.93
Annual Mean	7.356	7.356	0.000	0	21	10	266	−23	−274	−53870.0	−2.1	140	2.25

Table 7. Since the NZ is tideless, the tidal flushing, V_T was not included in the NZ. The mean tidal range of semi-diurnal tide is 16.2 cm in the SCZ and 4.2 cm in the NCZ (Smith, 1987). The longest flushing time occurred in May with minimum precipitation, and the shortest flushing time occurred in October with maximum precipitation (Kim, 2001).

5. Discussion

The natural physical features of the IRL system have been greatly altered by human infrastructures, such as

dredged navigational channels, stabilization of tidal inlets, construction of causeways, drainage system for flood control and irrigation, pumping well development, and impoundments for mosquito control. The causeways partially partitioned the IRL into a few sections, and prevented a hydrodynamic connection between each section, resulting in the changes in the circulation pattern. Local or synoptic winds, atmospheric pressure, episodic storm events, surface and groundwater discharge, and small tide effects lead to transient flows in the IRL, which may form large scale-circulation patterns that may vary daily to seasonal time scales (Zarillo and Surak, 1994). For more than a century, the human activities in the watershed caused substantial changes in the infiltration and runoff from the watershed, the surficial aquifer capacities, and eventually the water quality of the IRL water body. However, the Intra Coastal Waterway (ICW) of about 4 m depth may serve as a conduit for dense salt water to be transported into the IRL from the inlets (Smith, 1993). This ICW also connected the northern IRL and Mosquito Lagoon.

Belanger *et al.* (1997) measured a seepage rate using seepage meter deployed across 9 transects in the Mosquito Lagoon. The average seepage rate is 0.030 m/day, which is about one third of 0.092-0.12 m/day measured by Belanger and Walker (1990) in the IRL at Jensen Beach (latitude 27°15'). The average measured value is much higher than 3.0×10^{-4} m/day previously calculated by Montgomery (1990) using USGS 3-D MODFLOW model. Pandit and El-khazen (1990) also applied three-layer model to the Jensen Beach area and estimated the seepage rate as 7.6×10^{-4}-2.6×10^{-3} m/day. The numerical model in the SFWMD (1987) predicted a seepage rate as 3.0×10^{-3}-2.0×10^{-2} m/day in the St. Lucie Estuary (latitude 27°10'), and concluded only groundwater could explain the constant background freshwater flow into the St. Lucie Estuary. The model calculations are based on only the pressure gradient generated by the land surface topography. However, the seepage rate can be enlarged by other pressure gradients forced by the ocean wave set up and tidal fluctuation (Li *et al.*, 1999). The big difference between measured rate and model-based rate indicates that the groundwater seepage into the IRL plays a much more important role than previously expected in calculating the IRL water balance.

Generally, the high land surface makes a high potentiometric surface. Since the potentiometric surface and land surface concurrently increase to the west, the longitudinal land surface elevation is postulated to generally increase from north to south. This higher altitude to the south produces a higher topographic pressure gradient at the southern IRL, possibly causing a higher groundwater seepage rate of 0.092-0.12 m/day at Jensen Beach (Belanger and Walker, 1990) than that of 0.030 m/day in Mosquito Lagoon (Belanger *et al.*, 1997).

Assuming that the net flow is a tidally averaged current, Smith (1983) suggested a southward net flow of order of 1-2 cm/sec between the Sebastian Inlet, Ft. Pierce Inlet (40 km south from the Sebastian Inlet), and St. Lucie Inlet (30 km south from the Ft. Pierce. Using this net flow and distance between the inlets, the flushing time between the Sebastian Inlet and Ft. Pierce Inlet can be calculated to be about 43 days, and about 21 days between the Ft. Pierce and St. Lucie Inlets. A lagoon-wide one-dimensional model by Sheng, *et al.* (1990) showed that in the tidally affected regions, about 30 days are enough for the freshwater and seawater to reach a salinity equilibrium. Under a condition of high wind and tidal effect, it takes only about 5 to 10 days to reach a steady state in salinity. The time required for salinity to reach a steady state may be interpreted as a flushing time if the flushing time is defined to be the time needed for the concentration of the introduced pollutants to be almost zero. Using this definition for the flushing time, the times suggested by Sheng, *et al.* (1990) are considered to be fairly compatible with those calculated in this study. Consequently, the water balance confirms that high groundwater discharge into the IRL causes the net flow to be outward through the inlets, resulting in a relatively good water quality condition even with few narrow inlets (Kim, 2001).

Table 7. Flushing time in days at each zone.

Month	SCZ		NCZ		NZ	
	$T_{0.50}$	$T_{0.99}$	$T_{0.50}$	$T_{0.99}$	$T_{0.50}$	$T_{0.99}$
1	2	17	6	40	14	92
2	2	16	7	44	14	94
3	2	16	6	37	11	74
4	3	17	7	46	17	110
5	3	18	8	53	42	279
6	2	15	6	40	11	75
7	2	16	5	36	12	80
8	2	15	5	35	9	61
9	2	14	4	29	9	63
10	2	12	4	24	7	45
11	2	14	4	29	10	65
12	2	16	7	47	13	86
Wet	2	15	5	33	10	65
Dry	2	16	6	43	17	114

Acknowledgements

Author thanks Drs. Jae-Kwi So and Young-Min Oh for their constructive comments. A special note of thanks goes to Dr. Leel Knowles, Jr., and Peter W. Swarzenski at USGS.

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Received Feb. 10, 2003
Accepted Mar. 15, 2003