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# A box model to quantify groundwater discharge along the Kona coast of Hawaii using natural tracers

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**Abstract** Major islands such as Hawaii typically exhibit conditions favourable for high submarine groundwater discharges (SGD) to the ocean. Quantitative aerial thermal imaging along the leeward Kona coast of Hawaii reveals plumes of relatively cold groundwater discharging from distinct portals along the coastline. Many of these plumes are thought to represent substantial volumes of groundwater discharge. The goal of our tracer work is to quantify groundwater fluxes to the coastal ocean from some of these plumes as a means of calibrating the aerial imaging. We employed coincident mass balance equations for two tracers (salinity and radon) and water fluxes to develop a mass balance box model for quantifying groundwater discharge. Our results indicate that a small SGD discharge plume emanating from Kahualoa Bay represents water fluxes on the order of thousands of $m^3$/day to the coastal ocean.

**Key words** submarine groundwater discharge; radon; Hawaii; mass balance equations

## INTRODUCTION

By definition, submarine groundwater discharge (SGD) includes any and all outward movement of water from the aquifer to the overlying water column (Burnett *et al.*, 2003). Terrestrial factors that can enhance SGD include high precipitation rates, relief, and permeability, as well as a lack of a well-developed river system (Zektser, 2000). The islands of Hawaii exhibit all these characteristics, and so are ideal sites for developing SGD assessment tools. The “Big Island” of Hawaii is geologically the youngest of the islands, so all these factors are most pronounced on this island. Several authors have described the high volumes of SGD along the western coast of the Big Island of Hawaii (Fig. 1). While most of these prior studies (Kanehiro & Peterson, 1977; Kay *et al.*, 1977; Bienfang, 1980; Brock, 1980; Dollar & Atkinson, 1992; Oki, 1999) involved calculations of SGD via a water balance approach, an earlier study led by George Wilkins (Univ. Hawaii) produced a videotape in 1992 by flying over the coastline around the Kona coast of Hawaii with a hand-held infrared camera. That investigation revealed surface water temperature anomalies and demonstrated that there are distinct portals along the coastline where relatively cold groundwater discharges out of the aquifer and mixes with the warmer ocean water.

Working with the University of Hawaii’s Airborne Hyperspectral Imager (AHI), we conducted a more advanced and quantitative aerial infrared survey in the same

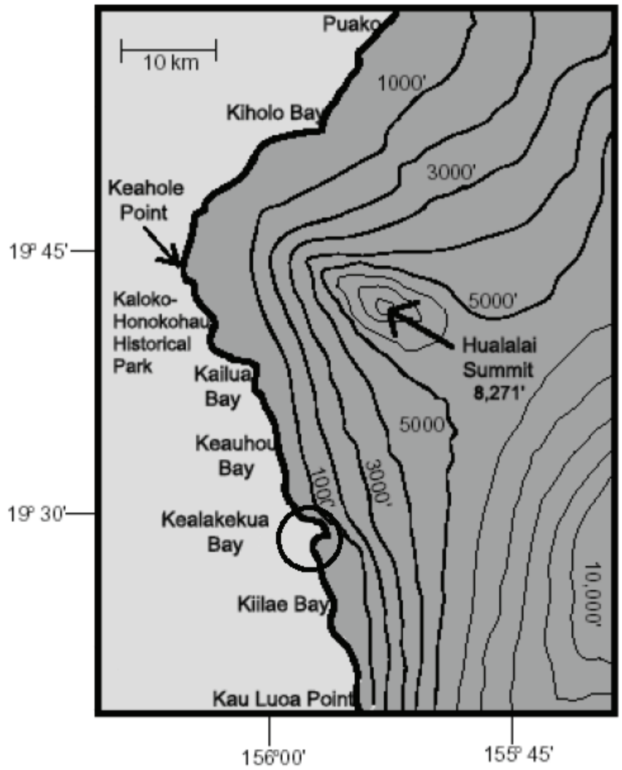


**Fig. 1** Map depiction of the study site in the western Kona coast area of Hawaii. Kealakekua Bay is marked by the circle, and Kahualoa Bay is found just south (below) the large bay in the circle. Contours are feet above mean sea level.

area. In order to calibrate the aerial technique, we are employing ground-truthing via radioisotopic methods. Burnett & Dulaiova (2003) described a radon box model approach to evaluate rates of SGD in coastal regions. However, that approach was designed for diffuse seepage flow and thus requires information regarding the area of seepage in order to convert specific discharge (e.g. $m^3/m^2$ day) to absolute discharge ($m^3$/day). To reduce that uncertainty, we designed a coincident series of interconnected tracer mass balance equations to determine the groundwater flux. The tracers employed in this model are salinity and radon with a temporal resolution of one hour that corresponds to the integration time of the radon measurements.

## STUDY SITE AND EXPERIMENTAL METHODS

The coastal regions on the western, leeward side of Hawaii are typically arid with a mean annual rainfall of only 25 cm. Within 10 km of the coastline, however, the porous mountain slopes receive a mean annual rainfall of 102 cm. These slopes are thus likely areas of groundwater recharge for the region (Kay *et al*., 1977). The study site discussed here, Kahualoa Bay, is actually a small inlet just south of the much larger Kealakekua Bay, approximately 20 km south of Kailua-Kona village. It measures approximately 130 m long, 20 m wide at the head of the bay, and 110 m wide at its mouth where uninhibited tidal exchange occurs. A gentle sloping bottom, predominantly composed of small lava rocks, extends out from the coastline to an average depth of 2.5 m about 25 m from shore.

Due to the lack of rainfall in the area, surface drainage to this small bay is negligible. In addition, seawater intrusion into the coastal aquifer prevents residents in this area from pumping substantial volumes of groundwater for domestic use. Therefore, no anthropogenic influences should affect the aquifer dynamics at this site.

Continuous measurements of $^{222}$Rn, temperature, salinity, and water level were taken over a several-day period from a fixed platform about 25 m from the shoreline. We measured radon concentrations in near surface waters (~0.5 m depth) at 1-hour intervals using a Durridge Co. Rad7 Radon-in-Air Monitor, modified to measure radon in water (Burnett *et al.*, 2001). Water temperatures and salinities were recorded at 1-minute intervals with a YSI 600 XLM probe, and water levels were recorded continuously using an Onset Corp. HOBO water level logger. In addition, end-member concentrations of radon and salinity from the adjacent open ocean and nearby groundwater wells were also recorded. Ocean end-members were taken from the results of a radon survey according to the procedure described in Dulaiova *et al.* (2005). Groundwater samples were collected and analysed for salinity as well as radon according to the procedure reported in Lee & Kim (2006).

## Model development

The mass balance box model presented here uses the relatively high radon, low salinity nature of groundwater and the low radon, high salinity conditions of open ocean water to determine the flux of groundwater into and out of the coastal ocean. By continuously monitoring the radon and salt concentrations in the coastal surface waters, one can examine how the groundwater flux changes over time.

We represent (Fig. 2) input fluxes of water to the coastal ocean from open ocean exchange ($Q_{IN}$) as well as SGD ($Q_{SGD}$). These flows are balanced by outward coastal water exchange to the open ocean ($Q_{OUT}$). We ignored any meteorological input or output of water that should be negligible compared to the other fluxes on these time scales (hours to days). The variables marked Rn represent the radon concentrations (dpm/m$^3$) found in the groundwater ($Rn_{SGD}$), coastal ocean ($Rn_c$) and the open ocean ($Rn_o$). Likewise, the variables marked S represent the salinity (g/kg) of the same waters, and variables marked ρ are corresponding densities (kg/m$^3$).

The geometry of the groundwater plumes such as the one exiting Kahualoa Bay allows for use of a simple, half-box type approximation of its volume (Fig. 2(b)). Estimating the volume of the coastal ocean at two different time steps allows determination of $\Delta V_c$. In order to simplify the geometry further, we assume that the length and width terms do not change throughout the tidal cycle, i.e. the bay has vertical walls. By convention, we consider fluxes directed offshore from the coastal bay as positive, and landward fluxes as negative.

The model is developed using three simultaneous equations for water, salt, and radon mass balance. Initially, these equations are set up for an entire tidal cycle, assuming steady state conditions with respect to the water and salt balances. Coastal water averages over a 24-hour period for radon, salinity, and density are used for $Rn_c$, $S_c$, and $\rho_c$. We used a modified version of the LOICZ box model approach (Gordon

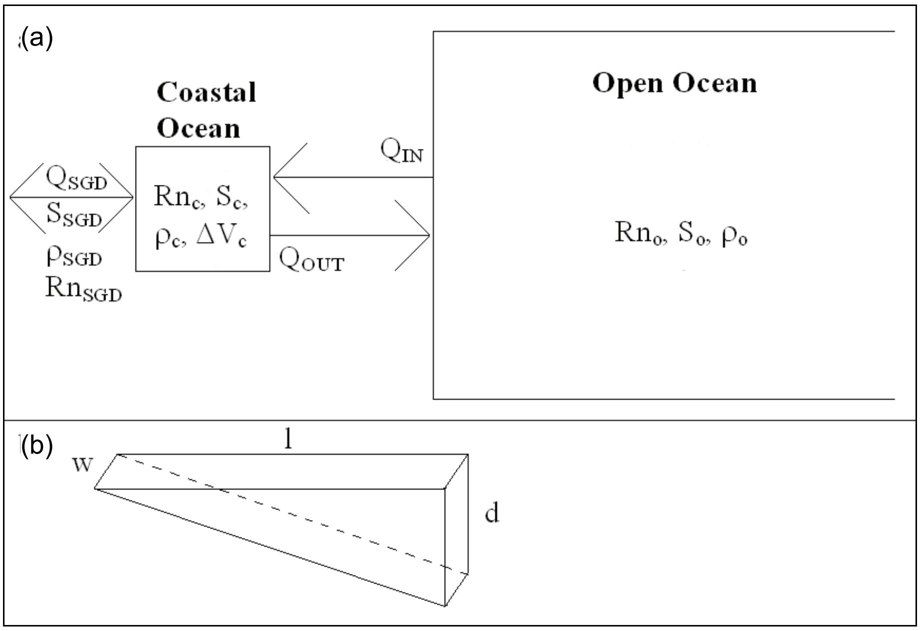


**Fig. 2** (a) Diagram of model variables and their interactions; (b) geometry used to simulate the changing volume of the Kahualoa Bay plume. The volume of the tidal wedge is approximated by V = lwd/2.

*et al.*, 1996) to derive the following equations for water balance:

$$\frac{\Delta V}{\Delta t} = 0 = Q_{out} - Q_{in} - Q_{sgd} \quad (1)$$

for salt balance:

$$\frac{lw(S_{c(t+1)}\rho_{c(t+1)}d_{c(t+1)} - S_{c(t)}\rho_{c(t)}d_{c(t)})}{\Delta t} = 0 = S_c\rho_c Q_{out} - S_o\rho_o Q_{in} - S_{sgd}\rho_{sgd}Q_{sgd} \quad (2)$$

and for radon balance:

$$\frac{lw(Rn_{c(t+1)}d_{c(t+1)} - Rn_{c(t)}d_{c(t)})}{\Delta t} = Rn_c Q_{out} - Rn_o Q_{in} - Rn_{sgd}Q_{sgd} \quad (3)$$

Terms marked with the subscript ($t$) represent the conditions at the beginning of the tidal cycle, and those marked by ($t$+1) represent the conditions at the end of the tidal cycle. In general, these equations are setup so that the left-hand side equates to a change in total mass (or volume for the case of water) over a set period of time, whereas the right-hand side of the equations represent the contributing effects of input or output fluxes to these mass changes in the groundwater plume. Solving these equations results in average values for water fluxes $Q_{IN}$, $Q_{OUT}$, and $Q_{SGD}$ over a complete tidal cycle.

We next obtain better temporal resolution by examining how these fluxes vary within smaller time steps. For 1-hour time steps, the assumption of steady-state conditions for the water and salt balances are no longer valid, but we can examine how the tracer masses change between two time steps. Since the individual water fluxes are known for the entire tidal cycle, it is now necessary to examine their relative change each hour (Q ± ΔQ). A few processes inherently require an inverse relationship between tracer concentration in the end-member and corresponding water flux to achieve an expected response. For these processes, we expect the water flux to decrease if the end-member tracer concentration increases, so we use (Q – ΔQ). The processes that follow this rule are input of radon from groundwater and input of salt from the open ocean.

The resulting equations are the following for water balance:

$$\frac{\Delta V}{\Delta t} = (Q_{out} + \Delta Q_{out}) - (Q_{in} + \Delta Q_{in}) - (Q_{sgd} + \Delta Q_{sgd}) \tag{4}$$

for salt balance:

$$\frac{lw(S_{c(t+1)}\rho_{c(t+1)}d_{c(t+1)} - S_{c(t)}\rho_{c(t)}d_{c(t)})}{\Delta t} = S_c\rho_c(Q_{out} + \Delta Q_{out}) - S_o\rho_o(Q_{in} - \Delta Q_{in}) - S_{sgd}\rho_{sgd}(Q_{sgd} + \Delta Q_{sgd}) \tag{5}$$

and for radon balance:

$$\frac{lw(Rn_{c(t+1)}d_{c(t+1)} - Rn_{c(t)}d_{c(t)})}{\Delta t} = Rn_c(Q_{out} + \Delta Q_{out}) - Rn_o(Q_{in} + \Delta Q_{in}) - Rn_{sgd}(Q_{sgd} - \Delta Q_{sgd}) \tag{6}$$

Atmospheric evasion losses of radon, while minimal (<1% of radon inventory per hour), can be accounted for by adding this loss term into equation (6). On 1-hour time scales, the radon decay losses are considered unimportant. Solving these simultaneous equations for $\Delta Q_{IN}$, $\Delta Q_{OUT}$, and $\Delta Q_{SGD}$ allows for the calculation of net water fluxes into and out of a coastal ocean system during each time step analysed.

## RESULTS

Several large diameter shallow coastal wells (remnants of Old Hawaiian ponds with brackish water: av. salinity = 6.4) exist in the vicinity of Kahualoa Bay. The average radon concentration of these waters is rather low at 4980 dpm/m$^3$, as compared to upland wells that often exceed 50 000 dpm/m$^3$. These wells respond to tidal changes very quickly, some even going completely dry during low tide. The open ocean waters offshore from this area have relatively constant radon activities of about 62 dpm/m$^3$ and average salinities of 35.5.

During the fieldwork in Kahualoa Bay, the platform where the continuous measurements were made was anchored 25 m from the shoreline. The radon platform is assumed to be in the middle of a concentration gradient between shore and the open ocean, and so twice the distance between shore and the platform is taken to be the length of the study domain.

The variation of radon and salinity at our measurement platform shows that both salinity and radon vary in opposite manners during tidal oscillations (Fig. 3). The radon activities are surprisingly low for an area so influenced by groundwater. This is likely due to the relatively low concentration of radon in the coastal groundwater. Since the aquifer solids are very young volcanic rock, radon's parent, $^{226}$Ra, may not have had sufficient time to grow into equilibrium with the parent uranium.

The results of our model indicate that positive groundwater fluxes occur during outgoing tides and last through the low tides (Fig. 4). While the concentrations of salt and radon as shown in Fig. 3 seem to be in phase with the tide, the calculated groundwater flux in Fig. 4 is out of phase. This is because the $Q_{SGD}$ calculation is based

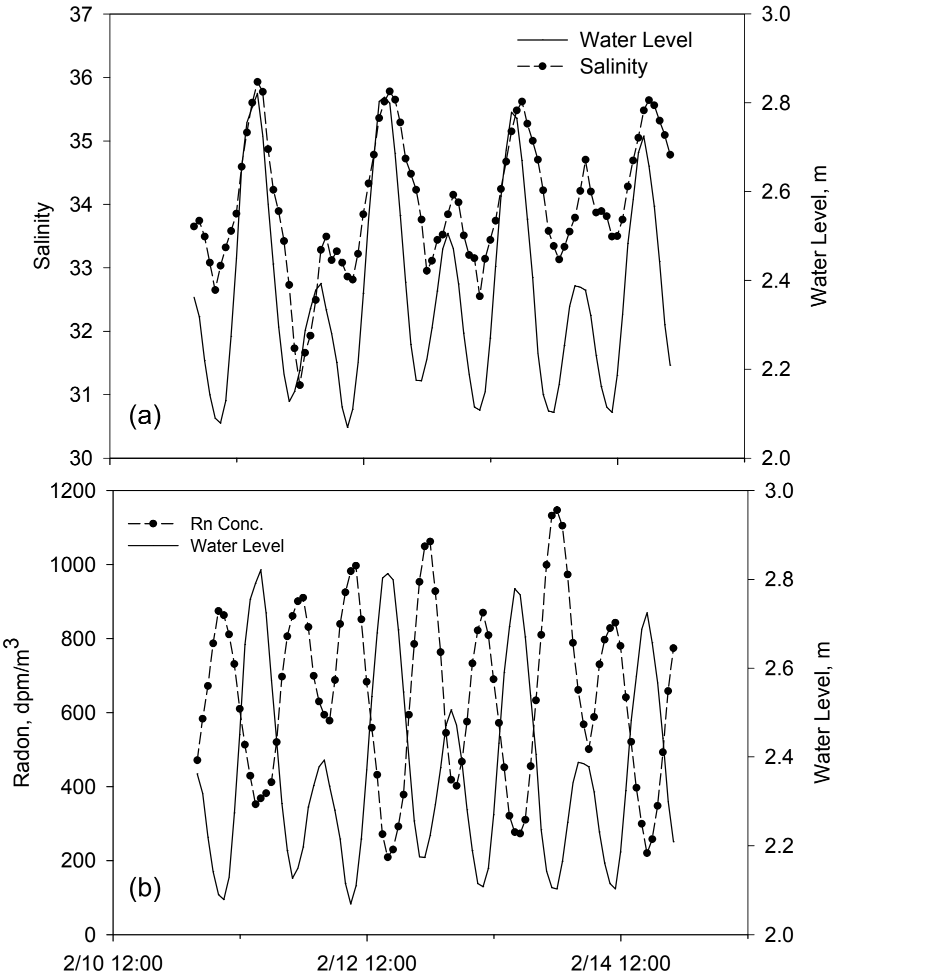


**Fig. 3** (a) Salinity; and (b) radon concentration variations together with the water level (solid line) through several days of measurements in Kahualoa Bay.

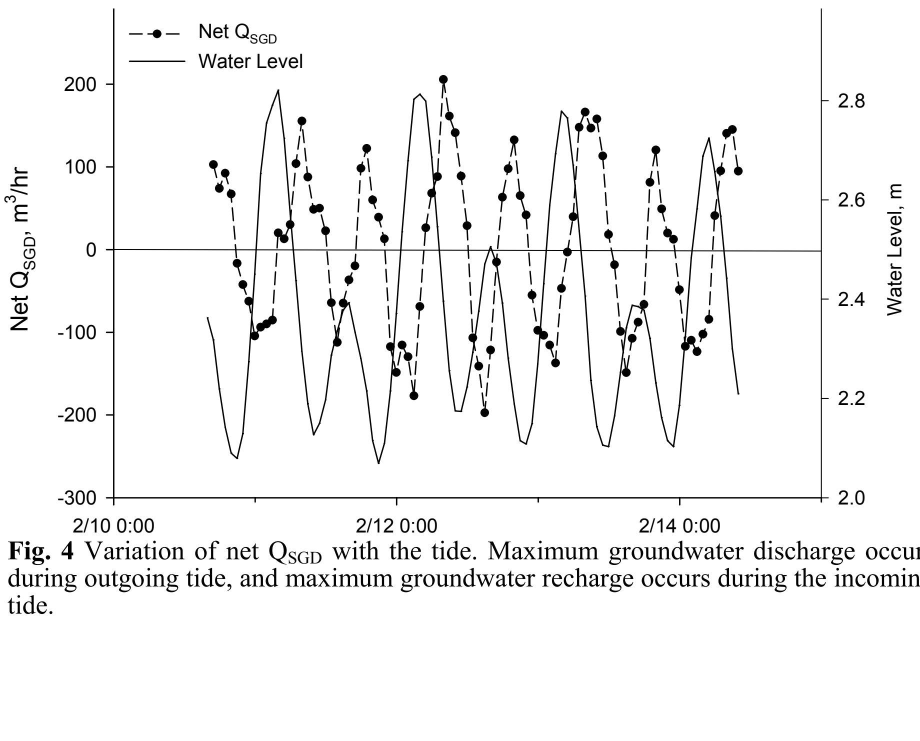


**Fig. 4** Variation of net $Q_{SGD}$ with the tide. Maximum groundwater discharge occurs during outgoing tide, and maximum groundwater recharge occurs during the incoming tide.

on the rate of change in the salt and radon masses (inventories), which peak in the middle of the tidal range. Once water levels begin to rise from the incoming tide, the groundwater discharge slows and eventually reverses direction, recharging the aquifer, presumably with saltier, lower radon water. By integrating all positive values of $Q_{SGD}$, over the course of a complete (24-hour) tidal cycle, the total flux of groundwater per day can be determined. In the case of Kahualoa Bay, we estimate the total groundwater flux at about 1120 $m^3$/day, with the terrestrial freshwater component of that flux to be 920 $m^3$/day.

## CONCLUSIONS

Our modelled groundwater flux calculations based on natural tracer measurements are comparable to earlier water balance estimates. Such estimates are based on regional water budgets which typically calculate total fresh groundwater discharge from an aquifer system as the total freshwater recharge (precipitation minus evapotranspiration) minus well pumping. Kanehiro & Peterson (1977), for example, estimated average groundwater discharges on the order of 15 000 $m^3$/d·km for a 26 km length of shoreline north of Kiholo Bay (Fig. 1). While the current model shows that the small, 40-m wide basin we studied discharges 1120 $m^3$/d, extrapolating to 1 km of shoreline would give the equivalent of 28 000 $m^3$/d·km. Bienfang (1980) estimated the groundwater discharge of a larger plume issuing from Honokohau Harbor (north of Kailua-Kona) to be between 5600 and 7600 $m^3$/d. Visual comparisons of the infrared images of these two plumes indicate that the Honokohau Harbor plume is likely on the order of 5–10 times the magnitude of that from Kahualoa Bay. Our modelled result thus appears to be of the correct magnitude.

The model is rather sensitive to changes in some end-members and other parameters. For example, a 5% change in dimensional distance changes the final SGD flux by 5%. Changing the groundwater radon end-member concentration by 5% results in a final SGD flux change of 4%. However, changes within reasonable bounds for $S_{SGD}$, $Rn_o$, and $S_o$ have only minor impacts on the final model outcome.

By using simultaneous mass balance equations for water, salt, and radon, it is possible to obtain reasonable results for groundwater fluxes throughout the course of a tidal cycle. In this paper, appropriate trends and values have been obtained for groundwater fluxes into a small coastal bay along the Kona coast of Hawaii. We hope to make additional enhancements to the model in the future including lessening the impact of dimensional length scales and groundwater radon concentration changes on the final result.

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