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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, ^{222}Rn, 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 ^{222}Rn 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.

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 (Buddemeier, 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 ^{222}Rn

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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 Hemond (1990) combined ^{222}Rn with NaCl 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 Pliocene 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).