

Quantification of point-source groundwater discharges to the ocean from the shoreline of the Big Island, Hawaii

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Abstract

Aerial thermal infrared imaging has revealed that submarine groundwater discharge (SGD) along the western coast of the Big Island of Hawaii is often focused as point-source discharges that create buoyant groundwater plumes that mix into the coastal ocean. We quantified the SGD fluxes associated with several plumes using natural geochemical tracers. Offshore transects of ²²²Rn and ²²⁴Ra show elevated activities and corresponding low salinities in the nearshore waters within the plumes, indicating that these naturally occurring radionuclides can be useful tracers of groundwater inputs in this area. Using a series of simultaneous mass balance equations for water, salt, and radon, we determined the groundwater fluxes of six plumes near Kona, Hawaii. The average SGD fluxes ranged from 1100 m³ d⁻¹ to 12,000 m³ d⁻¹ of total (fresh + saline) SGD. The fresh (meteoric) groundwater equivalents for the same flows, modeled by adjusting the groundwater end member to reflect freshwater rather than brackish groundwater composition, ranged from 630 m³ d⁻¹ to 8600 m³ d⁻¹. These fluxes are in general agreement with earlier results obtained by hydrological water budgets and physical oceanographic analyses of fresh SGD rates in this region.

Submarine groundwater discharge (SGD) has become a widely recognized transport mechanism between land and the coastal ocean. In the past, SGD was considered a hydrologic curiosity (Kohout 1966), but over the past few decades, investigations have shown that water and especially chemical fluxes via SGD may rival those of riverine inputs in some places (Cable et al. 1996; Church 1996; Burnett et al. 2006a). Groundwater typically contains elevated nutrient concentrations several times higher than those found in nearby rivers, so even though SGD may be volumetrically much less significant than river discharge, the nutrient inputs from SGD can be substantial (Garrison et al. 2003; Kim et al. 2005; Swarzenski et al. 2007; Santos et al. 2008). Continued residential and agricultural development in coastal areas is causing ever increasing N and, to a lesser degree, P concentrations in the groundwater. The results of this increased nutrient loading can be twofold: first, supply of the limiting nutrient increases coastal primary production, and, second, in extreme cases, the limiting nutrient could switch from N to P (Slomp and Van Cappellen 2004).

SGD is not simply freshwater but is a mixture of fresh groundwater that flows from the land and seawater that is driven landward beneath it. Many factors can influence the rates and patterns of fresh SGD as it occurs at the coast. High precipitation rates and aquifer permeability lead to elevated groundwater recharge rates relative to surface stream recharge. Steep relief between inland areas and the coast can generate a strong hydraulic gradient that drives groundwater seepage at the coast. Oceanic forcing within the subterranean estuary drives the recirculated seawater component of SGD. For example, high tidal levels and

wave activity can drive seawater into the subsurface, with subsequent discharge (Moore 1999). In all cases, the permeability of the aquifer(s) exerts an important control on hydraulic conductivity. It is the combined presence of several of these forcing factors that led Zektser (2000) to hypothesize that tropical islands, such as Hawaii, would have disproportionately high SGD fluxes compared to continental areas.

By nature, SGD is often spatially and temporally variable. Taniguchi et al. (2008), for example, used automatic seepage meters to show that SGD rates differ drastically along a shore-normal transect in the Yellow River delta and that the patterns at any one particular location change greatly over the course of several years. This characteristic makes quantifying SGD fluxes a very difficult task for both local and regional assessments. Natural geochemical tracers have proven to be effective tools for local-scale analysis, but an approach is needed for relating such results to a regional basis (Burnett et al. 2006b). Radon (²²²Rn) and radium isotopes (²²³Ra, ²²⁴Ra, ²²⁶Ra, and ²²⁸Ra) have been the most extensively used naturally occurring tracers for assessing SGD (*see reviews in* Burnett et al. 2006b; Swarzenski 2007; Charette et al. 2008). These radioisotopes are effective tracers because they are often enriched in groundwater relative to surface water, are relatively easy to measure, and are generally inert in marine settings. In fresh groundwater environments, radium is particle reactive and tends to be attached to aquifer solids. But once encountering saline waters, radium is removed from surfaces via ion exchange and released into solution. Gaseous radon is almost always found at elevated activities in groundwater regardless of composition. These characteristics led Mulligan and Charette (2006) to suggest that radon acts as a tracer for total SGD, whereas radium is best suited as a tracer of saline, recirculated seawater fluxes.

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We used these natural geochemical tracers to ground-truth several surface water SGD plumes of point-source origin along the Kona coast of the Big Island of Hawaii. We present offshore trends in ^{222}Rn ($T_{1/2} = 3.8$ d), ^{224}Ra ($T_{1/2} = 3.6$ d), and salinity to reveal nearshore inputs of these natural tracers. We then use a series of coincident mass balance equations for ^{222}Rn , salt, and water to model the SGD fluxes of six separate groundwater discharge sites. Our model calculations are based on continuous time-series measurements of these tracers' concentrations near the source of each of the discharge plumes over several days. Using different representative values for the overall and meteoric groundwater end members in these models, we examine both the total and the freshwater component of the discharge.

Methods

Study site—The coastline of western Hawaii (Fig. 1) is very arid, receiving a mean annual rainfall of only 25 cm. Within 10 km of the coastline, however, the mountain slopes receive an average of 102 cm annually. This is the likely area of groundwater recharge, and no rivers or streams exist in the area to act as conduits for runoff to the coast (Kay et al. 1977). Performing these studies on this side of the island thus eliminated the need to account for precipitation and riverine inputs to the coastal ocean, as virtually all freshwater input to the sea occurs as SGD.

Diffuse groundwater flow occurs along the coastline, but we emphasize here the focused, point-sourced groundwater discharges found at or very close to the shoreline (Johnson 2008; Johnson et al. 2008). In aerial thermal infrared (TIR) images examined along this shoreline (e.g., Fig. 2), it appears that point-source discharges dominate the flow. SGD exits at these point sources to form large surface water plumes of relatively cool, brackish groundwater that buoyantly float out from their exit points and mix seaward into the coastal ocean (Fig. 2). Permeability in the vesicular basalt country bedrock is high and enhanced by lava tubes, clinker zones, and downslope flow along and between individual lava flow sheets. In general, these plumes are commonly associated with coastal embayments, which we believe is the likely manifestation of subsurface focusing of water table flow lines toward such sites.

Intensive field-based campaigns were carried out at six SGD points and surrounding regions along the Kailua-Kona coast (Fig. 1). Kiholo Bay and Kailua-Kona Harbor were sampled in May 2007. Honokohau Harbor was examined in February 2006. Three distinct SGD plumes were measured further south in Kealahou Bay: Queen's Bath and Manini Beach in August 2006 as well as Kahauloa Bay, which was examined in both August 2005 and February 2006. Specific site characteristics are described in more detail below. Temperature-calibrated TIR images of these sites' freshwater plumes are detailed in Johnson (2008).

Measurements—Radon was measured using a RAD7 radon-in-air monitor (DurrIDGE) modified to analyze radon

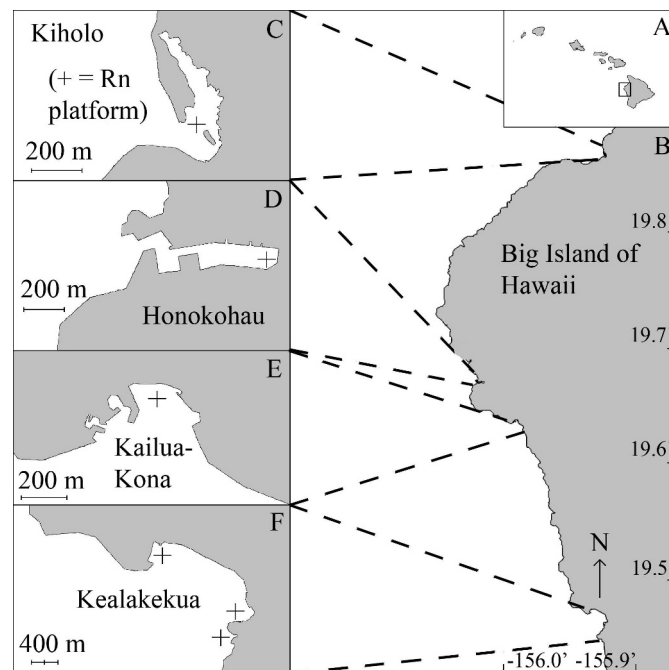


Fig. 1. Map of the (A) Hawaii Island chain, featuring the (B) western coast of the Big Island of Hawaii. Each plus symbol represents the radon platform position in the groundwater plumes associated with (C) Kiholo Bay, (D) Honokohau Harbor, (E) Kailua-Kona Harbor, and (F) Queen's Bath, Manini Beach, and Kahauloa Bay (north to south) in Kealahou Bay.

in water. A submersible pump delivered surface water (~ 1 -m depth) to an air–water exchanger that degassed the radon from the water (Burnett et al. 2001). During each continuous time-series analysis, we deployed the RAD7 system on a stationary floating platform within the groundwater plume at a known distance (up to ~ 160 m) from the source. Radon activities were integrated over either 30 or 60 min to achieve sufficient precision with reasonable resolution. In addition, we deployed a bottom-mounted pressure-based water-level meter (HOBO Water Level Logger, Onset Corp.) and an in situ conductivity probe (YSI 600 XLM Sonde) affixed to the submersible pump. Meteorological parameters (wind speed, air temperature, and radon in air activity) were monitored to correct for radon evasion losses to the atmosphere using standard gas exchange equations (MacIntyre et al. 1995).

For the offshore transects, we followed the procedure outlined by Dulaiova et al. (2005) to continuously survey for surface water radon activities. Three RAD7 monitors were connected in parallel to allow for better time integration (10 min for each data point), thereby maximizing the associated spatial resolution as the boat moved along the transect. We continuously monitored conductivity, temperature, and Global Positioning System coordinates during the offshore transects.

Relative to most continental margin sites we have monitored, radon levels in both groundwater and surface water in Hawaii are found at very low concentrations.

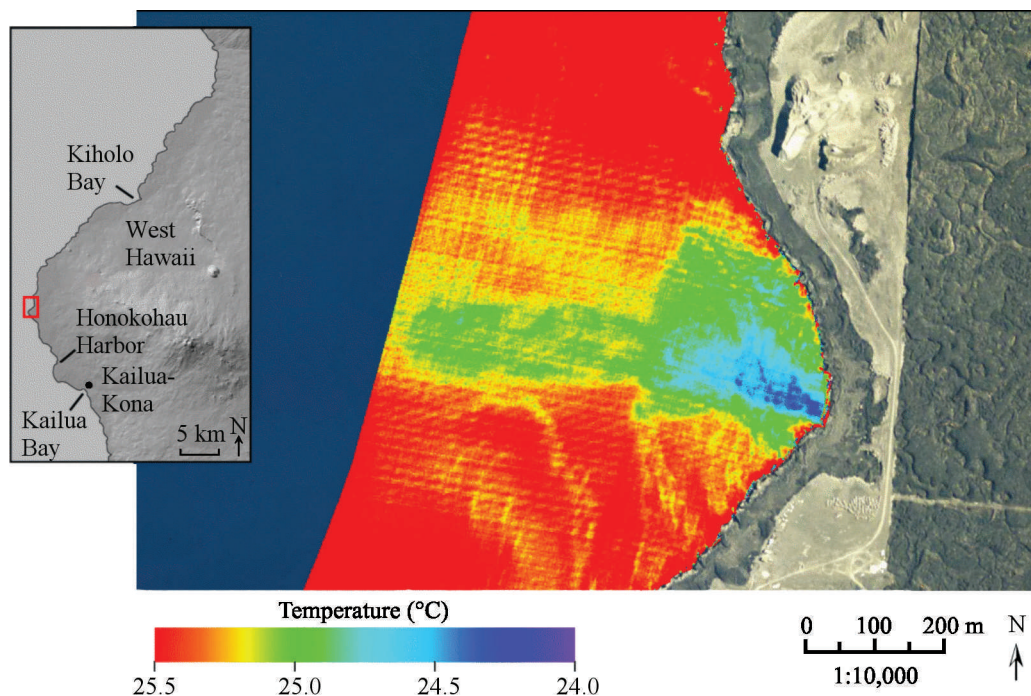


Fig. 2. Example of aerial TIR image of a buoyant SGD West Hawaii SGD plume, located north of Kailua-Kona in the vicinity of Kona International Airport, Makako Bay ($19^{\circ}44'09''\text{N}$, $156^{\circ}03'11''\text{W}$). Note the marked cool surface water temperature of the plume relative to ambient ocean water. Image from Johnson (2008).

Because of the low levels, we collected groundwater samples in 6-liter polyethylene bottles (Stringer and Burnett 2004) designed to be mounted directly to a RAD7 via a closed air loop (Lee and Kim 2006). The internal pump of the RAD7 circulated air through a diffusion stone in the bottle that released the radon gas from the water and then circulated it continuously through the RAD7 during measurement. Despite the relatively low groundwater activities, radon was still much higher than in the coastal ocean waters and thus serves as a quantitatively effective tracer.

An additional method used to assess the radon activity in groundwater utilized a porous membrane tubing (Accurel tubing made by Membrana) to collect radon from the water via diffusion across the membrane (Freyer et al. 2003; Schubert et al. 2008). A closed air loop was created between the RAD7 and the membrane tubing to allow for constant recirculation of the airstream until it reached activity equilibrium with the radon in the water. This method was deployed only one time in an open, brackish well near the Manini Beach site.

Radium isotopes were collected onto acrylic fibers impregnated with MnO_2 (Moore and Reid 1973). Large volumes (up to 200 liters) of seawater and groundwater were pumped at slow rates ($\sim 1 \text{ L min}^{-1}$) through cartridges containing this Mn fiber. Because of the relatively low radium activities in the water, even these sample volumes were often insufficient to collect enough radium to detect reliably. Short-lived radium isotopes (^{223}Ra and ^{224}Ra) were counted via a delayed coincidence counter system (RaDeCC; Moore and Arnold 1996), and the long-

lived isotopes (^{226}Ra and ^{228}Ra) were measured via gamma spectrometry (Dulaiova and Burnett 2004).

Mass balance model to quantify SGD—Groundwater fluxes are commonly modeled using a radon box model introduced by Burnett and Dulaiova (2003). This model assumes that the flow is occurring in a more or less uniform pattern upward through the seabed and thus expresses SGD rates in terms of vertical advection velocities (e.g., cm d^{-1} or $\text{cm}^3 \text{ cm}^{-2} \text{ d}^{-1}$). In order to convert these results into an absolute volumetric flux, one must know the area over which seepage is occurring. The point-source nature of the discharges in our study sites, however, dictated the need for a different approach because the flows originate from discrete portals along the shoreline. For this setting, we elected to use a modified version of a LOICZ-style box model approach (Gordon et al. 1996) to derive SGD rates from the point-source discharges. We defined a domain that captures the flow across a measured cross section and includes a salt balance to further constrain the assessments. The model used here was originally presented by Peterson et al. (2007), but our current version contains some slight modifications from that original form.

The non-steady-state mass balance box model employed in this study uses the relatively high-radon, low-salinity nature of discharging groundwater and the relatively low-radon, high-salinity character of open ocean water to determine the flux of groundwater and seawater into and out of a specified control volume, which in our case is described as a “plume” (Fig. 3). Water inputs to the plume are considered from open ocean intrusion (Q_{IN}) and SGD

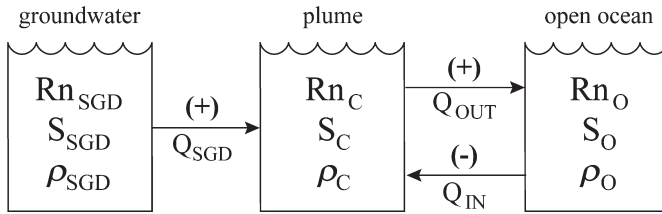


Fig. 3. Diagram of model variables and their interactions used to simulate the changing water fluxes into and out of the control volume, defined here as the groundwater “plume.” See text for details.

(Q_{SGD}). These fluxes are balanced by plume water loss to the open ocean (Q_{OUT}). By convention, we consider fluxes directed offshore from the plume to be positive (Q_{SGD} and Q_{OUT}), whereas landward fluxes are negative (Q_{IN}). We ignore any direct rainfall fluxes that are negligible at these sites compared to the other fluxes over these short time scales (hours to days). Constant values for each site are assigned to the radon and salinity end members for groundwater (Rn_{SGD} and S_{SGD} , respectively) and for open ocean water (Rn_O and S_O , respectively). Continuously monitoring the plume radon (Rn_C) and salt (S_C) concentrations allows us to examine how the groundwater flux changes over time. Here, reference to the measured radon activity implies “excess” radon, meaning the total radon activity in the water minus that activity supported by its parent, ^{226}Ra . Water densities (ρ_{SGD} , ρ_O , and ρ_C) are included to convert salinity to absolute salt mass.

Other parameters required by the model include the length, width, and depth of the groundwater plume. We take the length term (l) to be the distance between the SGD source location at the shoreline and the site where the radon and salinity are continuously monitored. Width (w) is taken as the shore-parallel distance across the buoyant water plume at the site of the radon platform; this is often based on measurements from the TIR images in Johnson (2008). At sites where the freshwater plume extends to the seabed at the radon platform, we take the measured depth record (d) as the vertical dimension for the model. In places where vertical temperature and salinity (T/S) profiling revealed a stratified water column (Johnson 2008; A. G. Johnson unpubl.), we instead use the thickness of the buoyant layer as a constant depth, which is a reasonable approximation within the length scales we are considering. At all of our study sites, the water depth dropped quickly within a few meters of the shoreline and thereafter maintained a constant depth to the radon platform. Thus, we estimate the plume volume as $V = lwd$.

The model is developed using three simultaneous mass balance equations for water, salt, and radon to solve for three unknowns: Q_{SGD} , Q_{IN} , and Q_{OUT} . We first parameterize the model using average values over an entire tidal cycle (24 h in this case) using the following equations for water balance:

$$\frac{\Delta V_C}{\Delta t} = Q_{OUT} - Q_{IN} - Q_{SGD} \quad (1)$$

for salt balance:

$$\frac{lw(S_{C(t+1)}\rho_{C(t+1)}d_{C(t+1)} - S_{C(t)}\rho_{C(t)}d_{C(t)})}{\Delta t} = S_C\rho_C Q_{OUT} - S_O\rho_O Q_{IN} - S_{SGD}\rho_{SGD} Q_{SGD} \quad (2)$$

and for radon balance:

$$\frac{lw(Rn_{C(t+1)}d_{C(t+1)} - Rn_{C(t)}d_{C(t)})}{\Delta t} = Rn_C Q_{OUT} - Rn_O Q_{IN} - Rn_{SGD} Q_{SGD} \quad (3)$$

Terms marked with subscripts (t) and ($t+1$) refer to consecutive measurements made throughout the time-series deployment. We ultimately solve these three equations for Q_{SGD} . For the parameterization, the left sides of the equations represent the average hourly change in water volume ($\Delta V_C \Delta t^{-1}$), salt mass ($\Delta S_C \Delta t^{-1}$), and radon activity ($\Delta Rn_C \Delta t^{-1}$) throughout a complete tidal cycle. The model used previously by Peterson et al. (2007) assumed steady-state conditions over the course of a tidal cycle (therefore, $\Delta V_C \Delta t^{-1}$, $\Delta S_C \Delta t^{-1}$, and $\Delta Rn_C \Delta t^{-1}$ were assumed to be 0), but parameterizing according to this current approach eliminates any error associated with that assumption. The right sides of the equations represent the cumulative effects of the coastal groundwater plume fluxing offshore, the offshore water flowing into the system, and the groundwater fluxing into the system. Solving these equations for the three unknowns, Q_{OUT} , Q_{IN} , and Q_{SGD} , establishes average water flux values over the tidal cycle.

We next examine the dynamics of the flows by using smaller time increments (as in $Q + \Delta Q$). A few processes inherently require an inverse relationship between tracer end member concentration and the corresponding water flux to achieve the expected response. For these processes, we expect the water flux to decrease if the end member tracer concentration increases, so we use $(Q - \Delta Q)$. Radon input via SGD and salt input from the open ocean follow this convention. All other fluxes are represented as $(Q + \Delta Q)$.

The resulting equations are used for time-series modeling for water balance:

$$\frac{\Delta V_C}{\Delta t} = (Q_{OUT} + \Delta Q_{OUT}) - (Q_{IN} + \Delta Q_{IN}) - (Q_{SGD} + \Delta Q_{SGD}) \quad (4)$$

for salt balance:

$$\frac{lw(S_{C(t+1)}\rho_{C(t+1)}d_{C(t+1)} - S_{C(t)}\rho_{C(t)}d_{C(t)})}{\Delta t} = S_C\rho_C(Q_{OUT} + \Delta Q_{OUT}) - S_O\rho_O(Q_{IN} - \Delta Q_{IN}) - S_{SGD}\rho_{SGD}(Q_{SGD} + \Delta Q_{SGD}) \quad (5)$$

and for radon balance:

$$\frac{lw(Rn_{C(t+1)}d_{C(t+1)} - Rn_{C(t)}d_{C(t)})}{\Delta t} = Rn_C(Q_{OUT} + \Delta Q_{OUT}) - Rn_O(Q_{IN} + \Delta Q_{IN}) - Rn_{SGD}(Q_{SGD} - \Delta Q_{SGD}) \quad (6)$$

Atmospheric evasion losses of radon as well as decay losses, while minimal (often $<1\%$ of radon inventory for the time steps used here), were accounted for by including these loss terms in Eq. 6. These losses are extrapolated through the entire domain, which extends to the shoreline. Solving these equations for ΔQ_{OUT} , ΔQ_{IN} , and ΔQ_{SGD} at each time step (30 or 60 min) allows for the calculation of the variation of the water fluxes from their average value found during the parameterization step and ultimately for the total water flux over the entire measurement interval.

Results

Kahauloa Bay—Our most extensively studied SGD plume was in Kahauloa Bay (Fig. 1F). This is a very small and narrow embayment (130 m long, 40 m wide) with steep, fixed walls constraining the size of the plume. Field observations indicate that the SGD inputs are limited to the innermost portion of the bay. We measured radon, radium, and salinity along an offshore transect from this bay on 16 August 2005 and performed two separate time-series analyses, 15–17 August 2005 and 10–14 February 2006.

The results of the offshore transect are shown in Fig. 4. The groundwater radium isotope and radon results from Tables 1 and 2 suggest that all these tracers are found in relatively low activities in this part of West Hawaii, with ^{223}Ra , ^{226}Ra , and ^{228}Ra often below reliable detection limits. Thus, for radium, we present only the ^{224}Ra trends offshore, which are very similar to the ^{222}Rn patterns, showing relatively high activities in the nearshore waters and decreasing quickly offshore. The ^{224}Ra data indicate a few offshore sites where elevated radium concentrations are found. This may be caused by the pulsing of groundwater discharge creating pockets of higher tracer concentration offshore. Excess radon has likely been removed from these areas by atmospheric evasion. Beyond about 2000 m from shore, open ocean signatures dominate the ^{222}Rn , ^{224}Ra , and salinity concentrations. We take the average ^{222}Rn and salinity values from this transect beyond 3000 m offshore (radon = 1.07 Bq m^{-3} ; salinity = 35.7) to represent the open ocean end members for the SGD model.

We sampled groundwater from six sites in the vicinity of this bay (reference nos. 23–28 in Tables 1 and 2). These samples were collected from brackish, rock-lined large-diameter wells and ancient “Hawaiian baths” along the coastline that exhibited dampened tidal fluctuations indicating that they are hydraulically connected to the ocean. Keei Well D (reference no. 27 in Tables 1 and 2) is an upland freshwater production well and likely does not represent the discharging groundwater, so we opt to neglect this sample. We use the results of the other groundwaters sampled in August 2006 ($n = 5$) to estimate the average groundwater end member for this bay to have a radon activity of $83 \pm 25 \text{ Bq m}^{-3}$ and a salinity of 6.5 ± 1.2 .

The raw data from the 2005 time-series analysis for radon, salinity, and temperature are shown in Fig. 5A, 5B, and 5C, respectively. The radon activities, while very low, show a pattern of fluctuating inversely with the tide, increasing during the ebb tide and decreasing during flood tide. Salinity does not show much response to the smaller

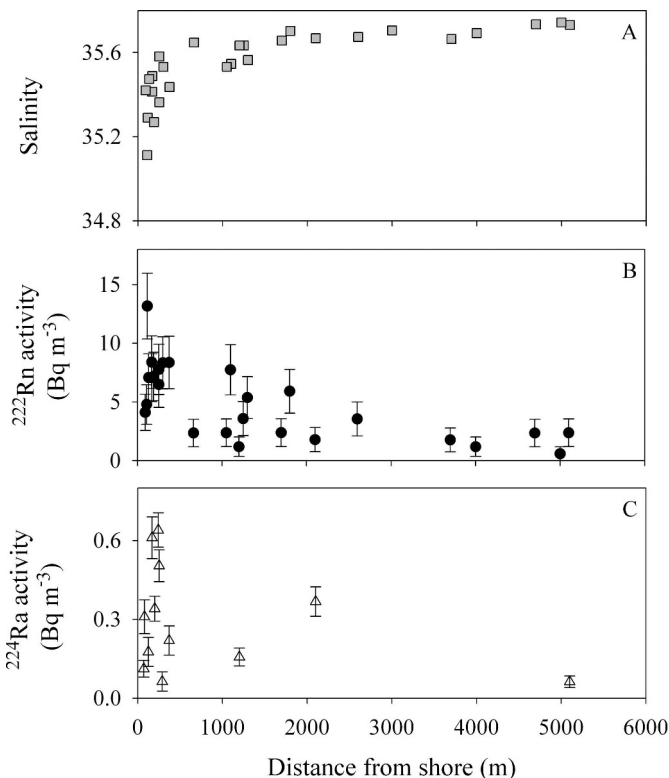


Fig. 4. Offshore transect of (A) salinity, (B) ^{222}Rn , and (C) ^{224}Ra from the plume emanating from Kahauloa Bay. This transect was collected in August 2005.

amplitude tides but varies directly with the extreme tide. Temperature indicates significant cooling following the largest high tide from the input of cold groundwater and significant warming during the flood tide leading to this high tide as a result of warmer ocean water mixing into the system. The lag shown between water-level fluctuations and tracer response is apparently due to the mixing between the bottom and surface layers at this site.

Figure 5D shows the model results for the SGD flux based on this time-series analysis. Constants and end member values used for this and all successive data sets are provided in Table 3. Positive fluxes represent groundwater discharge into the bay and tend to occur during ebb tide. Negative fluxes are found during flood tide and indicate an additional loss of the groundwater tracer parameters. Since the buoyant plumes that are visible via TIR result from positive groundwater fluxes, we average all positive discharges to find an overall SGD rate from this plume of $1100 \text{ m}^3 \text{ d}^{-1}$ (Table 3).

The radon, salinity, and temperature patterns measured in Kahauloa Bay during the February 2006 time series are shown in Fig. 6A, 6B, and 6C, respectively. The radon patterns are again inversely correlated to the tidal fluctuations, while the salinity shows a direct correlation. Water temperatures increase during the high tides and tend to decrease immediately following the high tides but are dominated by 24-h solar cycles rather than 12-h tidal cycles. During this deployment, the radon platform was 5 m farther from shore than during 2005, but all other

Table 1. Summary characteristics of the sampled groundwater sources. These sites are arranged in order from north to south. Reference numbers appear throughout the text. Those sites listed under the “Used for groundwater end member?” category show the samples that are averaged to provide an end member value at a specific site for the SGD model. n/a indicates that this particular parameter was not measured during the specific sampling.

Reference no.	Well name	Description	Time-series site proximity	Used for groundwater end member?	Latitude	Longitude	Depth (m)
1	Kiholo Lagoon	Surface water sample	Kiholo		N19°51.633'	W155°55.334'	n/a
2	Fishpond	Brackish pond	Kiholo		N19°51.318'	W155°55.185'	n/a
3	Lava tube	Freshwater in lava tube	Kiholo		N19°51.242'	W155°55.386'	3.0
4	Energy lab—well 6	Natural Energy Laboratory	Honokohau		N19°43.600'	W156°03.569'	n/a
5	Energy lab—well 2	Natural Energy Laboratory	Honokohau		N19°42.754'	W156°02.906'	4.8
6	Hualalai well	Upland well	Honokohau		N19°42.250'	W155°58.438'	485.6
7	KNP-1	Kalako National Historical Park well 4161-01	Honokohau		N19°1.233'	W156°01.750'	7.2
8	KNP-2	Kalako National Historical Park well 4161-02	Honokohau		N19°41.155'	W156°01.409'	17.8
9	Honokohau well	Upland well	Honokohau		N19°40.940'	W155°57.865'	557.4
10	KNP-3	Kalako National Historical Park well 4161-03	Honokohau		N19°40.705'	W156°01.330'	12.0
11	HW-14	Honokohau Harbor expansion well	Honokohau	Honokohau	N19°40.120'	W156°01.083'	n/a
12	HW-15	Honokohau Harbor expansion well	Honokohau	Honokohau	N19°40.113'	W156°01.155'	9.2
13	HW-16	Honokohau Harbor expansion well	Honokohau	Honokohau	N19°40.083'	W156°01.211'	15.7
14	HW-17	Honokohau Harbor expansion well	Honokohau	Honokohau	N19°40.076'	W156°01.265'	16.4
15	HW-6	Honokohau Harbor expansion well	Honokohau	Honokohau	N19°39.976'	W156°01.419'	13.1
16	HW-9	Honokohau Harbor expansion well	Honokohau	Honokohau	N19°39.878'	W156°01.491'	18.0
17	Kahalo well A	Upland production well	Kailua-Kona		N19°34.978'	W155°56.988'	283.8
18	Kahalo well C	Upland production well	Kailua-Kona		N19°34.962'	W155°56.971'	288.7
19	Kahalo well B	Upland production well	Kailua-Kona		N19°34.904'	W155°56.983'	300.2
20	Kahalo well D	Upland production well	Kailua-Kona		N19°34.884'	W155°56.954'	295.3
21	Keauhou bath	Ancient Hawaiian bath	—		N19°33.666'	W155°57.703'	1.5
22	Halekii well	Upland production well	—		N19°31.087'	W155°54.974'	105.0
23	Queen's bath	Ancient Hawaiian bath	Queen's Bath/ Kahauloa	Queen's Bath/ Kahauloa	N19°28.907'	W155°55.997'	0.3
24	Kelly's well	Ancient Hawaiian well	Manini/ Kahauloa	Kahauloa	N19°28.258'	W155°55.238'	0.5
25	Manini bath	Ancient Hawaiian bath	Manini/ Kahauloa	Manini/ Kahauloa	N19°28.249'	W155°55.243'	0.3
26	Vergi's well	Ancient Hawaiian well	Kahauloa	Kahauloa	N19°28.180'	W155°55.261'	1.0
27	Keei well D	Upland production well	Kahauloa		N19°27.725'	W155°52.820'	353.3
28	City of Refuge	Brackish pond	Kahauloa	Kahauloa	N19°27.486'	W155°55.469'	1.0

parameters remain the same for the SGD model. Figure 6D shows that the model results are similar in pattern to those seen in 2005, but the average positive flux is somewhat higher at $1600 \text{ m}^3 \text{ d}^{-1}$ (Table 3).

Manini Beach—Just north of Kahauloa Bay, inside the confines of Kealakekua Bay, another plume discharges at Manini Beach (Fig. 1F). There are several groundwater inputs along the southeast shoreline of Kealakekua Bay, but we examined only the one coming directly from Manini Beach. This is a narrow, rocky beach with lava outcrops lining the shoreline. Field observations indicate that the groundwater is discharging mostly from the beach face and along the base of the rock outcrops. We performed an

offshore transect from this plume on 03 August 2006 and a time-series analysis 08–11 August 2006.

Figure 7A, 7B, and 7C show the result of the offshore transect for salinity, ^{222}Rn , and ^{224}Ra , respectively. The transect represents an offshore to onshore sampling strategy, conducted during the outgoing tide to maximize the measured tracer concentrations. As with the transect from Kahauloa Bay, we see detectable elevations in the tracer concentrations (^{222}Rn and ^{224}Ra) and significantly lower salinity within the plume to about 2000 m from shore. Beyond that point, the salinity remains high and uniform, while the ^{222}Rn and ^{224}Ra remain at background levels. These transects reveal that a much more intense sampling scheme concentrated within the first several

Table 2. Measured parameters for each of the sampled groundwater sources. Reference numbers refer to the specific site characteristics listed in Table 1. Some sites were sampled during multiple field trips. n/a indicates that this particular parameter was not measured during the specific sampling, whereas BD indicates that the measurement was below the detectable activity.

Reference no.	Date sampled	Salinity	Temperature (°C)	^{222}Rn (Bq m $^{-3}$)	^{223}Ra (Bq m $^{-3}$)	^{224}Ra (Bq m $^{-3}$)	^{226}Ra (Bq m $^{-3}$)	^{228}Ra (Bq m $^{-3}$)
1	20 May 07	9.5	23.0	162±15	n/a	n/a	n/a	n/a
2	20 May 07	2.7	25.3	707±37	n/a	n/a	n/a	n/a
3	17 May 07	2.1	22.7	356±29	0.12±0.05	2.06±0.17	n/a	n/a
4	16 Feb 06	28.8	23.6	604±40	1.08±0.21	13.40±0.73	0.37±1.2	4.8±5.2
5	16 Feb 06	11.3	21.8	424±33	0.42±0.05	7.22±0.35	0.65±0.43	6.3±1.7
6	15 Feb 06	0.1	21.1	5730±120	BD	0.06±0.03	BD	BD
7	17 Aug 05	6.8	22.4	n/a	BD	2.76±0.36	n/a	n/a
8	14 Feb 06	7.3	20.9	192±18	0.08±0.03	1.48±0.11	0.80±0.45	1.7±1.6
	17 Aug 05	5.2	21.7	n/a	0.60±0.12	6.46±0.55	n/a	n/a
9	14 Feb 06	5.8	23.8	611±56	0.14±0.08	2.65±0.39	1.3±1.7	0.2±6.3
	15 Feb 06	0.1	21.8	1540±78	BD	0.22±0.08	BD	BD
10	17 Aug 05	11.5	22.5	n/a	0.19±0.11	1.27±0.23	n/a	n/a
11	14 Feb 06	11.8	21.5	242±22	0.35±0.08	2.43±0.18	1.02±0.04	2.3±1.3
	17 May 07	7.1	20.7	500±28	0.17±0.06	1.20±0.16	n/a	n/a
12	16 May 07	8.2	20.9	274±20	0.19±0.05	1.80±0.18	n/a	n/a
13	16 May 07	15.3	20.5	456±26	0.67±0.12	4.48±0.34	n/a	n/a
14	17 May 07	17.9	20.2	431±23	0.76±0.12	5.17±0.27	n/a	n/a
15	16 May 07	19.0	20.7	371±23	0.79±0.13	9.98±0.62	n/a	n/a
16	16 May 07	23.8	20.3	520±28	0.18±0.07	7.67±0.47	n/a	n/a
17	13 Feb 06	0.4	21.0	1450±48	BD	0.13±0.02	0.18±0.14	0.36±0.55
18	13 Feb 06	0.2	21.4	1140±50	BD	0.04±0.02	BD	1.06±0.93
19	13 Feb 06	0.5	21.0	1415±75	BD	0.26±0.06	0.19±0.49	1.9±1.7
20	13 Feb 06	0.4	21.0	1150±60	BD	BD	0.21±0.18	BD
21	09 Aug 06	4.9	22.0	321±18	0.02±0.01	0.28±0.03	BD	0.01±0.55
22	13 Feb 06	0.1	21.8	879±43	BD	BD	BD	BD
23	10 Aug 06	6.7	21.5	49±10	n/a	n/a	n/a	n/a
24	07 Aug 06	7.1	21.1	120±16	0.03±0.01	0.23±0.04	BD	0.39±0.74
25	06 Aug 06	5.1	22.2	86±14	0.06±0.01	0.73±0.09	BD	BD
26	19 May 07	6.5	20.4	131±14	n/a	n/a	n/a	n/a
	19 May 07*	6.5	20.4	106±20	n/a	n/a	n/a	n/a
	07 Aug 06	5.7	20.6	83±14	0.03±0.1	BD	BD	BD
27	13 Feb 06	0.1	19.8	340±26	BD	0.12±0.04	0.08±0.33	BD
28	15 Feb 06	0.1	19.6	375±32	n/a	n/a	n/a	n/a
	11 Aug 06	8.1	23.4	78±9	n/a	n/a	n/a	n/a

* Denotes a time-series record average of this well over 24 h.

hundred meters from shore would have been necessary in order to use offshore distributions of radium isotopes to independently quantify SGD, such as that employed by Street et al. (2007).

Several of the large-diameter rock-lined brackish wells and baths sampled for Kahauloa Bay are in the same vicinity as Manini Beach. We deployed the membrane tubing system in one of these (reference no. 25 in Tables 1 and 2) for 24 h to monitor the radon activity in the groundwater supplying this bath. We use the average results from this analysis (radon = 106 ± 20 Bq m $^{-3}$; salinity = 6.5 ± 0.1) as the appropriate end member values for this plume. These results are very similar to discrete samples collected from two other Manini Beach sites (reference nos. 24 and 26 in Tables 1 and 2).

Temperature and salinity profiling of the plume waters at Manini Beach revealed stratification of the buoyant water layer. We therefore use the thickness of this plume (1.2 m) at the radon platform (70 m from shore) as a constant plume thickness in the SGD model. The width of

this plume at the platform was measured from aerial TIR imagery to be 100 m (Johnson 2008).

The radon activities, salinity, and temperature measured during the Manini Beach time series are shown in Figs. 8A, 8B, and 8C, respectively. The tracer patterns for Manini Beach are very similar to those from Kahauloa Bay, with the radon peaking during low and ebb tide. Salinity and temperature again tend to vary directly with the tide. Figure 8D shows the resulting SGD fluxes for Manini Beach. The average positive SGD rate for this plume is $5100 \text{ m}^3 \text{ d}^{-1}$ (Table 3), but rates often reach closer to $10,000 \text{ m}^3 \text{ d}^{-1}$ during peak flows.

Queen's Bath—The SGD plume associated with Queen's Bath is located in the northern corner of Kealakekua Bay (Fig. 1F). A thin, shallow shelf extends seaward from this corner, before the seafloor drops to about 50 m near the mouth of the bay. Our platform was deployed along this shelf, about 100 m from the SGD source in the inside corner of the bay. The width of the plume at the platform

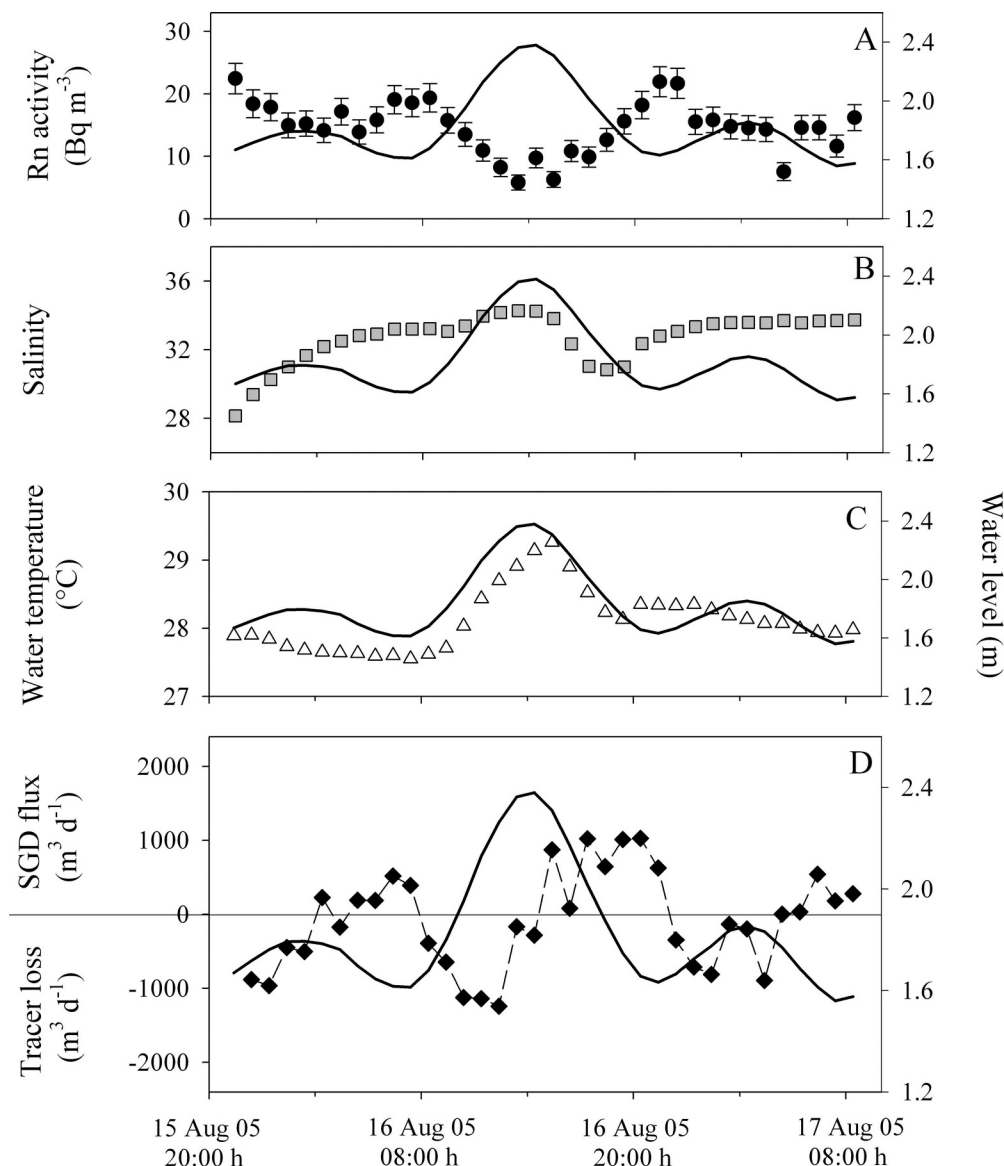


Fig. 5. Time-series analysis of (A) ^{222}Rn activity, (B) salinity, and (C) temperature in surface waters of the Kahauloa Bay plume measured in August 2005. (D) Modeled total SGD results are also included after a three-point smoothing function. Solid lines represent tidal variations.

was measured to be 40 m. Like Manini Beach, T/S profiling of this plume revealed a buoyant layer extending down to a depth of about 2.0 m at the platform, so we take this as a constant plume thickness throughout the time series.

As shown in Table 1, only one groundwater well was accessible in the vicinity of Queen's Bath (reference no. 23). It was an ancient Hawaiian bath, built into the ground in the woodlands near the coast. Unfortunately, sampling was difficult because even at high tide, the water depth in the bath was only about 30 cm. The sample collected from this well displayed a similar salinity as other groundwaters sampled in the area (6.7), but the very shallow depth may have led to substantial degassing of the radon (measured value = 48 Bq m^{-3}). We thus assigned a radon end member for this time series based on a plot of the measured radon versus salinity during the time series (Fig. 9A). The

inverse correlation of this plot displays reasonable linearity, so we extrapolate the trend to a salinity of 6.7 to find the radon end member of 107 Bq m^{-3} . Short temporal mixing scales and influence from other discharges likely cause the scatter in these data. Nonetheless, this value is reasonably close to the values measured in other groundwater sites around Kealahou Bay.

Figure 10A shows the model result for SGD during this time series. As seen before, the calculated SGD rates show the highest flux during the largest ebb tide of each day. The overall average positive SGD rate for this plume is $3500 \text{ m}^3 \text{d}^{-1}$ (Table 3).

Kailua-Kona Harbor—TIR imagery of Kailua-Kona Harbor (Fig. 1E) reveals numerous point-source discharges along the shoreline (Johnson 2008). We deployed the radon

Table 3. Model parameters selected for each groundwater plume and the associated total and freshwater SGD fluxes determined by averaging all positive SGD fluxes over the time series. The results are arranged in order from north to south.

Site	Ave. modeled depth (m)	Ave. excess* ^{222}Rn (Bq m^{-3})	Groundwater end members† $^{222}\text{Rn}/\text{salinity}$ (Bq m^{-3})	Distance to source (m)	Plume width (m)	Flow type‡	Estimated discharge ($\text{m}^3 \text{d}^{-1}$)
Kiholo Bay 15–18 May 07 $n=92$	1.3	120	636/0 546/4.8	130	82	FSGD TSGD	6300 7100
Honokohau Harbor 14–16 Feb 06 $n=87$	2.4	170	652/0 425/15.2	10	375	FSGD TSGD	8600 12,000
Kailua-Kona Harbor 18–20 May 07 $n=65$	1.0§	83	1264/0 713/15.2	162	86	FSGD TSGD	5100 8700
Queen's Bath 06–08 Aug 06 $n=44$	2.0§	9.8	130/0 107/6.7	100	40	FSGD TSGD	2900 3500
Manini Beach 08–12 Aug 06 $n=66$	1.2§	15	515/0 105/6.5	70	100	FSGD TSGD	1100 5100
Kahauloa Bay 15–17 Aug 05 $n=36$	1.8	15	153/0 83/6.5	20	40	FSGD TSGD	630 1100
Kahauloa Bay 10–14 Feb 06 $n=90$	2.4	13	153/0 83/6.5	25	40	FSGD TSGD	940 1600

* ^{226}Ra activity in surface water = 0.90 Bq m^{-3} (Kahauloa, Kiholo), 1.4 Bq m^{-3} for Kailua-Kona, 0.44 Bq m^{-3} for Manini, and 0.52 Bq m^{-3} for Queen's Bath.

† Ocean end members for radon and salinity were held constant at 1.1 Bq m^{-3} and 35.7 , respectively.

‡ FSGD, fresh submarine groundwater discharge; TSGD, total submarine groundwater discharge (recirculated seawater + freshwater).

§ Thickness of buoyant plume held constant rather than use absolute measured depths.

platform in an area where only the most northeastern plume exiting near the corner of the harbor would affect our results. This area is considerably deeper than the other sites we studied (average depth = 4.5 m). Here, T/S profiling was essential to constrain the thickness of the buoyant water plume, which was found to be a constant 1.0 m . A designated swimming area prevented us from deploying the platform closer than 162 m from the source, and the width of the plume here was measured to be 86 m .

No coastal wells were available in this area, and any direct measure of the discharging groundwater was not possible. Therefore, as with Queen's Bath, we estimate the radon end member based on a regression of the time-series linear radon versus salinity plot. This site is near Honokohau Harbor, where several coastal groundwater wells were available. The average salinity of the wells associated with Honokohau Harbor is significantly high (15.2), possibly as a result of groundwater pumping and subsequent seawater infiltration in this area. We chose to use the salinity of these wells as the end member for Kailua-Kona Harbor because of their close proximity. The corresponding radon activity based on the regression line at a salinity of 15.2 is thus found to be 713 Bq m^{-3} (Fig. 9B), although we recognize the inherent uncertainties associated with these assumptions.

The model results for SGD in the Kailua-Kona Harbor plume are shown in Fig. 10B. Averaging the positive fluxes yields an average discharge rate of $8700 \text{ m}^3 \text{d}^{-1}$ (Table 3), although rates notably reach close to $20,000 \text{ m}^3 \text{d}^{-1}$. As

with all other sites, the SGD tends to peak during the low or ebb tides, and the negative fluxes occur during flood tide.

Honokohau Harbor—Honokohau Harbor is a small boat basin located farther north along the coastline (Fig. 1D). This site is located in a protected area, as the tidal wedge can only pass through an 80-m -wide entrance. Honokohau Harbor was first constructed in 1970 and later expanded in 1978 by blasting and excavating the lava to form a vertical-walled basin (Bienfang 1983). Several authors have noted the abundance of groundwater discharging into the basin through the walls as a result of the landward excavation (Bienfang and Johnson 1980; Gallagher 1980; Bienfang 1983).

Examination of TIR images of this harbor (Johnson et al. 2008) reveals many different point-source SGD inputs along the entire perimeter of the basin, mostly apparent along the basin's back wall. Divers working with our group also identified diffuse flow occurring nearly ubiquitously around the basin's perimeter. As a result, we deployed our platform 10 m from the back of the harbor. Instead of using the width of the plume as the width dimension for the model, however, we use the perimeter length of the wall along the entire back section of the harbor (375 m), as this represents the likely source width. At our station, no detectable stratification of the buoyant layer was observed from T/S profiling, so we use the actual depths measured during the time series for the model.

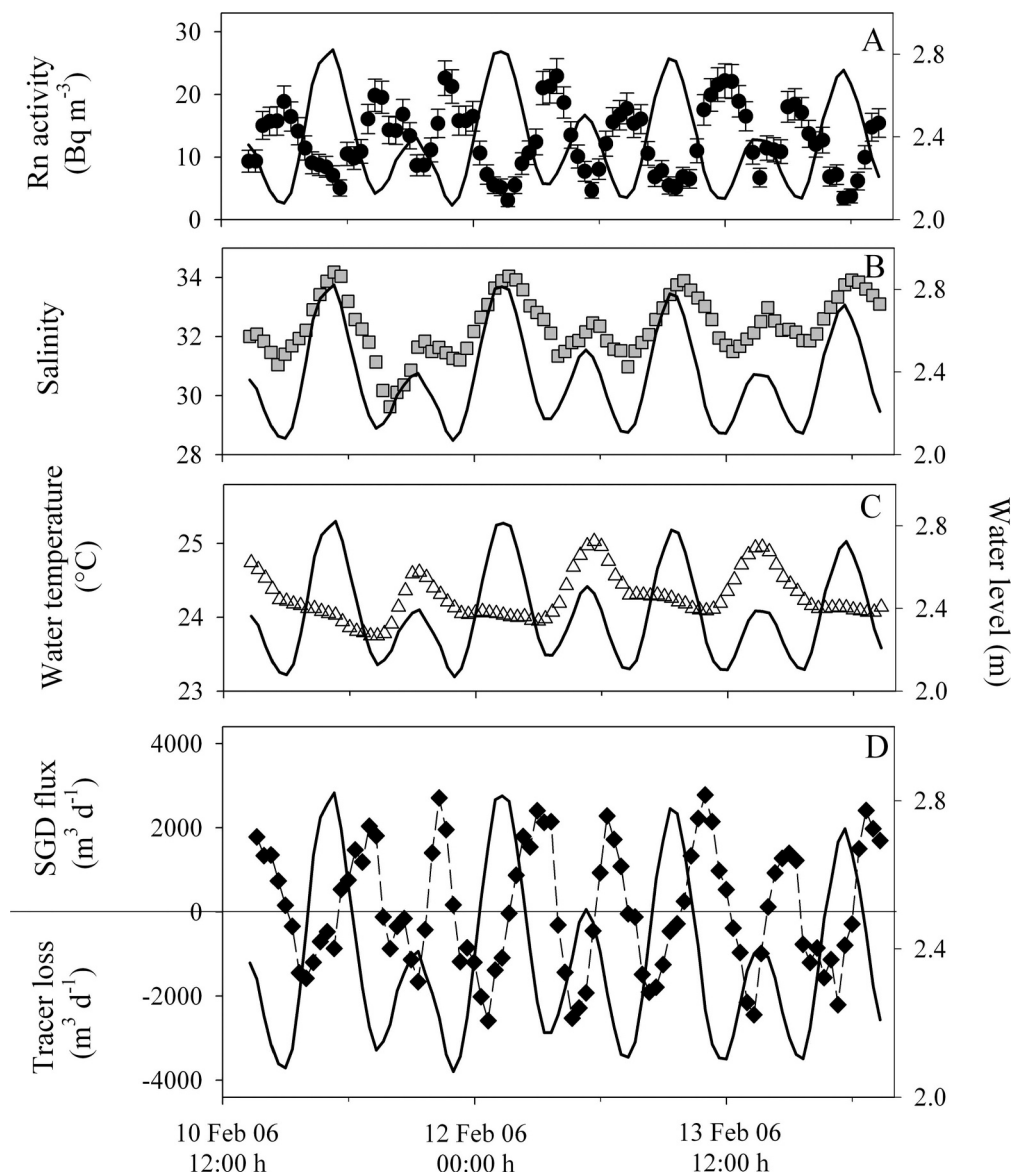


Fig. 6. Time-series analysis of (A) ^{222}Rn activity, (B) salinity, and (C) temperature in surface waters of Kahauloa Bay measured in February 2006. (D) Modeled total SGD and (E) tidal flux results are also included, and both represent a three-point smoothing. Solid lines represent tidal variations.

In the near future, harbor managers are planning another expansion project for this harbor. During the exploratory stages of the project, a series of wells were installed around the harbor location. We used the average radon and salinity from these wells, measured in May 2007 (reference nos. 11–16 in Tables 1 and 2), as the groundwater end member values (radon = $425 \pm 92 \text{ Bq m}^{-3}$; salinity = 15.2 ± 6.5). As noted previously, the end member salinity is considerably more saline than those from the other locations, indicating that saltwater intrusion into the aquifer in this area is more pronounced than at the other sites to the south.

A significant time shift was observed in both the radon and the salinity records, as those tracers peak several hours after the tidal peaks. This pattern is likely due to the protected nature of this harbor in that mixing is more

inhibited within the harbor than the other study sites. In spite of this time lag, Fig. 10C shows that the SGD patterns peak at the low tides, indicating that the hydraulic gradient affected by the changing ocean level inside the harbor influences the groundwater fluxes. The average positive discharge is estimated to be $12,000 \text{ m}^3 \text{d}^{-1}$ in Honokohau Harbor (Table 3).

Kiholo Bay—Our northernmost study site was at the mouth of a small lagoon along the north side of Kiholo Bay (Fig. 1C). At this site, a peninsula separates a deep inner lagoon from the open ocean. TIR imaging of this area (Johnson 2008) reveals that the lagoon is the receiving waters of the SGD discharge. A small island in the mouth of the lagoon further inhibits mixing of this groundwater offshore, so the plume exits the lagoon through two narrow

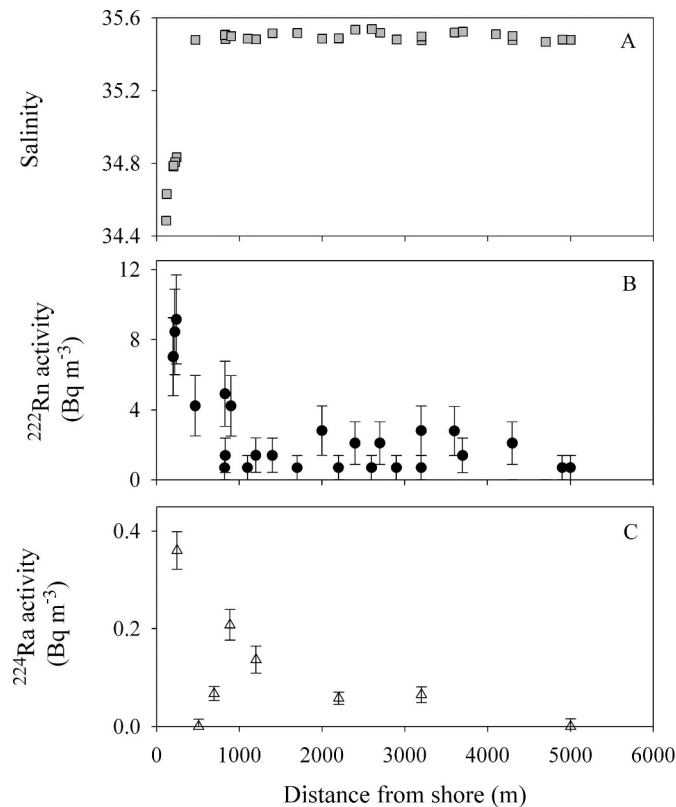


Fig. 7. Offshore transect of (A) salinity, (B) ^{222}Rn , and (C) ^{224}Ra from the plume at Manini Beach. This transect was collected in August 2006.

openings around the island. We chose to install our platform in the larger opening, between the peninsula and the island, about 130 m from the lagoon's back shore. The width is taken as the distance across the mouth of the lagoon (82 m). There was no detected stratification in this shallow area, so we use the measured water depths for the model.

Three sources of possible groundwater end members were sampled around the Kiholo area (reference nos. 1–3 in Tables 1 and 2), including brackish water inside a lava tube formerly used as a well (~400 m south of the bay), an expansive brackish fishpond fed by groundwater, and a relatively low-salinity water sample inside the inner bay. The average salinity of all these samples was 4.8, but the range in radon activities suggests that either different water masses were sampled or the samples were influenced by different amounts of gas exchange. We therefore use this salinity in the linear regression of the time-series radon versus salinity record to assign a radon end member of 546 Bq m^{-3} (Fig. 9C).

Figure 10D shows the calculated SGD fluxes based on this deployment. SGD rates slightly increase throughout the moderate tidal changes but sharply decrease to negative fluxes during the flood tide following the lowest low tides. The average positive SGD rate for the plume waters exiting the lagoon in Kiholo Bay was estimated to be $7100 \text{ m}^3 \text{ d}^{-1}$ (Table 3).

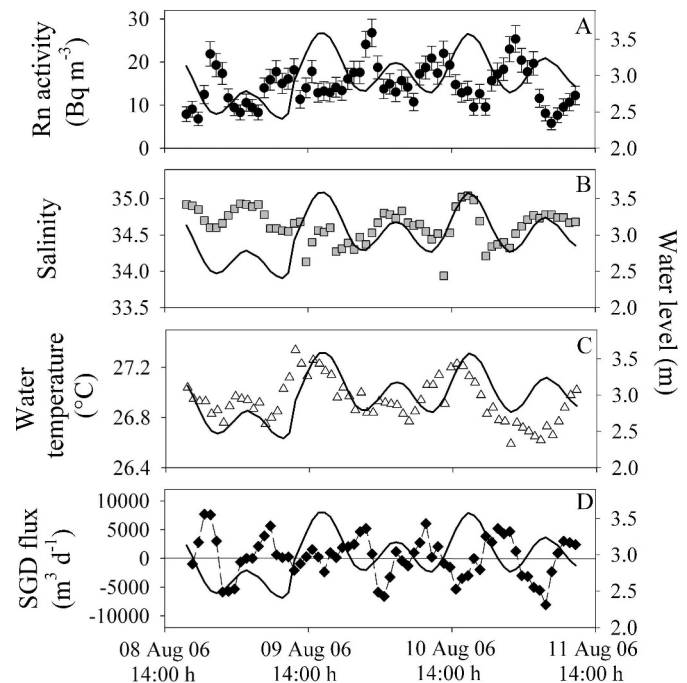


Fig. 8. Time-series analysis of (A) ^{222}Rn activity, (B) salinity, and (C) temperature in surface waters at Manini Beach measured in August 2006. (D) Modeled total SGD results are also included after a three-point smoothing function. Solid lines represent tidal variations.

Discussion

In addition to determining the total groundwater fluxes (meteoric + recirculated seawater) associated with each of these plumes, we can adjust the end members to estimate the flux of the purely fresh, meteoric component of the groundwater discharge. Extrapolating the linear time-series radon versus salinity plot for each site to zero salinity should yield an estimate of the radon activity in the pure meteoric water. This assumes that these trends remain linear throughout the salinity range. Table 3 includes the resultant end members for each site using an assumed salinity of 0 as well as the model results based on these end members. The radon end member estimates are still considerably lower than most of the freshwater, upland wells (reference nos. 6, 9, 17–20, 22, and 27 in Tables 1 and 2), likely because of different water-to-rock ratios or longer residence times that the upland waters spend in the perched aquifers found along the mountain slopes of the island. The modeled freshwater flux estimates range from roughly 20% of the total flow (Manini Beach) to nearly 90% (Kiholo Bay).

The estimates of both total and fresh SGD are subject to a number of uncertainties. Model parameters that exert the most influence over each result are the groundwater radon end member and the coastal plume volume. Varying the selected groundwater radon end member for any particular site leads to an inverse linear change in the model result; that is, an increase in the radon end member of 10% leads to a corresponding decrease in SGD flux by the same

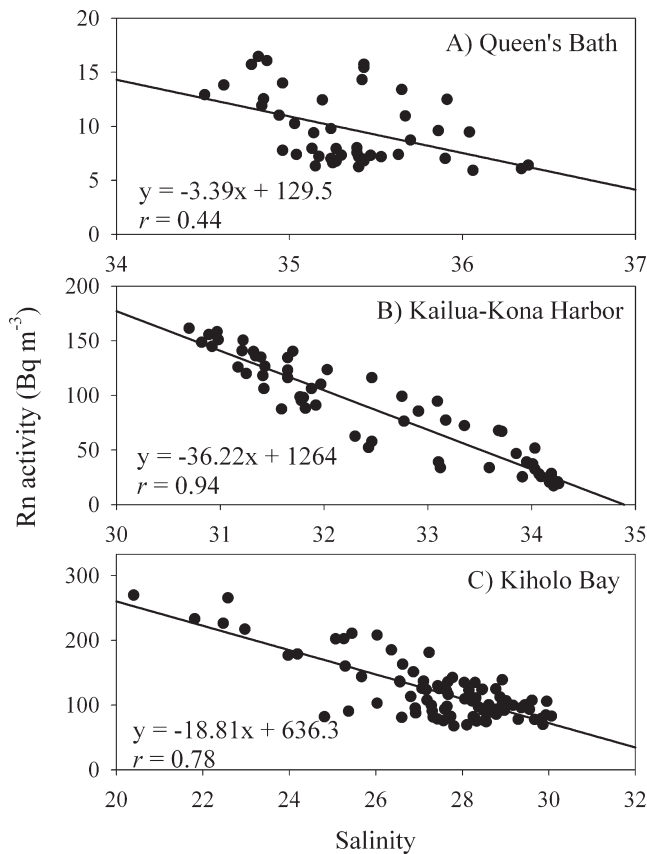


Fig. 9. ^{222}Rn versus salinity plots of the raw time-series measurement values collected at (A) Queen's Bath, (B) Kailua-Kona Harbor, and (C) Kiholo Bay. The regression lines are extrapolated to estimate a radon end member in the groundwater at these sites.

percentage. The lack of representative groundwater wells in the region of some of our study sites thus creates some uncertainty. This is especially true for sites like Kailua-Kona Harbor, where the radon end member could be assigned only from the linear radon versus salinity plot. However, one benefit of the model employed here is that it uses a combination of tracers for the groundwater end member in order to lessen the impact of this uncertainty. If a groundwater sample were collected closer to the coastline, for example, it would likely have a higher salinity but lower radon content. These factors should balance out in the model calculations to provide the same result.

All other end member values have considerably less effect on the modeled SGD results. Changing the salinity in groundwater as well as both radon and salinity end members in the open ocean vary the model result linearly but within the range associated with the measurement uncertainty of the parameters. The only requirement of these end members is that their values remain outside the range in which they are measured in the coastal groundwater plume; the open ocean salinity value, for example, must be greater than the highest measured plume salinity during the time-series measurement.

The model results are also largely dependent on our interpretation of the dimensions of the plume between our platform and the source. Varying a plume dimension results in a linear change in the corresponding model results for any particular site where a 10% increase in the dimension creates a subsequent 10% increase in the SGD flux. We are confident that our length (distance to shore) and depth dimensions are well constrained for each site because these have been directly measured. In cases where the depth is assigned based on temperature–salinity profiling, a relatively small-scale uncertainty (e.g., 0.5 m) would translate to a large uncertainty in the overall volume. The width uncertainty is rooted in our analysis of the TIR images in cases where that is the only means of assessing this dimension, and it may be that such dimensions vary over time. Kahauloa Bay is not subject to this uncertainty, nor is Kiholo Bay, as the plumes at these sites are horizontally constrained by physical landmasses.

Previous studies have assessed SGD rates along the west Hawaii coastline, although none of these was based on tracer measurements. Bienfang (1980) used physical oceanographic measurements to estimate the SGD flux into Honokohau Harbor. His study suggested that an equivalent of 5500–7500 $\text{m}^3 \text{d}^{-1}$ of total groundwater flow into the harbor. That study was conducted prior to the harbor expansion project of 1978, which likely resulted in higher discharge because of the greater exposure of aquifer surface provided by the new harbor rock walls after the expansion. Our estimate of 12,000 $\text{m}^3 \text{d}^{-1}$ (8600 $\text{m}^3 \text{d}^{-1}$ fresh SGD) is thus in reasonable agreement with the earlier measurement.

Kay et al. (1977) conducted a series of hydrologic water balance studies for the region directly north of Kiholo Bay and concluded that their best estimate of coastal groundwater discharge was 15,000 $\text{m}^3 \text{km}^{-1} \text{d}^{-1}$. Kanehiro and Peterson (1977) reached the same conclusion in their own hydraulic water balance estimates. These values would correspond to the fresh component of SGD that we have measured because they are based on groundwater recharge rates and do not consider recirculated seawater. Recent increases of groundwater pumping in this region in the three decades since those studies were conducted would likely result in a decrease of these estimates. Combined, the total fresh groundwater flux from the three plumes studied within Kealahou Bay (Fig. 1F) contributes 4900 $\text{m}^3 \text{d}^{-1}$ (2500 $\text{m}^3 \text{d}^{-1} \text{km}^{-1}$ shoreline). This flux estimate is a minimum, as TIR imagery reveals other large SGD plume inputs within the bay (Johnson 2008) that were not quantified. While these comparisons are an oversimplification, they clearly suggest that the fresh SGD fluxes are at least on the same order as the previous studies on the island.

On the Big Island of Hawaii, the western (leeward) side receives much less precipitation than does the windward side. As the population continues to increase in these dry regions (e.g., Kohala, Waikoloa, Kailua-Kona), groundwater promises to become even more important as a water resource. Golf courses, for example, rely heavily on groundwater for irrigation, and area managers can

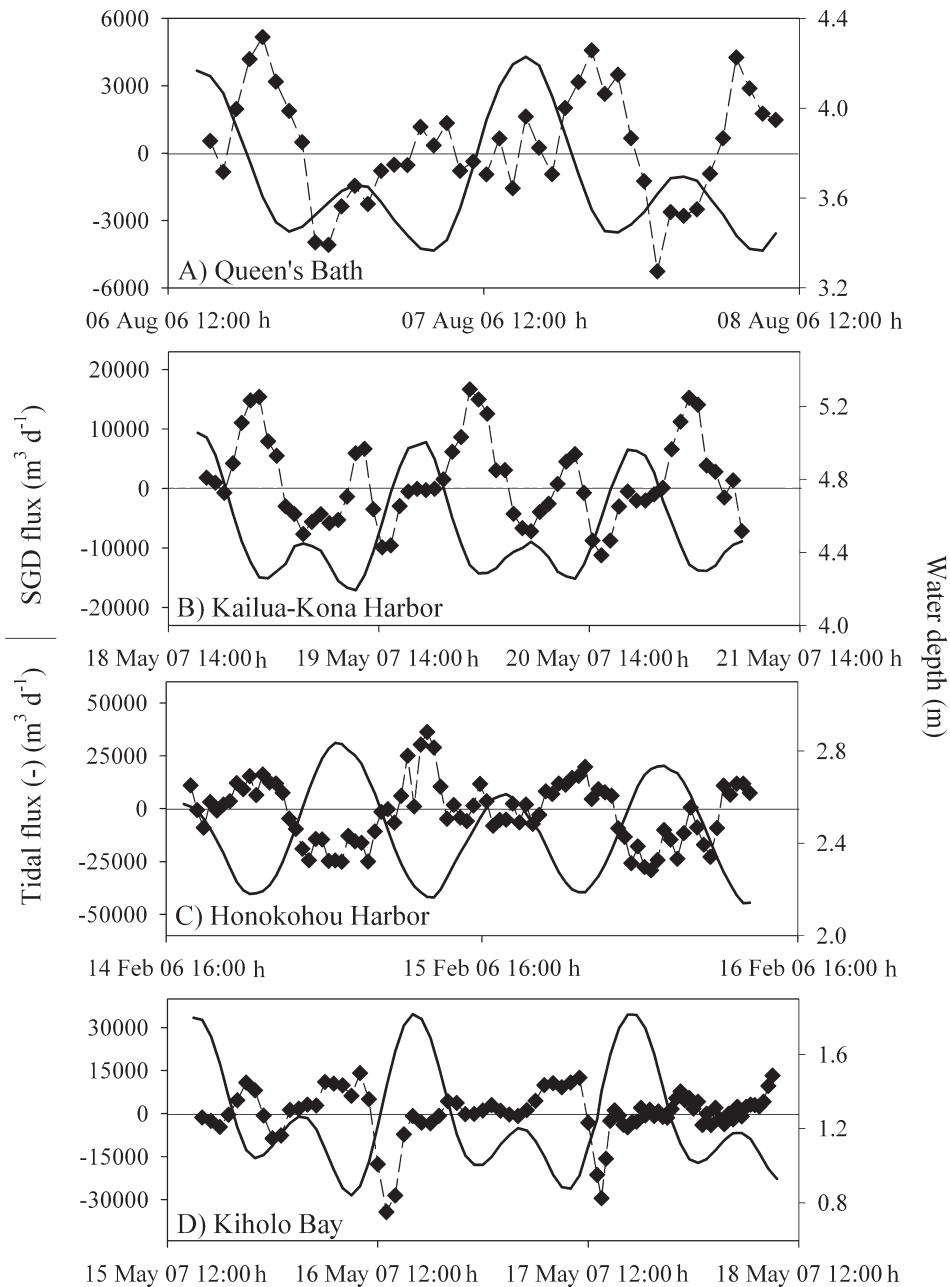


Fig. 10. SGD flux model results from the (A) Queen's Bath, (B) Kailua-Kona Harbor, (C) Honokohau Harbor, and (D) Kiholo Bay time-series deployments. All results represent a three-point smoothing. Solid lines represent tidal variations.

benefit from knowing where losses of groundwater are occurring. Since groundwater is the only link between land and the ocean in these areas, any contamination could begin to affect local coastal ecologies, including coral reefs.

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References

- BIENFANG, P. 1980. Water quality characteristics of Honokohau Harbor: A subtropical embayment affected by groundwater intrusion. *Pac. Sci.* **34**: 279–291.
- . 1983. The status of water quality, water circulation, and plankton populations in Honokohau small boat harbor, 1982. p. 11–31. *In* A decade of ecological studies following construction of the Honokohau Small Boat Harbor. Kona, Hawaii: Technical report. US Army Corps of Engineers.
- , AND W. JOHNSON. 1980. Planktonic properties of Honokohau Harbor: A nutrient-enriched subtropical embayment. *Pac. Sci.* **34**: 293–300.
- BURNETT, W. C., AND H. DULAIOVA. 2003. Estimating the dynamics of groundwater input into the coastal zone via continuous radon-222 measurements. *J. Environ. Radioact.* **69**: 21–35, doi:10.1016/S0265-931X(03)00084-5.
- , C. STRINGER, AND R. PETERSON. 2006a. Submarine groundwater discharge: Its measurement and influence on the coastal zone. *J. Coast. Res.* **39**: 35–38.
- , G. KIM, AND D. LANE-SMITH. 2001. A continuous monitor for assessment of ^{222}Rn in the coastal ocean. *J. Radioanal. Nucl. Chem.* **249**: 167–172, doi:10.1023/A:1013217821419.
- , AND OTHERS. 2006b. Quantifying submarine groundwater discharge in the coastal zone via multiple methods. *Sci. Total Environ.* **367**: 498–543, doi:10.1016/j.scitotenv.2006.05.009.
- CABLE, J. E., W. C. BURNETT, J. P. CHANTON, AND G. L. WEATHERLY. 1996. Estimating groundwater discharge into the northeastern Gulf of Mexico using radon-222. *Earth Planet. Sci. Lett.* **144**: 591–604, doi:10.1016/S0012-821X(96)00173-2.
- CHARETTE, M. A., W. S. MOORE, AND W. C. BURNETT. 2008. Uranium- and thorium-series nuclides as tracers of submarine groundwater discharge. p. 155–191. *In* S. Krishnaswami and J. K. Cochran [eds.], U-Th series nuclides in aquatic systems. Elsevier.
- CHURCH, T. M. 1996. An underground route for the water cycle. *Nature* **380**: 579–580.
- DULAIOVA, H., AND W. C. BURNETT. 2004. An efficient method for γ -spectrometric determination of radium-226,228 via manganese fibers. *Limnol. Oceanogr. Methods* **2**: 256–261.
- , R. N. PETERSON, W. C. BURNETT, AND D. LANE-SMITH. 2005. A multi-detector continuous monitor for assessment of ^{222}Rn in the coastal ocean. *J. Radioanal. Nucl. Chem.* **263**: 361–363, doi:10.1007/s10967-005-0063-8.
- FREYER, K., H. C. TREUTLER, G. JUST, AND H. V. PHILIPSBORN. 2003. Optimization of time resolution and detection limit for online measurements of ^{222}Rn in water. *J. Radioanal. Nucl. Chem.* **257**: 129–132, doi:10.1023/A:1024713830514.
- GALLAGHER, B. 1980. Physical structure and circulation in Honokohau, a small Hawaiian harbor affected by groundwater. *Pac. Sci.* **34**: 301–311.
- GARRISON, G. H., C. R. GLENN, AND G. M. MCMURTRY. 2003. Measurement of submarine groundwater discharge in Jahana Bay, Oahu, Hawaii. *Limnol. Oceanogr.* **48**: 920–928.
- GORDON, D. C. J., AND OTHERS. 1996. LOICZ biogeochemical modelling guidelines. LOICZ Publishers.
- JOHNSON, A. G. 2008. Groundwater discharge from the leeward half of the Big Island, Hawaii. M.S. thesis. Univ. of Hawaii.
- , C. R. GLENN, W. C. BURNETT, R. N. PETERSON, AND P. G. LUCEY. 2008. Aerial infrared imaging reveals large nutrient-rich groundwater inputs to the ocean. *Geophys. Res. Lett.* **35**: L15606, doi:10.1029/2008GL034574.
- KANEHIRO, B. Y., AND F. L. PETERSON. 1977. Groundwater recharge and coastal discharge for the northwest coast of the island of Hawai'i: A computerized water budget approach. Technical Report No. 110. Water Resources Research Center, Univ. of Hawaii.
- KAY, E. A., L. S. LAU, E. D. STROUP, S. J. DOLLAR, D. P. FELLOWS, AND R. H. F. YOUNG. 1977. Hydrologic and ecological inventory of coastal waters of west Hawaii. Technical Report No. 105. Water Resources Center, Univ. of Hawaii.
- KIM, G., J.-W. RYU, H.-S. YANG, AND S.-T. YUN. 2005. Submarine groundwater discharge (SGD) into the Yellow Sea revealed by ^{228}Ra and ^{226}Ra isotopes: Implications for global silicate fluxes. *Earth Planet. Sci. Lett.* **237**: 156–166, doi:10.1016/j.epsl.2005.06.011.
- KOHOUT, F. A. 1966. A neglected phenomenon of coastal hydrology. *Hydrology* **26**: 391–413.
- LEE, J.-M., AND G. KIM. 2006. A simple and rapid method for analyzing radon in coastal and ground waters using a radon-in-air monitor. *J. Environ. Radioact.* **89**: 219–228, doi:10.1016/j.jenvrad.2006.05.006.
- MACINTYRE S., R. WANNINKHOF, AND J. P. CHANTON. 1995. Trace gas exchange across the air-sea interface in freshwater and coastal marine environments. p. 52–97. *In* P. A. Matson and R. C. Harris [eds.], Biogenic trace gases: Measuring emissions from soil and water. Blackwell Science.
- MOORE, W. S. 1999. The subterranean estuary: a reaction zone of ground water and sea water. *Mar. Chem.* **65**: 111–125, doi:10.1016/S0304-4203(99)00014-6.
- , AND R. ARNOLD. 1996. Measurement of ^{223}Ra and ^{224}Ra in coastal waters using a delayed coincidence counter. *J. Geophys. Res.* **101**: 1321–1329.
- , AND D. F. REID. 1973. Extraction of radium from natural waters using manganese-impregnated acrylic fibers. *J. Geophys. Res.* **90**: 6983–6994.
- MULLIGAN, A. E., AND M. A. CHARETTE. 2006. Intercomparison of submarine groundwater discharge estimates from a sandy unconfined aquifer. *J. Hydrol.* **327**: 411–425, doi:10.1016/j.jhydrol.2005.11.056.
- PETERSON, R. N., W. C. BURNETT, C. R. GLENN, AND A. J. JOHNSON. 2007. Quantifying groundwater discharge plumes along the Kona coast of Hawaii using radon and radium isotopes, IUGG XXIV Earth: Our changing planet. IAHS Press.
- SANTOS, I. R., W. C. BURNETT, J. P. CHANTON, B. MWASHOTE, I. G. N. A. SURYAPUTRA, AND T. DITTMAR. 2008. Nutrient biogeochemistry in a Gulf of Mexico subterranean estuary and groundwater-derived fluxes to the coastal ocean. *Limnol. Oceanogr.* **53**: 705–718.
- SCHUBERT, M., A. SCHMIDT, A. PASCHKE, A. LOPEZ, AND M. BALCAZAR. 2008. In-situ determination of radon in surface water bodies by means of a hydrophobic membrane tubing. *Radiat. Meas.* **43**: 111–120, doi:10.1016/j.radmeas.2007.12.017.
- SLOMP, C. P., AND P. VAN CAPPELEN. 2004. Nutrient inputs to the coastal ocean through submarine groundwater discharge: Controls and potential impact. *J. Hydrol.* **295**: 64–86, doi:10.1016/j.jhydrol.2004.02.018.
- STREET, J. H., K. L. KNEE, E. E. GROSSMAN, AND A. PAYTAN. 2007. Submarine groundwater discharge and nutrient addition to the coastal zone and coral reefs of leeward Hawai'i. *Mar. Chem.* **109**: 355–376.
- STRINGER, C. E., AND W. C. BURNETT. 2004. Sample bottle design improvements for radon emanation analysis of natural waters. *Health Phys.* **87**: 642–646.

- SWARZENSKI, P. W. 2007. U/Th series radionuclides as coastal groundwater tracers. *Chem. Rev.* **107**: 663–674.
- , C. REICH, K. D. KROEGER, AND M. BASKARAN. 2007. Ra and Rn isotopes as natural tracers of submarine groundwater discharge in Tampa Bay, Florida. *Mar. Chem.* **104**: 69–84, doi:10.1016/j.marchem.2006.08.001.
- TANIGUCHI, M., AND OTHERS. 2008. Submarine groundwater discharge from the Yellow River delta to the Bohai Sea, China. *J. Geophys. Res.* **113**: C06025, doi:10.1029/2007JC004498.
- ZEKTSEY, I. S. 2000. *Groundwater and the environment: Applications for the global community*. Lewis Publishers.

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