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Measurement of submarine groundwater discharge in Kahana Bay, Oʻahu, Hawaiʻi

G. H. Garrison[1] *and C. R. Glenn*
Department of Geology and Geophysics, SOEST, University of Hawaiʻi, Mānoa, Honolulu, Hawaiʻi 96822

G. M. McMurtry
Department of Oceanography, University of Hawaiʻi, Mānoa, Honolulu, Hawaiʻi 96822

Abstract

Submarine groundwater discharge (SGD) is neither well understood nor commonly investigated in Hawaiʻi, but it is recognized as a potential pollution source to coastal environments. Between 1998 and 2000, this study located and quantified both total SGD and the terrestrial SGD fraction (f_{tgw}) in Kahana Bay, Oʻahu. CTD casts were used to profile the water structure and identify potential areas of SGD impact in the bay. Lee-type seepage meters were used to measure SGD rates and collect samples of SGD directly. Radon-222, Si, Cl^-, and total alkalinity (T_a) were used as natural tracers to measure the terrestrial groundwater fraction within SGD. Nutrient concentrations were also measured to calculate total nutrient fluxes into the bay via SGD. Ninety percent of the SGD in Kahana Bay occurs in the inner bay within 1 km of the shoreline. The average total SGD flux measured was 90×10^6 L d^{-1}, 16% of which was terrestrial groundwater. By comparison, the average annual surface runoff from Kahana River is 90.7×10^6 L d^{-1}. Estimated fluxes of total dissolved phosphorus and nitrogen by SGD to the bay were 500 and 200% greater than fluxes via surface runoff, respectively. Thus, SGD in Kahana Bay has proved to be a significant source of both freshwater and total nutrient input comparable to that from the surface runoff of Kahana River.

Submarine groundwater discharge (SGD) is the seepage of any fluids from coastal submarine sediments into the overlying coastal ocean. In this respect, coastal submarine sediments act as a subterranean estuary, an aquifer separate unto itself with a unique chemistry distinguishing it from either the meteoric or marine hydrologic systems (Moore 1999). SGD is neither well understood nor commonly investigated in Hawaiʻi. However, SGD has recently become recognized as a potential pollution source because it can include meteoric groundwater anywhere a terrestrial aquifer with positive head is in contact with the shoreline. In 1997, the Scientific Committee on Oceanic Research (SCOR) and the International Geosphere–Biosphere Program (IGBP) established Working Group 112 "to define . . . how SGD influences chemical and biological processes in the coastal ocean." Detailed research along the eastern seaboard of North America, the Caribbean, and the Gulf of Mexico has found SGD to be both present and often a startlingly significant aspect of coastal marine environments (Cable et al. 1996*b*; Moore 1996; Corbett et al. 1999). Such findings are reason to give chemical oceanographers pause when evaluating the evolution of the global ocean (Moore 1999).

One of the goals of the research reported here was to find whether SGD could be recognized and quantified in a volcanic island setting. The fractured basalt/caprock structure along the coasts of Oʻahu produces abundant meteoric groundwater supplies, and SGD is thought to play an important, though poorly understood, role (Takasaki et al. 1969; Lau 1973; Kay et al. 1977). We furthermore sought to specifically identify the terrestrial groundwater fraction of SGD in light of its potential as a conduit of anthropogenic impact. There is concern that sewage-affected SGD could provide an artificial nutrient supply, encouraging noncoral communities to flourish and threatening reef-building corals with asphyxiating algae (Hallock and Schlager 1986).

The Kahana Bay system—an example of a coastal Hawaiian environment

The meteoric groundwater of Oʻahu consists primarily of a Ghyben–Herzberg lens impounded within the island by a layer of caprock. Caprock is a regional term for the semi-impermeable calcareous reefal and volcanic alluvial deposits that overlie and confine the basaltic bedrock around the coastal edge of the island (Stearns and Vaksvik 1935; Takasaki et al. 1969; Hunt 1996). It is this caprock/floating

[1] To whom correspondence should be addressed. Present address: Department of Earth and Space Sciences, University of Washington, Seattle, Washington (garrison@ess.washington.edu).

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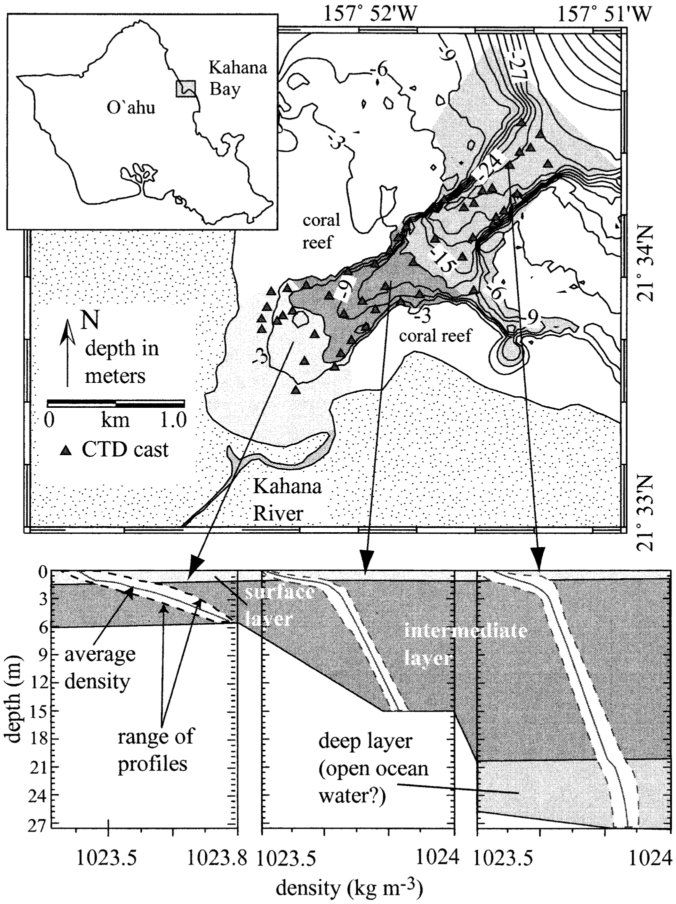

Fig. 1. Map showing the location of Kahana Bay on the windward coast of O'ahu. Kahana Valley extends to the southwest. CTD sample locations are plotted on the map, and the density profiles from the inner, middle, and outer bays are shown below. The white swaths show the breadth of the density profiles within each area of the bay; the solid line in each swath is the average of the profiles. The surface layer is formed by water from the Kahana River and becomes thinner and more saline farther from the river mouth. The intermediate layer has fairly constant salinity and might be due to seepage from the coastal aquifer.

lens system that has formed the large meteoric groundwater reservoir that supports O'ahu's urban development. Our hypothesis is that SGD from the system can be identified chemically within the overlying marine waters by naturally occurring tracers. The presence of elevated ^{222}Rn and Si relative to offshore marine waters is considered evidence of SGD since both tracers are more concentrated in terrestrial groundwaters because of ^{238}U decay and silicate mineral dissolution (Cable et al. 1996*a*; Corbett et al. 1999). Conversely, dilution of dissolved Cl^- and total alkalinity (T_a) relative to marine water is also considered evidence of SGD because these constituents are an order of magnitude less concentrated in Hawaiian meteoric groundwaters (Li 1988).

Kahana Bay (Fig. 1) was selected as the study site because it is undeveloped and there is abundant rainfall in the adjacent valley. With over 500 cm of rain annually (Takasaki et al. 1969), it was thought that SGD would be found in the bay. Kahana Bay is the submarine extent of Kahana Valley, a deeply incised drainage in the Ko'olau Range extending 6.44 km back from the shoreline. The bay is characterized by a paleochannel bordered by two ≥10-m vertical walls of Pleistocene coral–algal reef (Fig. 1). Within the channel, sediments are >10 m thick, and rudimentary seismic work observed two reflectors below the sediment surface, presumably an old reef surface or valley floor underlain by the basalt of the Ko'olau Range (Coulbourn et al. 1974). The topography and bathymetry of the valley, bay, and offshore canyons reveal their pre-Pleistocene formation during ≥100-m lower sea level stands (Coulbourn 1971; Coulbourn et al. 1974).

Within the valley, there are three basic geologic units. The Ko'olau range, which forms and surrounds Kahana Valley, is the erosional remnant of the basaltic Ko'olau shield volcano. It is the Ko'olau basalts that serve as a Ghyben–Herzberg aquifer for the eastern half of the island (Stearns and Vaksvik 1935), and in Kahana Valley, it is identified by the Hawaiian Aquifer codes 306022212 and 306022122 (Mink and Lau 1987). Dike-filled Ko'olau basalts, such as are found in Kahana Valley, have hydraulic transmissivities, which range between 3×10^{-4} and 2×10^{-3} $m^2\ s^{-1}$ (Takasaki et al. 1969). In the lower reaches of Kahana Valley, the Ko'olau basalts are overlain and confined by a sedimentary unit of weathered basaltic talus and alluvium. The unit is exposed from the head of the valley at 100 m elevation down to an elevation of 9 m, 1.5 km from the shore. This unit forms a separate aquifer identified by the Hawaiian Aquifer code 30602116 (Mink and Lau 1987), and well logs show this unit to be 49 m thick near the shoreline (Takasaki et al. 1969). The unit is believed to be at least Pleistocene in age based on its stratigraphy and elevation and is here referred to as the Pleistocene alluvium. Similar weathered alluvial units on O'ahu have transmissivities in the range of 10^{-6} $m^2\ s^{-1}$ (Takasaki et al. 1969). At the mouth of Kahana Valley, the Pleistocene alluvium is overlain by a younger and less lithified sedimentary deposit consisting of terrestrial alluvium and calcareous sands (Takasaki et al. 1969; Lau 1973). The top of this unit reaches 9 m elevation, which was the approximate height of sea level on O'ahu during the mid-Holocene sea level high stand (Stearns 1974; Grossman and Fletcher 1998). The unit forms the beach around Kahana Bay, is believed to be entirely Holocene in age, and is referred to here as the Holocene alluvium. According to the unpublished drilling log of USGS Well 405, located 100 m from the edge of the bay, the Holocene alluvium is approximately 15 m thick and reaches an elevation of −6 m near the shoreline (C. Lao, Honolulu Board of Water Supply, pers. comm.). There is no hydraulic data on this unit, but it has greater porosity and is less weathered than the Pleistocene alluvium and is believed to have a greater transmissivity. The last 3 km of the Kahana River are contained entirely within this unit.

In this paper, the bay is described in three areas, illustrated in Fig. 1: (1) the inner bay (water depths up to ~6 m, within ~1 km of the shore); (2) the middle bay (6–15 m depth, 1–2 km from shore); and (3) the outer bay (≥15 m depth). The inner bay is the area that overlays the Holocene alluvium, which is not thought to extend beyond a water depth of 6 m. This depth is also thought to be the depth of closure for

Table 1. End-member concentrations and average calculated f_{tgw} for SGD in the inner and middle bays using different tracers.

Tracer	Average C_{SGD}	Average C_{mw}	Average C_{tgw}	Average f_{tgw}
Inner Bay*				
Cl^- (mmol L^{-1})	451.99±2.16 n=10	546.43±2.61 n=12	15.59±4.19 n=4	0.2±0.06
T_a (meq L^{-1})	1.888±0.009 n=10	2.174±0.677 n=12	0.526±0.164 n=4	0.2±0.1
^{222}Rn (dpm L^{-1})	8.93±0.71 n=10	1.48±0.13 n=12	64.22±14.16 n=4	0.1±0.01
Si (mmol L^{-1})	9.90±1.92 n=10	2.68±1.02 n=9	175.41±35.98 n=4	0.04±0.01
Middle Bay†				
Cl^- (mmol L^{-1})	546.10±2.61 n=17	547.63±2.41 n=35	4.94±1.27 n=8	0.003±0.01
T_a (meq L^{-1})	2.224±0.011 n=17	2.247±0.021 n=11	0.506±0.040 n=8	0.009±0.01
^{222}Rn (dpm L^{-1})	3.68±1.52 n=17	2.10±1.04 n=35	412.77±295.58 n=8	0.003±0.01
Si (mmol L^{-1})	9.30±4.92 n=17	2.10±1.40 n=32	621.44±2.64 n=8	0.01±0.01

C_{SGD}, SGD tracer concentration measured in fluids emanating from seepage meters; C_{mw}, mean tracer concentration in marine water surround the dome; C_{tgw}, mean tracer concentration in terrestrial groundwater source; f_{tgw}, the fraction of SGD as terrestrial groundwater.
* tgw end-member, Holocene alluvium groundwater; mw end-member, inner bay ambient water.
† tgw end-member, averages of the Pleistocene alluvium and Ko'olau basalt groundwaters; mw end-member, middle bay ambient water.

the Kahana Bay beach system. The depth of beach closure is the point farthest from shore beyond which seafloor sediments are not significantly influenced by surface energy, as defined by Komar (1998). Closure depth is estimated at Kahana based on grain size measurements (Coulbourn 1971), greatest annual ocean swell heights, and observations of the seafloor over the course of the study. The seaward extent of the middle bay was defined by the depths at which the intermediate water mass (as measured by preliminary CTD surveys) is no longer in contact with the seafloor, whereas the most seaward portion of Kahana is considered the outer bay.

Methods

Sampling techniques—Field work was performed during the spring and summer months of 1998–2000, avoiding the high wave events for which the north-facing shores of O'ahu are famous. In January and February 1998, a Sea Bird SEACAT conductivity, temperature, and depth (CTD) profiler was used to measure the physical water structure of Kahana Bay. These profiles were used to identify the areas with the highest potential for meteorically affected SGD.

Typical Lee-type seepage meters were used both to measure SGD rates (Lee 1977) and to collect waters seeping from the seafloor for chemical analyses, as described below. By sampling waters directly from the chambers, we were able to collect discrete SGD samples that were isolated from ambient water in the bay. Thus, wherever SGD chemical concentrations are discussed in this paper, we are referring to analyses made directly on waters collected in the meters. This is particularly important in isolating SGD characteristics from those of waters coming from the Kahana River. The Plexiglas hemispherical chambers used as seepage meters measure 43 cm in diameter, 0.15 m^2 in footprint area, 19 cm in height, and 19.4 liters in volume. Each meter was fitted with a 1.9-cm exit port at its apex to which 10 liters of high-density polyethylene (HDPE) sampling bags were attached. At each sampling period, the chambers were sunk into the seafloor 7–10 cm and left for at least 24 h to allow SGD equilibration and displacement of marine waters trapped in the chambers by SGD. Seepage was measured 1–4 times per tidal half-cycle (high-to-low tide, or vice versa) depending on the seepage rate. A control meter was also installed to assess potential artifacts during the sampling periods from such phenomena as wave action. The control meters were identical to the regular seepage meters, except that they were installed within a half-buried, sediment-filled, 2-m-wide × 0.5-m-deep round, plastic kiddie pool. Any fluid exchange into or out of the control meters could not be from SGD. In general, the control measurements found no significant artificial fluid flux, and the largest fluid flux measured in a control meter was <1% of the average SGD measured.

At the beginning of each sampling period, 1.00 liters of ultrapure deionized water (18+ MΩ resistance) was added to each sampling bag to prevent anomalous influx (Shaw and Prepas 1989; Cable et al. 1997). Prefilling also provides a volume of water that allows measurement of seepage into the seafloor sediments. Before collection, valves at the base of each bag were closed, the time was recorded, and the bag was removed and brought to shore. Once the samples were brought to shore, the sampled waters were transferred to both the 4-liter radon bottles (avoiding atmospheric exposure) and the 125-ml HDPE bottles for return to the University of Hawai'i laboratories. The radon bottles were evacuated 4-liter amber glass jars sealed with #6 stoppers and marine-grade silicon sealant and fitted with tygon sampling tubes. These gas-tight vessels, originally designed by the SGD group at

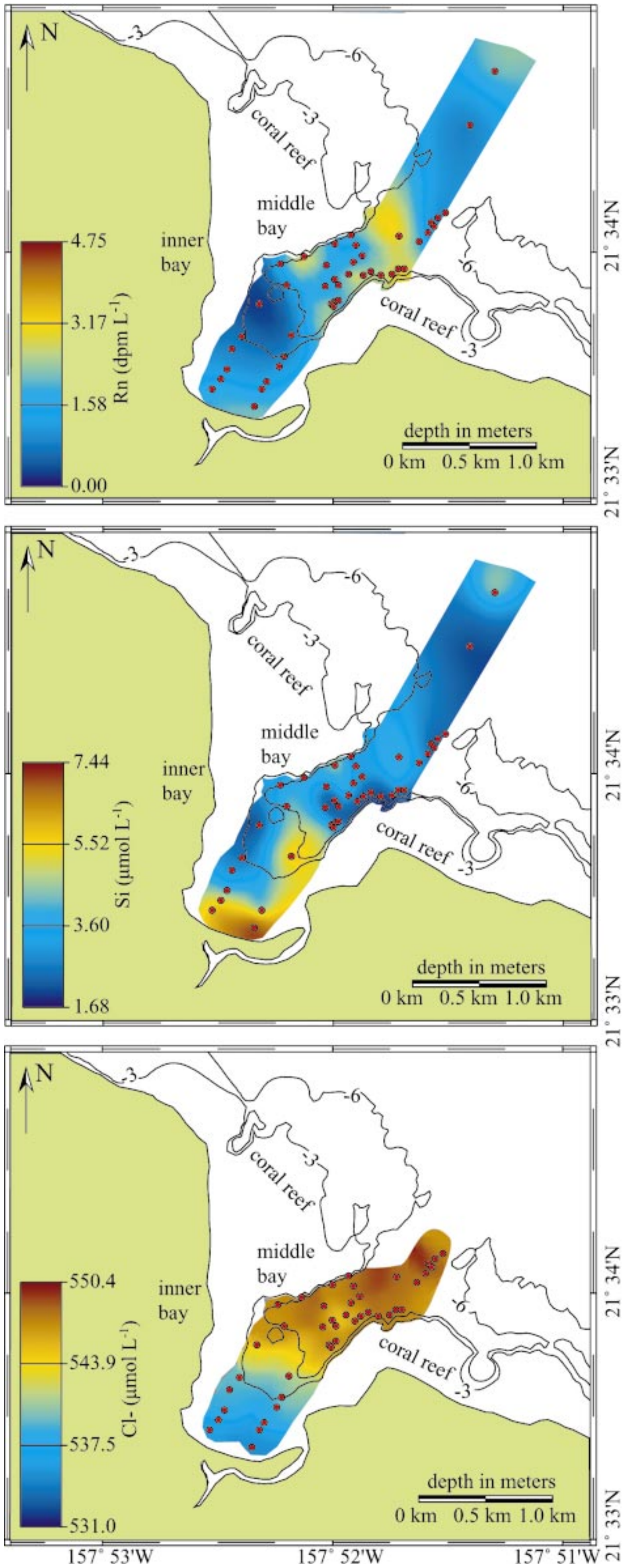

Fig. 2. Contour plots of measured ^{222}Rn, Si, and Cl^- concentrations from ambient water samples. Sample location are indicated by the filled circles.

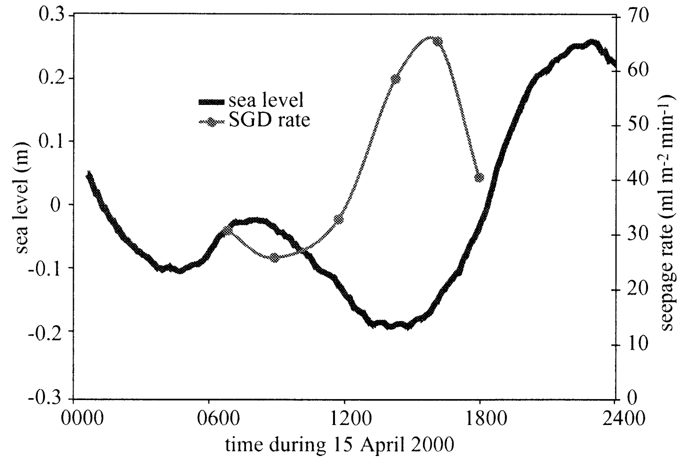

Fig. 3. Seepage rates measured from seepage meter station D5 plotted over time on 15 April 2001. Also plotted is sea level during 15 April 2001. Sea level data come from NOAA and the amplitude and timing are corrected for Kahana Bay. Station D5 is located in the inner bay, at 22.559750°N, 157.870800°W and at a water depth of 3.1 m.

Florida State University, can be directly attached to the radon extraction system with a reduced risk of sample loss.

In order to calculate the meteoric and marine mixing fractions in the fluids sampled from the seepage meters, water samples were collected from the bottom water surrounding the meters. These samples were used for the marine water end-member tracer concentrations (C_{mw}) for mixing calculations as listed in Table 1. Water samples were also collected from four piezometers installed in the Holocene alluvium at the mouth of the valley and from wells screened in the Pleistocene alluvium (HBWS well 3453-07) and in the Koʻolau basalt bedrock (USGS well W405). The piezometers consisted of 4.5-cm OD slotted polyvinyl chloride (PVC) casings driven directly into the soil to a depth approximately 1.5 m below the groundwater table. The piezometer and well samples were used for the terrestrial groundwater end-member tracer concentrations (C_{SGD}) for mixing calculations as listed in Table 1.

Analytical chemistry—Nutrient samples were filtered, frozen, and sent for analysis to either the SOEST Analytical Services (Ted Walsh, U. Hawaiʻi) or to the Marine Laboratory Facilities at the University of Washington (Kathy Krogslund). In either case, measurements were made using standard spectrophotometric flowthrough autoanalysis. Cl^- was measured titrimetrically with 0.1 mmol L^{-1} $AgNO_3$, a modification of the Mohr–Knudsen technique (e.g., Grasshoff et al. 1983). T_a was determined by Gran titration with a solution of 0.09553 mol HCl kg^{-1} of 600 mmol L^{-1} NaCl solution, and titrations were made with a Brinkmann Metrohm 655 Dosimat autotitrator. Radon-222 was measured using the technique described by Mathieu (*see* appendix I in Biscaye et al. 1976), modified such that the extracted radon was trapped in a stainless steel column placed in a bath of liquid nitrogen. Radon-222 decay was measured photometrically on an Applied Techniques AC/DC-DRC-MK10-2 counting unit. Radon-222 concentrations were corrected for instrument and counter blanks, cell backgrounds, and radioactive decay between the sampling time and the end of scintillation counting.

Mixing calculations—Conservative chemical tracers were used to calculate mixing between marine and terrestrial waters using a simple mixing model.

$$C_{SGD} = (f_{tgw} \cdot C_{tgw}) + (f_{mw} \cdot C_{mw}) \quad (1)$$

$$f_{mw} = 1 - f_{tgw} \quad (2)$$

$$f_{tgw} = (C_{SGD} - C_{mw})/(C_{tgw} - C_{mw}) \quad (3)$$

C_{SGD} is the SGD tracer concentration measured in fluids emanating from seepage meters, C_{tgw} is the mean tracer concentration in terrestrial groundwater source, f_{tgw} is the fraction of SGD as terrestrial groundwater, C_{mw} is the mean tracer concentration in marine water surrounding the dome, and f_{mw} is the fraction of SGD as marine water.

Results

Figure 1 illustrates CTD cast locations and average density profiles from the inner, middle, and outer parts of the bay. The profiles reveal a three-layered water structure in the bay: (1) a light surface layer, up to 3 m thick, ranging in density between 1,022.75 and 1,023.67 kg m^{-3}; (2) an intermediate layer 10–20 m thick with an average density of 1,023.75 kg m^{-3}; and (3) a bottom layer with a density averaging 1,023.88 kg m^{-3}. Figure 2 shows the contoured profiles of dissolved ^{222}Rn, Si, and Cl$^-$ in water samples collected from the ambient waters of Kahana Bay. Along the beach face, ^{222}Rn and Si are enriched and Cl$^-$ is depleted relative to offshore marine water. Within the middle bay are other areas of ^{222}Rn and Si enrichment and Cl$^-$ depletion. These areas are smaller and not continuous with the inner bay waters.

On a daily time scale, SGD rates are driven by sea level and tidal cyclicity. Figure 3 shows a plot of discharge rate from inner bay station D5 over the course of a tidal cycle on 15 April 2001. Also shown are sea level data taken from NOAA tide measurements at Honolulu Harbor and corrected for amplitude and arrival time at Kahana Bay. There is a clear inverse correlation between the two, as maximum discharge rates were measured during the lowest tide level. This is not surprising because the hydraulic gradient across the submarine aquifer will be steepest during low tide. There is also a time lag between the peak tides and the peak seepage rates.

^{222}Rn, Si, and T_a are plotted separately against Cl$^-$ in Fig. 4 for the waters sampled from the seepage meters, whereas the expanded panel highlights the results from just the middle bay seepage meters. The elevated terrestrial groundwater seepage into the inner bay can be seen in the depleted Cl$^-$ and T_a and enriched ^{222}Rn and Si SGD concentrations relative to the middle bay. Furthermore, in both parts of the bay, there is a strong linear correlation (R^2 = 0.987) between SGD Cl$^-$ and T_a, indicating that these constituents behave conservatively throughout the study area. Radon-222 and Si, however, behave differently between waters seeping into the

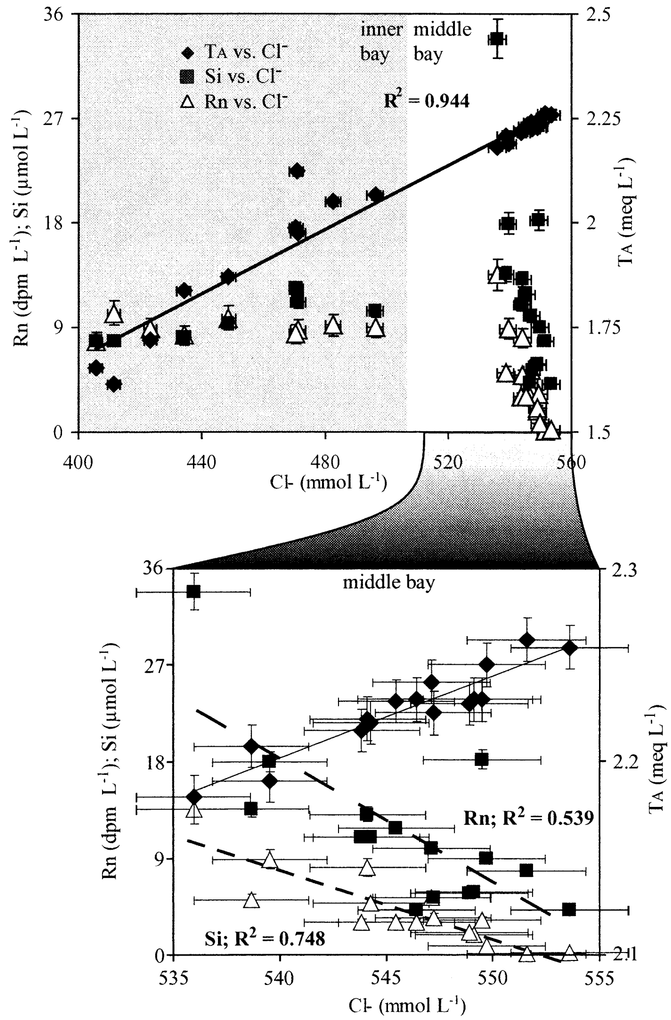

Fig. 4. T_a, ^{222}Rn, and Si plotted against CL$^-$ for SGD water collected from seepage meters in Kahana Bay. The upper panel is data from all samples collected, and the lower panel is an expansion of the data only from those chambers placed in the middle bay. Notice that T_a and Cl$^-$ trend positively in all areas of the bay, whereas ^{222}Rn and Si trend inversely with Cl$^-$ only in the middle bay.

inner bay versus the middle bay. Within the middle bay, ^{222}Rn and Si both trend inversely with Cl$^-$ (R^2 = 0.7475 and 0.5391, respectively), whereas in the inner bay, there is no discernable relation between either ^{222}Rn or Si and Cl$^-$ (R^2 < 0.1).

Table 1 lists the end-member data used to calculate the fraction of terrestrial groundwater in the SGD. The table lists the arithmetically averaged tracer concentrations of Cl$^-$, T_a, ^{222}Rn, and Si measured in the seepage meters (C_{SGD}), the ambient waters (C_{mw}), and the terrestrial groundwaters (C_{tgw}) for the inner bay and the middle bay. The fourth column of both tables is the average terrestrial groundwater fraction (f_{tgw}) measured in fluids emanating from the seepage meters using each tracer and Eq. 3; the f_{tgw} numbers listed are the average of values calculated for each seepage meter sample using the average C_{mw} and C_{tgw} end-member numbers. For the inner bay, the end-members used were the ambient water

Table 2. Expected and measured SGD tracer concentrations calculated using the end-member values listed and Eq. 1.

Tracer	C_{tgw}	C_{mw}	f_{tgw}	Expected C_{SGD}	Measured C_{SGD}
Inner bay					
Cl^- (mmol L^{-1})	15.6	546.43	0.2	451.45±61.75	451.99±2.16
T_a (meq L^{-1})	0.526	2.174	0.2	1.89±0.59	1.888±0.009
^{222}Rn (dpm L^{-1})	64.22	1.48	0.2	12.29±1.91	8.93±0.75
Si (μmol L^{-1})	175.41	2.68	0.2	33.59±14.62	9.90±1.92
TDP (μmol L^{-1})	4.0	0.4	0.2	1.03±0.71	0.75±0.10
TDN (μmol L^{-1})	13.2	8.3	0.2	9.21±6.15	17.45±4.05
Middle bay					
Cl^- (mmol L^{-1})	4.94	547.63	0.003	545.95±71.31	546.10±2.61
T_a (meq L^{-1})	0.506	2.247	0.003	2.24±0.11	2.224±0.011
^{222}Rn (dpm L^{-1})	412.77	2.10	0.003	3.43±2.37	3.68±1.21
Si (μmol L^{-1})	621.44	2.10	0.003	3.96±1.33	9.30±4.59
TDP (μmol L^{-1})	3.6	0.4	0.003	0.44±0.13	1.06±0.25
TDN (μmol L^{-1})	63.6	11.8	0.003	11.96±7.52	24.24±6.83

TDP, total dissolved phosphorus; TDN, total dissolved nitrogen.

of the inner bay and the Holocene alluvium groundwater data. For the middle bay, the end-members chosen were the ambient water of the middle bay and the average Koʻolau basalt and Pleistocene alluvium groundwater data. Cl^- is considered the most conservative of all four and should most closely reflect the actual terrestrial fraction. Table 2 lists the expected and measured values of both tracer and nutrient concentrations in SGD using the f_{tgw} calculated using Cl^- in Eq. 3; the end-members are the same as those listed in Table 1. In the inner bay SGD, f_{tgw} calculated with alkalinity and chloride agree the most closely of all the tracers, whereas both radon and silica concentrations are lower than would be expected. In the middle bay, however, the ^{222}Rn f_{tgw} agrees with chloride and alkalinity values, whereas silicate concentrations remain lower than expected.

Table 3 lists the arithmetically averaged total and terrestrial fluid seepage rates, f_{tgw}, and net chemical fluxes measured from the seepage meters in different parts of Kahana Bay. Figure 5 shows logarithmically contoured plots of both the total seepage rates and f_{tgw}. Ninety-nine percent of both total and meteoric seepage is within the inner bay, and patchy SGD was found in the middle bay, focused almost entirely in the central channel area. A total SGD rate of 90 $\times$ 10^6 L d^{-1} was measured within the study area as a whole, ~16% (14 $\times$ 10^6 L d^{-1}) of which is calculated to be meteoric groundwater. By comparison, the 37-yr average daily flow from Kahana River (USGS gauging station 16296500; http://water.usgs.gov/hi/nwis/annual/) is 90.7 $\times$ 10^6 L d^{-1}. Furthermore, in their terrestrial water budgets for Kahana Valley, Takasaki et al. (1969) calculated that 38 $\times$ 10^6 L d^{-1} should flow into the bay as meteoric groundwater, whereas Lau (1973) found that rate should be only 4 $\times$ 10^6 L d^{-1}.

Table 4 lists the annual net SGD nutrient loads to Kahana Bay. The fluxes were calculated by integrating the average chemical fluxes over the surface areas of the inner and middle bays (the total flux) and then subtracting the chemical fluxes into the sediments from marine water recharge. Recharge chemical fluxes were calculated with Eq. 2 using the marine water end-member concentrations and the SGD marine fraction (f_{mw}) as listed in Table 2. Also listed in Table 4 are the comparative ratios of the SGD nutrient fluxes to those measured from Kahana River from 1997 through July 2000, data produced by Hoover (2002). The SGD brings five times as much total phosphorus to Kahana Bay and two times as much total nitrogen as Kahana River, but less than one-tenth as much silica.

Table 3. Averaged measurements of SGD characteristics within Kahana Bay. The data listed are the arithmetic averages of measurements from seepage meters located at different parts of the bay (Fig. 5).

	Inner bay	Middle bay
Surface area ($\times 10^5$ m^2)	9.3	5.1
Total SGD rate (cm d^{-1})	8.4±2.1	2.3±1.0
Total SGD rate ($\times 10^6$ L d^{-1})	78±19	12±1.5
f_{tgw}	0.2	0.003
Terrestrial SGD ($\times 10^6$ L d^{-1})	14±0.3	0.038±0.007
T_a flux* (meq m^{-2} d^{-1})	5.9±1.2	−13±2
^{222}Rn flux* (dpm m^{-2} d^{-1})	570±250	16±5
Si flux* (μmol L^{-1} m^{-2} d^{-1})	640±180	99±38
TDP flux* (μmol L^{-1} m^{-2} d^{-1})	37±11	9±3
TDN flux* (μmol L^{-1} m^{-2} d^{-1})	920±300	160±57

TDP, total dissolved phosphorus; TDN, total dissolved nitrogen.

* Flux calculations are net fluxes (total SGD flux from the submarine aquifer minus marine flux into the aquifer).

Discussion and conclusions

Radon-222 proved to be a more effective tracer of terrestrial SGD in Kahana Bay than Si. Silica does show evidence of mixing when compared to Cl^- in the middle bay SGD, but Si concentrations were lower than expected (Table 2) and might indicate biogenic uptake. In the inner bay, SGD silica has a positive correlation with Cl^-, which would seem to indicate a marine source, although inner bay ambient water Si concentrations are far too low; Si concentrations in the inner bay SGD are a third of what we would expect based on conservative mixing (Table 2). It is possible that Si is being taken up from the shallow pore waters of the Holocene alluvium by terrestrial vegetation (Fox 1967) and

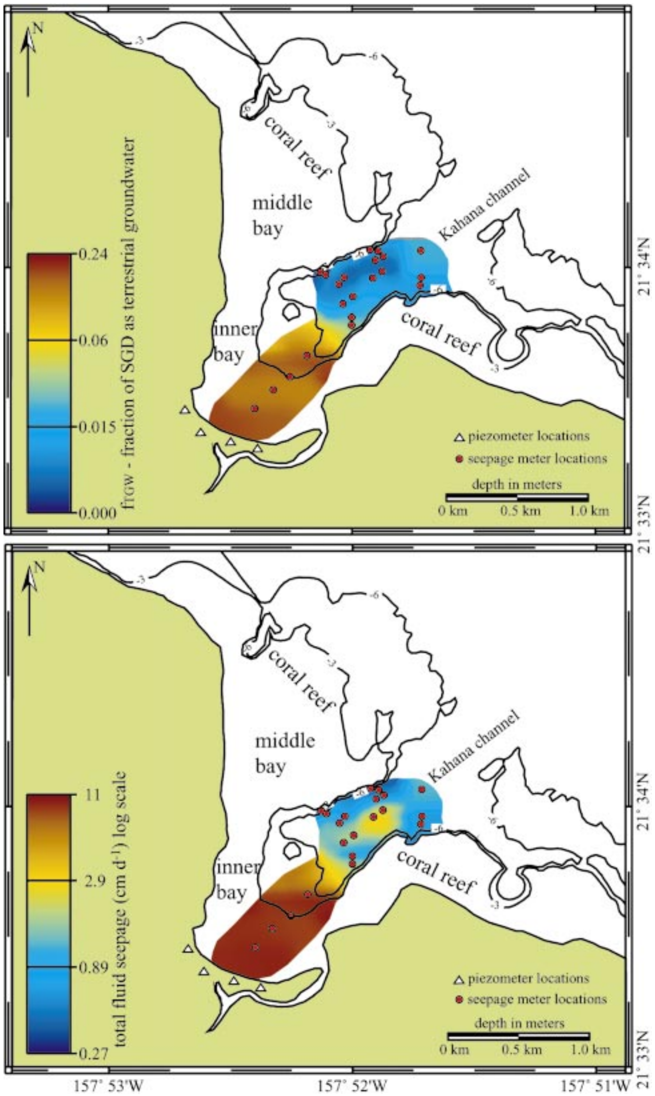

Fig. 5. Contour plots of total SGD flux and the SGD as terrestrial groundwater fraction (f_{tgw}) across Kahana Bay as measured from Lee-type seepage meters. Meter locations are marked by the filled circles. Locations of the Piezometers installed to sample groundwater from the Holocene alluvium are also shown. Data contours are plotted on a logarithmic scale.

that the positive correlation is just coincidental. The data do not present a more clear explanation.

SGD in Kahana Bay provides a significant source of dissolved nutrients (Table 4), and terrestrial SGD provides a important contribution to that nutrient supply. Figure 6 shows plots of SGD concentrations of total dissolved nitrogen (TDN) and total dissolved phosphorus (TDP) against f_{tgw} for the inner and middle bays. The positive correlation in both areas indicates that the higher the terrestrial groundwater fraction, the greater the SGD nutrient load to the bay. However, terrestrial groundwater is not the only source of nutrients in SGD. Table 2 also lists the expected TDP and TDN concentrations based on chloride f_{tgw}. Except for TDP in the inner bay, TDP and TDN are more concentrated in SGD than conservative mixing alone would predict. This could be evidence that sediment diagenesis is adding dissolved nutrients to the pore waters of the submarine aquifer.

Table 4. Annual SGD nutrient loads to Kahana Bay

Nutrient	Annual load via SGD (mol yr^{-1})	Ratio of SGD nutrient fluxes to Kahana River nutrient fluxes
TDP	5×10^4	5:1
TDN	1×10^6	2:1
Si	6×10^5	1:11

TDP, total dissolved phosphorus; TDN, total dissolved nitrogen.

The chemical tracer data indicate that there are different sources of terrestrial SGD in different parts of the bay and support the terrestrial end-members chosen in Table 1. Figure 4 differentiates the T_a, ^{222}Rn, and Si concentrations versus Cl^- in SGD between the inner and middle bays. T_a versus Cl^- shows that the SGD in the inner bay is fresher than in the middle bay and that both parts of the bay have a common tracer source (i.e., seawater). The ^{222}Rn and Si data, however, reveal a difference in terrestrial SGD sources. The exploded panel shows the inverse correlation between Cl^- and ^{222}Rn and Si in the middle bay SGD, reflecting a dilution of ^{222}Rn and Si by marine waters. In the inner bay, however, ^{222}Rn remains invariant relative to Cl^-, and Si actually has a positive correlation.

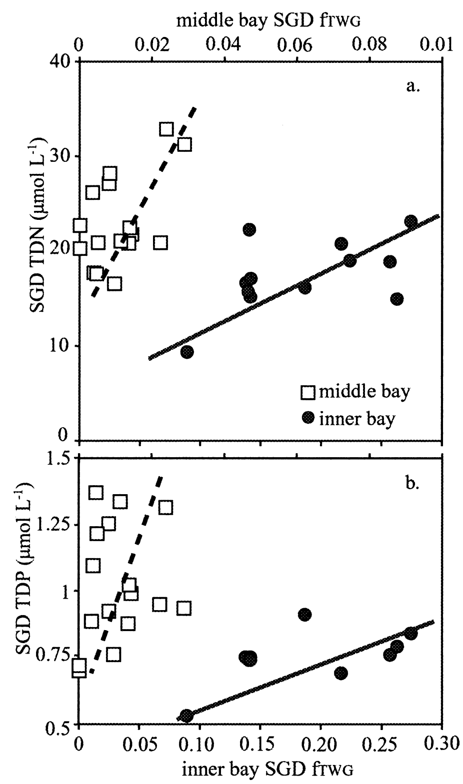

Fig. 6. Seepage of (a) TDN and (b) TDP concentrations versus f_{tgw} (the fraction of SGD as terrestrial groundwater) in samples collected from the seepage meters. Note the different abscissae on each graph for inner and middle bay samples.

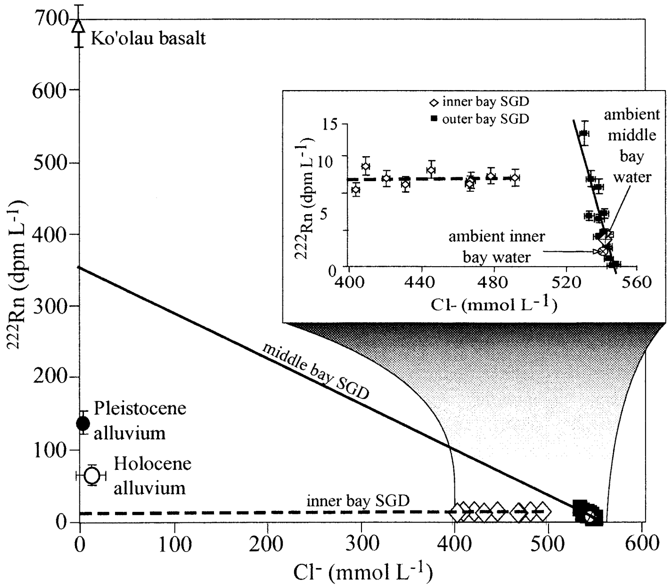

Fig. 7. Plot of ^{222}Rn versus Cl^- measurements from SGD, Holocene alluvium groundwater, Pleistocene alluvium groundwater (Honolulu BWS well 3453-07), and Ko'olau basalt groundwater (USGS well W405). The inner panel is an expansion of the SGD data.

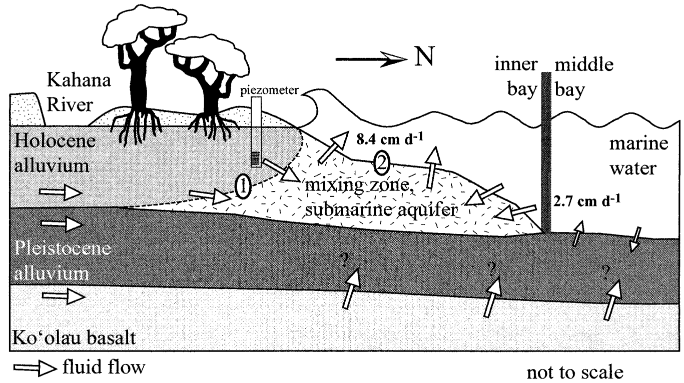

Fig. 8. A conceptual cross section of the inferred pathways of subsurface fluid flow along a shore-normal transect from the base of Kahana Valley into Kahana Bay. Total SGD rates are shown in bold; the inner bay had an average total seepage rate of 8.4 cm d^{-1}, whereas the middle bay had an average seepage rate of 2.7 cm d^{-1}. Position 1 is the landward edge of the meteoric/marine mixing zone. Position 2 is the seaward edge of the mixing zone where the submarine Holocene alluvium pore waters cross the sediment–water interface.

Figure 7 is a plot of ^{222}Rn versus Cl^- data from the terrestrial aquifers, the ambient waters of the inner and middle bays, and the waters sampled from the seepage meters. Linear regressions are plotted separately for the inner and middle bay SGD, and the exploded panel magnifies the inner and middle bay SGD data. The ^{222}Rn intercept for the middle bay SGD is 350 disintegrations min^{-1} (dpm) L^{-1}, falling almost evenly between the average values measured in groundwaters from the Ko'olau basalt and Pleistocene alluvium (USGS well W405 and Honolulu Board of Water Supply well 3453-07, respectively). The data do not identify a specific source of terrestrial groundwater for the middle bay SGD. However, because the ^{222}Rn intercept exceeds radon concentrations in both the Pleistocene and Holocene alluvium groundwaters, we consider this to be evidence of at least partial groundwater input from the Ko'olau basalt. The intercept could be affected by a mixture of waters between aquifers, addition or removal of ^{222}Rn along the flow path, or simply radioactive decay of ^{222}Rn. The data are not conclusive on this point because pore-water radon concentrations could be easily affected in all three ways.

Looking at the inner bay SGD regression and considering that this area is underlain by the Holocene alluvium, it appears that the primary source of terrestrial SGD in the inner bay is the Holocene alluvium groundwater. Inner bay SGD ^{222}Rn does not, however, show evidence of mixing when plotted against Cl^-. This absence of a trend could be a function of how marine and meteoric groundwaters mix in the Holocene alluvium. Figure 8 is a conceptualized cross section of the lower Kahana Valley and Bay. Because Cl^- and T_a have a marine source, submarine groundwater concentrations will begin to increase at the landward edge of the mixing zone, labeled position 1. Radon-222, however, is produced by the sediments of the Holocene alluvium. Pore-water ^{222}Rn concentrations won't begin to be diluted until the pore waters leave the submarine aquifer at position 2. Thus, ^{222}Rn concentrations are essentially the same in the inner bay SGD regardless of the fraction of freshwater present. The same behavior is not seen for middle SGD because, unlike the inner bay, ^{222}Rn dilution and Cl^- enrichment occur at the same time. The inner bay SGD ^{222}Rn that is so much lower than that measured in the piezometers (9 dpm L^{-1} vs. 64 dpm L^{-1}) could indicate that either pore-water ^{222}Rn is lower in the submarine part of the Holocene alluvium than in the terrestrial part, or that there is a vertical ^{222}Rn gradient in the Holocene alluvium pore water.

The results presented here can be considered first-order approximations of the total SGD effect within Kahana Bay. Seasonal variability in the valley hydrology (precipitation, river flow, and groundwater head) does not exceed 25% of the mean values (Takasaki et al. 1969; Lau 1973), thus constraining potential SGD variability. This work has demonstrated the applicability of natural chemical tracers and seepage meters to identify and quantify submarine groundwater discharge in Hawaiian waters. SGD is indeed present, and it provides an important chemical source to the waters of Kahana Bay. Furthermore, the intermediate water mass identified by the CTD surveys (Fig. 1) is in contact with the seafloor in the same areas where terrestrial groundwater seepage was identified. Thus, CTD meters might prove a simple but effective tool for identifying areas of a terrestrial SGD effect on a wider scale than is possible by discrete sampling alone. This study found SGD provides total phosphorus and nitrogen loads equal to or greater than those carried by surface runoff to the bay. Furthermore, the bay's SGD meteoric water flux is one-sixth as great as the river runoff. This study calculated that an average of 14×10^6 L d^{-1} of meteoric water enters Kahana Bay via SGD, a value that falls between the two previous hydrologic budget calculations that have been made for Kahana Valley. Terrestrial groundwater discharge in Kahana Bay is a small but significant part of the total SGD leaving the submarine aquifer.

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