Marine Chemistry 179 (2016) 44–55

Contents lists available at ScienceDirect

Marine Chemistry

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

Submarine groundwater discharge in Northern Monterey Bay, California: Evaluation by mixing and mass balance models

Alanna L. Lecher [a,*], Andrew T. Fisher [a], Adina Paytan [b]

[a] Department of Earth and Planetary Sciences, University of California Santa Cruz, Santa Cruz, CA 95064, United States
[b] Institute of Marine Sciences, University of California Santa Cruz, Santa Cruz, CA 95064, United States

ARTICLE INFO

Article history:
Received 28 July 2015
Received in revised form 19 January 2016
Accepted 20 January 2016
Available online 26 January 2016

Keywords:
Submarine groundwater discharge
Radium
Nutrients
Coastal

ABSTRACT

Monterey Bay, California (CA) receives nutrients from multiple sources, including river discharge, upwelling of deep water, and submarine groundwater discharge (SGD). Here we evaluate the relative importance of these sources to Northern Monterey Bay with a mixing model that integrates radium isotopes (^{224}Ra, ^{223}Ra, ^{228}Ra) and nutrient concentrations (SiO_4, NO_3, and PO_4). We also apply a radium isotope based mass balance model to determine SGD and associated nutrient fluxes to Monterey Bay at four sites. Our findings indicate that SGD is a relatively consistent source of nutrients across locations and seasons to Northern Monterey Bay, with fluid input on the order of 10–50 L min^{-1} m^{-1} of coastline, and the greatest impact of SGD fluxes is close to shore. In contrast, nutrient inputs from rivers and upwelling are more variable spatially and temporally. SGD nutrient fluxes are lower where seawater intrusion into coastal aquifers may limit flow of nutrient-rich meteoric groundwater into the coastal ocean.

1. Introduction

Submarine groundwater discharge (SGD) can be an important source of nutrients and other groundwater constituents to coastal ecosystems across the globe, particularly in areas where runoff, rivers, and other nutrient sources are minimal (Shellenbarger et al., 2006; Street et al., 2008; Kroeger and Charette, 2008; Knee and Paytan, 2011). SGD can be fresh meteoric groundwater or seawater that has entered the coastal aquifer through tide and wave action and is subsequently discharged back to the ocean (Knee and Paytan, 2011; Moore, 2006). In California (CA), SGD has been found to range from 6 to 43 L min^{-1} m^{-1} of shore at Stinson Beach, 4 to 9 L min^{-1} m^{-1} of shore at Huntington Beach, and <1 to 21 L min^{-1} m^{-1} of shore in San Francisco Bay (Boehm et al., 2006; de Sieyes et al., 2011; Null et al., 2012). In these locations, SGD is a source of nutrients to the coastal ocean water, although its importance relative to other nutrient sources is unclear. Most of the SGD at these sites is re-circulated seawater (Boehm et al., 2006; de Sieyes et al., 2011; Null et al., 2012).

No previous studies have evaluated the role of SGD as a source of nutrients to large open bays with natural nutrient inputs from upwelling processes, typical of Eastern Boundary Current Systems. We address this gap by quantifying the influence that SGD has on nutrient loading at a site where other nutrient sources to the coastal ocean (upwelling, deep mixing, rivers, runoff) are prevalent and well-studied. We use a mixing model to determine the area of influence of SGD and other nutrient sources to the coastal ocean, and a mass balance model to determine the nutrient loads from SGD.

Monterey Bay, CA lies within a national marine sanctuary and is characterized by a strong seasonal cycle with respect to nutrient and water sources. The major nutrient sources to Northern Monterey Bay (NMB) are upwelling of deep nutrient-rich water, deep mixing, river discharge, and runoff that is largely entrained in rivers (Breaker and Broenkow, 1994; Pennington and Chavez, 2000). Upwelling around NMB, which is largely governed by the intensity of off-shore winds, is strongest from March to August (Graham and Largier, 1997). However, the input of deep water in Monterey Canyon (central Monterey Bay) is more complex and can occur anytime of the year (Shea and Broenkow, 1982). The rainy season in Monterey Bay typically extends from October to April, and largely governs river flow into NMB, although a small amount of base flow (groundwater discharge to streams) may occur year round (Hanson, 2003). During the late summer many rivers that discharge into the NMB develop berms at their mouths, limiting exchange between the rivers and the bay. A companion study of one coastal site in NMB showed that SGD contributes to the nutrient load in this area throughout the year, and that nutrient loading through SGD can overcome nutrient limitation, increasing phytoplankton growth (Lecher et al., 2015b). Here we employ naturally occurring tracers to calculate the SGD flux at multiple sites in NMB using mixing and mass balance models; we also compare this flux to other nutrient sources to the surface water of the bay during different seasons.

Radium (Ra) has four commonly used isotopes, ^{224}Ra, ^{223}Ra, ^{228}Ra, and ^{226}Ra, with half-lives of 3.5 days, 11.5 days, 5.7 years, and 1600 years, respectively. Radium concentration is measured by way of

* Corresponding author.
E-mail address: alecher@ucsc.edu (A.L. Lecher).

http://dx.doi.org/10.1016/j.marchem.2016.01.001
0304-4203/

its decay to daughter isotopes. Therefore it is most commonly denoted by units of activity, disintegrations per minute (dpm) or Becquerels (Bq), per some volume of water. Brackish and saline groundwater are enriched in radium relative to seawater. River water, particularly if fed by groundwater base flow, can also be enriched compared to seawater (Moore and Krest, 2004). The enrichment is the result of interactions between groundwater and the aquifer substrate, in which radium is generated from the decay of parent isotopes and ultimately the origin isotopes of their decay series (^{238}U for ^{226}Ra, ^{232}Th for ^{228}Ra and ^{224}Ra, and ^{235}U for ^{223}Ra). This radium enrichment of brackish and saline groundwater makes radium a good natural tracer for submarine groundwater discharge (Moore, 1999).

2. Methods

2.1. Study site

Four sites in and around NMB were chosen for sampling as part of this study (Fig. 1). Three of the sites (listed in order north to south) Seabright Beach (SB, 36° 57.796′ N, 122° 0.524′ W), Rio Del Mar Beach (RDM, 36° 58.049′ N, 121° 54.291′ W), and Sunset Beach (SS, 36° 52.790′ N, 121° 49.685′ W) were located within NMB, whereas Salinas River Beach (SA, 36° 47.460′ N, 121° 47.594′ W) is located at the mouth of Elkhorn Slough, just south of NMB. Streams discharge into NMB near three of the study sites. The San Lorenzo River discharges into Monterey Bay at SB, Aptos Creek discharges at RDM, and Elkhorn Slough, which is connected to Carneros Creek, discharges ~1 km north of SA.

2.2. General sampling methods

Discrete seawater, groundwater, and river water samples were collected at each site, at the end of the wet season, herein referred to as “spring” (April–June 2012), and at the end of the dry season, herein referred to as “fall” (September–October 2012). Groundwater (which from here on refers to the fluid drawn from the coastal aquifer, the beach face where meteoric groundwater and re-circulated seawater mix) samples were collected from freshly dug pits or temporary PVC well points of a depth < 3 m. Near shore seawater (surf zone) and river water samples were collected by wading. Seawater samples were also collected along transects extending from shore to a common point at the mouth of Monterey Bay (Fig. 1). Ten seawater samples were collected from the surface, and another ten seawater samples were taken from 13–18 m below the surface (generally thought to be below the thermocline) from each transect (Kudela and Chavez, 2000; Ryan et al., 2008). Salinity and temperature were recorded with a YSI handheld Pro30.

2.3. Radium activity

Large volume (80–120 L) seawater and river water samples were collected using either submersible pumps or buckets, whereas groundwater samples (volume 13–120 L) were collected using submersible pumps. Sample water was passed through a plastic column containing MnO_2-coated acrylic fiber at a rate of <2 L min^{-1} for the collection of Ra isotopes (Moore, 1976). Samples were analyzed at the University of California Santa Cruz on a Radium Delayed Coincidence Counter

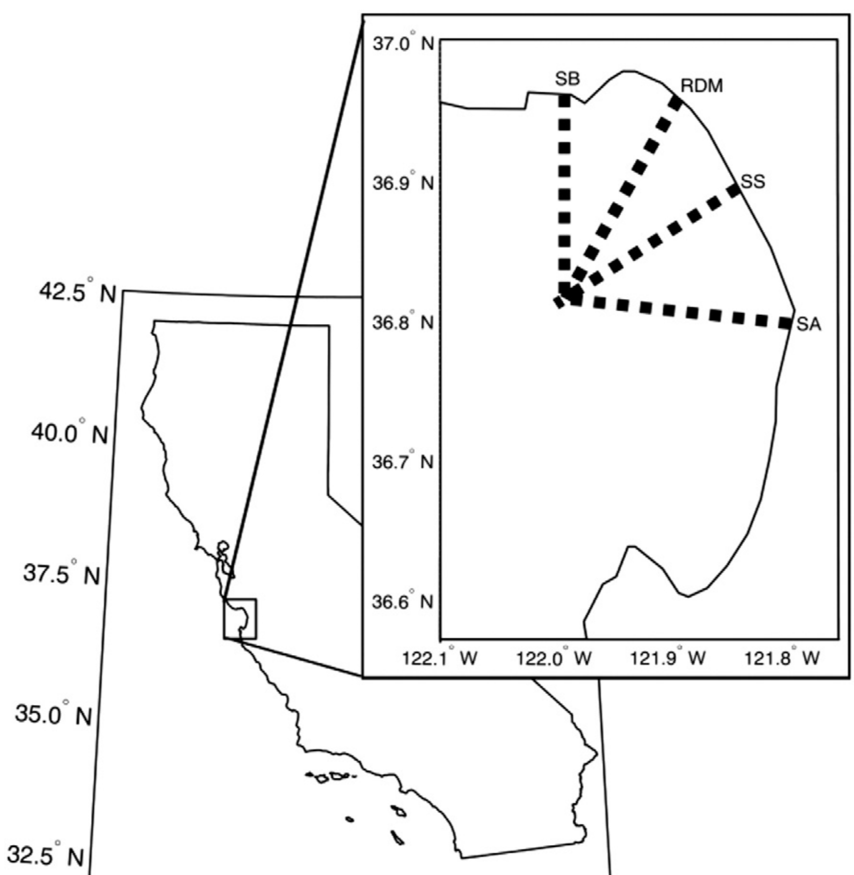

Fig. 1. A map of the transects and associated beaches in Monterey Bay.