

Ground Water and its Influence on Reef Evolution

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Ground water—water that is stored in and transported through the rocks and sediment below the Earth’s surface—is an important resource of water as well as a site for biologic, geologic, and chemical processes (fig. 1). The influence of human activities on this resource is of particular concern because such activities can produce nutrients and contaminants that may infiltrate the ground water and move with it to areas of discharge at the coast. Unlike streams and lakes, ground-water discharge is much more difficult to access and measure, and therefore our understanding of its quantity, character, fate, and ultimate role on coastal environments is still limited.

Because water flowing through rocks often moves slowly, it can have a long residence time within the rocks. As a result, the water can acquire a unique chemical signature, which can be used to distinguish its source. Where land-use activities (industry, agriculture, urbanization) are intense, ground water may contain concentrated levels of terrestrially derived nutrients, trace metals, and other organic and inorganic contaminants, including many synthetic compounds and those associated with human waste.

Ground water commonly plays a vital role in structuring coastal habitats and ecosystems. When either ground-water composition or ground-water discharge rate changes, it is likely to induce alteration of the environmental conditions at the coast. Submarine ground-water discharge (SGD) is that portion of ground water that enters the ocean below sea level and may be composed of fresh ground water or a mixture of fresh ground water and seawater (for example, brackish water). As a result, studying SGD and determining its effects on coastal ecosystems is very challenging.

Exciting advances in the technology of airborne sensors, submersible instruments, and marine chemistry are enabling better mapping of SGD along the coast and providing means to calculate the quantity, composition, and fate of SGD into the coastal ocean. These tools can help differentiate processes and pathways of contamination associated with land-use activities from those of natural phenomena by examining the chemistry of SGD. Analyzing compounds collected in the annual growth bands of coral skeleton may help determine past levels of discharge and temporal changes in them. Freshwater from surface or ground water has long been known to be more

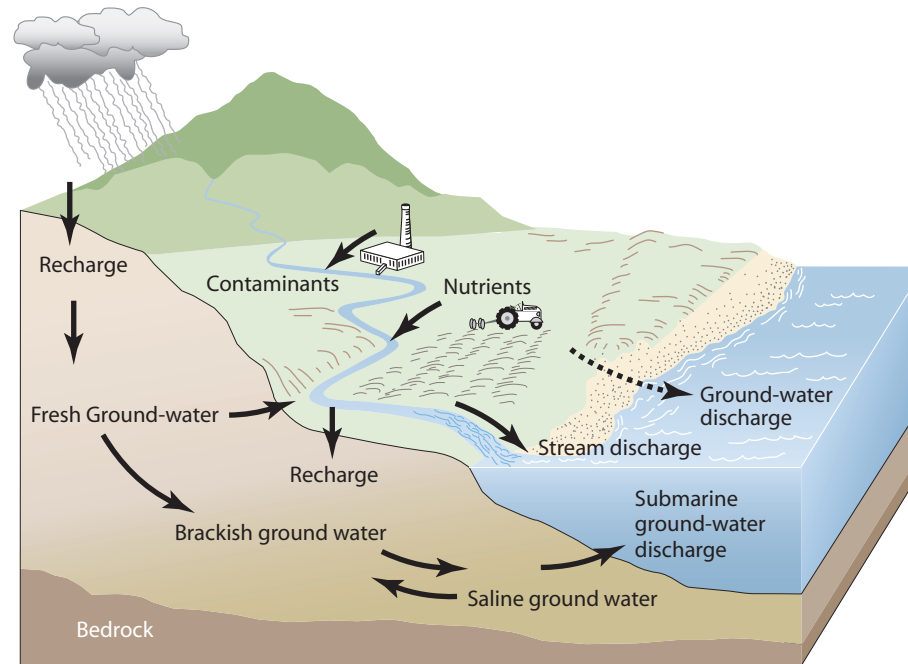


Figure 1. Diagram of the hydrologic cycle showing how upland precipitation and streams infiltrate into the soil and recharge ground water. Ground water is composed of fresh, brackish, and saline types, and their zonation fluctuates with changes in recharge and pumping through wells. Many land-use activities can add nutrients and contaminants to ground water, which eventually discharges to the coast.

acidic than seawater and, as a result, is notable for dissolving coral reefs on many scales: on the microscopic scale, submillimeter cements form within coral skeleton, and over tens to hundreds of kilometers, entire reef systems dissolve to produce karst landscapes.

Determining the role of ground water on Hawaiian reefs, and the south Moloka‘i reef in particular, is important for understanding the reef’s current health and future fate. A growing concern is the impact of excess nutrients derived from land-use activities, especially inorganic nitrogen in the form of nitrate and nitrite. These chemicals are often found in higher concentration in ground water and are considered a limiting nutrient in coastal waters. The addition of excessive amounts of nitrogen to relatively nutrient-poor coastal waters surrounding coral reefs therefore can have significant ecosystem

impacts. In many reef settings, excess inputs of nutrient have led to a shift from coral-rich communities to excessive algal and plant growth, which can smother and kill reefs (Hughes and others, 2003b; Szmant, 2002).

Understanding Submarine Ground-Water Discharge in Coastal and Reef Settings

Our understanding of ground-water discharge and its effects on coastal and reef settings is derived in four primary ways: (1) local knowledge and observation, (2) physical property surveys of the water column, (3) chemical analyses of water samples, and (4) hydrologic modeling. Specific sites of SGD in the shallow coastal zone of Hawai‘i, and of Moloka‘i specifically, as in many island settings, are often known from local observations of fisherman and coastal residents. Many legends are also validated today by observation of cold and/or fresh water emanating from the ground (fig. 2A–D) and through the shallow sea floor at sites known in Hawai‘i as “water holes” (lua wai), like the many cold-water springs around Kona on the Big Island of Hawai‘i and in Waikīkī (which means “spouting-water” in Hawaiian) on the island of O‘ahu.

Modern instruments, including airborne thermal infrared (thermal IR) imaging systems and CTDs (submersible instruments that measure water conductivity, temperature, and depth) are now sensitive enough to map and quantify physical properties of the water, including temperature and salinity (the dissolved salt content of water) at specific depths and over large areas rapidly. Thermal IR systems image Earth’s surface temperatures (in soil, water, and vegetation) by measuring the amount of radiation reflecting back to space in the thermal portion of the spectrum. Thermal IR imaging systems are typically flown on small aircraft and measure only the uppermost layer of the water column, whereas CTDs are often deployed from a boat to measure temperature and salinity through the entire water column. CTDs can also be fastened to a tripod on the sea floor to record temperature and salinity variations at a single point over time. These types of data allow discrete water masses to be mapped in order to examine pathways of freshwater into and through the coastal ocean, along with characteristics of its mixing. In Hawai‘i the shallow sea floor is commonly composed of porous coral reefs, and CTD data can be especially useful to help identify where SGD, characterized by being colder and of lower salinity, flows out to the sea through the reef.

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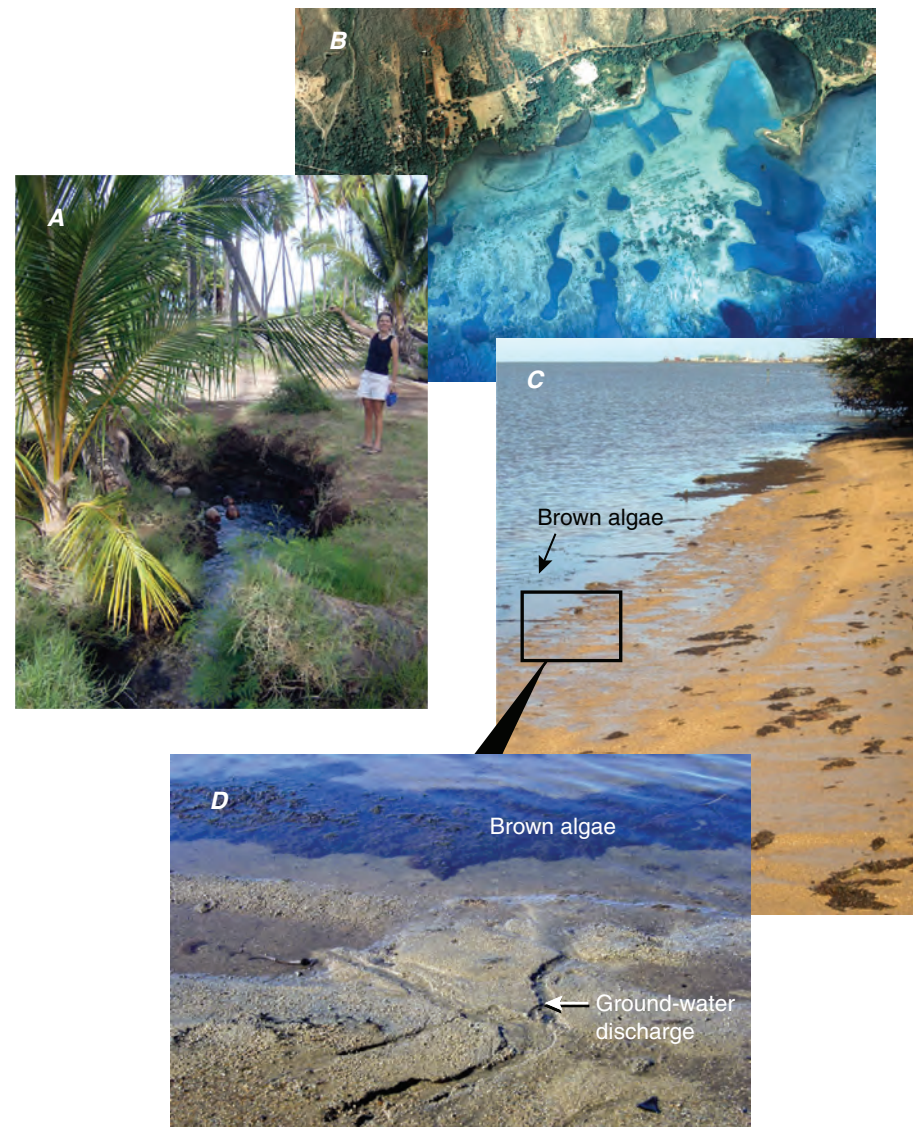


Figure 2. Photographs of landscape features associated with ground-water discharge. *A*, Ground water discharging through springs at the shoreline of Kapuāiwa coconut grove. *B*, The “blue holes” off Kamalō, characteristic of karst (dissolution) features. *C*, Ground water discharging through the beachface at Kamiloloa during low tide. *D*, Fleshy brown and/or green algae commonly found in coastal waters with high nutrient concentrations.

New chemical methods that determine the concentration of specific compounds and elements are used to determine the composition of water. Many chemicals and compounds can be used as tracers to differentiate water masses and sources, including SGD, in the coastal ocean. Several constituents, including barium, silica, lead, and iron, are indicative of freshwater and/or ground water, and recently the naturally occurring radioactive elements radon (Rn) and radium (Ra) have proven of excellent utility in identifying SGD to the coast (Moore, 1996). Rn and Ra occur in several isotopes (different forms of the same element having slightly different masses resulting from different

numbers of neutrons in their nuclei) that radioactively decay at specific rates. Knowing the rate of decay and activity of these isotopes in water samples enables calculations that help identify the source and mixing rate of fresh ground water (using Rn) and brackish ground water (using Ra). In Hawai‘i, Rn and Ra are often concentrated in ground water and are associated with nutrient concentrations, especially nitrogen as nitrate and nitrite (Garrison and others, 2003; Soicher and Peterson, 1997; Paytan and others, 2006). Other chemical methods include the use of stable isotopes of carbon (^{13}C) and nitrogen (^{15}N). These can be used to identify a wide range of sources and processes that influence the fate of nutrients, including terrestrial plant or organic material, fertilizers, sewage, and waste products, and to track the mediation of those nutrients through biologic uptake and geochemical cycling (Leichter and others, 2003; Umezawa and others, 2002; Yamamuro and others, 2003). Using a combination of stable isotopes, radioactive isotopes, and concentrations of various nutrients and elements, scientists can determine and in many cases quantify (1) SGD at the coast, (2) nutrient fluxes, and (3) nutrient sources.

Hydrologists and geologists use the rock properties and structure of coastal environments, rainfall patterns, and water levels in wells to map the distribution of ground water below the surface. By the use of tracers and a knowledge of ground-water behavior, the rate of ground-water flow from areas of recharge (where rainfall and infiltration are greatest) to the ocean can be determined (fig. 1). Using these data, models are constructed to estimate and describe flow patterns and locate suitable areas for ground-water development. In island settings like Hawai‘i, these models and direct observations reveal that within the island mass a freshwater lens commonly floats above more saline ground water and seawater. In times of high rainfall and recharge, freshwater discharge to the ocean increases. During times of drought and/or in areas of heavy well-water use, saline waters from the ocean intrude into the freshwater reservoirs, sometimes contaminating freshwater resources needed for local consumption. Understanding these processes and the nutrient and contaminant concentrations associated with freshwater discharging across coastal ecosystems is of critical importance as human activity increasingly alters the quality and composition of freshwater and coastal ocean water.

Results—Submarine Ground-Water Discharge Across the Moloka‘i Reef

There are multiple indicators of submarine ground-water discharge (SGD) to the Moloka‘i reef. These include morphologic evidence, remote sensing data (thermal IR), direct measurements of temperature and salinity, studies of chemical radioactive (Ra and Rn) and stable (C and N) isotopes, and measurements of nutrients.

Morphologic Evidence of Submarine Ground-Water Discharge

The “blue holes” of Kamalō (fig. 2*B*) are characteristic of karst topography, sculpted limestone terraines formed by dissolution by freshwater. They probably formed during periods of subaerial exposure (lower sea level). It

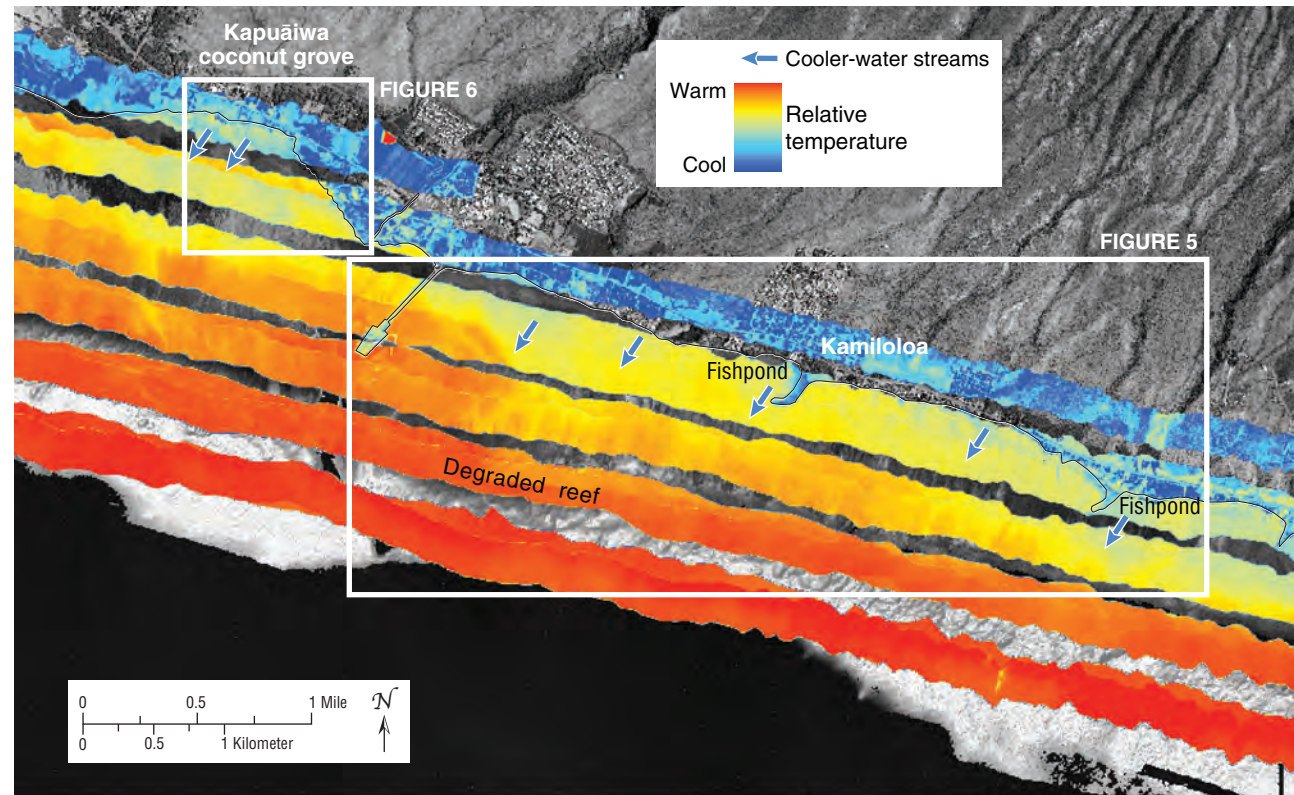
remains uncertain if the Kamalō blue holes are indeed karst, but significant freshwater outflow along the coast there, and at other sites such as the Kapuāiwa coconut grove, 2.5 km (1.5 mi) west of Kaunakakai, and Pālā‘au where similar features occur, points to ground-water dissolution as a likely cause for erosion of the holes. Subsequent reef accretion around the edges may add reefal material to the perimeter of the blue holes in time. Dissolution of carbonate reefs by freshwater occurs much as chalk is dissolved when dropped in a carbonated beverage, which is slightly acidic. Freshwater is relatively acidic compared to seawater and will dissolve calcium carbonate, which is the dominant mineral in reefal limestone. Karst features are found across the entire Moloka‘i reef in the form of isolated sand-filled circular basins. A prominent blue hole referred to herein as “The Pit” occurs near the reef crest between Pālā‘au and the Kapuāiwa coconut grove (Field and other, this vol., chap. 2). Local knowledge of its longtime existence suggests that this feature was naturally formed. Several other large karstlike features occur along the reef crest offshore of Kawela (Storlazzi and others, this vol., chap. 3). Drilling through the outer reef flat at the Kapuāiwa coconut grove (Engels and Fletcher, this vol., chap. 4) revealed a cavity or cave just below the sea floor extending to nearly 20 m (60 ft) below the reef surface. This type of cavity is uncommon in living reefs and is likely due to dissolution, probably during times of lower sea level. The blue holes of Moloka‘i offshore of the Kapuāiwa coconut grove and Kamalō have been the focus of conductivity, temperature, and depth (CTD) measurements and water analyses to determine if they are active conduits of SGD escaping through the reef. The reef flat and fore reef offshore of Kamiloloa also has been studied to examine SGD and potential nutrient flux where the reef shows signs of extensive deterioration and high algal growth.

Spatial Patterns of Submarine Ground-Water Discharge

Thermal IR images collected by scientists from the U.S. Geological Survey and University of Hawai‘i in 2001 using the Airborne Hyperspectral Imager (AHI) show the large-scale pattern of cool surface waters along the Moloka‘i south shore relative to further offshore (fig. 3). This version of the AHI data is qualitative and shows relative temperature variations of the surface water in the top 1 cm (0.4 in) across the reef. In the absence of surface-water runoff through rivers and streams during most of the year, cool surface waters along the coast suggest extensive SGD. Thermal IR data also show the cross-shore influence of fresh surface water near stream mouths, where active subsurface flow is likely concentrated because ground-water levels are higher than the elevation of the incised stream channel. On the island of Moloka‘i, modest rainfall in the upper elevations recharges ground-water levels sufficiently to maintain ground-water flow at the coast (fig. 4).

Measurements of surface-water temperature, conductivity, and salinity from 325 CTD casts and 50 point measurements using a temperature and conductivity probe across the Moloka‘i reef made during two different surveys (May and August, 2002) reveal a persistent pattern of freshwater discharge and mixing across the reef flat and inner reef crest (fig. 5). These

Figure 3. Map showing uncalibrated thermal infrared imagery collected March 8, 2001, across the south shore Moloka'i reef. The rainbow color codes represent relative temperature variations, where red is warm and blue is cool. Offshore of Kapuāiwa coconut grove several streams of cool water are observed flowing out across the reef flat (blue arrows). Along the Kamiloloa coast, several areas of cooler water are found flowing as streams across the reef flat (blue arrows) and are commonly associated with fishponds. In the absence of surface runoff from streams, these cooler water masses are best explained by ground-water discharge along the shore.



results are similar to what the thermal IR data show and suggest that freshwater is discharging along the south Moloka'i shoreline. In the absence of inflowing surface waters via streams, these data are a strong indication that ground water is the source of this freshwater.

At Kapuāiwa coconut grove, the influence of freshwater from springs and SGD is dramatic based on surveys collected in August 2004 (fig. 6). Cold freshwater emanates from the springs and extends more than 0.5 km (0.3 mi) offshore at the surface. This ground water rapidly warms over the shallow reef flat. In addition, ground water can be seen discharging through the reef (black arrow, fig. 6B) 0.5 km (0.3 mi) offshore of the coconut grove. Interestingly, however, cooler temperatures are not always indicative of freshwater, because marine water associated with the incoming tide may be cooler than freshwater that warms rapidly near shore on the reef flat (fig. 6C, D).

Across the reef offshore of Kamiloloa, sensors were mounted on tripods and left recording at the same location for several years. The resulting measurements show that water temperature and salinity vary both daily and seasonally. Although temperature varies by only a few degrees, salinity varies as much as ~10 practical salinity units (psu), whereas marine waters commonly have values around 35 psu (Ogston and others, this vol, chap. 20). Each day, as the tide rises it brings slightly cooler, more saline marine waters toward shore. They mix with surface waters across the shallow reef flats, which become warmer throughout the day as they are heated by the sun. Episodic decreases in temperature and salinity, however, may be related to discrete periods of high rainfall. Whether these variable conditions adversely affect coral directly remains uncertain.

Radiochemical Signatures of Submarine Ground-Water Flux

Elevated activities of radium isotopes measured in nearshore waters provide strong evidence of widespread SGD to the fringing reef along south Moloka'i. Water samples were collected on July 12, 2003, approximately 1 m (3 ft) from the shoreline at 12 sites between Kapuāiwa coconut grove and 'Ualapu'e fishpond east of Kamalō (fig. 5). ²²³Ra and ²²⁴Ra activities measured in these samples ranged from 0.3 to 2.5 and 9 to 47 decays per minute per 100 liters (dpm/100 L), respectively, showing a high degree of variability. Because these isotopes are evenly present in very low concentration in seawater, this likely reflects an uneven distribution of SGD along the coast. Peak Ra activities were measured just west of the Kaunakakai Wharf in high-salinity waters, and Ra activities at all sites were 10 to 100 times greater than those measured in the open ocean.

Samples were also collected along cross-shore transects at three sites along the south coast: Kapuāiwa coconut grove, Kamiloloa, and near 'Ualapu'e fishpond (two are shown in figure 7). Elevated ²²⁴Ra activities (17–34 dpm/100 L) were detected in samples as much as 60 m offshore on the reef flat. Assuming slow mixing rates and water residence times of 2–3 days (several tide cycles) in the protected back-reef areas (Ogston and others, 2004; Presto and others, 2006), the persistence and elevated activities of ²²³Ra and ²²⁴Ra offshore suggest high discharge of brackish ground water. The discharge may be occurring through the sea floor over a broad area of

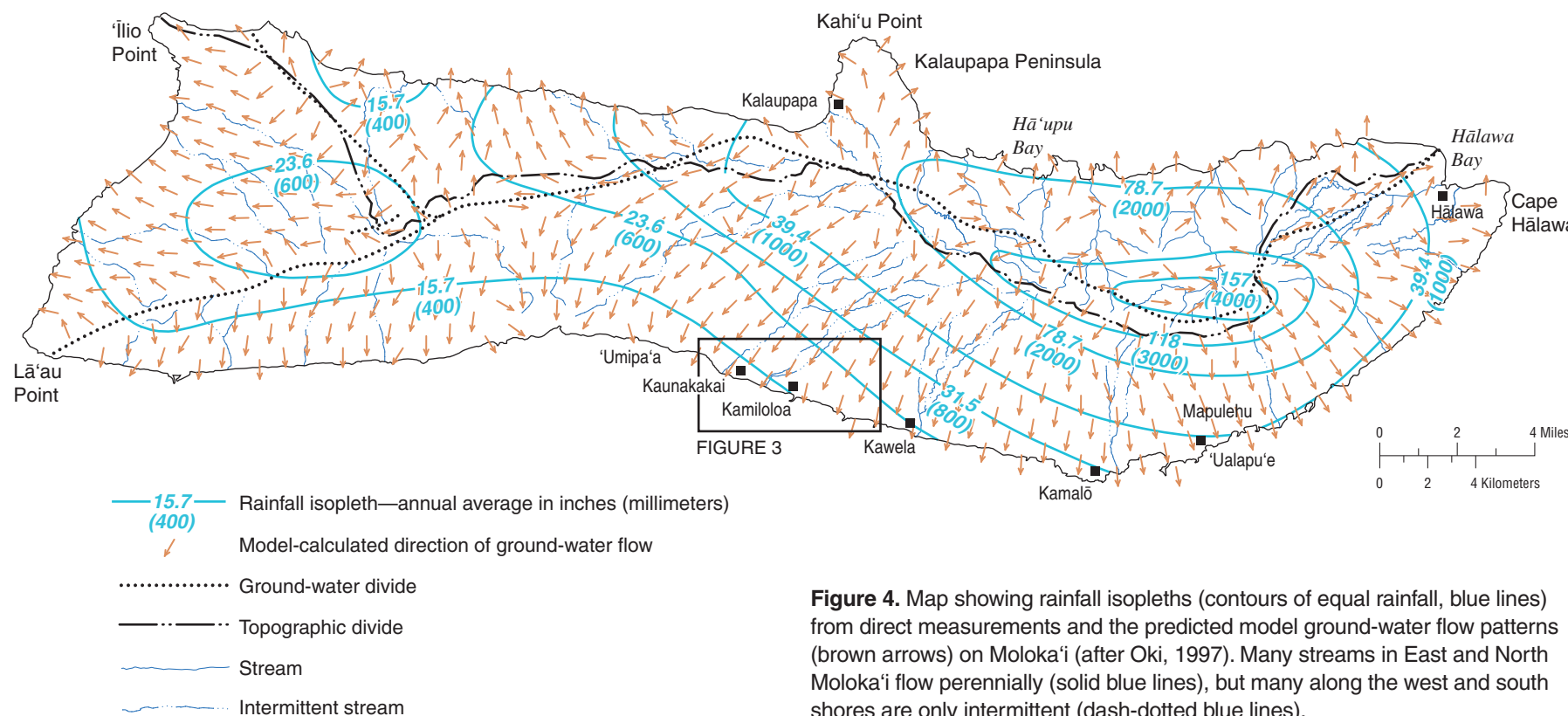


Figure 4. Map showing rainfall isopleths (contours of equal rainfall, blue lines) from direct measurements and the predicted model ground-water flow patterns (brown arrows) on Moloka'i (after Oki, 1997). Many streams in East and North Moloka'i flow perennially (solid blue lines), but many along the west and south shores are only intermittent (dash-dotted blue lines).

Figure 5. Diagrams showing depth-averaged water temperature and salinity (measured in practical salinity units, or psu) across the Kamiloloa reef flat from direct measurements during high tide. Sample locations include conductivity, temperature, and depth (CTD) casts (crosses) and water samples (triangles, see also figure 7). High-tide temperatures in August 2002 (A) are generally cooler along the shoreline than farther offshore on the reef flat and reef crest and are considerably higher near the Kaunakakai Wharf than to the east near One Ali'i. Similarly, salinities in August (B) and May (C) are significantly lower along the coast than offshore, consistent with a persistent input of freshwater at the shore.

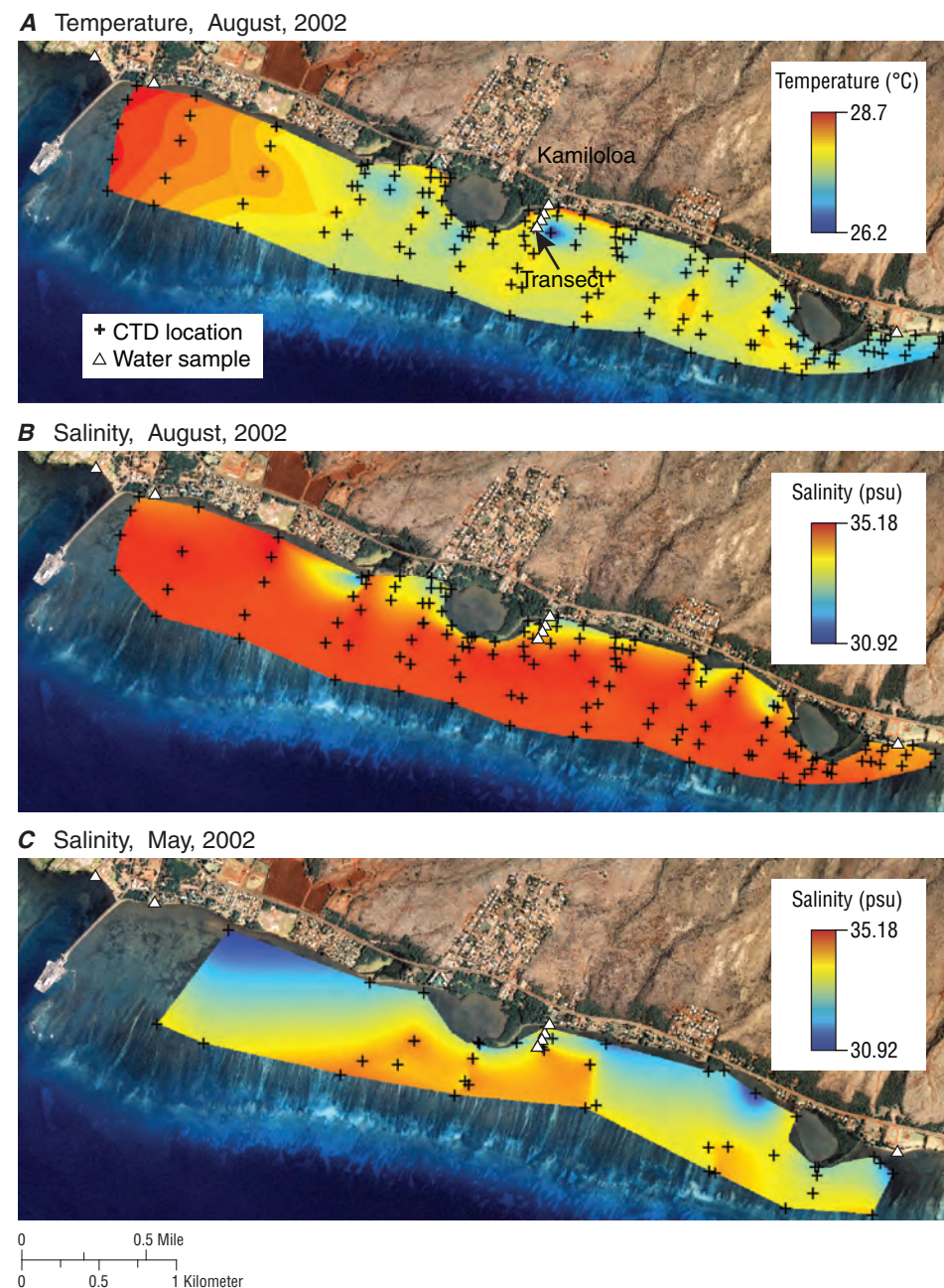


Figure 6. Diagrams showing seawater salinity (measured in practical salinity units, or psu) and temperature on the reef flat offshore of Kapuāiwa coconut grove in August 2004 during the initial stages of a rising tide. Sample locations include conductivity, temperature, and depth (CTD) casts (crosses) and water samples (triangles, see also figure 7). A, Sea-surface salinity shows a tongue of freshwater extending across more than 0.5 km (0.3 mi) of the inner reef flat, with values as low as 5 psu at the spring along the shore. B, Bottom salinity (~0.5 m or 1.6 ft above the sea floor) shows that freshwater in the form of submarine ground-water discharge (SGD) emanates from the springs along the shore as well as from a spring out in the middle of the study area (white arrow). C, Sea-surface temperatures reveal that the plume of freshwater is cool near the spring but quickly warms over the shallow inner reef flat. D, Bottom temperatures reveal that water is warmest in the shallowest parts of the reef flat and coldest near the offshore spring.

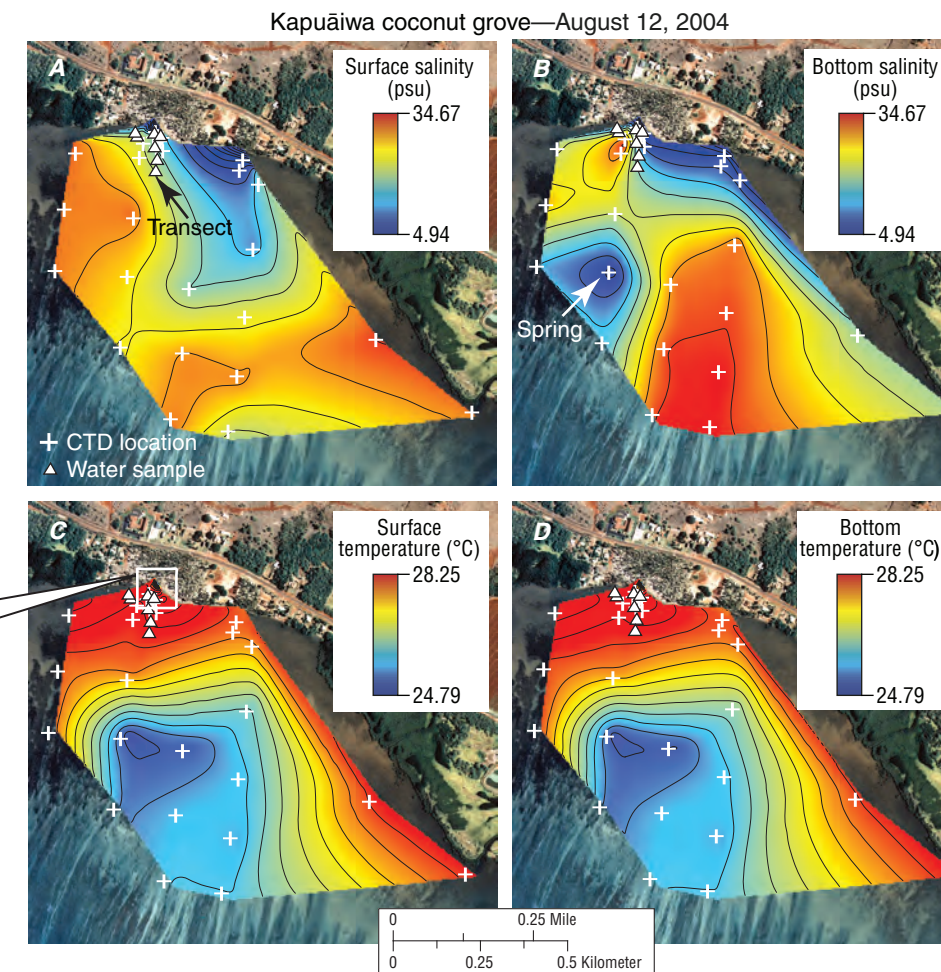
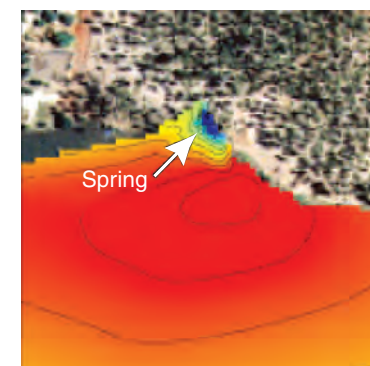
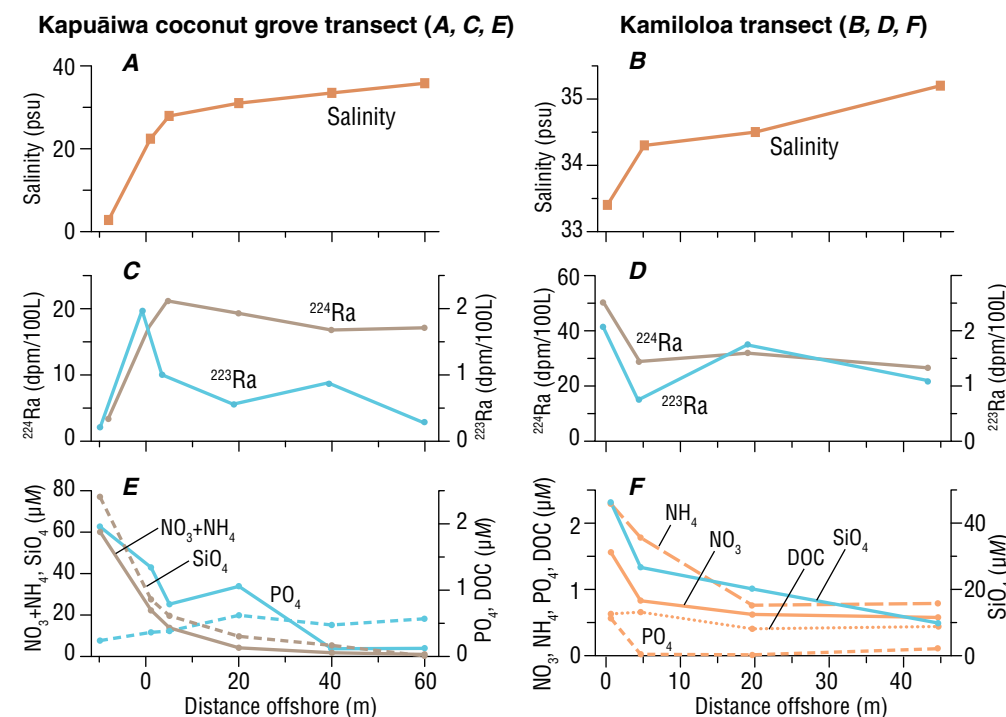


Figure 7. Plots of surface salinities, radium activities, and nutrients along transects offshore of Kapuāiwa coconut grove and Kamiloloa measured on July 10, 2003 (see figures 5 and 6 for locations). Salinity (A, B) generally increases away from the shore as expected with increasing influence of marine water (psu, practical salinity units). Activities of ^{223}Ra and ^{224}Ra (C, D) are higher near shore and correlated with each other as they decrease offshore with increasing salinity, suggesting a terrestrial source of Ra, likely from uranium and thorium decay in basalt source rocks. An exception at Kapuāiwa coconut grove, where Ra is lower in the fresh coastal spring, is consistent with a fresher source of ground water there and a more brackish source emanating from the offshore spring. Similarly, offshore of Kamiloloa a slight increase in Ra activities 20 m offshore may indicate submarine ground-water discharge (SGD) through the reef flat. Unit of activity is (radioactive) decays per minute per 100 liters (dpm/100 L). All nutrients measured (E, F) are significantly higher close to shore and, taken with the Ra results, indicate that the source of these nutrients is ground water. Dissolved organic carbon (DOC) is relatively uniformly distributed across the reef flat.



the reef flat, rather than from a discrete, onshore source. This observation is consistent with a subterranean source of ground water composed of a mixture of both terrestrial ground water and recirculated seawater discharging offshore, like the situation observed in figures 5 and 6.

A brackish to saline mixing zone is usually present within ground-water systems of many islands. This mixing zone migrates back and forth in a cross-shore direction under the influence of the tides and rainfall. These factors modulate the gradient of hydraulic head (equal to water level in unconfined systems) that drives ground-water discharge. At low tide, when ground-water flow across the reef flat is strongest (greatest water-level gradient), the brackish zone migrates offshore. Conversely, at high tide, or during dry periods when ground-water flow is weaker, the brackish zone moves inland. Because desorption (leaching) of radium from rocks and sediment is suppressed in freshwater, Ra isotopes are primarily tracers of saline ground water. They thus can show the location of the discharge of brackish mixing-zone water. This model of coastal aquifer dynamics on Moloka'i is consistent with the observation that Ra activities in nearshore waters are much higher than in onshore samples taken from the coastal aquifer at low tide. The spring at Kapuāiwa coconut grove (fig. 2A) was sampled at low tide and was found to have ^{223}Ra and ^{224}Ra activities of only 0.26 dpm/100 L and 3.19 dpm/100 L, respectively, and a salinity of only 2.9 psu. Just a few tens of meters offshore, where the saline ground water discharged, Ra activities and salinities on the reef flat were four to seven times greater.

Nutrient Concentrations Along the South Moloka'i Reef

Ground water discharging along the south Moloka'i shoreline is a major source of new nutrients, including inorganic nitrogen (N), phosphorus (P), and silica (SiO_2) to the Moloka'i reef (fig. 7). The mean molar concentration of inorganic nutrients in three low-tide samples of undiluted ground water collected from springs at Kapuāiwa coconut grove were $63.7 \pm 3.3 \mu\text{M}$, $2.20 \pm 0.18 \mu\text{M}$, and $823 \pm 32.6 \mu\text{M}$, for nitrate, orthophosphate, and silicate, respectively. These concentrations are 10 to 1,000 times greater than those measured in open-ocean samples. Elevated concentrations were also measured in the surface pool sampled near 'Ualapu'e fishpond ($7.20 \mu\text{M NO}_3^-$, $4.03 \mu\text{M PO}_4^{3-}$, $593 \mu\text{M Si(OH)}_4$), although nutrient concentrations of the original ground water there are likely modified by internal cycling and/or inputs and uptake by nearby vegetation. In the coconut grove ground-water samples, the N/P ratio is approximately 29, whereas in the 'Ualapu'e fishpond the ratio is less than 2, suggesting that biologic uptake of N within the pond is depleting the nitrogen.

Submarine Ground-Water and Nutrient Flux to the South Moloka'i Reef

We calculate submarine ground-water discharge (SGD) and nutrient fluxes to the Moloka'i reef at Kamiloloa and Kapuāiwa coconut grove using Ra isotope-tracer and salinity mass-balance methods adapted from Moore (1996) and our understanding of residence time of water on the reef, the

time required to replace water on the reef through tidal exchange or currents. Given the measurement uncertainties in the activities of ^{224}Ra and ^{223}Ra , it would take at least 1.5 days to detect a change in the ratio of ^{224}Ra to ^{223}Ra . Because we do not observe these ratios to vary across shore, it is assumed that there is negligible Ra decay within the residence time of water on the reef, and that the decrease in activities offshore is due to dilution with seawater. The dilution occurs with mixing through tidal exchange and currents. Because of uncertainties in our understanding of currents and water exchange in the shallow reef flat, we calculate SGD on the basis of residence times of water at two sites where we measured Ra activities across the inner reef flat—a box at Kamiloloa 45 m (148 ft) long (across shore) by 1 m (3.3 ft) wide (along shore) by 1 m (3.3 ft) deep and a box at Kapuāiwa coconut grove 60 m (197 ft) long, 1 m (3.3 ft) wide, 1 m (3.3 ft) deep (fig. 7). The residence times for these boxes range from 1.5 days (based on our Ra measurements) to 37 minutes (based on net cross-shore currents of 2 cm/sec) (Presto and others, 2006).

Calculations of SGD based on Ra decay and salinity mass balance range from 8.8 to 638 L/min/m (liters per minute per meter of shoreline) (2.3 to 169 gal/min/m) at Kamiloloa and from 4.7 to 204 L/min/m (1.2 to 54 gal/min/m) at Kapuāiwa coconut grove (fig. 8). A key difference between the sites is the presence of natural springs at Kapuāiwa coconut grove, which can be observed to discharge freshwater directly to shore. The SGD estimates derived from using current measurements of Presto and others (2006) are significantly higher than those derived from the Ra activity and salinity mass balance. This may result from the fact that the current measurements, like most instantaneous observations, are biased toward higher rates (for example, higher flushing rates, lower residence time across reef). In contrast, the extrapolations of residence time across larger portions of the reef via the Ra activity and salinity mass-balance methods tend to average out instantaneous rates over longer time and space scales. It is probable that the residence time of water across the reef used in our Ra activity and salinity mass-balance calculations is closer to 1.5 days because of incomplete exchange within one tidal cycle. However, during periods of strong currents caused by high trade winds and/or large waves, the residence time of water across the reef may be shorter and on the order of hours, as reflected by Presto and others (2006). The results here based on tidal exchange are in close agreement with estimates based on ground-water models, which predict regional trends (fig. 4). The model predictions of SGD range from 1.7 cubic feet per second per mile of shoreline (1.9 L/min/m) at Kamiloloa to 3.2 cubic feet per second per mile (3.4 L/min/m) at Kapuāiwa coconut grove (Oki, 1997; D.S. Oki, written commun., 2007).

We calculate nutrient fluxes to the South Moloka'i reef by multiplying the concentration of nutrient in SGD by the SGD flux rates noted above. For example, the nitrogen flux to the reef is the product of total inorganic nitrogen (TIN, nitrate plus ammonium) concentration in ground water emanating to the reef (fig. 7) and the SGD rate converted to grams of elemental nitrogen flux per day to the reef. At Kamiloloa, we calculate a range of TIN between 0.7 and 50.2 grams of nitrogen per day (g/d of N) entering the reef with ground water. At Kapuāiwa coconut grove, TIN flux to the reef in ground

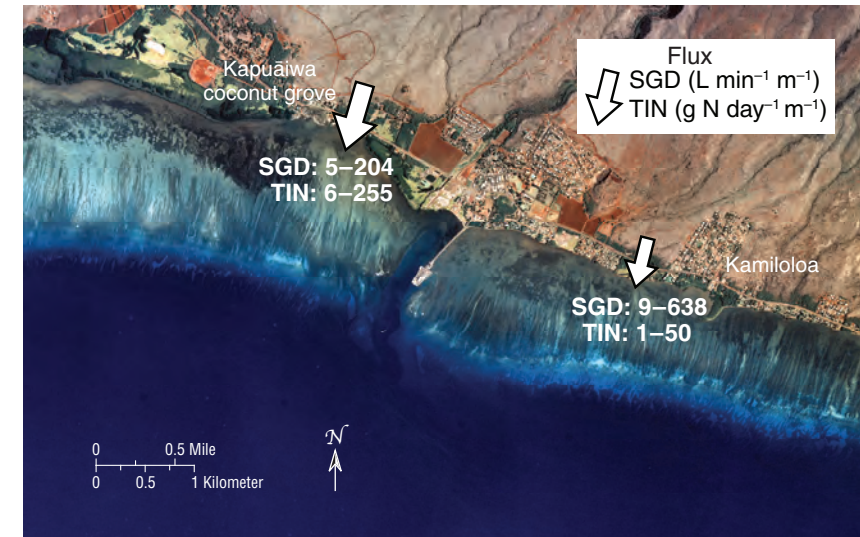


Figure 8. Map showing calculated submarine ground-water discharge (SGD) and total inorganic nitrogen (TIN) flux at the Kapuāiwa coconut grove and Kamiloloa. Although ranges of SGD are higher for Kamiloloa, nitrogen flux to the reef is higher at Kapuāiwa because of higher nitrogen concentration in the fresh ground water there. Estimates range considerably because of our limited knowledge of residence times of water on the reef and because of the complex mixing of fresh and brackish ground water with recirculated seawater in the coastal aquifer.

water ranges from 5.9 to 255 g/d of N. Again, the TIN fluxes based on current measurements are higher than those from the other two methods, reflecting the more rapid SGD flux estimated by the process measurements. The measured concentrations of N found here are comparable to nutrient concentrations found in ground water in other areas of the Hawaiian coastal zone, which range from 13.2 to 63.6 μM (at Kahana; Garrison and others, 2003), 60 to 95 μM (at Waikoloa and Keahou; Dollar and Atkinson, 1992), and 0.45 to 1.7 μM (at West Maui; Soicher and Peterson, 1997). More importantly, the nutrient concentrations found in ground water at Kamiloloa and Kapuāiwa coconut grove are 10 to 100 times higher than concentrations found in open ocean water. The higher levels of nutrients discharging from the spring at Kapuāiwa coconut grove are likely a result of being associated with fresh ground water, while at Kamiloloa nutrients discharging in brackish to saline ground water may be diluted by recirculated seawater.

Dissolved Carbon and Carbon-Isotope Signatures of Water Source and Mixing

Ground-water discharge appears to be only a minor contributor of dissolved organic carbon (DOC) to the Moloka'i reef (fig. 7E, F). The average DOC concentration and standard deviation for all nearshore and back-reef samples collected during July 2003 are 0.66 ± 0.24 ppm ($54.6 \pm 20.2 \mu\text{M}$, $n=30$). This places the Moloka'i reef within the lower to middle portions

of the range of DOC (9 to 290 μM in coral-reef sites globally; Atkinson and Falter, 2003). This result is consistent with the semiarid climate of the Hawaiian region. Samples collected within a few meters of the Moloka'i shore are on average slightly enriched in DOC (0.73 ± 0.30 , $60.6 \pm 25.8 \mu\text{M}$, $n=15$) relative to samples from farther offshore, likely reflecting carbon from mangroves and terrestrial plant debris, although the springs at the Kapuāiwa coconut grove contain a lower average concentration of DOC (0.35 ppm, $29.0 \mu\text{M}$, $n=3$). These data suggest that some other source, such as export of DOC from the fore reef and reef crest, are necessary to support the higher observed DOC concentrations in the nearshore and on the reef flat.

Measurements of stable-isotope ratios ($\delta^{13}\text{C}$) of DOC also suggest that ground water is not a dominant source of carbon to the Moloka'i reef. The vast majority of nearshore samples have $\delta^{13}\text{C}$ signatures of DOC in the range of -17 to -24 permil (parts per thousand), consistent with the $\delta^{13}\text{C}$ signatures of marine phytoplankton (-18 to -24 permil) and marine algae (-15 to -22 permil) (Michener and Schell, 1994). These values fall within the broad range of published values for marine and estuarine systems (see, for example, Coffin and others, 1994), the DOC of which is commonly enriched in ^{13}C relative to rivers and freshwater. Exceptions occur within the 'Ualapu'e fishpond (-26.77 permil) and in a shoreline sample collected between Kawela and Kamalō (-30.92 permil), where an abundance of emergent terrestrial vegetation (mangroves) that have low $\delta^{13}\text{C}$ values (-22 to -30 permil) is likely exporting carbon to the reef flat (Michener and Schell, 1994). The $\delta^{13}\text{C}$ values in spring-water samples from Kapuāiwa coconut grove average -21.46 ± 0.99 permil ($n=3$), a signature not distinguishable from most inner reef-flat samples.

Gaps in our Knowledge of SGD Flux, Phasing, and Impact to the Moloka'i Reef

It is evident from the foregoing that submarine ground water does discharge on the south shore of Moloka'i and that the discharge contains high concentrations of nutrients. It may also contain contaminants, but this is not yet documented. Understanding the variability of ground-water composition, flux, and circulation processes that determine its fate is important to predict impacts to coastal ecosystems. A particularly challenging issue is being able to identify (1) the origin of ground water and contaminant additions, (2) transport pathways, and (3) the timing of discharge relative to rainfall and recharge. To these ends, scientists are actively pursuing experiments to quantify these processes. With suitable measurements, adequate models can be developed and applied to societally relevant issues concerning

ground-water effects on coastal ecosystems. For example, ground-water flow models can predict travel times, discharge rates, and nutrient fluxes to the coast that are important parameters to resource managers tasked with balancing the needs of human water supplies and coastal ecosystems.

Summary

Submarine ground-water discharge (SGD) to the coast is highly variable along the shore and through time because of the complex nature of subsurface flow through a variety of different rock and sediment types. Along the Moloka'i reef, evidence in the form of legends, reef morphology, thermal infrared imaging, CTD (conductivity, temperature, and depth) studies, water chemistry, and modeling studies indicate that a significant amount of freshwater discharges at the shoreline or below sea level on the nearby reef flat. Although springs like those at the Kapuāiwa coconut grove have only a localized effect on the reef, their persistent nature may shape nearshore reef communities and at the same time dissolve the reef below, as has been observed in drill cores. Localized areas of SGD occur across the reef, although the timing and amount of this flow remains uncertain. Further inquiry into the range of nutrient sources to ground water and nutrient concentrations reaching the coast in ground-water discharge will aid in future planning and resource management.



Kapuāiwa coconut grove.

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