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 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 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.

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 $^{222}\text{Rn}$ and $^{226}\text{Ra}$. Ground water discharge rates ranged from 4 to 9 cm/d using seepage meters and 3 to 20 cm/d using $^{222}\text{Rn}$ and $^{226}\text{Ra}$. 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, $^{222}\text{Rn}$, and $^{226}\text{Ra}$ 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.

Advection Within Shallow Pore Waters of a Coastal Lagoon, Florida

by Jaye E. Cable, Jonathan B. Martin, Peter W. Swarzenski, Mary K. Lindenberg, and Joel Steward

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 $^{222}\text{Rn}$ and $^{226}\text{Ra}$. Ground water discharge rates ranged from 4 to 9 cm/d using seepage meters and 3 to 20 cm/d using $^{222}\text{Rn}$ and $^{226}\text{Ra}$. 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, $^{222}\text{Rn}$, and $^{226}\text{Ra}$ 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 surface waters 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
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, \(^{222}\text{Rn},^{223,224,226,228}\text{Ra, }^{4}\text{He, and Cl}^{-}\) (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 \(^{222}\text{Rn}\) 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; Grosszos 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.

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 km² in the northern study area and 67 km² 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 m²) 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 222Rn (t₁/₂ = 3.83 d) and 226Ra (t₁/₂ = 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 into the sediments, as in previous studies (Lee 1977; Shaw and Prepas 1989; Cable et al. 1997). The volume of advecting fluids was measured as a function of time and seepage meter area (0.25 m²) 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.

Sediment slurry experiments were performed to estimate the maximum amount of pore water 222Rn 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 222Rn (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 226Ra and is measured via cryogenic extraction and alpha scintillation counting. The equilibrium activity (Cₑₒₜ) is calculated using the porosity (φ) and wet bulk density (ρₚₑₒₜ) of the sediments. Upper limit diffusive fluxes were calculated from these Cₑₒₜ activities in slurry experiments and overlying bottom water activities (Martens et al. 1980; Cable et al. 1996). Measured activities (dpm/m³ 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 222Rn as a geochemical tracer (Figure 2). Diffusive 222Rn fluxes calculated using sediment matrix 226Ra equilibration in a slurry ranged between 111 and 756 dpm/m²/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
each site. In the northern study area, benthic $^{222}\text{Rn}$ advection was $4190 \pm 650 \text{ dpm/m}^2/\text{d}$ ($n = 2$); in the central study area benthic $^{222}\text{Rn}$ advection was $1750 \pm 450 \text{ dpm/m}^2/\text{d}$ ($n = 3$). 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 $^{222}\text{Rn}$ and $^{226}\text{Ra}$ 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 $^{222}\text{Rn}$ activities increase from $7 \text{ dpm/L}$ at 10 cmbsf to $88 \text{ dpm/L}$ at 110 cmbsf (Figure 3b). Pore water $^{222}\text{Rn}$ 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 $5.8 \pm 3.1 \text{ cm/d}$ in May 1999 and $9.1 \pm 4.5 \text{ cm/d}$ in August 1999. Seepage meter control experiments using an impermeable barrier over the sediments revealed the technique has about a $1.6 \text{ cm/d}$ blank (i.e., the lower limit of detection for seepage meter measurements in IRL). Geochemical tracer estimates of benthic advective rates are $2$ to $> 20 \text{ cm/d}$ using $^{222}\text{Rn}$ and $^{226}\text{Ra}$ flux measurements. In the central study area, advection using 24 seepage meters was less overall and found to average between $4.0$ and $5.5 \text{ cm/d}$ during seasonal studies. The seepage meter blank estimates were $1 \text{ cm/d}$, which is similar to the northern study area and to blanks observed by Chanton et al. (2003) in Florida Bay. Geochemical tracer ($^{222}\text{Rn}$) estimates of benthic advective inputs were $2$ to $12 \text{ cm/d}$. The

### Table 1

<table>
<thead>
<tr>
<th>Station ID</th>
<th>Pore Water $^{222}\text{Rn}$ $\phi C_{eq}$ (dpm/L)</th>
<th>Water $^{222}\text{Rn}$ Column $C_o$ (dpm/L)</th>
<th>Calculated $^{222}\text{Rn}$ Diffusive Flux (dpm/m²/d)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Northern Sites</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>IRL-1</td>
<td>31.7 ± 4.6</td>
<td>4.489 ± 0.084</td>
<td>214 ± 17</td>
</tr>
<tr>
<td>IRL-2</td>
<td>26.2 ± 4.3</td>
<td>3.814 ± 0.078</td>
<td>177 ± 16</td>
</tr>
<tr>
<td>IRL-3</td>
<td>28.0 ± 4.4</td>
<td>3.836 ± 0.081</td>
<td>190 ± 17</td>
</tr>
<tr>
<td>IRL-4</td>
<td>16.8 ± 4.1</td>
<td>4.155 ± 0.082</td>
<td>111 ± 16</td>
</tr>
<tr>
<td>IRL-5</td>
<td>19.1 ± 4.1</td>
<td>5.015 ± 0.098</td>
<td>125 ± 16</td>
</tr>
<tr>
<td>IRL-6</td>
<td>19.3 ± 4.2</td>
<td>4.144 ± 0.087</td>
<td>128 ± 16</td>
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<tr>
<td>IRL-7</td>
<td>86.1 ± 4.7</td>
<td>4.052 ± 0.081</td>
<td>594 ± 18</td>
</tr>
<tr>
<td>IRL-8</td>
<td>80.2 ± 4.5</td>
<td>4.406 ± 0.083</td>
<td>552 ± 17</td>
</tr>
<tr>
<td>IRL-9</td>
<td>75.5 ± 4.4</td>
<td>5.653 ± 0.105</td>
<td>520 ± 17</td>
</tr>
<tr>
<td>IRL-10</td>
<td>57.8 ± 3.0</td>
<td>5.439 ± 0.092</td>
<td>396 ± 11</td>
</tr>
<tr>
<td>IRL-11</td>
<td>70.8 ± 3.3</td>
<td>4.435 ± 0.034</td>
<td>486 ± 12</td>
</tr>
<tr>
<td>IRL-12</td>
<td>57.6 ± 4.2</td>
<td>4.884 ± 0.092</td>
<td>395 ± 16</td>
</tr>
<tr>
<td>IRL-13</td>
<td>33.5 ± 2.4</td>
<td>4.087 ± 0.078</td>
<td>226.5 ± 8.9</td>
</tr>
<tr>
<td>IRL-14</td>
<td>37.3 ± 2.5</td>
<td>4.141 ± 0.089</td>
<td>253.9 ± 9.5</td>
</tr>
<tr>
<td>IRL-15</td>
<td>36.3 ± 2.4</td>
<td>4.704 ± 0.089</td>
<td>246.0 ± 9.1</td>
</tr>
<tr>
<td>IRL-16</td>
<td>24.9 ± 2.1</td>
<td>3.099 ± 0.139</td>
<td>167.0 ± 8.0</td>
</tr>
<tr>
<td>IRL-17</td>
<td>46.9 ± 2.8</td>
<td>2.741 ± 0.070</td>
<td>322 ± 11</td>
</tr>
<tr>
<td><strong>Central Sites</strong></td>
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<td></td>
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<tr>
<td>IRL-29 0–20 cm</td>
<td>42.0 ± 1.2</td>
<td>0.92 ± 0.26</td>
<td>291.2 ± 4.6</td>
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<td>IRL-29 20–40 cm</td>
<td>85 ± 7</td>
<td>0.92 ± 0.26</td>
<td>590 ± 28</td>
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<tr>
<td>IRL-29 40–60 cm</td>
<td>36.9 ± 2.2</td>
<td>0.92 ± 0.26</td>
<td>255.5 ± 8.4</td>
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<td>IRL-29 60–73 cm</td>
<td>41.7 ± 1.1</td>
<td>0.92 ± 0.26</td>
<td>289.2 ± 4.3</td>
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<tr>
<td>IRL-31</td>
<td>22.7 ± 2.1</td>
<td>0.56 ± 0.47</td>
<td>157.3 ± 7.9</td>
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<tr>
<td>IRL-32</td>
<td>77.9 ± 2.4</td>
<td>0.79 ± 0.67</td>
<td>541.5 ± 9.1</td>
</tr>
<tr>
<td>IRL-39</td>
<td>109 ± 10</td>
<td>1.01 ± 0.47</td>
<td>756 ± 37</td>
</tr>
<tr>
<td>BRL-1</td>
<td>25.2 ± 2.2</td>
<td></td>
<td>178.3 ± 8.3</td>
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<tr>
<td>BRL-2</td>
<td>49.4 ± 5.3</td>
<td></td>
<td>346 ± 20</td>
</tr>
<tr>
<td>BRL-5</td>
<td>68.0 ± 6.5</td>
<td>0.12 ± 0.30</td>
<td>474 ± 25</td>
</tr>
<tr>
<td>BRL-6</td>
<td>34.7 ± 5.0</td>
<td></td>
<td>243 ± 19</td>
</tr>
<tr>
<td>BRL-7</td>
<td>42.4 ± 2.3</td>
<td></td>
<td>296.4 ± 8.6</td>
</tr>
</tbody>
</table>
following discussion first shows how $^{222}\text{Rn}$-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>
<thead>
<tr>
<th>Table 2</th>
<th>Mean ($\pm 1\sigma$) Advective Rate Comparisons Across the Sediment-Water Interface Between Seasons and Sites for the Indian River Lagoon/Banana River Lagoon System</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Location/Technique</strong></td>
<td><strong>May 1999</strong></td>
</tr>
<tr>
<td>Northern Study Area</td>
<td></td>
</tr>
<tr>
<td>Seepage meter (n = 28)</td>
<td>5.8 ± 3.1</td>
</tr>
<tr>
<td>Seepage meter blank (n = 2)</td>
<td>1.4 ± 1.6</td>
</tr>
<tr>
<td>Excess $^{222}$Rn Flux Model</td>
<td>8 to &gt; 20</td>
</tr>
<tr>
<td>$^{226}$Ra Benthic Flux (Martin et al. 2002)</td>
<td>2 to 17</td>
</tr>
</tbody>
</table>

(n = number of measurements)
conservative approach by maximizing these diffusion estimates. Diffusion \((I_{\text{diff}})\) was calculated using the following equation (Martens et al. 1980):

\[
I_{\text{diff}} = -\phi D_s (C_{eq} - C_o)
\]

For a measured porosity \((\phi)\) of –0.44, the effective wet sediment diffusion coefficient \((D_s)\) was estimated to be \(6.0 \times 10^{-6}\ \text{cm}^2/\text{s}\) after correcting for tortuosity \((D_s = \phi D_o; D_o\) is the molecular diffusion coefficient = \(1.14 \times 10^{-5}\ \text{cm}^2/\text{s}\) [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/m²/d.

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

\[
\frac{dC}{dt} = D_s \frac{\partial^2 C}{\partial z^2} + \omega \frac{\partial C}{\partial z} + P + \lambda C
\]

where \(C\) is the radon activity in the sediments (dpm/m³) at some depth \(z\), \(z\) is depth positive downward in the sediments (cmbsf), \(D_s\) is explained previously, \(\omega\) is the vertical advective velocity (cm/d), \(P\) and \(\lambda C\) are in situ production \((+)\) and decay \((-)\) of \(^{222}\text{Rn}\) in the pore waters, respectively, \(\lambda\) is the \(^{222}\text{Rn}\) decay constant \((1.25 \times 10^{-4}/\text{min}\)), 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 \(^{222}\text{Rn}\), the solution to Equation 2 reduces to the following (Cable et al. 1996):

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

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 \(D_s/\omega\), and \(\Lambda = [1 + 4z^* (\lambda/\omega)]0.5\), which includes radioactive decay and advection. Lower and upper limits for \(C_{eq}\) were 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 \(^{222}\text{Rn}\) \((C_o)\) 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 \((\omega)\) 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 \(^{222}\text{Rn}\) 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 \(^{222}\text{Rn}\) activity gradient (Figure 3c). The \(^{222}\text{Rn}\) pore water activity becomes deficient in the sediments only near the surface due to diffusion \((\omega = 0 \ \text{cm/d})\) into the overlying water column. When advection enhances the diffusive flux \((\omega = 3.5 \ \text{cm/d})\) 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 \(^{222}\text{Rn}\) as a tracer in this region and the reproducibility of rates among techniques. Average advection measured using seepage meters, the \(^{222}\text{Rn}\) flux model, and \(^{226}\text{Ra}\) 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 \(^{222}\text{Rn}\) gradient at the sediment-water interface relative to a diffusion-only gradient. Pore water \(^{222}\text{Rn}\) is present in excess of \(^{226}\text{Ra}\), 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 \(^{222}\text{Rn}\) 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 \(^{222}\text{Rn}\) activities are similar to observed activities in land-based wells (Martin et al. 2002). Above this depth threshold, the shape of the pore water \(^{222}\text{Rn}\) gradient indicates either consumption of \(^{222}\text{Rn}\) in the sediments or a vertical flux of \(^{222}\text{Rn}\) 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 222Rn 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 m², 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 222Rn 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 222Rn 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 (222Rn, 226Ra) 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 222Rn 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 km³) 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, 222Rn, and 226Ra.

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
artifacts (Shaw and Prepas 1989; Cable et al. 1997; Shinn et al. 2002; Corbett and Cable 2003). Our $^{222}\text{Rn}$ and $^{226}\text{Ra}$ 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 ($^{222}\text{Rn}$, $^{226}\text{Ra}$) and seepage meter flux estimates are much greater than the estimates from the geochemical tracer, $\text{Cl}^-$, 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.

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