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Evaporation, Precipitation, and Associated Salinity Changes at a Humid, Subtropical Estuary

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ABSTRACT: The distilling effect of evaporation and the diluting effect of precipitation on salinity at two estuarine sites in the humid subtropical setting of the Indian River Lagoon, Florida, were evaluated based on daily evaporation computed with an energy-budget method and measured precipitation. Despite the larger magnitude of evaporation (about 1,580 mm yr^{-1}) compared to precipitation (about 1,180 mm yr^{-1}) between February 2002 and January 2004, the variability of monthly precipitation induced salinity changes was more than twice the variability of evaporation induced changes. Use of a constant, mean value of evaporation, along with measured values of daily precipitation, were sufficient to produce simulated salinity changes that contained little monthly (root-mean-square error = 0.33‰ mo^{-1} and 0.52‰ mo^{-1} at the two sites) or cumulative error (<1‰ yr^{-1}) compared to simulations that used computed daily values of evaporation. This result indicates that measuring the temporal variability in evaporation may not be critical to simulation of salinity within the lagoon. Comparison of evaporation and precipitation induced salinity changes with measured salinity changes indicates that evaporation and precipitation explained only 4% of the changes in salinity within a flow-through area of the lagoon; surface water and ocean inflows probably accounted for most of the variability in salinity at this site. Evaporation and precipitation induced salinity changes explained 61% of the variability in salinity at a flow-restricted part of the lagoon.

Introduction

Salinity can act as a critical control on estuarine ecosystem viability. The interplay between seawater inputs, groundwater-estuarine interflows, atmospheric deposition, diluting effects of stream inputs and precipitation, and salinity-increasing effects of evaporation generate the temporal variation in estuarine salinity. Estuarine hydrodynamic and salinity models can incorporate these factors to allow resource managers to estimate salinity variations under historical or real-time settings or future scenarios of management or environmental forcing. Relatively easily available data for stream flow and precipitation can readily be incorporated within such models. Seawater inputs to the estuary can either be simulated within the model or prescribed based on field measurements of flow and concentrations; groundwater-estuarine interflows can be estimated (e.g., seepage meters, geochemical approaches, or Darcian methods; Martin et al. 2002); and atmospheric deposition can be measured using wet and dry deposition collectors (National Atmospheric Deposition Program 2004; Clean Air Status and Trends Network 2004).

The effects of evaporation on variability of lagoon salinity are often difficult to define because of a lack of evaporation data; several previous investigators have necessarily approximated evaporation based on available data. Evaporation from Point Phillip Bay, Australia, was estimated based on land-based measurements, with error introduced when these values were extrapolated to the open bay (Harris et al. 1996). Walker (1997) noted that calibration of a salinity transport model for Point Phillip Bay was only possible with substantial (reduction of evaporation by 30% or increase in rainfall by 60%) changes in measured and estimated values of atmospheric fluxes of water. In a study of the hydrology of a tropical estuarine system in Brazil, Medeiros and Kjerfve (1993) estimated evaporation from open water using an empirical formulation (Holland 1978) based solely on air temperature without consideration of other factors (water temperature, relative humidity, and wind speed) that have been shown to have a role in explaining variations in open water evaporation (Brutsaert 1982). In a hydrodynamic simulation of flow and salinity in the Indian River Lagoon for 1998 for which measured values of evaporation were not available, Sheng and Davis (2003) applied a constant pan coefficient (0.78) to estimated monthly pan evaporation data from a land-based evaporation pan in the vicinity of the lagoon. Brutsaert (1982, p. 251–253) points out that evaporation pans are of ''uncertain and dubious applicability as a measure of evaporation in nature'' and ''can be considered useful only to provide a rough estimate of lake evaporation, mostly on an annual basis.''

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Evaporation induced changes in estuarine salinity can be an important component of the total variation in estuarine salinity. Ridd and Stieglitz (2002) determined that rapid salinity increases in estuaries in arid parts of Australia were largely the result of evaporative distilling. In a study of estuarine dynamics in a semiarid coastal lagoon in Mexico, Valle-Levinson et al. (2001) concluded that the (unknown) seasonal variability of the net evaporation rate (evaporation reduced by precipitation) should prove to be critical for understanding lagoon hydrodynamics. For estuaries in more humid settings, the effects of evaporation on variability of salinity might be expected to be less important than in arid settings because of the relatively high precipitation and stream flow and the associated diluting effects of these inputs.

In this study, the effects of the atmospheric water fluxes of evaporation and precipitation on estuarine salinity were investigated at two monitoring sites (differing from one another in the degree of estuarine flushing) in the humid subtropical setting of the Indian River Lagoon, Florida. The objectives of this paper were to describe daily evaporation computed with an energy-budget method, present the evaporation and precipitation induced salinity changes, evaluate the importance of salinity changes induced by evaporation and precipitation relative to measured salinity changes, and investigate the efficacy of using coarse estimates of evaporation in estimating salinity changes.

Site Description

A humid, subtropical climate prevails in the east-central Florida location (Fig. 1) of the Indian River Lagoon, which is characterized by warm, relatively wet summers and mild, relatively dry winters. The Indian River Lagoon is a biologically diverse estuary, providing habitats for various species of fish, birds, mammals, oysters, crabs, clams, and plants (Martin et al. 2002). Restricting salinity within a suitable range is critical to maintaining suitable estuarine habitats (Montague 1993; Hanisak 2002).

The Indian River Lagoon estuarine system consists of three distinct, but hydraulically connected, water bodies: Indian River, Banana River, and Mosquito Lagoon (Fig. 1). Indian River and Banana River can more aptly be described as lagoons rather than rivers. The surface area of the Indian River Lagoon is approximately 910 km^2, with width varying from 1 to 9 km and a mean depth of 1 m. A narrow barrier island, breached by four inlets, separates the Indian River Lagoon from the Atlantic Ocean. Indian River receives direct inputs of flows from several streams (Fig. 1) and is better flushed than are Banana River and Mosquito Lagoon, which do not receive direct stream input. Banana River is connected to Indian River by a narrow (150-m wide) inlet near Dragon Point at the southern end of Banana River and by the 100-m wide Cape Canaveral barge canal. Haulover Canal provides the only connection between Mosquito Lagoon and Indian River. Wind and tidal flow are the dominant forces for lagoon circulation (Sheng and Davis 2003).

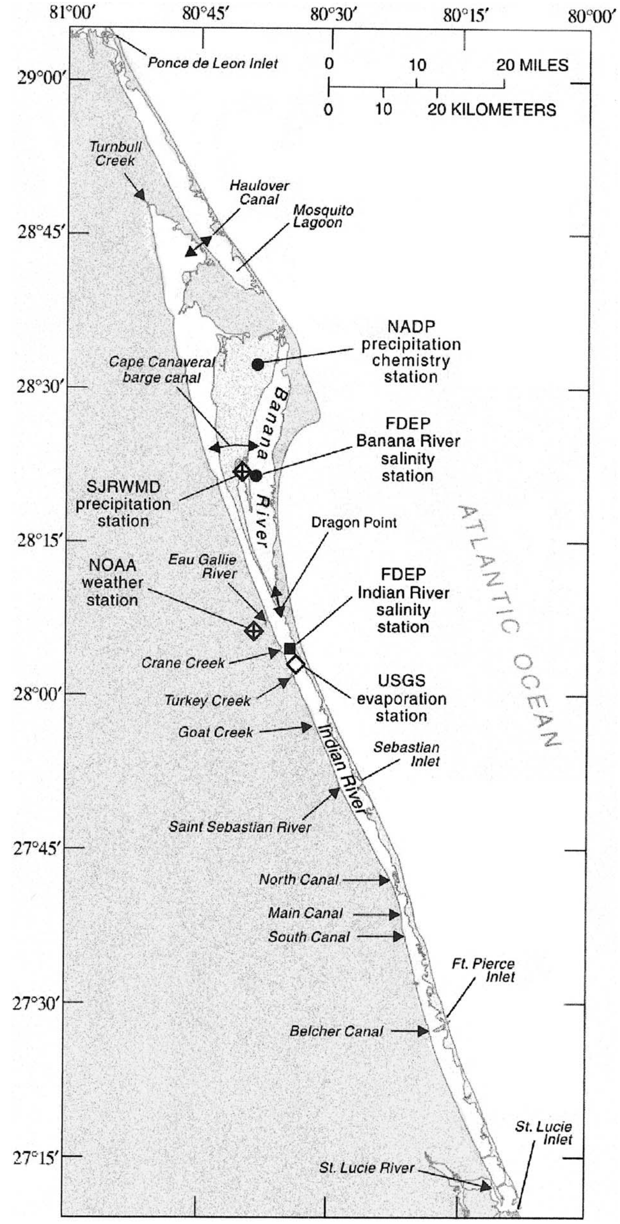

Fig. 1. Location of study area.

Seawater (salinity of about 35‰) enters the lagoon through several inlets to the Atlantic Ocean during flood tide, providing the dominant source of salinity to the lagoon. Freshwater enters the lagoon from streams, canals, precipitation, and groundwa-

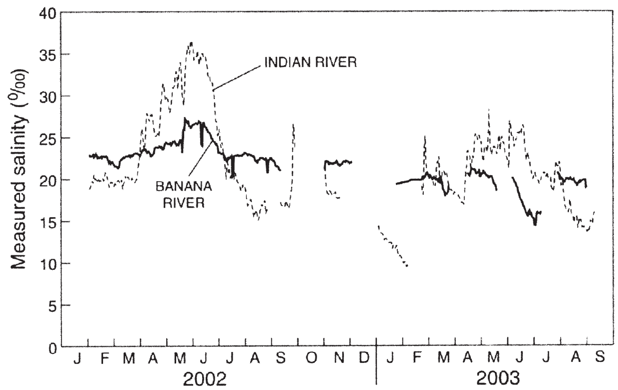

Fig. 2. Measured values of depth-averaged salinity at Indian River (Florida Department of Environmental Protection No. 872 1843) and Banana River (Florida Department of Environmental Protection No. 872 1647) salinity stations. Missing data are shown as gaps.

ter, and is either evaporated or exits to the ocean during ebb tide. Control structures are located at the end of the larger canals to regulate freshwater inflow to the lagoon. Glatzel and Da Costa (1988) report that approximately equal amounts of the freshwater flow into the lagoon originate on either side of Ft. Pierce Inlet; this appraisal is also supported by Hydrologic Simulation Program–Fortran simulations for the Indian River Lagoon watershed (Applied Environmental Engineering LLC 2003; Adkins et al. 2004). More flow-restricted parts of the Indian River Lagoon (such as Banana River) show less temporal variability in salinity than parts of the lagoon, such as Indian River, which are less flow-restricted or are close to stream input or inlets to the ocean (Fig. 2). The lagoon shows little vertical stratification in salinity (generally $<$1–2‰ variation from water surface to bottom of the lagoon) within the water column, except at the mouth of major tributaries such as Saint Sebastian River.

Methods

Description of Meteorological Monitoring Sites

An evaporation station, constructed on a single wooden pile near the center of Indian River, was installed and maintained by the United States Geological Survey (USGS) for the collection of half-hour resolution meteorological, stage, and water temperature data (Fig. 1, Table 1) from February 1, 2002, to January 31, 2004. These data were used to compute daily values of evaporation. Daily precipitation data were obtained at the National Oceanic and Atmospheric Administration (NOAA) weather station at the Melbourne International Airport (NOAA 2004), about 7 km northwest of the Indian River salinity station and a St. Johns River Water Management District (SJRWMD) station at Kiwanis Island, about 3 km west of the Banana River salinity station (Fig. 1).

Description of Salinity Monitoring Sites

Hourly salinity data from sensors at the top and bottom of the water column were obtained from data collected from February 1, 2002, to August 31, 2003, at Florida Department of Environmental Protection (FDEP) stations within Indian River, about 3.2 km west-northwest of the evaporation station, and Banana River, about 33 km north-northwest of the evaporation station (Fig. 1). Values of water temperature and electrical conductivity were measured with a Stevens-Greenspan Model EC250 meter at the FDEP stations. These values were converted to salinity using the revised definition of salinity in the United Nations Educational, Scientific, and Cultural Organization Practical Salinity Scale of 1978-PSS78 (UNESCO 1978). Daily values of representative water depth in the vicinity of each of the salinity stations were estimated based on local bathymetry and water level measurements made with pressure transducers at the Indian River evaporation station and the Banana River FDEP station.

TABLE 1. Study instrumentation at evaporation station. CSI is Campbell Scientific, Inc.

Type of measurement	Instrument	Height (m)
Air temperature and relative humidity	Vaisala Model HMP45C temperature and relative humidity probe	2.3–2.9 above water
Net radiation	REBS Model Q-7.1 net radiometers (2)	3.2–3.8 above water
Wind speed and direction	Handar Model 425 ultrasonic anemometer	3.9–4.5 above water
Incoming solar radiation	LI-COR, Inc. Model LI200X pyranometer	3.2–3.8 above water
Stage	Handar 436B incremental shaft encoder with float	–
Water temperature	Chromel-constantan thermocouple wire (prior to August 21, 2002) and CSI Model 107 temperature probes (after August 21, 2002)	0 and 0.3 below water and 1.8, 1.2, and 0 above lagoon bottom
Data logging	CSI Model 10X data loggers (2); 12 volt deep-cycle batteries (2); 20 watt solar panels (2)	–

The two salinity monitoring sites chosen for this study are distinguished from each other primarily by the degree of flushing by stream or ocean inputs. The Indian River site has greater exchange with stream flow and ocean water than does than the more hydraulically isolated Banana River site (Fig. 1). Sheng and Davis (2003) estimated residence times (50% renewal times) of 22 and 314 d for the Indian River and Banana River sites, respectively, for 1998 conditions. Two streams, Crane and Turkey Creeks, enter the lagoon within 1 and 6 km, respectively, of the Indian River salinity station; these streams constituted about 6% and 18%, respectively, of the total freshwater flow into the Indian River Lagoon north of the Indian River-St. Lucie County line during 1989–1991 (Knowles 1995). Both salinity monitoring sites are remote (> 20 km) from the nearest inlet (Sebastian Inlet) to the ocean. The flow-through geometry of Indian River allows greater flushing by ocean water than does the dead-end geometry of Banana River. Lagoon depths vary, primarily based on wind speed and direction and to a lesser extent on ocean tides, from about 1.6 to 2.2 m and 1.0 to 1.5 m in the vicinity of the Indian River and Banana River sites, respectively.

Computed Evaporation

Daily evaporation was computed using the Bowen ratio energy-budget method (Bowen 1926; Anderson 1954; Ficke 1972; Sacks et al. 1994). This method relies on the relatively large component that latent heat flux (energy flux required to produce the evaporative phase change) constitutes within the energy budget of a water body. Energy-budget methods have a distinct advantage over seemingly more direct water-budget methods for estimating evaporation from a water body; uncertainty in difficult-to-measure water budget terms (e.g., groundwater seepage, tidal flows, and intra-estuarine flows) can be much more detrimental to the latter than the former method (Anderson 1954).

The energy budget for a specified control volume can be given as:

$$Q_{nr} + Q_{as} + Q_{ag} + Q_{ap} - Q_{ae} - Q_e - Q_h = Q_s \quad (1)$$

The control volume was a hypothetical water column of unit surface area representative of the area in the vicinity of the evaporation station. Q_{nr} is net radiation to the surface of the control volume, Q_{as} is energy advected into the control volume with lateral flows (intraestuarine circulation), Q_{ag} is energy advected into the control volume with groundwater seepage, Q_{ap} is energy advected into the control volume with precipitation, Q_{ae} is energy advected from the control volume with evaporated water vapor, Q_e is latent heat flux from the control volume, Q_h is sensible heat flux from the control volume, and Q_s is change in stored energy within the control volume. All terms in Eq. 1 are defined in units of Watts per square meter ($W\ m^{-2}$).

Net radiation (Q_{nr}), consisting of incoming solar radiation, reflected solar radiation, downwelling longwave radiation, and upwelling longwave radiation, was measured with net radiometers (Table 1).

Energy can move into or out of the control volume as a result of fluxes of water of a given temperature into or out of the control volume. This advected energy can be computed for a particular form of water flux i as:

$$Q_i = \rho_w c_w q_i (T_i - T_b) \quad (2)$$

where Q_i is the energy flux associated with a given water flux q_i ($m^3\ m^{-2}\ s^{-1}$) of temperature T_i (°C) into the control volume and the subscript i identifies the particular form of water flux (groundwater seepage, precipitation, evaporation, or lateral flows). Water density (ρ_w) and specific heat of water (c_w) were assumed to have constant values of 1,000 kg m^{-3} and 4,184 J $kg^{-1}\,°C^{-1}$, respectively. Equation 2 can be applied individually to each form of water flux if the appropriate q_i and T_i for that form can be determined. Estimates of groundwater seepage to the lagoon vary widely (Martin et al. 2002), ranging from $3.4 \times 10^7\ m^3\ yr^{-1}$ (Pandit and El-Khazen [1990] using groundwater modeling) to $1.6 \times 10^{13}\ m^3\ yr^{-1}$ (Belanger and Walker [1990] using seepage meters). Cable et al. (2004) attributed the disparity in seepage rate estimates to a distinction between land recharged-derived seepage estimated with groundwater models and the sum of land-recharged- and recirculated surface water-derived seepage measured with seepage meters. In this study, the base temperature (Eq. 2), T_b, was set equal to the expected temperature of groundwater in central Florida (22.2°C) to minimize error in advected energy associated with uncertainty in groundwater seepage (Anderson 1954); under this assumption, Q_{ag} can be approximated as equal to zero. Energy advected into the control volume within precipitation was estimated (Eq. 2) based on measured precipitation data and precipitation temperature estimated as the dew point, computed as a function of measured values of air temperature and relative humidity. Energy advected within evaporated water was estimated based on an implicit (Bowen ratio energy budget) estimate of the evaporation rate and evaporated water vapor temperature assumed equal to air temperature. Advected energy into the control volume associated with lateral flows (Q_{as}) was assumed negligible relative to other terms in the energy budget; this assumption was supported by an analysis to be discussed later in this paper.

Latent heat flux (Q_e) can be related to evaporation as:

$$Q_e = \rho_w \lambda E \tag{3}$$

where λ is latent heat of vaporization of water (J kg^{-1}), estimated as a function of air temperature (Stull 1988), and E is evaporation rate (m s^{-1}).

The ratio of sensible to latent heat flux (Q_h:Q_e), or the Bowen ratio (B), can be estimated (Brutsaert 1982) as:

$$B = \gamma \frac{T_{ws} - T_a}{e_w - e_a} \tag{4}$$

where γ is the psychrometer constant (kPa °C^{-1}), computed as a function of atmospheric pressure and air temperature (Fritschen and Gay 1979), T_{ws} is the temperature of water surface, T_a is air temperature, e_w is saturation vapor pressure at water surface (kPa), and e_a is vapor pressure in air (kPa). Vapor pressure was computed as a function of air temperature and relative humidity (Buck 1981). The reduction in the vapor pressure at the water surface resulting from the presence of dissolved salts was estimated (Raoult's Law) to be about 1% or less for values of salinity prevalent within the lagoon and was ignored in this analysis.

The Bowen ratio energy-budget method requires that the variables of Eq. 4 be evaluated within the atmospheric boundary layer equilibrated to the surface of interest. Campbell and Norman (1998, p. 96) stated that the boundary layer has equilibrated to about a height h at a distance 100 times h downwind of a change in surface cover. The minimum distance to the evaporation station from the shore is about 1,300 m, implying that the boundary layer at the station has equilibrated to a height of 13 m, a height much greater than the 2.3–2.9 m height at which temperature and relative humidity measurements are made. The measurements of air temperature and relative humidity made at the evaporation station are considered to have been within the fully developed boundary layer above the lagoon surface.

The change in stored heat energy within the control volume (Q_s) for a given day i is given by:

$$Q_s = \rho_w c_w d_i \frac{(T_{wa}^{i} - T_{wa}^{i-1})}{\Delta t} \tag{5}$$

where d_i is the average lagoon depth (m) for day I, $T_{wa}{}^{i-1}$ and $T_{wa}{}^{i}$ (°C) are the depth-averaged lagoon water temperatures for the beginning and end of day i, respectively, and Δt is the time interval (equal to 86,400 s or 1 d).

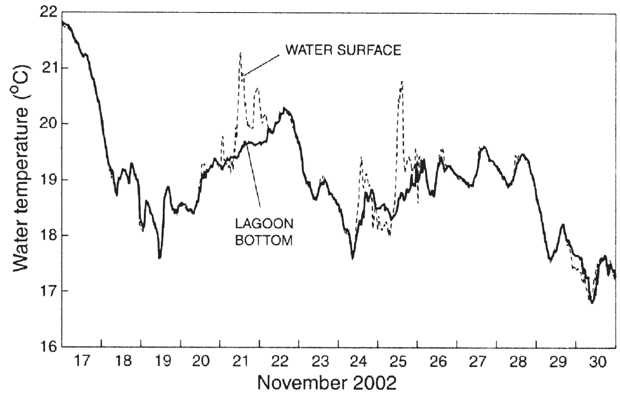

Fig. 3. Water temperature at the evaporation station during November 17–30, 2002.

The water temperature values in Eqs. 4 and 5 should most appropriately represent the water surface and depth-averaged water temperatures, respectively. Because of missing water temperature data resulting from failed temperature sensors, the water temperature in both Eqs. 4 and 5 generally was derived from the shallowest, operational water temperature sensor below the water surface (generally the 30-cm deep sensor). The error associated with use of a single water temperature sensor to define surface and depth-averaged water temperature is expected to be small because of the generally well-mixed conditions in the lagoon (Fig. 3), although temperature stratification can develop during low winds. A sensitivity analysis of the expected error in computed evaporation was performed based on a 100-d period when all water temperature sensors were operational.

Combining Eqs. 1, 2, and 3, and assuming Q_{as} and Q_{ag} are negligible leads to an equation for daily evaporation:

$$E = \frac{Q_{nr} + Q_{ap} - Q_s}{\rho_w[\lambda(1 + B) + c_w(T_a - T_b)]} \tag{6}$$

Data screening (Ohmura 1982) culled suspect evaporation data when the denominator of Eq. 4 was less than 0.04 kPa, the daily Bowen ratio was between −0.9 and −1.1, or the direction of vapor flux was opposite of the measured vapor pressure gradient. These missing evaporation data were gap filled with a mass transfer approach discussed below.

Daily evaporation estimates derived from the evaporation station in Indian River were assumed to be appropriate for Banana River. This assumption may be violated by variations in meteorological conditions between the two sites. The greater water depth (averaging about 0.6 m deeper) at the Indian River site compared to the Banana River site implies that variations in storage of heat energy in the water column, and variations in latent heat flux, may exist between the two sites. Although the meteorological and water column heat storage variations between the two sites could produce evaporation variations of short-term duration (e.g., daily), longer-term (e.g., monthly) estimates of evaporation were expected to be relatively unaffected.

Mass Transfer Methods for Gap Filling Missing Evaporation Measurements

Mass transfer methods for estimating evaporation (Anderson et al. 1950; Marciano and Harbeck 1954; Harbeck 1962) are based on the assumption that evaporation is proportional to the product of the measured water-to-air vapor pressure differential and wind speed.

$$E_{mt} = Nu(e_w - e_a) \qquad (7)$$

where E_{mt} is the mass transfer-estimated evaporation rate (mm d^{-1}), N is the mass transfer coefficient (mm d^{-1} s m^{-1} kPa^{-1}), and u is the wind speed 2 m above the water surface (m s^{-1}). Wind speed was measured between 4.2 and 4.8 m above the water surface. Wind speed at a height of 2 m was estimated based on a logarithmic wind profile and a momentum roughness length of 0.01 cm (characteristic of a calm, open sea; Hansen 1993). The value of N is site specific and represents a variety of effects including the wind profile, geometry of the water body, roughness of the water surface, atmospheric stability, barometric pressure, density, and viscosity of the air, and averaging period over which the variables in the equation are measured (Harbeck 1962; Jobson 1972). Values of Bowen ratio energy-budget estimated daily evaporation that were culled based on data screening procedures were gap filled with a mass transfer equation. The value of N was determined by regression between measured values of evaporation and the remaining variables of Eq. 7.

Calculation of Evaporation and Precipitation Induced Changes in Salinity

The distilling effect of evaporation can be approximated based on mass budgeting in a manner similar to Eq. 8 of Ridd and Stieglitz (2002) as:

$$\Delta S_i = S_{i-1}\frac{E_i}{d_{i-1}} \qquad (8)$$

where ΔS is change in salinity (‰) over day i; S_{i-1} is the depth-averaged salinity for the day preceding day i; E_i is the evaporation (m) during day i; and d_{i-1} is the average lagoon depth (m) for the day preceding day i.

The diluting effect of precipitation on lagoon salinity was calculated in a similar manner and assumed precipitation of zero salinity:

$$\Delta S_i = S_{i-1}\frac{-P_i}{d_{i-1}} \qquad (9)$$

where P_i is the precipitation (m) during day i.

Evaporation and precipitation induced changes in salinity are dependent on the ambient salinity (Eqs. 8 and 9); the effect of a given atmospheric flux (evaporation or precipitation) on salinity is greatest during periods of high lagoon salinity. The net evaporation and precipitation induced salinity change is the sum of Eqs. 8 and 9.

Salinity, water depth, and precipitation for Indian River were obtained from the Indian River salinity station, the evaporation station, and the NOAA weather station at Melbourne, respectively. For Banana River, salinity and water depth were obtained from the Banana River salinity station and precipitation data were obtained from the SJRWMD precipitation station at Kiwanis Island.

Concentrations of salts in precipitation are low relative to salt concentrations in the lagoon water, supporting the assumption in Eq. 9 that precipitation is devoid of salts. Lagoon salinity measured at the salinity stations varied from about 9‰ to 37‰ during the monitoring period (Fig. 2). The concentrations of the two primary ions (sodium and chloride) in precipitation averaged 0.0021‰ (sodium + chloride) and showed a maximum of 0.014‰ at a nearby National Atmospheric and Deposition Program station (Fig. 1; NADP 2004).

Results

Evaporation and Precipitation Measurements

Daily and monthly values of evaporation are shown in Figs. 4 and 5. Monthly values of precipitation are shown in Fig. 5. Considerable day-to-day variability in evaporation was the result of variations in incoming solar radiation associated with variations in cloud cover and variations in wind speed, air temperature, and humidity. A seasonal pattern of evaporation was evident; highest rates generally occurred in late spring to summer and lowest rates occurred in winter. Annual evaporation varied from 1,502 to 1,614 mm and averaged 1,580 mm.

Evaporation measurements were not available for 63 d of the 730 d of the study. Evaporation data from 33 d were missing because of a power failure and were gap filled with a constant value based on adjacent measured data. Also, 30 d failed the Ohmura (1982) criteria and were gap filled with the mass transfer method. These days generally occurred during low energy (winter) periods when vapor-pressure gradients were small.

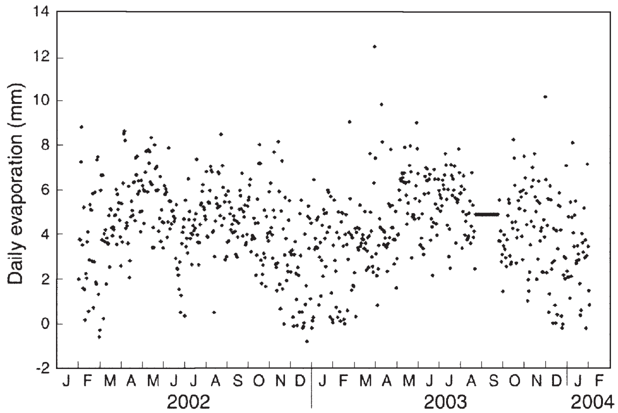

Fig. 4. Daily values of energy-budget computed or gap filled evaporation.

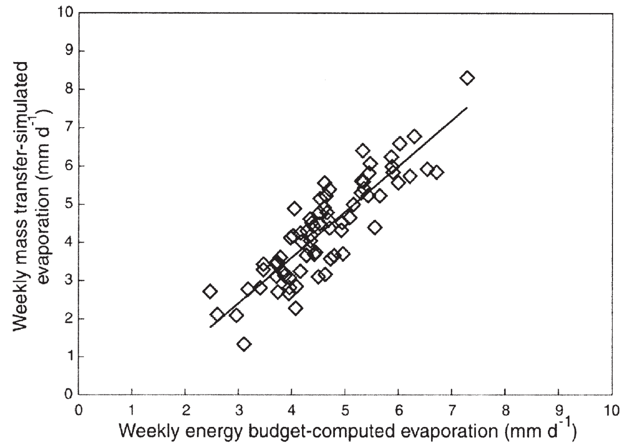

Fig. 6. Energy-budget computed and mass transfer simulated values for average weekly evaporation rates.

Calibration of the mass transfer equation (Eq. 7) yielded an N value equal to 1.01; daily and weekly (Fig. 6) values of computed evaporation were simulated with standard errors of 1.24 and 0.66 mm d^{-1}, respectively. The relative success of the mass transfer method is encouraging given that this method requires only a subset of the variables (air temperature, water temperature, relative humidity, and wind speed) required by the energy-budget method and, in particular, does not require the maintenance-intensive net radiometer.

The monthly energy budget was dominated by net radiation and latent heat flux (Fig. 7). Over the study period, 89% of the available energy derived from net radiation, stored heat in the lagoon, and heat advected by rainfall and evaporated water was partitioned to latent heat flux, whereas 11% of available energy was partitioned to sensible heat flux. Advected heat energy from rainfall and evaporated water was negligible over the study period, accounting for 0.1% and 0.5% of available energy, respectively. Release of heat energy stored in lagoon water was important (supplying most of the available energy) at the daily scale during passage of cold fronts, but generally was a minor component of the monthly energy budget.

The importance of lateral redistribution of energy within the lagoon can be expected to be greatest when substantial amounts of stream flow enter the lagoon. During these periods, the assumption that Q_{as} is negligible may not be valid. Differences in water temperature between the incoming stream water and lagoon water can produce net lateral advection of energy into or out of the control volume as stream water entering the control volume is warmer or cooler than the water exiting the control volume. To investigate this effect, daily data were partitioned into two groups representing high (>5 m^3 s^{-1}) and low (<5 m^3 s^{-1}) combined flow from Turkey and Crane Creeks, the two USGS-gaged creeks flowing into the Indian River Lagoon

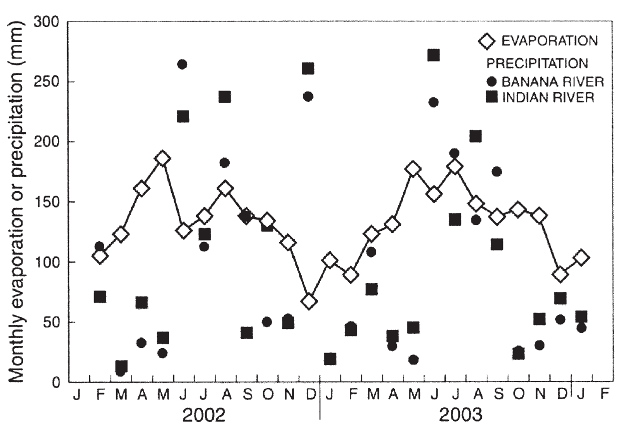

Fig. 5. Monthly values of energy-budget computed evaporation and measured precipitation; station locations shown on Fig. 1.

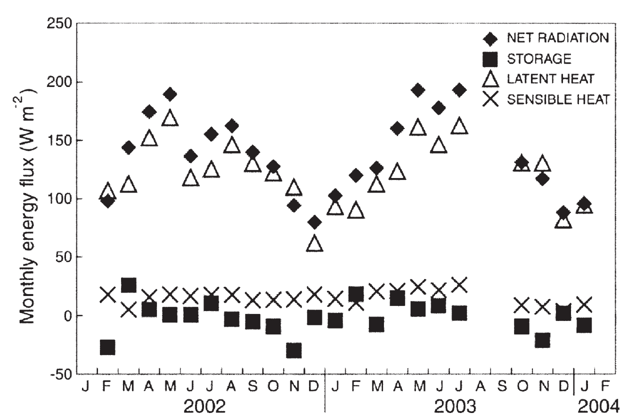

Fig. 7. Monthly time series of measured and computed energy fluxes to and from Indian River.

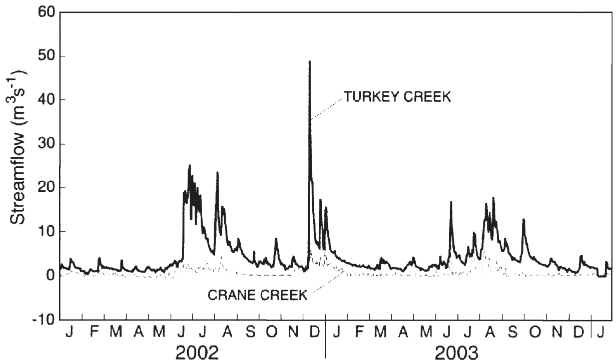

Fig. 8. Daily values of stream discharge for Turkey Creek (U.S. Geological Survey station 02250030) and Crane Creek (U.S. Geological Survey station 02249518).

closest to the evaporation station (Fig. 8). Flow at other streams entering the lagoon followed temporal patterns similar to those of Turkey and Crane Creeks. Each group of evaporation measurements was individually calibrated to the mass transfer equation (Eq. 7). The resulting mass transfer N values were 1.04 and 1.00 for high and low flows, respectively. These values of N were not significantly different from one another at the 95% confidence level. Given that the mass transfer equation is independent of estimates of advected heat energy, the relatively small and statistically insignificant difference between these N values implies that neglect of the net energy advected into the control volume through lateral redistribution does not substantially detract from energy-budget derived evaporation values.

The effect of using a single water temperature probe to represent both surface and depth-averaged water temperature was evaluated for a 100-d period (August 23, 2002-November 30, 2002). Evaporation was computed using three temperature variations (surface, 30-cm depth, and bottom temperature) in Eqs. 4 and 5. Computed evaporation over the 100-d period varied less than 1% between the three variations. Computed evaporation for 4-wk periods within this period varied by less than 5% between the variation using bottom temperature and those using the two shallower temperatures; computed evaporation for 4-wk periods varied less than 1% between the two variations using surface and 30-cm deep temperatures. These results indicate that the use of a single water sensor to represent both surface and depth-averaged water temperatures produces relatively small error in estimated evaporation. The low sensitivity of evaporation estimates to water temperature sensor location arises from the generally strong vertical mixing within the lagoon, the dependence of both the numerator and denominator of Eq. 4 on water temperature, the relatively small value of open-water Bowen ratios (median value was 0.14) relative to the value 1 in the denominator of Eq. 6, and the tendency for the rate of temperature change with time, an input to Eq. 5, to be comparable at all depths.

Precipitation followed a typical seasonal pattern for the study area, with late spring through summer being relatively wet and fall through winter being relatively dry, although December 2002 was unusually wet (Fig. 5). Annual precipitation for February 2002-January 2004 showed little variation between the precipitation stations, averaging 1,197 mm at the NOAA weather station at Melbourne and 1,161 mm at the SJRWMD precipitation station at Kiwanis Island. These annual precipitation values are close to the mean annual rainfall for the Indian and Banana Rivers of 1,170–1,270 mm (Knowles 1995). The difference between annual precipitation and evaporation averaged about −400 mm, indicating that atmospheric water fluxes were a net extraction from the lagoon. Surface-water input to the lagoon more than compensated for this net extraction. Knowles (1995) estimated that 25 m^3 s^{-1} (or about 1,000 mm yr^{-1} over the lagoon surface) of stream and surface runoff entered the 789-km^2 area of the lagoon north of the Indian River-St. Lucie County line during a representative rainfall period (1989–1991).

Simulated Evaporation and Precipitation Induced Salinity Changes

Measured salinity changes were compared to evaporation and precipitation induced salinity changes to assess the sensitivity of salinity to these components of the water budget. Measured values of monthly salinity change at the Indian River site showed much greater variability (variance [σ^2] = 31.2‰^{2}) than did simulated evaporation or precipitation induced salinity changes (σ^2 = 0.43‰^{2} and 1.00‰^{2}, respectively; Figs. 9 and 10). The variance of the net evaporation and precipitation induced salinity changes (σ^2 = 1.15 ppt^2) also is small relative to the variance in measured salinity. The ratio of variances (that of evaporation and precipitation induced salinity change to that of measured salinity change) indicates that evaporation and precipitation explain little (about 4%) of the measured variability in monthly salinity change at the Indian River site. Other factors, most likely surface water inflows from streams or the ocean, control most of the variability in salinity. Evaporation induced salinity changes were greatest at the Indian River site (about 3.2‰ during May 2002) at the end of the dry season (April to May) when evaporation and salinity were relatively high. Precipitation induced salinity changes were greatest

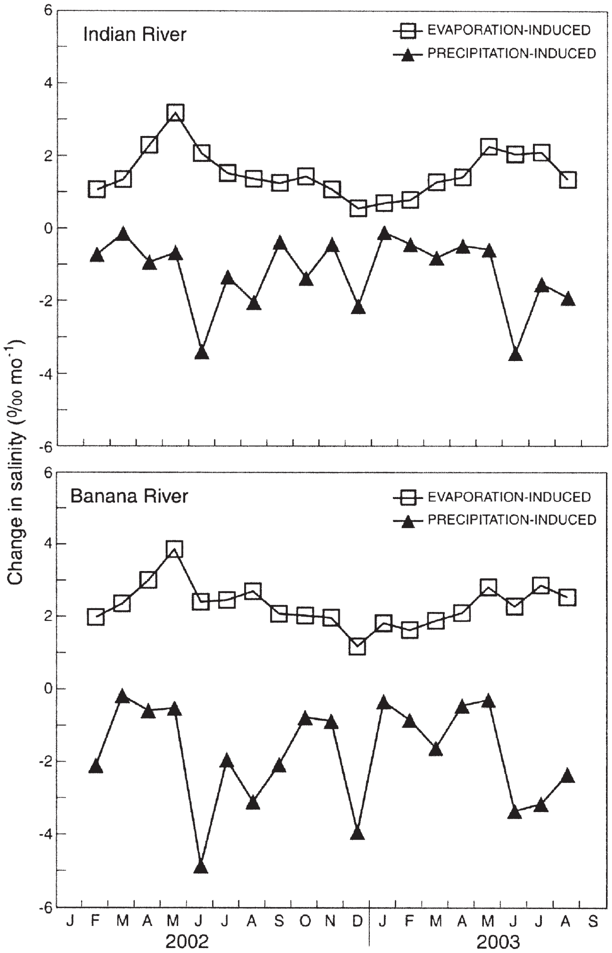

Fig. 9. Monthly values of evaporation and precipitation induced changes in salinity at sites in Indian River and Banana River.

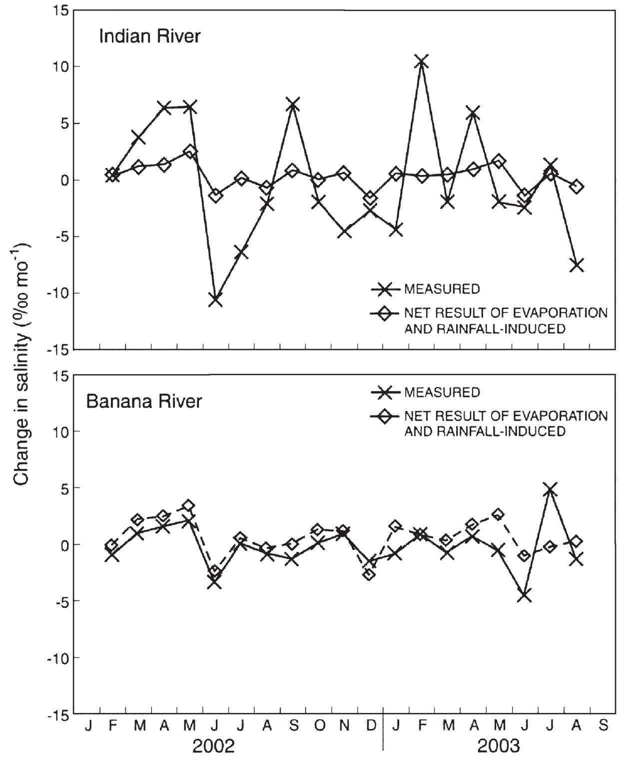

Fig. 10. Monthly values of measured salinity change and net salinity change resulting from evaporation and precipitation induced salinity change at sites in Indian River and Banana River.

(about −3.5‰ during June of 2002 and 2003) during the wet season.

Measured values of monthly salinity change at the Banana River site (σ^2 = 4.1‰^{2}) showed only 13% of the variability of measured values at the Indian River site and were more comparable to simulated evaporation and precipitation induced salinity changes (σ^2 = 0.35‰^{2} and 1.95‰^{2}, respectively; Figs. 9 and 10). The variability of the net evaporation and precipitation induced salinity changes (σ^2 = 2.55‰^{2}) indicates that evaporation and precipitation explain a substantial amount (about 61%) of the measured variability in monthly salinity change at the Banana River site. Evaporation and precipitation induced salinity changes followed seasonal patterns similar to those at the Indian River site.

The variability in the net result of monthly evaporation and precipitation induced changes in salinity was primarily explained by variability in precipitation induced salinity changes. The variance of precipitation induced salinity changes was 2.3 (Indian River) and 5.8 (Banana River) times the variance of evaporation induced changes. The dominance of precipitation induced salinity changes in explaining the variability of the net result of evaporation and precipitation induced changes results from the much greater temporal variability of precipitation (σ^2 = 6,550 mm^2 mo^{-2} at NOAA station at Melbourne) compared to evaporation (σ^2 = 906 mm^2 mo^{-2}; Fig. 5) and despite the greater absolute magnitude of evaporation (averaging about 1,580 mm yr^{-1}) compared to precipitation (averaging about 1,180 mm yr^{-1}).

The relative dominance of precipitation over evaporation in determining the temporal variability of the net evaporation and precipitation induced salinity changes indicates that a coarse approximation of evaporation may be sufficient for the purpose of estimating salinity changes. Sensitivity analyses indicated that the use of a constant, mean value of evaporation (4.44 mm d^{-1} for February 2002–August 2003) and measured values of precipitation produced a close approximation to monthly net evaporation and precipitation induced salinity changes calculated using measured daily evaporation at both Indian River (root-mean-square error [RMSE] = 0.33‰ mo^{-1}, coefficient of determination [r^2] = 0.91) and Banana River (RMSE = 0.52‰ mo^{-1}, r^2 = 0.89; Fig. 11). The use of a constant mean value of precipitation (3.61 mm d^{-1} for February 2002-August 2003) and measured values of evaporation produced a poor approximation at both sites (Indian River RMSE = 0.92‰ mo^{-1}, r^2 = 0.23; Banana River RMSE = 1.43‰ mo^{-1}, r^2 = 0.22) of the result obtained using measured values of precipitation, further illustrating the importance of precipitation induced variability in salinity over that produced by evaporation. Use of a mean constant value of evaporation to estimate cumulative rates of change in salinity owing to evaporation and precipitation had only a small effect (reduction of about 0.6‰ and 0.1‰ yr^{-1} at Indian River and Banana River, respectively, from rates estimated using daily values of energy-budget computed evaporation).

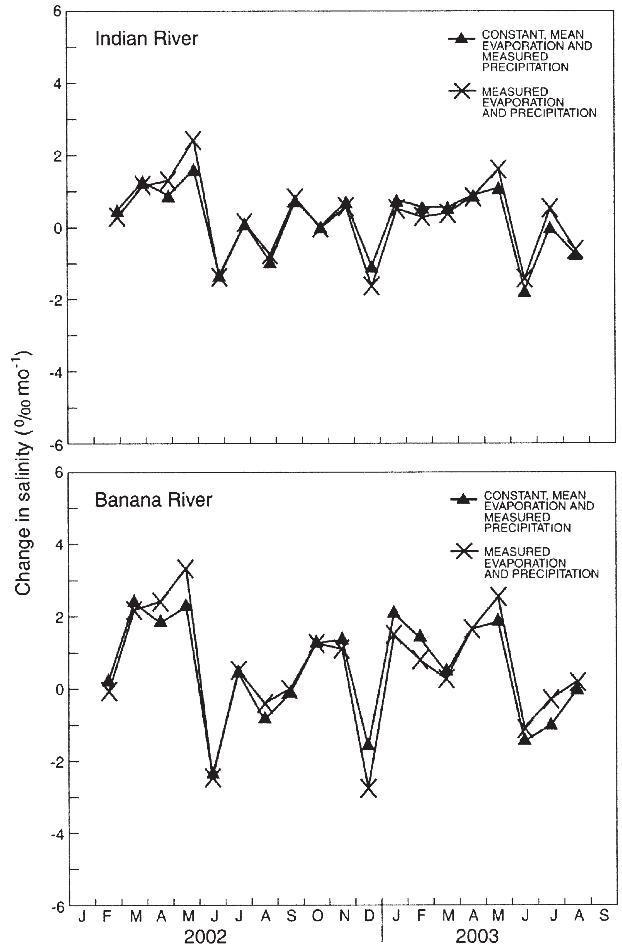

Fig. 11. Comparison of simulated, monthly, net evaporation and precipitation induced change in salinity using energy-budget computed and mean values of evaporation at sites in Indian River and Banana River.

Discussion

The computed annual evaporation (1,502–1,614 mm) at the estuarine study site was slightly greater than the value of about 1,500 mm estimated by Glatzel and Da Costa (1988) for Indian River Lagoon based on pan evaporation data for the period 1955–1984 and an assumed pan coefficient of 0.78. Monthly values of evaporation estimated by these researchers followed a similar seasonal pattern to that determined within the present study; monthly minimum and maximum evaporation occurred during December and May, respectively, in both studies. Computed annual evaporation generally was higher than values determined for inland lakes in Florida: 1,280 and 1,510 mm for Lakes Five-O and Barco, respectively (Sacks et al. 1994); 1,470 mm for Lake Lucerne (Lee and Swancar 1997); and 1,419–1,450 mm for Lake Starr (Swancar et al. 2000). Our value was lower than the estimated evaporation of 2,000 mm from the Atlantic Ocean along the east coast of Florida (Korzoun 1977). The discrepancy between the measured lagoon evaporation and that measured at relatively small inland lakes may be related to generally higher winds (sea breeze or land breeze) and rougher water conditions prevalent in a large coastal water body. Increased wind speed has been shown empirically to increase lake evaporation (Assouline and Mahrer 1993), presumably through the effect of wind speed on aerodynamic resistance to vapor transport (Monteith and Unsworth 1990). Increasing surface roughness (and the associated increase in lake surface area) can be expected to lower aerodynamic resistance. Regional variations in incident solar radiation (both latitude and cloud cover related) may be a factor in the observed discrepancy in measured open water evaporation rates in Florida.

The study results indicated that month-to-month variability in evaporation and precipitation induced changes in salinity was primarily the result of variation in precipitation induced salinity changes. This result is a natural consequence of the greater variability of monthly precipitation compared to that of monthly evaporation at the study site. A 5-yr (1996–2000) data set of evaporation and precipitation at Lake Starr in Florida (Swancar written communication) suggests that the variability of annual precipitation is also greater than that of annual evaporation. At this lake site, annual evaporation varied by only −70 to +80 mm (−5% to +6%) from a mean value of 1,430 mm, whereas precipitation varied by −370 to +230 mm (−32% to +20%) from a mean value of 1,160 mm.

These results indicate that evaporation and precipitation induced changes in salinity in the humid, subtropical study area primarily are a consequence of variations in precipitation at a variety of temporal scales. This finding may not be valid at other, climatically different, sites where the temporal variability of evaporation relative to that of precipitation is greater than at the study site. In the arid Upper Gulf of California (Lavin et al. 1998) where evaporation is high (about 1,100 mm yr^{-1}) and surface water and precipitation inputs are negligible, variations in evaporation may be an important determinant of estuarine salinity variations.

Conclusions

The effect of evaporation and precipitation on variations in lagoon salinity was highly dependent on site location. At a flow-through site (Indian River) with a relatively short residence time (estimated by Sheng and Davis [2003] as 22 d for 1998), monthly variations in salinity were controlled primarily (greater than 96%) by factors other than evaporation induced distilling and precipitation induced diluting (most likely the timing and redistribution of surface water inflows from streams or the ocean). At a flow-restricted site (Banana River) with a relatively long residence time (estimated by Sheng and Davis [2003] as 314 d for 1998), evaporation and precipitation accounted for most (61%) of the measured salinity variations. At both evaluated sites, a constant mean value of evaporation was sufficient to replicate about 90% of the variability in monthly evaporation and precipitation induced changes in salinity and produced only a slight ($<$1‰ yr^{-1}) potential cumulative error in salinity estimates. The relative insensitivity of atmospherically induced changes in salinity to temporal variability in evaporation is a consequence of the greater temporal variability of precipitation compared to that of evaporation. The findings of this study suggest that evaporation data of high temporal resolution may not be necessary for quantification of salinity changes in estuaries in humid, subtropical settings.

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The use of firm, trade, and brand names in this report is for identification purposes only and does not constitute endorsement by the U.S. Geological Survey or the St. Johns River Water Management District.

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