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Submarine groundwater discharge from the South Australian Limestone Coast region estimated using radium and salinity

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ABSTRACT

The Tertiary Limestone Aquifer (TLA) is one of the major regional hydrogeological systems of southern Australia. Submarine groundwater discharge (SGD) of freshwater from the TLA occurs through spring creeks, beach springs and diffusively through beach sands, but the magnitude of the total flux is not known. Here, a range of potential environmental tracers (including temperature, salinity, ^{222}Rn, ^{223}Ra, ^{224}Ra, ^{226}Ra, ^{228}Ra, and ^{4}He) were measured in potential sources of SGD and in seawater along a 45 km transect off the coastline to evaluate SGD from the TLA. Whilst most tracers had a distinct signature in the sources of water to the coastline, salinity and the radium quartet had the most distinct SGD signal in seawater. A one-dimensional advection-dispersion model was used to estimate the terrestrial freshwater component of SGD (Q_{fw}) using salinity and the recirculated seawater component (Q_{rsw}) using radium activity in seawater. Q_{fw} was estimated at 1.2–4.6 $m^3\ s^{-1}$, similar in magnitude to previously measured spring creek discharge (~3 $m^3\ s^{-1}$) for the area. This suggests that other terrestrial groundwater discharge processes (beach springs and diffuse discharge through beach sands) were no more than 50% of spring creek discharge. The largest component of total SGD was Q_{rsw}, estimated at 500–1000 $m^3\ s^{-1}$ and possibly greater. The potential for wave, storm, or buoyancy-driven porewater displacement from the seafloor could explain the large recirculation flux for this section of the Southern Ocean Continental Shelf.

1. Introduction

Along coastlines, groundwater loss occurs by pumping extraction, evapotranspiration from shallow watertables, discharge to surface water, inter-aquifer exchange, and by discharge to the marine environment. Of these mechanisms, submarine groundwater discharge (SGD) is often the most poorly known component of the water balance. SGD is now well recognised for its role in the water balance (Bokuniewicz and Pavlik, 1990; Moore, 1996), solute transport (Burnett et al., 2006; Santos and Eyre, 2011) and, increasingly, for its ecological significance to coastal zones (Gleeson et al., 2013; Johannes, 1980; Stieglitz et al., 2013). In addition to terrestrial (usually fresh) groundwater, a large component of SGD can be seawater recirculated from beaches and shallow sediments by tidal pumping and other coastal processes (Burnett et al., 2003; Webster, 2003).

Environmental tracers have been one of the most widely used techniques to study SGD (Burnett et al., 2006). A key advantage of this approach is that it can be used to locate and quantify groundwater discharge at a range of scales, including at the regional one. Some relatively simple tracers in SGD studies include salinity (Stieglitz et al., 2010) and temperature (Varma et al., 2010). Radionuclides from the U and Th radioisotope decay series have also been widely used as they are often relatively enriched in SGD relative to seawater (Cable et al., 1996; Moore, 2003). This includes ^{222}Rn, a short lived ($t_{1/2} = 3.82$ days) radioactive noble gas, and the four radioisotopes of Ra, or 'radium quartet' (^{224}Ra, ^{223}Ra, ^{228}Ra, ^{226}Ra) with a range of half-lives (3.5 days, 11 days, 5.75 years and 1600 years, respectively). Helium-4, a stable noble gas, is one of the products of all alpha decay processes in the U and Th decay chains and tends to accumulate in groundwater over long time periods (Solomon, 2000). Helium-4 can be an ideal tracer for regional groundwater discharge (Gardner et al., 2011) but has apparently received limited attention to date in SGD studies. A potential

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advantage of ^{4}He relative to many other radionuclides is that, because of the need for a long contact time with geological materials, recirculated seawater should not contain this tracer, but terrestrial groundwater could.

The purpose for this study was to estimate SGD from the Tertiary Limestone Aquifer, a significant regional hydrogeological system of southern Australia. This was achieved by first determining the signature for a range of geochemical tracers of SGD (including temperature, salinity, ^{222}Rn, ^{223}Ra, ^{224}Ra, ^{226}Ra, ^{228}Ra, and ^{4}He) in potential sources of water to the coastline (regional groundwater, spring-fed creeks, intertidal groundwater and Glenelg River) and then in seawater along a 45 km transect perpendicular to the coastline. The terrestrial freshwater (Q_{fw}) and recirculated seawater components of SGD (Q_{rsw}) where then estimated using a one-dimensional advection–dispersion model of solute transport from the coastline using the trends in the tracers with the strongest SGD signal in seawater.

2. Methods

2.1. Study area

The Limestone Coast region is part of the Gambier Basin, a large (30,000 km^2) economically and environmentally significant hydrogeological system at the border of South Australia and Victoria (Harrington and Lamontagne, 2013). Climate in the region is Mediterranean, with cool wet winters and hot dry summers. Daily maxima range up to 40 °C in summer and as low as 10–12 °C in winter. Annual rainfall ranges from 450 to 835 mm year^{-1} and declines inland. The hydrogeological system comprises the uppermost Tertiary Limestone Aquifer (TLA) and the lowermost Tertiary Confined Sands Aquifer (TCSA) and, at the coastline, is approximately 1000 m thick. The TLA is a dual porosity aquifer, with locally important karst features, and three sub-aquifers (Camel Back, Green Point and Greenways formations). The TLA is also the principal water supply for agriculture (vineyards, dairy), industry (forestry) and local communities (Mt Gambier, ~25,000 people) in the region. A major regional groundwater discharge area occurs at the southern edge of the basin, between Port MacDonnell and the Victorian border. Groundwater discharge to the coastline occurs in at least three forms: spring-fed creeks, beach springs and diffusively through beach sands. Only the uppermost section of the TLA outcrops at the coastline, but the TCSA has artesian conditions there. All sampling took place during a field trip held during 11–18 November 2012 in the Port MacDonnell – Victorian/SA border area, including at the Piccaninnie Ponds Conservation Park (Fig. 1). This period was selected because the regional water table tends to be highest at that time of year (austral spring; Harrington and Lamontagne, 2013).

The South Australian coastline is a high-energy environment due to strong seasonal winds and swells associated with the Southern Ocean (Dong et al., 2008; Walker, 2003). Tidal amplitude is generally ~1.2 m, swells frequently 2–4 m, and there is a seasonal pattern for higher mean sea levels (~0.2 m) in winter (Walker, 2003; Webster, 2010; Wood and Harrington, 2014). In the vicinity of Port MacDonnell, the Shelf is relatively narrow (~45 km) and is the site for an occasional regional upwelling system driven by summer southeasterly winds (Kämpf et al., 2004).

2.2. Tracer signatures in potential source waters

The constituents measured in all water sources included: electrical conductivity (EC), temperature, the radium quartet, ^{222}Rn, and noble gases (including ^{4}He). The water sources sampled included:

- Spring creeks (Piccaninnie Pond outlet, 8-Mile Creek, Deep Creek and Cress Creek)
- Regional groundwater (beach springs, TLA piezometers)
- Intertidal groundwater (at Brown Bay)
- Glenelg River estuary

The only potential source on non groundwater-derived surface runoff in the region is the Glenelg River, but surface runoff there is mainly episodic during winter. In contrast, flow from the spring creeks is nearly constant throughout the year. The regional groundwater wells selected for sampling aimed to capture the range of salinity found in groundwater in the area. In particular, one nested piezometer straddling the fresh/saltwater interface near the coastline was included (CAR059, CAR060, CAR061; Mustafa et al., 2012). Intertidal groundwater (that is, beach sand porewater) was sampled to characterise the potential signature of recirculated seawater (Lamontagne et al., 2008).

Spring creek water samples were collected as close to the outlet to the sea as possible (but above the high tide mark). Due to access problems, the Piccaninnie Pond outlet sample was collected from Piccaninnie Ponds. The Glenelg River estuary sample was collected from the boat dock at Nelson (Victoria). Samples from beach springs were collected at Piccaninnie Ponds Conservation Park (Fig. 1). This included two vents from the 'Spring 79' complex and another sample from an unnamed smaller spring ~1 km west from it (hereafter referred to as 'Goyder Spring'). Beach spring samples were collected by inserting a small PVC piezometer (1.5 m long with a 50 cm screen) in the spring vents and by pumping with a bilge pump into a well-rinsed container. Intertidal groundwater samples were collected by installing similar shallow PVC piezometers along a beach face at Brown Bay (Lamontagne et al., 2008). A sample from the surf zone was also collected at Brown Bay.

Water samples for electrical conductivity, temperature, radium and radon were collected using a bilge pump connected to an in-line filtering system (Puretec FP10M with a 20 μm cartridge) with nylon tubing or, for groundwater samples, a submersible pump (Grundfos MP1) with nylon tubing. Electrical conductivity was measured in the field with daily-calibrated probes and also back in the laboratory in a constant temperature room on a 50 mL, 0.45 μm filtered sample. Radon-222 samples were collected following the 'PET' method of Leaney and Herczeg (2006) that is, by extracting radon from 1.25 L water samples using a small volume of mineral oil/scintillant. Radium samples were collected in well-rinsed 20 L carboys (20–40 L per sample) and later extracted in a field laboratory using manganese dioxide (MnO_2) coated fibres ('Mn-fibre'; Moore, 1976) following the procedures outlined in Lamontagne et al. (2008). Two methods were used to collect samples for ^{4}He and other noble gases. Whenever possible, passive head-space diffusion samplers (Gardner and Solomon, 2009) were left overnight to equilibrate in the waterway. Alternatively (some groundwater, recirculated seawater and beach springs samples) a bubble-free water sample was collected in a copper tube following Weiss (1968).

2.3. Tracers in seawater

The trends in environmental tracers for seawater were evaluated by sampling seawater along a 45 km transect perpendicular to the coastline off Piccaninnie Ponds Conservation Park on 13 November 2012 on the charter boat 'Jaymar Star', from Port MacDonnell. The farthest station (45-km) was at the edge of the continental shelf and aimed to collect oceanic seawater, that is, to determine the background activity or concentration for the tracers. The period selected for the field study (austral spring) preceded the