Magnitudes of submarine groundwater discharge from marine and terrestrial sources: Indian River Lagoon, Florida

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[1] Magnitudes of terrestrial (fresh) and marine (saline) sources of submarine groundwater discharge (SGD) are estimated for a transect across Indian River Lagoon, Florida. Two independent techniques (seepage meters and pore water Cl− concentrations) show terrestrial SGD decreases linearly to around 22 m offshore, and these techniques, together with a model based on the width of the outflow face, indicate a cumulative discharge of between 0.02 and 0.9 m3/d per meter of shoreline. Seepage meters and models of the deficiencies in 222Rn activity in shallow sediments indicate marine SGD discharges of roughly 117 m3/d per meter of shoreline across the entire 1800-m-wide transect. Two surface streams nearest the transect have an average discharge of about 28 m3/d per meter of shoreline. Marine SGD is thus 4 times greater then surface water discharge and more than 2 orders of magnitude greater than terrestrial SGD. The magnitude of the terrestrial SGD is limited by the amount of regional precipitation, evaporation, recharge, and groundwater usage, while marine SGD is limited only by processes circulating marine water into and out of the sediments. The large magnitude of marine SGD means that it could be important for estuarine cycling of reactive components such as nutrients and metals with only slight modification from estuarine water compositions. The small magnitude of terrestrial SGD means that large differences from estuarine water composition would be required to affect chemical cycling.


1. Introduction

[2] Submarine groundwater discharge (SGD) was initially considered to be fresh meteoric water in coastal aquifers flowing to an outflow face on the seafloor [e.g., Herzberg, 1901; Cooper, 1959], but recently reported magnitudes of SGD were found to be larger than can be supported from meteoric recharge. For example, in the South Atlantic Bight, SGD was measured to equal 40% of total surface water runoff from the region [Moore, 1996]. Water mass balances indicate that the coastal aquifers cannot sustain this magnitude of flow, which led to the recognition that some fraction of SGD must originate from seawater [Moore and Church, 1996; Younger, 1996; Li et al., 1999]. Subsequently, freshwater and seawater fractions of SGD were defined by Taniguchi et al. [2002] as “submarine fresh groundwater discharge (SFGD)” and “recirculated saline submarine groundwater discharge (RSGD),” but we refer to them simply as “terrestrial SGD” and “marine SGD,” respectively, with the combination of the two referred to as “total SGD.”

[3] Seawater can mix with fresh water in coastal sediments at two interfaces, one at the base of the freshwater lens and the other across the sediment-water interface at the outflow face (Figure 1). The region of mixed fresh and salt water is referred to as the subterranean estuary by analogy to surface water estuaries [Moore, 1999]. Water-sediment reactions in the subterranean estuary are critical to mass fluxes associated with SGD, particularly of reactive solutes such as nutrients and metals [Cable et al., 2002; Slomp and Cappellen, 2004; Charette and Sholkovitz, 2006]. Mixing across the sediment-water interface can occur both at the outflow face as well as offshore of the outflow face to depths that depend on the mixing processes (Figure 1). These processes include density-driven convection [Bokuniewicz et al., 2004; Moore and Wilson, 2005], pumping across the sediment-water interface through tidal fluctuations [Riedl et al., 1972; Nielsen, 1990], wave set up [Shum, 1992, 1993; Li et al., 1999], flow across positive features on the seafloor [Huettel and Gust, 1992; Huettel et al., 1998], and irrigation by burrowing organisms [Dworschak, 1981; Koike and Mukai, 1983; Stamhuis and Videler, 1998; Meile et al., 2001; Cable et al., 2006].

[4] A variety of techniques are used to measure SGD. Groundwater flow models have been used to estimate the magnitude of terrestrial SGD [Pandit and El-Khazen, 1990; Robinson and Gallagher, 1999], and recent models also include marine SGD [Destouni and Prieto, 2003; Kaleris, 2006]. Direct measurements of total SGD have long been
made using seepage meters [Lee, 1977], utilizing a variety of manual and electronic techniques to detect flow [e.g., Taniguchi and Fukuo, 1993; Krupa et al., 1998]. Recently, chemical and isotopic tracers have been used to estimate magnitudes of total SGD [Bugna et al., 1996; Cable et al., 1996a, 1996b; Moore, 1996] and, depending on sampling techniques, may represent a point source or an integrated value across a wide region. Where multiple techniques were used to determine magnitudes of SGD, numerical groundwater flow estimates of terrestrial SGD are several orders of magnitude smaller than direct measurements of total SGD. The difference is assumed to be marine SGD [e.g., Cable et al., 2004].

Quantification of marine and terrestrial SGD has not been accomplished previously at a single location because of difficulties separating these components. Marine and terrestrial SGD could be separated through observations of variations in chemical compositions of pore water at the outflow face. Pore water chemistry has been used recently to estimate mixing rates across the sediment-water interface [Schluter et al., 2000; Cable et al., 2004; Martin et al., 2006], but none of these studies directly sampled the outflow face. Our objectives here are to separate marine and terrestrial SGD and to compare their magnitudes in a microtidal lagoon in Florida using pore water chemistry and seepage meters. Our results suggest that magnitudes of marine SGD are greater than terrestrial SGD, which has important implications for associated mass fluxes.

2. Hydrogeology of the Field Site

The Indian River Lagoon estuarine system extends 250 km along Florida’s central Atlantic coast and averages about 2 to 4 km (up to 10 km) wide, with an average water depth of 1.5 m and maximum depth of 5 m in a dredged channel (Figure 2). The lagoon receives fresh water via direct precipitation, urban storm water runoff, and discharge from small rivers draining a watershed of approximately 3575 km². Tidal amplitudes are less than 10 cm, but wind drives larger changes in water depth, keeping the lagoon well mixed [Smith, 1987, 1993]. Exchange with the ocean is limited to three inlets in the southern half of the lagoon, so that water residence times may be as long as a year in its northern end [Smith, 1993]. The lagoon is rimmed by Pleistocene beach ridges underlain by the Anastasia Formation, which is composed of interbedded quartz sands and coquina [Scott, 1992]. The Anastasia Formation crops out along the mainland side of the lagoon and extends inland tens of kilometers in the immediate study area. The regional climate is humid subtropical with a summer rainy season and dry winters; nearly half of the average 125 cm of annual rainfall occurs during the summer months (June to September). Regional hydrostratigraphy is divided into three principal units: the Floridan, Intermediate, and Surficial aquifers [Miller, 1986; Scott, 1988; Groszos et al., 1992; Scott, 1992]. The Intermediate Aquifer is contained within the Hawthorn Group, a Miocene aged siliciclastic unit that confines the Floridan Aquifer below [Scott, 1988; Groszos et al., 1992].

Previous work indicates both marine and terrestrial SGD are likely in Indian River Lagoon. In the southern reaches, seepage meters were used to measure an average SGD rate of 12 cm/d, ranging up to 132 cm/d [Belanger and Walker, 1990], but finite element models of flow from the Surficial Aquifer indicate an average flow rate of 0.23 cm/d, ranging from 0.14 to 0.36 cm/d [Pandit and El-Khazen, 1990]. Discharge from the Floridan Aquifer to Indian River Lagoon has not been independently documented to explain the high seepage rates found by Belanger and Walker [1990], although fresh water in continental shelf wells and springs reflects freshwater flow through the Floridan Aquifer below.
the Hawthorn Group [Rosenau et al., 1977; Hathaway et al., 1979; Swarzenski et al., 2001]. Exchange of water across the sediment-water interface, representing marine SGD, has been documented several hundred meters from shore in Indian River Lagoon [Martin et al., 2004; Martin et al., 2006]. Exchange is likely driven by bioirrigation and occurs to depths of about 50–70 cm below seafloor (bsf) at rates of tens to hundreds of centimeters per day, similar to the high rates measured by Belanger and Walker [1990] with seepage meters.

3. Methods

Sampling and field observations were made at two spatial scales within a single transect near the town of Eau Gallie, Florida: one at high resolution within 30 m of the western shore of the lagoon (Figure 2c) and the other at four sites extending across the entire 1800-m width of the lagoon (Figure 2b). The nearshore location consists of eight sites distributed 2.5–7.5 m apart along a 30-m transect perpendicular to the shoreline. These sites are designated as EGNx (Eau Gallie North) with x reflecting distance (meters) from shore. The four sites extending across the lagoon are located about 350 m apart with the site closest to the nearshore transect (IRL39, Figure 2b) approximately 250 m from the shoreline. These sites are numbered sequentially as IRLn with n the site numbers derived from a previous study [Martin et al., 2002, 2005].

Seepage meter measurements were made in May, August, and December 2000 at each of the four offshore sites, in May, June, July, September 2003 and May 2004 at IRL39, and in September 2005 at each nearshore site. Duplicate seepage meters were placed approximately 1 m apart at each offshore site in 2003 and 2004 and at EGN15 in September 2005. Seepage meters were constructed from the ends of 55-gal. (208 L) barrels with a footprint of 0.255 m$^2$ and a port to attach a plastic measurement bag. After deployment, all seepage meters were allowed to equilibrate with the environment at least 24 hours prior to sampling. Seepage measurements involved standard techniques [Shaw and Prepas, 1989; Cable et al., 1997] including precharging plastic seepage bags with 1000 mL of lagoon water, allowing 1–2 hours for each seepage measurement, and repeating each measurement in triplicate. The reported flow rates do not include the initial 1000 mL and are averages of the triplicate measurements. Tidal stage does not influence seepage rates in Indian River Lagoon [Martin et al., 2002; Cable et al., 2006] and was not considered.
during sampling. Seepage meters were also used to collect water discharging across the sediment-water interface offshore in 2000 and nearshore in 2005 by installing clean, dry and empty seepage bags to the ports following measurements of seepage rate. Water column samples were collected at the same time. Considering a mean measured seepage rate of 7.4 ± 4.0 cm/d of all seepage measurements and time since installation, at least 2.5 times the headspace volume of the seepage meters was flushed prior to sampling the seepage water.

Pore water was sampled at the nearshore sites in November 2004 and February, May, and September 2005 using multilevel piezometers (“multisamplers”) [Martin et al., 2003] extending to a maximum depth of 230 cm bsf. Multisamplers were installed in November 2004 about 10 m north of each seepage meter and remained in place throughout the project (Figure 2c). Water was pumped from eight multisampler ports into an overflow cup with a peristaltic pump while monitoring specific conductivity, salinity, dissolved oxygen, and temperature. Samples were collected once these parameters stabilized. Less than 2 L of water were pumped to minimize induced vertical flow through the sediments. In September 2005, pore waters were also collected to 30 cm bsf with “sippers” along a transect about 1 m south of the location of the multisamplers (Figure 2). Sippers consist of silicon tubing threaded through a 60-cm-long and 0.5-cm-diameter aluminum pipe with a small glass frit (aquarium bubbler) fitted to the end of the tubing and attached to the end of the aluminum pipe. The pipe, tubing, and glass frit were pushed into the sediments at 5-cm depth increments until refusal. Approximately 60 mL of water was withdrawn at each depth with a plastic syringe.

Pore waters were collected for measurement of $^{222}\text{Rn}$ activities to a depth of 230 cm bsf at IRL39 using a multisampler with procedures identical to those at the nearshore transect in May, June, July, September 2003 and May 2004. Triplicate 10-mL pore water samples were collected from the bottom of the overflow cup using a gastight glass syringe and transferred to 20-mL glass vials prefilled with a 10-mL high-efficiency mineral oil scintillation cocktail. Samples were analyzed by liquid scintillation counting on a Wallac 1400 W with alpha-beta discrimination for a background of about 0.9 cpm and efficiency correction factor of about 3.49 [Clesceri et al., 1989]. All radon samples were decay-corrected to the time of collection. One liter of water was collected and analyzed at Louisiana State University for dissolved $^{226}\text{Ra}$ via cryogenic extraction of $^{222}\text{Rn}$ in equilibrium with $^{226}\text{Ra}$, transferred to Lucas cells, and counted by alpha scintillation [e.g., Mathieu et al., 1988]. The difference between total $^{222}\text{Rn}$ activities (via liquid scintillation) and dissolved $^{226}\text{Ra}$ (via cryogenic extraction) yielded in situ excess $^{222}\text{Rn}$ ($^{222}\text{Rn}_{\text{ex}}$).

The $^{222}\text{Rn}$ production rate (i.e., mineral bound $^{226}\text{Ra}$) was determined using vibrocore samples collected from IRL39 at depths of 28, 78, 110, 158, and 190 cm bsf. Approximately 50-g sediment samples were equilibrated with 300 mL of seawater in sealed Erlemeyr flask slurry experiments for 30 days [e.g., Hammond et al., 1977; Key et al., 1979]. The $^{222}\text{Rn}$ in the slurry was then deamated using the same cryogenic extraction procedure as the dissolved phase. To compare the sediment production fraction (disintegrations per minutes (dpm) L$^{-1}$ of wet sediment) with pore water (pw) activities (dpm L$^{-1}_{pw}$), the $^{222}\text{Rn}$ sediment production activities were divided by porosity.

Water samples with salinity similar to the lagoon were measured for Cl$^-$ concentration by AgNO$_3$ titration. These samples included shallow pore waters from the nearshore transect, water collected from the offshore seepage meters, and water column samples. Precision of the titration was estimated to be about 1% of the measurement using replicate measurements of an internal seawater standard. Samples with low salinity were measured for Cl$^-$ concentrations using an automated Dionex 500 ion chromatograph at University of Florida. Precision of the ion chromatography technique was estimated to be about 2% of the measurement by replicate measurements of an internal freshwater standard.

Horizontal hydraulic conductivity was estimated at 150 and 300 cm bsf using slug tests on three sets of nested wells located 0, 15, and 30 cm from the shoreline and about 10 m south of the nearshore seepage meters. Wells were pumped at a rate of 1 L/min for 10 min, and water level response was recorded for 20–30 min after pumping stopped. The slug test recovery data were analyzed using the Hvorslev [1951], Bouwer and Rice [1976], and Hyder et al. [1994] methods. Vertical hydraulic conductivity was measured using a Mariotte style constant-head permeameter on three 10-cm whole round sections of vibracores collected about 2 m north of the multisampler transects at depths of 94–104 cm bsf (EGN0), 101–111 cm bsf (EGN20), and 110–120 cm bsf (EGN30).

4. Results

4.1. Seepage Meter Flow Rates and Chemical Compositions

Specific discharge rates from the offshore transect average 6.5 ± 3.3 (2σ) cm/d (n = 21), but range from 1.5 cm/d at IRL41 on 17 May 2000 to 14.3 cm/d measured at IRL40 on 9 December 2000 (Table 1). The 13 measurements made over 5 years at IRL39 average 7.3 ± 2.5 (2σ) cm/d also with a large range, from 4.3 to 13.6 cm/d. Duplicate measurements at IRL39 show smaller average differences between the two measurements (0.7 cm/d) than between different sites or times of measurement. Although environmental characteristics at the time and location of seepage meter measurements could be important [e.g., Shinn et al., 2002], recent work shows physical processes such as wind velocity, wave height, and current speed are unlikely to influence seepage rates in Indian River Lagoon [Cable et al., 2006].

At the nearshore transect, seepage rates decrease with distance from shore (Table 2), from 18.4 cm/d at the shoreline to 1.6 cm/d 30 m offshore (Figure 3a). Although some variability in seepage rates was measured on 16 and 17 September 2005, both days show the same offshore decrease in seepage rate. Seepage rates are within the same order of magnitude and have approximately the same range for both the nearshore and offshore transects, but the offshore transect has no systematic distribution of seepage rates with distance from shore.

Chloride is conservative in reactions between lagoonal sediments and pore water, making it a good tracer for mixing of fresh water from terrestrial aquifers and saline lagoon water [e.g., Martin et al., 2006]. In the seepage meters in the IRL transect, the average Cl$^-$ concentration is about 15 mM.
lower (about 3.6%) than the average lagoon water concentration of 420 mM during the sampling period (Table 1). Lagoon-water salinity is sensitive to precipitation and evaporation and varies greatly between dry and rainy seasons; exchange of water across the sediment-water interface causes similar salinity variations in shallow pore waters. This exchange was previously recognized to cause slight differences in salinity of seepage water and lagoon water where seepage water had both higher and lower salinity than the lagoon water, reflecting the lag in circulation of lagoon water through the sediment [Martin et al., 2004, 2006].

Table 1. Seepage Meter Results: Offshore Transect

<table>
<thead>
<tr>
<th>Location</th>
<th>Date</th>
<th>Specific Discharge</th>
<th>Cl(^{-}), mM</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>SM(^{a}) cm/d</td>
<td>SM(^{b}) cm/d</td>
</tr>
<tr>
<td>IRL39</td>
<td>17 May 2000</td>
<td>4.4</td>
<td>378</td>
</tr>
<tr>
<td></td>
<td>18 Aug 2000</td>
<td>13.6</td>
<td>423</td>
</tr>
<tr>
<td></td>
<td>9 Dec 2000</td>
<td>6.5</td>
<td>403</td>
</tr>
<tr>
<td></td>
<td>12 May 2003</td>
<td>7.1</td>
<td>8.1</td>
</tr>
<tr>
<td></td>
<td>18 Jun 2003</td>
<td>8.2</td>
<td>8.4</td>
</tr>
<tr>
<td></td>
<td>13 Jul 2003</td>
<td>7.4</td>
<td>7.8</td>
</tr>
<tr>
<td></td>
<td>26 Sep 2003</td>
<td>4.3</td>
<td>4.0</td>
</tr>
<tr>
<td></td>
<td>25 May 2004</td>
<td>7.2</td>
<td>5.8</td>
</tr>
<tr>
<td>IRL40</td>
<td>17 May 2000</td>
<td>8.3</td>
<td></td>
</tr>
<tr>
<td></td>
<td>9 Dec 2000</td>
<td>14.3</td>
<td>415</td>
</tr>
<tr>
<td>IRL41</td>
<td>17 May 2000</td>
<td>1.5</td>
<td>395</td>
</tr>
<tr>
<td></td>
<td>18 Aug 2000</td>
<td>2.4</td>
<td>437</td>
</tr>
<tr>
<td></td>
<td>9 Dec 2000</td>
<td>5.1</td>
<td>409</td>
</tr>
<tr>
<td>IRL42</td>
<td>17 May 2000</td>
<td>4.9</td>
<td>401</td>
</tr>
<tr>
<td></td>
<td>18 Aug 2000</td>
<td>4.0</td>
<td>423</td>
</tr>
<tr>
<td></td>
<td>9 Dec 2000</td>
<td>2.5</td>
<td>415</td>
</tr>
</tbody>
</table>

\(^{a}\)Seepage specific discharge measured in primary seepage meter.
\(^{b}\)Duplicate seepage rate measured in seepage meter placed ~1 m from primary seepage meter.
\(^{c}\)Water column.

[18] Large differences occur in Cl\(^{-}\) concentration between seepage and lagoon waters in the nearshore seepage meters, with the differences becoming smaller farther offshore (Figure 4). Chloride concentrations of seepage water increase from 115 mM at the shoreline (EGN0) to 269 mM 30 m from shore (EGN30). Over this same distance, the Cl\(^{-}\) concentration of the water column increased from 267 to 275 mM with a maximum value of 285 mM 20 m from shore. Assuming terrestrial SGD contains no Cl\(^{-}\), its fraction in the seepage water can be calculated as a ratio of the Cl\(^{-}\) concentration of the seepage water to the Cl\(^{-}\) concentration of the lagoon water (Figure 4). This calculation shows that the terrestrial SGD fraction ranges from 57% at EGN0 to 2% at EGN30. Multiplying this fraction by the discharge rate provides an estimate of the magnitude of terrestrial SGD from each seepage meter. A linear regression fits the data better than an exponential regression and shows a relationship of

\[ q = 0.079 - 0.0036x, \]  

\( r^2 = 0.79 \) where q is specific discharge in m/d and x is the distance from the shoreline in meters (Table 2; Figure 3b). Rearranging the equation and solving for the point of zero discharge indicates the outflow face extends 22 m offshore.

The discharge Q of terrestrial SGD for a unit length of the coastline is the area under the line times a 1-m length of the shoreline:

\[ Q = 1m \int_{0}^{22} (0.079 - 0.0036x)dx. \]  

Solving for Q indicates discharge of about 0.9 m\(^3\)/d of terrestrial SGD per meter of shoreline (Figure 1).

Figure 3. (a) Specific discharge of all water measured with Lee-type manual seepage meters versus distance from the shoreline. (b) Specific discharge of fresh water measured with Lee-type manual seepage meters versus distance from the shoreline. The line represents a linear regression fit to the data and extrapolates to zero discharge at 22 m from shore. The area under the curve yields a total discharge of 0.9 m\(^3\)/d per meter of shoreline.
boundary may vary through time (Figure 1). In modeling times below 20 cm bsf at the seaward edge of the outflow face suggests the position of the freshwater–saltwater boundary may vary through time (Figure 1). In modeling described below, we assume steady state conditions recognizing this assumption will need to be verified through high-resolution and long-period sampling of salinity variations at the distal end of outflow face.

Most sites show similar Cl⁻ concentration profiles between the sipper and the multisamplers, suggesting little induced vertical flow at the shallow multisampler ports (Figure 6). The largest differences occur above 15 cm bsf at EGN0 and EGN5 where lagoon water may have been drawn into the multisampler ports. These locations have the sharpest contrast between pore water and lagoon water and are thus likely to be affected by induced vertical flow through the sediments. Chloride concentrations of sipper samples at EGN20 are highly variable, while the multisampler shows smoothly varying concentrations.

4.3. Discharge Rates Estimated From Cl⁻ Concentration Profiles

Two processes should control mixing between the saline lagoon water and fresh water at the outflow face: upward advection of the fresh water driven by inland hydrologic head and diffusive transport of Cl⁻ downward from the lagoon water. These two processes can be modeled for one-dimensional profiles with an advection-diffusion-reaction model [Berner, 1980] of the form

\[
\frac{\partial C}{\partial t} = D_s \frac{\partial^2 C}{\partial z^2} - v \frac{\partial C}{\partial z} + \Sigma R, \tag{3}
\]

where C is the concentration of Cl⁻ in the pore water, t is time, z is the sediment depth, positive downward, D_s is the sediment diffusion coefficient for Cl⁻, v is the average linear velocity for the fresh water, and \(\Sigma R\) is the sum of all reactions that could alter Cl⁻ concentrations [e.g., Martin et al., 1996]. Chloride is conservative (i.e., \(\Sigma R = 0\)), and assuming flow is steady state and D_s is constant with depth, equation (3) simplifies to

\[
0 = D_s \frac{d^2 C}{dz^2} - v \frac{dC}{dz}. \tag{4}
\]

Constant concentration boundary conditions were chosen on the basis of the Cl⁻ concentration profiles at each site to provide an analytical solution to equation (4) (Figure 5). The lower boundary condition was chosen as depth where the Cl⁻ concentrations asymptotically approach a constant value, z = L, where L generically denotes the lower depth of the model domain. The upper boundary was chosen to be the top of the concave upward curvature in each profile and is designated z = U, where U generically

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**Table 2. Estimates of Specific Discharge Based on Various Techniques**

<table>
<thead>
<tr>
<th>Site</th>
<th>Seepage meter 16 Sep 2005</th>
<th>Seepage meter 17 Sep 2005</th>
<th>Fresh Seepage 16 Sep 2005</th>
<th>Fresh Seepage 17 Sep 2005</th>
<th>Pore Water 16 Sep 2005</th>
<th>Pore Water 17 Sep 2005</th>
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<tr>
<td>EGN 0</td>
<td>13.0</td>
<td>18.4</td>
<td>7.4</td>
<td>10.5</td>
<td>0.20</td>
<td></td>
</tr>
<tr>
<td>EGN 5</td>
<td>15.3</td>
<td>13.7</td>
<td>6.9</td>
<td>6.1</td>
<td>0.10</td>
<td></td>
</tr>
<tr>
<td>EGN 10</td>
<td>11.2</td>
<td>7.5</td>
<td>1.6</td>
<td>1.0</td>
<td>0.10</td>
<td></td>
</tr>
<tr>
<td>ENG 15A</td>
<td>7.6</td>
<td>7.3</td>
<td>2.7</td>
<td>2.6</td>
<td>0.05</td>
<td></td>
</tr>
<tr>
<td>EGN 15B</td>
<td>9.6</td>
<td>7.6</td>
<td>3.8</td>
<td>3.0</td>
<td></td>
<td></td>
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<tr>
<td>EGN 17.5</td>
<td>7.2</td>
<td>9.0</td>
<td>1.6</td>
<td>2.1</td>
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<td></td>
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<tr>
<td>EGN 20</td>
<td>5.1</td>
<td>5.2</td>
<td>0.8</td>
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<tr>
<td>EGN 22.5</td>
<td>2.9</td>
<td>2.7</td>
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<td>EGN 30</td>
<td>1.6</td>
<td>1.6</td>
<td>0.0</td>
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</tbody>
</table>

*Values are cm/d.

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Figure 4. Cl⁻ concentration in the water column (solid circles) and seepage meters (open circles) plotted versus distance from the shoreline. Samples collected 17 September 2005. The diamonds represent an estimate of the fraction of fresh water collected by the seepage meters assuming two end-member mixing with no Cl⁻ in the fresh water and the saline end member having a Cl⁻ concentration identical to the one measured in the water column.
denotes the upper depth of the model domain. For EGN0 and EGN5 this point is at the sediment-water interface \((U = 0)\); Figure 5). For EGN10, EGN15, EGN17.5, and EGN20 this point is within the sediment \((U > 0)\) as a result of exchange across the sediment-water interface (Figure 1). To account for this variability in the upper boundary condition, the model domain was shifted vertically downward by the factor \(U\). Bioirrigation has been shown to drive exchange to 50–70 cm bsf at IRL39 offshore from the outflow face \([\text{Martin et al.}, 2004, 2006]\), but the depth of bioirrigation is unknown for areas where pore water salinity changes rapidly with depth. Mixing depth should increase as the upward flow of fresh water decreases and mechanical mixing (e.g., density-driven flow and wave and tidal pumping) and bioirrigation become more dominant with distance from shore (e.g., Figure 1). The generic representation of the boundary conditions is thus

\[
C(z = U) = C_U \\
C(z = L) = C_L.
\]

The value of \(C_U\) was based on sipper data at EGN0, 5, 10, 15, and 17.5. The value of \(C_L\) was chosen to be the lowest \(\text{Cl}^-\) concentration in the profile.

With these boundary conditions, the analytical solution to equation (4) is

\[
C(z) = \frac{1}{1 - \exp \left(\frac{v}{D_s}L\right)} \left\{ C_L \left[1 - \exp \left(\frac{v}{D_s}z\right)\right] \\
+ C_U \left[\exp \left(\frac{v}{D_s}z\right) - \exp \left(\frac{v}{D_s}L\right)\right]\right\}.
\]  

Equation (5) can be used to estimate average linear velocity, \(v\), given a constant value of the diffusion coefficient, \(D_s\), and fitting the calculated \(\text{Cl}^-\) concentration to the measured profiles (Figure 5). \(Li and Gregory\) [1974] report values of the molecular diffusion coefficient, \(D_m\), of 20.3 \(\times 10^{-6}\) cm\(^2\)/s at 25°C and infinite dilution. This value was modified for sediment tortuosity using the formulation from \(Boudreau\) [1996] with a porosity of 0.45 \(\text{[Martin et al., 2005; Hartl, 2006]}\) to calculate a value of \(D_s\) of 7.8 \(\times 10^{-6}\) cm\(^2\)/s. Flow rate \(v\) was solved by matching the modeled to measured \(\text{Cl}^-\) profiles (Figure 6) with the best fit estimated by minimizing the sum of the squared residuals between these measured and modeled concentrations. The value of \(v\) was multiplied by porosity of 0.45 to convert to specific discharge for direct

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**Figure 5.** \(\text{Cl}^-\) concentrations versus depth for samples collected in November 2004 (open squares), February 2005 (solid squares), May 2005, (open circles), and September 2005 (solid circles). Except for February 2005 sampling at EGN5, and at EGN20, the \(\text{Cl}^-\) concentrations change little with time from each port reflecting steady state flow conditions over the sampling period.
comparison to seepage meter results. At EGN0 and EGN5, data from the sipper samples were used to estimate the flow rates because of potential artifacts in the multisampler data and for greater vertical resolution. Data from the multisamplers were used to estimate flow rates at the other sites because of their greater depth penetration.

Equation (5) shows specific discharge ranges from 0.20 cm/d at EGN0 to no flow at ENG22.5 and ENG30 (Table 2) or at least 10–20 times lower than estimates from seepage meters. Similar to seepage meter results, specific discharge estimated from pore water profiles also decrease with distance from shore with a better linear regression fit than from an exponential regression (Figure 7). The linear relationship in units of m/d is

$$D = 0.0016 - 0.0064x.$$  

Rearranging equation (6) indicates the width of the outflow face is 25 m, similar to the 22-m width found on the basis of the seepage meters (equation (1)). Integrating under the curve and extrapolating to a unit distance of shoreline (e.g., equation (2)) indicates a flux of 0.02 m$^3$/d per meter of shoreline, about 15 times less than the estimate from seepage meters.

### 4.4. Terrestrial SGD Based on Width of Outflow Face

The width of an outflow face, $w$, is controlled by a balance between the hydraulic head driving freshwater flow and elevated density of salt water overlying fresh water [Glover, 1964]. The width of the outflow face can thus be used to estimate the discharge, $Q$, with

$$Q = \frac{2wK'}{G},$$  

where $K'$ is the effective hydraulic conductivity for an anisotropic aquifer material [Freeze and Cherry, 1979] and $G$ is the density difference between the fresh and salt water, calculated by

$$G = \frac{\rho_{sw}}{\rho_{fw}} - \frac{\rho_{fw}}{\rho_{fw}},$$

where $\rho_{fw}$ and $\rho_{sw}$ are the density of the fresh and salt water, respectively.
Activities of $^{222}$Rn in water greatly exceed dissolved $^{226}$Ra activities (Figure 8) due to its solubility in water and ability to migrate through pore spaces conservatively [Moore, 1992]. For five separate sampling events spaced over a 13-month period at IRL39, pore water $^{222}$Rn$_{ex}$ consistently displayed inflections in its depth profile at 70–100 cm bsf with constant activities of 50–500 dpm/L$_{pw}$ below this depth at different sampling times. At depths above about 70 cm bsf, pore water $^{222}$Rn$_{ex}$ demonstrated a concave upward profile (Figure 8). This curvature is similar to pore water Cl$^-$ concentrations, where inflections found at 50–70 cm bsf were attributed to exchange of pore water with the overlying lagoon water [Martin et al., 2006]. This exchange would reduce in situ pore water $^{222}$Rn activities and could contribute to the observed inflection. Above 70 cm bsf, $^{222}$Rn activities are 5 times to several orders of magnitude less than deep pore water activities.

[27] Densities of the fresh and salt water were estimated on the measured salinity and temperature values using the seawater equation of state online calculator (http://fermi.jhuapl.edu/denscalc.html). Vertical hydraulic conductivity measurements made with the permeameter range from $4 \times 10^{-4}$ to $4 \times 10^{-5}$ cm/s, while horizontal hydraulic conductivity using slug tests range from $2 \times 10^{-2}$ to $3 \times 10^{-3}$ cm/s. Average horizontal and vertical hydraulic conductivities are $9.6 \pm 6.7 \times 10^{-3}$ and $2.4 \pm 1.9 \times 10^{-4}$ cm/s, respectively; producing a hydraulic conductivity anisotropy ($K_h/K_v$) of 41 and an effective hydraulic conductivity of about $1.5 \pm 1 \times 10^{-3}$ cm/s. This effective value is consistent with average hydraulic conductivity measurements found at five offshore locations around the lagoon, including IRL39, using slug tests of shallow (<2 m deep) wells [Martin et al., 2005], testing of core material with a falling head permeameter [Hartl, 2006], and calculations based on the Carmen-Kozensky relationship [e.g., Carmen, 1937]. With this value of effective hydraulic conductivity and a width of the outflow face of 22 m, discharge of fresh water estimated with equation (7) is about 0.45 m$^3$/d per meter of shoreline.

4.5. Radon-222 Estimates of SGD in the Offshore Transect

[28] Radon-222 activities in pore waters are controlled by decay, production from mineral-bound $^{222}$Ra, advective-diffusive transport, and mixing processes, which exchange low-activity lagoon water with higher-activity pore waters. Lagoon water activities are negligible relative to pore waters because of atmospheric evasion, thus producing a steep gradient at the sediment-water interface. Additional controls include lithology, which influence production rates and may alter flow within sediments.

Figure 7. Specific discharge calculated from the Cl$^-$ profiles measured from samples collected from multisamplers versus distance from the shoreline. The line represents a linear regression fit to the data and extrapolates to zero discharge at 25 m from shore. The area under the curve yields a discharge of 0.02 m$^3$/d per meter of shoreline.

[29] Radon-222 activities in pore waters are controlled by decay, production from mineral-bound $^{222}$Ra, advective-diffusive transport, and mixing processes, which exchange low-activity lagoon water with higher-activity pore waters. Lagoon water activities are negligible relative to pore waters because of atmospheric evasion, thus producing a steep gradient at the sediment-water interface. Additional controls include lithology, which influence production rates and may alter flow within sediments.

\[
y = 0.16 - 0.0064x \\
\frac{\Delta v}{\Delta z} = \frac{y}{x} \\
\]

[30] An additional factor controlling the pore water profiles is in situ production, which is greatest in the deep sediments. Production rates ranged from $48.0 \pm 5.8$ dpm/L at 28 cm bsf to 4232 $\pm 26$ dpm/L at 191 cm bsf (Figure 8). The base of the shallow mixing zone at 78 cm bsf had production rates of $309 \pm 13$ dpm/L, while intermediate deep zone depths at 111 and 159 cm bsf showed lower production rates of $151 \pm 9$ dpm/L and $74 \pm 6$ dpm/L, respectively (Figure 8f). The shallow production rates are close to results from a previous study of Florida lagoon sediments where production rates were estimated from numerous samples from surface and near-surface sediments to be about $52$ dpm/L [Cable et al., 2004]. Sediments in the upper 50 cm were 98–100% sand, and sediments below this depth have a 7% increase in mud content, 0.1 increase in porosity, and order of magnitude drop in vertical hydraulic conductivity across a gradational lithologic contact at 50–60 cm bsf in IRL39 sediments [Hartl, 2006]. This lithologic boundary corresponds to an observed increase in sediment-bound $^{226}$Ra and indicates $^{222}$Rn$_{ex}$ profiles may also in part be controlled by in situ production.

[31] Rn-222 profiles have previously been modeled based on the deficit of in situ pore water $^{222}$Rn$_{ex}$ activities relative to sediment production rates to estimate rates of exchange across the sediment water interface [e.g., Hammond and Fuller, 1979; Smethe et al., 1981]. We apply a similar approach here. To estimate the deficit in pore water $^{222}$Rn$_{ex}$ activities relative to the mineral $^{222}$Ra source, pore water $^{222}$Rn$_{ex}$ was subtracted from the $^{222}$Rn production rate, $P$. At depths of 0 to 50 cm bsf, all pore water $^{222}$Rn$_{ex}$ activities were subtracted from the production rate measured in sediment from 28 cm bsf (48.0 $\pm 5.8$ dpm/L), while the 60 cm bsf $^{222}$Rn$_{ex}$ activity was subtracted from the 78 cm bsf production rate sample (309 $\pm 13$ dpm/L). At 60 cm bsf, $^{222}$Rn$_{ex}$ pore water activities reflect the production rate measured in the sample from 78 cm bsf, which is representative of the base of the shallow mixing zone prior to mixing pore waters with overlying lagoon water. The integrated zone of deficiency, $\Sigma D$ (dpm/m$^2$), associated with the differences in $^{222}$Rn$_{ex}$ and $P$ represents $^{222}$Rn lost from the sediments due to transport and can be estimated with

\[
\Sigma D = \lambda \int_{z=0}^{78} (P - \lambda C(z)) dz \approx \lambda \sum_{z=0}^{78} (P - \lambda C(z)) \Delta z, \quad (9)
\]
where $C(z)$ is the pore water $^{222}\text{Rn}_{\text{ex}}$ activity at depth $z$, $C(z) = 0$ at $z = 0$, and $C(z) \to P$ as $z \to 78$ cm bsf.

$^{[12]}$ This integrated deficiency, expressed as a flux, represents the total loss of radon without accounting for diffusive transport in pore spaces. Diffusion of $^{222}\text{Rn}_{\text{ex}}$ across the sediment-water interface was estimated at IRL39 to be $756 \pm 37$ dpm/m$^2$/day $^{[26]}$ [Cable et al., 2004].

The net advective flux from the sediments was calculated as the difference between $\Sigma D$ and diffusion and is assumed to be controlled by exchange of lagoon water with pore water in a piston-like flow, which drives $^{222}\text{Rn}$ from the sediment to the water column. This mass flux was divided by the near-surface (~10 cm bsf) pore water activity for each sample time and multiplied by porosity to yield specific

Figure 8. $^{226}\text{Ra}$ and $^{222}\text{Rn}_{\text{ex}}$ pore water activities versus depth at IRL39 for times corresponding to seepage meter measurements: (a) 12 May 2003, (b) 18 June 2003, (c) 13 July 2003, (d) 26 September 2003, and (e) 25 May 2004. Figure 8f represents the production rate of $^{222}\text{Rn}$ via mineral-bound $^{226}\text{Ra}$ (note scale change). The top 60 cm bsf show deficits in $^{222}\text{Rn}_{\text{ex}}$ relative to the production term, suggesting depletion by exchange of water across the sediment-water interface. The deficits are used to estimate vertical flow rates.
discharges of 13–116 cm/d, with an average flow of 61 ± 43 cm/d (Table 1). These specific discharge estimates based on \(^{222}\)Rn\(_{ex}\) are much higher than seepage meters, but are of the same order of magnitude as other irrigation rates measured at this location. Martin et al. [2006] found irrigation rates could be as high as 150 cm/d using the diurnal signal of pore water and surface water temperature propagating through the sediments. Although the net water flow across the sediment-water interface is zero, the exchange is important for the \(^{222}\)Rn flux from the sediment and, by analogy, should be important for other reactive solutes produced during sediment-water reactions.

5. Discussion

5.1. Flow Estimates for Terrestrial SGD

[33] Assuming all terrestrial SGD is confined to the observed freshwater plume (Figure 1), we estimate terrestrial SGD ranges from 0.02 to 0.9 m\(^3\)/d per meter length of shoreline. The highest estimate is from the seepage meter measurements. Although many studies indicate seepage meters accurately measure flow [Lee, 1977; Shaw and Prepas, 1989, 1990; Belanger and Montgomery, 1992; Cable et al., 1997], recent work indicates they may enhance flow [Shinn et al., 2002; Cable et al., 2006]. For our work in Indian River Lagoon, seepage meters always penetrated 10 to 12 cm into sediments, which at EGN0 and EGN5 extend the sides of the seepage meter into the fresh pore water lens, completely sealing fresh pore water from the overlying seawater (Figure 9). Nonetheless, Cl\(^-\) concentrations in seepage meters were 43% of the lagoon water at EGN0 and 55% of the lagoon water concentration at EGN5. Although not embedded in the freshwater lens, the seepage meter at EGN10 also discharged water with Cl\(^-\) concentrations elevated above the pore water concentrations at the base of the meter (e.g., compare Figures 4 and 9). These increases in Cl\(^-\) concentrations in the discharged water relative to water at the base of the seepage meters indicate the devices may pull lagoon water through bottom sediments into the seepage meters. Several researchers have suggested pressure gradients may exist around the seepage meters and drive flow into the devices [Shaw and Prepas, 1989; Cable et al., 1997; Shinn et al., 2002; Cable et al., 2006]. Although excess flow is only recognized by the increase in Cl\(^-\) concentrations in the seepage meters over the Cl\(^-\) concentration at the base of the meter, we speculate that pressure gradients could enhance flow of fresh water as well and cause erroneously high estimates of terrestrial SGD.

[34] The lowest estimated discharge rate is based on steady state models of the Cl\(^-\) concentration profiles (Figures 6 and 7). Steady state conditions appear valid for profiles nearest to shore, but Cl\(^-\) concentrations vary somewhat at the seaward end of the outflow face (Figure 5). These variations suggest that flow at the seawater end of the outflow face may be transient. This region has the slowest flow and thus contributes little to the total flow of terrestrial SGD. Altering the models to include transient flow is unlikely to greatly alter the estimated magnitude of terrestrial SGD based on Cl\(^-\) concentration profiles.

[35] The pore water Cl\(^-\) concentration models also assume diffusive transport of Cl\(^-\) from the overlying water column. If dispersion were also important, the value used for D\(_s\) in equation (5) would have to be increased. Dispersion coefficients as high as 1.8 to 3.9 \(\times\) 10\(^{-6}\) m\(^2\)/s would have to be used in the model to increase those results to values similar to estimates based on the width of the outflow face (0.45 m\(^3\)/d) or the integrated point measurements with seepage meters (0.9 m\(^3\)/d). This comparison points out that good estimates of diffusion or dispersion coefficients are going to be required to model fluxes of reactive solutes, such as organic matter regeneration, nutrient diagenesis, metals, or radioisotope tracers [Smith et al., 2006].

5.2. Flow Estimates for Marine SGD

[36] Although only four stations were used to estimate the magnitude of marine SGD from the offshore transect, all seepage meter measurements fall within an order of magnitude of each other and are similar to the range of values found by Belanger and Walker [1990]. No systematic variations with distance from shore were found in this study or by Belanger and Walker [1990], which suggests increased sampling density is unlikely to change the average seepage rate. Pore water \(^{222}\)Rn profiles provide a range of exchange rates from 13 to 116 cm/d and are generally greater than discharge measured by the seepage meters at these same locations, but of the same magnitude as irrigation rates calculated from heat flux estimates [Martin et al., 2006]. This difference may result from each technique responding differently to processes driving exchange. Pore water \(^{222}\)Rn activities are modeled as two directional exchange across the sediment-water interface, while seepage meters only measure outflow. Downward flow could reduce the discharge from the seepage meter measurements, and seepage meters have been found to measure flow into sediments [e.g., Taniguchi et al., 2002]. Downward flow is an important factor in exchange models using \(^{222}\)Rn pore water activities [e.g., Shinn et al., 2002; Cable et al., 2006; Martin et al., 2006].

[37] Recognizing the difficulties of using these various techniques, estimated flow rates can be converted to a volume of total SGD discharging from the offshore transect by extrapolating the average seepage rates across the 1800-m width of the lagoon along a 1-m unit width of the shoreline. With these dimensions, the total SGD from the offshore transect would range from 27 to 257 m\(^3\)/d, averaging about 117 m\(^3\)/d, or more than 2 orders of magnitude greater than the estimate for terrestrial SGD only.

5.3. Flow Estimates for Surface Water

[38] Surface water drainage basins do not correspond exactly to the locations of estimates for marine and terrestrial SGD, but two streams drain to Indian River Lagoon near the study area (Figure 2). Eau Gallie River, with a 10-km\(^2\) drainage basin, discharges to Indian River Lagoon 1 km north of the transect, while Crane Creek, with a 47-km\(^2\) drainage basin, discharges to the lagoon 4 km south of the transect. Daily discharge measurements were obtained from gauging stations located less than 1 km from the river mouths (http://nwis.waterdata.usgs.gov/). Eau Gallie River (USGS 02249518) had an average discharge of 34,560 m\(^3\)/d between January 1991 and September 2004 (n = 4555). Crane Creek (USGS 02249007) had an average discharge of 103,680 m\(^3\)/d between February 1987 and September 2004 (n = 6377). The average combined discharge of 138,240 m\(^3\)/d reflects an average discharge of about 28 m\(^3\)/d per meter.
length of shoreline if distributed across the 5-km distance separating the streams. Surface discharge is probably even smaller than 28 m$^{3}$/d, considering the rivers also drain portions of the areas north and south of their mouths. Additional surface water could discharge to the lagoon from the barrier islands on the eastern side of the lagoon, but the volume would be small because of the small surface area of the island and high rate of recharge to the unconsolidated and highly permeable sands making up the islands.

5.4. Comparison of Discharge Estimates and Implications for Mass Fluxes

Terrestrial SGD is a significantly smaller source of water to Indian River Lagoon than either surface water or marine SGD, which appears to be the largest subterranean source of water to the lagoon. Terrestrial SGD (approximately 0.02 to 0.9 m$^{3}$/d per meter of shoreline) represents between 0.07 and 3% of the surface water discharge to the region from Eau Gallie River and Crane Creek (approximately 28 m$^{3}$/d per meter of shoreline) and only 0.02 to 0.7% of the marine SGD (approximately 117 m$^{3}$/d per meter of shoreline). In Indian River Lagoon, marine SGD appears to be lagoon water cycled through bottom sediments [Cable et al., 2004; Martin et al., 2004; Martin et al., 2006], for which an unlimited source of water is available. Magnitudes of both surface runoff and terrestrial SGD are restricted by the amount of precipitation and evapotranspiration in the region. Terrestrial SGD is further limited by the magnitude of inland aquifer recharge and groundwater withdrawal. Regardless of the relative magnitudes of terrestrial SGD, marine SGD, or surface water discharge, the flow path of each water source has important implications for the flux of dissolved mass.

The magnitudes of terrestrial and marine SGD are critical for potential fluxes to coastal zones of terrestrial pollutants and sediment redox biogeochemistry, respectively [Rutkowski et al., 1999; Charette and Sholkovitz, 2002; Bratton et al., 2004; Reay, 2004; Slomp and Cappellen, 2004; Martin et al., 2006]. The small quantity of terrestrial SGD at our study site indicates that only components highly enriched relative to lagoon water will provide significant fluxes of new material to the lagoon. Terrestrial pollutant concentrations may also be modified as they pass through the subterranean estuary depending on the effects of changing ionic strength of pore waters, redox composition of the mixed water, and reactivity of the components, thereby influencing their contributions to lagoon mass fluxes. Terrestrial SGD should be most important for anthropogenic components not found naturally in coastal waters, such as pesticides, hydrocarbon compounds, and pharmaceuticals.

In contrast, small changes in composition of marine SGD could be important for mass fluxes because of its large flux compared with terrestrial SGD or surface runoff. Even though the marine SGD starting composition is identical to that of the lagoon water, changes in its composition could
occur as water circulates through the bottom sediments. Lagoon water is well oxygenated, making this circulation important to redox conditions in the shallow sediments to cycling of redox sensitive elements such as metals [Charette and Sholkovitz, 2002; Charette et al., 2005; Charette and Sholkovitz, 2006] and organic matter and nutrients [e.g., Hopkinson, 1987; Aller and Aller, 1998; Cable et al., 2002; Martin et al., 2006]. In addition, the large volumes of marine SGD may also alter sediment compositions. For example, marine SGD could decrease the amount of organic matter buried in coastal sediments by enhancing its remineralization or alter adsorption of metals through oxidation and reduction of Fe-oxide phases [Charette et al., 2005].

An additional point to consider in the role of SGD to coastal water elemental budgets is the rate of removal of these input fluxes, specifically the residence time of water in estuaries. Both the input fluxes from SGD and output fluxes from estuaries will control how important SGD is to the water composition. Estuaries with short residence times will require large increases in elemental fluxes from terrestrial SGD to change water chemistry. For any system where terrestrial or total SGD are included in an examination of benthic biogeochemical loading, the surface water residence time should be considered to understand the impact on the chemistry and ecology.

6. Conclusions

Measurements of pore water Cl− concentrations allow separation of marine and terrestrial SGD and provide the first direct estimates of the relative magnitudes of terrestrial and marine SGD in an example from Indian River Lagoon Florida. Observations of pore water chemistry were necessary to separate marine and terrestrial SGD by clearly defining the zone of terrestrial aquifer discharge (Figure 1). These estimates show terrestrial SGD is about 30–5000 times smaller than surface water discharge and marine SGD to Indian River Lagoon Florida, and demonstrate the importance of separating the two sources of water as potential sources for mass fluxes to coastal zones. The large difference in terrestrial and marine SGD magnitudes occurs because of limitations on the amount of terrestrial water available for discharge as terrestrial SGD and from extensive and rapid exchange of lagoon water across the sediment-water interface providing an essentially unlimited source for marine SGD. Other geological settings are also likely to have larger magnitudes of marine than terrestrial SGD, but processes controlling sources of SGD will undoubtedly vary from region to region.

Differences in the relative magnitudes of marine and terrestrial SGD have important implications for mass fluxes associated with SGD. In Indian River Lagoon, marine SGD circulates through shallow sediments in hours to days [Martin et al., 2006] and thus marine SGD would be important only for mass fluxes of components with fast reaction kinetics, such as organic matter oxidation and dissolution of redox-sensitive metals. On the other hand, dissolved components in terrestrial SGD would need to be highly enriched relative to lagoon water to provide a significant source of mass to coastal waters. Terrestrial SGD could be a source of anthropogenic pollution to coastal zones if it originates from or flows through contaminated sites regardless of its small magnitude. The magnitude of these pollutants could be greatly modified, however, by salinity changes and variation of sediment types at the outflow face.

Differences in measured SGD observed using multiple techniques at the same location highlight how the method chosen will impact estimates of the magnitude of SGD. Seepage meters, pore water modeling of Cl− and 222Rn, and estimates based on the width of the outflow face were all used here to distinguish the terrestrial and marine components of SGD. Chloride concentrations and the width of the outflow face provide similar estimates for the magnitude of terrestrial SGD. Estimates of marine SGD are more complicated, especially at seafloor locations beyond the freshwater seepage face, and in this example have been obtained with seepage meters and models of 222Rn profiles. These estimates show a wide range in values for marine SGD, which reflects the impact of water exchange across the sediment-water interface. Refinement of the estimates of total SGD will require careful use of multiple techniques, but are critical to determine mass fluxes to coastal zones.

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