ground water

Advection Within Shallow Pore Waters of a Coastal Lagoon, Florida

by Jaye E. Cable[1], Jonathan B. Martin[2], Peter W. Swarzenski[3], Mary K. Lindenberg[2], and Joel Steward[4]

Abstract

Ground water sources can be a significant portion of a local water budget in estuarine environments, particularly in areas with high recharge rates, transmissive aquifers, and permeable marine sediments. However, field measurements of ground water discharge are often incongruent with ground water flow modeling results, leaving many scientists unsure which estimates are accurate. In this study, we find that both measurements and model results are reasonable. The difference between estimates apparently results from the sources of water being measured and not the techniques themselves. In two locations in the Indian River Lagoon estuarine system, we found seepage meter rates similar to rates calculated from the geochemical tracers ^{222}Rn and ^{226}Ra. Ground water discharge rates ranged from 4 to 9 cm/d using seepage meters and 3 to 20 cm/d using ^{222}Rn and ^{226}Ra. In contrast, in comparisons to other studies where finite element ground water flow modeling was used, much lower ground water discharge rates of ~0.05 to 0.15 cm/d were estimated. These low rates probably represent discharge of meteoric ground water from land-recharged aquifers, while the much higher rates measured with seepage meters, ^{222}Rn, and ^{226}Ra likely include an additional source of surface waters that regularly flush shallow (< 1 m depth) sediments. This resultant total flow of mixed land-recharged water and recirculated surface waters contributes to the total biogeochemical loading in this shallow estuarine environment.

Introduction

Evidence of ground water discharge to the ocean and its significance to hydrologic and biogeochemical budgets have been well documented in recent decades (Valiela et al. 1978; Valiela et al. 1990; Giblin and Gaines 1990; Rutkowski et al. 1999; Krest et al. 2000; Sutula et al. 2001). This input has been implicated in coastal eutrophication through the delivery of nutrient-laden ground waters to coastal water bodies (Sewell 1982; Johannes 1980; Johannes and Hearn 1985; Lee and Olsen 1985; Valiela et al. 1990; Lapointe and Matzie 1996). Ground water inputs and their dissolved constituents are also considered responsible for local biological zonation in coastal water bodies by either preferentially excluding or encouraging flora and fauna growth (Kohout and Kolipinski 1967; Williams et al. 1991; Miller and Ullman this issue). Ground water discharge is often represented by a disperse seepage across the sediment-water interface in coastal water bodies, though it may also be delivered through less common features such as submarine springs (Kohout 1966). As a result of this seepage, advection across the sediment-water interface can consist of both water from on-land recharge and recirculated sea water that mixes into the upper sediments from the overlying water column.

Ground water discharge to coastal waters has been studied from many different perspectives including those of biologists, hydrogeologists, geochemists, ground water modelers, and oceanographers (Johannes 1980; Harvey et al. 1987; Pandit and El-Khazen 1990; Moore, 1999; Li et al. 1999). Likewise, the techniques chosen for ground water input estimates are based on disciplinary expertise and have led to a wide range in estimates of ground water discharge for some study sites based on the techniques applied. While this range is expected for different environments due to

[1]Corresponding author: Department of Oceanography and Coastal Sciences, Coastal Ecology Institute, Louisiana State University, Baton Rouge, LA 70803; (225) 578–9402; (225) 578–6326; jcable@lsu.edu

[2]Department of Geological Sciences, University of Florida, Gainesville, FL 32611

[3]U.S. Geological Survey, Center for Coastal Geology, 600 Fourth St. South, St. Petersburg, FL 33701

[4]St. Johns River Water Management District, P.O. Box 1429, Palatka, FL 32178–1429

Copyright © 2004 by the National Ground Water Association.

differences in geology and climate, within a single environment ground water discharge estimates would likely be similar unless extreme climatic conditions occurred between estimates, ground water pumping was excessive, or estimates were limited by the technique applied. Physical field measurements typically employ seepage meters (Israelson and Reeve 1944; Lee 1977) or head measurements (Freeze and Cherry 1979; Harvey and Odum 1990). Geochemical estimates have utilized a variety of natural tracers, including, but not limited to, ^{222}Rn, ^{223,224,226,228}Ra, ^{4}He, and Cl^{-} (Rama and Moore 1996; Cable et al. 1996; Top et al. 2001; Martin et al. 2002; Martin et al. this issue). In addition, numerical modeling and water budget methods have been used to estimate ground water inputs to coastal water bodies (Pandit and El Khazen 1990; Giblin and Gaines 1990; Li et al. 1999).

Studies where multiple techniques are used to quantify ground water discharge to coastal waters generally focus on determining the most reproducible estimates of ground water inputs (Millham and Howes 1994; Tobias et al. 2001) and on evaluating the effectiveness of various techniques (Giblin and Gaines 1990; Burnett et al. 2002). Often, discrepancies among estimates at a single location are attributed to one of the techniques being inaccurate. Another possible explanation is the source of the water included as ground water in various estimates. Shallow recirculating pore water (< 1 m) from the overlying water column may represent a significant fraction of the total ground water input in some cases. In this paper, total ground water discharge refers to advective fluxes at the sediment-water interface, which includes recirculating surface water mixed with land-recharged meteoric water. We describe the use of multiple techniques to determine the volume of total ground water discharge in the Indian River Lagoon estuarine system, Florida. Our objectives are (1) to evaluate ^{222}Rn diffusive and advective benthic fluxes to the lagoon waters, and (2) to assess advective transport across the sediment-water interface based on comparisons of several geochemical and physical techniques.

Field Site

The Indian River Lagoon/Banana River Lagoon (IRL/BRL) system is a 250 km long estuary located along a highly populated coastline between Daytona Beach and West Palm Beach, Florida (Figure 1). Land uses in the lagoon watershed range from agricultural to urban, with urbanization increasing southward. The estuary averages 2 to 4 km wide and ~1.5 m deep. Tidal ranges within the lagoon are ~10 cm. Sediments are permeable sands, shell hash, and some fine-grained sediment with porosities in the upper 20 cm of sediments of ~0.37 to 0.48. Permeable surface sediment thicknesses are highly variable and may be < 50 cm in some areas of the central study area (Martin et al. 2002). Two study sites were chosen, the northern and central lagoon areas, to target different hydrostratigraphic formations. Three main aquifers, the Floridan, Intermediate, and Surficial, underlie this region (Miller 1986; Scott 1988, 1992; Groszos et al. 1992). The Intermediate Aquifer occurs within the Miocene Hawthorn Group (Scott 1988), which acts as a confining unit for the Floridan. In the northern IRL, the Hawthorn Group is missing, allowing easier communication between the Floridan and Surficial aquifers, and overlying surface waters. Along the central study area the Floridan Aquifer is completely confined by the Hawthorn Group (~30 m thickness), and the Surficial Aquifer is the principal source of ground water to the overlying waters.

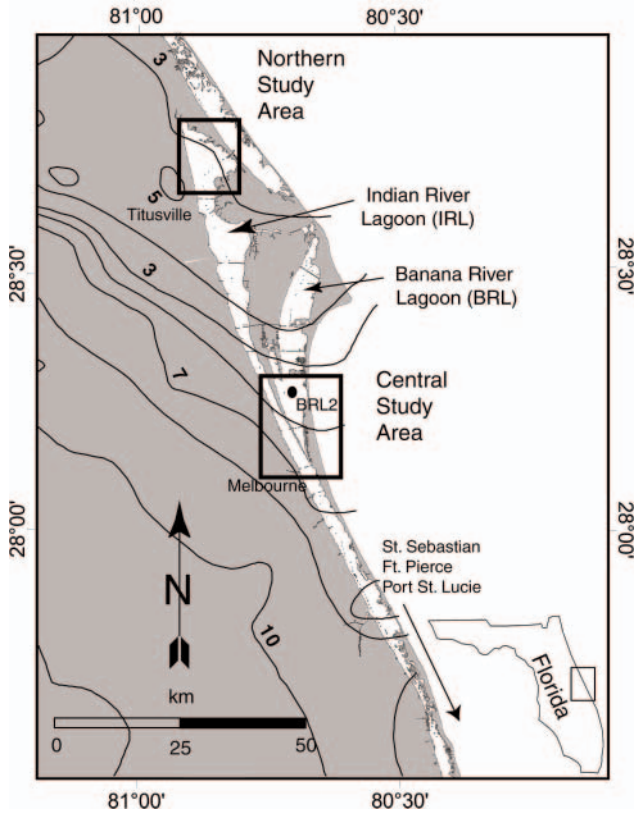

Figure 1. Indian River Lagoon estuary is made up of several coastal lagoons (Mosquito, Banana River, and Indian River) on the eastern coast of Florida. We studied a northern IRL area (28 stations in 1999) and a central IRL/BRL area (24 stations in 2000) for ground water inputs. Potentiometric surface of the Floridan Aquifer is shown as contour lines on the map (1.5 m intervals).

A total of 52 field stations were established, with 28 in the northern study area and 24 in the central study area (Figure 1). Water surface areas are ~48 km^2 in the northern study area and 67 km^2 in the central study area. Annual precipitation ranges from 123 to 134 cm within the field area between Melbourne and Titusville, Florida (National Climatic Data Center 2002). Direct estuarine communication with the Atlantic Ocean is limited to three inlets (St. Sebastian, Ft. Pierce, and St. Lucie) located > 50 km south of the central field site. Previous research in the central and northern IRL estimated ground water discharge between 0.06 and 0.15 cm/d, respectively, based on a finite element ground water flow model (Pandit and El-Khazen 1990; Smith 1993).

Sampling and Analytical Techniques

Field Methods

Manual seepage meters were used at 52 stations in the lagoon to evaluate the advective flux across the sediment-water interface. These meters were constructed using the

end sections of 208 L drums, placed open end down into the sediments, as in previous studies (Lee 1977; Shaw and Prepas 1989, 1990; Cable et al. 1997). The volume of advecting fluids was measured as a function of time and seepage meter area (0.25 m^2) after a 24 h equilibration time with the sediments. Each seepage bag was prefilled with 1000 mL of ambient water prior to attachment (Shaw and Prepas 1989). Measurements were made sequentially at least three times on each seepage meter over 6 to 8 h periods. Seepage meter blanks were also measured on a seepage meter placed on an impermeable plastic barrier over the sediments in the field, following Cable et al. (1997), to assess the magnitude of background fluxes potentially associated with the technique itself.

Water sample collection took place over three discrete sampling seasons (May, August, and December) for bottom water and pore water samples. In addition, in the areas surrounding each field site, ground water wells, a spring, and numerous rivers and inlets were sampled to obtain end-member concentrations for the tracers. Water column samples for ^{222}Rn ($t_{1/2}$ = 3.83 d) and ^{226}Ra ($t_{1/2}$ = 1620 yr) analyses were collected in 4 L evacuated glass sampling bottles using either the bottle vacuum or a peristaltic pump that drew water from depth directly into the bottles. Samples were collected in a closed system to prevent contact with ambient air, and all bottles were sealed immediately after collection to eliminate gas loss.

Pore water samples were collected via peristaltic pump from multilevel piezometers (multisamplers) (Martin et al. 2003). Water was pumped slowly (< 0.8 L/min) from individual sediment depths to the surface and collected in an open overflow container where temperature, conductivity, and dissolved oxygen were monitored constantly. Sample collection began when these parameters stabilized (usually ~3 to 5 min). Pore water was quantitatively transferred using a 10 mL glass syringe from the pumping apparatus to a 20 mL clear glass scintillation vial prefilled with 10 mL extraction scintillation cocktail for ^{222}Rn. Separate ~1 L pore water samples were collected for ^{226}Ra.

Benthic flux chambers were deployed at two locations (north, n = 2 chambers; central, n = 3) in ~1 m of water. These plexiglass chambers (30 cm high, 0.21 m^2 area) were carefully deployed by pushing each chamber ~3 to 5 cm into the sediments. A weight was placed on top of the chamber to maintain the seal at the sediment-water interface. Chamber waters were stirred gently to maintain a well-mixed water column during the experiment. Initial (t = 0) and time series water samples (t = 4, 8, or 24 h) were collected from the benthic chambers, and all were analyzed for ^{222}Rn and ^{226}Ra. The ^{222}Rn activities were corrected for decay and the benthic flux was calculated as shown in Martens et al. (1980).

Laboratory Methods

All water column samples were analyzed for ^{222}Rn within 6 to 36 h after collection using a standard cryogenic approach for radon extraction from sea water by sparging with helium (Broecker 1965; Key et al. 1979; Mathieu et al. 1988). Measurements of pore water and surface water ^{226}Ra were obtained by resparging the same sample at least 5 d after the initial sparge. Samples were then counted by alpha scintillation using radon flask counters after a 3 h ingrowth to allow secular equilibrium between ^{222}Rn and its daughters. The unsupported or excess radon (total ^{222}Rn at time of first analysis minus ^{226}Ra) was decay-corrected back to the time of sampling to obtain the in situ excess ^{222}Rn. All water column ^{222}Rn activities are reported as excess and corrected to the time of collection. Pore water ^{222}Rn was measured using alpha liquid scintillation counting. Activities are reported in disintegrations per minute (dpm) per unit volume.

Sediment slurry experiments were performed to estimate the maximum amount of pore water ^{222}Rn that may be at equilibrium with the solid phase sediments for samples from the northern study area (n = 17) and central study area (n = 12) sites. This increased particle exposure artificially increases porosities and alters recoil geometries to increase pore fluid ^{222}Rn (Key et al. 1979; Smethie et al. 1981). Each equilibration experiment consisted of mixing ~50 g wet sediment aliquots with 250 to 300 mL of sea water in 500 mL Erlenmeyer flasks for 30 d. After this period, radon in the water is assumed to be equilibrated with sediment ^{226}Ra and is measured via cryogenic extraction and alpha scintillation counting. The equilibrium activity (C_{eq}) is calculated using the porosity (ϕ) and wet bulk density (ρ_{wet}) of the sediments. Upper limit diffusive fluxes were calculated from these C_{eq} activities in slurry experiments and overlying bottom water activities (Martens et al. 1980; Cable et al. 1996). Measured activities (dpm/m^3 of wet sediment) are converted to dpm/L in pore water using the fractional porosity.

Results

Diffusive and benthic advective fluxes across the sediment-water interface were measured at the northern and central sites using ^{222}Rn as a geochemical tracer (Figure 2). Diffusive ^{222}Rn fluxes calculated using sediment matrix ^{226}Ra equilibration in a slurry ranged between 111 and 756 dpm/m^2/d at the north and central lagoon sites (Table 1). Total fluxes across the sediment-water interface (advection + diffusion) using benthic chambers were 5 to 14 times greater than the average diffusive flux measurements at

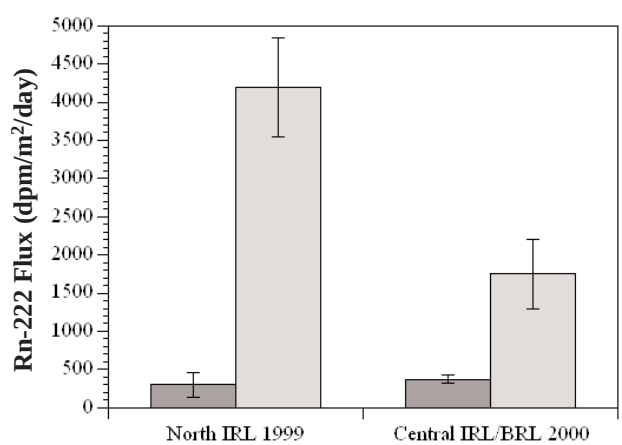

Figure 2. Mean (± 1σ) flux results of excess ^{222}Rn diffusion (dark gray) and benthic chamber advection-diffusion measurements (light gray) across the sediment-water interface at the northern sites and central sites.

Table 1
Measured Water Column ^{222}Rn, Calculated Pore Water Equilibrium ^{222}Rn Activities, and Diffusive Fluxes as Determined from Sediment Slurry Experiments

Station ID	Pore Water ^{222}Rn ϕC_{eq} (dpm/L)	Water ^{222}Rn Column C_o (dpm/L)	Calculated ^{222}Rn Diffusive Flux (dpm/m^2/d)
Northern Sites			
IRL-1	31.7 ± 4.6	4.489 ± 0.084	214 ± 17
IRL-2	26.2 ± 4.3	3.814 ± 0.078	177 ± 16
IRL-3	28.0 ± 4.4	3.836 ± 0.081	190 ± 17
IRL-4	16.8 ± 4.1	4.155 ± 0.082	111 ± 16
IRL-5	19.1 ± 4.1	5.015 ± 0.098	125 ± 16
IRL-6	19.3 ± 4.2	4.144 ± 0.087	128 ± 16
IRL-7	86.1 ± 4.7	4.052 ± 0.081	594 ± 18
IRL-8	80.2 ± 4.5	4.406 ± 0.083	552 ± 17
IRL-9	75.5 ± 4.4	5.653 ± 0.105	520 ± 17
IRL-10	57.8 ± 3.0	5.439 ± 0.092	396 ± 11
IRL-11	70.8 ± 3.3	4.435 ± 0.034	486 ± 12
IRL-12	57.6 ± 4.2	4.884 ± 0.092	395 ± 16
IRL-13	33.5 ± 2.4	4.087 ± 0.078	226.5 ± 8.9
IRL-14	37.3 ± 2.5	4.141 ± 0.089	253.9 ± 9.5
IRL-15	36.3 ± 2.4	4.704 ± 0.089	246.0 ± 9.1
IRL-16	24.9 ± 2.1	3.099 ± 0.139	167.0 ± 8.0
IRL-17	46.9 ± 2.8	2.741 ± 0.070	322 ± 11
Central Sites			
IRL-29 0–20 cm	42.0 ± 1.2	0.92 ± 0.26	291.2 ± 4.6
IRL-29 20–40 cm	85 ± 7	0.92 ± 0.26	590 ± 28
IRL-29 40–60 cm	36.9 ± 2.2	0.92 ± 0.26	255.5 ± 8.4
IRL-29 60–73 cm	41.7 ± 1.1	0.92 ± 0.26	289.2 ± 4.3
IRL-31	22.7 ± 2.1	0.56 ± 0.47	157.3 ± 7.9
IRL-32	77.9 ± 2.4	0.79 ± 0.67	541.5 ± 9.1
IRL-39	109 ± 10	1.01 ± 0.47	756 ± 37
BRL-1	25.2 ± 2.2		178.3 ± 8.3
BRL-2	49.4 ± 5.3		346 ± 20
BRL-5	68.0 ± 6.5	0.12 ± 0.30	474 ± 25
BRL-6	34.7 ± 5.0		243 ± 19
BRL-7	42.4 ± 2.3		296.4 ± 8.6

each site. In the northern study area, benthic ^{222}Rn advection was 4190 ± 650 dpm/m^2/d (n = 2); in the central study area benthic ^{222}Rn advection was 1750 ± 450 dpm/m^2/d (n = 3). Additionally, pore waters were collected at six stations in the central lagoon study area in 2000, but most stations yielded incomplete pore water profiles. Station BRL2 is used here because it was the only site to provide good resolution pore water profiles on every sampling trip (Figure 3). Generally, pore water ^{222}Rn and ^{226}Ra increases rapidly with depth to an inflection at around 100 to 150 cm below the sediment surface (cmbsf) where the increase is less pronounced. Seasonal changes in the activities with depth in the sediments are observed for both isotopes, but the most significant temporal rate of change occurs in the upper 100 cm of the sediment column where ^{222}Rn activities increase from ~7 dpm/L at 10 cmbsf to 88 dpm/L at 110 cmbsf (Figure 3b). Pore water ^{222}Rn activity profiles are atypical with respect to both a diffusion-controlled gradient and an advective-diffusive gradient derived from a subsurface source as discussed later.

Comparisons of benthic advection rates to overlying waters between the northern and central study sites are given to assess the effectiveness of various physical and geochemical techniques for evaluating ground water inputs to coastal waters (Table 2). In the northern study area, seepage meter measurements indicate the advection into the water column varied between 5.8 ± 3.1 cm/d in May 1999 and 9.1 ± 4.5 cm/d in August 1999. Seepage meter control experiments using an impermeable barrier over the sediments revealed the technique has about a 1.6 cm/d blank (i.e., the lower limit of detection for seepage meter measurements in IRL). Geochemical tracer estimates of benthic advective rates are 2 to > 20 cm/d using ^{222}Rn and ^{226}Ra flux measurements. In the central study area, advection using 24 seepage meters was less overall and found to average between 4.0 and 5.5 cm/d during seasonal studies. The seepage meter blank estimates were ~1 cm/d, which is similar to the northern study area and to blanks observed by Chanton et al. (2003) in Florida Bay. Geochemical tracer (^{222}Rn) estimates of benthic advective inputs were 2 to 12 cm/d. The

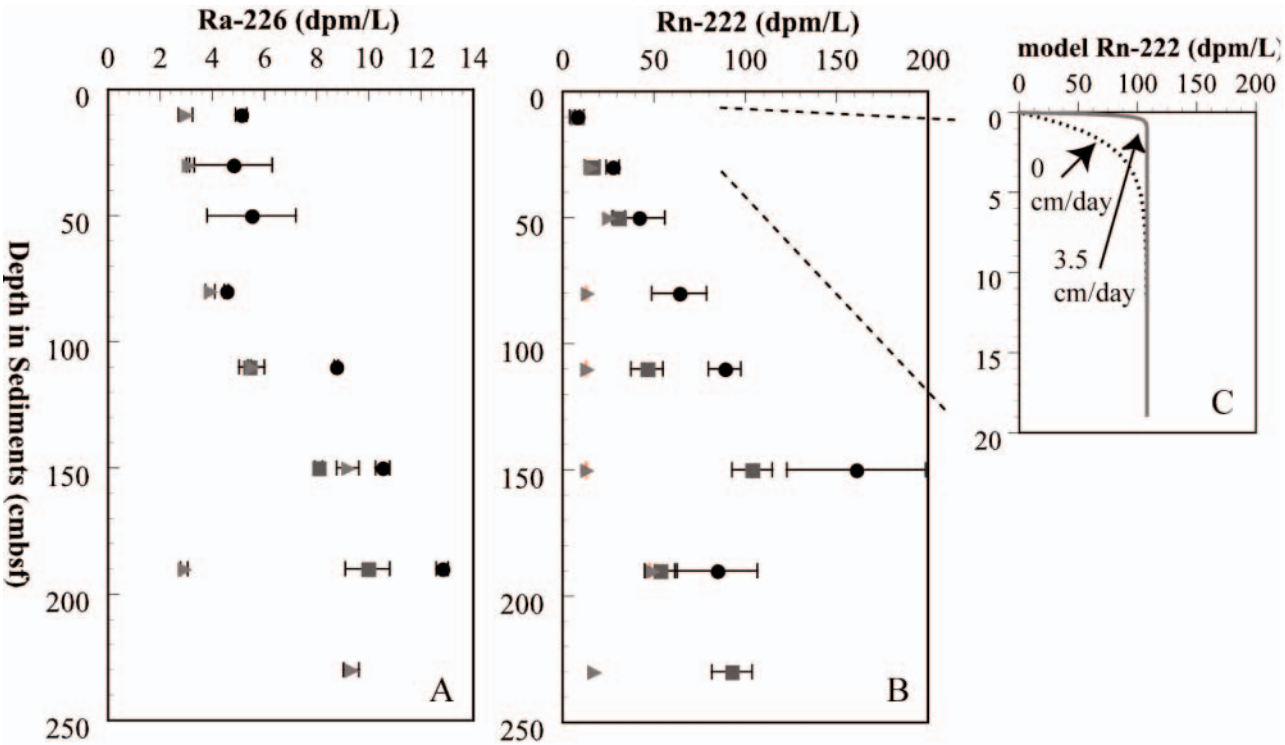

Figure 3. Pore water profiles of measured (a) ^{226}Ra and (b) ^{222}Rn activities (± 1σ) are given for station BRL2 during May (squares), August (circles), and December (triangles) 2000. An inset of modeled ^{222}Rn pore water curves in the upper 20 cm (c) shows the theoretical shape for diffusion-only (0 cm/d) or advection-diffusion inputs (3.5 cm/d).

following discussion first shows how ^{222}Rn-based discharge rates were estimated and then outlines a possible explanation for the different pore water advection rates and their relationship to submarine ground water discharge.

Discussion

Radon is generally considered a valuable tracer in ground water discharge studies due to its conservative geochemistry, its ease of collection and measurement, and its activities in ground water typically being two to three orders of magnitude greater than surface waters. Radium is typically a dissolved ion (Ra^{2+}) in sea water, which behaves similarly to other alkaline earth elements. Its presence in the water column provides a constant source for ^{222}Rn. Measured water column excess ^{222}Rn activities ranged from < 1 to 7 dpm/L, while average water column ^{226}Ra ranged from 2 to 3 dpm/L (Martin et al. 2002). Observed radium activities indicate production in the water column is not always sufficient to support observed radon activities, demonstrating at times that excess ^{222}Rn must be derived from another source. Alternatively, because radon is a gas, atmospheric loss from shallow surface water environments can produce a deficiency of ^{222}Rn relative to its parent, ^{226}Ra, when wind speeds are > ~5 m/s (Burnett et al. 2003). Wind speeds in the Indian River Lagoon averaged ~3 to 5 m/s with gusts between 5 and 10 m/s during our study periods. Although occasionally excess water column ^{222}Rn activities were observed, generally the ^{222}Rn inventory at lagoon sites was depleted during the study period. Under these conditions, a water column mass balance of excess ^{222}Rn for determining advection from IRL sediments is complicated. The more direct ^{222}Rn approach in this environment is to evaluate pore water advection using flux measurements at the sediment-water interface, which will not be affected by atmospheric evasion.

Diffusive and benthic advective ^{222}Rn flux measurements are used to evaluate the likelihood of a subsurface component to the hydrologic budget of the estuary in the northern and central lagoon sites. If diffusion was found to be greater than or equal to total benthic advection, then an advective subsurface source would not likely be an important part of the overall lagoon hydrology. In addition, application of the sediment slurry technique in this study takes a

Table 2
Mean (±1σ) Advective Rate Comparisons Across the Sediment-Water Interface Between Seasons and Sites for the Indian River Lagoon/Banana River Lagoon System

Location/Technique	May 1999	August 1999	
Northern Study Area		Rate (cm/d)	
Seepage meter (n = 28)	5.8 ± 3.1	9.1 ± 4.5	
Seepage meter blank (n = 2)	1.4 ± 1.6	1.8 ± 1.2	
Excess ^{222}Rn Flux Model	8 to > 20		
^{226}Ra Benthic Flux (Martin et al. 2002)	2 to 17		
	May 2000	**August 2000**	**December 2000**
Central Study Area		Rate (cm/d)	
Seepage meter (n = 24)	4.0 ± 1.9	5.5 ± 3.3	5.5 ± 3.0
Seepage meter blank (n = 1)	1.1 ± 0.7	0.9 ± 1.0	NA
Excess ^{222}Rn Flux Model	1.1 ± 0.7	2 to 12	

(n = number of measurements)

conservative approach by maximizing these diffusion estimates. Diffusion (J_{diff}) was calculated using the following equation (Martens et al. 1980):

$$J_{diff} = -\phi D_s (C_{eq} - C_o) \quad (1)$$

For a measured porosity (ϕ) of ~0.44, the effective wet sediment diffusion coefficient (D_s) was estimated to be 6.0×10^{-6} cm^2/s after correcting for tortuosity ($D_s = \phi D_o$; D_o is the molecular diffusion coefficient = 1.14×10^{-5} cm^2/s [Rona 1917]), C_{eq} is the radon activity determined from sediment slurry equilibrations, and C_o is the water column radon activity. Even using upper limit diffusive fluxes, diffusion is clearly lower than in situ total benthic fluxes across the sediment-water interface for each study location (Figure 2). In the Indian River Lagoon, measured advective fluxes are greater than diffusion by a factor of five or more. For 29 sites in the lagoon, diffusion is typically < 500 dpm/m^2/d.

We applied a benthic exchange ^{222}Rn model modified from Craig (1969) and Cable et al. (1996) to investigate advective fluid transport:

$$\frac{dC}{dt} = D_s \frac{\partial^2 C}{\partial z^2} + \omega \frac{\partial C}{\partial z} + P + \lambda C \quad (2)$$

where C is the radon activity in the sediments (dpm/m^3) at some depth z, z is depth positive downward in the sediments (cmbsf), D_s is explained previously, ω is the vertical advective velocity (cm/d), P and λC are in situ production (+) and decay (–) of ^{222}Rn in the pore waters, respectively, λ is the ^{222}Rn decay constant (1.25×10^{-4}/min), and the first and second terms to the right of the equation represent diffusion and advection, respectively. For a short-lived, conservative radioactive tracer, such as ^{222}Rn, the solution to Equation 2 reduces to the following (Cable et al. 1996):

$$C(z) = \frac{(C_o - C_{eq})[\exp(z/2z^*)]\left\{\sinh\left[A(z_{eq} - z)/2z\right]\right\}}{\sinh\left[AZ_{eq}/2z^*\right]} + C_{eq} \quad (3)$$

where C_o and C_{eq} are defined previously, z_{eq} is a depth in the sediments much deeper than the depth where C_{eq} initially occurs (> 70 cmbsf), z^* is a one-dimensional mixing parameter described by D_s/ω, and $A = [1 + 4z^* (\lambda/\omega)]0.5$, which includes radioactive decay and advection. Lower and upper limits for C_{eq} are 17 to 86 dpm/L in the northern study area and 23 to 85 dpm/L in the central study area (BRL2 C_{eq} was 49 dpm/L) (Table 1). Mean water column ^{222}Rn (C_o) was 6.2 dpm/L in the northern area and 0.77 dpm/L in the central area (Martin et al. 2002). Based on these boundary conditions for C_{eq} and C_o, modeled radon fluxes were compared to measured benthic chamber fluxes, and vertical velocities (ω) were found by iteration until the measured and modeled fluxes were the same.

The benthic exchange model can be applied to produce theoretical profiles of the ^{222}Rn pore water gradient at BRL2. When the vertical advective velocity is held at zero and assuming no mixing occurs in shallow sediments, diffusion controls the pore water ^{222}Rn activity gradient (Figure 3c). The ^{222}Rn pore water activity becomes deficient in the sediments only near the surface due to diffusion (ω = 0 cm/d) into the overlying water column. When advection enhances the diffusive flux (ω = 3.5 cm/d) in a nonmixing environment, the activity gradient is increased toward the sediment-water interface, which decreases the zone of deficiency (Figure 3c). Modeled advective transport velocities across the sediment-water interface are compared to other techniques in Table 2 to evaluate the effectiveness of ^{222}Rn as a tracer in this region and the reproducibility of rates among techniques. Average advection measured using seepage meters, the ^{222}Rn flux model, and ^{226}Ra activities is on the same order of magnitude for each technique and ranged from ~5 to > 20 cm/d. This similarity suggests that benthic advective inputs are reasonably well established from these estimates. In the central area, the overall benthic advective input was lower than the northern area, but all estimates confirmed that seepage meters are not measuring an artifact associated with the field instrument.

To investigate the influences on the advective transport across the sediment-water interface, geochemical pore water gradients were compared to theoretical gradients (Figure 3). If land-recharged ground water alone supported the excess radon signal observed in benthic flux measurements, then pore waters should have elevated radon activities and the observed pore water gradient should show a source term at depth in the sediments. Ideally, a ground water source term would produce a flux upward in the sediments that would increase the ^{222}Rn gradient at the sediment-water interface relative to a diffusion-only gradient. Pore water ^{222}Rn is present in excess of ^{226}Ra, which supports a subsurface source of radon in the sediments, but activity gradients indicate another process or processes control pore water activities (Figures 3a and 3b). In a dynamic environment, such as a shallow coastal lagoon, shallow pore water mixing processes would limit the development of an intact advection-controlled activity gradient driven by a subsurface source. Mixing processes have been documented to occur at depths that range from a few centimeters up to a meter in sediments; the causes of this pore water mixing are attributed typically to bioturbation (Aller 1980; Boudreau 1998; Hancock et al. 2000), but may also occur due to density-driven flow and wave setup (McCaffrey et al. 1980; Li et al. 1999; Rasmussen 1998). Regardless of the cause, the consequences of shallow pore water mixing are that surface sea water infiltrating the sediments will alter the signal that may be associated with subsurface sources such as ground water.

Observed pore water ^{222}Rn activities in the Indian River Lagoon indicate a boundary zone exists in the sediments at ~70 to 100 cmbsf (Figure 3b). Below this 70 to 100 cmbsf threshold, pore water ^{222}Rn activities are similar to observed activities in land-based wells (Martin et al. 2002). Above this depth threshold, the shape of the pore water ^{222}Rn gradient indicates either consumption of ^{222}Rn in the sediments or a vertical flux of ^{222}Rn in the sediments. In the first situation, radon is an inert gas, and except for weak van der Waals forces, chemical interactions or biological

consumption do not occur. Radioactive decay is not sufficient to support the loss of ^{222}Rn in upper pore waters (above 100 cmbsf) because the sediment flushing rate is more rapid than decay based on seepage meter measurements. Seepage rates at BRL2 average 3.6 to 6.9 cm/d for a seepage meter area of 0.25 m^2, which is equivalent to ~9 to 17 L/d—a sufficiently large rate to rapidly flush permeable sediments. Given the shallow overlying water column, observed wind speeds during our measurements, and the porosity of these permeable sediments, rapid sediment flushing implies a physical dilution could occur as low activity lagoon waters mix downward into pore waters at BRL2 (Figure 3b).

For every measured pore water ^{222}Rn activity gradient at BRL2, we observed a deficiency that extended well below the expected depth in the benthic exchange model. Based on the shape of the activity gradient and the permeable sediments of this environment, physical mixing in shallow sediments may be a reasonable explanation for this apparent ^{222}Rn sink (dilution). Martin et al. (this issue) recognizes similar mixing on the basis of Cl^- concentrations within the upper zero to 70 cmbsf, and they suggest mixing could be caused by bioturbation, variations in water levels from winds and tides, density-driven flow based on density calculations of pore waters and overlying waters, or a combination of these factors. While the actual cause of mixing in this environment is not confirmed, the excess volume of water in measured ground water rates appears to be derived from surface waters circulating through the sediments. Martin et al. (this issue) found that Cl^- yielded rates of ~0.008 to 0.019 cm/d when modeled in the zone beneath 70 cmbsf. Additionally, when these estimates are compared to finite element model estimates of ground water inputs to the northern and central Indian River Lagoon, these rates of ~0.06 to 0.15 cm/d (Pandit and El-Khazen 1990; Smith 1993) are best duplicated by the Cl^- approach. These differences among independent techniques suggest seepage water represents more than simply land-recharged ground water.

Discrepancies among ground water flow models and field measurements have been observed in other areas of the Indian River Lagoon. Seepage meters have been used in the St. Lucie Inlet region, southern IRL, by previous researchers to measure ground water inputs. Zimmermann et al. (1985) found seepage rates of 6.7 to 8.9 cm/d, while Belanger and Walker (1990) found seepage rates of ~12 cm/d. In contrast, Pandit and El-Khazen (1990) modeled ground water inputs of 0.08 to 0.26 cm/d for the St. Lucie Inlet region. The discrepancy among modeling and seepage meter rates does not seem to be an error associated with the seepage meter measurements because, in our current study, other techniques (^{222}Rn, ^{226}Ra) corroborate seepage advection. Additionally, in the northern and central areas, control experiments with seepage meters reveal blank measurements much less than the environmental measurements. The difference among the modeled and measured rates may be at least a qualitative indication that another source of water contributes to the total advective input to the lagoon.

Other studies have also identified differences among estimates of ground water inputs based on application of multiple techniques. For example, Giblin and Gaines (1990) used seepage meters and two independent budgets (salt and water) in the Town Cove, Massachusetts, estuary to estimate ground water flow. They found seepage meters yielded rates that were at least one order of magnitude greater than either budget calculation (Table 3) and concluded that seepage meters were overestimating the total input to the cove. Likewise, Burnett et al. (2002) compared five field techniques (three seepage meter types and two tracers) to evaluate the effectiveness of the techniques at measuring ground water inputs. In their study at Turkey Point, Florida, the ^{222}Rn method was based on water column inventory measurements and estimates of atmospheric evasion at the site. Their study also evaluated the traditional Lee-type seepage meter, a heat pulse automatic seepage meter, and an acoustic Doppler automatic seepage meter. They found very good agreement among all field techniques, but also noted that a ground water flow model for their study indicated ground water inputs should be 8 to 10 times less than field measurements. Researchers in two other ground water studies used only aquifer-based methods (tracers in wells or Darcy's law) or similar salt and water budgeting methods to obtain ground water inputs to Little Pond, Massachusetts, and Ringfield Marsh, Virginia (Millham and Howes 1994; Tobias et al. 2001). In each of these studies, the three independent methods showed reasonably good agreement for ground water inputs. When similar comparisons are made among the techniques used in the Banana River Lagoon at BRL2 for our study, discrepancies in measured rates develop similar to those observed by Giblin and Gaines (1990) and Burnett et al. (2002).

Circulation of sea water through shallow sediments is not a new concept, but it appears to play an important role in estimates of ground water discharge and mass transfer to the Indian River Lagoon. Subtidal pumping has been suggested in the past as a mechanism for circulating sea water through sediments. Riedl et al. (1972) used their understanding of subtidal pumping on the continental shelf of the southeastern United States to extrapolate water exchange to a global scale. They predicted a significant volume of sea water (~90,000 km^3) passes through sediments annually along the world's coastlines. This kind of exercise may not produce a precise estimate of recirculating sea water in shallow sediments, but we get an idea of the potential magnitude of the phenomenon. In the Indian River Lagoon, differences between the Cl^- model (below 70 cmbsf) and ground water model results are small, and these estimates most clearly approximate ground water discharge from distant sources (i.e., continental aquifers). These low rates appear to indicate shallow mixing in the upper sediment column represents as much as 90% of the much higher total discharge estimated using seepage meters, ^{222}Rn, and ^{226}Ra.

Conclusions

Field estimates of ground water discharge based on geochemical tracers and seepage meters are similar in most cases. In situations where they do not agree, it may be due to a misperception about the source of water, not the misapplication of a technique. Previous criticisms of seepage meters stem from the localized flux they measure, as well as concerns that external forcing may produce measurement

Table 3
Ground Water Discharge Rate Comparisons Given for Studies Where Multiple Techniques Were Applied

Technique	Town Cove, Cape Cod, Massachusetts	Little Pond, Cape Cod, Massachusetts	Ringfield Marsh, Virginia	Turkey Point, Florida	Banana River Lagoon, Florida
			Rate (cm/d))		
Seepage meters	2.4 to 7.2[a]	—	—	11.5 to 18[a] 13.0[b]	3.6 to 6.9[a]
Excess ^{222}Rn	—	—	—	12.2 to 18[c]	3.5
Radium isotopes	—	—	—	10.8	—
Major ions	—	—	1.6[d]	—	0.008 to 0.019[e]
Salt/tidal balance	0.6	2.8 to 5.9	0.06 to 2.2	—	—
Water budget	0.09 to 0.12	2.4	—	—	—
Hydrologic model	—	—	—	~1.5[f]	0.06 to 0.15[g]
Darcian flow	—	2.1 to 2.3	–0.8 to 8	—	—
Citation	Giblin and Gaines (1990)	Millham and Howes (1994)	Tobias et al. (2001)	Burnett et al. (2002)	This study

[a]Lee-type seep meter (Lee 1977)
[b]Automatic seep meters (Taniguchi and Fukuo 1993; Paulsen et al. 2001)
[c]Continuous water column radon monitor (Burnett et al. 2001)
[d]Introduced Br^- tracer
[e]Natural pore water Cl^- (Martin et al., this issue)
[f]Hydrogeologic modeling results suggest rates 8 to 10 times less than field methods; precise values were not reported but would be ~1.5 cm/d using results reported.
[g]Finite element ground water flow model for IRL near our central study area (Pandit and El-Khazen 1990)

artifacts (Shaw and Prepas 1989; Cable et al. 1997; Shinn et al. 2002; Corbett and Cable 2003). Our ^{222}Rn and ^{226}Ra estimates of flux corroborate the seepage meter measurements. In addition, seepage meter blank measurements support conclusions that a real advective transport occurs across the sediment-water interface. Geochemical tracers (^{222}Rn, ^{226}Ra) and seepage meter flux estimates are much greater than the estimates from the geochemical tracer, Cl^-, and from a hydrogeologic model. The difference here appears to result from shallow mixing in the upper sediment column, where the magnitude of pore water advective transport may at times be as great as 90% of the total ground water discharge measurement in the Indian River Lagoon. We can only speculate on the mechanisms driving this pore water advection, such as tides, waves, bioturbation, and fluid density differences. Nonetheless, subsurface water sources to the overlying water column must be a sum of land-recharged ground water and shallow pore water advection. Separation of these terms will be helpful in accurately assessing lagoon water budgets, but total benthic advective inputs are still critical terms to consider in biogeochemical loading to coastal water bodies.

Acknowledgments

We thank our field and laboratory support, Brian Vosburg, Henri deLaunay, Rita Bowker, Roxanne Benoit, Donny Smoak, and Kevin Hartl, and the contributions of Bob Virnstein and Gilbert Sigua during the evolution of this project. This manuscript benefited greatly from the thoughtful comments of R. Corbett, B. Fry, M. Taniguchi, T. McKenna, and an anonymous reviewer. This research was funded by the St. Johns River Water Management District (#99G245).

References

Aller, R. 1980. Quantifying solute distributions in the bioturbated zone of marine sediments by defining an average microenvironment. *Geochimica et Cosmochimica Acta* 44, 1955–1965.

Belanger, T.V., and R.B. Walker. 1990. Groundwater seepage in the Indian River Lagoon, Florida. In *Tropical Hydrology and Caribbean Water Resources: Proceedings of the International Symposium on Tropical Hydrology and Caribbean Water Resources*, ed. J.H. Krishna, V. Quinones-Aponte, F. Gomez-Gomez, and G.L. Morris, 367–375. Herndon, Virginia: American Water Resources Association.

Boudreau, B. 1998. Mean mixed depth of sediments: The wherefore and the why. *Limnology and Oceanography* 43, 524–526.

Broecker, W. 1965. An application of natural radon to problems in oceanic circulation. In *Proceedings of the Symposium on Diffusion in the Oceans and Fresh Waters*, Lamont Doherty Earth Observatory, Palisades, New York, ed. T. Ichiye, 116–145. Palisades, New York: LDEO

Burnett, W., G. Kim, and D. Lane-Smith. 2001. Use of a continuous radon monitor for assessment of radon in coastal ocean waters. *Journal of Radioanalytical and Nuclear Chemistry* 249, 167–172.

Burnett, W., J. Chanton, J. Christoff, E. Kontar, S. Krupa, M. Lambert, W. Moore, D. O'Rourke, R. Paulsen, C. Smith, L. Smith, and M. Taniguchi. 2002. Assessing methodologies for measuring ground water discharge to the ocean. *Eos Transactions, American Geophysical Union* 83, no. 11: 117–123.

Burnett, W., J. Cable, and R. Corbett. 2003. Radon tracing of submarine ground water discharge in coastal environments. In *Land and Marine Hydrogeology*, ed. T. Gamo and M. Taniguchi. Oxford: Elsevier Publications.

Cable, J., W. Burnett, J. Chanton, and G. Weatherly. 1996. Estimating ground water discharge into the northeastern Gulf of Mexico using radon-222. *Earth and Planetary Science Letters* 144, 591–604.

Cable, J., W. Burnett, J. Chanton, R. Corbett, and P. Cable. 1997. Field evaluations of seepage meters in the coastal marine environment. *Estuarine, Coastal, and Shelf Science* 45, 367–375.

Chanton, J., W. Burnett, M. Taniguchi, H. Dulaiova , M. Lambert, and R. Corbett. 2003. Seepage rate variability in Florida Bay driven by Atlantic tidal height. *Biogeochemistry* 66, 187–202.

Corbett, R., and J. Cable. 2003. Seepage meters and advective transport in coastal environments: Comment on "Seepage meters and Bernoulli's revenge." *Estuaries* 26, 1383–1389.

Craig, H. 1969. Abyssal carbon and radiocarbon in the Pacific. *Journal of Geophysical Research* 74, no. 23: 5491–5506.

Freeze, R.A., and J.A. Cherry. 1979. *Groundwater*. Englewood Cliffs, New Jersey: Prentice Hall.

Giblin, A., and A. Gaines. 1990. Nitrogen inputs to a marine embayment: The importance of ground water. *Biogeochemistry* 10, 309–328.

Groszos, M., R. Ceryak, D. Allison, R. Cooper, M. Weinberg, M. Macesich, M. Enright, and F. Rupert. 1992. Carbonate units of the Intermediate Aquifer system in the Suwannee River Water Management District, Florida. Florida Geological Survey Open File Report 54.

Hancock, G., I. Webster, P. Ford, and W. Moore. 2000. Using Ra isotopes to examine transport processes controlling benthic fluxes into a shallow estuarine lagoon. *Geochimica et Cosmochimica Acta* 64, 3685–3699.

Harvey, J., P. Germann, and W. Odum. 1987. Geomorphological control of subsurface hydrology in the creekbank zone of tidal marshes. *Estuarine, Coastal and Shelf Science* 25, 677–691.

Harvey, J., and W. Odum. 1990. The influence of tidal marshes on upland ground water discharge to estuaries. *Biogeochemistry* 10, 217–236.

Israelson, O., and R. Reeve. 1944. Canal lining experiments in the delta area, Utah. Utah Agricultural Experiment Station Technical Bulletin 313.

Johannes, R. 1980. The ecological significance of the submarine discharge of ground water. *Marine Ecology Progress Series* 3, 365–373.

Johannes, R., and C. Hearn. 1985. The effect of submarine ground water discharge on nutrient and salinity regimes in a coastal lagoon off Perth, Western Australia. *Estuarine, Coastal and Shelf Science* 21, 789–800.

Key, R., N. Guinasso, and D. Schink. 1979. Emanation of radon-222 from marine sediments. *Marine Chemistry* 7, 221–250.

Kohout, F. 1966. Submarine springs: A neglected phenomenon of coastal hydrology. *Hydrology* 26, 391–413.

Kohout, F., and M. Kolipinski. 1967. Biological zonation related to ground water discharge along the shore of Biscayne Bay, Miami, Florida. In *Conference on Estuaries*, March 31–April 3, Jekyll Island, Georgia, ed. G. Lauff, 488–499. AAAS No. 83. Washington, D.C.: American Association for the Advancement of Science.

Krest, J., W. Moore, L. Gardner, and J. Morris. 2000. Marsh nutrient export supplied by ground water discharge: Evidence from radium measurements. *Global Biogeochemical Cycles* 14, 167–176.

Lapointe, B., and W. Matzie. 1996. Effects of stormwater nutrient discharges on eutrophication processes in nearshore waters on the Florida Keys. *Estuaries* 19, 422–435.

Lee, D. 1977. A device for measuring seepage flux in lake and estuaries. *Limnology and Oceanography* 22, 140–147.

Lee, V., and S. Olsen. 1985. Eutrophication and management initiatives for the control of nutrient inputs to Rhode Island coastal lagoons. *Estuaries* 8, 191–202.

Li, L., D. Barry, F. Stagnitti, and J. Parlange. 1999. Submarine ground water discharge and associated chemical input to a coastal sea. *Water Resources Research* 35, 3253–3259.

Mathieu, G., P. Biscayne, R. Lupton, and D. Hammond. 1988. System for measurements of ^{222}Rn at low levels in natural waters. *Health Physics* 55, 989–992.

Martens, C., G. Kipphut, and J. Klump. 1980. Sediment-water chemical exchange in the coastal zone traced by in situ radon-222 flux measurements. *Science* 208, 285–288.

Martin, J.B., J.E. Cable, and P.W. Swarzenski. 2002. Quantification of ground water discharge and nutrient loading to the Indian River Lagoon, Palatka, Florida. St. Johns River Water Management District Final Report.

Martin, J.B., J.E. Cable, P.W. Swarzenski, and M.K. Lindenberg. 2004. Enhanced submarine ground water discharge from mixing of pore water and estuarine water. *Ground Water* 42, no. 7: 1000–1010.

Martin, J.B., K. Hartl, R. Corbett, P. Swarzenski, and J.E. Cable. 2003. A multi-level pore water sampler for permeable sediments. *Journal of Sedimentary Research* 73, 128–132.

McCaffrey, R., A. Meyers, E. Davey, G. Morrison, M. Bender, N. Luedtke, D. Cullen, P. Froelich, and G. Klinkhammer. 1980. The relation between pore water chemistry and benthic fluxes of nutrients and manganese in Narragansett Bay, Rhode Island. *Limnology and Oceanography* 25, 31–44.

Miller, J.A. 1986. Hydrogeologic framework of the Floridan aquifer system in Florida and parts of Georgia, Alabama, and South Carolina. U.S. Geological Survey Professional Paper 1403-B.

Miller, D.C., and W.J. Ullman. 2004. Ecological consequences of ground water discharge to Delaware Bay, United States. *Ground Water* 42, no. 7: 959–970.

Millham, N., and B. Howes. 1994. Fresh water flow into a coastal embayment: Ground water and surface water inputs. *Limnology and Oceanography* 39, 1928–1944.

Moore, W. 1999. The subterranean estuary: A reaction zone of ground water and sea water. *Marine Chemistry* 65, 111–125.

National Climatic Data Center. 2002. Monthly station normals of temperature, precipitation, and heating and cooling degree days 1971–2000, Florida. Climatography of the United States No. 81.

Pandit, A., and C. El-Khazen. 1990. Ground water seepage into the Indian River Lagoon at Port St. Lucie. *Florida Scientist* 53, 169–179.

Paulsen, R.J., C.F. Smith, D. O'Rourke, and T.-F. Wong. 2001. Development and evaluation of an ultrasonic ground water seepage meter. *Ground Water* 39, 904–911.

Rama and W. Moore. 1996. Using the radium quartet for evaluating ground water input and water exchange in salt marshes. *Geochimica et Cosmochimica Acta* 60, 4245–4252.

Rasmussen, L.L. 1998. Groundwater flow, tidal mixing and haline convection in coastal sediments. M.S. thesis, Department of Oceanography, Florida State University.

Riedl, R., N. Huang, and R. Machan. 1972. The subtidal pump: A mechanism of interstitial water exhchange by wave action. *Marine Biology* 13, 210–221.

Rona, E. 1917. Diffusionsgrosse und atomdurchmesser der radiumemanation. *Zeitschrift fur Physikalische Chemie* 92, 213–218.

Rutkowski, C., W. Burnett, R. Iverson, and J. Chanton. 1999. The effect of ground water seepage on nutrient delivery and seagrass distribution in the northeastern Gulf of Mexico. *Estuaries* 22, 1033–1040.

Scott, T.M. 1988. The lithostratigraphy of the Hawthorn Group (Miocene) of Florida. Florida Geological Survey Bulletin Report #59.

Scott, T.M. 1992. A geological overview of Florida. Florida Geological Survey Open File Report #50.

Sewell, P. 1982. Urban groundwater as a possible nutrient source for an estuarine benthic algal bloom. *Estuarine, Coastal and Shelf Science* 15, 569–576.

Shaw, R.D., and E.E. Prepas. 1989. Anomalous, short-term influx of water into seepage meters. *Limnology and Oceanography* 34, 1343–1351.

Shaw, R., and E. Prepas. 1990. Ground water-lake interactions, 1. Accuracy of seepage meter estimates of lake seepage. *Journal of Hydrology* 119, 105–120.

Shinn, E., C. Reich, and D. Hickey. 2002. Seepage meters and Bernoulli's revenge. *Estuaries* 25, 126–132.

Smethie, W.M., C.A. Nittrouer, and R.F.L. Self. 1981. The use of radon-222 as a tracer of sediment irrigation and mixing on the Washington continental shelf. *Marine Geology* 42, 173–200.

Smith, N. 1993. Tidal and nontidal flushing of Florida's Indian River Lagoon. *Estuaries* 16, 739–746.

Sutula, M., J.W. Day, J. Cable, and D. Rudnick. 2001. Hydrological and nutrient budgets of fresh water and estuarine wetlands of Taylor Slough in southern Everglades, Florida, USA. *Biogeochemistry* 56, 287–310.

Taniguchi, M., and Y. Fukuo. 1993. Continuous measurements of ground water seepage using an automatic seepage meter. *Ground Water* 31, 675–679.

Tobias, C., J. Harvey, and I. Andersen. 2001. Quantifying ground water discharge through fringing wetlands to estuaries: Seasonal variability, methods comparison, and implications for wetland-estuary exchange. *Limnology and Oceanography* 46, 604–615.

Top, Z., L. Brand, R. Corbett, W. Burnett, and J. Chanton. 2001. Helium as a tracer of ground water input into Florida Bay. *Journal of Coastal Research* 17, 859–868.

Valiela, I., J. Teal, S. Volkman, D. Shafer, and E. Carpenter. 1978. Nutrient and particulate fluxes in a salt marsh ecosystem: Tidal exchanges and inputs by precipitation and ground water. *Limnology and Oceanography* 23, 798–812.

Valiela, I., J. Costa, K. Foreman, J. Teal, B. Howes, and D. Aubrey. 1990. Transport of ground water-borne nutrients from watersheds and their effects on coastal waters. *Biogeochemistry* 10, 177–179.

Williams, M., G. Simmons, and W. Reay. 1991. Preliminary evidence of biological indicators of submarine ground water discharge. In *New Perspectives in the Chesapeake Bay System: A Research and Management Partnership*, Chesapeake Research Consortium Publication 137, ed. J. Mihursky and A. Chaney, 623–634.

Zimmermann, C.F., J.R. Montgomery, and P.R. Carlson. 1985. Variability of dissolved reactive phosphate flux rates in nearshore estuarine sediments: Effects of ground water flow. *Estuaries* 8, 228–236.