Evaluating groundwater discharge to tidal rivers based on a Rn-222 time-series approach

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ABSTRACT

The natural flux of groundwater into coastal water bodies has recently been shown to contribute significant quantities of nutrients and trace metals to the coastal ocean. Groundwater discharge and hyporheic exchange to estuaries and rivers, however, is frequently overlooked though it often carries a distinctly different chemical signature than surface waters. Most studies that attempt to quantify this input to rivers use multiple geochemical tracers. However, these studies are often limited in their spatial and temporal extents because of the labor-intensive nature of integrating multiple measurement techniques. We describe here a method of using a single tracer, 222Rn, to rapidly characterize groundwater discharge into tidally-influenced rivers and streams. In less than one week of fieldwork, we determined that of six streams that empty into the Indian River Lagoon (IRL), Florida, three (Eau Gallie River, Turkey Creek, and Main Canal) did not receive substantial groundwater inputs, one canal (C-25 Canal) was dominated by groundwater exchange, and the remaining two (Sebastian River system and Crane Creek) fell somewhere in between. For more detailed discharge assessments, we focused on the Sebastian River system, a stratified tidal river estuary, during a relatively dry period (June) and a wet period (July) in 2008. Using time-series 222Rn and current velocity measurements we found that groundwater discharge into all three branches of the Sebastian River increased by 1–2 orders of magnitude during the wetter period. The estimated groundwater flow rates were higher than those reported into the adjacent IRL, suggesting that discharge into these rivers can be more important than direct discharge into the IRL. The techniques employed here should work equally well in other river/stream systems that experience significant groundwater discharge. Such assessments would allow area managers to quickly assess the distribution and magnitude of groundwater discharge nature into rivers over large spatial ranges.

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1. Introduction

Submarine groundwater discharge (SGD) is defined as any fluid flow (including both terrestrial- and marine-derived pore water) from bottom sediments into the overlying seawater (Burnett et al., 2003a). In coastal settings, this process can be a significant pathway for dissolved nutrients (Slomp and Van Cappellen, 2004; Paytan et al., 2006; Kroeger et al., 2007; Swarzenski et al., 2007; Santos et al., 2008a) and trace metals (Windom and Niencheski, 2003; Charette and Sholkovitz, 2006; Windom et al., 2006), and can thus have important implications for coastal biogeochemical cycles. Groundwater discharge into a river environment can either be composed of terrestrial groundwater or river water circulating through the sediments. The latter process is termed ‘hyporheic exchange’ (see reviews in Findlay, 1995; Sophocleous, 2002). The effect of groundwater discharge directly into rivers is often overlooked in part because of different perspectives among scientific disciplines. Marine scientists tend to only consider river discharge to the coastal zone as runoff, regardless of whether it was originally derived from groundwater inflows or surface runoff. Terrestrial hydrologists, on the other hand, view groundwater discharge into a gaining river channel (one where the water table is at a higher elevation than the river channel) as an endpoint boundary condition. As a result, this process is somewhat understudied despite the fact that subterranean hydraulic gradients often direct groundwater flows toward inland river channels (Buddeemeier, 1996).

Naturally-occurring geochemical tracers have become widely used in tracing groundwater discharge to receiving water bodies, especially in coastal environments (see reviews in Burnett et al., 2006; Swarzenski, 2007; Charette et al., 2008). In particular, gaseous 222Rn...
has proven to be an effective tracer because it is greatly enriched in groundwater relative to surface water, relatively easy to measure, and chemically conservative (Cable et al., 1996; Corbett et al., 1998; Burnett et al., 2003b; Peterson et al., 2009a; Santos et al., 2009). Several researchers have applied \(^{222}\)Rn to assess groundwater discharge and hyporheic exchange in rivers (Ellins et al., 1990; Mullinger et al., 2007) and estuaries (Schwartz, 2003). Many studies also incorporate a suite of other tracers to better constrain various assumptions. For example, Genereux and Hemon (1990) combined \(^{222}\)Rn with NaCl and \(^{222}\)Rn and propane to correct for mixing and evasion losses, whereas Genereux et al. (1993) incorporated calcium into their study of riverine groundwater discharge. Cook et al. (2003, 2006) combined \(^{222}\)Rn with CFCs, ionic tracers, and SF\(_6\) to examine groundwater discharge into Australian rivers. Swarzenski et al. (2006) incorporated radium isotopes and other geophysical measurements (seepage meters, subsurface electrical resistivity profiling) with \(^{222}\)Rn to examine discharge into a river in South Florida.

Multi-tracer studies offer an elegant approach toward quantifying groundwater discharge but are also limited in their spatial and temporal coverage due to the high demands of such an approach. In addition, most previous studies relied on traditional \(^{222}\)Rn measurement techniques involving the collection of grab samples and subsequent laboratory analysis – a time-consuming process that further limits the sampling resolution. Taking advantage of novel technology that allows continuous, precise, and automatic radon measurements, Burnett et al. (in press) proposed a more rapid approach using \(^{222}\)Rn alone with current meter measurements to estimate a range of possible groundwater discharges into a South Florida canal. This method lends itself to management applications where one can quickly and easily estimate groundwater discharge and associated mass loadings to inland water bodies.

The U.S. Environmental Protection Agency’s Clean Water Act requires all states (through Section 303(d)) to establish Total Maximum Daily Loads (TMDLs) for surface waters that do not meet pre-defined water quality standards (classified as ‘impaired waters’). These TMDLs are intended to set the maximum amount of a certain pollutant that can be delivered to a water body without exceeding these standards, and do not differentiate between groundwater and surface water runoff sources for these pollutants. Literally thousands of ‘impaired’ water bodies have been identified just in the state of Florida alone and quantifying the groundwater inflow to each of these via multi-tracer approaches or elaborate numerical models (e.g., Li et al., 2009) is not practical. Alternatively, neglecting the groundwater contribution to such impaired waters may underestimate the contamination potential via this pathway. Therefore, environmental managers need an approach with which they can more easily assess the likelihood of groundwater impact on a water body and determine the general magnitude of this discharge.

We build here upon the technique proposed by Burnett et al. (in press) which was limited to a non-tidal, non-stratified freshwater canal and illustrate the applicability of the method over much larger and complex systems that drain into the Indian River Lagoon (IRL), Florida. We first surveyed six streams for \(^{222}\)Rn to determine their relative likelihood of groundwater influence. These rivers are all considered ‘impaired’ by the Florida Department of Environmental Protection (FDEP) as they have been previously found depleted in dissolved oxygen (Gao, 2009). We then focused on the lower reaches of the Sebastian River to quantify groundwater and hyporheic inflows to each upstream branch of this estuarine system. We present a simple model capable of defining a reasonable range of upstream groundwater discharges capable of producing the measured \(^{222}\)Rn signals. Results produced by these techniques only require a limited amount of field time and thus offer the opportunity to provide more spatial coverage at a reasonable cost.

2. Geographic setting

The Indian River Lagoon extends 250 km along Florida’s central Atlantic coastline from Daytona Beach to Stuart (Fig. 1). The IRL is mostly 2–4 km wide with an average depth of 1.5 m and is separated from the Atlantic Ocean by a chain of barrier islands. Three inlets in the southern half of the IRL allow exchange with the Atlantic Ocean and are located in Sebastian, Fort Pierce, and Stuart at the southern extent at the St. Lucie River estuary. Smith (1987, 1993) described mixed, semi-diurnal tides in this lagoon and showed that while amplitudes are small (<10 cm), tidal flushing is sufficiently active to dominate over non-tidal exchanges in the central and southern sections of the IRL where the inlets are located. Conversely, in the northern basin, tidal exchange is limited by the absence of inlets so non-tidal flushing becomes much more dominant where a distinct seasonality exists in the flushing rate of these waters – faster during the wet season and slower in the dry season.

River runoff and groundwater discharge directly to the IRL comprise two of the more significant sources of this non-tidal flushing. A substantial number of studies have been performed on the nature of groundwater discharge to the IRL, most of which indicate a range in groundwater advection rates between 3 and 25 cm d\(^{-1}\) in the upper 70 cm of sediments. These studies employed seepage meters (Zimmermann et al., 1985; Cable et al., 2004, 2006; Martin et al., 2004), geochemical tracers (Cable et al., 2004; Martin et al., 2004), heat flux (Martin et al., 2006), and modeling (Smith et al., 2008a) to estimate fluxes. Terrestrial, meteoric discharge is isolated to within about 25 m of the western shoreline of the IRL (Martin et al., 2007; Smith et al., 2008a), whereas recirculated seawater dominates the fluxes elsewhere, often driven by bioirrigation (Martin et al., 2006) and tropical storm events (Smith et al., 2008b).

The surficial aquifer in this area is about 30 m thick and consists of undifferentiated Pleistocene and Holocene coquina, sand, silt, and clay with hydraulic conductivities of around 8.3 m d\(^{-1}\) (Martin et al., 2007; Smith et al., 2008a). While these previous groundwater discharge studies have all focused solely on the IRL itself, they suggest that the relative contribution of terrestrial (fresh) groundwater discharge decreases farther offshore. Interpolating this trend inland, it is reasonable to assume that groundwater discharge will continue to increase in magnitude where river channels incise the surficial aquifer.

3. Methods

3.1. Field measurements

We completed three sampling trips to the IRL field sites in the spring and summer of 2008. During the first trip (April 23–29), we performed radon surveying in six different rivers and canals that discharge into the IRL in order to evaluate where discharge may be more important. We conducted several time-series analyses to quantify groundwater discharge in parts of the Sebastian River system during our second trip (June 9–13). These first two trips occurred during a dry period (low discharge with little preceding rainfall; North Prong average discharge \(=0.23\) m\(^3\)/s), whereas we captured a wet period (high discharge with abundant preceding rainfall; North Prong average discharge \(=1.45\) m\(^3\)/s) during our third trip (July 13–19) when we revisited the time series sites in the Sebastian River during and just after several large storms.

During our first field trip, we surveyed for \(^{222}\)Rn using an automated radon system as described by Dulaiova et al. (2005).
Fig. 1. Map showing Florida’s Indian River Lagoon and surrounding rivers and canals that were surveyed. Radon-222 activities are shown at the locations corresponding to the midpoint of each survey measurement integration time. The highest value encountered in each water body is also given. Note the different scales for $^{222}\text{Rn}$ in each water body. Within the Sebastian River box, arrows point to time-series locations at each site and stars (with corresponding eight digit numbers) display the USGS gauging station location and identification number.
Briefly, surface water (~20 cm depth) was pumped to an air-water mixing chamber that degassed the radon until achieving air-water equilibrium. The air space from this chamber was circulated through desiccant to a series of three radon-in-air monitors (RAD7; Durridge Co.) arranged in parallel. Radon-222 activities were integrated over 10 minute counting intervals while water temperature and conductivity (Van Essen Data Divers) and GPS coordinates were continuously logged. Spatial resolution for each 222Rn value was controlled by the speed of the boat while driving upstream. At a typical velocity of 4 km hr⁻¹, each radon point would represent integration along about 400 m of river length.

In order to quantify groundwater discharges during our second and third field trips, we fixed this system as a stationary time-series mooring over ~24 hours (Burnett and Dulaiova, 2003). For these moorings, we deployed one RAD7 along with a 2-D acoustic current meter (Falmouth Scientific, Inc.) and a recording water level logger (Onset Corp., HOBO water level logger). The current meter was fixed to the river bed (acoustic sensors were located approximately 70 cm above the bottom) whereas the radon system was fixed to a floating platform. We aimed to deploy the current meter at water depths where its sensors would measure at roughly the same level as the radon pump. In order to correct for supported 222Rn (from dissolved 226Ra decay), we collected large volume (~20 L) water samples and concentrated dissolved radium onto MnO2-impregnated acrylic fibers (Moore and Reid, 1973). Ra-226 was measured according to procedures outlined by Peterson et al. (2009b). We downloaded weather parameters (wind speed, direction, and air temperature) from local meteorological stations (www.weatherunderground.com) to correct for 222Rn evasion losses to the atmosphere based on calculations presented in MacIntyre et al. (1995). This estimate depends on the 222Rn concentration gradient across the air-water interface, temperature, and wind velocity ultimately yielding a 222Rn flux (Burnett and Dulaiova, 2003).

In section 4.2, we show that the Sebastian River exhibits stratification throughout, with a freshwater lens of upstream water overlying estuarine water driven by tidal exchange. We maintained our time-series measurements (radon and current velocity) in the surface layer at all times to monitor upstream waters that may be influenced by groundwater discharge. However, it is possible that this layer may occasionally thin significantly and we thus measured some influence of the bottom layer as well.

While the automated time-series monitoring was deployed, individual grab samples were collected to quantify the groundwater end-member radon activity and salinity using a push-piston piezometer system (Charlette and Allen, 2006). Water samples were collected into either 250 mL glass bottles designed for radon analysis (WAT-250 system; Durridge Co.) or 7 L Nalgene bottles (Stringer and Burnett, 2004) to be analyzed according to the method described in Lee and Kim (2006). We also performed sediment equilibration experiments with surface sediments by sealing them for three weeks with overlying water to allow 222Rn to grow into equilibrium with particle-bound 226Ra. The resulting radon activity in the water phase should represent the end-member value if the pore water residence time in these sediments is sufficiently long (~3 weeks) to allow equilibrium (Corbett et al., 1998). Other pore water and surface water parameters (temperature, pH, and conductivity) were measured with a YSI Model-85 handheld unit. We also used this instrument to measure cross-section salinity profiles at each time-series site.

### 3.2. Upstream groundwater discharge model

In order to estimate a range in possible groundwater discharge fluxes to each river branch, we calculated upper and lower estimates based on two sets of extreme conditions (Fig. 2). The minimum range estimate assumes all groundwater (and thus 222Rn) was input to the system directly at the point of measurement (downstream-most extent). This provides a minimum estimate as the radon is not subject to any atmospheric evasion or decay losses through transit downstream (correcting for such losses would require higher groundwater inputs). We simply correct the measured radon activity (Rn Conc.) for supported 222Rn (from dissolved 226Ra; Bkgd.) and divide this excess radon activity by the radon concentration in the discharging fluids (End-member) to derive the fraction of groundwater in the water column passing through a vertical plane at the point of measurement (where we have measured the cross-sectional area). This fraction is then multiplied by the total volume flux through this plane (via the measured current velocity; QTOTAL) to estimate the volume of groundwater fluxing out of the system. This flux must be supported by groundwater discharge (QGW). Mathematically, this may be expressed as:

\[
Q_{GW} \left( \frac{m^3}{d} \right) = \left[ \frac{Rn \text{ Conc.} \left( \frac{dpm}{m^3} \right) - Bkgd \left( \frac{dpm}{m^3} \right)}{End - member \left( \frac{dpm}{m^3} \right)} \right] \cdot QTOTAL \left( \frac{m^3}{d} \right)
\]

(1)

and is derived from Burnett et al. (in press).

The maximum range estimate of groundwater discharge (Eq. (2)) assumes all groundwater was input at the most upstream

\[
Q_{GW} \left( \frac{m^3}{d} \right) = \left[ \frac{Rn \text{ Conc.} \left( \frac{dpm}{m^3} \right) - Bkgd \left( \frac{dpm}{m^3} \right)}{End - member \left( \frac{dpm}{m^3} \right)} \right] \cdot QTOTAL \left( \frac{m^3}{d} \right)
\]

(2)
extent of the considered branch (often at the point of a USGS gauging station). Dividing an estimate of the upstream water volume (surface area multiplied by average depth) by measured discharge yields the residence time $R$ of the water within the domain. Using this residence time, radon concentrations are corrected for total atmospheric evasion (Atm. Evas.) and decay losses ($e^{-\lambda t}$) during transit. Diffusive inputs of $^{222}$Rn from sediments could also be considered, but have been neglected here. We describe the rationale for assuming diffusion is unimportant in section 5.2. The corrected radon inventory is again converted to a fraction of groundwater passing through the vertical plane at the measurement site by dividing by the groundwater end-member value.

In Eq. (2), $\lambda$ is the decay constant of $^{222}$Rn (0.18 day$^{-1}$) and Depth is the average depth of the river cross-section.

During the course of our field campaigns, we lost some current meter data so we also derived the current velocity according to a tidal prism approach. We define the tidal prism as change in water depth over time multiplied by the inundated area of our domain upstream of the observation site. Surface areas were estimated by examination of satellite photos from online sources such as Google Earth.$^2$. To this value, we add the freshwater flux measured at upstream USGS gauging stations. To convert these values (m$^3$ d$^{-1}$) into current velocities, we simply divide by the estimated river cross-sectional area measured at each site. Positive changes in water depth (flood tide) yield negative (upstream) tidal prism current velocities, whereas negative changes in water depth (ebb tide) yield positive (downstream) current velocities.

The generally diffuse nature of groundwater discharge implies that neither the minimum nor the maximum estimates are correct, since they both consider the discharges as point-source. Instead, groundwater is likely input throughout the river length so we cannot quantitatively correct for the exact amount of evaporation and decay losses using this approach. While the minimum and maximum estimates constrain boundary conditions for the groundwater discharge nature into a particular river channel, the real flux is almost certainly somewhere between these estimates.

We performed a sensitivity analysis of the model response to the most likely sources of uncertainty of field measurements: the current velocity ($Q_{TOTAL}$) which may be variable across the channel, and the groundwater end-member (see discussion of the end-member uncertainty in section 5.2). As $Q_{TOTAL}$ is a multiplier in Equations (1) and (2), an overall 25% change in measured current velocity results in a direct linear change of 25% in $Q_{SW}$. Alternatively, the radon end-member is a divisor in the above equations, so displays an inverse linear response.

In summary, the model presented allows researchers to assign a reasonable range in likely groundwater discharge rates affecting a river channel based mostly on relatively simple field measurements. While in the field, measurement parameters include $^{222}$Rn, water depth, and current velocity over a relatively short time period as well as an assessment of the cross-sectional area, pore water $^{222}$Rn activity, and dissolved $^{226}$Ra activity. Other parameters were downloaded or derived, including upstream discharge, meteorological parameters, and river surface area.

4. Results

4.1. Radon survey

The $^{222}$Rn survey of six river/stream segments conducted in April 2008 (Fig. 1) served as a qualitative indicator of groundwater discharge to each water body. The surveys were conducted from a small boat and were run throughout the entire navigable stretch of each segment, concluding at upstream extents either by shallow water or flow control devices (dam or weir). All data were collected throughout the course of just one work week. Radon activities generally increased in the upstream direction but their absolute concentrations cannot be directly applied as a quantitative indicator of groundwater discharge because many factors (e.g., pore water $^{222}$Rn activity, water volume, wind fetch, flow length) beyond the rate of groundwater discharge can affect the surface water $^{222}$Rn activity.

Nevertheless, the general distribution of radon activities in these streams is a useful guide to groundwater inputs. Radon data collected in or near the IRL are all significantly lower than upstream samples, so the IRL cannot be the source of high radon water. In some cases, radon activities in the streams reached over 80 dpm L$^{-1}$ (Cane Creek, Sebastian River, C-25 Canal) which is extremely high for surface waters and likely related to groundwater inputs. For comparison, Swarzenski et al. (2006) found radon activities up to only 28 dpm L$^{-1}$ in the Loxahatchee River in southeastern Florida which is known to have significant groundwater discharge.

We used the overall radon and salinity results from these rivers (Fig. 3) to classify the relative probability of groundwater input to these water bodies. Eau Gallie River, Turkey Creek, and Main Canal exhibited lower radon activities and higher overall salinities which imply that IRL surface water dominates the water sources within these segments and groundwater inputs are likely lower than the other streams investigated. The C-25 Canal showed the highest overall radon activity and lowest salinity (due to a weir at its mouth that prevented saline IRL waters from intruding the canal) and thus the highest likelihood of groundwater inputs. Burnett et al. (in press) described the results from this canal and calculated its associated groundwater discharge rate to be around 300,000 m$^3$ d$^{-1}$. The remaining water bodies, Sebastian River and Crane Creek, show...
reasonably high radon activities and lower salinities so we qualita-
tively classify these as having a moderate likelihood of significant
groundwater input.

4.2. Sebastian River

We focused on quantifying groundwater discharge into the
Sebastian River because FDEP has identified a number of impaired
branches in this river system (Gao, 2009). The Florida Legislature
and Florida Inland Navigation District (FIND) have recently funded
a muck-removal project in the Sebastian River because the thick
bottom muds have become an ecological problem. It is currently
unclear whether groundwater inputs or the organic muck is driving
the low dissolved oxygen levels which have caused this system to
be considered impaired.

Three upstream branches (South Prong, North Prong, and C-54
Canal) flow into the main body of the Sebastian River (Fig. 1). We
established a time-series measurement site near the mouth of the
upstream branches to characterize the groundwater discharge from
each. All sites exhibited stratification, showing typical salt-wedge
estuarine circulation where saline lagoon water was capped by
a freshwater lens flowing downstream (Fig. 4). The fresh-saline
significantly lower than the 222Rn values. Radon-222 activities appear to be related to periods of high wind speed as wind velocities showed sharp drops just after 07:00 both mornings. These radon drops remained relatively constant at 1 m depth during both sampling trips (Fig. 5). The much lower radon concentrations in the bottom layer suggest that groundwater discharge to this layer is minimal relative to that into the upper layer, implying that groundwater is input from the margins of the river rather than from the bottom. This is likely a result of sandy sediments generally found on the canal margins while the bottom sediments tend to be muddy (i.e., more impermeable).

At both the North and South Prong sites, one might expect that the shallow water depths (less than 1.5 m) combined with mixing forces (wind, waves, tides) would prevent stratification from forming. However, we observed significant stratification at both sites during both field campaigns.

4.3. South Prong time-series

The South Prong is a shallow (~1 m depth) river segment that originates roughly 9 km upstream from our time-series site and flows into the main body of the Sebastian River just downstream of our deployment. We performed time-series measurements of radon and other parameters in the surface layer at the South Prong site in both June and July 2008 (Fig. 6). The June time-series covered nearly 36 hours whereas the July time-series was conducted for about 19 hours immediately after a thunderstorm passed through the area. In both cases, the tidal range was about 15 cm and the current velocities were similar in magnitude. The general current velocity patterns using both the tidal prism approach and direct current meter measurement indicate faster downstream current velocities during ebb tide and slower velocities (even reversing directions at times) during flood tide. Salinities were much lower in July and continued to drop as the freshwater surge from the thunderstorm passed the site. Salinity varied directly with the tide in June. While mid-summer months are considered the wet season in this part of Florida, the differences we observed between the June and July sampling campaigns are likely more related to the storm events immediately preceding and during the July sampling.

Background 226Ra activities were high (Table 1), but still significantly lower than the 222Rn values. Radon-222 activities remained relatively constant at ~8 dpm L⁻¹ in June except for two sharp drops just after 07:00 both mornings. These radon drops appear to be related to periods of high wind speed as wind velocities approached 5 m s⁻¹ both mornings but were calm at all other times. Radon levels were almost five times higher in July and continued to drop as the freshwater surge from the thunderstorm passed the site. Salinity varied directly with the tide in June. While mid-summer months are considered the wet season in this part of Florida, the differences we observed between the June and July sampling campaigns are likely more related to the storm events immediately preceding and during the July sampling.

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4.4. North Prong time-series

The North Prong is a shallow (<1 m depth) tributary that flows into the main stem of the Sebastian River just downstream of the C-54 Canal (Fig. 1). We performed time-series measurements (Fig. 7) in the surface layer of the North Prong in both June (20 hours) and July (25 hours). The tidal range at this site was somewhat depressed compared to the South Prong, with about a 10 cm amplitude. We were unable to retrieve current meter data in June and those measurements in July did not match the tidal prism approach. A thunderstorm passed through the area during this time-series measurement, so the tidal prism approach indicates increasing downstream current flow throughout the time-series. The current meter data shows a clear tidal response, its sensors were apparently located in the bottom layer and did not capture the increasing freshwater discharge that occurred in the upper layer.

Salinity was generally lower in July during higher discharge than in June, but its trends are opposite those of the South Prong site. Instead of observing high salinities at high tide, we documented peaks at the low tides during both deployments. The radon concentrations also show different patterns than expected: maximum activities during high tides and minimum levels at low tides. One possible explanation for this observation is that at low tide, the freshwater lens thinned and the intake pump (suspended below the floating platform) may have been sampling from closer to the bottom layer (higher salinity, lower radon). Nonetheless, our modeled groundwater discharge rates still peak during ebb tide and show a minimum at flood tide in June because of the model dependency on current velocity. In July during the thunderstorm, the flux of groundwater past our time-series site rapidly increased due to the faster flushing of the surficial aquifer and upstream water volume.

Assuming this flux of groundwater through our time-series site is balanced by upstream inputs, we find that June groundwater fluxes averaged between 1600 and 3100 m³ d⁻¹. These fluxes contribute 9 to 17% of the overall North Prong discharge. In July, average groundwater inputs ranged from 28,000 to 30,000 m³ d⁻¹ (19–20% of overall discharge; Table 1). These estimates are significantly lower than baseflow estimates during the entire study period (Table 1), presumably due to the influence of the storm during our sampling.

4.5. C-54 Canal time-series

The C-54 Canal is a deep (5 m) man-made canal that drains mostly agricultural land before discharging into the main stem of the Sebastian River. A dam controls water flow from the C-54 Canal into the Sebastian River about 1 km upstream from our time-series measurements.
Fig. 6. Water level, current velocity, salinity, and \(^{222}\text{Rn}\) activity measured during the time-series measurements in the South Prong, as well as calculated fraction of groundwater passing our measurement site and groundwater (\(Q_{\text{GW}}\)) discharge rate. Left column shows those data and results from June; the right column shows those for July. Note the different vertical scales between June and July for each parameter. The two lines in the Fraction GW and \(Q_{\text{GW}}\) discharge plots represent the minimum estimate (Eq. (1)) and maximum estimate (Eq. (2)). When values less than 0 are plotted, dashed horizontal lines show the zero point. Positive current velocities represent downstream flow and negative values represent upstream flow. Negative current velocities cause negative \(Q_{\text{GW}}\) values which represent our groundwater tracers entering the system from downstream. TP denotes the tidal prism-derived current velocities, whereas CM represents the current meter measurements.
site. Bottom sediments here consist of a shallow sandy layer (along the banks to about 1 m water depth) and a deeper muddy layer. During June, our time-series measurements were collected from the bottom layer and did not reveal any significant signal of groundwater flow (very low radon activities and high salinity as in Fig. 5) and will not be discussed further. During July, we performed a 37 hour time-series in the surface layer of the C-54 Canal (Fig. 8).

During this time-series, the tidal amplitude was about 18 cm and showed a general increase in water level throughout the measurement. The current meter sensors were located within the bottom layer and displayed upstream, estuarine-type circulation throughout the entire time-series. However, the tidal prism approach revealed net downstream flow during the same period, a result of upstream inputs from the dam. The surface layer showed relatively low salinity as well as the highest radon levels (> 120 dpm L⁻¹) detected among all Sebastian River time-series measurements. Neither salinity nor radon displayed consistent variation with the water level record.

Surface water grab samples collected behind the dam showed radon levels of only 10 dpm L⁻¹, so the majority of the radon measured at our site must be derived from discharge below the dam. Therefore, our modeled domain extends from the time-series site upstream to the dam and we subtract this 10 dpm L⁻¹ as part of the supported ²²²Rn activity in the model. Groundwater discharge rates (up to about 500,000 m³ d⁻¹) tend to peak at low/ebb tide and average between 150,000 and 240,000 m³ d⁻¹ (between 51 and 82% of the total C-54 Canal discharge; Table 1). Much like the South and North Prongs, our observation of discharge at both discharge sites agrees with the observation of groundwater discharge in the South and North Prongs. Our observation of discharge at both discharge sites supports its existence and further supports its existence and may therefore have produced an oversimplification of the water movement, as we noticed for the C-54 Canal (Fig. 8). For future studies, we recommend using a profiling current meter capable of integrating velocities throughout the entire water column. In the case of the C-54 Canal, the current meter was measuring within the bottom layer, so it reported the salt wedge estuarine circulation where deeper saline waters were constantly flowing upstream. Using the tidal prism approach, however, we observed net water movement constantly downstream as a result of the freshwater flow in the surface layer.

The main uncertainty associated with the tidal prism approach is the quantification of the upstream inundated surface area. However, readily available satellite imagery makes this estimate reasonably simple. In our case, independent estimates of the same area performed by different users rarely differed by more than 10%. We thus only used current meter measurements to compare to the range of current velocities derived from the tidal prism approach to validate our estimated surface areas. The agreement of the tidal prism approach with the patterns and scales of water velocity is quite good in the situations where the current meter was deployed at the correct level (e.g., Fig. 6) and further supports its use as our primary source of current velocities in our modeling.

5.2. Groundwater discharge model

The time-series model employed here accounts for all the major inputs and outputs of ²²²Rn into a river branch. We consider inputs of radon from groundwater discharge and upstream inflows (only if
Fig. 7. Water level, current velocity, salinity, and $^{222}$Rn activity measured during the time-series measurements in the North Prong, as well as calculated fraction of groundwater passing our measurement site and groundwater ($Q_{GW}$) discharge rate. Results presented in the same manner as Fig. 6.
considering a portion of the river as in the C-54 Canal instead of the entire upstream length). The only other possible source of $^{222}$Rn to a river system would be via diffusion from sediments and suspended particles that may contain $^{226}$Ra. In the case of a stratified estuary such as the Sebastian River where only the freshwater lens contains significant groundwater, we can neglect these diffusive inputs of $^{222}$Rn because the active area of sediments that interacts with the upper water layer is isolated to the banks of the river and only comprises a small fraction of the river bed. In addition, as the stratification here is sufficiently strong to prevent interlayer mixing, $^{222}$Rn diffusion from sediments to the deeper layer would likely have a trivial impact on the upper layer. In a system that does not exhibit stratification, it might be necessary to account for this input of radon, although diffusive inputs are rarely significant when advection is present. Suspended particles may also contribute some small amount of $^{222}$Rn to the system via alpha-recoil associated with $^{226}$Ra decay but this is also expected to be very minor because most of the particle-bound $^{226}$Ra would have already desorbed from the particles in the brackish, relatively low turbidity waters of the Sebastian River (Martin and Akber, 1999; Nozaki et al., 2001; Peterson et al., 2008a). In this case, we have already accounted for this source of supported $^{222}$Rn. In-situ $^{226}$Ra decay is a minor $^{222}$Rn source even though dissolved $^{226}$Ra activities were relatively high (0.2 to 3.9 dpm L$^{-1}$) for surface waters but still significantly lower than the $^{222}$Rn values. This source is accounted for in Eqs. (1) and (2).

The model also accounts for all the possible losses of $^{222}$Rn in this system including downstream advection out of the domain, atmospheric evasion, and decay losses. The latter two losses are difficult to properly quantify without knowing the $^{222}$Rn residence time between the point of entry and the point of measurement, which is likely different for each $^{222}$Rn atom in the system. Thus, we feel that the best option is to quantify these losses based on two possible extreme assumptions: (1) all inputs of $^{222}$Rn are at the location of the time-series moorings and thus have no significant residence time between the point of entry and the point of measurement, which is likely different for each $^{222}$Rn atom in the system. Thus, we feel that the best option is to quantify these losses based on two possible extreme assumptions: (1) all inputs of $^{222}$Rn are at the location of the time-series moorings and thus have no significant residence time (in this case, there are no evasion and decay losses), and (2) all the $^{222}$Rn atoms are input at the most upstream extent of the river domain and thus have the longest possible lifetime. In the latter case, they are subject to maximum evasion and decay losses, which after correcting for these losses make the calculated $Q_{GW}$ values higher.

Figs. 6–8 show that the model results are driven primarily by the measured radon activities and the current velocity. The fraction of groundwater that passes our measurement site responds directly to the measured $^{222}$Rn activity. While the patterns of the calculated $Q_{GW}$ values are dependent upon current velocity, the magnitudes of these discharges are related to the $^{222}$Rn activity via the fraction of groundwater passing this site.

The ranges of possible groundwater discharge rates (less than a factor of 3; Table 1) determined by this model seem reasonable compared to other tracer-based estimates and should be representative of expected results in other tidally-influenced river systems. While this range is only a product of the maximum and minimum extents of the model and does not encompass uncertainties in measured current velocities or end-members (see section 3.2), the relative range would not change if we used a different end-member value (i.e., there would be a constant offset). Burnett et al. (2006) document several worldwide intercomparison exercises between tracer-based approaches ($^{222}$Rn, radium isotopes) as well as direct physical (seepage meters) and

![Fig. 8. Water level, current velocity, salinity, and $^{222}$Rn activity measured during the July time-series in the C-54 Canal, as well as calculated fraction of groundwater passing our measurement site and groundwater ($Q_{GW}$) discharge rate. Results presented in the same manner as Fig. 6. Groundwater discharge rates over 100% are an artifact of the calculations and have no meaning. We consider these values as maximized at 100%.]
Results of the push-point piezometer pore water sample measurements arranged by depth profiles. Note several profiles were sampled during both June and July. Radon-222 activity were observed. Assigning an end-member based on depth profiles. particularly site, the range in SGD estimates can be anywhere from a factor of 2–30. Peterson et al. (2008b) also showed groundwater discharge rates based on high-frequency radium time-series measurements (Kim et al., 2005; Paytan et al., 2006; Taniguchi et al., 2008) and nearby areas in the IRL, where discharge rates reach 25 cm d−1 (estimated by dividing the groundwater flux by the river surface area), the Sebastian River displays much greater groundwater flux rates than several other worldwide environments (Kim et al., 2005; Paytan et al., 2006; Taniguchi et al., 2008) and several other worldwide environments (Kim et al., 2005; Paytan et al., 2006; Taniguchi et al., 2008) and nearby areas in the IRL, where discharge rates reach 25 cm d−1 but are typically much lower (Cable et al., 2004; Martin et al., 2004, 2006, 2007; Smith et al., 2008a). The small tidal range in the Sebastian River limits the action of tidal pumping and other driving forces of bottom water recirculation through these permeable sediments. Therefore, while terrestrial forces drive the input of these samples would thus be subject to a large degree of uncertainty. However, the agreement of the sediment equilibration results (Table 3) for the shallow sandy samples is much better. We feel more confident in assigning an end-member based on these results. Other studies (e.g., Corbett et al., 1998; Burnett and Dulaiova, 2003; Dulaiova et al., 2008; Santos et al., 2008a, b, c) have also shown that sediment equilibration is often the most useful technique in determining the pore water 222Rn end-member activity. This analysis assumes that the residence time of groundwater within the shallow sediments was long enough to reach equilibration with the sedimentary 226Ra (≈3 weeks). This seems to be a reasonable assumption as bottom water flushing through the sediments is not significant (saline pore waters were generally absent) and surface water radon activities are within the range of equilibrated values (Table 3). If, in fact, the residence time was shorter than the equilibration time, the concentration would be overestimated and discharge underestimated in a linear fashion. While the overall scale of the model output would change with a different end-member value, the relative difference between the minimum and maximum estimates would remain the same provided that the end-member is constant over time. Our data are not sufficiently detailed to shed insight into any short-term (i.e., hours to days) temporal changes in end-member values, although these changes are likely with varying environmental conditions (e.g., storms and subsequent aquifer flushing). While these changes would be significant, their impacts would likely be small when considering the overall scale of QIW revealed by this model.

5.3. Discharge implications

Along Florida’s east coast, the surficial aquifer (and thus coastal rivers) responds rapidly to rainfall events (Burnett et al., in press). Comparing the South Prong of the Sebastian River between June (dry period) and July (wet period) reveals over a 50-fold increase in groundwater discharge with higher precipitation. The North Prong responds similarly, showing a 10-fold increase in discharge between the two periods. Rainfall recharges the local surficial aquifers to levels above the river channels, thus driving enhanced discharge with a short lag time between precipitation and discharge. With average vertical advection rates ranging between 90 and 150 cm d−1 (estimated by dividing the groundwater flux by the river surface area), the Sebastian River displays much greater groundwater flux rates than several other worldwide environments (Kim et al., 2005; Paytan et al., 2006; Taniguchi et al., 2008) and nearby areas in the IRL, where discharge rates reach 25 cm d−1 but are typically much lower (Cable et al., 2004; Martin et al., 2004, 2006, 2007; Smith et al., 2008a). The small tidal range in the Sebastian River limits the action of tidal pumping and other driving forces of bottom water recirculation through these permeable sediments. Therefore, while terrestrial forces drive the input of
fresh groundwater (and new nutrients) into the Sebastian River, most groundwater discharged to the IRL is composed of recirculated seawater driven by marine forces (Martin et al., 2007).

We do not attempt to separate the effects of terrestrial groundwater discharge from hyporheic exchange. Hyporheic exchange is often driven by obstructions, bottom roughness, and high current velocities (Sophocleous, 2002). In the case of the Sebastian River, the muddy bottom sediments are generally uniform with low porosity. The low current velocities (on the order of a few cm s\(^{-1}\); Figs. 6–8) associated with the small tidal range are likely insufficient to drive much exchange in the bottom layer. Since all of our radon measurements were collected in the surface layer, hyporheic exchange would not likely contribute greatly to our measured radon activities as these inputs would be mostly isolated to the bottom layer. There may be some limited exchange through the sandy sediments along the edges of the river but this is unlikely to significantly affect the radon budget.

These groundwater fluxes comprise a significant-to-dominant fraction of the surface discharge flux from each river segment (Table 1). Groundwater discharge to the South Prong accounts for 21 to 80% of the total discharge and comprises a somewhat lower fraction during the higher discharge period. The North Prong has higher groundwater discharge accounting for around 10–20%, whereas the C-54 Canal runoff is dominated by groundwater (50–80%). These contributions are quite high when compared to global estimates (0.01 to 30% of river discharge) and other local- to regional-scale estimates (3–40%; Taniguchi et al., 2002).

Considering dissolved component delivery pathways, these high rates of groundwater discharge can potentially deliver large amounts of dissolved species to tidal rivers. Zimmermann et al. (1985) found that even the low rates of groundwater discharge to the IRL (up to about 10 cm d\(^{-1}\)) deliver significant fluxes of dissolved reactive phosphorus. In a coastal lagoon in southern Brazil, groundwater contributes only 2% to the total water budget but accounts for over 50% of major ion inputs (Santos et al., 2008c). The groundwater in the Sebastian River area are naturally oxygen-deficient and contain high amounts of dissolved organic matter, so their fluxes could create suboxic conditions that caused this system to be considered ‘impaired.’ The extremely high groundwater discharge rates observed in the Sebastian River (and likely in other streams shown in Fig. 1) associated with possible subterranean urban contamination sources could also be a major driver of the recurrent suboxic events in these rivers. Future studies should quantify the fluxes of nutrients and organic matter to these ‘impaired’ water bodies in order to validate a possible link between groundwater discharge and de-oxygenation.

6. Conclusions

We demonstrate the applicability of a rapid assessment method using \(^{222}\)Rn to determine the likelihood of groundwater discharge to tidally-influenced rivers and to assign reasonable upper/lower limits for the discharge rate. Performing \(^{222}\)Rn and conductivity surveys in six canal and river systems that drain into the Indian River Lagoon, we were able to determine that: (1) the C-25 Canal exhibits very high radon and low salinity conditions and therefore likely exhibits high groundwater discharge; (2) the Eau Gallie River, Turkey Creek, and the Main Canal likely receive a small amount of groundwater discharge based on their relatively low \(^{222}\)Rn activities and higher salinities; and (3) Crane Creek and the Sebastian River system likely receive intermediate groundwater inputs. While these assessments serve as qualitative indicators only, the information is gathered quickly and can be used to determine where to perform additional studies.

Focusing on the Sebastian River system, we showed that time-series moorings covering ~24 hours in tidal river estuaries were sufficient to make reasonable estimates of the minimum and maximum upstream groundwater discharge rates. During these time-series measurements, we continuously measured \(^{222}\)Rn, water depth, and current velocity and also measured the cross-sectional area, pore water radon activity, and dissolved \(^{222}\)Rn activity at each site. With these data, we found that under dry conditions in June 2008, groundwater discharge to the South Prong contributed between 31 and 80% of the total discharge, and even though these fluxes increased by nearly two orders of magnitude in July, their relative contribution to the overall river flux was lower (21–41%). Groundwater inputs contributed between 9 and 17% of the North Prong discharge in June and the discharges increased by an order of magnitude in July to contribute a slightly greater percentage (19–20%) of the overall discharge. Groundwater fluxes to the C-54 Canal were found to contribute between 51 and 82% of the total discharge from this segment in July.

These groundwater discharge rates are much higher than those found in the adjacent Indian River Lagoon, so can be a significant source of nutrients and metals to the local estuarine ecosystems. We recommend future studies attempt to quantify the nutrient and organic matter inputs and the associated de-oxygenation potential of groundwater discharge into some of these tidal rivers and estuaries along the east coast of Florida.

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