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Coastal groundwater dynamics off Santa Barbara, California: Combining geochemical tracers, electromagnetic seepmeters, and electrical resistivity

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This paper presents repeat field measurements of ^{222}Rn and ^{223,224,226,228}Ra, electromagnetic seepage meter-derived advective fluxes, and multi-electrode, stationary and continuous marine resistivity surveys collected between November 2005 and April 2007 to study coastal groundwater dynamics within a marine beach in Santa Barbara, California. The study provides insight into magnitude and dynamics of submarine groundwater discharge (SGD) and associated nutrient loadings into near-shore coastal waters, where the predominant SGD drivers can be both spatially and temporally separated. Rn-222 and ^{223,224,226,228}Ra were utilized to quantify the total and saline contribution, respectively, of SGD. The two short-lived ^{224,223}Ra isotopes provided an estimate of apparent near-shore water mass age, as well as an estimate of the Ra-derived eddy diffusion coefficient, K_h (^{224}Ra $= 2.86 \pm 0.7$ m^2 s^{-1}; ^{223}Ra $= 1.32 \pm 0.5$ m^2 s^{-1}). Because ^{222}Rn ($t_{1/2} = 3.8$ day) and ^{224}Ra ($t_{1/2} = 3.66$ day) have comparable half-lives and production terms, they were used in concert to examine respective water column removal rates. Electromagnetic seepage meters recorded the physical, bi-directional exchange across the sediment/water interface, which ranged from −6.7 to 14.5 cm day^{-1}, depending on the sampling period and position relative to the low tide line. Multi-day time-series ^{222}Rn measurements in the near-shore water column yielded total (saline + fresh) SGD rates that ranged from 3.1 ± 2.6 to 9.2 ± 0.8 cm day^{-1}, depending on the sampling season. Offshore ^{226}Ra ($t_{1/2} = 1600$ year) and ^{222}Rn gradients were used with the calculated K_h values to determine seabed flux estimates (dpm m^{-2} day^{-1}), which were then converted into SGD rates (7.1 and 7.9 cm day^{-1}, respectively). Lastly, SGD rates were used to calculate associated nutrient loads for the near-shore coastal waters off Santa Barbara. Depending on both the season and the SGD method utilized, the following SGD-derived nutrient inputs were computed (mol per day per meter of shoreline): $NH_4^+ = 0.06$–0.29 mol day^{-1} m^{-1}; $SiO_4 = 0.22$–0.29 mol day^{-1} m^{-1}; $PO_4^{3-} = 0.04$–0.17 mol day^{-1} m^{-1}; $[NO_2^- + NO_3^-] = 0$–0.52 mol day^{-1} m^{-1}; dissolved inorganic nitrogen (DIN) = 0.01–0.17 mol day^{-1} m^{-1}, and dissolved organic nitrogen (DON) = 0.08–0.09 mol day^{-1} m^{-1}. Compared to the ephemeral nature of fluvial and marine inputs into this region, such SGD-derived loadings can provide a sustained source of select nutrients to the coastal waters off Santa Barbara, California that should be accounted for in mass balance estimates.

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1. Introduction

It is now well accepted that submarine groundwater discharge (SGD), an almost ubiquitous coastal process, may substantially impact certain near-shore material budgets (Capone and Bautista, 1985; Moore, 2006; Burnett et al., 2006; Swarzenski, 2007; Charette et al., 2008). While the contribution of SGD-derived nutrients, bacteria, carbon, and select trace elements such as Ba or U (Charette and Sholkovitz, 2006; Swarzenski and Baskaran, 2007) can vary widely depending on both local hydrogeologic conditions and anthropogenic perturbations, accurate assessments of the spatial and temporal distribution of SGD along a particular coastline remain rare (Burnett et al., 2002; Dulaiova et al., 2006b). This paucity of reliable data stems in large part in that SGD remains the 'hidden' vector in water and material transport from land to the sea, and that the physical drivers of SGD are complex, often interrelated, and still poorly constrained (Taniguchi, 2002; Michael et al., 2005; Robinson et al., 2007a,b). Furthermore, the discharge of submarine groundwater is usually expressed not through well-defined marine springs (Swarzenski et al., 2001), but rather through diffuse discharge that is often ephemeral and patchy in nature (Burnett et al., 2002; Taniguchi et al., 2003).

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Nonetheless, significant advances have recently been made in the application of select U/Th-series radionuclides as quantitative tracers of SGD (Moore, 1996, 2000a,b; Moore and de Oliveira, 2008; Burnett et al., 2001, 2002, 2003; Charette et al., 2001, 2008; Dulaiova and Burnett, 2004, 2006; Dulaiova et al., 2005, 2006a,b). Such tracer techniques can yield unprecedented information on: (i) SGD 'hotspots'; (ii) the source waters for SGD; (iii) the magnitude and dynamics of SGD rates; and (iv) the relative composition of SGD (i.e., fresh versus saline contributions). As proxies for fluid exchange these tracers are limited by how well they move with a mixed-salinity water parcel, and local quantification of fluid exchange is still most directly measured by some seepage meter device (Mulligan and Charette, 2006). Seepmeters, outfitted with autonomous salinity, temperature, and pressure sensors, can measure the bi-directional exchange of fluid across the sediment/water interface with high resolution (Taniguchi and Fukuo, 1993; Taniguchi et al., 2003, 2007). Such datasets can provide useful constraints on the geochemical tracer-derived SGD results (Burnett et al., 2006; Swarzenski et al., 2007a). An additional complementary tool to study the movement of the fresh water/salt water interface and to map the geographic extent of a coastal SGD zone is stationary (land-based) electrical resistivity (Swarzenski et al., 2006a, 2007a,b; Taniguchi et al., 2007).

In environments that are fresh water limited or have low hydraulic gradients, the submarine exchange of groundwater often contains a large component of recycled sea water (Colbert and Hammond, 2007a,b; Colbert et al., 2008a,b; Weinstein et al., 2007). In such systems, even though the net discharge may be small or even negative (i.e., sea water infiltration), this continuous cycle of recharge and discharge, driven by waves and tides, may still significantly impact the flow of nutrients from land to the sea. In this paper, we address the exchange of groundwater with sea water at West Beach in Santa Barbara, California (Fig. 1), using a suite of geochemical tracers and electrical geophysical techniques. From

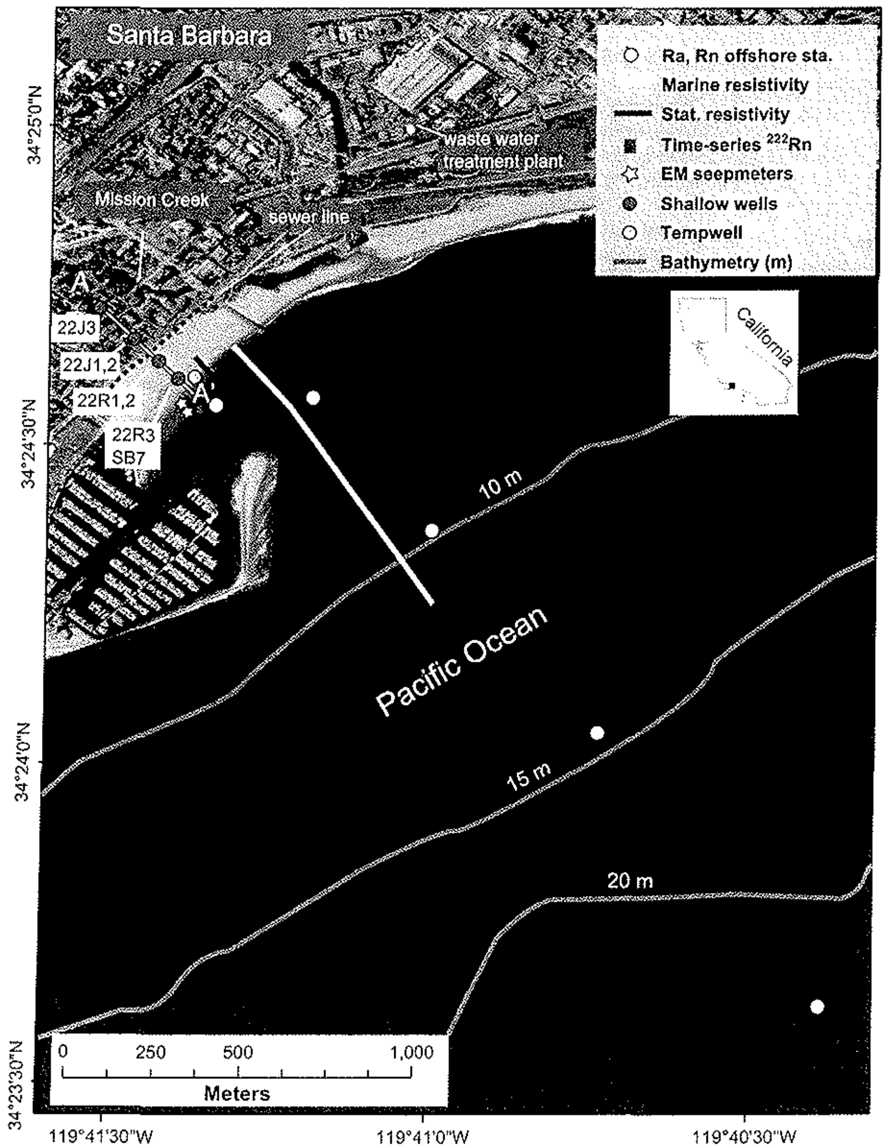


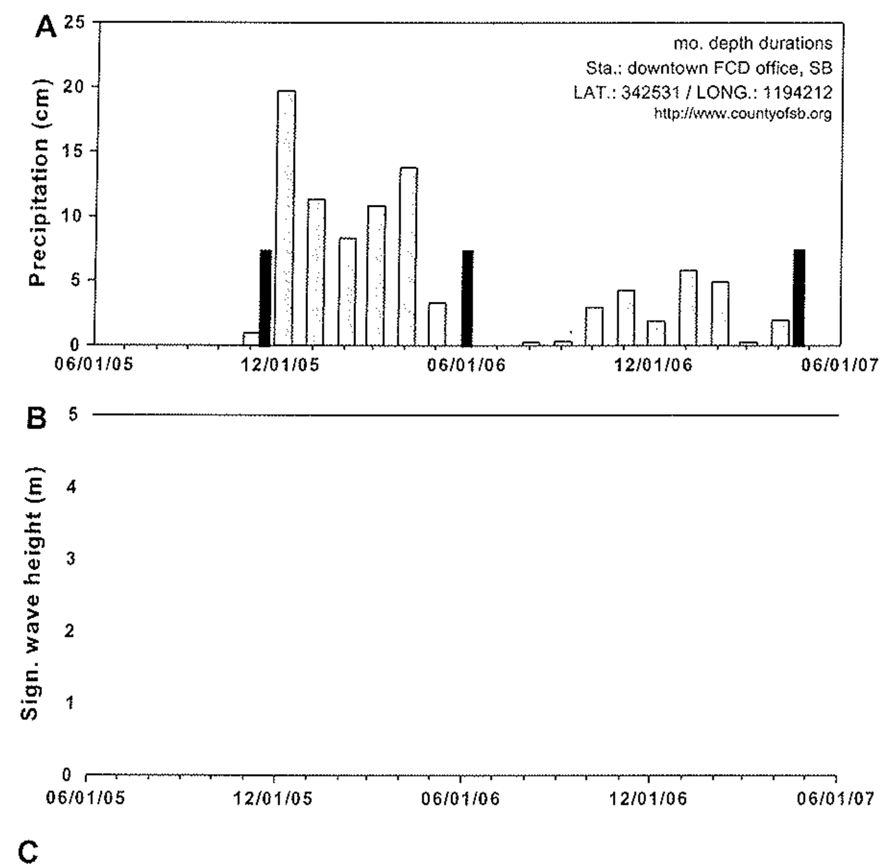
Fig. 1. West Beach, Santa Barbara, California showing the position of the electromagnetic seepmeters, time-series Rn deployments, offshore transect sites (Rn and Ra) and the streamer location for land-based, multi-electrode and the marine continuous resistivity profile. Also shown is the shore-parallel running sewer line (which may be a source of excess nutrients and bacteria to the beach), the nearby waste water treatment plant, and the position of the hydrogeologic transect (A–A′) shown in Fig. 3.

calculated fluid exchange rates per season, we are able to derive SGD nutrient loading estimates. On the basis of our results, we have determined that the wave/tide-driven exchange of shallow groundwater with coastal sea water can convey a sustained load of select nutrients and trace elements to the near-shore waters off Santa Barbara, California, even without a net flow of fresh groundwater towards the sea.

2. Study site

Field data were collected at a meso-tidal, sandy beach ('West Beach') adjacent to Santa Barbara, California (Fig. 1), where fecal indicator bacteria (FIB) in the surf zone are occasionally present at high enough concentrations to necessitate beach warnings or closures (Izbicki et al., in review). Three beach and water column sampling campaigns targeted spring tide (November 2005, April 2007) and neap tide (May/June 2006) cycles, as well as seasonal variations (Fig. 2). Mission Creek, which discharges adjacent to West Beach, is an obvious potential source for FIB, as are subaerial and submarine groundwater discharge (Boehm et al., 2004; Paytan et al., 2004; Boehm and Weisberg, 2005; Boehm, 2007; Yamahara et al., 2007) and any possible leakage from the shore-parallel municipal sewer line that lies buried beneath the landward edge of West Beach. While a companion report addresses the various sources of FIB and their hydrologic forcing in coastal Santa Barbara (Izbicki et al., in review), here we examine the marine effects (i.e., tides) on groundwater exchange and associated nutrient loading to the coastal waters of Santa Barbara Harbor. Details on the hydrogeologic setting of this study site can be found in Muir (1968), Martin (1984), and Freckleton et al. (1998).

Santa Barbara, located about 150 km northwest of Los Angeles along the Pacific coast of the United States, has a Mediterranean-



type climate characterized by relatively dry and mild summers and winter months that can be periodically cool and wet. Temperatures are moderated by the sea; mean winter temperatures are ~13 °C, while summer temperatures average 18 °C. The population of Santa Barbara exceeded 90,000 in 2004 (http://www.santabarbaraca.gov) and is confined along a narrow (~5 km wide) but highly developed coastal strip that is bounded to the north by the Santa Ynez coastal mountains. Average annual rainfall in Santa Barbara is ~45 cm and about 95% falls between November and March (Fig. 2). The Santa Barbara watershed is drained by several streams that are mostly intermittent along their lower reaches, including Mission Creek, which flows through the town's center and discharges into the Pacific Ocean within the study site (MacFadden et al., 1991).

Nearly all groundwater recharge and surface water flow is derived from precipitation within the region (Martin, 1984). Principal groundwater-bearing deposits of the regional aquifer system include the alluvium (terrace deposits, poorly-sorted sands, gravel, silt and clay) and the Santa Barbara Formation (marine origin, fine to coarse sands, gravel, silt and clays) (Freckleton et al., 1998). Historically, some groundwater has been locally artesian. Under sustained and heavy groundwater pumping along the coast, salt water intrusion is likely to occur wherever the water table of a coastal aquifer approaches sea level. In Santa Barbara, since the early 1960s, the groundwater levels at the coast have been below sea level, and salt water has locally intruded the shallow deposits as water levels have declined. In the late 1970's, groundwater levels declined by more than 30 m in response to increased municipal pumping, and salt water subsequently intruded deeper water-bearing deposits close to the coast. Presently, salt water intrusion along coastal Santa Barbara is carefully monitored (Martin, 1984).

Winter precipitation events can deliver substantial amounts of dissolved and particulate nitrogen, phosphate, and carbon to the coastal ocean, particularly from watersheds heavily influenced by agriculture and urban development (Beighley et al., 2008). During winter months, marine nitrogen inputs tend to be low, which contributes to a strong seasonality in both physical and geochemical signals in the coastal waters off Santa Barbara (Warrick et al., 2005; McFee-Shaw et al., 2007).

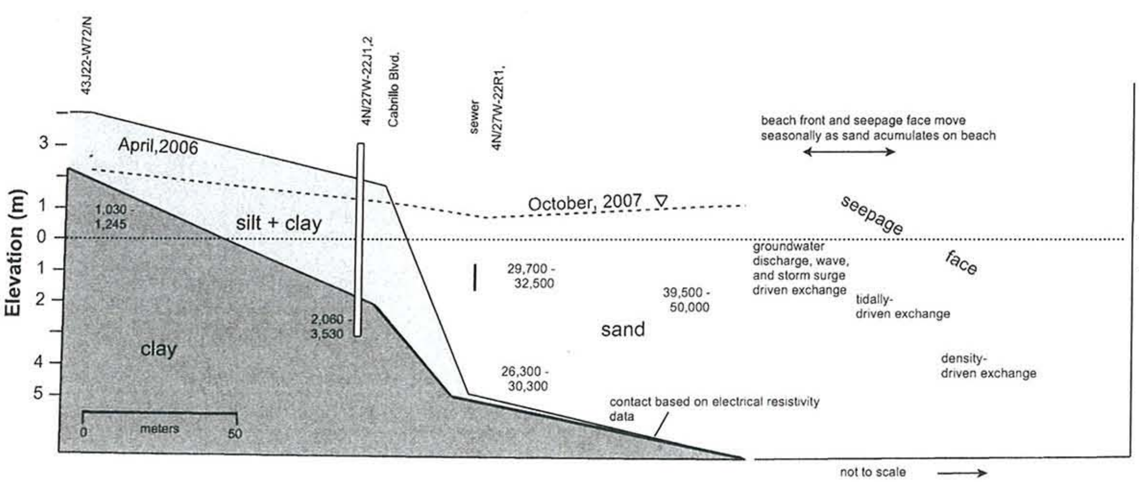
3. Field and analytical methods

3.1. Groundwater

A set of shallow monitoring wells, located either along a shore-perpendicular beach transect (Fig. 3), or within close proximity of the beach, were sampled in mid-November 2005, late May/early June 2006, and in mid-April 2007 for groundwater ^{222}Rn, $^{223,224,226,228}Ra$, nutrients (NH_4^+, SiO_4, PO_4^{3-}, $[NO_2^- + NO_3^-]$, DIN, TDN, and DON). For the duration of the study, groundwater levels in these monitoring wells were continuously recorded with pressure transducers and manually confirmed using a hydro-tape (Izbicki et al., in review). During each of the three sampling efforts, the monitoring wells were sampled following standard USGS protocols that included purging at least three well volumes before sample collection. In April 2007, a temporary well ('tempwell') was installed just landward of the high tide line by excavating sand to a depth of 1.5 m and installing a 10 cm diameter slotted irrigation pipe that was also screened to exclude larger-sized particulates. This tempwell was instrumented with a Solinst CTD DIVER to monitor salinity, temperature, and water levels (pressure), and also continuously (30 min updates) sampled for ^{222}Rn using one RAD7 ^{222}Rn monitor. The tempwell was sampled for a suite of nutrients and trace metals, before, during, and after a low tide event. The tempwell groundwater time-series was also complemented with simultaneous water column grab samples collected in the adjacent swash zone ('surface water'), as well as with a suite of time-series samples collected in the adjacent shallow groundwater well SB7 (see Fig. 3 for locations of SB7, tempwell, and surface water sites). Nutrients were immediately preserved in the field and analyzed at the Woods Hole Oceanographic Institution (WHOI) nutrient facility as per methods described in Charette and Buesseler (2004).

3.2. Surface water column

The near-shore coastal waters adjacent to Santa Barbara harbor and beach were sampled to achieve the following three objectives: (1) continuous ^{222}Rn surveys were first used to identify potential SGD 'hotspots' where elevated ^{222}Rn might reveal enhanced



Malibu Creek, Malibu Lagoon and Surfrider Beach 2009 Human Specific Bacteriodales

Site	2/16/09 Wet-Open	3/20/09 Dry-Open	4/29 & 4/30/09 Dry - Open	5/5 & 5/7/09 Dry-Open	5/21/09 Dry-Transitional Open	7/18/09 Dry-Closed	10/30/09 Dry-Closed	Total Samples
1	N	N	-	-	N	N	N	5
2	N	N	-	-	N	N	-	4
2D[1]	N	-	-	-	-	N	-	2
3	**Y**	N	-	-	N	**Y**	I	4
3D[1]	N	N	-	-	N	N	-	4
4 (MC1)	-	N	N	-	N	N	-	4
5 (MC3)	**Y**	N	N	-	N	N	N	6
6	N	N	-	-	N	**Y**	N	5
7 (MC4)	N	N	N	-	N	**Y**	N	6
8	N	N	-	-	N	N	-	4
8D[1]	N	N	-	-	-	-	-	2
9	N	N	-	-	N	N	-	4
10	N	N	-	-	N	N	-	4
11	-	-	-	-	N	N	-	2
A	I	N	-	-	N	N	-	3
B	N	N	-	-	N	N	-	4
C	N	N	-	-	N	N	-	4
Y (MC5)	-	N	NN	NN	N	N	-	7
X	-	N	-	-	N	N	-	3
Bridge (MC2)	-	N	N	-	N	I	-	3
	2 of 14	**0 of 18**	**0 of 6**	**0 of 2**	**0 of 18**	**3 of 18**	**0 of 4**	**5 of 80**

[1] No samples taken in dry weather from drains at 2 D, 3D or 8 D because there were no dry weather discharges from drains. *Samples at these sites were taken from where drains would outfall within the Lagoon if there had been a discharge. Therefore these samples could be counted as duplicates samples of 3, 2 and 8 during dry weather. Samples were collected at 3D and 8D in March; 3D in May; and 2D and 3D in July.*

Y Positive for HSB
N Negative for HSB and sample was collected from this site.
I No result due to interference and sample was collected from this site.
\- No sample taken from this site on a specific date.

No drain samples were taken in dry-weather. A total of 80 samples were collected and analyzed for HSB with only 5 samples positive for HSB. Only 6.25% of the samples were positive in Malibu Creek, Malibu Lagoon and Surfrider Beach. A similar study was conducted in Santa Monica Canyon for HSB with 60% of the samples positive for HSB in less urbanized channels and 35% in more urbanized channels.