Journal of Hydrology 380 (2010) 298–304

Contents lists available at ScienceDirect

Journal of Hydrology

journal homepage: www.elsevier.com/locate/jhydrol

Use of automated radon measurements for rapid assessment of groundwater flow into Florida streams

William C. Burnett [a,*], Richard N. Peterson [a,1], Isaac R. Santos [a,2], Richard W. Hicks [b]

[a] Department of Oceanography, Florida State University, Tallahassee, FL 32306, USA
[b] Ground Water Protection Sections, Florida Department of Environmental Protection, 2600 Blair Stone Road, Tallahassee, FL 32399, USA

ARTICLE INFO

Article history:
Received 6 February 2009
Received in revised form 14 September 2009
Accepted 10 November 2009

This manuscript was handled by L. Charlet, Editor-in-Chief, with the assistance of Eric C. Gaucher, Associate Editor

Keywords:
Submarine Groundwater Discharge
Radon
Tracer
Florida

SUMMARY

Naturally occurring ^{222}Rn (radon; $t_{1/2} = 3.8$ days) is a good natural tracer of groundwater discharge because it is conservative and typically 2–3 orders of magnitude higher in groundwater than surface waters. In addition, new technology has allowed rapid and inexpensive field measurements of radon-in-water. Results from the C-25 Canal, a man-made canal in east-central Florida thought to be dominated by groundwater inflows, display how one can quickly assess a water body for locations of groundwater inputs. Although only the eastern portion of the canal was surveyed, use of a few assumptions together with some continuous radon measurements allowed reasonable estimates of the groundwater inflows to be made. Groundwater discharge estimates of 327,000 m^3/day and 331,000 m^3/day were measured for two stations based on determining the groundwater fraction of the total stream flow. This fraction in each case was calculated by correcting radon concentrations for decay over transit times determined from concentration differences between the apparent focal point of groundwater discharge (with a concentration of 520 ± 80 dpm/L) estimated to be ∼17.7 km upstream from the downstream sample locations. During the same period, an average flow of 312,000 ± 70,000 m^3/day was determined from time-series measurements of radon at a fixed downstream location. Coincident current meter readings and a measured cross-section area allowed an independent assessment of the total stream discharge of 336,000 m^3/day. The radon-derived estimates thus indicate that >90% of the total flow is groundwater derived, consistent with the known characteristics of this waterway.

Introduction

It has been recognized for several years that natural radon (^{222}Rn; $t_{1/2} = 3.84$ days) may be used as an excellent tracer of exchange between groundwaters and surface waters (Lee and Hollyday, 1987; Low, 1996). While radon has been used to assess infiltration of surface waters into aquifers (Hoehn and von Gunten, 1989; Hamada and Komae, 1998), it is more powerful as a tracer of groundwater discharge into surface receiving bodies of water (Ellins et al., 1990; Cook et al., 2003, 2006; Mullinger et al., 2007). The much higher concentration (by 2–4 orders of magnitude) of radon in most groundwaters compared to surface waters provides the source strength that makes it an excellent tracer. In addition, recent technological advances have allowed automation of radon-in-water measurements in the field (Burnett et al., 2001; Dulaiova et al., 2005). It is now possible, for example, to survey a water body from a small boat and obtain a radon-in-water measurement every 5–15 min, depending upon the concentration. As a noble gas, radon does not react with other species so it is conservative, although evasion to the atmosphere may be important in some circumstances.

By performing radon surveys along individual streams, one can quickly make qualitative comparisons among different segments of the streams and rank them in terms of their probable groundwater contributions. While one cannot establish a simple one-to-one relationship between radon concentration and groundwater discharge because of complicating factors (different source waters, current velocities, evasion rates, etc.), radon is clearly a useful tool for exploratory purposes. Such an approach allows one to target selected individual water bodies for more extensive studies in order to quantify the groundwater input rates.

Prior studies have shown that multiple tracers are preferable to any single tracer for quantitative assessments of groundwater discharge as the additional tracers can constrain many of the assumptions that are inherent in the modeling process. Genereux and Hemond (1990), for example, used radon together with two artificial tracers – one conservative (NaCl) and the other volatile

* Corresponding author. Tel.: +1 850 644 6703; fax: +1 850 644 2581.
E-mail address: wburnett@fsu.edu (W.C. Burnett).
[1] Present address: Center for Marine and Wetland Studies, Coastal Carolina University, Conway, South Carolina 29528 USA.
[2] Present address: Centre for Coastal Biogeochemistry, Southern Cross University, Lismore, NSW, 2480, Australia.

0022-1694/$ - see front matter © 2009 Elsevier B.V. All rights reserved.
doi:10.1016/j.jhydrol.2009.11.005

(propane). This allowed the investigators to correct for dilution as well as atmospheric evasion in their modeling of groundwater discharge into streams. Genereux et al. (1993) used naturally occurring radon and calcium to develop a three end-member mixing model for streamflow generation consisted of vadose zone water, soil groundwater, and bedrock groundwater. Cook et al. (2003) used radon, CFCs and several ionic tracers (conductivity, Mg^{2+}, Cl^{-}) to estimate the groundwater flow into a tropical river in the Northern Territory of Australia. Cook et al. (2006) later used radon, together with SF_6 for estimates of the gas transfer velocity, to quantify the groundwater discharge to Cockburn River in south-eastern Australia.

Another approach that has been followed in some areas including Florida's Indian River Lagoon (IRL), the same general area as our research, is to measure pore water profiles of Rn and/or Cl^{-} and then estimate advective flow of groundwater by modeling these profiles (Smith et al., 2008; Cable and Martin, 2008). This approach works very well and has been shown to be consistent with hydrogeologic modeling in the case of the IRL. However, the approach is very labor-intensive and can only cover a rather limited area as installation of multi-level piezometers for pore water sampling is required. Our approach described here relies on surface water measurements that can be made rapidly and will integrate the tracer signal over a larger area.

In Florida and elsewhere, it has recently become important to develop a better understanding of groundwater influences on surface water systems. To address federal requirements under the Clean Water Act (CWA), the State of Florida identifies and assesses the characteristics of "impaired" surface waters that do not meet water quality standards and establishes Total Maximum Daily Loads (TMDLs) for these waters on a prioritized schedule. TMDLs are intended to set the maximum amount of a pollutant that a water body can assimilate without exceeding water quality standards. The flux of a pollutant could obviously originate from groundwater as well as surface discharges. The practical problem is that just in the State of Florida, there are literally thousands of such "impaired waters" as defined by the CWA. Incorporating the groundwater component of a water budget and mass balance calculation of pollutant loading to a water body requires assessing the groundwater discharge into the impaired surface water segments. In addition, in order to achieve the water quality benefits intended by the CWA, it is critical that TMDLs be developed and implemented in a timely manner. Doing so by traditional means (hydrogeologic investigations, numerical modeling, etc.) is a time-consuming and costly process. As a result of this situation, many of these assessments are being performed neglecting groundwater pathways or using less than optimum data for possible groundwater inputs.

While it is clear that the use of multiple tracers is an elegant approach and preferable for achieving the most precise results, there are advantages to using radon as a single tracer when results are needed quickly and inexpensively. Recent technological advances in radon-in-water measurements have opened up the possibility for very rapid field assessments. This paper will report on a trial assessment in one waterway in Florida that has been designated as impaired and is known to be dominated by groundwater inputs. A companion paper extends the approach to a series of waterways characterized by extensive surface as well as groundwater pathways (Peterson et al., 2010).

Study site and experimental

The C-25 (Belcher) Canal and the Fort Pierce Farms Water Control District Canal #1 both discharge through Taylor Creek into the IRL in northern St. Lucie County, Fort Pierce, Florida (Fig. 1). These canals are major contributors of fresh water flows and associated

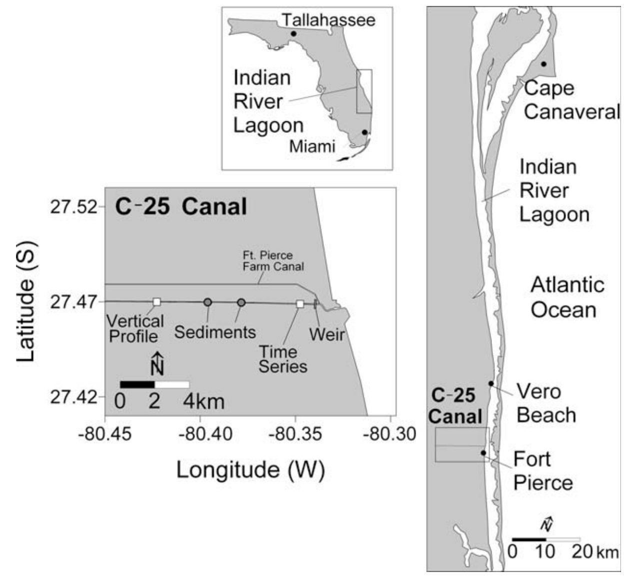

Fig. 1. Index map showing the location of the C-25 Canal near Fort Pierce, Florida. The radon survey on April 25, 2008 began just west of the weir and continued approximately 8 km upstream. Sediment and pore water samples were collected at the sites marked "sediments," the vertical profiles of the canal water and estimated cross-sectional areas were done at both the locations labeled "time-series" and "vertical profile." All activities besides the survey were conducted during July 13–14, 2008.

pollutant loadings to the lagoon. The C-25/Belcher Canal is a major canal maintained by the South Florida Water Management District and extends across northern St. Lucie County and southern Indian River County for a distance of approximately 35 km. Midway along the canal, it intersects with the C-24 canal from the south. There are two flow control structures on the canal, the S99 structure, which is a gate and the S50 structure, which is a weir. The eastern segment (~8.5 km) of the C-25 Canal was surveyed upstream from the S50 flow control structure (weir) just above the intersection with the Fort Pierce Farm Canal. The weir prevents saline waters from the IRL from intruding into the canal. Base flow in the C-25 Canal is mainly derived from groundwater except for temporary and localized inputs of storm water runoff or transfers of water from other areas. In this part of Florida, most of the land was originally unsuitable for development due to high water table conditions. A major network of canals in the area was excavated by the US Army Corps of Engineers for dewatering the surficial aquifer, thereby creating farmland and land for development as well as providing flood control. The C-25 is a relatively deep (~4–5 m) canal that had some of the highest radon activities measured during several surveys of waterways in east-central Florida.

The research described in this paper was performed on two occasions: (1) an initial survey to map the distribution of radon in the canal's eastern segment; and (2) a concentrated period of sampling at specific locations as well as a time-series deployment at a fixed site. The methods employed for the radon survey part of this work (April 25, 2008) were based on those reported in Dulaiova et al. (2005). Briefly, three radon-in-air monitors (RAD7, Durridge Co.) were installed in parallel and connected via a closed air loop through an air–water equilibrium spray chamber. Surface water (~30 cm depth) was pumped using a submersible pump into the top of the equilibrium chamber, where the radon within the air loop equilibrates with the radon in the water stream. By measuring the radon concentration in the air loop together with the temperature in the mixing chamber (via a HOBO temperature probe), one can calculate the amount of radon within the water based on its solubility. With the high radon concentrations encountered in this