Journal of Hydrology (2008) **353**, 275–293

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

Tracing anthropogenically driven groundwater discharge into a coastal lagoon from southern Brazil

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Received 1 August 2007; received in revised form 11 January 2008; accepted 15 February 2008

KEYWORDS
Radium isotopes;
Oxygen isotopes;
Submarine groundwater discharge;
Hydrologic cycle;
Permeable sediments

Summary We investigated the distribution of naturally occurring geochemical tracers (^{222}Rn, ^{223}Ra, ^{224}Ra, ^{226}Ra, CH_4, $\delta^{18}O$, and $\delta^{2}H$) in the water column and adjacent groundwater of Mangueira Lagoon as proxies of groundwater discharge. Mangueira Lagoon is a large (90 km long), shallow (~4–5 m deep), fresh, and non-tidal coastal lagoon in southern Brazil surrounded by extensively irrigated rice plantations and numerous irrigation canals. We hypothesized that the annual, intense irrigation for rice agriculture creates extreme conditions that seasonally change groundwater discharge patterns in the adjacent lagoon. We further supposed that dredging of irrigation canals alters groundwater fluxes.

While the activities of ^{222}Rn in shallow groundwater were 2–3 orders of magnitude higher than in surface water, CH_4 and radium isotopes were only ~1 order of magnitude higher. Therefore, ^{222}Rn appears to be the preferred groundwater tracer in this system. Radon concentrations and conductivities were dramatically higher near the pump house of rice irrigation canals, consistent with a groundwater source. Modeling of radon inventories accounting for total inputs (groundwater advection, diffusion from sediments, and decay of ^{226}Ra) and losses (atmospheric evasion, horizontal mixing and decay) indicated that groundwater advection rates in the irrigation canals (~25 cm/d) are over 2 orders of magnitude higher than along the shoreline (~0.1 cm/d). Nearly 75% of the total area of the canals is found in the southern half of the lagoon, where groundwater inputs seem to be higher as also indicated by methane and stable isotope trends. In spite of the relatively small area of the canals, we estimate that they contribute nearly 70% of the total

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doi:10.1016/j.jhydrol.2008.02.010

($\sim$57,000 m^3/d) groundwater input into the entire Mangueira Lagoon. We suggest that the dredging of these canals cut through aquitards which previously restricted upward advection from the underlying permeable strata. The irrigation channels may therefore represent an important but previously overlooked source of nutrients and other dissolved chemicals derived from agricultural practices into the lagoon.

Introduction

The importance of groundwater discharge into coastal environments is becoming increasingly recognized because of its potential significance as a source of natural and anthropogenically derived dissolved species. Since the concentrations of dissolved species in groundwater are often higher than surface waters, even small amounts of groundwater input into lakes, streams, and the coastal ocean may have important effects. Recent research suggests that high dissolved N:P ratios in contaminated coastal groundwater may drive the coastal areas towards P-limitation within the coming decades (Slomp and Van Cappellen, 2004). Such inputs would be especially significant in heavily fertilized areas.

The relative impact of groundwater to a particular water body is controlled by the underlying strata and the source of groundwater-derived constituents (Swarzenski et al., 2007). Factors that enhance fresh groundwater discharge include high precipitation rates, relief, and permeability (Zektser and Loaiciga, 1993). In addition, convection induced by denser water overlying less dense groundwater has also been reported to drive seepage (Smith, 2004). Not only short- (e.g., tides and wave setup) and long-term natural processes (e.g., changes in the hydraulic gradient), but also anthropogenic factors (such as pumping and irrigation) can change the pressure head, the most important single factor controlling groundwater discharge. While recent progress has been made concerning natural groundwater discharge driving forces (Burnett et al., 2006; Chanton et al., 2003; Kim and Hwang, 2002; Michael et al., 2005; Santos et al., 2008), there is still a need to investigate how anthropogenic changes in the hydrologic cycle influence groundwater discharge into coastal lagoons.

Coastal lagoons occupy nearly 13% of the world's coastline and their basins are among the sites of fastest human development. They are usually shallow water bodies, oriented parallel to shore, separated from the ocean by a sand barrier, hypo- or hyper-saline and highly productive (Knoppers et al., 1999). The function of subterranean pathways for water and solute flow is still one of the great gaps for a better comprehension of processes in coastal lagoons. Since alterations in either groundwater quantity or quality could result in deterioration of coastal ecosystems, knowledge of the complete hydrologic budget, including groundwater contributions, is essential for development of good water management strategies (Corbett et al., 1997).

A major factor that does not allow an accurate assessment of the importance and implications of groundwater discharge on a global scale is the limited number of studies in key areas of developing countries that are characterized by increasing population densities and fertilizer use (Slomp and Van Cappellen, 2004; Taniguchi et al., 2002). Because of significant alterations in the regional water cycle (i.e., lagoon damming, building of irrigation canals, large-scale irrigation, and heavy fertilization), the southern Brazil coastal environment represents an extreme example of this scenario and thus offers a good opportunity to learn about the relationships between land use and groundwater discharge.

Groundwater discharge is often patchy, diffuse, temporally variable, and may be in response to multiple driving forces (Burnett et al., 2003a). Basically, there are three approaches for measuring groundwater discharge: modeling, direct measurements with vented benthic chambers (seepage meters), and geochemical tracers. A promising approach is the utilization of geochemical tracers because the water column integrates the tracers coming into the system via groundwater. Smaller-scale variations are smoothed out, so the tracer approach is a good way to deal with the large spatial heterogeneity problems that are associated with groundwater pathways (Burnett et al., 2006; Cook et al., 2003; Swarzenski, 2007).

In this study, we investigate the distribution of a suite of naturally occurring geochemical tracers (^{222}Rn, ^{223}Ra, ^{224}Ra, ^{226}Ra, CH_4, δ^2H, δ^{18}O, and conductivity) collected from the water column and groundwater of Mangueira Lagoon (Southern Brazil) as possible indicators of groundwater discharge. Because no regional background information was available (this is the first attempt to assess the groundwater contribution to a Brazilian coastal lagoon), we initially aimed at determining the most suitable tracer for the environmental conditions of Mangueira Lagoon. Later, the efforts were focused on the use of that tracer (^{222}Rn) as a quantitative natural tracer. We hypothesized that (1) the annual, intense irrigation for rice agriculture creates extreme conditions that seasonally change groundwater discharge patterns in the adjacent lagoon, and (2) dredging of numerous irrigation canals alters the groundwater fluxes.

Materials and methods

Site description

Mangueira Lagoon is a large, non-tidal, shallow, fresh water body and one part of the largest coastal lagoon system in the world (the Patos-Mirim-Mangueira system — Fig. 1). The southern Brazilian coastal plain was formed by successive sea level fluctuations during the Quaternary. Mangueira Lagoon was formed during the Holocene $\sim$5,100 years ago (Villwock and Tomazelli, 1995). The lagoon is 90 km long and has an area of nearly 900 km^2 with a catchment of a similar size. The regional geology is complex but little