MIXING IN THE SUBTERRANEAN ESTUARY: A COMPARISON OF RADON-222 PORE WATER MODELS

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ABSTRACT

The magnitude of terrestrial groundwater discharge to coastal systems is poorly constrained due to complications associated with fluxes of recirculated seawater. It is essential to resolve the contribution of these two sources to the mixed zone to understand their impacts on coastal systems and the implications for water resource management, for example through organic matter re-mineralization and metal diagenesis. Pore water and surface water samples collected from a multilevel piezometer located 10 m offshore into the micro-tidal Indian River Lagoon, Florida and analyzed for total ²²²Rn show that a mixed zone extends 25 to 35 cm below the seafloor (cmbsf). A water-column mass-balance model of ²²²Rn requires upward velocities of 1.2 to 6.96 cm day⁻¹. In contrast, advection rates obtained using an optimizing, advection-diffusion-reaction model for pore water ²²²Rn activities require downward velocities of 0.9 to 4 cm day⁻¹ to match observed pore water distributions. The downward advection rates might be associated with piston-like flow resulting from wave/tidal pumping, bioirrigation, and/or density-driven convection, while the upward rates are driven by hydrostatic head from the mainland.

29.1. INTRODUCTION

The magnitude of groundwater discharge to coastal water bodies has been debated extensively in recent literature, with global fluxes estimated to range from 0.01 to 10% of
total riverine discharge (Taniguchi et al., 2002) and local fluxes as high as 40% of riverine discharge (Moore, 1996). If such high estimates are accurate, non-point source discharge of nutrients and land-based pollutants (e.g. hydrocarbons, chlorinated solvents, and metals) may be a serious concern. However, a majority of this discharging water is not derived from meteorically-recharged groundwater but rather from infiltrated seawater circulating locally through sediments. This observation raises the question: How can sources of groundwater being discharged to coastal systems be distinguished?

A commonly accepted definition of submarine ground water discharge (SGD) is any and all fluids that pass across the sediment-water interface (Burnett et al., 2003). Accepting this definition along with a source from seawater, SGD can be divided into two general end-members: 1) recirculated seawater (RSGD) and 2) gravity-driven, terrestrially-derived groundwater (SFGD, Burnett et al., 2001; Taniguchi et al., 2002; Burnett et al., 2003). Recent SGD research has focused on identifying contributions from each of these two end-members to total SGD flux and their impacts on biogeochemical processes within the sediments and the lagoon. Although the total flux may originate from both sources, it is their individual contributions that ultimately define the biogeochemical influence. Distinguishing between the contributions of each end-member is thus essential to understand the overall environmental impact.

Three general measurement techniques have been employed to assess SGD fluxes: 1) direct measurement (e.g. seepage meters); 2) water budgets and flow models; and 3) chemical tracers. The techniques have proven inconsistent with one another, even at the same site at the same time, because each technique measures different sources of water. For example, seepage meters generally measure total SGD flux without distinguishing between the contributions of each end-member. On the other hand, water budgets estimate only magnitude of gravity driven, terrestrial ground water discharge. Tracers rely on understanding interactions of the tracer with the system, and their ability to represent the physical processes controlling flow within the system.

Traditionally, inert radiogenic tracers like $^{222}$Rn ($t_{1/2} = 3.82$ d) and conservative tracers like Cl$^-$ have been used to understand pore water processes in low-permeability systems (e.g., Hammond et al., 1977; Martens et al., 1980; Martin and Banta, 1992); more recently, these tracer applications have been expanded into higher permeability systems (e.g., Corbett et al., 1997; Cable et al., 2004; Martin et al., in press). Combining these tracers is effective at distinguishing SGD end-members, since Cl$^-$ is a seawater tracer and $^{222}$Rn acts as a natural groundwater tracer. However, modeling pore water distributions of these tracers have yielded contrasting advection rates (cf. Cable et al., 2004; Martin et al., 2004). Our objectives in this paper are thus to address some of the basic assumptions applied to $^{222}$Rn tracer models using pore water data collected from shallow sandy sediments within the Indian River Lagoon, Florida. We compare and contrast the results obtained from a $^{222}$Rn water-column mass-balance model and $^{222}$Rn advection-diffusion-reaction (ADR) model. We discuss alternative explanations for why these models do not agree and what mechanisms affect the observed activity distributions.

### 29.2. GEOLOGIC SETTING

Indian River Lagoon (IRL) system is a large, back-barrier lagoonal system made up of three interconnected lagoons (Mosquito Lagoon, Banana River Lagoon, and Indian River Lagoon) located along the east central coast of Florida (Fig. 1). The main IRL lagoon
begins at the mouth of Turnbull Creek (28°47.957'N, 80°51.085'W) and terminates 250 km south at St. Lucie Inlet (27°09.870'N, 80°10.235'W). Lagoonal width averages ~2 to 4 km (maximum of 10 km) and depth averages 1.5 m (maximum 5 m). Three jettied inlets connect Indian River Lagoon to the Atlantic Ocean; from north to south, they are Sebastian (~65 km south of the primary study site), Ft. Pierce, and St. Lucie Inlets. Indian River Lagoon is a well-mixed, micro-tidal estuary (tidal amplitude ≤10 cm; Smith, 1987; Smith, 1992) where water levels are controlled primarily by winds (Smith, 1992). Maximum significant wave heights average 30 to 60 cm due to the lagoon fetch and frequent boat traffic. Three hydrostratigraphic units make up the IRL region, including the Floridan, Intermediate, and Surficial Aquifers (Toth 1988; Toth 1993). The Intermediate Aquifer is located in the Hawthorne Group, which is the semi-confining unit to the Floridan Aquifer and limits exchange between the Surficial Aquifer and the Floridan Aquifer (Miller, 1986; Scott, 1988; Tibbals, 1990; Miller, 1997). Because of confinement, the primary source of terrestrial groundwater to Indian River Lagoon is provided by the Surficial Aquifer, which has an average thickness of about 30 m on land and thins to 15 to 20 m beneath the lagoon. This aquifer consists primarily of undifferentiated Holocene interbedded coquina, sand, silt, and clay.

29.3. METHODS

Pore water samples were collected on four separate occasions from a shore-normal transect off the mainland coast of Florida near the town of Melbourne (Fig. 1a). The transect consists of eight multi-level pore water samplers spaced every 2.5 to 5 m from the shoreline to 30 m offshore (Fig. 1b; Martin et al., 2003). Each sampler has eight sampling ports at discrete depths, which are sampled using a peristaltic pump. Dissolved oxygen is used to ensure pristine pore waters are sampled, while other field parameters (conductivity,
temperature, salinity, and pH) are used to monitor cross-sampling pore water from adjacent ports. Sampling for total \(^{222}\)Rn consists of drawing a 10-mL aliquot of pore water using a glass syringe and injecting it into a 20-mL vial pre-filled with 10-mL of high efficiency mineral oil. Pore waters were also collected for dissolved \(^{226}\)Ra and stored until return to the laboratory. Total \(^{222}\)Rn activity was measured using a Packard Tri-Carb 3100-TR Liquid Scintillation Counter at Louisiana State University. Triplicate samples of water were collected for measurement of total \(^{222}\)Rn activity and all raw data were calibrated using standards of known activity, then decay-corrected to collection time. In addition to total pore water \(^{222}\)Rn activity, dissolved \(^{226}\)Ra activity, and maximum sediment supported \(^{222}\)Rn activity (from sediment bound \(^{226}\)Ra) were measured. Pore water \(^{226}\)Ra activity was measured using a cryogenic extraction technique modified from Mathieu et al. (1988). Maximum sediment supported \(^{222}\)Rn activity was estimated using a sediment slurry experiment and cryogenic extraction.

### 29.4. MODEL DESCRIPTION

#### 29.4.1. \(^{222}\)Rn Water-Column Mass-Balance

Cable et al. (1996b) developed a water column \(^{222}\)Rn mass balance model to examine the role ground water advection had on the total benthic flux of \(^{222}\)Rn (and other chemical constituents) at a site in northeastern Gulf of Mexico:

\[
J_{\text{benthic}} = J_{\text{bent, adv}} + J_{\text{bent, diff}} = J_{\text{atm}} + \lambda C_{\text{Rn}} z - \lambda C_{\text{Ra}} z
\]

where \(J_{\text{benthic}}\) and \(J_{\text{atm}}\) are the fluxes out of the benthos and into the atmosphere \([\text{ML}^{-2}\text{T}]\), respectively; \(\lambda (\sim 0.2618 \text{ d}^{-1})\) is the decay coefficient for \(^{222}\)Rn \([\text{T}^{-1}]\); \(\lambda C_{\text{Ra}}\) and \(\lambda C_{\text{Rn}}\) are production and decay of \(^{222}\)Rn in the water column \([\text{ML}^{-3}\text{T}^{-1}]\), respectively; and \(z\) is the depth of the water column \([\text{L}]\). The benthic flux can be broken into two components: advective flux \((J_{\text{bent, adv}})\) and diffusive flux \((J_{\text{bent, diff}})\). Cable et al. (1996b) estimated \(J_{\text{benthic}}\) (and subsequently the advection rate) using a standard diagenetic equation for a radioactive species in a homogeneous and isotropic porous media:

\[
\frac{\partial C}{\partial t} = \frac{\partial}{\partial z} \left( D_s \frac{\partial C}{\partial z} \right) - \frac{\partial}{\partial z} \left( vC \right) - \lambda C + P(z). \tag{2a}
\]

Assuming \(\frac{\partial C}{\partial t} = 0\) and boundary conditions, \(C(z=0) = C_0\) and \(\frac{dC}{dz}_{z=eq} = 0\), the analytical solution has the form:

\[
C(z) = \left( C_0 - C_{eq} \right) \left( \frac{e^{2z^*}}{e^{2z}} \right) \sinh \left( \frac{A(z_{eq} - z)}{2z^*} \right) \sinh \left( \frac{Az_{eq}}{2z^*} \right) \tag{2b}
\]
where \( z^* = \frac{D_s}{v} \) and \( A = \left(1 + 4z^*\right)\left(\lambda/v\right)^{0.5}. \) \( D_s \) is the bulk sediment diffusion coefficient [L^2 T^{-1}]; \( v \) is seepage velocity [L T^{-1}]; \( C(z), C_0, \) and \( C_{eq} \) are concentrations [M L^{-3}] at \( z \), in the water column \((z=0)\), and at \( z_{eq} \), respectively; and similarly \( z_{eq} \) is the equilibration depth (where \( C = C_{eq} \)). The sediment diffusion coefficient is the tortuousity corrected diffusion coefficient, \( D_s = D_m/\theta^2 \) and like \( v \), and \( P(z) \), is assumed to be equal to \( \lambda C_{eq} \) and constant with depth. The \( C_{eq} \) term has traditionally been expressed as the total activity of \(^{222}\)Rn supported by the shallow sediments (< 10 cm; e.g., Cable et al., 1996a; Cable et al., 1996b). Outside of the study by Cable et al. (1996b) in the Gulf of Mexico, this mass balance model has been applied in several open bay systems, including Florida Bay (Corbett et al., 1999; 2000) and Brazil (Oliveira et al., 2003).

### 29.4.2. Advection-Diffusion-Reaction Model for \(^{222}\)Rn.

The \(^{222}\)Rn water-column mass-balance model (eq. 1) uses the standard advection-diffusion-reaction equation (ADR; eq. 2) to determine the role advection plays in total benthic flux; however, the \(^{222}\)Rn water-column mass-balance model previously has been calibrated by the inventory \(^{222}\)Rn in the water column rather than the distribution of \(^{222}\)Rn activities in the pore waters (Cable et al., 1996b). The more traditional application of the ADR model is to estimate advection rates through calibrating the model with observed \(^{222}\)Rn activities. Application of both models to one set of data should provide similar values for flux and/or flow rates of total SGD; differences in model results would reflect errors in assumptions of the models. For this study, a backward-difference finite approximation to Equation 2a for \(^{222}\)Rn is used to compute pore water distributions; the backward-difference finite approximation model takes the form:

\[
C_{j+1} \left( \frac{D_s}{\Delta z^2} \right) - C_{j} \left( \frac{2D_s}{\Delta z^2} + \frac{v}{\Delta z} + \lambda \right) + C_{j-1} \left( \frac{D_s}{\Delta z^2} + \frac{v}{\Delta z} \right) = P(z). \tag{3}
\]

The \(^{222}\)Rn ADR models is solved for advection using two dirichlet boundary conditions at \( z = Z_0 \) and \( z = Z_L \), where \( Z_0 \) is the top of the zone of interest and \( Z_L \) is the base of the zone of interest. The model domain was vertical discretized to 0.01 cm, this permits advection rates as high as 200 cm day^{-1} to be tested before exceeding a Peclet number (Pe) of 4. The model was solved using a downhill simplex (Nelder-Mead) technique with advection as the unknown fitting parameter; the quality of fit was determined using the root-mean-square error (RMSE) between observed and computed values. Since the number of observed points is far less than the computed number, a shape preserving spline was used in computing the RMSE.

### 29.5. RESULTS

The results of this study include advection rates obtained from the following \(^{222}\)Rn models: 1) water-column mass-balance model and 2) an advection-optimized, ADR model, referred to as the mass-balance model and ADR model, respectively, from this point forward. Several general assumptions were made for each model; the bulk \(^{222}\)Rn sediment diffusion coefficient \( (D_s = 6.00 \times 10^{-6} \text{ cm}^2 \text{ sec}^{-1}) \), porosity \( (\phi = 0.35) \), solute distribution (at the time of
sampling), and $^{222}\text{Rn}$ production were assumed constant with depth and time. The upper boundary of the ADR model domain was difficult to determine due to the well-mixed nature of the upper 10-15 cm, therefore, two separate scenarios were considered (upper boundary condition at 7 and 15 cm). The most complete $^{222}\text{Rn}$ data set (i.e., total and all supported fractions) was from EGN-10; therefore, all model experiments were conducted on this one sampling location, but over all the sampling periods. At this site, the measured total $^{222}\text{Rn}$ activity (pore water and water column) exceeded the dissolved and sediment-supported fraction by a factor of four during each of the sampling periods, which implies an additional source of $^{222}\text{Rn}$ to maintain the observed pore water and water column activities (Fig. 2)

Fig. 2. Vertical profile showing the distribution of total, sediment supported, and dissolved supported $^{222}\text{Rn}$ activities collected from EGN-10 multi-sampler. Total $^{222}\text{Rn}$ measurements were conducted on four separate occasions as indicated by month and year in the legend; sediment and dissolved supported fractions were collected on May 2005, only. Under the assumption that the sediments contain a steady-state supply of $^{226}\text{Ra}$, it can be inferred that there is always an excess of $^{222}\text{Rn}$ in this system.

29.5.1. ($^{222}\text{Rn}$ Water Column) Mass Balance Model

The disequilibrium between supported and observed $^{222}\text{Rn}$ activities can be problematic when computing advection rates using the ($^{222}\text{Rn}$ water column) mass balance model. The choice of $C_{eq}$ has traditionally been taken as the activity measured from grab samples;
however, along the nearshore of Indian River Lagoon, FL, the lack of sediment-supported 
$^{222}\text{Rn}$ precludes this assumption. Thus, our choices of $C_{eq}$ were derived from total pore 
water $^{222}\text{Rn}$ activity as opposed to the sediment-supported levels. Advection rates obtained 
using the mass balance model with two choices of $C_{eq}$ (i.e., total $^{222}\text{Rn}$ activities observed at 
7 and 35 cmbsf for each sampling trip) are given in Table 1. The vertically-upward advection rates range over a factor of 40 (1.1 to 41.2 cm day$^{-1}$) that are generally much 
greater than other estimates from the same or nearby sites (Pandit and El-Khazen, 1990; 
Cable et al., 2004; Martin et al., 2004; Martin et al., 2005). These estimated advection rates 
result in pore water $^{222}\text{Rn}$ activity distributions different than the observed pattern (Fig. 3). 
The computed $^{222}\text{Rn}$ activity distributions have a shallow mixed zone (< 10 cm) accented 
by a steep concentration gradient, whereas the observed distributions have a mixed zone 
extending to depths of 35 to 55 cm with a more gentle gradient.

**Table 1.** Seepage velocities from the three base models; negative numbers indicate 
vertical upward flow and positive numbers indicate vertically, downward 
flow.

<table>
<thead>
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<td>$^{222}\text{Rn}$ Mass Balance</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$C_{eq}$ (dpm L$^{-1}$) @ 7 cm</td>
<td>781.10</td>
<td>858.20</td>
<td>946.50</td>
<td>1126.00</td>
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<td>Advection Rate (cm day$^{-1}$)</td>
<td>-11.21</td>
<td>-24.90</td>
<td>-41.31</td>
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<tr>
<td>Standard Error (cm day$^{-1}$)</td>
<td>1.44</td>
<td>2.27</td>
<td>3.70</td>
<td>0.61</td>
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<tr>
<td>$^{222}\text{Rn}$ Mass Balance</td>
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<tr>
<td>$C_{eq}$ (dpm L$^{-1}$) @ 35 cm</td>
<td>4816.70</td>
<td>3481.70</td>
<td>4567.80</td>
<td>4689.70</td>
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<tr>
<td>Advection Rate (cm day$^{-1}$)</td>
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<td>-4.78</td>
<td>-6.49</td>
<td>0.01</td>
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<tr>
<td>Standard Error (cm day$^{-1}$)</td>
<td>1.44</td>
<td>0.44</td>
<td>0.58</td>
<td>0.01</td>
</tr>
<tr>
<td>$^{222}\text{Rn}$ ADR</td>
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<td></td>
<td></td>
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<tr>
<td>Advection Rate (cm day$^{-1}$)</td>
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<td>1.79</td>
<td>1.93</td>
<td>1.38</td>
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<tr>
<td>Upper Boundary at 7 cm</td>
<td>RMSE (dpm L$^{-1}$)</td>
<td>1009.00</td>
<td>980.00</td>
<td>1108.00</td>
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<tr>
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<td>0.25</td>
<td>0.66</td>
<td>No results</td>
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<tr>
<td>Upper Boundary at 15 cm</td>
<td>RMSE (dpm L$^{-1}$)</td>
<td>305.00</td>
<td>440.00</td>
<td>260.00</td>
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</table>

**Sensitivity Analysis**
Given the large range of advection rates, a sensitivity analysis 
was performed on two dominant parameters: 1) $C_{eq}$ and 2) wind velocity (proxy for $J_{atm}$). 
As shown in equation 2a, $C_{eq}$ is a key coefficient in the determination of $C(z)$. In the first 
sensitivity experiment, $C_{eq}$ (all other parameters constant for appropriate sampling period) 
were varied among several total pore water and sediment supported $^{222}\text{Rn}$ activities 
observed during each of the four sampling periods. Results show that the advection rates 
increase exponentially (from 0.0014 to 151 cm day$^{-1}$) with a decrease in $C_{eq}$ (Fig. 4A). The 
high advection rates result in shallower equilibration depths (<<10 cm), than the observed 
$^{222}\text{Rn}$ distribution.
Fig. 3. Computed pore water $^{222}\text{Rn}$ profiles/distributions based on the mass balance approach where A and B are based on total $^{222}\text{Rn}$ values from 7 and 35 cmbsf, respectively. Table 1 shows the advection rates obtained from each scenario. Circles, inverted triangles, squares, and pyramids are used to represent measured data for November 2004, February 2005, May 2005, and September 2005, respectively, while, solid, dash-dotted, dashed, and dotted lines are used to represent fitted data for November 2004, February 2005, May 2005, and September 2005, respectively.

The second sensitivity analysis used wind velocity as a proxy for atmospheric evasion, which is another important, yet poorly constrained parameter in the mass balance model. Atmospheric evasion is estimated using

$$J_{atm} = k \left( C_0 - \alpha C_{air} \right)$$

(4)

where $k$ is the gas transfer coefficient (m sec$^{-1}$) proportional to wind velocity, $u$, raised to 1.6 power (m sec$^{-1}$) and $\alpha$ is the Oswald’s solubility constant (dimensionless) for a gas. In this exercise, wind velocity varies within a range of 1.8 to 6.5 m sec$^{-1}$, only 2.5 m sec$^{-1}$ higher than observed during any sampling period. For all cases except Sept 2005 the advection rate increases at a power of 1.5 and range between 1.5 and 18 cm day$^{-1}$ (Fig. 4B).
Fig. 4. Sediment equilibration/supported fraction (A) and wind velocity (B) sensitivity results for the water-column mass-balance model.

29.5.2. Advection-Diffusion-Reaction (ADR) Model

Unlike the mass balance model, the ADR model calibrates a physical model of pore water $^{222}$Rn activity from all observed depths in the pore water, rather than estimating a single boundary layer flux at the sediment-water interface. Advection rates obtained from the ADR model are given in Table 1 and the optimized fits to the data are presented in Figure 5. Advection rates using the 7 cm upper boundary are between 1.37 and 2.29 cm day$^{-1}$, but
Fig. 5. Best-fit model results for the advection optimized ADR model when the upper boundary is set at 15 cm (Panel A) and 7 cm (Panel B). Circles, inverted triangles, squares, and pyramids are used to represent measured data for November 2004, February 2005, May 2005, and September 2005, respectively, while, solid, dash-dotted, dashed, and dotted lines are used to represent fitted data for November 2004, February 2005, May 2005, and September 2005, respectively.

the RMSE values suggest a relatively poor fit to the observed data (average ~970 dpm L⁻¹, Table 1). In contrast, when the 15 cm upper boundary condition is used, advection rates are half the previous estimates (between 0.25 and 0.73 cm day⁻¹) and the RMSE values (average ~335 dpm L⁻¹) suggest better fits (Table 1). Unlike the mass balance model, solutions to the ADR models require a vertically-downward flux of fluid over the entire 35 to 50 cm model domain. Although the magnitude of these estimates seems reasonable, the implication of sustained, vertically downward flow contradicts the results of the mass balance model, which requires net upward flux of ²²²Rn from the sediment to the water column. Flow of water has previously been observed in Cl⁻ concentration profiles from these sediments, although the flow rates are poorly constrained (Martin et al., 2004; Martin et al., in press).

29.6. DISCUSSION

We discuss below the implications of the contradiction between these two models to pore water exchange in Indian River Lagoon, FL. Here we follow the definition of pore water
exchange as outlined by Tanguichi et al. (2002) and Burnett et al. (2003); where pore water discharge (SGD) is comprised of recirculated seawater (RSGD), and terrestrially-derived fresh ground water (SFGD), while recharge (SGR) is comprised solely of infiltrated seawater.

The mass balance model requires a total benthic flux (combined advective and diffusive flux) to support the water column $^{222}$Rn inventory but does not indicate the driving force for this advective flow. As stated in the introduction, SGD consists of two components (RSGD and SFGD); thus, the high advection rates computed for Indian River Lagoon using the mass balance model represent a combination of both components. Similar observations have been made in Florida Bay (Corbett et al. 1999; Chanton et al. 2003) and in Banana River Lagoon (Cable et al., 2004; Martin et al., 2004; Martin et al., in press).

In contrast, the ADR model requires a vertically downward flow to explain the pore water distribution. Flow into the sediments may seem somewhat contradictory with respect to the general principles that define the mass balance model. In order to conserve fluid mass, water must infiltrate or recharge at the same rate at which it discharges plus or minus small changes in storage due to the compressibility of the solid matrix and the fluid. Recirculated seawater therefore represents piston-like flow rather than uni-directional flow. Numerous processes occur within the shallow, coastal water bodies that could drive piston-like flow, including thermohaline-driven convection within the sediments, bio-irrigation, wave/tidal pumping, and sample collection (Martin et al. in press). If we assume that the compressibility of the matrix and fluid is small, then the flow velocities implied by the ADR model represent infiltration rates for submarine groundwater recharge (SGR) minus the background freshwater discharge (SFGD). Therefore, the following continuity equation can be designed for the advective fluxes across the sediment-water interface:

$$\text{SGR} - \text{RSGD} - \text{SFGD} \pm \Delta S = 0 \quad (5)$$

where $\Delta S$ is change in the storage in the unconfined aquifer due to the compressibility of the water and solid matrix. Putting the mass balance and ADR model into context of equation 5 and assuming steady state flow, it is apparent that the ADR model provides an estimate for RSGD and the mass balance model provides an estimate of SGR ($\approx$SGD). This implies that the difference is the resulting SFGD (e.g. meteoric ground water) assuming small fluid and matrix compressibility.

This simple equation inherits a lot of assumptions and care should be taken in its application. As observed in the sensitivity analysis for the mass balance model, the ability to accurately estimate representative advective fluxes resides in the ability to properly estimate atmospheric evasion as well as the choice of an appropriate supported fraction. For the EGN-10 data, the best comparison between mass balance and ADR estimates would be where boundary conditions are the same, for example for $C_{eq}$ observed at 35 cm (Table 1). Using this rationale, fresh ground water discharge (-) or excess seawater recharge (+) for the Nov 2004, Feb 2005, May 2005, and Sept 2005 sampling trips would be -0.62 to 0.96, -2.99 to -4.53, -4.56 to -5.83, and 1.39 cm day$^{-1}$, respectively. The excess recharge results are observed where the standard deviations of the advection rates obtained from the mass balance model are greater than the mean. This observation raises an additional concern with the proposed model, in that the error of the input (SGR and RSGD) may exceed the magnitude of output (SFGD). To examine this problem is beyond the scope of this paper and requires an additional means to measure the individual components of SGD.
These estimates of fresh ground water discharge are much greater than estimates reported by numerical models and other tracer studies but are similar to freshwater discharge suggested by seepage meters. Pandit and El-Khazen (1990) estimated average seepage velocities (assuming the entire width of the lagoon and one meter of shoreline) of 0.05 cm day\(^{-1}\) using a finite element, freshwater equivalent head model for the IRL region near St. Lucie Inlet. Martin et al. (2005) found fresh water advection rates on the order of tenths of cm day\(^{-1}\) from models of pore water Cl\(^-\) concentrations, and rates of 1.5 to 7 cm day\(^{-1}\) from seepage meters located at 5, 10, and 15 m from the shoreline and ~10 m south of the site reported here. The salinity of the seepage water indicated that the discharging water included a significant fraction of salt water, which probably represents the RSGD estimated by the ADR model. Although our fresh groundwater discharge and total submarine groundwater discharge rates are on the higher end of the modeled discharge estimates for Indian River Lagoon, they fall in-line with physical measurements made in this area.

29.7. CONCLUSION

The results presented here collectively provide an alternative way to view \(^{222}\text{Rn}\) data and its application to understanding pore water exchange, as well as some of the pitfalls and sensitivities to fundamental underlying assumptions often employed in these models. These results also show that fluxes estimated by the traditional mass balance model represent total SGD, including discharge of both recirculated seawater and fresh ground water from the seabed into the overlying water column. The vertically downward fluid flux required by the 1-D \(^{222}\text{Rn}\) ADR model is interpreted as a recharging fraction of seawater driven by infiltration, pumping, and/or convective circulation. Differences in these estimates for Indian River Lagoon, FL, provide estimates for terrestrially-derived submarine ground water discharge (plus or minus small changes in storage) that are on the order of 4 to 5 cm day\(^{-1}\). Rates of this magnitude suggest that fresh groundwater discharge may play an important role to chemical fluxes to the nearshore Indian River Lagoon; however, extrapolation to the entire lagoon requires a more detailed study along with model validation.

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