Hydrology of three Loko I‘a, Hawaiian fishponds, on windward Hawai‘i Island, Hawai‘i

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Abstract

Groundwater is a primary source of nutrients for loko iʻa, Hawaiian fishponds, in Hawaiʻi. Freshwater inputs are a key component to these dynamic coastal ecosystems yet flow rates are variable. The focus of this study was to (1) understand the changes in groundwater flow through time, (2) determine differences in groundwater composition among shoreline and loko iʻa springs and (3) analyze how climate change may impact these groundwater dependent ecosystems. Three groundwater-fed loko iʻa kuapā were the focus of this study: Honokea, Hale o Lono and Waiāhole loko iʻa, in Keaukaha, HI. Through time series measurements and the application of mass balance equations, groundwater flow over a 12-month period was found to significantly vary at monthly time scales. Daily and 3-day sum rainfall amounts and groundwater flow were positively correlated. Sampling of three loko iʻa springs and 12 additional shoreline springs characterized major ion chemistry and nutrient concentrations. The highest NO_2 + NO_3 concentrations were at Waiāhole and the highest PO_4 concentrations were at Honokea. Based on $\delta^{18}O$, the mean rainfall recharge elevation that contributed to regional recharge of aquifers discharging into loko iʻa and shoreline springs ranged between 400 and 900 m, with the elevation of source water increasing at springs farther east. Predicted increases in rainfall between 20-40% could increase groundwater flow equivalent to that observed after >75 mm of rain over a 48 hr period. Future sea level rise, 0.4 m by the year 2040, could result in the daily high tide salinity increasing from 3-8 to >16. This study provides baseline information and predictions for managers restoring these unique environments to prepare for future changes in loko iʻa hydrology. Furthermore, the methods used here can be applied to larger groundwater dependent ecosystems throughout Hawaiʻi.

Preface

Aia i hea ka wai a Kāne? Where is the freshwater of Kāne? Kāne is an akua, god, in the Hawaiian belief system. A kinolau, physical embodiment, of Kāne is wai meaning freshwater, the source, sustenance and continuation of life. Wai is everywhere as described in an oli, Hawaiian chant, called Ka Wai a Kāne. Wai exists from the rising to the setting sun. Wai is released from the clouds as rain. Wai falls on the land in the uplands and traverses through the rivers and streams. Wai trickles down through the cracks in the earth recharging groundwater aquifers. Wai travels within the earth until it surfaces as springs. Wai is evaporated by the sun and held in the clouds until it is released again as rain. Kūpuna of Hawaiʻi, ancestors, understood this cycle of wai and respected the balance that wai provided for all.

Relationships between kūpuna and the landscape of Hawaiʻi were intimate and built through keen observations and interactions within a specific place. Hānau ka ʻāina[1], hānau ke aliʻi, hānau ke kanaka. Born was the land, born were the chiefs and born were the people (ʻŌlelo Noʻeau #466). This was the order of life and therefore the order in which it was respected.

The history of Hawaiʻi tells a tale of how the relationships between wai and kanaka had changed. In the late 1700's, the arrival of western societies (Kamakau 1961) shifted what was once a reciprocal relationship to wai into a relationship of possession for profit. The bartering system which once sustained Hawaiʻi shifted resources like wai into commodities to be owned and sold at a price. During this time other resources in Hawaiʻi were heavily affected, among them were loko iʻa, Hawaiian fishponds.

[1] ʻĀina: land, earth, that which feeds us.

Hawai‘i once consisted of over 400 loko i‘a providing an estimated 950 – 1,150 tons of fish per year (Costa-Pierce 1987; Kikuchi 1976). Loko i‘a spread throughout the coastlines (Stokes 1908; Summers 1964), were once a source of food security and protein that sustained the islands (Clifford 1991; Kittinger et al. 2011). Through Hawai‘i’s history the care for these places declined and the practice of loko i‘a was nearly lost.

Today (2017) in Hawai‘i there are 50+ loko i‘a in the process of restoration. It was once said that the health of a loko i‘a was a reflection upon the health of a community. With help from many, including kia‘i loko i‘a, fishpond caretakers or guardians, scientists, non-profit organizations, government and non-government agencies, students and local communities, the practice of loko i‘a in Hawai‘i is being revived.

Introduction

Groundwater provides essential nutrients to coastal ecosystems (Paytan et al. 2006; Wabnitz et al. 2010). However, groundwater flow is difficult to study due to complex interactions with hydrogeologic, oceanographic and climatologic processes (Fetter 2001). Near the coast, the flow of groundwater is influenced by the hydraulic gradient between the water table and sea level at a given tide (Abarca et al. 2013; Swarszenski et al. 2016). During high tides the level of the ocean is higher than the level of the water table within a coastal aquifer, and sea water flows inland. During low tides the level of the water table within a coastal aquifer is higher than the level of the ocean, therefore water from the coastal aquifer flows seaward (Colbert et al. 2008).

Groundwater in Hawaiʻi is particularly important in the function and success of loko iʻa, unique brackish water ecosystems that are dependent upon the mixing between fresh groundwater via coastal springs and water from the ocean. Loko iʻa are constructed by enclosing these brackish water habitats with permeable rock walls separating them from the adjacent marine environment (Costa-Pierce 1987). The overall function and success of loko iʻa relies upon deep understandings of place with emphasis on moon phases, tides, water movement within the ponds and the location of groundwater springs.

Groundwater flow is influenced by weather processes, including rain events and storms. Rainfall recharges aquifers that discharge at shoreline springs. Storm events and droughts can increase and decrease flow, respectively. The amount of precipitation during storm events is directly propotional to the magnitude of groundwater springs (Cable et al. 1997). Groundwater recharge is increased by extreme rain events (Owor et al. 2009).

While groundwater flow is complex, the impacts of climate change could further complicate these processes as we know them today through changes in sea level and rainfall. It is predicted that sea level could rise by 0.68 m in the year 2100 (IPCC 2014), which as result can increase salt water intrusion (Werner and Simmons 2009). Furthermore, rainfall patterns are predicted to shift fairly dramatically ultimately impacting groundwater recharge and resulting discharge along the shore.

Groundwater is a primary resource for freshwater in the Hawaiian Islands (Gingerich & Oki 2000). Average annual rainfall for Hawai‘i Island ranges between 240 and 10,271 mm (Giambelluca et al. 2013). Rainfall accounts for 100% of the groundwater recharge, where 49% of the rainfall flows into the aquifer (Engott 2011). The remainder is primarily lost to rivers and evapotranspiration. Scenarios of future climate conditions show droughts decreasing groundwater recharge across Hawai’i Island (Engott 2011). Along the coastlines of the Hawaiian Islands are countless groundwater springs (Fischer et al. 1966). These groundwater springs originate from unconfined aquifers (Mink & Lau 1993).

The movement of water underground is largely controlled by the geology of the land. Basalt, an igneous rock which makes up a large portion of the Hawaiian Islands, is among the most permeable on earth. The cooling that occurs as these rocks are created generate cracks at the surface. These surface cracks act as voids with which water is able to fill and move through. Relatively young lava flows, the most recent occurring on Hawai‘i Island today (2017), are especially important to the hydrogeology of the land as the hydraulic conductivity is greatest at the surface or near-surface layers (Peterson 1972) of these once active flows.

Few studies have documented the variability of freshwater inputs to groundwater dependent ecosystems in Hawai‘i. A better understanding of the groundwater resources that support loko iʻa in Hawaiʻi needs to be established. The objectives of this study are to (1) understand the changes in relative groundwater flow through time, (2) determine differences in groundwater composition among shoreline and loko iʻa springs and (3) recognize how climate change could impact these groundwater dependent ecosystems.

Methods

Site Description

The focus of this study was three loko iʻa located along the Keaukaha coastline in the Hilo Bay watershed on the windward side of Hawaiʻi Island, HI (Fig 1). Annual rainfall for Hilo can reach up to 4,000 mm and up to 6,000 mm at higher elevations (Giambelluca et al. 2013). The geologic makeup of the island is highly permeable basalt, which has a hydraulic conductivity of up to 336 m/d (Rotzoll and El-Kadi 2008). Groundwater recharge for Hawaiʻi Island is estimated at ~25,000 million liters per day (Engott 2011), resulting in large amounts of freshwater discharging along the coast as springs (Lau and Mink 2006).

The loko iʻa within this study are three loko iʻa kuapā (further referred to here as loko iʻa), bodies of sea water enclosed by permeable rock walls (see further details on loko iʻa kuapā in Keala et al. 2007; Costa-Pierce 1987; Kikuchi 1976). There are two additional hydrological components to loko iʻa in Keaukaha: the mākāhā and groundwater springs. Mākāhā, sluice gates, are the primary connection to the sea. They provide additional movement of salt water in and out of the loko iʻa by way of shifting tides. Pūnāwai, fresh groundwater springs, provide essential nutrients for the growth of algae, phytoplankton and other aquatic organisms (Payton et al. 2006; Hwang et al. 2005). Pūnāwai are also important in regulating salinity and temperature, which are key variables in loko iʻa productivity.

Three loko iʻa in the process of restoration were the focus of this study: Honokea (Fig 2), Hale o Lono and Waiāhole (Fig 3) (further referred to here by their respective names). These loko iʻa are located within a 2.4 km stretch of one another and serve as a source of cultural identity, food for local communities and educational centers for schools across Hawaiʻi (Table 1).

In order to gain a regional representation of the groundwater springs along the Keaukaha shoreline, 12 springs were also sampled (Fig 4). These springs were chosen to be distributed along the shoreline, based on their importance to a particular loko iʻa, and having a relatively large groundwater flow. Groundwater springs along the shoreline stretched over a distance of about 5 km.

Freshwater Distribution Surveys

To determine locations of groundwater flow and groundwater spring chemistry measurements, temperature and salinity surveys were completed throughout each loko iʻa within about two hours of the lower low tide of each samping day. Perimeter surveys were conducted by walking along the boundaries of the loko iʻa and taking measurements every 2 m as well as at locations that consisted of obvious groundwater springs using a handheld multiparameter sensor (YSI Pro 2030). Groundwater springs were identified by bubbling of water at the surface and movement of limu, algae, within the area. Each point of measurement within the perimeter surveys was mapped using Google Earth Pro 7.3.1 software. Measurements of temperature, salinity and location througout the loko iʻa were collected using a kayak at every 2-3 m and YSI Castaway. These measurements along with suggestions by the kiaʻi determined groundwater flow and groundwater chemistry sampling locations.

Relative Groundwater Flow Data Collection

Relative groundwater flow within this study is defined as an index describing variations over time accounting for both flows of groundwater into the loko iʻa and reverse flows from loko iʻa to groundwater. To calculate the relative groundwater flow into loko iʻa, the depth of water within the loko iʻa had to be calculated based on the measurements of conductivity, temperature and pressure, which were collected using Odyssey Conductivity and Temperature (Z412), Onset HOBO Conductivity (U24-02), Onset Water Level (U20L-01) and SBE 37SMP loggers. Logger sets consisted of one conductivity and one water level logger, which were attached to cement bricks that were submerged for up to 365 days. Loggers at Honokea and Waiāhole were deployed from December 16, 2016 to December 14, 2017. Loggers at Hale o Lono were deployed from December 16, 2016 to November 20, 2017. Loggers recorded data every six minutes requiring logger data downloads and redeployments every 30-45 days. YSI Castaway measurements were used for logger calibration after each brick deployment and before each brick recovery.

Each loko iʻa contained 2-3 logger sets. One logger set was located near the largest groundwater spring, which in each loko iʻa was the most inland point from the marine environment, while a second logger set was located near the mākāhā. Hale o Lono contained three logger sets due to having a channel connecting the largest groundwater spring location to the mākāhā. Also due to Hale o Lono consisting of four ocean connecting mākāhā, the location nearest the mākāhā with the most movement of sea water at shifting tides was used.

Calculating Relative Depth

Water depth at each station was calculated based on the practical salinity and water pressure data. Practical salinity was calculated using conductivity, temperature and absolute pressure data using the PSS-78 algorithm (UNESCO 1981). Water pressure was calculated by subtracting absolute pressure measured with the logger from atmospheric pressure obtained from the NOAA Hilo Bay Tide Gauge (https://tidesandcurrents.noaa.gov, Station ID – 1617760). Water density was then calculated from practical salinity, temperature and water pressure. Finally, water depth was calculated using the water density and water pressure, assuming no stratification, which is here and after referred to as water level.

Adjusting to Mean Lower Low Water Datum

To compare water levels between loko iʻa and the ocean, the loko iʻa water level data were adjusted to the mean lower low water datum (MLLW) at the NOAA Hilo Bay Tide Gauge (https://tidesandcurrents.noaa.gov, Station ID – 1617760), here and after referred to as h_B. To do this, the water level in the loko iʻa was subtracted from the water level at the tide gauge at high tide. For the six highest tides for each deployment, the differences in depth in the loko iʻa and the tidal height was calculated and averaged to obtain a single datum difference value. The deployment datum difference was then subtracted from the loko iʻa water level measurements, which is here and after referred to as relative depth, h_A. This assumes that there is no flow of water in or out of the loko iʻa at the time of a higher high tide. Salinity was used to further support this assumption; an immediate decrease in salinity was observed after a high tide, indicative of a change from an inward to an outward flow of water.

Calculating Relative Groundwater Flow

Due to the entering and exiting of both seawater and groundwater in the loko iʻa, a mass balance equation was applied (Eq. 1).

$$\text{Eq 1.} \qquad \frac{\Delta\ \text{Storage}}{\Delta\ \text{Time}} = (Q_{SI} + Q_{GI}) - (Q_{LO} + Q_{LG})$$

where, Q_{SI} is flow of seawater into the loko iʻa, Q_{GI} is flow of groundwater into the loko iʻa, Q_{LO} is flow of water from the loko iʻa to the ocean and Q_{LG} is flow of water from the loko iʻa back in to the groundwater (Fig 5). Equation 1 was applied over the course of a tidal day (defined below); each term on the right has units of volume and represents the sum or integral over the entire tidal day. Tidal days were selected so that the change in storage (between the beginning and end of the day) was zero, in which case the net groundwater inflow (Q_{GI} - Q_{LG}) equaled the net outflow of water to the sea (-Q_{SI} + Q_{LO}). It was assumed that at any given moment the exchange of water between the loko iʻa and the ocean was proportional to the water level difference between the loko iʻa and the ocean (h_A - h_B)[2], based on Darcy's Law. This assumes that the hydraulic conductivity cross-sectional area of flow and flow path between the sampling station and outside the loko iʻa remain constant. Net groundwater flow over the tidal day is therefore proportional to the averaged six-minute water level differences:

$$\text{Eq 2.} \quad Q_{GI} - Q_{LG} = -Q_{SI} + Q_{LO} \propto \frac{1}{n} \sum (h_A - h_B)$$

where n is the number of six-minute time steps in a tidal day. The right-most term in Equation 2 (average water level difference) is here and after referred to as relative groundwater flow. The term "relative" refers to the fact that this is a proportional index rather than an actual flow rate. In order to obtain data that best represented the movement of water in and out of the loko iʻa, relative groundwater flow was calculated from loggers located near the largest groundwater spring.

[2] Between the ocean and the loko iʻa, water can move through the mākāhā, the porous rock wall and porous rock bottom.

Calculating Tidal Day and Daily Relative Groundwater Flow

Use of the tidal day was necessary to apply the mass balance equation, but for further analysis flow during a 24-hour calendar day was needed. The beginning and end of the tidal day was referenced to the median of h_A. Values above the median were classified as high tides and values below were classified low tides. At least two high and two low tides of relative groundwater flow values were taken until >23.5 hours were reached to obtain the period of a tidal day. Then, the relative flow values calculated for each 6-minute period were averaged for each tidal day. Finally, to calculate the average flow for each calendar day, the weighted mean of the relative groundwater flow on the two concurrent tidal days was calculated. Tidal days where there were not at least one high and one low tide were removed. For analysis of groundwater flow, samples where waves were greater than 2.8 m were also removed, since waves may be overtopping the wall, violating the assumptions that the water depth outside the loko iʻa was the same as sea level.

Chemical Analysis of Water Samples

Water samples were collected to determine the chemistry of groundwater springs in each loko iʻa. Samples were taken at the surface of the water nearest the largest groundwater spring. Loko iʻa samples were collected twice a month for a total duration of nine months between March and December 2017. Water samples collected at shoreline springs were taken directly from the spring source and were collected a total of four times between June and August 2017.

Major ion and nutrient samples were collected using 2-50 ml plastic amber HDPE bottles at each station. Nutrient samples were filtered using pre-combusted (500°C for 6 hours) GF/F filters (pore size = 0.7 µm) (Whatman). Water samples were frozen until further analysis at the University of Hawaii at Hilo Analytical Laboratory. Major ions were analyzed using an ICP-

OES Spectrometer (Varian Vista MPX) (Na^{+1}, Mg^{2+}, Ca^{2+} and K^{+1}, with a detection limit (DL) of 1.00mg/L). Cl^{-1}, SO_4^{2} and nutrients were analyzed using a Lachat Quikchem 8500 Series II (NO_2^-+NO_3^- [DL 0.07 µmol/L, EPA 353.2], PO_4^{3-} [DL 0.03 µmol/L, EPA 365.5], H_4SiO_4 [DL 1.00 µmol/L, EPA 366] and NH_4^+ [DL 0.36 µmol/L, EPA 349]). Alkalinity samples were collected using a 150ml Leuer lock syringe and gas-tight Tedlar® bags. Samples were stored at 4°C until processed by a modified gran titration method (Hansson and Jagner 1973) using a Thermo Orion Sage Dispensing System with a Ross Ultra pH electrode.

Stable isotopes (δ^2H and δ^{18}O) of water samples were collected at loko iʻa and coastline spring locations four times between June and August 2017. Samples were collected using 60 ml BOD bottles and sealed with silicone vacuum grease to prevent atmospheric exchange. Isotope samples were stored in the dark at 23°C until further analysis at the University of Hawaii at Hilo Analytical Laboratory. Isotopes were analyzed using a Thermo Scientific Gasbench II coupled to a Thermo Delta V Advantage continuous flow isotope ratio mass spectrometer (δ^2H vs VSMOV = -10.3, USGS 45 and δ^2H vs VSMOV = -235.8, USGS 46) and oxygen isotope data was normalized to (δ^{18}O vs VSMOV = -2.238, USGS 45 and δ^{18}O vs VSMOV = -29.8, USGS 46). Mean recharge elevation was calculated using the linear relationship from Scholl et al. (1996) for trade wind areas in Hawaiʻi. Due to the samples being a mixture of recharged rain and seawater, adjusted values representing only recharged rain was calculated using end members of 0.44 δ^{18}O, 2.4 δ^2H and a salinity of 35 (Schmidt et al. 1999).

Sea Level Rise Scenarios

Sea level rise scenarios were chosen according to NOAA (2017). Calculations were conducted using salinity data calculated from the loggers. At each station, a 2-D histogram was computed to calculate the number of days that the daily maximum salinity fell within a range (bin size = 2) of daily maximum tidal heights (bin size = 0.1 m). The number of days with a specific tidal height remained the same, but with an increase in sea level. For example, the number of days with a 0.9 m maximum tidal height was the same as the number of days with a 1.1 m after 0.2 m of sea level rise. Then, for a given tidal height, the frequency of daily maximum salinity was used to calculate the new distribution of maximum salinity.

Statistical Analyses

To determine differences in relative groundwater flow among months, Kruskal-Wallis tests were used. Data were tested for normality and equal variances, however assumptions for parametric analyses were not met. Correlations were used to evaluate associations between relative groundwater flow and rain at different time scales; daily, the sum of 3-day rainfall periods, two consecutive days of rain (sum >75 mm) and seven consecutive days of nearly no rain (sum <0.5 mm). Parametric t-tests were used to further evaluate differences between rain (sum >75 mm) and nearly no rain (sum <0.5 mm) events. Correlations were also used to evaluate relationships between relative groundwater flow and rainfall recharge at high and low elevation. Rain data used within these analyses were averaged daily values taken from Global Historical Climatology Network (GHCN) stations: Hilo International Airport 87, Hilo 0.4 SW, Hilo 5 S and Kurtistown 6.6 SSE (https://www.ncdc.noaa.gov/cdo-web/), except when evaluating relative groundwater flow in response to high and low rainfall recharge elevations, the Kurtistown 6.6 SSE and Hilo International Airport 87 stations were used, respectively.

To determine differences in groundwater chemistry among all spring locations, one-way analyses of variance (ANOVA) and Kruskal-Wallis tests were used. Linear regressions were used to determine relationships between Cl^{1-} and nutrients (NO_2^{-}+NO_3^{-}, PO_4^{3-}, H_4SiO_4, and NH_4^{+}) within loko iʻa springs. An ANOVA and Kruskal-Wallis tests were used to determine differences in calculated rainfall recharge elevations among all spring locations. A non-parametric post-hoc test was used to further determine differences. Statistical analyses were conducted using RStudio 1.0.136 (2016) and Minitab Express 1.5.1 (2017) software, and a statistical significance of 0.05 was used.

Results

Temperature

Temperature was characterized at each loko iʻa. The highest mean temperature was observed at Hale o Lono, while the lowest temperature was observed at Waiāhole (Table 2). Temperature of groundwater and brackish water were also characterized during the summer (Jun ʻ17 – Sept ʻ17) and winter (Dec ʻ16 – Mar ʻ17) months. Groundwater was determined as the temperature at the 10th percentile with the lowest salinity, while brackish water was determined as the temperature at the 95th percentile with the highest salinity at each location. At Honokea, the temperature of both groundwater and brackish water decreased only slightly from summer to winter. At Hale o Lono the temperature decreased slightly in groundwater from summer to winter, while a greater change was observed in brackish water. At Waiāhole, in both groundwater and brackish water the temperature increased slightly from summer to winter (Table 3).

Salinity

Salinity among loko iʻa varied. The highest daily average occurred at Hale o Lono (7.09 ± 2.12), while the lowest occurred at Waiāhole (3.79 ± 0.46) with Honokea in between (5.88 ± 2.53) (Table 2). In determining the varying factors that contribute to high salinity within each loko iʻa, percentages due to tides (>0.95m), waves (>2.8m), a combination of the two and other potential factors were calculated. High daily maximum salinity at each location was defined as values above the 75th percentile. Honokea experienced 97 days of high salinity (>11) throughout the sampling period with 36% not accounted for by large waves or tides. Waiāhole experienced 84 days of high salinity (>4.3), with 44% due to tides. Hale o Lono experienced 84 days of high salinity (>11), with 68% due to tides (Table 4).

Relative Groundwater Flow

Due to the nature of the relative groundwater flow index, the magnitude of flow at one loko iʻa cannot be compared to the magnitude of flow at another loko iʻa. It is possible, however, to examine variations over time at each loko iʻa. Monthly variations in relative flow were evaluated by comparing monthly median daily flow values. Statistically significant differences at each loko iʻa were found.

At Honokea, at least one monthly median flow value varied from the median flow of another month ($p<0.001$). January had the greatest flow, while March had the least (Fig 6). Similar results were obtained at Hale o Lono were significant ($p<0.001$), except that the highest flow occurred in February, while the least flow occurred in September (Fig 7). At Waiāhole, median monthly flow values also varied with at least one month differing from at least one other ($p<0.001$). January had the most flow while March had the least (Fig 8). Average relative groundwater flow values throughout the sampling period can be found in Table 2.

Statistical analyses were also conducted to determine differences among anahulu (period of ten days in the Hawaiian moon calendar), daily moon phase, Hoʻoilo (wet) versus Kau (dry) (Kanahele et al. 2009) seasons as well as winter, spring, summer and fall seasons. The time periods for the Hoʻoilo season ranged from January 1 – April 25, 2017 and October 20 – November 30, 2017, while the Kau season ranged from April 26 – October 19, 2017. Winter fell between January 1 – March 19, 2017 and spring ranged from March 20 – June 19, 2017. Summer was between June 20 – September 21, 2017 and fall ranged from September 22 – November 30, 2017. Results of these analyses were not significant across all loko iʻa, therefore was not the focus here.

Relative Groundwater Flow and Rain

Significant positive correlations were found between relative groundwater flow and rainfall (Table 5). Analyses were conducted at different time steps specifically daily ($p<0.001$ for all loko iʻa) and the sum of 3-day rain periods ($p<0.001$ for all loko iʻa) (Fig 9). Rainfall at high- and low- elevations summed over three days were also positively correlated with relative groundwater flow at all loko iʻa ($p<0.001$) (Fig 10 and 11).

Additionally statistical differences between flow during two consecutive days of rain (sum >75 mm) and flow during seven consecutive days of nearly no rain (sum <0.5 mm) were significant at Honokea Hale o Lono and Waiāhole ($p=0.004$, 0.002 and 0.016, respectively) (Table 6).

Groundwater Chemistry

Major ion composition differed among loko iʻa. K^{1+} ($p = 0.03$) and Na^{1+} ($p<0.001$) were highest at Hale o Lono and lowest at Waiāhole. Cl^{1-} and SO_4^{2-} ($p<0.001$ for both parameters) were also highest at Hale o Lono and lowest at Waiāhole. Alkalinity, A_T ($p<0.001$), similar to the other ions, was highest at Hale o Lono, however lowest at Honokea. Ca^{2+} and Mg^{2+} were equal among loko iʻa. Major ion composition of all sampled springs were not significant between stations except for SO_4^{2-} and A_T. SO_4^{2-} ($p = 0.04$) was highest at station 2 and lowest at station 6. A_T ($p<0.001$) was highest at station 1 and lowest at Honokea (Table 7 and 8).

Nutrient concentrations of $NO_2^- + NO_3^-$, PO_4^{3-} and NH_4^+ varied among loko iʻa ($p = 0.01$ for each parameter). $NO_2^- + NO_3^-$ was highest at Waiāhole and lowest at Hale o Lono. PO_4^{3-} was highest at Honokea and lowest at Hale o Lono. NH_4^+ was highest at Hale o Lono and lowest at Honokea. There were no significant differences in H_4SiO_4 concentrations among loko iʻa ($p = 0.61$). Across all groundwater springs along the shoreline, nutrient concentrations were not significantly different ($p>0.10$) (Table 9).

Regressions showed positive relationships between Cl^{1-}, a proxy for salinity, and $NO_2^- + NO_3^-$, PO_4^{3-} and H_4SiO_4 at Hale o Lono and Waiāhole, however no significant relationships were observed at Honokea (Table 10).

$\delta^{18}O$ varied from -1.4 to -3.9, and $\delta^{2}H$ varied from -6.1 to -17.6 (Table 11). After accounting for the influence of seawater on samples, the $\delta^{18}O$ of meteoric water was used to calculate differences in groundwater recharge elevation. The location with the highest median groundwater recharge elevation was Kailiwai (left) (863 m), while the lowest was at Puhi Bay (474 m). Differences in median elevation of rainfall recharge across all spring locations were significant ($p<0.001$). Puhi Bay was significantly less than Hokea and Honokea.

Sea Level Rise

Projected increases in global sea level are 0.2 m in the late 2020's and 0.4 m by 2040 based on the NOAA (2017) "Extreme" scenario. Island subsidence could cause even greater rises in relative sea level (Caccamise et al. 2005; Moore and Fornari 1984). Sea level rise could impact loko iʻa by way of increased salinity. At current sea level (2017), Honokea reaches a salinity between 6-8 on 93 days out of the year (Fig 12). However, if a 0.2 m and 0.4 m increase in sea level occurs, Honokea could reach a salinity between 6-8 and >16 on 91 and 201 days out of the year, respectively. Hale o Lono, at current sea level (2017), reaches a salinity between 6-8 on 104 days per year. However, if a 0.2 m and 0.4 m increase in sea level occurs Hale o Lono could experience a salinity between 12-14 and >16 on 178 and 209 days per year, respectively.

Similar to the other two loko iʻa, Waiāhole could experience increased salinity with rising sea levels. At current sea level (2017), Waiāhole reaches a salinity between 2-4 on 193 days out of the year. However, if a 0.2 m and 0.4 m increase in sea level occurs, salinity between 4-6 and 6-8 could be reached 216 and 250 days out of the year, respectively.

Discussion

Relative Groundwater Flow

Rainfall recharge of groundwater was important to relative groundwater flow at Honokea, Hale o Lono and Waiāhole loko iʻa as the magnitude of flow increased in direct response to rainfall. Observed relative groundwater flow trends in each loko iʻa from January to November 2017 were similar to rainfall trends throughout the Hilo Bay watershed (Fig 13). Reduced flow in July and August relative to rainfall was likely due to changes in evapotranspiration, which increased by 66% during the summer relative to winter (Engott 2011). Furthermore, flow during periods of rain for two consecutive days (sum >75 mm) and flow during periods of nearly no rain for seven consecutive days (sums <0.5 mm) were significant at Honokea, Hale o Lono and Waiāhole. Previous studies have also found similar relationships between groundwater recharge and rain on Hawaiʻi Island (Engott 2011; Izuka et al. 2016).

Positive correlations between relative groundwater flow and daily rain as well as the sum of rain for 3 days were found at each loko iʻa. These results suggests a relatively fast (<1 day) response to rain. While few studies in Hawaiʻi have documented the groundwater flow response to rain, stream flow response to rain was found to have a zero-lag time between rainfall and total stream flow in Mākaha Valley on Oʻahu, HI (Mair and Fares 2010). Similar results were observed at Wailuku River on Hawaiʻi Island, HI (Wiegner et al. 2013).

Mean rainfall recharge elevation along the Keaukaha coastline was found to range within the elevations of maximum precipitation for Hawaiʻi Island (Giambelluca et al. 2013). Local recharge areas consist of shorter flow paths, while regional recharge areas consist of longer flow paths of groundwater (Toth 1963). Regional recharge contributed to Keaukaha coastline springs as rainfall recharge elevations increased with distance towards the east (Fig 14, Table 12) (Fetter 2001). Furthermore, regional recharge consists of larger springs and provides a fairly continuous flow of water (Maxley 1968), which was observed at the spring locations within each loko iʻa. While results here show mean rainfall recharge elevation values ranging from 400-900 m there is a possibility that groundwater contributing to shoreline springs could be from as high as snow melt atop the summits of Mauna Kea and Mauna Loa and mixing with water at lower elevations (Scholl et al. 1996).

Groundwater Chemistry

Groundwater provides essential nutrients for the growth of algae, phytoplankton and other aquatic organisms in loko iʻa, therefore understanding how groundwater chemistry differs among them is important. Major ion concentrations increased with salinity at Hale o Lono, which was to be expected as this loko iʻa is the most exposed to the marine environment. Nutrients within loko iʻa, particularly NO_2^-+ NO_3^- and PO_4^{3-}, could be affected by the flow paths with which the groundwater travels. Differences in concentrations can also either increase or decrease due to limu growth as well as growth of California grass (Urochloa mutica), particularly at Waiāhole.

Nutrient concentrations were relatively high in the springs at each loko iʻa. The Department of Health (DOH) has established reference values for NO_2^- + NO_3^- and PO_4^{3-} in estuaries and nearshore marine environments, respectively, to protect humans and ecosystems

(HDOH 2014). At every spring location sampled, $NO_2^- + NO_3^-$ and PO_4^{3-} concentrations exceeded the reference value by neary two orders of magnitude (Fig 15 and 16). Furthermore, these analyses shed light on the importance of identifying sources of pollution to groundwater feeding springs along this groundwater dependent coastline.

Positive relationships between Cl^{1-} and $NO_2^- + NO_3^-$, PO_4^{3-} and H_4SiO_4 were unusual. Across estuaries and nearshore environments in Hawai'i, negative relationships are typically found (Abaya et al. 2018; Johnson et al. 2008; Johnson & Wiegner 2013). These results suggest that the nutrient and salinity concentration of springs is not fixed in time (Santos et al. 2008), and that the characterization of specific springs may require multiple samples to adequately characterize the mean concentration. Changes in nutrient concentration suggest different pathways of groundwater flow, which may differ whether the source of groundwater is from local or regional flow. Alternatively, recirculated seawater that mixes with fresh groundwater to make the brackish water measured at the springs may contain significant nutrients that differ in time or samples were a mixture of groundwater from various springs that contributed to different nutrient concentrations and salinities.

Salinity

Daily maximum salinity at Hale o Lono and Waiāhole were dominated by tides. This can be explained by the tidal shifts in water levels (Burnett et al. 2006). At high tide inland flow of seawater occurs increasing the salinity at each loko iʻa. At Honokea, waves > 2.8 m were a more important driver of the high salinity days, and 36% was due to other factors (Table 4). This suggests that Honokea was more sensitive to smaller tides and waves than the other two loko iʻa. A potential explanation for this could be the height of the wall that separates the loko iʻa from the marine environment not being high enough, resulting in overtopping of seawater during high tides and large wave conditions.

Climate Change

To identify impacts of climate change on relative groundwater flow, analyses were conducted focusing on rising sea level and changes in rainfall. If sea levels continue to rise over the next decade, salinity could increase in loko iʻa due to the heightened water level of the ocean. For example, greater than 0.95 m were an important indicator of higher daily maximum salinity at Hale o Lono and Waiāhole. As sea levels continue to rise over the next decade, tides greater than 0.95 m will occur more frequently resulting in an increase in frequency of high salinity days. Furthermore, rises in sea level could potentially shift the mixing zones between fresh and salt water within loko iʻa.

A projected rainfall increase for the windward side of Hawaiʻi Island between 20-40% (Zhang et al. 2016), could also increase relative groundwater flow within loko iʻa. This would generate increases in flow similar to after two consecutive days of rain (sum >75 mm), where all three loko iʻa experienced an increase in relative groundwater flow between 25-50%. In other studies an observed decrease in rainfall has occured ~26.5 mm per decade since 1920 (Frazier and Giambelluca 2017). With approximately 5 m/yr of rainfall within the source region of groundwater (400-900 m elevation), this is approximately 0.5% less rainfall per decade. If this trend continues for another century, then we could expect a 5% decrease in groundwater flow, which is much less than the relative groundwater flow decreased between 25-60% at Honokea and Hale o Lono after seven consecutive days of nearly no rain (sum <0.5 mm) (Table 6).

Conclusion

The relative groundwater flow at Honokea, Hale o Lono and Waiāhole responds to rainfall, specifically in the case of Honokea and Hale o Lono. The groundwater along the Keaukaha coastline was fed from a regional source within a rainfall recharge elevation between 400-900 m, with higher elevation recharge supplying springs farther east. Groundwater chemistry within these loko iʻa were dependent on the groundwater flow path. Furthermore, multiple groundwater springs with different chemistry could be a reason why nutrient levels within loko iʻa increased with salinity.

Climate change has the potential to impact these unique brackish water ecosystems through rising sea levels and changes in rainfall. Particularly increased sea level could lead to higher frequencies of high salinity days and increased rainfall could lead to increased groundwater flow. The hypotheses made here are simply catalyst points in which these impacts should be further investigated.

Epilogue

Changes in Hawai‘i’s past reshaped kanaka relationships to wai and land. However, loko i‘a restoration efforts are bringing them back today (2017). Research, with emphasis on community needs and collaboration, has the potential to contribute to the renewed growth of those once intimate relationships. Kūpuna of Hawai‘i understood the cycle of wai in all aspects of life. It is now up to us to perpetuate this lifestyle and protect the balance that wai provides for all. Aia i laila ka wai a Kāne, There is the water of Kāne.

List of Tables

Table 1. Description of three loko i‘a in Keaukaha, HI.

Loko I‘a	Land Owned By	Cared for By	Restoration Since	Surface Area (m^2)	Ocean Connectivity
Honokea	County of Hawai‘i	Hui Hooleimaluo	2011	~ 1,762	Moderate
Hale o Lono	Kamehameha Schools	Edith Kanaka‘ole Foundation	2002	~ 4,772	High
Waiāhole	Kamehameha Schools	Kamehameha Schools	2012	~ 10,279	Low

Table 1 cont.

Loko I‘a	Surrounding Environment	Makeup of Bottom	Accessibility to Public
Honokea	Minimal Vegetation	Fine Sediments	High
Hale o Lono	Mostly invasive vegetation	Combination of rock and fine sediments	Low
Waiāhole	Combination of native and invasive vegetation	Combination of rock and fine sediments	Low

Table 2. Average ± SD and [range] of temperature, salinity, daily relative groundwater flow and depth for the freshest locations within each loko iʻa for December 2016 through December 2017. Relative depth is water level within loko iʻa in relation to water level of the ocean. Samples with waves >2.8 m were removed from these values.

Location	Temp (°C)			Practical Salinity			Relative Groundwater Flow			Depth (m)		
Honokea	19.90	±	0.96	5.88	±	2.53	0.07	±	0.02	0.85	±	0.20
	[18.38	-	24.97]	[2.46	-	18.60]	[0.02	-	0.14]	[0.25	-	1.66]
Hale o Lono	20.68	±	0.95	7.09	±	2.12	0.04	±	0.03	1.02	±	0.21
	[19.59	-	28.21]	[3.30	-	20.45]	[-0.03	-	0.12]	[0.45	-	1.72]
Waiāhole	18.94	±	0.12	3.79	±	0.46	0.12	±	0.02	1.03	±	0.24
	[18.77	-	20.79]	[2.45	-	7.52]	[0.06	-	0.22]	[0.31	-	1.72]

Table 3. Average ± SD of temperature (°C) in groundwater and brackish water. Samples below the 10th percentile represented groundwater and samples above the 95th percentile represented brackish water. Data were taken during the summer (June 2017 through September 2017) and winter (December 2016 through March 2017) seasons. Samples with waves >2.8 m were not removed from this analysis.

Location	Season	Groundwater Salinity	Groundwater (°C)	Brackish Water Salinity	Brackish Water (°C)
Honokea	Summer	3.7	19.6 ± 0.28	8.8	22.1 ± 0.79
	Winter	3.4	18.6 ± 0.13	11.7	21.0 ± 0.54
Hale o Lono	Summer	5.8	20.7 ± 0.43	12.5	25.3 ± 1.45
	Winter	4.3	19.9 ± 0.08	8.2	20.9 ± 0.60
Waiāhole	Summer	3.3	18.8 ± 0.04	5.1	18.9 ± 0.14
	Winter	3.4	19.1 ± 0.03	3.5	19.1 ± 0.01

Table 4. Factors associated with high practical salinity during December 2016 through December 2017. High salinity was defined as values above the 75th percentile within each loko iʻa. Samples with waves >2.8 m were not removed from this analysis.

Location	High salinity	Number of high salinity days	% due to tides >0.95 m	% due to waves >2.8 m	% due to tides >0.95 m and waves >2.8 m	% Other
Honokea	11	97	22	30	12	36
Hale o Lono	11	84	68	10	14	8
Waiāhole	4	84	44	7	4	45

Table 5. Statistics table for correlations between relative groundwater flow at each loko iʻa and different rainfall scenarios. Rain data used within these analyses were averaged daily values taken from Global Historical Climatology Network (GHCN) stations: Hilo International Airport 87, Hilo 0.4 SW, Hilo 5 S and Kurtistown 6.6 SSE (https://www.ncdc.noaa.gov/cdo-web/), except when evaluating relative groundwater flow in response to high and low rainfall recharge elevations, the Kurtistown 6.6 SSE and Hilo International Airport 87 stations were used, respectively. Asterisk indicates significant correlations (alpha = 0.05).

	Location					
Rainfall Scenario	Honokea		Hale o Lono		Waiāhole	
	r	p	r	p	r	p
Daily	0.253	<0.001*	0.225	<0.001*	0.317	<0.001*
3-Day Sum	0.315	<0.001*	0.258	<0.001*	0.335	<0.001*
3-Day Sum HI Elev	0.268	<0.001*	0.210	<0.001*	0.269	<0.001*
3-Day Sum LW Elev	0.255	<0.001*	0.229	<0.001*	0.319	<0.001*

Table 6. Average ± SD of relative groundwater flow under varying rain conditions during December 2016 through November 2017. Samples with waves > 2.8m were removed from this analysis. (n = sample size for each scenario)

Location	n	Mean Flow	After nearly no rain for 7 consecutive days (sum <0.5 mm)	After rain for 2 consecutive days (sum >75 mm)
Honokea	308, 2, 11	0.07 ± 0.02	0.03 ± 0.01	0.09 ± 0.03
Hale o Lono	308, 2, 11	0.04 ± 0.03	0.03 ± 0.01	0.06 ± 0.02
Waiāhole	308, 2, 11	0.12 ± 0.02	0.12 ± 0.00	0.15 ± 0.03

Table 7. Average ± SD of Ca^{2+}, K^{+}, Mg^{2+} and Na^{+} concentrations (mg/L) collected from Keaukaha, HI between June and July 2017. Sample size = 3 for all stations.

Location	Ca^{2+}			K^{+}			Mg^{2+}			Na^{+}		
1	117.2	±	27.2	124.1	±	30.8	217.7	±	42.6	3920.6	±	1594.0
Honokea	59.0	±	21.5	46.7	±	15.9	101.0	±	29.5	1152.3	±	335.3
2	44.0	±	2.4	33.6	±	4.4	85.1	±	22.9	846.5	±	151.0
3	45.8	±	8.9	36.4	±	2.5	86.7	±	10.8	885.0	±	19.9
4	34.4	±	19.2	28.6	±	8.5	70.2	±	22.6	879.0	±	144.8
5	46.9	±	33.8	41.9	±	25.4	92.1	±	52.6	1630.5	±	1184.1
6	36.4	±	12.6	30.5	±	7.6	73.9	±	14.7	731.4	±	140.6
7	61.3	±	25.3	47.4	±	17.1	104.0	±	25.9	1238.6	±	464.0
8	37.4	±	12.5	27.6	±	6.2	74.8	±	24.5	847.9	±	130.8
Hale o Lono	69.5	±	30.0	64.4	±	31.2	133.4	±	64.0	1952.1	±	1245.1
Waiāhole	39.6	±	13.8	29.0	±	10.6	80.5	±	38.3	888.3	±	240.9
9	51.2	±	46.5	39.6	±	29.2	83.8	±	42.9	1148.0	±	506.4
10	68.6	±	24.1	52.1	±	22.9	108.5	±	47.6	1888.7	±	939.4
11	69.2	±	14.1	44.2	±	13.6	101.8	±	26.7	1254.9	±	695.5
12	50.2	±	7.6	36.3	±	2.9	92.9	±	17.6	1013.1	±	106.8

Table 8. Average ± SD of Cl^-, SO_4 and alkalinity concentrations (mg/L) collected from Keaukaha, HI between June and July 2017. Sample size = 3 for all stations.

Location	Cl^-			SO_4			Alkalinity		
1	6961.5	±	429.5	1251.0	±	553.9	2059.7	±	203.9
Honokea	2204.2	±	395.6	256.5	±	64.3	794.3	±	84.6
2	1868.7	±	806.4	249.6	±	74.8	889.2	±	31.8
3	1798.0	±	1317.4	229.4	±	119.1	966.1	±	162.4
4	1773.0	±	1304.8	210.5	±	94.0	840.2	±	11.1
5	2270.0	±	784.3	317.5	±	116.5	875.9	±	41.9
6	1373.8	±	95.5	173.1	±	24.7	893.5	±	19.3
7	2317.4	±	484.4	346.6	±	100.5	1087.2	±	27.8
8	1629.5	±	869.1	230.5	±	80.2	1028.7	±	7.0
Hale o Lono	3244.4	±	1297.7	413.4	±	119.4	1089.4	±	199.4
Waiāhole	1669.8	±	680.7	214.0	±	74.8	955.2	±	38.4
9	1920.6	±	1070.3	299.5	±	82.6	1118.8	±	113.7
10	3478.1	±	333.4	456.5	±	146.9	1219.3	±	140.8
11	2011.5	±	193.3	269.5	±	68.8	1462.6	±	118.0
12	2159.0	±	818.8	347.8	±	104.0	1121.5	±	34.8

Table 9. Geometric means ± SD of NO_2^- + NO_3^-, PO_4^{3-}, H_4SiO_4 and NH_4^+ concentrations (µmol/L) collected from Keaukaha, HI between June and July 2017. Sample size = 3 for all stations.

Location	NO_2^- + NO_3^-			PO_4^{3-}			H_4SiO_4			NH_4^+		
1	10.94	±	5.09	0.67	±	0.27	168.58	±	15.57	2.14	±	2.43
Honokea	22.62	±	3.96	1.59	±	0.42	280.60	±	79.89	0.56	±	0.13
2	22.97	±	4.27	1.53	±	0.52	106.26	±	159.46	0.27	±	0.25
3	22.59	±	8.05	1.37	±	0.79	186.35	±	43.73	0.48	±	0.61
4	20.23	±	6.97	1.35	±	0.58	26.64	±	114.84	1.04	±	0.78
5	28.25	±	1.45	1.71	±	0.18	128.51	±	184.52	0.66	±	0.42
6	28.27	±	8.27	1.32	±	0.58	27.85	±	123.21	0.58	±	0.49
7	32.67	±	7.32	1.25	±	0.50	122.20	±	196.09	0.23	±	0.12
8	29.09	±	7.46	1.14	±	0.36	163.68	±	189.39	0.49	±	0.43
Hale o Lono	20.49	±	6.30	0.33	±	0.90	230.69	±	94.65	1.48	±	0.49
Waiāhole	22.15	±	7.03	1.34	±	0.53	207.82	±	185.68	0.66	±	0.76
9	16.28	±	8.51	1.08	±	0.37	213.00	±	97.99	0.44	±	0.51
10	20.57	±	9.50	1.09	±	0.36	299.64	±	92.84	0.66	±	0.64
11	21.91	±	6.48	0.97	±	0.48	350.49	±	78.43	0.92	±	0.36
12	28.97	±	8.37	1.51	±	0.42	265.13	±	27.43	0.62	±	1.12

Table 10. Statistics table for regressions between Cl^-, a proxy for salinity and nutrients at each loko iʻa from March – December 2017. Asterisk indicates signigicance (alpha = 0.05).

	Location					
Nutrients	Honokea		Hale o Lono		Waiāhole	
	R^2	p	R^2	p	R^2	p
NO_2^-+NO_3^-	0.59	0.310	30.01	0.011*	63.39	<0.001*
PO_4^{3-}	0.00	0.507	38.46	0.004*	55.56	<0.001*
H_4SiO_4	0.00	0.408	41.03	0.003*	38.7	0.004*

Table 11. Average ± SD of mean rainfall recharge elevation (m) calculated from $\delta^{18}O$ values, practical salinity, $\delta^{18}O$ and $\delta^{2}H$ of groundwater springs in Keaukaha, HI. Data were collected between June and August 2017. Vertical brackets identify pairs of stations for which there is a significant difference in rainfall recharge elevation. (n = sample size)

Location	n	Elevation (m)			Practical Salinity			$\delta^{18}O$			$\delta^{2}H$		
1	3	743.9	±	135.1	12.6	±	0.7	-3.5	±	0.8	-14.1	±	3.4
Honokea	4	859.0	±	57.9	4.0	±	0.6	-4.3	±	0.1	-17.9	±	1.1
2	4	857.3	±	82.2	3.4	±	1.2	-4.3	±	0.1	-18.3	±	1.0
3	4	834.1	±	165.3	3.3	±	1.9	-4.2	±	0.3	-17.5	±	1.1
4	4	862.7	±	142.2	3.2	±	1.9	-4.3	±	0.2	-17.4	±	1.4
5	4	732.7	±	42.7	4.1	±	1.1	-4.1	±	0.1	-16.2	±	0.4
6	4	645.5	±	60.3	2.5	±	0.1	-3.9	±	0.1	-15.0	±	0.8
7	4	531.4	±	63.8	4.2	±	0.7	-3.7	±	0.1	-14.8	±	1.8
8	4	601.3	±	52.7	3.0	±	1.2	-3.8	±	0.1	-14.1	±	1.2
Hale o Lono	4	557.2	±	152.1	5.9	±	1.8	-3.8	±	0.2	-13.9	±	2.3
Waiāhole	4	557.4	±	70.1	3.0	±	0.9	-3.8	±	0.1	-13.7	±	1.3
9	4	595.8	±	90.7	3.5	±	1.6	-3.8	±	0.1	-13.5	±	1.3
10	3	659.9	±	76.2	6.1	±	0.4	-3.8	±	0.3	-13.5	±	1.9
11	3	483.0	±	42.3	3.5	±	0.1	-3.7	±	0.1	-12.5	±	1.2
12	4	474.1	±	63.5	3.9	±	1.2	-3.6	±	0.1	-13.4	±	1.0

Table 12. Latitude and longitude of groundwater spring locations sampled from December 2016 through December 2017 in Keaukaha, HI.

Station	Latitude (°N)	Longitude (°E)
Puhi Bay	19.73211	-155.04525
Keonekahakaha	19.73760	-155.03754
Kamokuna	19.73757	-155.03602
Waiāhole	19.73308	-155.03336
Hale o Lono	19.73463	-155.03230
Hale o Lono channel	19.73479	-155.03184
Outside Hale o Lono	19.73417	-155.03169
Waiāhole mākāhā	19.73375	-155.03151
Hale o Lono mākāhā	19.73454	-155.03142
Peiwe (front)	19.73312	-155.02812
Peiwe (back)	19.73392	-155.02696
Lalakea	19.73288	-155.02334
Red House	19.73283	-155.01819
Kailiwai (left)	19.73435	-155.01482
Kailiwai (right)	19.73434	-155.01452
Hokea	19.73480	-155.01430
Honokea mākāhā	19.73480	-155.01415
Honokea	19.73466	-155.01377
Puumaile	19.73470	-155.00929

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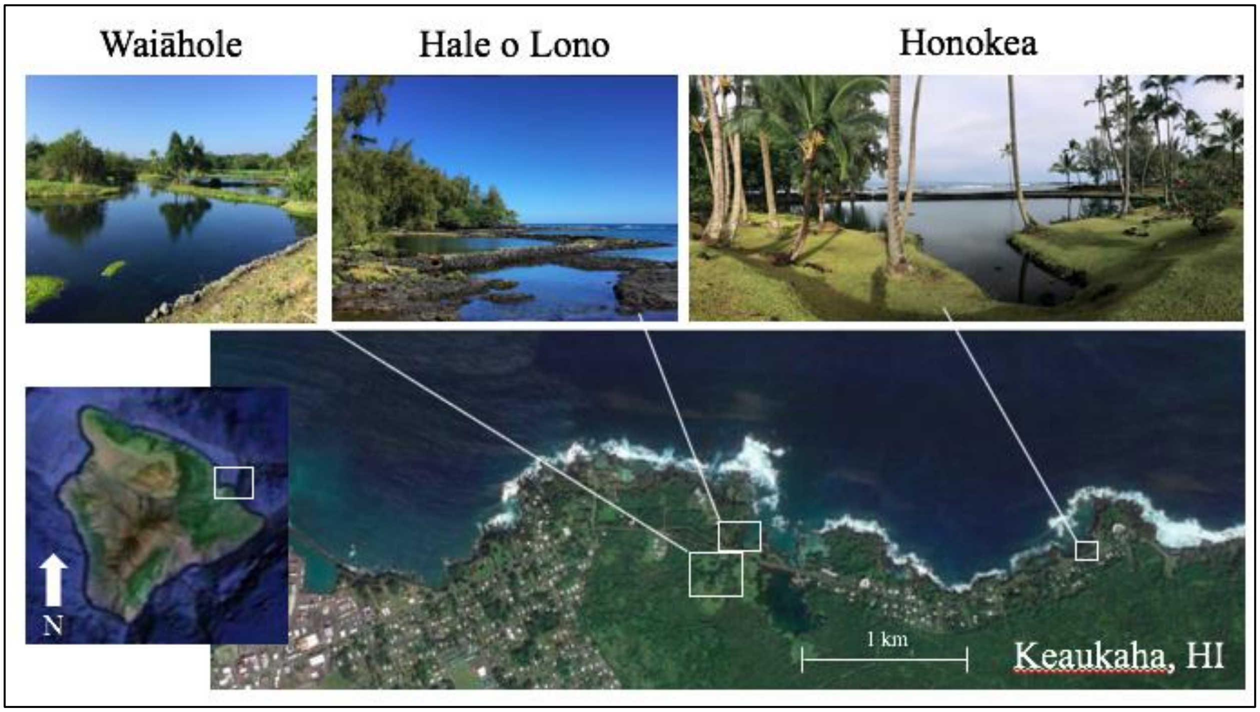

Figure 1. Inset map of study sites in Keaukaha located on the windward side of Hawai'i Island, HI.

Figure 2. Map of Honokea loko i‘a at Waiuli, also known as Richardson’s Beach Park, located on the windward side of Hawai‘i Island, HI.

Figure 3. Map of Hale o Lono and Waiāhole loko iʻa in the ahupuaʻa of Honohononui located on the windward side of Hawaiʻi Island, HI. The mākāhā at Waiāhole is connected to the ocean by a culvert situated under Kalanianaʻole Avenue.

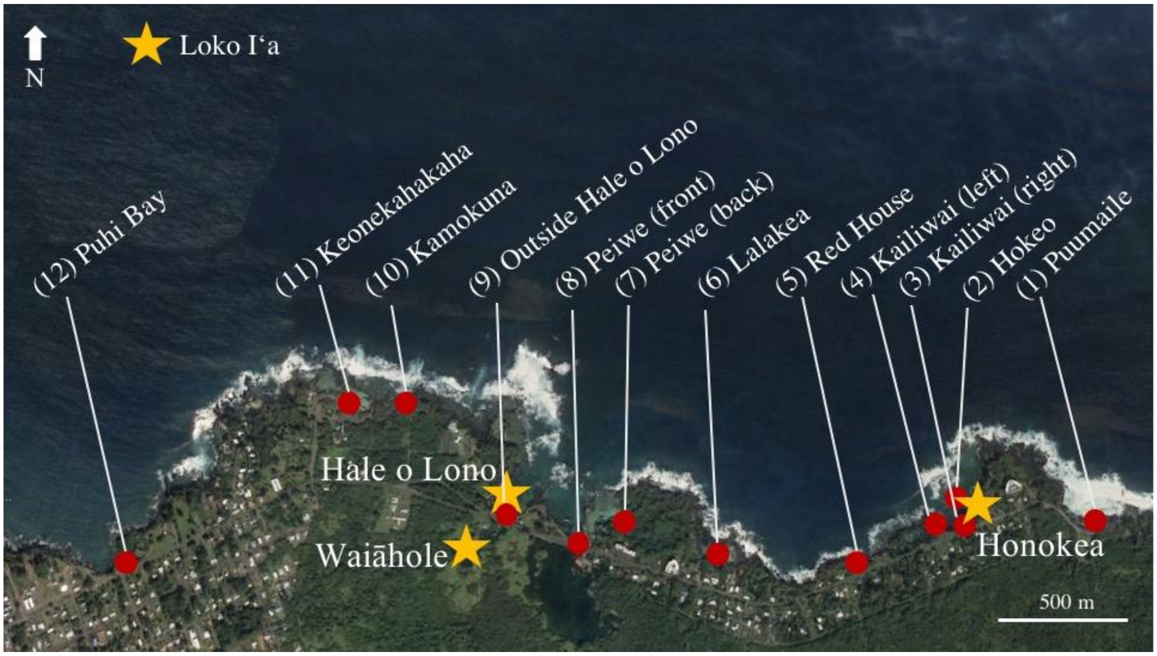

Figure 4. Keaukaha, HI shoreline map highlighting the spring locations along the coast. Stars represent loko i‘a.

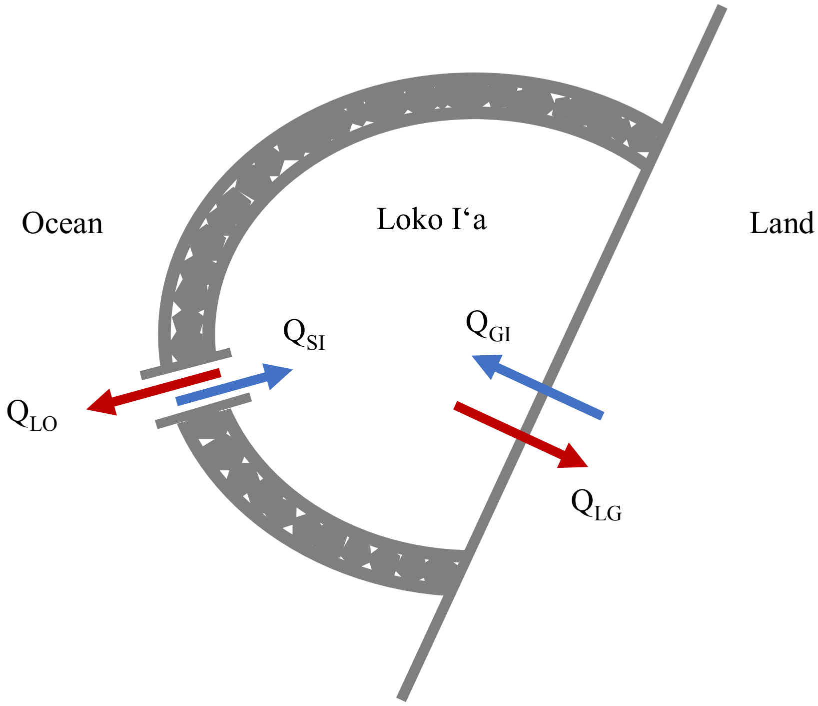

Figure 5. Simplified representation of the mass balance equation applied to loko i‘a where, Q_{SI} is flow of seawater into the loko i‘a, Q_{GI} is flow of groundwater into the loko i‘a, Q_{LO} is flow of water from loko i‘a to the ocean and Q_{LG} is flow of water from loko i‘a into groundwater.

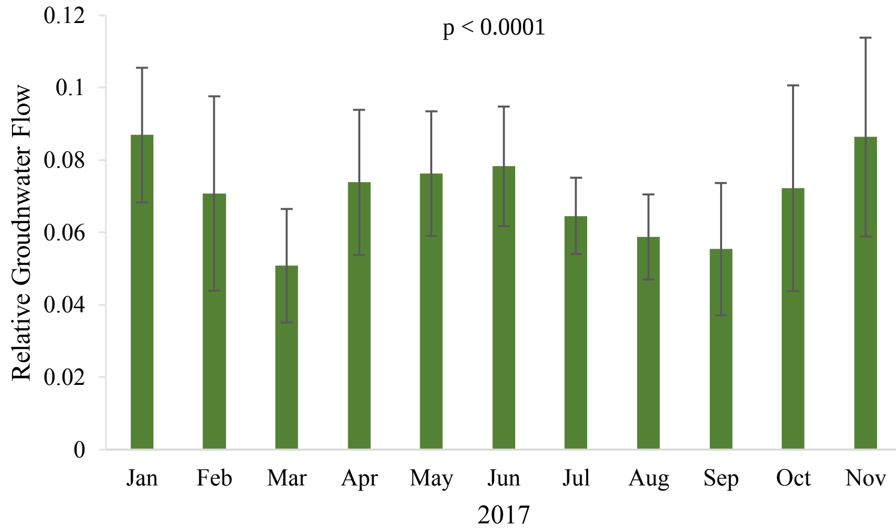

Figure 6. Average ± SD of relative groundwater flow for January – November 2017 at Honokea loko iʻa. Standard deviations calculated from daily values.

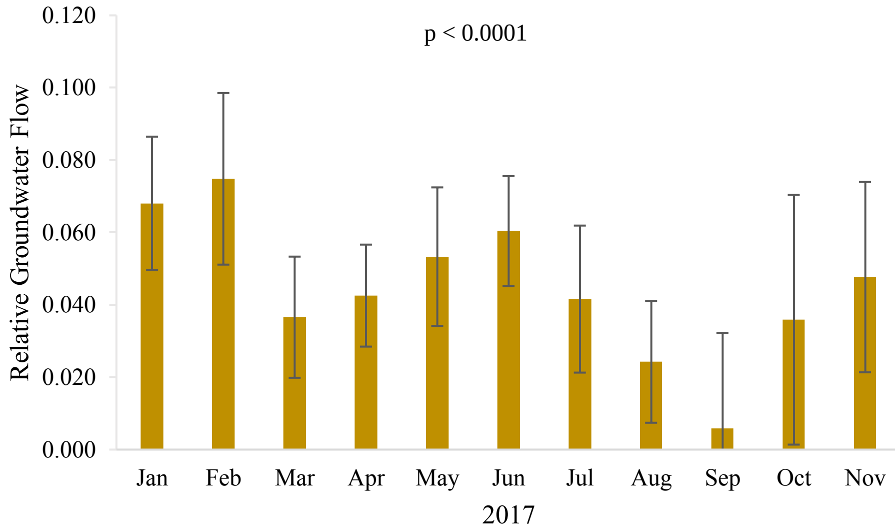

Figure 7. Average ± SD of relative groundwater flow for January – November 2017 at Hale o Lono loko i‘a. Standard deviations calculated from daily values.

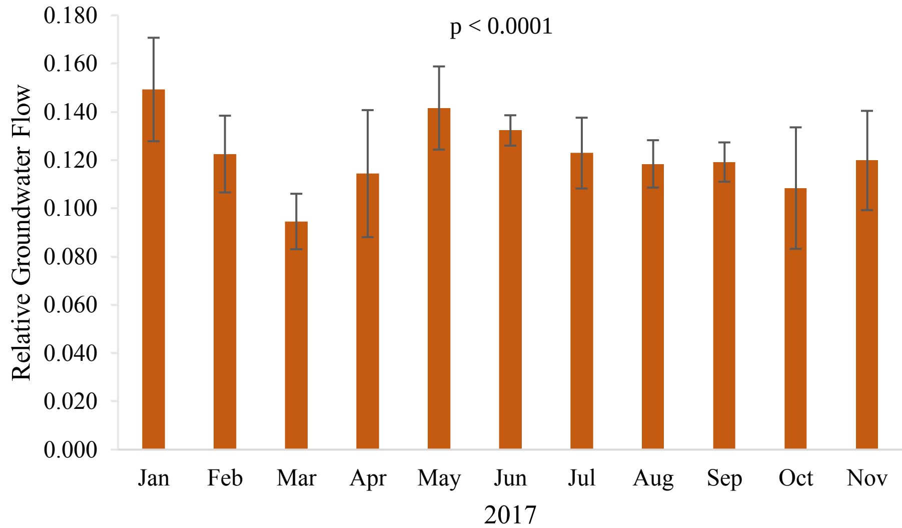

Figure 8. Average ± SD of relative groundwater flow for January – November 2017 at Waiāhole loko iʻa. Standard deviations calculated from daily values.

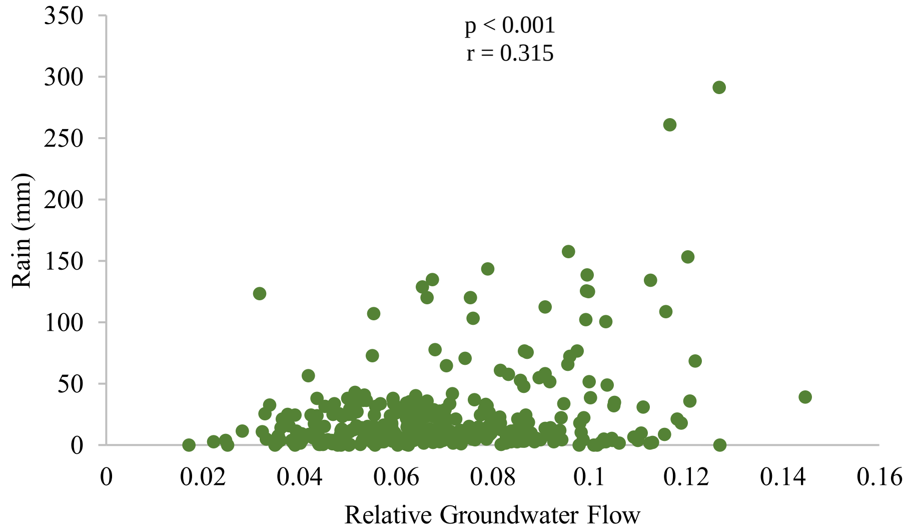

Figure 9. Correlation between 3-day sums of averaged rainfall and relative groundwater flow at Honokea loko iʻa. Rain data was averaged daily values taken from Global Historical Climatology Network (GHCN) stations: Hilo International Airport 87, Hilo 0.4 SW, Hilo 5 S and Kurtistown 6.6 SSE (https://www.ncdc.noaa.gov/cdo-web/).

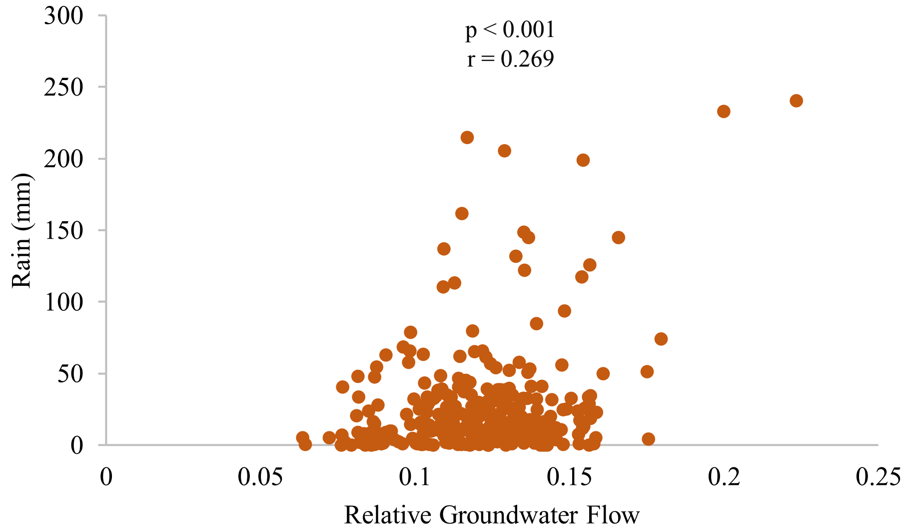

Figure 10. Correlation between 3-day sums of high elevation rainfall (rain data from Kurtistown 6.6 SSE) and relative groundwater flow at Waiāhole loko iʻa.

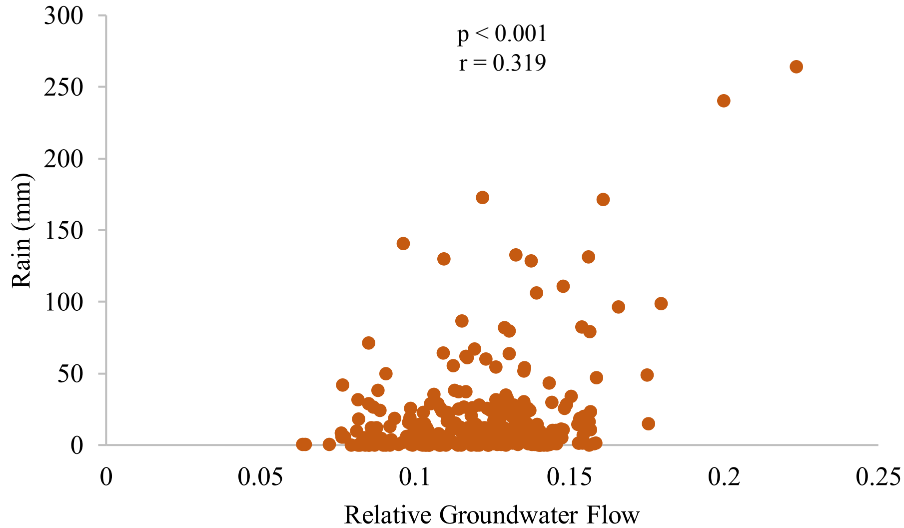

Figure 11. Correlation between 3-day sums of low elevation rainfall (rain data from the Hilo International Airport 87) and relative groundwater flow at Waiāhole loko iʻa.

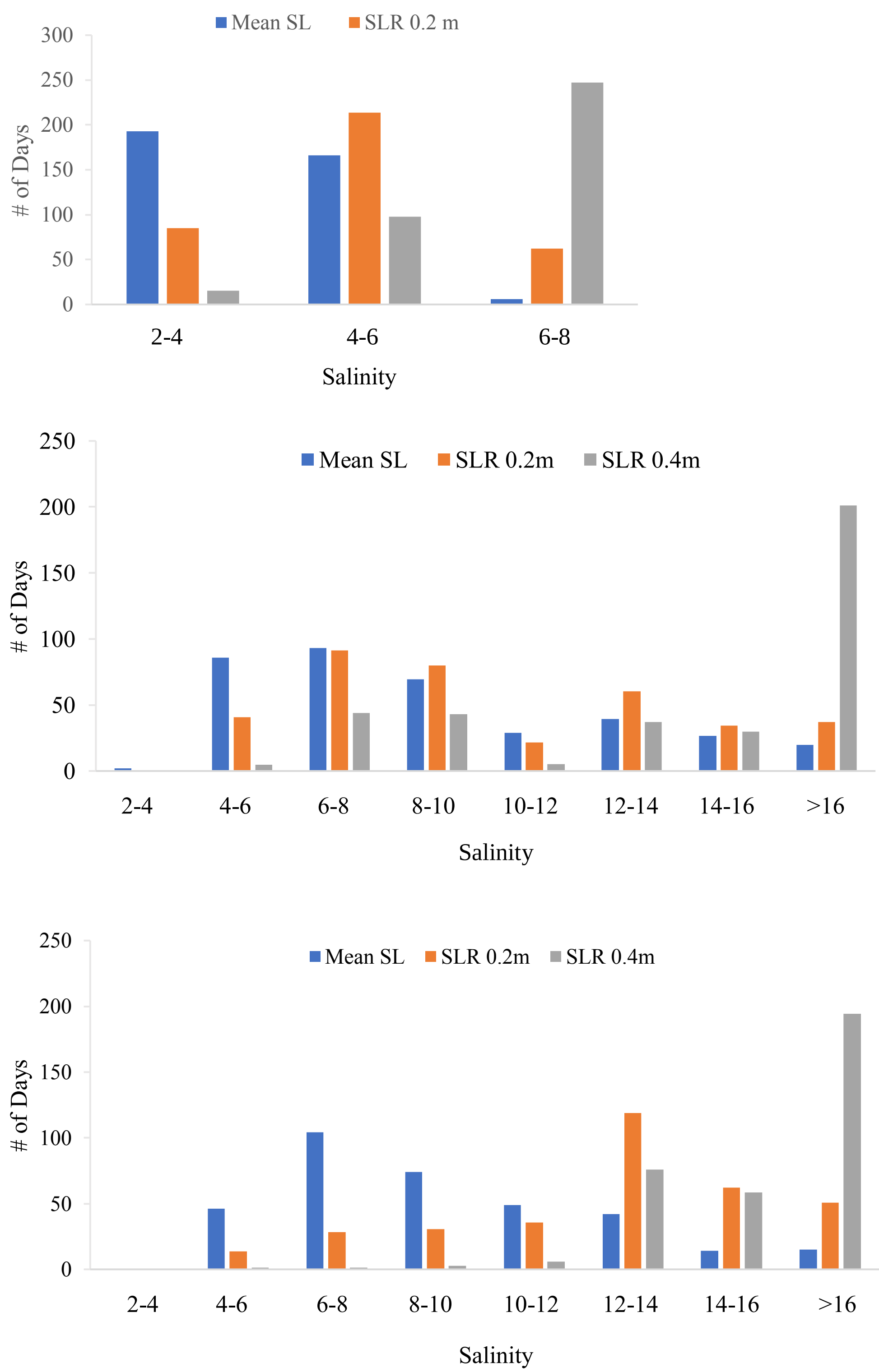

Figure 12. A comparison between mean sea level for 2017 and projected sea level rise scenarios (0.2 m and 0.4 m) on salinity at Waiāhole (top), Honokea (middle) and Hale o Lono (bottom) loko iʻa.

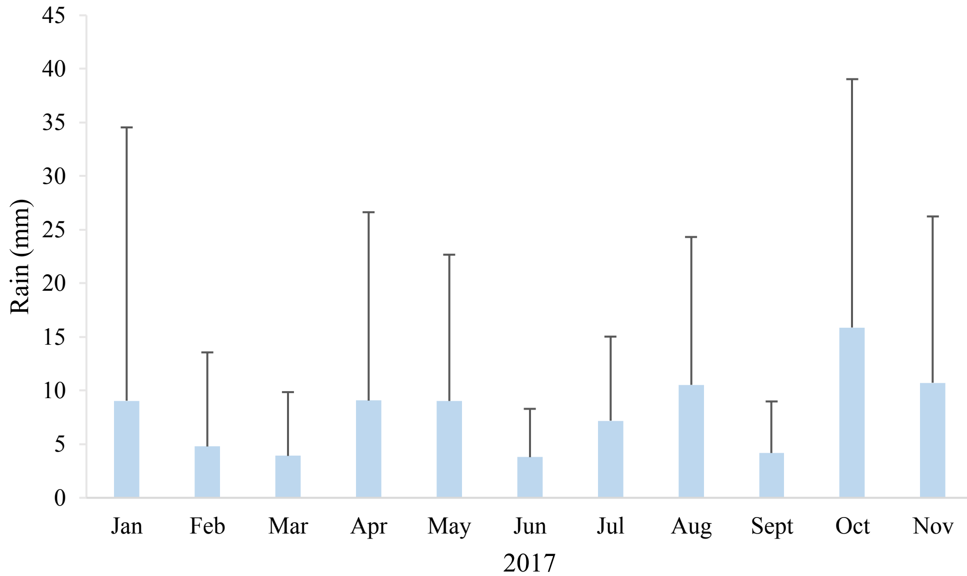

Figure 13. Average ± SD of rain in the Hilo Bay watershed from January to November 2017. Standard deviations calculated from daily values. Rain data used within these analyses were averaged daily values taken from Global Historical Climatology Network (GHCN) stations: Hilo International Airport 87, Hilo 0.4 SW, Hilo 5 S and Kurtistown 6.6 SSE (https://www.ncdc.noaa.gov/cdo-web/).

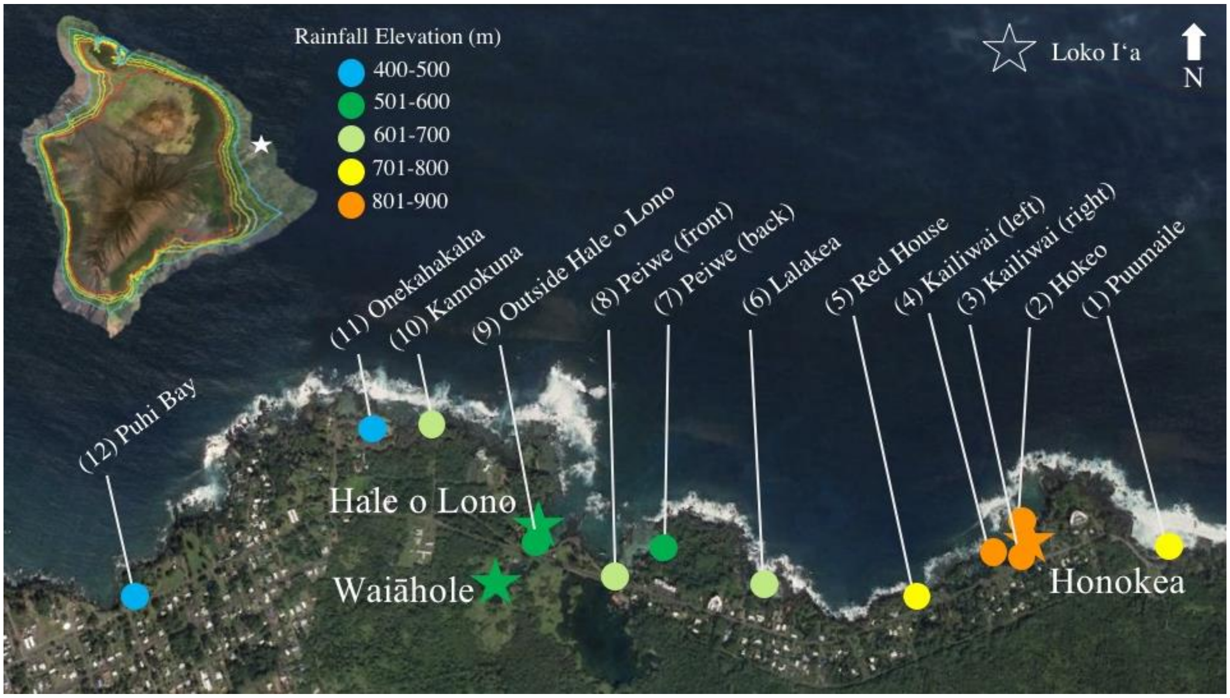

Figure 14. Keaukaha, HI shoreline map highlighting the rainfall recharge elevation of spring locations along the coast. Rainfall recharge elevation was calculated using the relationship from Scholl et al. (1996) for $\delta^{18}O$ in rainfall on trade wind areas of Hawai‘i Island.

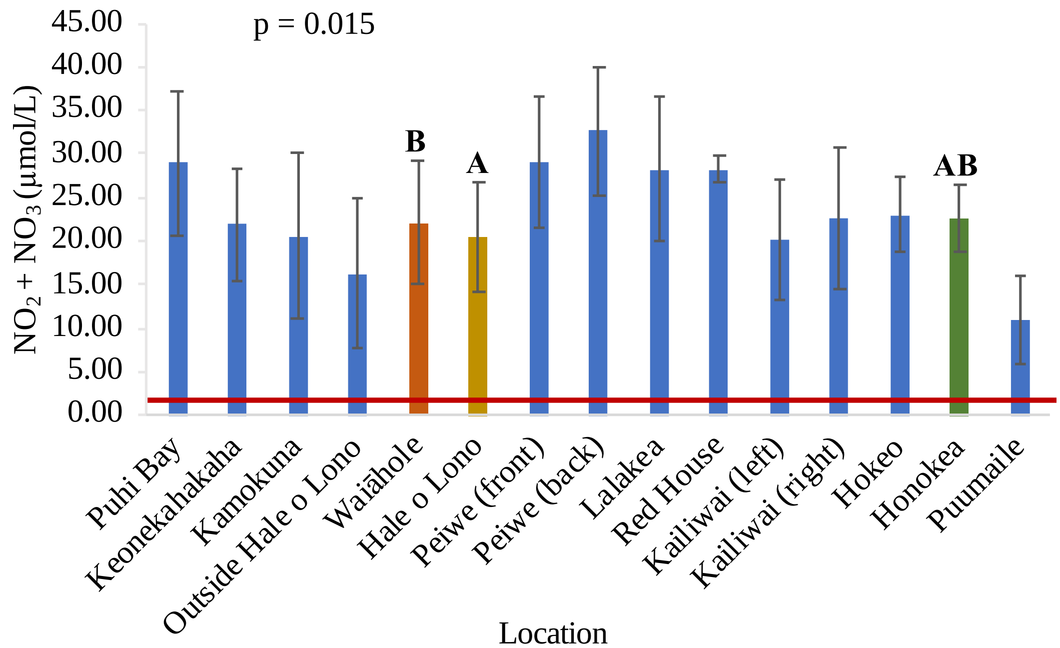

Figure 15. Average ± SD of NO_2^- + NO_3^- at groundwater spring locations sampled in Keaukaha, HI. The red line indicates the Department of Health (DOH) reference value 0.57 µmol/L. The value used here is for estuaries in Hawaiʻi (DOH 2014).

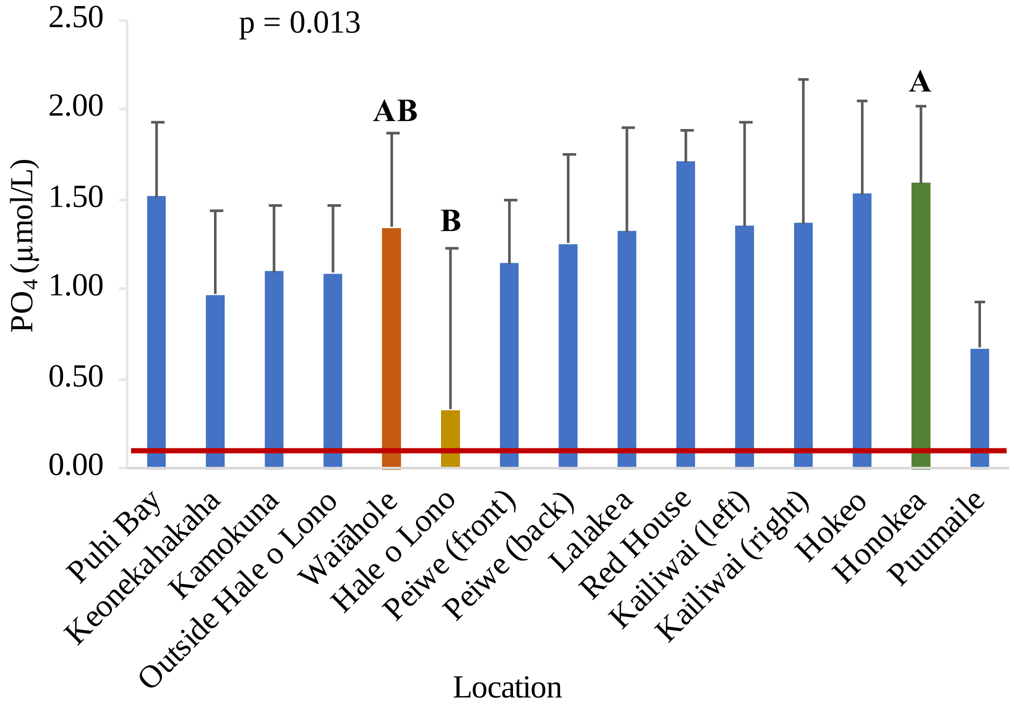

Figure 16. Average ± SD of PO_4^{3-} at groundwater spring locations sampled in Keaukaha, HI. The red line indicates the Department of Health (DOH) reference value 0.16 µmol/L. The value used here is for nearshore marine waters with a salinity >32 ppt (DOH 2014).

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