VOLUMETRIC EXCHANGES BETWEEN A MANAGED MARSH AND A COASTAL ESTUARY

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ABSTRACT: *The dominant term in the estimation of net flux calculation, between a marsh and a source of tidal water is often the exchange of water. The purpose of this study was to provide a description of the methodology used to estimate the volumetric exchange of surface waters between a managed marsh and the Indian River Lagoon during the managed and unmanaged periods. The paper also documents the simplifying assumptions that had to be made to estimate the exchanges both during the managed and unmanaged period. These assumptions had to be made either because the data were limited mainly due to the cost constraints of the project, or the hydrologic variables were functions of random processes that were difficult to model. The volumetric exchanges during the managed period were computed using direct flow measurements as well as by water balance and the estimated values were within 4.4 percent of each other. The exchanges during the unmanaged period were computed using only direct flow measurements. During the unmanaged period, the bulk of the water is exchanged during mid tide but the magnitude of the exchange depends on the high tide elevation.*

IN his review of twenty years of research on the role of salt marshes in estuarine productivity, Nixon (1980), compiled the methods used in determining water exchanges between salt marshes and estuaries, as well as their uncertainties and drawbacks. He reported that virtually all of the studies used one of two methods in determining exchange volumes. The first method consisted of using flow meters to determine direct discharges (Boon 1975 and 1978; Kjerfve et al., 1978; Kjerfve and Proehl, 1979; Valiela et al, 1978). The second method estimated volumetric exchanges using information on tide heights and hypsographic curves. Boon (1975) also performed a detailed comparison of both methods in a Virginia marsh and concluded that " . . . the determination of time-varying tidal discharge by means of an area-height model, rather than by direct flow measurements, is not recommended for the calculation of net transport." The purpose of this study was to determine and compare the volumetric exchange of surface waters between a managed marsh in St. Lucie County, Florida, and the Indian River Lagoon during the managed and unmanaged period. The volumetric exchanges during the managed period were computed using direct flow measurements as well as by water balance. The exchanges during the unmanaged period were computed using only direct flow measurements.

A brief description of marsh management practices in Saint Lucie County is provided so that the readers can understand the term "managed marsh". Since 1935, dikes were installed around the marshlands in St. Lucie County and the water from the marshlands was pumped out into the Indian River Lagoon for the control of sandflies. Soil was excavated from within the "impounded" marshlands, also known as impoundments, to build these dikes and the resulting depressions created a ditch, termed as the perimeter ditch, along the estuarine periphery of the impoundments. The dike constructions, however, caused a loss of estuarine-marsh connections and resulted in the physical isolation of the salt-marsh and mangrove habitats from the waters of the Indian River Lagoon. As a result, a two-phase marsh restoration program, known as Rotational Impoundment Management (RIM), began in 1984 and is currently on going in St. Lucie County. First, culverts are being installed through the dikes to hydraulically connect the lagoon and the marsh and to provide free flow between these two water bodies. These culverts allow for life-sustaining water quality in the marsh and access to the marsh by aquatic life in the lagoon. Second, water circulation is being created within marshes during the summer months (management period) by pumping lagoon water into one end of the marsh and releasing it back into the lagoon at the other end through specifically constructed tide-gates attached to culverts. Marshes, which are managed by this type of water circulation, are termed "managed" marshes.

Water, during the managed period, is released by bottom-water-release culverts or overflow culverts. A bottom water release culvert allows poor quality impoundment water, with a high BOD, to be released into the lagoon from a depth of approximately 1 m. An overflow culvert allows surface water to be released from the impoundment into the lagoon. A managed marsh undergoes three periods; a managed period which is usually from May 1 through August 31; a transitional period, usually from September 1 to October 31, during which tide gates are removed and pumping is gradually stopped; and the remainder "open" period during which water flows freely between the lagoon and the marsh based on tidal conditions

Study Location and Culvert Description—The study location was a managed marsh in Hutchinson Island which is in Saint Lucie County, Florida. Hutchinson Island forms the eastern boundary of the county, and also separates the Indian River Lagoon from the Atlantic Ocean (Fig.1). The western fringe of Hutchinson Island consists of mangrove swamps and high salt-marshes. The location of Impoundments 1 through 11A–B are also shown (Fig.1). Impoundment 2, which is located west of highway AIA (N 27° 25′ 30″; W 80° 16′ 30″) in St. Lucie County and extends over an area of 76 ha (188 acres) (Figure 2), was selected for the purpose of this study. Water flows between the impoundment and the Indian River Lagoon through seven 0.76 m diameter corrugated aluminum culverts (numbered A through G in Fig. 2), which connect the lagoon to the perimeter ditch. These culverts are approximately 12.2 m long. In addition to these seven culverts, there are three 1.2 m diameter culverts (marked as H, I, and J in Fig. 2), within the impoundment which connect the east and west ends of the impoundment situated on either side of state road A1A. Water is continuously pumped from the lagoon at the north end of the impoundment during the managed period and the marsh water is discharged back into the lagoon through four surface water release (or overflow)

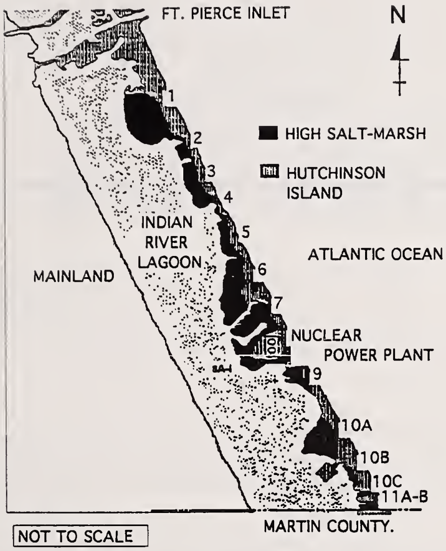

FIG. 1. Locations of some of the impounded marshes within Saint Lucie County.

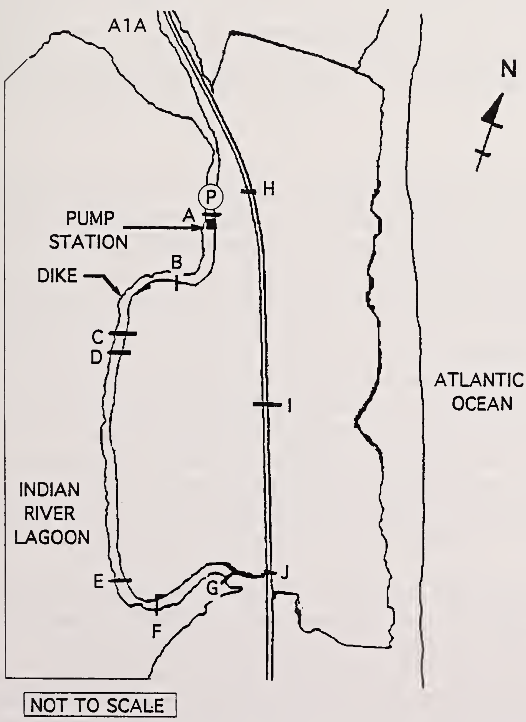

FIG. 2. Map of Impoundment 2 showing culvert locations.

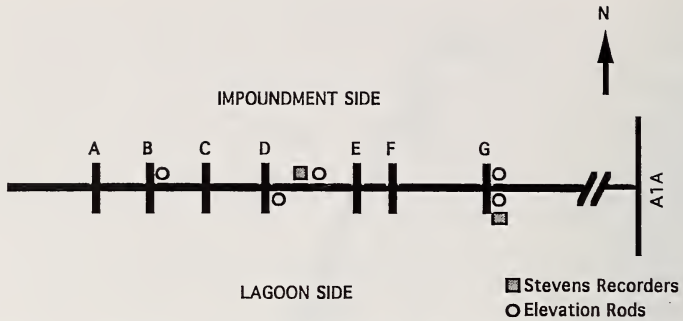

FIG. 3. Locations of continuous water level recorders and elevation rods.

culverts, culverts B, C, D, and F, and two bottom-water-release culverts, culverts E and G. As noted earlier, the tide gates are removed from all culverts during the unmanaged period, and there is unrestricted flow between the impoundment and the lagoon through the culverts during this period.

Culvert A is closed during the managed period because of its proximity to the pump station. This is done in an attempt to maintain a constant water level within the impoundment. In 1991, the pump was switched on June 15, 1991, although data collection began from July 8, 1991. The managed period in 1991 was, therefore, from June 15 to September 5. Tide gate weirs attached to the culverts were removed while the pump remained in operation during a transition period between September 6 and September 30, 1991. The pump was turned off on September 30, 1991, and the unmanaged period occurred between October 1 and April 30, 1992. During the unmanaged period, water exchange between the impoundment and lagoon was unregulated, with the direction of flow dependent on the lagoon and impoundment water elevations.

METHODS—Continuous water level measurements were taken in Impoundment 2 between July 9, 1991 and May 1, 1992 although some data were lost due recorder malfunction, moisture leakage through the wooden housing, insects, and vandalism. The locations of two continuous stage recorders and five elevation rods, also installed for measuring water elevations, are shown in Figure 3. Figure 4 is a fair representation of the water levels measured during the managed period. The impoundment water level, during the managed period, remained relatively constant between 0.52 m and 0.64 m above the National Geodetic Vertical Datum (NGVD) although relatively small abrupt rises and falls were observed during and after rainfall events. The lagoon water elevations during this period ranged from 0.14 m below NGVD to 1.0 m above NGVD. Figure 5 is indicative of the data measured during the unmanaged period. During this period, there were tidal fluctuations in both the lagoon and impoundment water levels with a lag of approximately one hour between the impoundment and lagoon high and low water levels. Lagoon water levels ranged from 0.07 m below NGVD to 0.78 m above NGVD during this period with a maximum tidal range of 0.44 m. Marsh water levels ranged form 0.05 m below NGVD to 0.68 m above NGVD during this period with a maximum tidal range of 0.36 m.

Estimation of flow rates through culverts-managed period—During the managed period, velocities were measured at the lagoon end of the culverts on August 30 and September 3, 1991, at all culvert locations with the exception of location A (since it was closed) using a Marsh-McBirney Model 527 Electromagnetic Water Current Meter. The lagoon water level was rising during the measurement period on both days. Velocities were measured across the culvert cross-section at three locations and an average velocity was computed. The difference in the lagoon and marsh water levels, h, was also recorded at the same time.

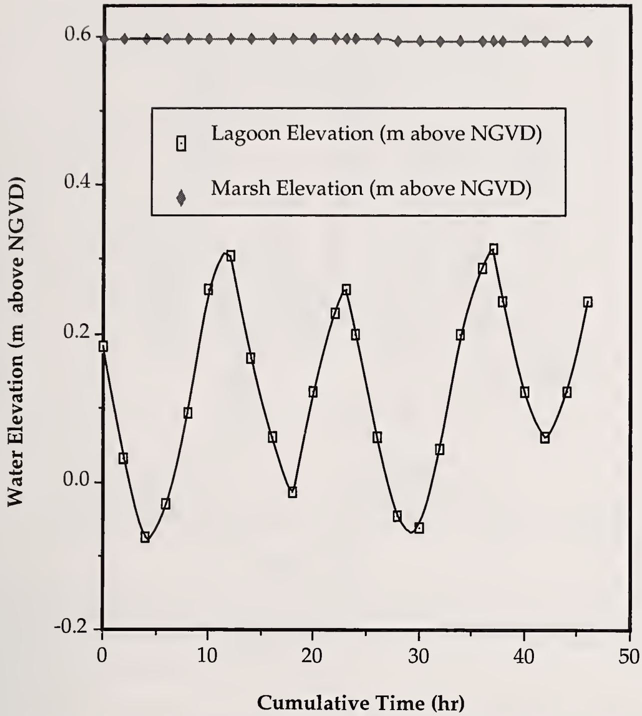

FIG. 4. Lagoon and marsh water level elevations during the managed period (from 1:45 AM on August 15 to 11:45 PM on August 16, 1991).

Culvert discharges (or flow rates), Q, were calculated by multiplying the average velocity by the submerged area. An attempt was made to develop a rating curve for each culvert by plotting graphs between Q and h. However, there was extreme scatter in the data plotted between the two variables. This scatter was most likely due to the fact that debris such as leaves, sticks and other objects, gathered at the overflow inlet, had more influence on the flow rate through the culvert than the head differential between the lagoon and impoundment water levels. This is evident from the data shown in Table 1; the flow rate remained fairly steady (standard deviations in the range of 0.01 m^3/s to 0.02 m^3/s) while the h values ranged from 0.17 m to 0.47 m. Rating curves, developed after cleaning the debris, would not have been useful in future projections since the debris would have reassembled at the overflow inlets. In the absence of meaningful rating curves, it was decided to use the average flow rates (Table 1) to estimate volumetric exchanges through overflow culverts. This approximation, although seemingly crude, can be justified by the fact that the standard deviations in the measured flowrate values were relatively small (which implies that the flowrates remained close to the average value) even though there was a 0.3 m differential in the measured h values.

The data between Q and h for the two bottom water release culverts, culverts E and G, were better correlated as shown in Figures 6 and 7, respectively. These figures show the rating curves obtained at these culverts in August 1991 and August 1992, respectively. In 1991, some of the flow data for culvert G was lost due to equipment malfunction. The rating curves were, therefore, also determined in 1992. The rating curves of 1992 are lower because 1992 had a relatively dry summer and the bottom water release culverts were opened to a lesser degree, thus allowing the water to be discharged at a lower flow rate compared to 1991. The 1992

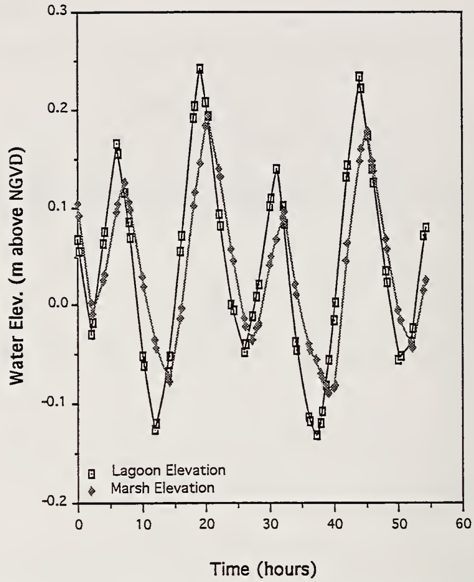

FIG. 5. Lagoon and marsh water level elevations during the unmanaged period (from 1: 45 AM on August 15 to 11:45 PM on August 16, 1991).

rating curves were not used for estimating the volumetric exchanges in 1991; they are shown for comparison purposes and to indicate that the slope and location of the 1991 rating curve for culvert G appears to be accurate even though it is based on just three data points. Linear relationships (Eqn. 1 and 2) were obtained from the graphs

$$Q_E = 4.6751 + 6.1469h \tag{1}$$

$$Q_G = -2.2759 + 19.687h \tag{2}$$

where Q_E and Q_G are the respective flow rates (m^3min^{-1}) for culverts E and G.

Unmanaged period—During the unmanaged period, velocity measurements were taken on March 25, September 11, September 25, and October 8, 1992, using a Model 2031H2 General Oceanics Low-Speed Current meter. The high tide elevations on these days varied from 0.28 m NGVD (March 25) to 0.68 m NGVD (October 8). Velocities were measured at all culvert sites on March 25 and September 11 but were measured only at culverts A and G on the other days. Measurements were taken, approximately every 45 minutes, at three locations across the

TABLE 1. Average flowrates and standard deviations for the overflow culverts.

Culvert	No. of Measurements	Flow Rate Range cm*	Average cm*	Standard Deviation cm*
B	6	0.03–0.07	0.05	0.01
C	6	0.05–0.08	0.07	0.01
D	11	0.05–0.10	0.09	0.02
F	7	0.05–0.09	0.07	0.01

* m^3/sec.

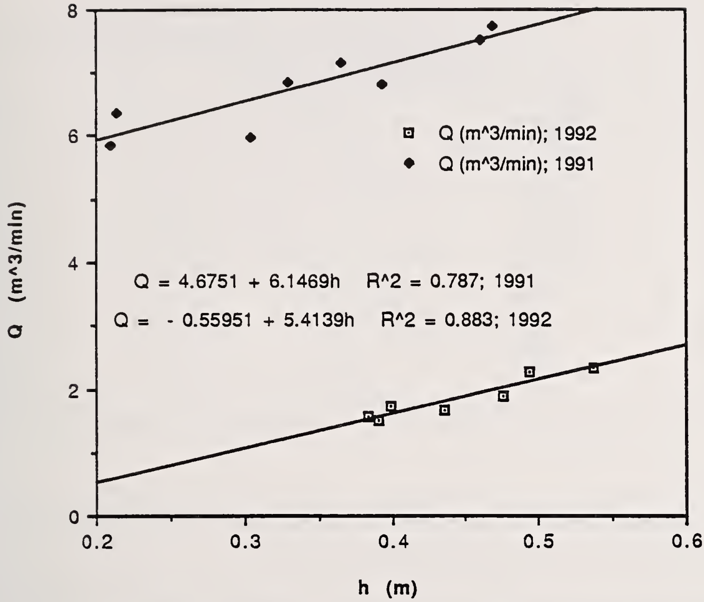

FIG. 6. Rating curves of the bottom water release culvert 2E. The water level difference between the marsh and the lagoon is designated by h.

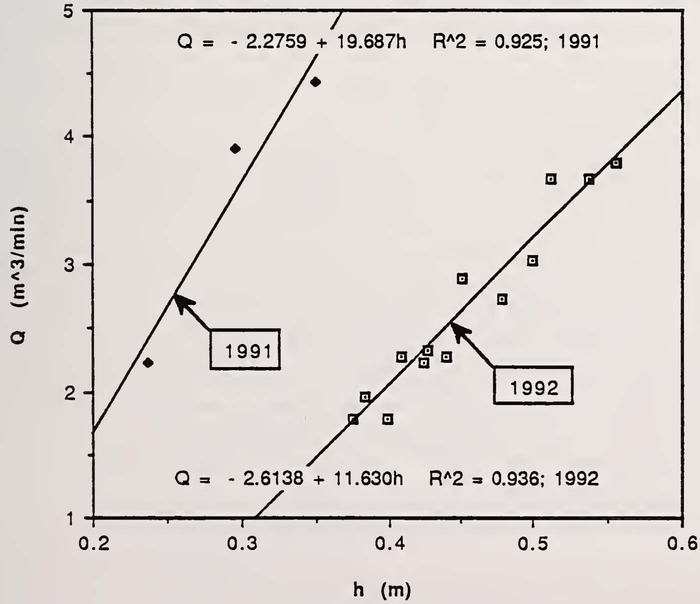

FIG. 7. Rating curves of the bottom water release culvert 2G. The water level difference between the marsh and the lagoon is designated by h.

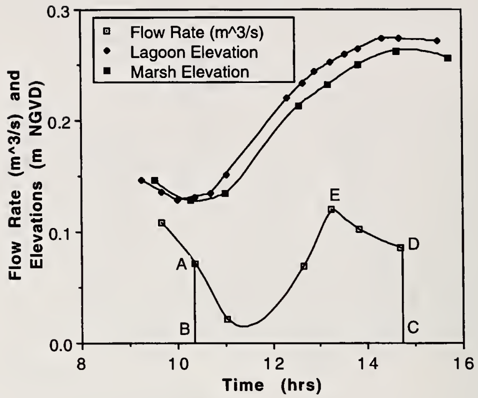

FIG. 8. Variation of marsh and lagoon water levels and flowrates through culverts with time.

culvert cross-section, and an average value was calculated. The water elevations in the lagoon and the impoundment were also noted at the same time.

Again, it was initially expected that the flowrate through the culverts would be a function of the head difference between the lagoon and impoundment water levels. However, graphs plotted between these two variables once again showed no consistent relationship for any of the culverts. On the other hand, graphs between estimated flow rates, lagoon water levels and impoundment water levels versus time, such as the one shown in Fig. 8, were more revealing. These graphs showed that flow rates were lowest when the lagoon and marsh water levels were equal, i.e., shortly after high and low tides in the lagoon, and reached a maximum value somewhere in the middle of the tide. Graphs for all other culverts were very similar to the one shown in Fig. 8. The flow rates plotted in Fig. 8 are absolute values and do not reflect the direction of flow. The direction of flow, however, can be determined from the change in impoundment water level; if the impoundment water level is increasing, the flow is into the impoundment otherwise it is into the lagoon.

The average flow rate for each culvert was found by dividing the area under the flow rate curve (area ABCDE on Fig. 8) by the time interval (duration between B and C on Fig. 8). The estimated average flow rates using this method, based on data collected on various days, are shown in Table 2. The high tide elevation at the time of measurement, and the average flow rates for all culverts on the four days that data were measured are also noted in this table. A comparison of these values clearly shows that flow rates are higher when the lagoon tides are high, i.e., more water is exchanged between the marsh and the lagoon if the hightide elevation is relatively higher. The cumulative flow rates through all culverts, which were determined by multiplying the average flow rate by seven (number of culverts), are also shown (Table 2).

An exponential rating curves provided the best fit ($r^2 = 0.813$) between high tide elevation and the cumulative flow rate through all culverts, based on the data collected on March 25, September 11, September 16, and October 8, 1992. The range of measured high tide elevations on these dates were from 0.28 m NGVD to 0.68 m NGVD (Table 2) and the equation for the rating curve was found to be:

$$y = (0.26)10^{(1.63x)} \tag{3}$$

where y is the cumulative flow rate (m^3s^{-1}) through all culverts and x is the high tide elevation (m). A second order polynomial fitted the data points more precisely but was rejected on the basis that it showed a decreasing trend, i.e., flow rate decreased as high tide elevation increased after the maxima on the curve.

TABLE 2. Measured average and cumulative flowrates (in cubic meters per second) at different high-tide elevations in Impoundment 2.

	High-Tide Elevation			
Culvert	0.28 m	0.29 m	0.46 m	0.68 m
A	0.070	0.100	0.327	0.396
B	0.072	0.135	NM	NM
C	0.083	0.122	NM	NM
D	0.097	0.139	NM	NM
E	0.077	0.125	NM	NM
F	0.076	0.151	NM	NM
G	0.057	0.121	0.316	0.411
Average	0.076	0.128	0.322	0.404
Cumulative	0.532	0.893	2.251	2.825

Note: NM implies not measured.

Estimation of pumped flow rates—Tests were conducted by the company of Knight and Mathis to determine the rate at which water was discharged into the marsh from the pump station using a Doppler flow meter. These tests measured a pump flow rate of 28.6 m^3min^{-1}. The margin of error for the test was stated to be 0.2 m^3min^{-1}. These tests were conducted when the lagoon water level was approximately 0.76 m below the discharge pipe elevation.

RESULTS—*Estimation of volumetric exchanges during the managed period from direct measurements*—Volumetric exchanges between the lagoon and the impoundment through the bottom water release culverts E and G were estimated by Eqns. (1) and (2). The incremental flow volume, $V_{BWR,}$ that was discharged through these culverts, during interval Δt, was calculated as follows:

$$V_{BWR} = \{[Q_{(E)t=0} + Q_{(E)t=t+\Delta t}]/2 + [Q_{(G)t=0} + Q_{(G)t=t+\Delta t}]/2\}(\Delta t) \qquad (4)$$

where $Q_{(E)t=0}$ and $Q_{(G)t=0}$ are the flow rates through E and G at the beginning of the interval, and $Q_{(E)t=t+\Delta t}$ and $Q_{(G)t=t+\Delta t}$ are the flow rates through E and G at the end of the interval. The time period, Δt, was selected as two hours and the difference in water levels, h, was computed at every two hours. The incremental flow volume, V_O, that was discharged through the overflow culverts, A, B, C, D and F, was obtained by multiplying the cumulative average flow rates shown in Table 1 by Δt. Approximately 2.7 million m^3 (270 ha-m) of water was discharged into the lagoon from the impounded marsh through the culverts during the managed period over a period of 59 days (from July 9 to September 5) at an average rate of 31.8 m^3 min^{-1}.

Estimation of volumetric exchanges during the managed period by water mass balance—The water balance equation for the marsh during the managed period can be written as:

$$P + R_L = D + ET + GWD + S \qquad (5)$$

where P is the rainfall, R_L is the water pumped from the lagoon, D is the outflow from the impoundment through the culverts, ET is the loss due to evapotranspiration, GWD represents the ground water discharge, and S is the water stored into the marsh during the managed period. If at no time is there a deficiency of water in the soil for vegetation use, then Eqn.(4) can be rewritten as:

$$P + R_L = D + PET + GWD + S \tag{6}$$

in which PET is the annual potential evapotranspiration. Viessman and coworkers (1977) suggested that in practice PET is equal to lake evaporation (LE) as determined from National Weather Service Class A records. Therefore, Eqn. (5) can be further reduced to:

$$P + R_L = D + LE + GWD + S \tag{7}$$

There was no appreciable storage in the marsh since the water level within the marsh did not change except during storm events, i.e., S = 0. Therefore, Eqn. (7), after rearrangement, can be modified to:

$$D = P + R_L - LE - GWD \tag{8}$$

The total rainfall from July 9 to September 5 was 0.42 m, the lagoon water pumped into the marsh was 3.20 m, and the pan evaporation was 0.33 m. The actual evaporation from the marsh during the managed period was estimated to be 0.23 m assuming a pan coefficient of 0.7. If groundwater seepage is considered negligible compared to the other terms in Eqn. (8), then D = 3.4 m from Eq (8) and the estimated volume discharged into the lagoon is 258 ha-m. The volumetric discharges computed by water balance is within 4.4 % of the volumetric discharge estimated by direct measurement (270 ha-m).

Estimation of volumetric exchanges during the unmanaged period—Estimations of the volume of water exchanged between the impoundment and the lagoon, using the exponential model are shown in Table 3. The procedure used to estimate the volume of water exchanged between the lagoon and the marsh between the two high tides occurring at 9:45 AM and 9:30 PM is described subsequently. Since the impoundment water elevation was dropping from 9:45 AM to 3:45 PM (column 2) from 0.27 m NGVD to 0.16 m NGVD (column four) during a period of 6.00 hours (column three), the flow direction, during this period, was from the impoundment into the lagoon. Similarly, since the impoundment water elevation was rising from 3:45 PM to 9:30 PM (column 2) from 0.16 m NGVD to 0.18 m NGVD (column four) during a period of 5.75 hours (column three), the flow direction, during this period, was from the lagoon into the impoundment. The cumulative flow rate through all culverts at 9:45 AM and 9:30 PM were calculated from Eq. 3 (column 5) and the average cumulative flow rate during this period is tabulated in column 6. Finally, the volume of water into lagoon (column 7)

TABLE 3. Sample volume calculations with the exponential model in Impoundment 2 during the unmanaged period.

Date 1	Time 2	Time Interval (hours) 3	Water Elevation (in NGVD) 4	Flowrate (cm)* 5	Average Flowrate (cm)* 6	Volume into Lagoon (cubic meters) 7	Volume into Impoundment (cubic meters) 8
12/1/91	2:15 AM		0.14				
	9:45 AM	7.50	0.27	0.361			
	3:45 PM	6.00	0.16		0.342	7392	
	9:30 PM	5.75	0.18	0.324			7084
12/2/91	2:30 AM	5.00	0.03		0.323	5816	
	12:00 PM	9.50	0.18	0.323			11050
	3:45 PM	3.75	0.11		0.314	4243	
	11:00 PM	7.25	0.13	0.306			8202
12/3/91	3:00 AM	4.00	0.02		0.312	4493	
	12:15 PM	9.25	0.16	0.318			10391
	4:15 PM	4.00	0.05		0.313	4501	
	9:15 PM	5.00	0.13	0.317			5626

* m^3/sec.

or the volume of water into impoundment (column 8) is calculated by multiplying the respective numbers in column 3 and column 6.

The monthly volumes exchanged between the lagoon and the marsh during the unmanaged period are shown in Table 4. A comparison of the average monthly volumes exchanged between the marsh and the lagoon during the unmanaged period indicates that the highest exchanges occurred during the months of October and November which are also the months in which the tides are highest. July and August numbers were not averaged because these months were during the managed period, and the flow, during these months, was only in one direction, i.e., from the marsh to the lagoon. It can also be noted from Table 4 that the monthly volumes discharged into

TABLE 4. Estimated monthly volume exchanges in 1991–1992.

Month	Volume into Lagoon (mil. cubic meters)	Volume into Impoundment (mil. cubic meters)	Average Exchange Volume (mil. cubic meters)
July	1.44	1.28	—
August	1.45	1.28	—
September	*	*	*
October	2.17	2.07	2.12
November	2.32	1.92	2.12
December	0.93	0.92	0.92
January	1.21	1.07	1.14
February	1.09	1.01	1.05
March	0.83	0.68	0.76
April	1.18	1.00	1.09

the lagoon were always estimated to be greater than the monthly volumes discharged into the marsh. These differences occur mainly for two reasons. First, some of the rainfall is also discharged into the lagoon during the storm periods. Second, it is assumed that for a given tidal height, the average flow rate during an ebb tide is equal to the average flow rate during the flood tide. This assumption could also lead to the observed discrepancies since it was noted that the average duration of the flood tide (when water is discharged into the marsh) for the month of December was 5.78 hours while the average duration of the ebb tide was 6.63 hours. It was assumed for the purpose of this study that the actual monthly volume exchanged was the average of the estimated discharges into the lagoon and the marsh.

Discussion—Nixon (1980) pointed out that the dominant term in the estimation of net flux calculation, between a marsh and a source of tidal water is often the exchange of water. An effort has been made to describe, in detail, the somewhat tedious methodology that has to be used to estimate the volumetric exchanges between a tidal estuaries and managed marshes. A number of simplifying assumptions had to be made to estimate the exchanges both during the managed and unmanaged period. These assumptions had to be made either because the data were limited mainly due to the cost constraints of the project, or the hydrologic variables were functions of random processes that were difficult to model. For example, it was noted that the flow rate from the overflow culverts, during the managed period were, to an extent, a function of leaves and other debris accumulating over weirs. Volumetric exchanges were, therefore, also estimated by the water balance equation and the results obtained from the two methods were fairly close (within 4.4 percent).

An examination ofwater levels measured during the unmanaged period (Fig. 5) shows that the there were times when there was considerable difference in the water levels at low and high tides. Yet flow measurements at this time showed almost no flow through the culverts. This is why we could not obtain the expected rating curve between flowrate and the elevation difference between lagoon and marsh water levels. The bulk of the water was exchanged during mid tide and not during the high or low tide when the water reverses direction from the marsh to the lagoon or vice versa. However, the magnitude of the exchange during a tidal cycle depends on the high tide elevation and much greater volumes of water were exchanged when high tide elevations were 0.5 m or higher.

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