Below the Surface: Unveiling Submarine Groundwater Discharge at Playa de la Estación

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Abstract:

Submarine groundwater discharge (SGD) is the outflow of an aquifer into the coastal ocean and is affected by oceanic, geologic, and anthropogenic processes. The basal aquifer of Santa Cruz Island, Galápagos, Ecuador has been over-pumped and poorly managed, resulting in saltwater intrusion, a brackish aquifer, and contamination of recreational sites such as Las Ninfas Lagoon. Further exploitation and contamination of the aquifer may harm coastal ecosystems and increase the potential for invasive species to establish and flourish. This study identifies the salinity gradient associated with SGD at Playa de la Estación, one of the few beach accesses on Santa Cruz Island. We consistently found low salinity near the shoreline ranging from 8-18 ppt. Although low salinity output was consistently observed, rainfall varied over the course of the study and was ruled out as a potential cause for the low salinity measured. There appears to be three main points of SGD seepage that also consistently had the lowest dissolved oxygen content averaging at 4.2 (mg/L) while the overall average was approximately 7.8 (mg/L). The island was thought to be waterless and lacking SGD, thus the existence and impacts of this phenomenon have been historically overlooked and underestimated. Uncontaminated SGD is beneficial and a preferred environment for native marine life in other regions of the Pacific Ocean, and anthropogenic alteration and contamination of the aquifer can change an ecosystem drastically. By identifying SGD seepage points, the water quality of the aquifer can be better understood and managed. Due to its scarcity, the groundwater of Santa Cruz must be studied in terms of aquifer health and SGD. Because SGD is seeping into the Galapagos Marine Reserve, further investigation can provide valuable foresight to those responsible for its protection.

Introduction:

The geology and morphology of Santa Cruz Island are largely responsible for the availability of fresh and brackish groundwater. All the Galapagos islands were produced by a hotspot combined with magma from a nearby mid-ocean ridge (Hey et al. 1977). After centuries of isolation, the Galápagos Islands have joined several archipelagos in the intense growth of the tourism industry, coastal economic development, and the need for more water resources (Violette 2008). Throughout the archipelago, five of the main islands are inhabited by humans, but Santa Cruz is the tourism and economic center of the Galápagos island chain, as well as the island of focus in this study. The island was largely formed from alkaline basalt deposited during steady effusive events, characterized by pahoehoe lava flows and leaving behind a smooth shield volcano. Millions of years of rainfall successfully displaced saltwater beneath the island, creating a freshwater lens, which today acts as a low-lying basal aquifer. Currently throughout the archipelago, springs are scarce but have been identified historically on Santa Cruz, located on the flanks of volcanic cones and fed by small perched aquifers (D'Ozouville et. al 2010).

The El Niño Southern Oscillation (ENSO) induces extreme inter-annual climatic variations globally. In the Galápagos archipelago, El Niño events are characterized by increased sea surface temperatures, deepening of the thermocline, and a dramatic increase in rainfall in terrestrial areas (Trueman and d'Ozouville, 2010). La Niña events are associated with colder-than-average sea surface temperatures and drought occurrences in the terrestrial areas (Snell and Rea,1999; Trueman and d'Ozouville, 2010). Subsequently, two seasons are clearly defined: the cool season (also known as garúa which translates to "light misty rain") season, from June to December, and the hot season, from January to May (Trueman and d'Ozouville, 2010). From a hydrological perspective, the onset of the cool season in June defines the beginning of the hydrological year (d'Ozouville, 2007). During the garúa season, the cool air creates an inversion layer and brings a moisture-laden mist approximately 250 m above sea level, however, the lowland areas remain dry. Additionally, the orographic precipitation gradient is well-defined during the cool season when accompanied by wind. This season is also characterized by a high hydrogeological potential on the windward (southern) mountainside, meaning rainfall can infiltrate and recharge the perched or basal aquifers. Porosity is a percentage signifying the ability of water to travel through rocks and is strongly related to how much it allows to permeate or travel down to the water table. Studies have shown estimated ranges of porosity using soil-preserved samples in the laboratory to be 15–25% for the highlands, and 35–40% for the low elevations (Adelinet et al., 2008). Available water for runoff or infiltration, also known as effective rainfall, only occurs above 200 m elevation regularly and its availability increases with elevation (Violette 2008). Fracture analysis of a Digital Elevation Model (DEM) shows that the drainage network is affected by fractures that act as drains to water flow, and also massive lava flows, which may form barriers to surface flow. In the highlands during the garúa season, weak surface runoff is maintained along the low permeable bedrock of the ravines above 450 m, which rapidly infiltrates the pervious fractured basalts when the slope decreases or when the surface flow encounters open vertical fractures (Violette 2008).

The basal aquifer on Santa Cruz Island has been identified visually through grietas (i.e., large, vertical, open fractures that provide access to the water table, and two deep boreholes: Pozo Testigo and Pozo Profundo. The aquifer is brackish as a result of seawater intrusion (Ghyben Herzberg principle) and is subject to anthropogenic contamination from the growing urban areas (Liu and d'Ozouville 2012). Since its use for municipal Puerto Ayora water demand, Pozo Profundo groundwater has experienced increased electric conductivity, suggesting that the basal aquifer is overexploited and that the seawater wedge is slowly migrating inland. In contrast to San Cristóbal, where weathered pyroclastic cover over the summit favors surface flow concentration, the highlands of Santa Cruz favors processes of infiltration through the thin cover of weathered basalt.

Despite several studies assessing water quality, there is limited knowledge of the status of the water resources in the archipelago and even less on freshwater availability (Re et al., 2023). Data is scattered and rarely adequately shared with other institutions both at scientific and institutional levels, as a result of the scarce coordination among different projects. The main consequence is that scientific outcomes are often not effectively used to support improved environmental management strategies, as proven by the poor sanitation supply and water tank disinfection, and lack of coordinated strategies for water quality protection. In addition, groundwater suffers from human-induced contamination due to the lack of adequate sewage and wastewater treatment facilities. In particular, the leaking septic tanks in Puerto Ayora is a well-known phenomenon and has worsened over the years due to population growth and the increase of tourists visiting the island (d'Ozouville et al. 2008b; INGALA et al., 1987). For example Las Ninfas Lagoon, in the city of Puerto Ayora, is a shallow saline lagoon used by the local population as a recreational site, but often affected by domestic wastewater contamination resulting in periodic *Escherichia coli* contamination (Stumpf et al. 2013).

At present the sources of natural water for domestic use are (i) groundwater, withdrawn from Pozo Profundo, located 5 km inland at 160 m above sea level and 160 m deep, tapping the brackish basal aquifer, providing water for Bellavista households, and (ii) water stored in three crevices connected to the municipal network of Puerto Ayora (Grieta colegio San Francisco, Grieta INGALA, and Grieta la Camiseta (Sarango 2010). Illegal and uncontrolled pumping from other crevices also occurs on the island, supplying water for both private and commercial use (Liu 2011). Additionally, rainwater harvesting is a widespread practice, especially in the upper part of the island, where agricultural and farming activities are dominant. For drinking purposes, most of the inhabitants resort to purified water withdrawn from higher elevation springs present on the island and sold in reusable containers (Liu, 2011).

With increasing coastal development and popularity among tourists, development on these islands is inevitable, thus the need to document the initial baseline information and meaningful interpretation of water quality is vital for management purposes (Hunt, 2021; Mohamed et al., 2015). The current water management system was created based on limited technological knowledge (Alcaldia de Santa Cruz 2019). The energy consumed by the pumping systems is a substantial expense for water companies, which makes the service more expensive and hinders financial sustainability. The pumping technology used requires expensive maintenance and technical expertise, which makes this infrastructure vulnerable to damage. Human alterations of groundwater resources and climate change-driven shifts also bring modifications to the magnitude and composition of submarine groundwater discharge (SGD) (Dulai 2021).

Salt is found in connate water, sea water trapped inland, and is commonly removed by applying irrigation water at a rate faster than the evaporation rate. Excess water removes salt from the root zone however deep percolation water then carries increased salt load that continues downward to the groundwater table. It can also carry residues of fertilizers and pesticides applied by farmers, groundskeepers, and homeowners. This threatens the groundwater quality beneath irrigated lands, inevitably contaminating it until it is too salty to drink or irrigate crops and vegetation. In addition, as water infiltrates the substrate, it will find a way to encounter many elements, nutrients, bacteria, and more as it falls to the earth. By monitoring both the inorganic and organic fractions, a more complete picture of catchment nutrient fluxes can be determined, and sources of pollution pin-pointed (Lloyd et al. 2019). The rapid growth of the human population on the "waterless" volcanic island of Santa Cruz in the Galápagos demands an urgent investigation into its hydrological system to avoid ecosystem alterations and provide viable solutions to the increasing water demand. The extent and continuity of the perched aquifer give unprecedented weight to their role in such an investigation.

Although dissolved oxygen (DO) can be precisely measured, concentrations are not monitored as part of many groundwater quality investigations (Rose 1988). DO concentration should be considered a critical parameter in any investigation of groundwater contamination as it often controls the fate of dissolved organic contaminants by constraining the types and numbers of microorganisms present within an aquifer. In turn, bacteria can either decompose or, in some cases, produce organic contaminants as part of their metabolism. For example, most alkyl benzene and chlorobenzene groups are probably biodegradable in aerobic water while stable in anaerobic water (Rose 1988).

SGD has varying impacts across different ecosystems. Human-disturbed watersheds, particularly those with urban development and conventional agriculture, show a common suite of impacts. Downstream of watersheds, SGD can be polluted by wastewater high in nutrients, and even common-use pharmaceuticals. (Bishop et al. 2017; Dailer et al. 2010; McKenzie et al. 2020; Richardson et al. 2017 Valiela et al. 1997; Welch et al. 2019). The volcanic basalt islands of the Hawaiian archipelago share many similarities in their origin, as well as increased coastal development and contamination of groundwater. Similar to Santa Cruz, many springs in Hawaiʻi that were documented to be fresh in the past are now brackish as human withdrawals deplete coastal aquifers and changes in land-use reduce recharge and groundwater flows, which contribute to seawater intrusion into coastal aquifers (Kelly et al. 2019). An example is the Pearl Harbor aquifer on Oʻahu that stored about 1.47×10^{10} m^3 of groundwater prior to development (Liu & Dai, 2012). The forced draft of the basal aquifer resulted in saltwater intrusion, resulting in about 0.63×10^{10} m^3 of freshwater storage in 2012. The Beretania basal-aquifer on O'ahu was similarly affected by development, as was Porto Santo of Portugal and Santiago of Cape Verde (de Melo 2008). Furthermore, climate change-driven seasonal variation in precipitation directly influences recharge patterns and sea level rise amplifies seawater intrusion and salinization of coastal groundwater. SGD which supports precious coastal cultural resources is therefore threatened on multiple fronts (Boulton 2020). SGD is dynamic, and most importantly it is affected by seasonal precipitation patterns, daily tides and sea level fluctuations (Dulai et al. 2016; Gonneea et al. 2013). As discharge is continuous, its magnitude and composition vary. As SGD provides nutrients and moderate temperatures, algae and benthic animals are subject to tolerate and if not thrive in these twice-a-day tidal, large salinity and nutrient shifts. For example, native macroalgal species are likely to have evolved under conditions of natural SGD inputs throughout the Hawaiian Islands where coastal springs and seeps occur (Huisman et al. 2007). These fresh, nutrient-rich plumes provide a subsidy of nitrogen while providing stress in the diurnal transition between salinities from fresh SGD influence at low tide to saline marine waters during high tide (Dulai 2021). Many more tropical native algae are also likely to favor SGD but remain understudied. Macroalgal community structure may change due to modifications to SGD volume, salinity, and nutrient concentrations but also with the introductions of non-native macroalgae (Dulai 2021). Native and invasive macroalgal species have been documented to reach bloom conditions in extensive areas near SGD seeps with nutrient pollution. In coastal Maui waters, invasive algal species, *Cladophora sericea*, *Ulva lactuca*, and *Hypnea musciformis* persistently bloomed in regions near wastewater treatment plants during the 1990s (Smith et al. 2005; Dailer et al. 2012). Overall, blooms of invasive species occur in regions impacted by sewage or effluent discharge. While the evidence provided here is drawn from Hawai'i, the points deduced are relevant to coastal environments across the Pacific and beyond, where climate and human perturbations affect coastal aquifer salinities and nutrient levels. The various benefits of SGD to groundwater-dependent ecosystems range from constrained muffled temperatures, the presence of colder temperatures and lower salinities that have been linked to higher oxygen content that is beneficial and preferred by fish, and nutrient inputs that promote bottom-up regulation of food chains (Duarte et al. 2010; Starke et al. 2020).

Due to its scarcity, the water quality of Santa Cruz must be studied concerning SGD and groundwater seepage. The island was thought to be waterless and without groundwater discharge thus their impacts were overlooked and underestimated. I expect to see a hydraulic gradient due to SGD from the intruded basal aquifer and will test this by measuring the salinity, temperature, and dissolved oxygen concentrations of Playa de la Estación. Potential points of discharge will be pin-pointed using data collected over three weeks at a single site. If groundwater is seeping out of the sample site, further exploitation and contamination of the aquifer have the potential to harm coastal ecosystems and house invasive species. The existence of SGD on Santa Cruz Island is a considerable cause for concern and should encourage increased aquifer management and future research assessing the impacts of this low oxygen, low salinity and potentially contaminated input on the protected flora and fauna of the Galápagos Marine Reserve.

Methods:

Study Site:

This study was conducted at Playa de la Estación (PE), a beach located just east of Puerto Ayora and on the Charles Darwin Research Station (CDRS). This site was chosen due to anecdotal observation of a salt wedge, in which a layer of salt water is found below a layer of fresh water, or brackish water. This was observed visually at PE as a “shimmering” density gradient and gustatorially through comparison of the taste of rivulets of notably fresher water draining into the sea at low tide in comparison with ocean water (Fig. X). PE is surrounded by a rocky barrier reef that impedes seawater from mixing with the discharged freshwater. Various rocky reefs further impede this mixing during low tide, when SGD is most evident. As long-term observations are the most useful in understanding the nuances of groundwater discharge and its effects on coastal geochemistry, environmental conditions, and ecosystems, PE was sampled through a variety of conditions such as rainfall (Richardson et al. 2017a,b).

Kilo:

Nana is the Hawaiian word for watching but to practice *kilo* is a Hawaiian observation approach that includes observing the environment by listening to the subtleties of a place to help guide decisions for management. This approach prioritizes creating an intimate relationship with a single place to gain the capability to notice the less obvious differences in the environment. Thus, *kilo* was done throughout the day before each sampling trial and for approximately 20 minutes prior to sampling. Practicing *kilo* in the modern world can create a means for individuals to gain the knowledge and wisdom needed for better management of the environment of any place (Morishige et al., 2018).

Each day of sampling was categorized into three groups: no rainfall (NR), garua rainfall (GR), and recorded rainfall (RR). Categories were assigned according to kilo and the climatology database of the Charles Darwin Foundation.

Sampling Design:

The sampling design started from the most western point of the beach closer to the beach access area to the most eastern point near the Marine Biology building of CDRS. Due to the non-uniform bathymetry of the beach and the presence of smaller bodies of rocky reefs, the sampling points in between were unable to follow simple transect lines and thus were placed at irregular intervals. In total, 30 sampling points were chosen and their UTM coordinates collected using a Garmin eTrex 22x GPS. Each sampling period began roughly 45 minutes before the peak low tide to allow for the sampling of brackish water rivulets which are only exposed at the peak of the low tide. As basalt rock barricades this beach from the ocean during low tide, allowing the salinity gradient to be more obvious and uninterrupted by forces like swells and wave action, it was imperative to the study that sampling be conducted at low tide. At each point the temperature (°C), salinity (ppt), dissolved oxygen (mg/L), and depth (cm) were measured (x) times over a month. Of the 30 sampling points, 19 were deep enough to allow for both surface- and bottom-water measurements while the other 11 were only surface-water measurements only.

Salinity & DO Measurements:

Measurements were taken using a YSI Quatro, an instrument consisting of a series of probes working in tandem to create a multiparameter water-sensing instrument used in environmental monitoring. Before use, each probe was calibrated with its respective calibration fluids. The probes used and calibrated include salinity, temperature, specific conductivity, and dissolved oxygen.. The probe itself is 13 cm (~5 in) long, thus "surface" water readings were taken 20 cm below the surface. For readings taken at the bottom, the YSI probes were placed just above the ocean floor and this depth recorded to the nearest 10 cm increment.

Statistics:

Statistical analysis was performed using the R Studio (R Core Team, 2024) and visualized with ArcGIS (Esri 2021). ArcGIS was used to map the surface-water salinity gradients of each sampling trial. For each day of sampling, a spline raster interpolation was made in a polygon encompassing the study site. The 12 maps were put together to create a .gif file that would be used during powerpoint presentations and a map of the mean salinity seen in Figure 1.

Each sampling day was categorized as either NR (no rainfall) or GR (garua rainfall). R Studio was used to calculate the mean surface salinity at each waypoint for each category. The difference between each observed measurement of salinity and the calculated mean was made into a box-whisker plot where the normality was assessed using the Shapiro-Wilk test and the Wilcoxon test was used to assess the difference between the two groups.

The distance from each waypoint to the nearest potential seepage point was measured using Google Earth and uploaded into R Studio to map in relation to salinity.

Finally, the correlation between salinity and dissolved oxygen was visualized as a scatter plot and calculated using Pearson's Correlation.

Results & Figures:

A total of 565 samples were measured showing freshwater dissipating away to the ocean. Figure 1 maps the mean salinity measurements. Overall, the range of measurements across all 565 samples was 7.01-34.34 ppt.

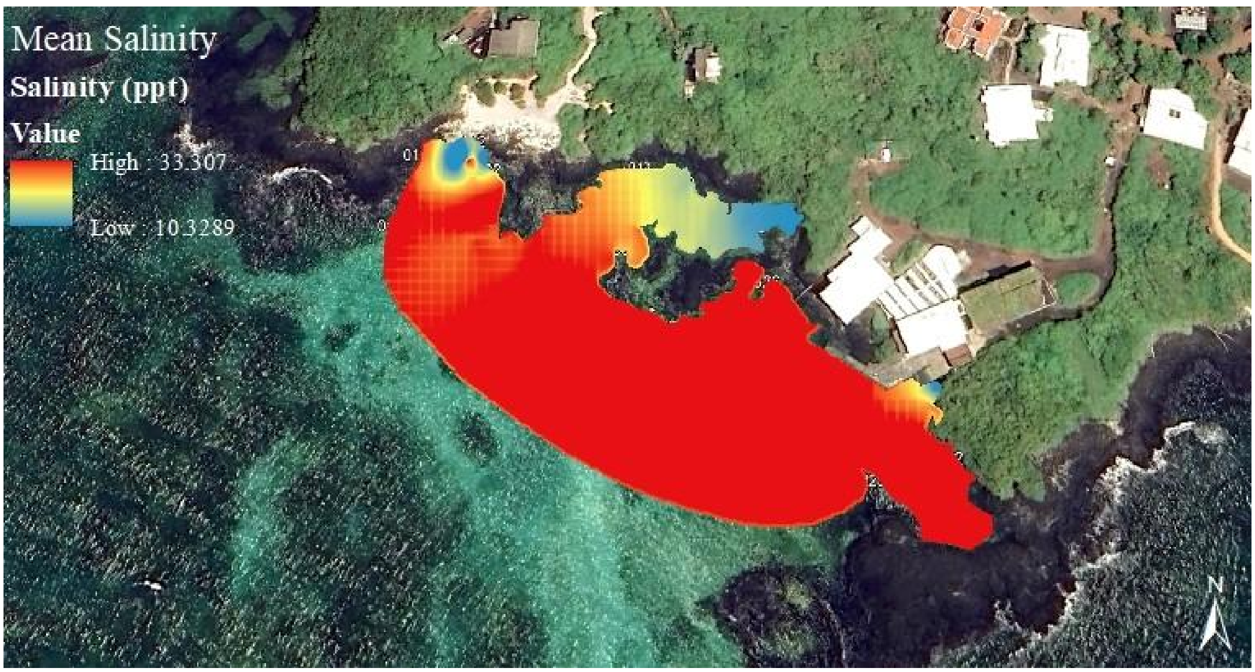

Figure 1. Map of mean salinity at Playa de la Estación in Puerto Ayora, Galápagos. Brackish water presence is indicated by low salinity levels and dissipates as the source mixes with saltwater offshore. The data shown is an interpolation between 30 sampling points taken from surface water.

Of the 12 sampling days there were six that had garua rain prior, none with recorded precipitation, and six with no precipitation. Although none of the sampling days had recorded rainfall within 24 hours of sampling, one had recorded precipitation within 72 hours of sampling; July 5th with 4mm of precipitation. The Shapiro-Wilk test was used for Figure 2 and indicated that the data is normally distributed. $p<0.05$ thus not normal. Then the Wilcoxon test ($p=0.22$) which reveals no differences between the groups in Figure 2.

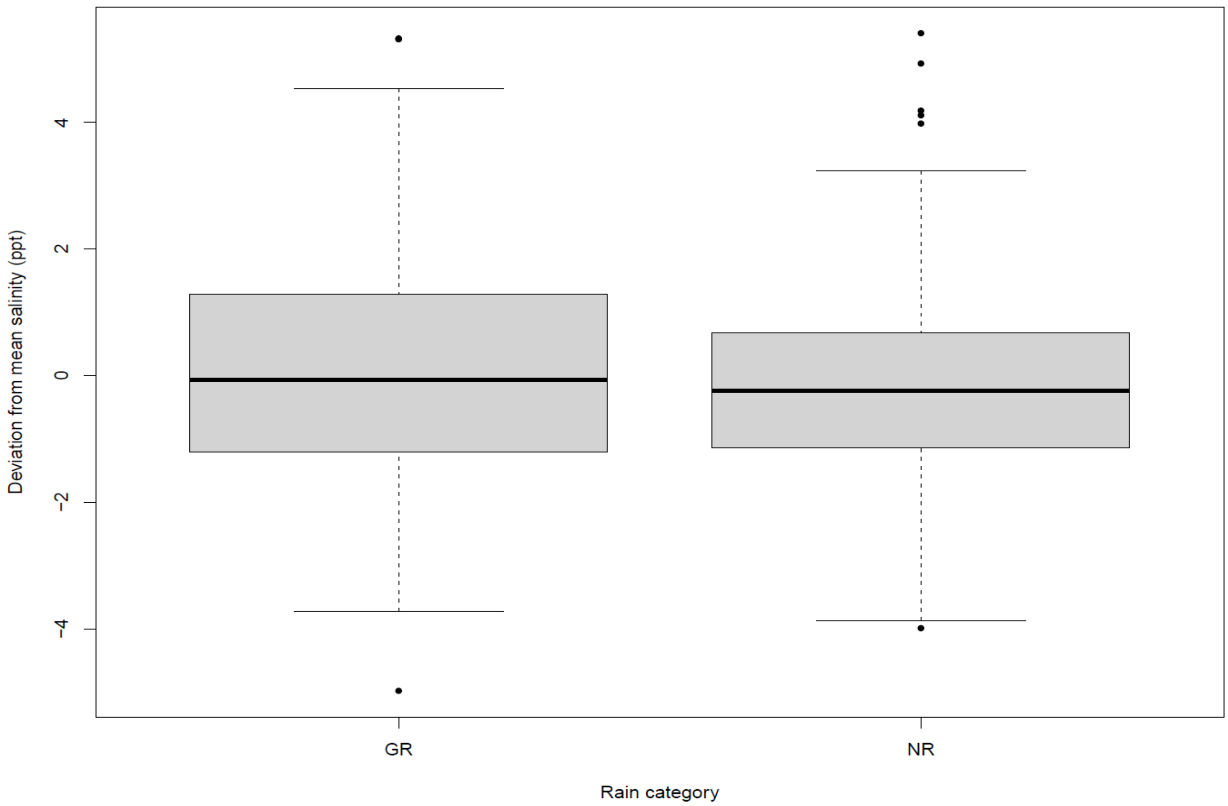

Figure 2. Relationship between precipitation and salinity at Playa de la Estacion. Each day of sampling was categorized based on whether or not rainfall was present at least 24 hours prior to sampling. This data shows the mean salinity for each category of rain and how much the observed salinity measurements of each category deviated from the mean.

Four sites never had a salinity greater than 18.01 ppt and visible discharge was observed at sites BR, MRE, and MR (Fig 3). The fourth site is waypoint nine, referred to as “lagoon”. In Fig. 1, the three sites with the lowest salinity were MR/MRE referred to as “beach”, the lagoon, and BR otherwise referred to as “BioMar “.

Figure 3. Visible discharge at sites BR (A), MRE (B), and MR (C).

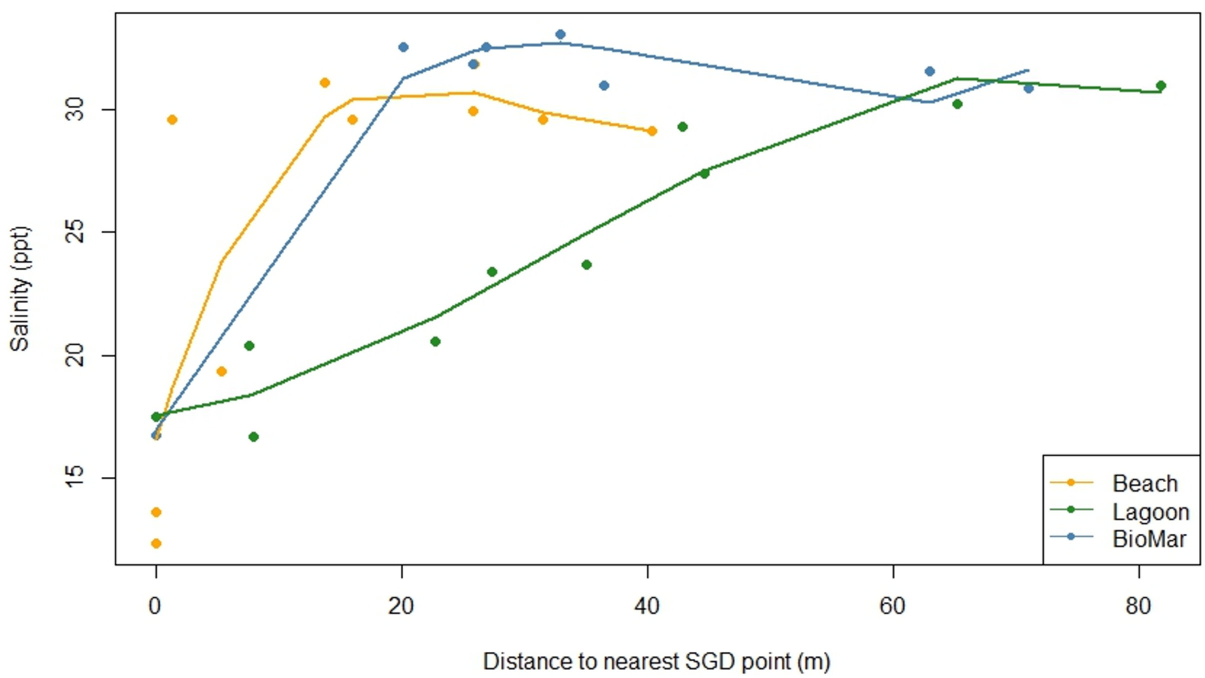

Figure 4. Each waypoint's distance from the nearest potential seepage point was measured and compared to their mean surface salinity. The goldenrod line represents the beach, the green line represents the lagoon, and the blue line represents BioMar.

Sampling sites MR, MRE, BR, and 9 whose salinity was never greater than 18 ppt had dissolved oxygen values that were much lower than sample sites with greater salinity and expressed in Figure 4. The correlation between salinity and dissolved oxygen was calculated using Pearson's correlation and had an r-value of 0.61 and a p-value less than 0.0001.

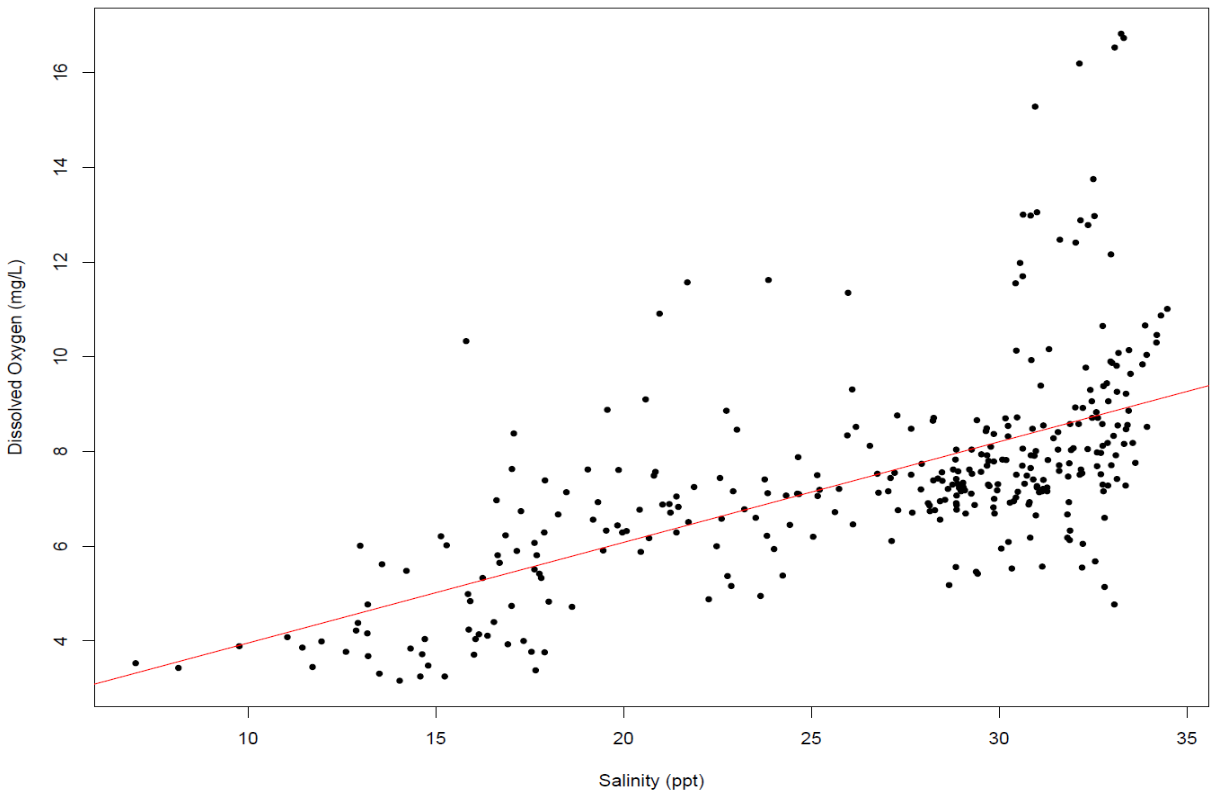

Figure 4. Salinity and dissolved oxygen plotted in scatter plot with a line of best fit whose r-value was 0.61.

Discussion:

Measurements of salinity at PE show consistent inputs of freshwater dissipating from the shoreline to the ocean. PE has a salinity range of 7.01-34.34 ppt while the average salinity of seawater is about 35 ppt and ranges from 33-37 ppt (NOAA). The study site had a very pronounced salinity gradient and brackish conditions at many sample sites. This was measured via salinity probe and in comparison to tap water (~3.33 ppt) it is very likely that the water at the shoreline of PE (7.01 ppt) is the outflow of the aquifer. In Santa Cruz, Galapagos, there have been very few studies done on groundwater and none that acknowledge SGD is present at PE. Measurements of salinity at a single place over an extensive period of time is just one of the many tests one can do to prove SGD presence therefore this study should be one of many.

There is no evidence of rain influence on SGD despite heavy garua rainfall events. Regardless of rainfall prior to or during sampling, salinity did not vary nearshore or offshore while precipitation varied greatly throughout the study. Rain precipitating on PE does not impact its salinity but infiltrated rain of the highlands does. Furthermore, if it were influenced by rain, all surface measurements would have reflected that, not just the seepage points, especially with the absence of streams. If the low salinity is not due to rainfall and streams, and the island itself experiences little to no runoff, the low salinity output at PE must be attributed to SGD. The insignificant correlation between precipitation and the low salinity values at CDF allows us to rule out rainfall as a possible cause for the freshwater input and allows the question of "where is the groundwater seeping from?" to be asked.

In the region surveyed there were four points believed to be SGD discharge. The average salinity was (x) at site MR, (y) at site MRE, (z) at site BR, and (w) at waypoint 9. At these sites, salinity was consistently a fraction of the salinity measured offshore. HERES THE REGIONS THAT WERE CONSISTENTLY FRESH REGARDLESS OF RAINFALL, BRING UP DISTANCE PLOT. Even though the aquifer is intruded by saltwater and the amount intruding increases during high tide, brackish water leaking out is much fresher than anticipated if there weren't SGD. There are direct leakages from the aquifer at these three sites. Now that the points of discharge have been identified, previous studies can be utilized to better understand and manage them and what might be expelled into these areas. These sites are where people should be concerned with and observing water quality. DULAI PAPER THAT SHOW THAT POINTS OF SGD DRIVE THE PROBLEM AND THIS STUDY CONFIRMS THAT

With a consistent measurement of freshwater and a weak correlation between it and precipitation, we move on to assessing what sort of impacts the groundwater may experience and consequences thereof. DO is considerably low in the groundwater and directly proportional to salinity at PE (as salinity decreased so did DO), suggesting its vulnerability. At sites MR, MRE, BR, and 9 dissolved oxygen had an average of (x) and never exceeded (y) whereas the measurements of DO everywhere else had an average DO of (z). Furthermore the DO of the bottom water was always greater than the surface. As suggested, dissolved oxygen can be used to assess the stability of dissolved trace metals and organic contaminants in groundwater. Examples of organic contaminants include herbicides, pesticides, pharmaceuticals, and animal and plant tissues. With the current management system of the groundwater, recreational sites have already faced contamination due to overexploitation. Due to lack of equipment and tools, nutrients were not measured at PE and why dissolved oxygen was prioritized in its place. Dissolved oxygen can be used in order to determine how vulnerable the groundwater is to contamination and was also measured for each sampling point. Typically saltier and warmer ocean water holds less oxygen but it is evident that at PE, colder and fresher water has less oxygen. This could be due to oxygen being low in the groundwater or oxygen being removed at the coast due to high microbial productivity or respiration as a result of nutrients being delivered via groundwater. At present, the cause remains unknown but the latter reasoning has implications of future anoxic events linked to SGD.

Very few researchers are aware of the low salinity output at PE but locals have known about the phenomenon prior to our arrival. Many have approached during data collection out of curiosity but were able to assist in pinpointing points of seepage. Their advice varied but what they had in common was the question of "why does it matter?". Although very helpful in many ecosystems, SGD also has the capability to carry anthropogenic contaminants to coastal environments leading to the proliferation of harmful algae. Changes in the coastal environment can induce high amounts of stress on the native environment, allowing opportunistic and invasive species to establish and push out native species (Lecher 2018). As seen throughout many coastal ecosystems, invasive alga have the potential to outcompete native species, decrease light availability for benthic organisms, decrease biodiversity, and produce even more algal blooms as they take over the system. Thanks to poorly managed and policed agriculture in the highlands, where groundwater recharge primarily occurs, a positive feedback loop becomes evident where salinity in the aquifer increases resulting in a decrease in DO. Everywhere you see SGD it ends up being a problem and now that we see it here it'll most likely be a problem. Throughout this study, the Galapagos archipelago was compared to the Hawaiian archipelago. This is because those responsible for natural resource management here in the Galapagos should learn from the mistakes made by those managing natural resources throughout Hawaii.

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