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Sources of Nutrients and Fecal Indicator Bacteria to Nearshore Waters on the North Shore of Kaua`i (Hawai`i, USA)

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Abstract Water quality monitoring in Hanalei Bay, Kaua`i (Hawai`i, USA) has documented intermittent high concentrations of nutrients (nitrate, phosphate, silica, and ammonium) and fecal indicator bacteria (FIB, i.e., enterococci and *Escherichia coli*) in nearshore waters and spurred concern that contaminated groundwater might be discharging into the bay. The present study sought to identify and track sources of nutrients and FIB to four beaches in Hanalei Bay and one beach outside the bay, together representing a wide range of land uses. ^{223}Ra and ^{224}Ra activity, salinity, nutrient and FIB concentrations were measured in samples from the coastal aquifer, the nearshore ocean, springs, the Hanalei River, and smaller streams. In addition, FIB concentrations in beach sands were measured at each site, and the enterococcal surface protein (*esp*) gene assay was used to investigate whether the observed FIB originated from a human source. Nutrient concentrations in groundwater were significantly higher than in nearshore water, inversely correlated to salinity, and highly site specific, indicating local controls on groundwater quality. Fluxes of groundwater into Hanalei Bay were calculated using a mass-balance approach and represented at least 2–10% of river discharges. However, submarine groundwater discharge (SGD) may provide 2.7 times as much nitrate+nitrite to Hanalei Bay as does the Hanalei River. It may also provide significant fluxes of phosphate and ammonium, comprising 15% and 20% of Hanalei River inputs, respectively. SGD-derived silica inputs to the bay comprised less than 3% of Hanalei River inputs. FIB concentrations in groundwater were typically lower than those in nearshore water, suggesting that significant FIB inputs from SGD are unlikely. Positive *esp* gene assays suggested that some enterococci in environmental samples were of human fecal origin. Identifying how nutrients and FIB enter nearshore waters will help environmental managers address pressing water quality issues, including exceedances of the state *Enterococcus* water quality standard and nutrient loading to coral reefs.

Keywords Hanalei (Kaua`i, Hawai`i, USA) · Submarine groundwater discharge (SGD) · Coastal water quality · Nutrients · Fecal indicator bacteria (FIB) · Radium isotopes · Land use

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Introduction

Importance of Submarine Groundwater Discharge on Islands

The importance of submarine groundwater discharge (SGD) to coastal ecosystems has been recognized for several decades (Taniguchi et al. 2002; Burnett et al. 2006). SGD can alter the salinity, temperature, and chemistry of seawater, introduce anthropogenic substances from land including pathogens, toxins, and other pollutants, and support aquatic plants and algae by providing nutrient subsidies (Burnett et al. 2006; Paytan et al. 2006). On volcanic islands, including Jeju Island, Korea (Kim et al. 2003), Guam (Marsh 1977), and the Hawaiian archipelago (Dollar and Atkinson 1992; Garrison et al. 2003; Paytan et al. 2006; Street et al. 2008), SGD is often an important source of nutrients and potentially other substances of terrestrial origin.

Intermittent high levels of nutrients and fecal indicator bacteria (FIB) have been observed in Hanalei Bay on the north shore of Kaua`i since 2000 (Hanalei Watershed Hui website, www.hanaleiwatershedhui.org). This is a cause for concern because good coastal water quality is vital to the area’s coral reef ecosystems, fisheries, tourism-based economy, and local culture. All homes and businesses in Hanalei town use onsite wastewater disposal systems, and the water table in the area is often less than 1 m below the ground surface, so leakage of wastewater from these systems into groundwater is a distinct possibility. Thus, SGD was hypothesized to be a source of nutrients and FIB to coastal waters. Indeed, high SGD fluxes would be expected in this area because of its permeable, fractured bedrock and the high relief of the central portion of the island, a feature that contributes to heavy rainfall and groundwater recharge (Shade 1995).

Use of Radium Isotopes to Study Submarine Groundwater Discharge

Moore (1996, 2000) and collaborators pioneered the use of radium (Ra) isotopes for studying SGD and coastal mixing processes. Many other workers (Krest et al. 2000; Charette et al. 2003; Boehm et al. 2004; Hwang et al. 2005; Shellenbarger et al. 2006, and others; see also *Marine Chemistry* v. 109 [2008], and *Biogeochemistry* v. 66 [2003], which are special issues focusing on SGD and the use of Ra isotopes to measure it) have since used this approach in numerous SGD studies around the world. ^{223}Ra and ^{224}Ra are the respective decay products of ^{235}U and ^{232}Th, which occur naturally in most of the earth’s rocks. In a freshwater aquifer, Ra remains sorbed to particle surfaces; however, in the presence of water with high ionic strength, Ra desorbs and is released into solution. In coastal aquifers, fresh water often mixes with saline groundwater, resulting in brackish, high-Ra groundwater discharge (Church 1996; Burnett et al. 2006). This mixing zone is referred to as a subterranean estuary (Moore 1999).

Study Objectives

The present study used Ra isotopes to elucidate the impact of SGD on coastal water quality on the north shore of Kaua`i. Our specific goals were: (1) to estimate the SGD flux into the coastal ocean at the study sites, (2) to characterize groundwater and surface water quality, in terms of nutrients and FIB, at sites with varying land uses, (3) to identify likely sources of nutrients and FIB to the coastal ocean, and (4) to compare potential nutrient and FIB fluxes from groundwater to those from the Hanalei River and area streams. The overarching objective was to evaluate if SGD represents a threat to nearshore water quality on the north shore of Kaua`i.

Study Sites

Four beach sites in Hanalei Bay (Hono Iki, Pier, Pavilion, and Wai`oli and one other nearby site (Ha`ena State Park) were studied (Fig. 1). Hono Iki beach is adjacent to Princeville (population 1,698), a planned resort community with 1,640 housing units (US Census 2000, www.census.gov) including vacation condominiums, two large hotels, two golf courses, and a wastewater treatment plant. Pier, Pavilion, and Wai`oli are public beaches in Hanalei town (population 500), located about 6 km west of Princeville. Hanalei town has 303 housing units and a considerable amount of taro (“kalo”) agriculture, which is integral to the local culture. Unlike Princeville, it lacks centralized sewage treatment, relying instead on approximately 225 cesspools and 85 septic systems (Carl Berg, personal communication).[1] Ha`ena State Park is located at the western terminus of Hawai`i Route 560, surrounded almost entirely by undeveloped land. Land use within a 1 km radius of each site is summarized in Table 1. When the entire aquifer or watershed containing each study site is considered, the predominant land use (>95%) is undeveloped at all sites because commercial, residential, and agricultural development is restricted to the coast (Fig. 1).

All beaches included in this study are sandy, although at Ha`ena State Park, the sand is underlain by bedrock at a depth of less than 1 m. At Ha`ena State Park and Hono Iki, a coral shelf is present in the nearshore sampling area, while the nearshore area at other Hanalei Bay beaches is sandy bottomed. The Hanalei Pier and Hono Iki sites are located

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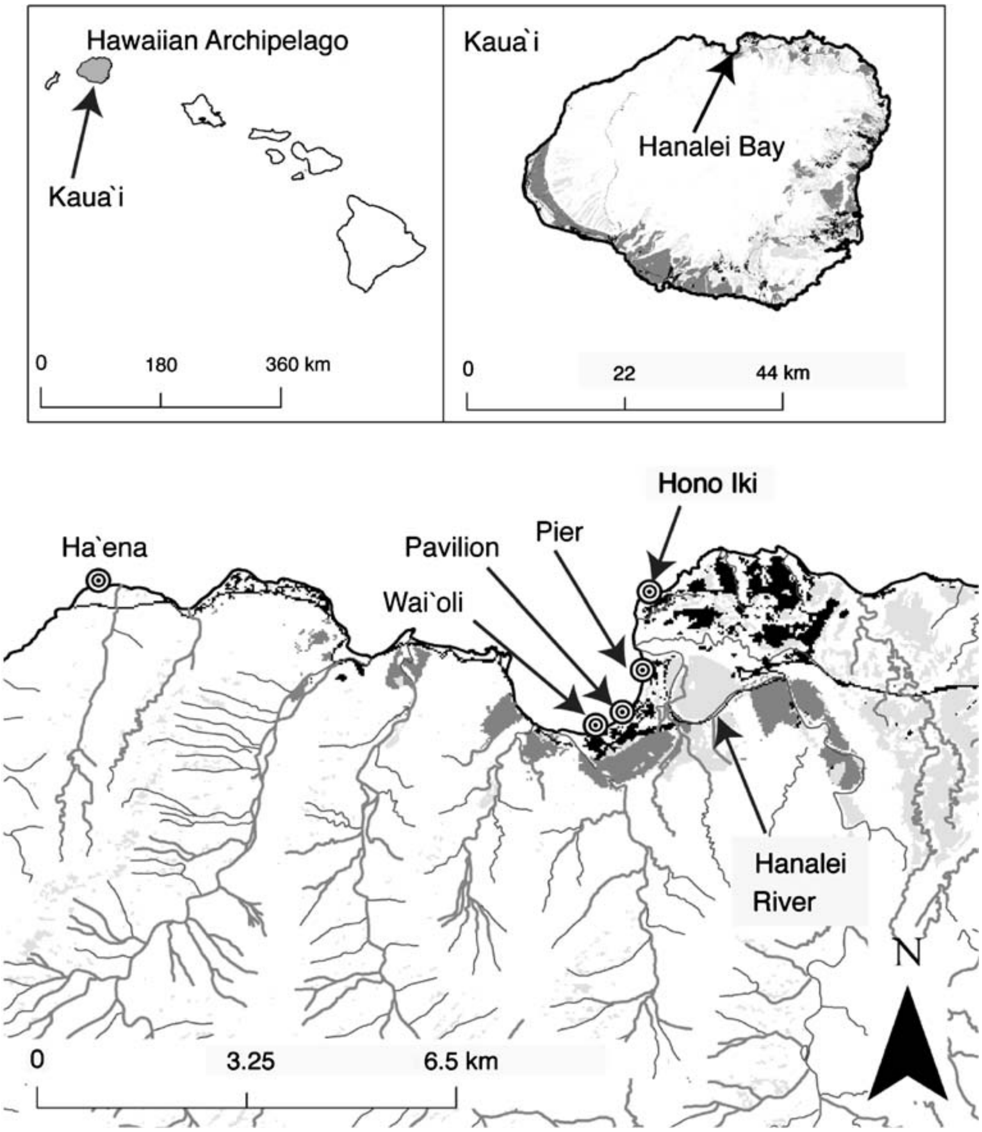

Fig. 1 Map of study sites. The study sites were located in and near Hanalei Bay on the north shore of Kaua`i, the most northwestern of the main Hawaiian Islands. The *top left panel* (Hawaiian Archipelago) extends from 18°30′21″ to 22°42′50″ N and from 154°18′50″ to 161°39′27″ W; the *top right panel* (Kaua`i) from 21°46′23″ to 22°16′13″ N and from 159°10′27″ to 159°51′32″ W; and *the bottom panel* (study sites) from 22°10′58″ to 22°10′58″ N and from 159°27′20″ to 159°35′49″ W. Site locations are indicated by a *bull's eye symbol* in the *bottom panel*. *Shading* indicates land use: *black* is high- and low-intensity developed land, *dark gray* is cultivated, *light gray* is grassland (including rangeland and unaltered grassland), and *white* is undeveloped (including forest, wetland, and barren land). *Gray lines* on the *bottom panel* indicate rivers and streams. Land use data are from National Oceanographic and Atmospheric Administration Coastal Services Center (land use/land cover data, www.csc.noaa.gov/crs/lca/hawaii.html)

Table 1 Land use within a 1-km radius of each site, not including water or unconsolidated shore (reef flat)

Site	Urban/built-up (%)	Agricultural (%)	Undeveloped (%)
Hono Iki	23.9	0.1	76.0
Hanalei Pier	13.8	0.1	86.1
Hanalei Pavilion	22.6	27.8	49.9
Hanalei Wai`oli	18.3	32.5	49.4
Ha`ena State Park	3.9	0.1	96.0

Urban/built-up land refers to urban land cover with greater than 25% impermeable surface. Undeveloped land includes forest, grassland, wetland, and bare land. Data from NOAA Coastal Services Center (http://www.csc.noaa.gov/crs/lca/hawaii.html).

near the Hanalei River mouth, and the Wai`oli site is located approximately 500 m from the mouth of the Wai`oli Stream. The maximum predicted tidal range in this area is about 0.85 m (WWW Tide and Current Predictor, Using XTide program by David Flater, http://tbone.biol.sc.edu).

Materials and Methods

Sampling Strategy

Samples were collected in March 2005, August 2006, and February 2007 as follows. At each site, one to two nearshore transects extending from the shoreline to an offshore point corresponding to a water depth of approximately 1.5 m, usually between 10 and 25 m from the shore, were sampled. Each transect consisted of three samples at ~10-cm, 1-m, and 1.5-m depths. At one of the two Ha`ena State Park transects, depth did not increase gradually with distance from shore because the nearshore zone out to about 100 m from shore was covered by a coral shelf. Therefore, at that site, we collected samples at three points (0, 3, and 25 m from shore) with similar water depths of 0.5–1 m. In addition, one long (100-m) transect at Pier was sampled three times in June 2005 (Derse et al. 2007). Groundwater was sampled from one to five wells installed in a shore-perpendicular transect in the beach face at each site. Wells were made of screened polyvinyl chloride (PVC) pipe approximately 10 cm in diameter, installed just deep enough (0.5–2 m) to enable the pumping of groundwater, and thus represent a mixed sample of the upper 10–30 cm of the coastal aquifer at the time of installation. Water level in the wells rose and fell with the tides, so high-tide samples generally represent a greater degree of depth integration (30–60 cm) and perhaps mixing with recently infiltrated seawater. Over the course of the tidal cycle, some wells were inundated by seawater or dried out, making it impossible to sample them throughout a tidal cycle.

Each coastal transect, including the associated wells, was sampled during at least one high and one low tide during each sampling trip to account for variability related to tidal cycles (Taniguchi et al. 2002; Boehm et al. 2004). Additionally, samples were collected from mid-Hanalei Bay and offshore (150–1,000 m from shore), the Hanalei River, four smaller streams flowing into Hanalei Bay (Pu`u Poa Stream at Hono Iki and Wai`oli, Waipa, and Waikoko Streams on the western side of the Bay), the Wainiha River and three smaller streams flowing into the ocean in the vicinity of Ha`ena, and the Princeville Wastewater Treatment Plant (WWTP), which uses its treated wastewater for golf course irrigation. All water samples were analyzed for salinity, Ra isotope activities, nutrient concentrations, and FIB. Since sand may be an important source of FIB to the coastal ocean (Yamahara et al. 2007), especially in Hawai`i (Oshiro and Fujioka 1995), we also sampled surface sand adjacent to the most inland and seaward wells at each transect for FIB content.

Radium and Salinity

Ra from 20–100 L of water was concentrated by passing it though 10–20 g (dry mass) of manganese-coated acrylic fiber prepared according to Moore (1976). The ^{223}Ra and ^{224}Ra activities (disintegrations per minute per 100 L of water, dpm $[100\ \mathrm{L}]^{-1}$) of each fiber was measured on a RaDeCC delayed coincidence counter as described by Moore and Arnold (1996). Samples were analyzed within 1 week of collection, and a subset (30–80%, depending on the sampling trip) of samples was rerun 3 to 6 weeks after collection to correct for the contribution of ^{228}Th to the original ^{224}Ra activity. The ^{224}Ra activities of samples that were not rerun were corrected by subtracting the average percent ^{228}Th for that trip from the original ^{224}Ra activity (typically about 5%).

Salinity was measured on 10 mL of 0.2- or 0.45-µm-filtered water samples using an Anton-Paar densitometer (DMA 4500 with SH-3 sample-handling unit, accurate to 0.0001 g cm^{-3}). Density measurements were converted to salinity values using the United Nations Educational, Scientific and Cultural Organization equation of state for seawater as described by Fofonoff (1985).

Nutrients

Thirty milliliters of water were filtered through a 0.2- or 0.45-µm syringe filter into a sample-rinsed high-density polyethylene bottle, immediately placed on ice, frozen within 8 h of collection, and kept frozen until analysis. Analyses for nitrate, nitrite, ammonium, silica, and phosphate were performed on a continuous segmented flow system consisting of components of both a Technicon Autoanalyzer II™ and an Alpkem RFA 300™ (March 2005) or on a QuickChem 8000 Flow Injection Analyzer™ (August 2006 and February 2007). A subset of 25 samples from August 2006 was run on both machines and showed very strong linear relationships (r^2>0.99) between concentrations of each nutrient in duplicate samples. Concentrations of combined nitrate and nitrite (nitrate+nitrite), phosphate, and silica run on the QuickChem were systematically 5–15% lower, and concentrations of ammonium were 5% higher, compared to duplicate samples run on the Technicon/Alpkem system. Nutrient concentrations from March 2005 were adjusted based on the linear relationships mentioned above to make them directly comparable to QuickChem results. For the sake of consistency, adjusted, rather than raw, values from March 2005 are used in all tables and calculations in this paper.

Fecal Indicator Bacteria

Enterococci and Escherichia coli

Concentrations of enterococci (ENT) and *Escherichia coli* (EC) were measured following the procedure described by Boehm et al. (2004) in all groundwater, river, and stream samples and all 10-cm depth or shoreline nearshore samples collected between nightfall and noon. FIB concentrations were not measured at nearshore sites in the afternoon because FIB are deactivated by sunlight in seawater (Boehm 2007). Fifty milliliters of each sample were collected in a sterile container, immediately stored on ice, and transported to the laboratory for analysis. ENT and EC were quantified from 10 mL of water diluted with 90 mL of Butterfield buffer (Weber Scientific, Hamilton, NJ, USA) using Colilert-18 and Enterolert kits (IDEXX, Westbrook, ME, USA). Within 6 h of water collection, tests were implemented in a 97-well format following the manufacturer's directions.

These tests allow detection of organisms between 10 and 24,192 most probable number (MPN) (100 mL)$^{-1}$.

FIB concentrations in sand were measured near the most seaward well (wet sand, recently inundated with seawater) and near the most inland well (dry sand, above the high tide line). Approximately 30 mL of sand were collected from the beach surface and placed in a sterile container. Distilled water was added to a total volume of 100 mL. The water and sand were shaken together for 2 min and then allowed to settle for 30 s. The supernatant was then analyzed for FIB. FIB concentrations in sand are reported as MPN per 100 mL sand.

Enterococcal Surface Protein Gene Analysis

A subset of ENT-positive samples was analyzed for the enterococcal surface protein (*esp*) gene, a putative human-specific marker in ENT (Scott et al. 2005) that has been tested in Hawaiian waters with promising results (Betancourt and Fujioka 2007). Media from positive IDEXX wells were removed using a 21.5-gauge needle and syringe and combined for each tray. One milliliter of Enterolert media was enriched in trypic soy broth for 4–6 h at 41°C. Deoxyribonucleic acids (DNAs) were extracted from a 1-mL aliquot of enrichment using QIAamp DNA Mini Kit (Qiagen, Valencia, CA, USA). Polymerase chain reactions (PCRs) containing the 3-μL template were run using the conditions, primers, and buffers described by Scott et al. (2005), except that Platinum *Taq* (Invitrogen, Eugene, OR, USA) was used. PCR products were run on a 1.5% agarose gel and stained with SYBR Gold (Invitrogen, Eugene, OR, USA). Positive and negative PCR and extraction controls were run in conjunction with unknowns.

Clostridium perfringens

Spores of *Clostridium perfringens* were enumerated in a subset of samples (n=10). Each 100-mL sample was membrane-filtered, and the membrane was then exposed to boiling water. Filters were placed on mCP agar and incubated anaerobically, and colony-forming units (CFU) were counted.

Statistical Methods

To compare sample groups, the Lilliefors test (MATLAB Statistics toolbox) was used to determine normality. If all groups were normally distributed, a *t* test was used to assess whether the means of the groups were significantly different; if not, the Kruskal–Wallis nonparametric test (MATLAB Statistics toolbox) was used to assess whether the medians of the groups were significantly different. Box and whiskers plots were created, and linear regressions were performed, using Statview 5.0.1. ArcGIS was used for mapping and land use statistics.

Because of the large number of FIB samples falling below the method detection limit, the chi-square test was used to assess whether FIB were more likely to be detected in a particular group of samples. To calculate means and 95% confidence intervals, FIB concentrations below the lower limit of detection were replaced with 5 MPN (100 mL)$^{-1}$. The FIB concentration of each sample was then log-transformed, and the means and 95% confidence intervals for the log-transformed values were calculated.

To assess correlations between variables, Pearson correlation coefficients and simple linear regression were used. *t* tests were used to assess the significances of Pearson correlations, and analysis of variance *F* tests were used to assess the significances of simple linear regressions. Unless otherwise noted, statistical significance for all tests was determined using a cutoff of $p<0.05$.

Results and Discussion

Salinity

The 95% confidence interval for nearshore salinity over all sites and all trips was 33.4–34.3, slightly lower than the average mid-bay value ($\bar{x}$=34.8; σ=0.17) reported by Storlazzi et al. (2006). If we take 34.8 to be the local seawater salinity value, then freshwater constituted 1–4% of nearshore water volume. At Pavilion, Wai`oli, and Ha`ena, freshwater comprised up to 4% of the nearshore water volume. At Hono Iki and Pier, both located near the Hanalei River (Fig. 1), freshwater comprised as much as 13% of the total water volume.

In well samples, salinities ranged from less than 1 to 35. Salinity was lowest at the most inland well of each transect and increased in the seaward direction and into the nearshore ocean (Fig. 2). The single exception to this pattern occurred at Ha`ena, where water collected from a spring discharging at the shoreline was much less saline ($\bar{x}$=18.5, n=3) than that from a well located 2 m further inland ($\bar{x}$=34.9, n=3). However, this spring emanated from a crack in the exposed bedrock and likely resulted from channelized fresh groundwater flow. Although each site was sampled at various points in the tidal cycle, no consistent pattern of tidal variability in salinity, in either nearshore or groundwater samples, was observed.

^{223}Ra and ^{224}Ra Activities and Activity Ratios

General patterns of Ra activity observed in this study indicated that SGD is occurring at the coast. The activities of ^{223}Ra and ^{224}Ra were highest in groundwater ($\bar{x}$=1.2 and

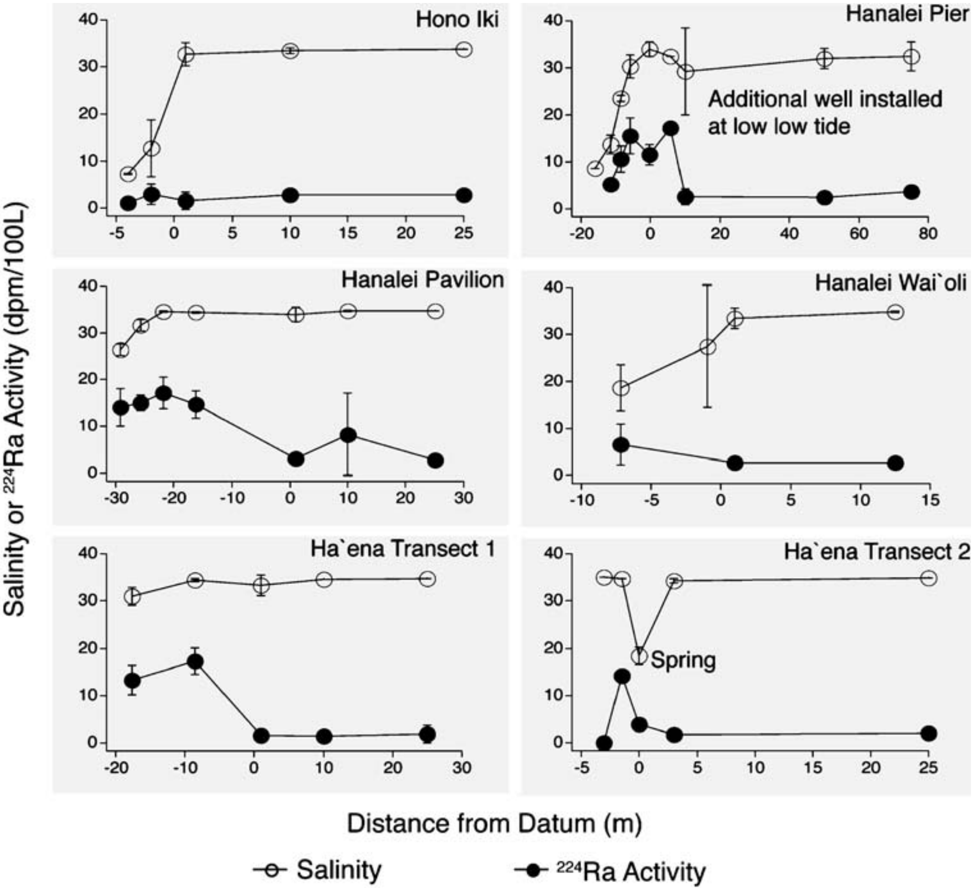

Fig. 2 Variation in salinity and ^{224}Ra activity of well and nearshore samples along each transect. *Datum* indicates the location of the water line when the well transect was installed at each site. Negative distances are in the inland direction (wells) and positive distances are in the seaward direction (nearshore samples). *Error bars* indicate the 95% confidence interval of repeated measurements made at the same well or nearshore transect point at different times in the tidal cycle ($1 \leq n \leq 4$)

9.7 dpm [100 L]$^{-1}$, respectively; $n=116$), intermediate in the nearshore zone ($\bar{x}=0.2$ and 2.8 dpm [100 L]$^{-1}$, respectively; $n=187$) and lowest in mid-Hanalei Bay and 1 km offshore Hono Iki and Ha`ena ($\bar{x}=0.1$ and 1.1 dpm [100 L]$^{-1}$, respectively; $n=19$). Differences in Ra activity between groundwater, nearshore, and offshore water were statistically significant ($p<0.05$). Ra activities in samples from the Hanalei River and three smaller streams discharging into Hanalei Bay were comparable to offshore activities ($\bar{x}=0.1$ and 1.0 dpm [100 L]$^{-1}$, respectively, $n=15$). ^{224}Ra activities in all sample types tended to be an order of magnitude greater than the corresponding ^{223}Ra activities, resulting in a smaller associated error calculated as described by García-Solsona et al. (2008). The average errors for ^{224}Ra and ^{223}Ra were 8% and 30% of the final calculated activities of the respective isotopes. At the 100-m Pier transect, a roughly linear, inverse relationship was observed between Ra activity and distance from the shore, consistent with a Ra source at the shoreline and increasing dilution further offshore (Fig. 3). It is unlikely that this pattern was related to the influence of the Hanalei River because (1) the Hanalei River is much fresher than nearshore water at Pier, but there was no discernible salinity gradient along the 100 m Pier transect, and (2) ^{224}Ra activities in samples from the Hanalei River mouth ($\bar{x}=1.2$ dpm [100 L]$^{-1}$; $n=9$) were low compared to nearshore activities. By the 100-m sampling point, Ra activities had decreased to offshore levels (0.1 and 1.2 dpm [100 L]$^{-1}$ for ^{223}Ra and ^{224}Ra, respectively).

The $^{224/223}$Ra activity ratio (AR) was significantly lower in both nearshore and groundwater samples from Ha`ena ($\bar{x}=3.5$, $n=45$) compared to Hanalei Bay sites ($\bar{x}=9.3$; $n=229$; Fig. 4). AR did not differ significantly between groundwater and nearshore samples at any site. Using the method of Moore (2000) and the calculations presented by Street et al. (2008) but substituting the average isotope-specific errors of 8% and 30% rather than the uniform 10% error estimate used in that paper, we estimated that Ra in nearshore water would need to be disconnected from its groundwater source for more than 2.7 days in order for a measurable decrease in the shorter-lived ^{224}Ra compared to the longer-lived ^{223}Ra (i.e., a higher AR in groundwater compared to nearshore) to become apparent. Since this was not observed, we can infer that the residence time of water in the nearshore zone was less than 2.7 days.

Water Quality: Nutrients

In well-transect samples, significant inverse linear relationships were observed between salinity and phosphate

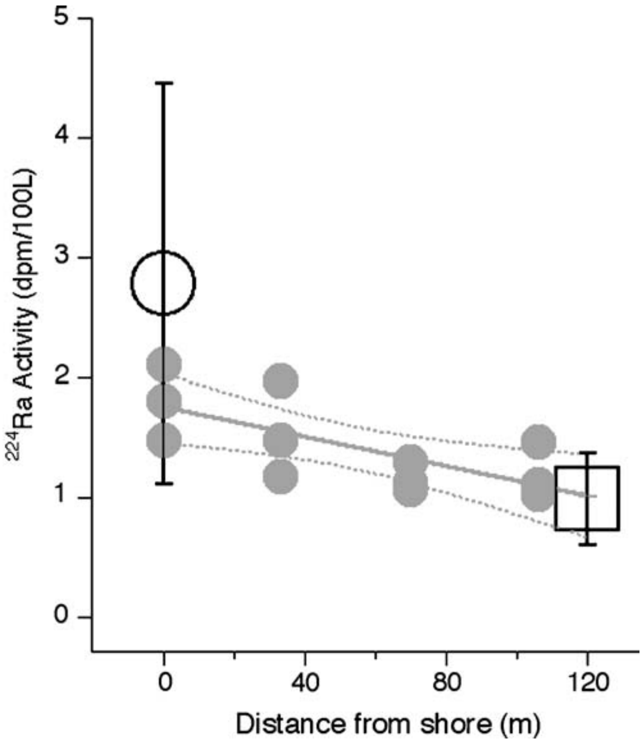

Fig. 3 Linear decrease in ^{224}Ra activity with distance from shore at the 100-m Pier transect (June 2005). Each *gray dot* represents one measurement, the *solid gray line* represents the linear regression, and the *dotted gray lines* are the 95% confidence intervals about the regression. The *large black circle* and *large black square* represent the mean ^{224}Ra activities of all nearshore (0–25 m from shore) and all offshore (>100 m from shore) samples, respectively, ±1 standard deviation

(Ha`ena), silica (Ha`ena, Pavilion and Wai`oli), nitrate+nitrite (Wai`oli), and ammonium (Hono Iki and Wai`oli). Due to the low number of samples at some well transects ($n<10$), linear relationships were deemed significant when the p value was less than 0.1. While salinity was a good predictor of certain nutrient concentrations within transects, differences in salinity did not explain differences in nutrient concentrations between transects at different sites. Scatter of data points about the lines of best fit was generally random and did not suggest consistent nonconservative behavior in the coastal aquifer. The nutrient concentrations of the fresh groundwater endmember (i.e., groundwater inland of any dilution by seawater) at each transect were calculated as the y-intercepts of the regression lines between salinity and nutrient concentrations (i.e., the predicted nutrient concentration at salinity=0; see Table 2).

Fresh groundwater endmember nutrient concentrations varied by over an order of magnitude between sites. The highest nitrate+nitrite concentrations were inferred for Wai`oli (99 $\mu$mol L$^{-1}$) and Pavilion (142 $\mu$mol L$^{-1}$), the highest ammonium concentrations for Wai`oli (98 μmol L^{-1}), and the highest phosphate and silica concentrations for Ha`ena (7 and 1,097 μmol L^{-1}, respectively). Since endmember nutrient concentrations were calculated for sample sets in which the relationship between salinity and nutrient concentration was not statistically significant, the significance of the relationship (Table 2) should be considered when evaluating the results. Additionally, this method assumed that nutrients behaved conservatively in the subsurface, an assumption supported by strong linear correlations between salinity and nutrient concentrations at some sites but that may not hold true at other sites or beyond the salinity ranges of the well-transect samples. Despite these limitations, it is clear that (1) nutrient concentrations in groundwater were consistently and significantly higher than in the nearshore ocean, (2) the presence of fresh, high-nutrient groundwater contributes to elevated nutrient concentrations in the coastal aquifer, and (3) nutrient concentrations in fresh groundwater varied dramatically over a small (~1 km) spatial scale, indicating local controls on groundwater quality.

In nearshore samples, no significant differences in nutrient concentrations were observed between sites (Fig. 5), nor did a consistent relationship between nutrient concentrations and either Ra or salinity exist in the nearshore zone. This may simply indicate that nearshore waters in Hanalei Bay

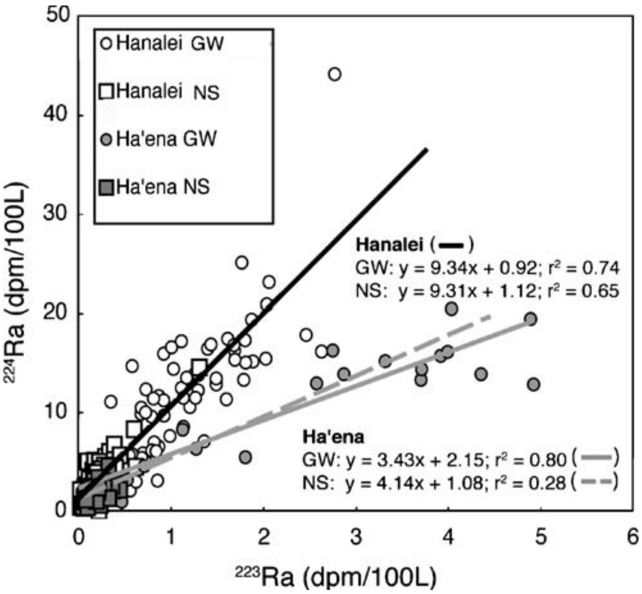

Fig. 4 $^{224/223}$Ra ARs in groundwater (*GW*) and nearshore (*NS*) samples from Ha`ena and Hanalei Bay. Ha`ena groundwater included both well and spring samples. The regression lines for Hanalei Bay nearshore and groundwater samples were so similar that they cannot be distinguished visually; thus, both are represented by the *solid black line*. Ninety-five percent confidence intervals for the linear regressions (not shown) confirm that Ha`ena had a significantly different AR than other sites. No differences between other sites were observed, nor was the AR of groundwater significantly different from that of nearshore water within either site group

Table 2 Nutrient concentrations (μmol L^{-1}) in (1) the fresh groundwater endmember at each study site, calculated by extrapolating the site-specific linear relationship between salinity and nutrient concentration to salinity=0, with italic values representing the results of statistically significant *(*p<0.1) regressions (top section), (2) rivers, streams, and WWTP effluent (middle section), and (3) all site types (bottom section)

		Number	Nitrate+ nitrite	Phosphate	Silica	Ammonium
Hono Iki	Inferred fresh groundwater endmember	5	2.7	0.4	40	*1.8*
Hanalei Pier		15	22.5	0.2	82	1.5
Hanalei Pavilion		15	141.5	0.5	*167*	0.9
Hanalei Wai\`oli		5	*98.6*	0.3	*99*	*97.6*
Ha\`ena Well		11	3.2	*7.0*	*1,097*	2.8
Ha\`ena Spring		4	6.0	3.6	480	–
Hono Iki: Pu\`u Poa Stream	95% confidence interval for all measurements	3	0–1.24	0.09–0.21	114–188	0.52–1.88
Hanalei River		12	0.71–1.95	0.16–0.26	145–231	0.70–1.86
Hanalei Streams		12	0.81–2.59	0.18–0.39	141–297	0.63–3.23
Ha\`ena: Wainiha river and streams		5	3.03–5.01	0.32–0.46	165–347	0–18.06
Princeville WWTP effluent		2	880–1,066	52–284	475–791	182–362
All groundwater	95% confidence interval for all measurements	104	13.4–25.7	0.25–0.34	47–70	0.97–3.88
All rivers and streams		32	1.26–2.23	0.21–0.31	168–238	0.77–3.71
All nearshore		184	1.29–1.62	0.11–0.13	6–13	0.70–0.91
All offshore		19	0.43–1.36	0.08–0.10	3–29	0.23–0.58

'Number' represents either the number of points included in the regression or the number of measurements used in calculating the 95% confidence interval. No ammonium value for the fresh groundwater endmember at Ha\`ena Spring could be calculated because ammonium was positively correlated with salinity, resulting in a negative ammonium value at a salinity of 0. The spring likely represents a distinct groundwater flow path, with different redox conditions or ammonium sources.

and Ha\`ena are well mixed, a conclusion consistent with previous work on Hanalei Bay (Storlazzi et al. 2006; Derse et al. 2007). Another possibility, supported by the lack of correlation between salinity and nutrients in nearshore samples, is that nutrients are rapidly utilized by phytoplankton, algae, bacteria, and other flora and fauna, drawing down their concentrations (Derse et al. 2007).

Groundwater concentrations of all nutrients were significantly higher than nearshore concentrations (Table 2). When nutrient concentrations in groundwater were compared to those in rivers and streams, nitrate+nitrite concentrations were significantly higher in groundwater ($\bar{x}$=18.7 μmol L^{-1}, n=113, compared to $\bar{x}$=1.76 μmol L^{-1}, n=40), while silica concentrations were significantly higher in rivers and streams ($\bar{x}$=209 μmol L^{-1}, n=40 compared to 59 μmol L^{-1}, n=113, respectively), and no significant difference was observed in phosphate or ammonium concentrations between groundwater and rivers. When rivers and streams were compared to the nearshore zone, concentrations of phosphate, silica, and ammonium were significantly higher in rivers and streams, while concentrations of nitrate+nitrite were not significantly different (Table 2). In general, river and stream nutrient concentrations were similar across all locations sampled (i.e., Pu\`u Poa Stream at Hono Iki, Hanalei River, western Hanalei Bay streams, and Ha\`ena rivers and streams). The exception was that significantly higher concentrations of nitrate+nitrite were observed in rivers and streams at Ha\`ena compared to other locations (Table 2).

Interestingly, the highest nitrate+nitrite concentrations in the fresh groundwater endmember were inferred for Pavilion and Wai\`oli, the two sites with the highest percentage of agricultural land use (27.8% and 32.5%, respectively; see Table 1). This result, combined with the observation by Derse et al. (2007) that nitrogen isotope ratios in Hanalei Bay macroalgae were consistent with a fertilizer, rather than sewage, nitrogen source, suggest that agriculture may be an important nitrogen source to groundwater.

Outside of the relationship described above between agricultural land use and groundwater nitrate+nitrite concentrations, variation in fresh groundwater endmember nutrient concentrations did not suggest an obvious relationship to land use. The highest fresh groundwater endmember phosphate and silica concentrations were inferred for Ha\`ena, where 96% of land within a 1-km radius is undeveloped (Table 1). Leaching from bedrock is expected to be an important source of silica and phosphate to groundwater, and the high concentrations of these nutrients

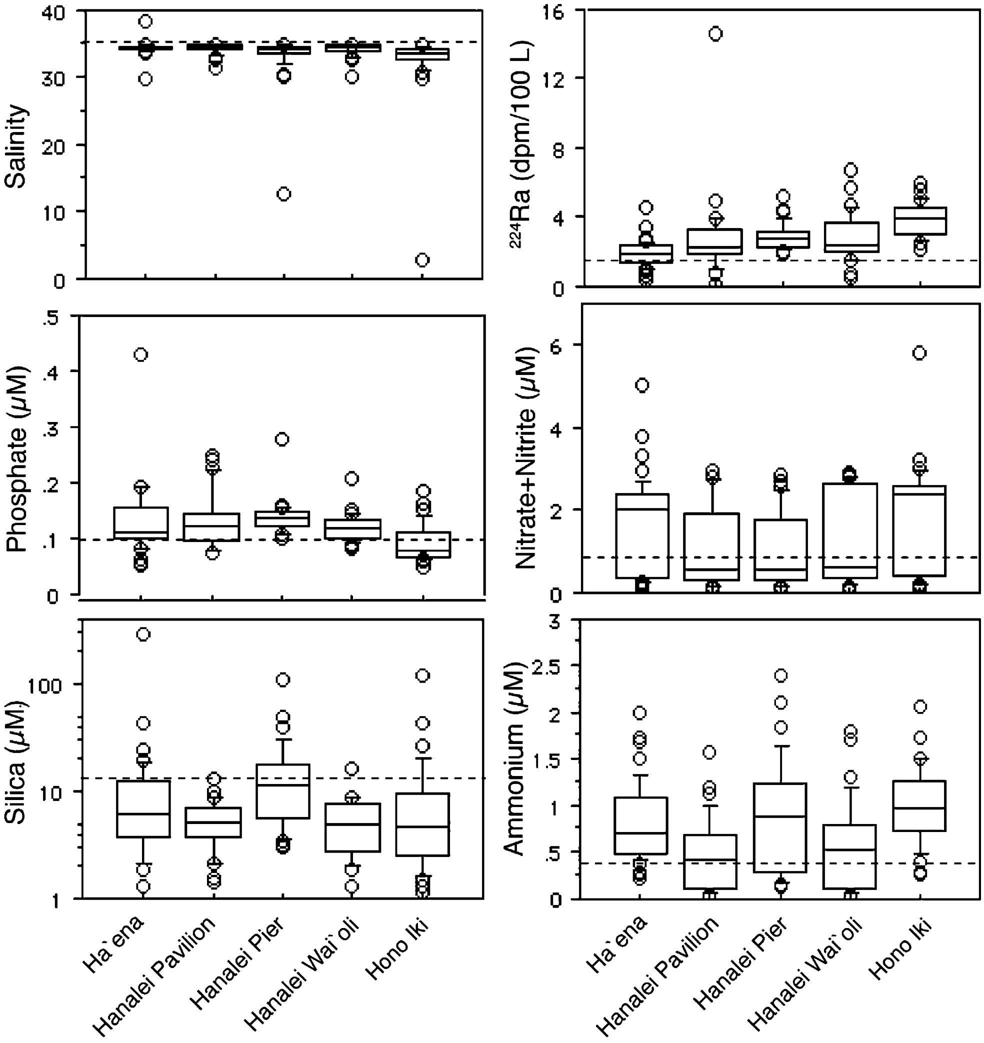

Fig. 5 Water quality parameters in the nearshore zone at all study sites. No significant differences between sites were observed. Silica concentrations are presented on a log scale due to the wide range of variability observed. The *dashed line* on each panel indicates the average offshore value

in groundwater at Ha`ena, combined with that site's distinct $^{224/223}$Ra AR, indicate that either the geological substrate and/or the aquifer-flushing patterns at Ha`ena are different from those at Hanalei Bay sites.

Broad patterns of land use within a 1-km radius do not provide a plausible explanation for the strikingly high ammonium concentrations observed in fresh groundwater at Wai`oli. Land use within a 1-km radius of Wai`oli was similar to that of Pavilion (Table 1), but ammonium concentrations in the Wai`oli fresh groundwater endmember were over two orders of magnitude greater (Table 2). In fact, the ammonium concentration of fresh groundwater at Wai`oli was more similar to that of wastewater effluent than to groundwater sampled at any other site. Possible explanations include: (1) The septic system at Wai`oli Beach Park or another nearby cesspool or septic system is leaking and contributing a large ammonium subsidy to the surrounding groundwater, and (2) The subsurface redox chemistry at this site may be more reducing than at other sites, favoring ammonium over other nitrogen species. However, the high nitrate+nitrite concentrations observed in groundwater at Wai`oli (Table 2) suggest that we are not observing a simple reduction of nitrogen species to ammonium in the subsurface.

SGD Flux Calculations

SGD fluxes into the nearshore zone of Hanalei Bay and Ha`ena State Park were estimated based on ^{224}Ra enrichment using a simple mass-balance approach (box model). This method was developed by Moore (1996) and has been employed in numerous later studies (e.g., Krest et al. 2000; Charette et al. 2001, Hwang et al. 2005; Beck et al. 2007). Since ^{224}Ra and ^{223}Ra displayed a uniform AR throughout Hanalei Bay sites (Fig. 4) and ^{224}Ra had a lower error associated with it due to its higher activity, ^{224}Ra was used as a groundwater tracer in the present flux calculations. Ra activities in the Hanalei River and local streams were not significantly different from offshore background values, and diffusive fluxes from sediments are generally expected to be low in the Hawaiian Islands due to the mafic composition of the aquifer substrate (Street et al. 2008). Thus, SGD was considered to be the only important source of ^{224}Ra in this area.

For Hanalei Bay, the nearshore zone was defined as extending out to 100 m from shore along the entire semicircular coastline of Hanalei Bay. The 100-m width of the nearshore "box" was based on the observation that ^{224}Ra activities decreased to offshore levels within 100 m from shore at the Pier site (Fig. 3). Based on Fig. 2 of Storlazzi et al. (2006) and observations during sampling, the average depth of the box (D) was estimated at 2 m, and the volume (V_{box}; m^3) was calculated as $^1\!/_2\pi\left(R_o^2 - R_i^2\right)(D)$, where R_{o}, the outer radius, is the approximate distance from the center of the Bay to the shoreline (1,000 m) and R_{i}, the inner radius, is the distance from the center of the Bay to 100 m from shore (900 m). This resulted in an estimated volume of 5.97×10^5 m^3 (Table 3).

For Ha`ena State Park, the length of the box was defined as the distance between the two transects (220 m). The width was defined as the approximate distance from the shoreline to the edge of the coral shelf (100 m), which separated the shallow, protected area where we collected samples from much deeper, rougher water. The average depth within this area was estimated to be 1 m based on observations during sampling. Thus, the estimated volume of the Ha`ena nearshore box was 2.2×10^4 m^3.

The ^{224}Ra activity within the Hanalei Bay box was estimated by calculating the average nearshore ^{224}Ra activity measured at all Hanalei Bay sites (Hono Iki, Pier, Pavilion, and Wai`oli) and assuming that ^{224}Ra activity decreased linearly from the average nearshore value (Ra$_{\mathrm{ns}}$) at the shoreline to the average offshore value (Ra$_{\mathrm{os}}$) at 100 m offshore:

$$\mathrm{Ra_{box}} = (\mathrm{Ra_{ns}} - \mathrm{Ra_{os}})/2$$

At Ha`ena, $^{224}$Ra measurements collected from 0 to 25 m from shore were assumed to be representative of the entire shallow nearshore area (0–100 m). For both Hanalei Bay and Ha`ena, the excess ^{224}Ra activity (Ra$_{\mathrm{x}}$) in each box was calculated as follows: $\mathrm{Ra_x}=\mathrm{Ra_{box}}–\mathrm{Ra_{os}}$. Because significant differences in nearshore ^{224}Ra activity were observed between sampling trips, Ra$_{\mathrm{ns}}$ was calculated separately for each trip (Table 3). No significant differences in offshore ^{224}Ra activities were observed between sites or sampling trips, so the average value over all sites and sampling trips (1.1 dpm [100 L]$^{-1}$) was applied in all flux calculations.

The average ^{224}Ra activity of groundwater discharging into Hanalei Bay (Ra$_{\mathrm{gw}}$) was estimated as the mean ^{224}Ra activity of all samples collected from the closest well to shore at the Hono Iki, Pier, Pavilion, and Wai`oli well transects. Correspondingly, Ra$_{\mathrm{gw}}$ at Ha`ena was estimated as the average ^{224}Ra activity of all samples from the closest well to shore at both transects and the spring discharging at the shoreline at transect 2. The residence time of water in the nearshore box (T_{r}) at both Hanalei Bay and Ha`ena was estimated to be 2.7 days, which is the maximum possible residence time based on the ^{224}Ra/^{223}Ra AR (see "^{223}Ra and ^{224}Ra activities and Activity Ratios"). The SGD flux into each box was then estimated as: $\mathrm{SGD}=(\mathrm{Ra_x}/\mathrm{Ra_{gw}})(V_{\mathrm{box}}/T_{\mathrm{r}})$. For comparison, we also calculated the average hourly discharge rate of the Hanalei River for the months of

Table 3 SGD flux calculation parameters and results

		Ra$_{\mathrm{gw}}$	Ra$_{\mathrm{ns}}$	Ra$_{\mathrm{os}}$	Ra$_{\mathrm{x}}$	T_{r} (h)	V_{b} (m^3)	Hanalei River discharge (m^3 h^{-1})	Minimum SGD (m^3 h^{-1})	Minimum SGD (% of Hanalei River discharge)	Minimum SGD per meter shoreline (Lmin^{-1} m^{-1})
Hanalei Bay	March 2005	9.7	2.1	1.1	1.0	64.6	6.0×10^5	2.8×10^4	485	2%	2.6
	August 2006	7.4	3.5	1.1	2.4	64.6	6.0×10^5	1.5×10^4	1473	10%	7.8
	February 2007	11.4	3.4	1.1	2.3	64.6	6.0×10^5	2.5×10^4	953	4%	5.1
Ha`ena State Park	August 2006	9.5	2.1	1.1	1.0	64.6	2.2×10^4	–	36	–	2.7
	February 2007	11.8	1.7	1.1	0.6	64.6	2.2×10^4	–	17	–	1.3

All Ra terms are ^{224}Ra activities in decays per minute per 100 L water. Ra$_{\mathrm{gw}}$ is groundwater Ra activity, Ra$_{\mathrm{ns}}$ is nearshore Ra activity, Ra$_{\mathrm{os}}$ is offshore and mid-Bay Ra activity, and Ra$_{\mathrm{x}}$ is excess, or SGD-supported, Ra activity in the nearshore zone. T_{r} is the estimated maximum residence time of water in the nearshore "box." Since the maximum residence time was used, these estimates are conservative, and actual SGD fluxes could be considerably greater than those presented here.

March, August, and February over the past 10 years using data from US Geological Survey Stream Gauge 16103000 (water data website, http://waterdata.usgs.gov).

Estimated minimum SGD fluxes into Hanalei Bay were 490, 1,500, and 950 m^3 h^{-1} in March 2005, August 2006, and February 2007, respectively, corresponding to 2%, 10%, and 4% of Hanalei River flow (Table 3). These are referred to as minimum fluxes because 2.7 days is the upper bound on a residence time that is most likely considerably shorter. At Ha`ena, estimated SGD fluxes into the coastal ocean were 36 and 17 m$^3$ h$^{-1}$ in August 2006 and February 2007 (no data were collected at Ha`ena in March 2005). When normalized by shoreline length, Ha`ena fluxes (1.3–2.7 L min^{-1} m^{-1}) were similar in magnitude to Hanalei Bay fluxes (2.6–7.8 L min^{-1} m^{-1}).

SGD-related fluxes of nitrate+nitrite, phosphate, silica, and ammonium were calculated by multiplying the average nutrient concentrations in the most shoreward wells of each Hanalei Bay or Ha`ena transect (i.e., the same wells used to estimate $\mathrm{Ra}_{\mathrm{gw}}$) by the SGD flux estimated above. River-derived nutrient fluxes were estimated by multiplying the average nutrient concentrations measured in Hanalei River water during each trip by the average flow for the corresponding month over the past 10 years (Table 4).

In Hanalei Bay, estimated SGD-derived nutrient fluxes in March 2005, August 2006, and February 2007 were as follows (Table 4). Nitrate+nitrite fluxes were 65, 890, and 230 mol day^{-1} in March 2005, August 2006, and February 2007, respectively, corresponding to 9–270% of estimated river fluxes. Phosphate fluxes were 3.3, 9.3, and 6.1 mol day^{-1}, corresponding to 2–15% of estimated river fluxes. Silica fluxes were 530, 1,100, and 870 mol day^{-1}, corresponding to 0–2% of river fluxes. Ammonium fluxes were 9, 80, and 16 mol day^{-1}, corresponding to 1–20% of river fluxes. The highest fluxes of water and nutrients from SGD were estimated for August 2006, when both the discharge and the nitrate+nitrite concentration of the Hanalei River were lowest. When normalized by shoreline length, fluxes of all nutrients were similar in magnitude at Ha`ena and Hanalei Bay (Table 4).

The SGD flux estimates presented here should be interpreted as first-order approximations because considerable uncertainty surrounds the calculated values. This uncertainty is associated with several key elements of the calculations: the dimensions of the nearshore box, the residence time of water in the box, and the characteristics of the groundwater endmember. In Hanalei Bay, we observed that ^{224}Ra activity decreased linearly to offshore levels

Table 4 Average nutrient concentrations in discharging groundwater or river water, SGD and river-derived nutrient fluxes into nearshore waters, and SGD-derived nutrient fluxes into Hanalei Bay and Ha`ena normalized by shoreline length

			Nitrate+nitrite	Phosphate	Silica	Ammonium
Average concentration in discharging groundwater or river water (µmol L^{-1})	Hanalei Bay	March 2005	5.6	0.3	45	0.8
		August 2006	25.1	0.3	32	2.3
		February 2007	10.1	0.3	38	0.7
	Hanalei River	March 2005	1.1	0.2	202	0.7
		August 2006	0.9	0.2	203	1.1
		February 2007	2.2	0.3	222	2.7
	Ha`ena State Park	August 2006	6.5	0.2	66	1.0
		February 2007	3.4	0.5	110	2.6
Minimum SGD flux or estimated river flux (mol day^{-1})	Hanalei Bay	March 2005	65	3.3	530	9.0
		August 2006	890	9.3	1,100	80
		February 2007	230	6.1	870	16
	Hanalei River	March 2005	760	140	140,000	470
		August 2006	330	62	74,000	390
		February 2007	1,300	210	130,000	1,600
	Ha`ena State Park	August 2006	5.7	0.17	57	0.83
		February 2007	1.4	0.20	46	1.1
Minimum flux per m shoreline (mol day^{-1} m^{-1})	Hanalei Bay	March 2005	2.07×10^{-2}	1.04×10^{-3}	1.68×10^{-1}	2.85×10^{-3}
		August 2006	2.83×10^{-1}	2.97×10^{-3}	3.61×10^{-1}	2.55×10^{-2}
		February 2007	7.32×10^{-2}	1.93×10^{-3}	2.76×10^{-1}	4.94×10^{-3}
	Ha`ena State Park	August 2006	2.58×10^{-2}	7.63×10^{-4}	2.59×10^{-1}	3.75×10^{-3}
		February 2007	6.39×10^{-3}	9.31×10^{-4}	2.07×10^{-1}	4.87×10^{-3}

SGD-derived nutrient fluxes represent conservative estimates based on a maximum residence time of 2.7 days; actual fluxes may be considerably greater.

between 0 and 100 m from the shore at the Pier site during one sampling session and then assumed this was also true at other sites around the bay and during other sampling trips. At Ha`ena, we assumed that the ^{224}Ra activities measured 0–25 m from the shore were representative of the entire shallow shelf area 0–100 m from the shore, and that no Ra enrichment existed beyond the shelf. Since the boxes in these models represent the entire zone of ^{224}Ra enrichment, a box that is too small (i.e., excludes areas of Ra enrichment) would lead to an underestimate of SGD fluxes, and a box that is too large (i.e., includes some areas that are not enriched in ^{224}Ra) would lead to an overestimate.

Similarly, the residence time estimate used in all flux calculations (2.7 days) was a maximum value, resulting in minimum, conservative flux estimates. Actual fluxes of water and nutrients from SGD may be considerably higher if the water residence time is shorter than 2.7 days, as might be expected within 100 m from shore in an area influenced by waves and tides. For example, if the residence time of water in the nearshore box was 6 h (the approximate time between high and low tides), water and nutrient fluxes from SGD would be about ten times greater than the conservative values presented in Tables 3 and 4. The use of the same residence time for all flux calculations may also obscure true SGD flux patterns, since it is unlikely that the true residence time was constant across all sites and sampling trips.

Finally, groundwater quality can vary greatly over a small spatial scale (Santos et al. 2008). In our study area, groundwater salinity, Ra activities, and nutrient concentrations were highly variable, making the precise characterization of a "groundwater endmember" problematic. Our solution was to collect a large number of groundwater samples, which could be averaged together to obtain more representative values of water quality parameters. In addition, we only considered the closest well to shore in our flux calculations, with the rationale that this water would best represent what was actually discharging. However, groundwater quality varied with site, distance inland from the dynamic shoreline, and season, as well as with other parameters like rainfall that were not addressed in this study. Thus, SGD-related fluxes of water and nutrients should be considered estimates based on a large but still limited data set.

Despite the uncertainties in these parameters, we believe the SGD flux calculations presented here provide a useful first approximation of the importance of SGD in delivering water and nutrients to the coastal ocean on the north shore of Kaua`i. They indicate that, even given a conservative residence time estimate, inputs of phosphate, ammonium, and especially nitrate+nitrite from SGD may be significant compared to river and stream inputs. Additionally, spatial heterogeneity in groundwater nutrient concentrations indicates that SGD-derived nutrient subsidies may be much greater at some sites than at others. These sites would not only be more likely to experience observable impacts from nutrient inputs, but they would also have a disproportionate effect on Bay-wide nutrient budgets.

Water Quality: Fecal Indicator Bacteria

E. coli and Enterococci

EC and ENT were detected in well, river, stream, spring, and nearshore samples (Table 5). In both March 2005 and August 2006, river and stream samples were significantly more likely to test positive for both EC and ENT than groundwater. However, no significant difference in the occurrence of measurable EC or ENT between groundwater and nearshore samples was observed. In February 2007, river and stream samples were significantly more likely to test positive for ENT than were nearshore samples, which, in turn, were significantly more likely to test positive than were groundwater samples. River, stream, and nearshore samples were not significantly different from each other in terms of EC presence (almost 100% tested positive), but both sample types were significantly more likely to test positive than were groundwater samples. It is notable that, over the three trips, every river or stream sample tested positive for EC, and 77% tested positive for ENT. In comparison, 80% and 30% of nearshore samples and 38% and 12% of groundwater samples tested positive for EC and ENT, respectively.

Rivers and streams had much higher concentrations of EC and ENT ($\bar{x}$=2.39 and 1.50 log [MPN $\{100\ \text{mL}\}^{-1}$] for EC and ENT, respectively) than either groundwater ($\bar{x}$=1.14 and 0.78 log [MPN $\{100\ \text{mL}\}^{-1}$]) or the nearshore zone ($\bar{x}$=1.56 and 0.91 log [MPN $\{100\ \text{mL}\}^{-1}$]).In contrast to the notable between-site variation observed in groundwater nutrient concentrations, no site was significantly more likely to have EC or ENT in its groundwater or nearshore water than any other, nor did FIB concentrations in groundwater or nearshore water differ significantly between sites.

In sand, EC and ENT were each detected in 9 of 15 samples collected, representing four of the five beaches sampled. The 95% confidence intervals for EC concentrations in sand were 1.4–2.0 and 1.4–2.8 log (MPN $[100\ \text{mL sand}]^{-1}$) in samples from above the high-tide line and near the shoreline, respectively. Corresponding confidence intervals for ENT were 1.5–2.5 and 1.3–2.0 (log MPN $[100\ \text{mL sand}]^{-1}$). A paired *t* test showed no significant difference in EC or ENT between samples collected above the high-tide line versus near the shoreline.

In general, aqueous FIB concentrations did not correlate with salinity, radium activity, or nutrient concentrations. This was true both when samples were grouped based on type (nearshore, river/stream, and groundwater) and sampling trip and when they were all considered together. The two exceptions were: (1) In August 2006, log-transformed FIB concentrations showed a significant positive correlation with salinity in groundwater samples (r=0.50 for EC and 0.33 for ENT), and (2) in February 2007, log-transformed FIB concentrations showed a significant negative correlation with salinity in nearshore samples (r=−0.50 for EC and −0.70 for ENT). These correlations may reflect transient environmental conditions, such as fortnightly variability in tidal range (Boehm and Weisberg 2005) that affect the input, transport, and distribution of FIB.

Microbial Source Tracking Using the Enterococcal Surface Protein (*esp*) Gene

Twenty-five samples, including 21 samples from field sites (ENT concentration 20–4,160 MPN [100 mL]$^{-1}$) and four positive controls from area cesspools and septic systems (ENT concentration >24,190 MPN [100 mL]$^{-1}$ for all samples) were assayed for the presence of the *esp* gene (Table 5). Samples included groundwater, nearshore, stream, river, and sand samples collected in August 2006 and February 2007. As expected, all positive controls (cesspool and septic system samples) tested positive for the *esp* gene. Five of the field samples—groundwater and

Table 5 Summary of fecal indicator bacteria (FIB) data including nearshore (NS) and groundwater (GW) samples from all transect sites, rivers, and streams, sewage/septic system samples, and sand

Site	Number (EC and ENT)	EC		ENT		*C. perfringens*			*esp* gene	
		Percent positive	95% CI	Percent positive	95% CI	Number	Percent positive	log CFU (100 mL)$^{-1}$	Number (*esp*)	Percent positive
Hono Iki (NS)	5	40	0.45–1.76	40	0.66–1.05	1	100	0.26	0	–
Hono Iki (GW)	9	44	0.73–1.33	11	0.88–1.40	3	0	<0	1	0
Hanalei Pier (NS)	14	100	1.7–2.24	36	0.72–1.31	1	100	0.46	4	25
Hanalei Pier (GW)	29	34	0.82–1.28	7	0.67–0.87	1	0	<0	2	0
Hanalei Pavilion (NS)	15	73	1.20–1.80	27	0.68–1.05	1	100	1.15	1	100
Hanalei Pavilion (GW)	22	23	0.69–1.37	9	0.67–0.84	1	0	<0	1	100
Hanalei Wai`oli (NS)	14	86	1.10–1.71	29	0.65–1.27	0	–	–	1	0
Hanalei Wai`oli (GW)	12	42	0.82–2.23	8	0.64–0.87	0	–	–	1	0
Ha`ena (NS)	8	75	1.07–2.17	25	0.64–0.88	0	–	–	0	–
Ha`ena (GW)	12	67	0.79–1.76	33	0.69–0.89	0	–	–	1	0
All groundwater	84	38	0.97–1.32	12	0.73–0.84	5	0	<0	6	17
All rivers and streams	39	100	2.21–2.57	77	1.23–1.77	1	0	<0	6	17
All nearshore	56	80	1.40–1.73	30	0.79–1.02	3	100	0.62	6	33
Sand	15	57	0.89–1.61	57	0.88–1.40	1	100	1.04	1	100
Septic tank/ sewage	4	100	>4.4	100	>4.4	0	–	–	4	100

Data from March 2005, August 2006, and February 2007 have been combined. 95% confidence intervals (CI) are in log (MPN [100 mL]$^{-1}$). *C. perfringens* values represent averages of log-transformed values if more than one measurement exists in the category.

nearshore water from Pavilion, nearshore water from Pier, sand from Wai`oli, and a sample from the Hanalei River mouth—also tested positive. This result suggests that at least some of the FIB measured in this area (in all sample types) originated from human waste. Interestingly, while streams consistently had the highest FIB concentrations, none of the five stream samples assayed for the presence of the *esp* gene tested positive. None of Hanalei's streams flow through the town's more urbanized areas, where cesspool/septic system density is the greatest; rather, they originate in forested uplands and then flow through agricultural areas, past a few houses, and into the sea.

Although concentrations of EC and ENT in groundwater were generally low compared to rivers, streams, and even nearshore samples, the occurrence of FIB in groundwater and the presence of the *esp* gene point to anthropogenic contamination. The detection of even low FIB levels in groundwater indicates that human sewage may be present. Therefore, further research on the sources of FIB (e.g., human, animal, or soil) to groundwater and the nearshore zone on the north shore of Kaua`i should be completed.

Clostridium perfringens

Of the ten samples where *C. perfringens* spores were enumerated, four were above the detection limit of 1 CFU $(100\ \mathrm{mL})^{-1}$. Concentrations ranged from less than 1 to 14 CFU $(100\ \mathrm{mL})^{-1}$ (Table 5). All samples that tested positive for *C. perfringens* also tested positive for EC and ENT, although the converse was not true. When concentrations of *C. perfringens*, EC, and ENT were log-transformed, a significant, positive correlation was observed between *C. perfringens* and both EC and ENT (r=0.76 and 0.78, respectively).

Limitations of FIB as Indicators of Human Risk

It is important to recognize the limitations associated with the use of EC, ENT, and the *esp* gene as proxies for human fecal pollution and health risk. While EC and ENT are invariably elevated in human sewage, they are also found in the feces of numerous other animals (Gordon and Cowling 2003; Harwood et al. 1999; Souza et al. 1999). If these bacteria originate from a nonhuman source, their relationship to waterborne illness in humans is unclear. Additionally, their persistence, growth, and transport in aquatic ecosystems are different from those of the pathogens whose presence they are meant to indicate (Field and Samadpour 2007). The *esp* gene also has some notable limitations. It is estimated that only 3% of healthy humans carry the gene in their intestinal flora (Shankar et al. 1999), suggesting that the assay may under-represent sewage contamination. Conversely, recent work indicates that the gene may not be exclusive to human hosts (Whitman et al. 2007), raising the possibility of false positive results. Further research on the utility of this assay as a microbial source tracking tool is needed.

Interactions between Groundwater, Rivers, and Streams

An important question raised by this study is how rivers and streams interact with groundwater in coastal areas. We have identified SGD as an important source of nitrate+nitrite and perhaps also of phosphate and ammonium, while the Hanalei River and smaller local streams appear to be important sources of all nutrients and the dominant sources of silica and FIB. But, is coastal groundwater truly distinct from river and stream water? A high degree of hydrologic connectivity characterizes most stream–groundwater systems, causing streams to either gain water from or lose water to the aquifers through which they flow (Winter et al. 1998). Rivers and streams can impact regional patterns of groundwater flow (Hinkle et al. 2001), and recent work by Dulaiova et al. (2006) shows that river valleys can focus shallow groundwater contours near the river mouth, enhancing SGD fluxes by more than an order of magnitude. To understand why high concentrations of nutrients, FIB, and other pollutants occur where they do, a more sophisticated understanding of the interactions between groundwater, rivers, streams, and the ocean is needed.

Summary and Conclusions

This study elucidates the sources of nutrients and FIB, two key aspects of coastal water quality, to Hanalei Bay and nearby sites on the north shore of Kaua`i. Groundwater samples were enriched in nutrients relative to the nearshore ocean, and nutrient concentrations showed site-dependent, generally inverse correlations to salinity in the coastal aquifer. Since rivers and streams did not have significantly higher nitrate+nitrite concentrations than nearshore waters, but groundwater did, we infer that SGD-related subsidies provide at least a partial explanation for the significant elevation of nearshore nitrate+nitrite concentrations above offshore levels. SGD flux calculations confirm that, even using a conservative residence time estimate of 2.7 days, SGD-derived nitrate+nitrite inputs represent 9–270% of Hanalei River inputs. Site-specific differences in groundwater nitrate+nitrite concentrations reflected a possible agricultural nitrogen source. Phosphate and silica appeared to have a natural soil source, and ammonium at the Wai`oli site had a potential wastewater source. Further research is necessary to confirm these patterns.

The four smaller streams draining into Hanalei Bay (Pu`u Poa Stream on the eastern side of the Bay and Wai`oli, Waipa, and Waikoko Streams on the western side) are also potentially important nutrient sources to Hanalei Bay. Nutrient concentrations in these streams were similar to those measured in the

Hanalei River (Table 2), but no data are available on their discharge rates, so quantitative nutrient fluxes cannot be calculated. Observations during sampling suggested that the contribution of these streams is small compared to that of the Hanalei River because their mouths are narrow (generally less than 2 m across) and water at stream mouths typically flowed slowly or not at all, at times terminating behind a sand berm rather than reaching the sea.

During all sampling trips, our data suggested that the Hanalei River and smaller streams dominated FIB inputs to all study sites. The flow of the Hanalei River alone was 10–58 times greater than estimated shoreline-integrated groundwater flows, and both the likelihood of detecting FIB and the FIB concentrations measured were greater in river and stream samples than in groundwater. Since ENT is currently used as a water quality indicator in this area, with exceedances leading to public concern and potential loss of tourism revenues, it is important to address when, where, and how ENT enter rivers, streams, groundwater, and sand. Although SGD does not appear to be an important contributor to FIB in the nearshore zone, the very presence of FIB in groundwater, even at a low level, as well as the presence of the *esp* gene in some ENT, indicates contamination by human sewage and warrants further investigation.

This study illustrates the hydrological complexity inherent in a coastal area where groundwater, rivers, streams, and the ocean jointly determine water quality. Despite this complexity, we were able to identify probable sources of nutrients and FIB to the nearshore ocean. Future research should focus on understanding how and why these sources acquire high nutrient and FIB concentrations, the connections between the sources, and the effects of nutrient and FIB subsidies to coastal waters, in terms of environmental quality, economics, and human health.

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