EVALUATION OF ANTHROPOGENIC IMPACTS ON THE FLOW OF TWO COASTAL SPRINGS IN MAUNALUA BAY, SOUTH SHORE, O`AHU

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We certify that we have read this thesis and that, in our opinion, it is satisfactory in scope and quality as a thesis for the degree of Bachelor of Science in Global Environmental Science.

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Abstract

Groundwater discharge has long been known to fringe O`ahu's south shores as springs and beach seeps, with many examples sporadically described since the early works of Stearns and Vaksvik (1935). Hawaiians have used these freshwater resources for centuries, primarily for creating brackish water environments that formed the setting for many of the fishponds that were found throughout the islands. Coastal development over the years has impacted these unique aquaculture practices and left most in ruin. The road widening project of Kalanianaole Highway in 1993 effectively severed all flow of water from the freshwater conduit that fed one of the last remaining fishponds on O`ahu, Lucas Spring, and allowed an estimated 1 million gallons of groundwater per day to infiltrate into an adjacent sewer line damaged during the construction. The proposed rehabilitation project of the sewer line in 2010 created a unique opportunity to study the possible restoration of groundwater flow to Lucas Spring. Continuous radon measurements combined with a salt mass-balance approach was used to determine groundwater flow rates into the impacted Lucas Spring, as well as in Kanewai Spring, which was selected as a comparison site. Over the course of this study, groundwater discharge to Lucas Spring increased from less than 1 m^3 day^{-1} to ~140 m^3 day^{-1} and the volume of water increased from ~8 m^3 to ~190 m^3 with no effective change in the nearby comparison spring. Although a spring discharge of 140 m^3 day^{-1} only represents ~20% of the historic flow, it is still a significant improvement over the prior decades' average flow when the pond was almost completely dry.

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1 Introduction

Submarine groundwater discharge (SGD) has received a tremendous amount of attention in recent years, principally for two reasons. The first is because of the realization that SGD can, in many instances, rival the total amount of fresh water exchanged from the land to the sea surface interface via surface water runoff (Moore et al., 2008). Second, extensive urbanization and agricultural development of coastal areas have vastly increased the amount of nutrients and other dissolved components that can then be transported to the ocean via subterranean coastal aquifers which line and feed coastal zones (e.g. see reviews in Slomp and Van Cappellen, 2004, and Burnett et al., 2006). Thus, most studies of SGD have concentrated largely on the current status of existing SGD systems from the viewpoint of how each system is perturbed by variations in naturally occurring SGD fluid driver phenomena, such as seasonal tides, variations in rainfall, or hydraulic head, and/or how SGD systems influence nutrient or other dissolved flow to the ocean. In contrast, to the author's knowledge, the study presented here is the first of its kind to apply SGD quantifications methods to monitor changes in groundwater discharge as a function of a major municipal groundwater diversion project.

Groundwater discharge has long been known to fringe O`ahu's south shores, with many examples described since the early works of Stearns and Vaksvik (1935). Historically, the most obvious of these south shore discharges have been manifested as natural springs that tap the Ko`olau basal aquifer (e.g. Kawaikui, Lucas, and Kanewai Springs), providing the brackish waters that formed many of the region's early Hawaiian fishponds (Figure 1). Very few of these fishponds remain today and are threatened by continued urbanization of Hawai`i's coastal areas.

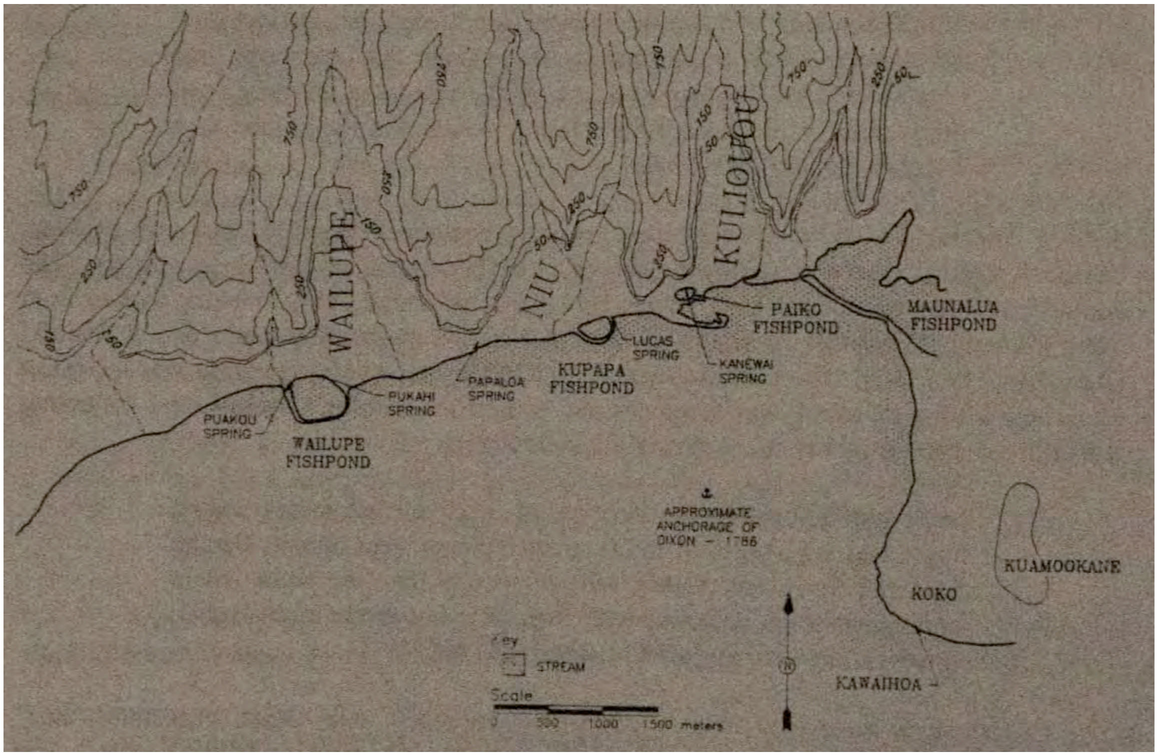

Figure 1. Historic locations of known fishponds and springs within Maunalua Bay (Erlens and Athens, 1994).

In 1993, the Department of Transportation (DOT) completed a road-widening project of Kalanianaole Highway, between East Honolulu and Hawai`i Kai. During that construction, the aquifer conduits that fed Lucas Spring, also known as Kalauha`iha`i fishpond, were diverted, resulting in dramatic reduction of the groundwater discharge that fed that site. A city-contracted study in 1997 found that sections of the sewer line in the vicinity of Lucas Spring were broken by the construction, allowing direct infiltration of the ground water into the sewer lines at an estimated rate of one million gallons per day (Fukunaga and Associates, 2005). This research capitalized on the opportunity to monitor changes in groundwater exit locations and flux rates that occurred due to the sewer line rehabilitation construction project that took place in 2010.

2 Background

2.1 Hawaiian fishponds

Hawaiians have known about the importance of groundwater springs in coastal ecosystems for centuries, and water resources throughout the Hawaiian Islands have played a pivotal role in the development of pre-contact Hawaiian society (Kikuchi, 1976). Historically, fishponds provided a constant source of easily accessible food, though both Kikuchi (1976) and Wyban and Wyban (1989) state that the fishponds were not run to maximize production but to serve as a food source for the *ali`i* or chiefs who ruled the *ahupua`a* or land division in which they resided. The fishponds also served as status symbols for the *ali`i* of the *ahupua`a* and maintained a key role in Hawaiian culture (Kikuchi, 1976).

The discovery of Hawai`i in 1778 by Captain James Cook led to the downfall of Hawaiian society, including the fishponds. When Cook first arrived in the Hawaiian Islands, it has been estimated that over 350 fishponds were in use (Wyban and Wyban, 1989). The destruction of the *kapu* system (traditional Hawaiian codes of ethics) in 1819 took all power away from ruling chiefs, paving the way for private land ownership (Kikuchi, 1976). Without the protection of the chiefly rule, fishponds were left unprotected from western influences and ways of life (Kikuchi, 1976). The influx of various cultures and western influences brought about a change of thought regarding fishpond use. Chinese immigrants turned some fishponds into fish farms with the intent to sell the fish to the local markets (Wyban and Wyban, 1989). Others, like Wailupe and

Niu fishponds, were filled in for coastal development (Figure 2 and Figure 3) or underutilized and left to deteriorate over time (Kikuchi, 1976; Wyban and Wyban, 1989).

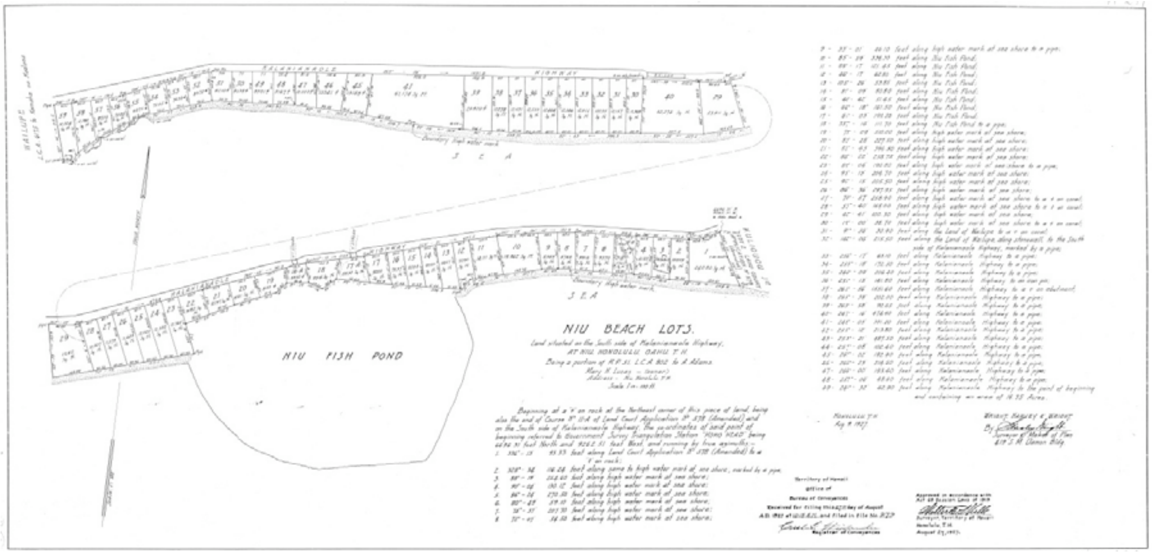

Figure 2. Parcel map of Niu Beach lots around former Niu fishpond, 1927 (Courtesy of MFHC).

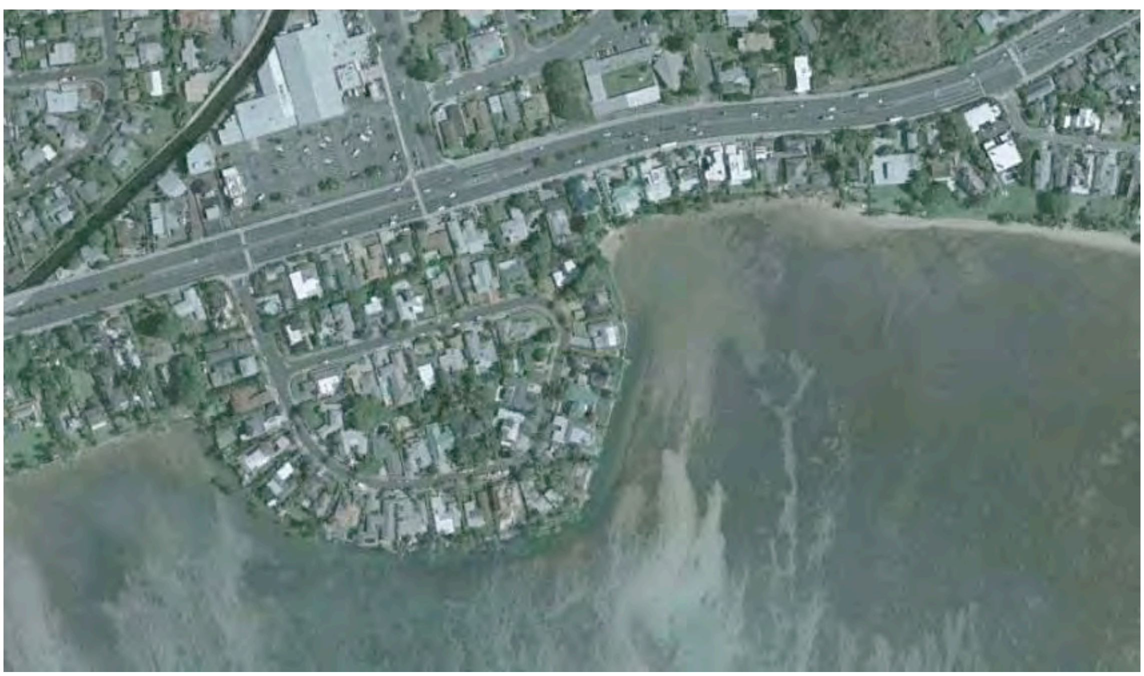

Figure 3. Aerial view of the remnants of Niu fishpond, filled in today and turned into a housing development known as Niuiki Peninsula. Extracted from Google Earth, 2010.

Today, most Hawaiian fishponds are merely relics that are only visible in some locations throughout the island chain. Very few fishponds are actually in working order, and most are on the verge of being taken away from the community due to private land ownership or continued development. This paper will show the impact modern day society has had on the flow rates of groundwater springs that currently feed water to two specific Hawaiian fishponds, Lucas Spring, also known as Kalauha`iha`i Fishpond and Kanewai Spring. Also, despite the continued urbanization, the paper will show evidence that there still exists the possibility of restoration of the few that remain.

The nonprofit organization, Maunalua Fishpond Heritage Center (MFHC), was founded in 2006 to raise awareness about the current state of Hawaiian fishponds, with its mission to restore fishponds on the verge of being lost forever, most notably Lucas Spring, Kanewai Spring and the adjoining fishpond known as Kanewai Fishpond. The goal was in conjunction with the University of Hawai`i's Hawaiian Studies Malama `Aina Program to create a place that would allow for cultural education for the benefit of Native Hawaiians and the community. The primary endeavor for MFHC was Lucas Spring (Figure 4).

Figure 4. Lucas Spring, 1980's (Photo: T. Hara, courtesy MFHC) and in April 2010. Photo: J. Kennedy.

2.2 Kalanianaole Highway widening and sewer line rehabilitation

Lucas Spring was owned and maintained by Mr. Tad Hara from the early 1970's to mid-1990's. Historical records show that an estimated 200,000 gallons (~750 m^3) of water a day flowed from Lucas Spring (Stearns and Vaksvik, 1935). With this much freshwater constantly flowing into the fishpond, the water in the pond was always clear. In 1993, construction during the road-widening project of Kalanianaole Highway disrupted the freshwater conduit that fed the spring, flooding the utility corridors that ran alongside the highway (Figure 5, Figure 6, Figure 7). For years, speculation surrounded where the groundwater went that once flowed into Lucas Spring.

Figure 5. Water flowing out of probable broken lava tube conduit during the Kalanianaole Highway widening project, ca. 1993. Photo: T. Hara, courtesy MFHC.

Figure 6. Water being pumped from flooded construction site landward of the Lucas Spring Study Site, ca. 1993. Photo: T. Hara, courtesy MFHC.

Figure 7. Water being pumped from flooded utility corridor during the Kalanianaole Highway widening project, ca. 1993. Photo: T. Hara, courtesy MFHC.

Throughout the widening project Mr. Hara photographically documented the impact the construction had on the area. His house was eventually condemned by the Hawai`i Department of Transportation due to the disrupted water supply and the proximity of the newly widened road to the house. With no one to take care of the fishpond and no freshwater flowing into it, Lucas Spring quickly deteriorated (Figure 8, Figure 9).

Figure 8. View of Lucas Spring after the freshwater conduit was severed and beginning to deteriorate, ca. 1993. Photo: T. Hara courtesy of MFHC.

Figure 9. View of desiccated Lucas Spring after the freshwater conduit was disrupted, ca.1993. The T. Hara property was noted for its "house with the glass floor" which looked down into the spring-fed fishpond over which it stood. Photo: T. Hara, courtesy MFHC.

The nearby Kanewai Fishpond (Figure 10) is listed on the State of Hawai`i Historic Register as one the last functioning shoreline fishponds in Honolulu. The fishpond's history dates back over 1000 years based on artifacts that were found in the area and it is listed as one of a few remaining royal fishponds (www.maunalua.net). The fishpond is fed by a freshwater spring known as Kanewai Spring (one of our research locations), which is located on private property. Historic records estimate 200,000 gallons (~750 m^3) of water a day once flowed from the spring (Stearns and Vaksvik, 1935).

Figure 10. Kanewai Fishpond, one of the few remaining fishponds on O`ahu, April 2010. Photo: J. Kennedy

The widening of Kalanianaole Highway in 1993 not only disrupted water flow to Lucas Spring, but it was also suspected to have damaged the sewer lines running parallel to the highway, possibly allowing infiltration of the groundwater directly into the sewer lines themselves. In January 1997, the Wastewater Division of the City and County of Honolulu had the sewer line investigated by MGD Technologies, Inc and Geltech Contractors, Inc. Manhole flow depth and velocity calculations determined that 1 million gallons per day (mgd) of groundwater during dry-weather conditions was infiltrating into the broken sewer line (Fukunaga and Associates, 2005). These flow volume calculations were then followed by video camera assessment of the broken sewer line (Fukunaga and Associates, 2005). The Wastewater Division then created a project based on the findings, though further investigation during dry-weather conditions of the sewer line infiltration continued through January 2003 (Fukunaga and Associates, 2005). The goal of the project was to eliminate the 1 mgd (3,780 m^3 day^{-1}) of dry-weather infiltration, reducing the costs associated with pumping and treatment of the extraneous wastewater (Fukunaga and Associates, 2005). The project, and thus the initiation of this thesis research, began in the middle of 2010.

Both research locations, Lucas Spring and Kanewai Spring, were on the verge of being auctioned off by the DOT when the rehabilitation project brought the possibility of restoring Lucas Spring to the community's attention. The sewer line rehabilitation project brought hope that the once diverted freshwater could be directed back to the conduit that fed Lucas Spring. The DOT allowed access to both sites for scientific research while MFHC attempted to obtain legal protection of the fishponds (presently Act 210), and it was with this restoration attempt in mind that the present research was initiated and conducted. The major goal was to provide scientific evidence of Lucas Spring's groundwater state and document the possible changes that might occur after the sewer line rehabilitation project was completed. Kanewai Spring was chosen as a control site for flow rate comparison that should otherwise mimic changes that may occur as a result of rainfall and infiltration variability of the area. The portion of the Sewer line rehabilitation project fronting Lucas Spring was completed at the end of October 2010.

2.3 Geologic pathway for groundwater flow

Groundwater discharge has the potential to occur anywhere there is an aquifer that is connected with the ocean by way of permeable rock or sediments (Burnett et al., 2006). As seen in Figure 11, groundwater moves from areas of higher hydraulic head toward the ocean where it discharges into the ocean as well as mixing with saltwater in an area known as the zone of diffusion (Johannes, 1980). The mixing zone generally intersects at the land ocean interface where some mixture of saltwater and freshwater discharge into the coastal environment as SGD. SGD is temporally variable, diffuse and patchy, making it difficult to quantify (Burnett et al., 2006). Unlike rivers and streams, there are generally no specific boundaries that contain its flow path. The term SGD can refer to any aspect of groundwater that discharges into the ocean, though it is usually described as all fresh and brackish water that flows from an aquifer into the ocean at the land-ocean interface that is below the mean high tide level (Burnett et al., 2006). Since Lucas Spring and Kanewai Spring do not necessarily fall below the mean high tide line but are at the land-ocean interface, this paper will refer to the spring flow as groundwater discharge.

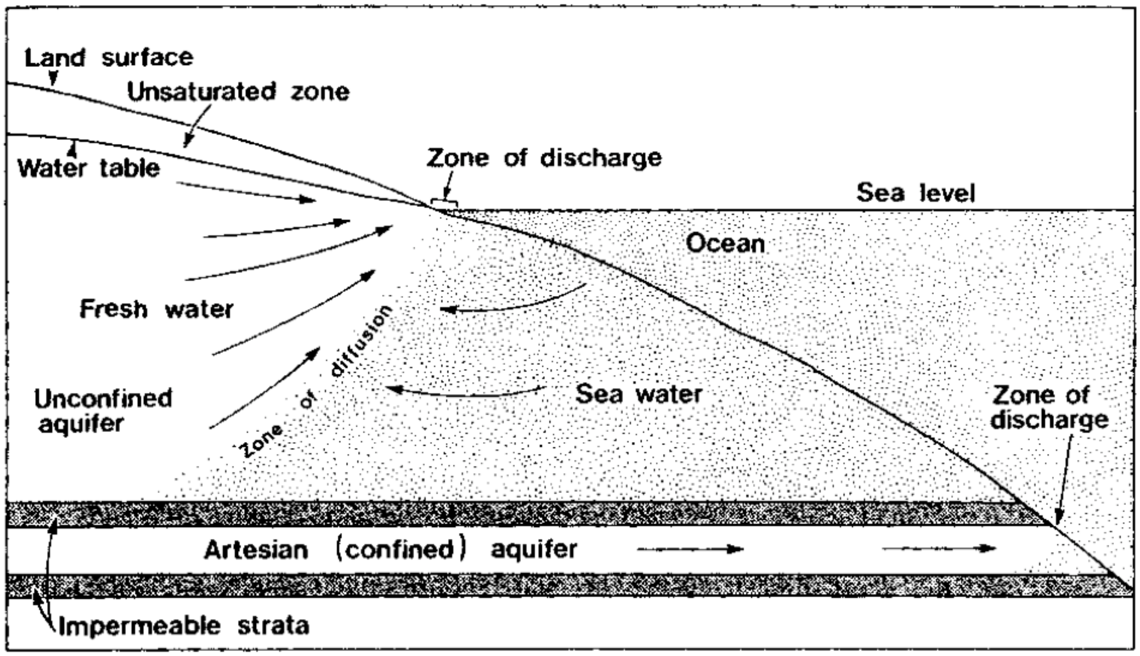

Figure 11. Idealized geologic representation of groundwater flow allowing for SGD (Johannes, 1980).

2.4 Groundwater quantification techniques

Determining locations and quantifying flow rates of groundwater discharge is difficult because it cannot easily be observed, and neither the flow patterns nor the flow rates can be precisely predicted (Hwang et al., 2005). Heterogeneity of sediments makes it extremely difficult to predict where the conduits are and where springs or slowly seeping groundwater can be expected to occur. Recently, however, the use of aerial thermal infrared (TIR) imaging technology has changed how researchers locate both coastal freshwater plumes and non-point source diffuse flow of groundwater (Johnson et al., 2008). The use of TIR imaging has enabled the collection of high-resolution sea-surface temperature data for identifying groundwater discharge over large areas and pinpointing key locations for further analysis. TIR imaging was collected and processed along the South Shore of O`ahu (Kelly et al., in prep) and Figure 12 shows the present research area imaged with this technique. The TIR method produces sea surface temperature maps with blue and green colors representing colder water temperatures indicative of groundwater seepage, while the warmer red and orange colors represent ambient ocean temperature. The leakage of colder groundwater in immediate proximity to the Lucas Spring site is notably lacking.

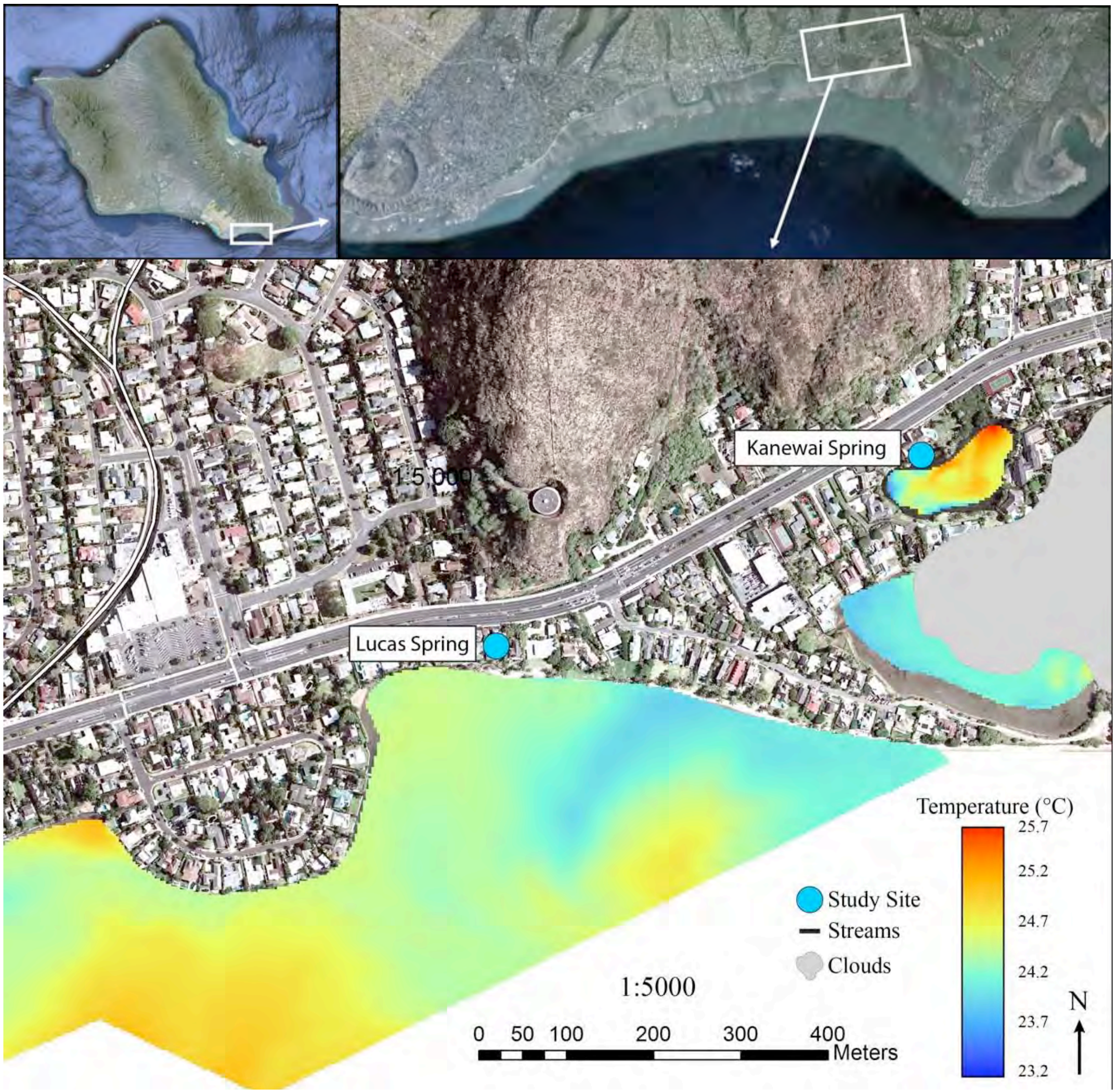

Figure 12. TIR image showing an overview of the research location. Flight occurred on July 6, 2009 at 2:09 am. Tide: +0.067 m, Altitude: 2133 m, Spatial resolution: 3.24 m, Temperature resolution: 0.5 degree C. Image: J. Kelly.

Among all the direct and indirect techniques of groundwater discharge assessment, the use of conservative geochemical tracers has been the most widely applied in various environments and geological settings. Radium and radon isotopes, along with salinity, are used to determine flow rates of water using a mass balance approach that accounts for all sources and sinks of these isotopes in the coastal zone (Charette et al., 2008). Groundwater discharge is thus determined by a flux-by-difference approach. For example, the use of continuous radon measurements in the coastal zone over periods of hours to days allows for temporal fluctuations and spatial variability when calculating groundwater discharge rates (Burnett and Dulaiova, 2003).

Radon is a naturally occurring radioactive gas that is non-reactive and has a short half-life of 3.8 days (Burnett and Dulaiova, 2003). The concentration of radon in groundwater is up to three orders of magnitude greater than ocean or surface water, making it a perfect geochemical tracer for groundwater that has been in contact with radon emitting aquifer materials (Burnett and Dulaiova, 2003). Any water within the aquifer, independent of its salinity, becomes enriched in radon, so the estimated flux rates represent the discharge of both fresh and brackish groundwater. These fluxes are calculated from the radon inventory in the surface water that is corrected for losses from atmospheric evasion and losses due to tidal flushing (Burnett and Dulaiova, 2003). The excess radon in the system is then used to determine a groundwater flow rate (Burnett and Dulaiova, 2003).

3 Methods

3.1 Study site description

Two springs with fishponds were selected for the study of groundwater discharge. Both sites are located on the South Shore of O`ahu, Hawai`i at the terminus of the ridge that separates Niu and Kuli`ou`ou Valleys (Figure 12). Lucas Spring is located between the ocean and Kalanianaole Highway. The man made basalt rock walled fishpond has a surface area of 368 m^2. It is connected to the sea by a 0.5 m wide channel or *`auwai* 10 m long and is inundated by ocean water only during extreme spring tide events and intense storm swells. The *`auwai* was filled with sand during the entire research period. There is a house built on the property with a large corner overhanging the fishpond, which shelters Lucas Spring from the strong trade winds common to the area (Figure 13).

Figure 13. Lucas Spring, April 2011. Photo: J. Kennedy.

Kanewai Spring is located half a kilometer to the east-northeast of Lucas Spring. The spring is also located between Kalanianaole Highway and the ocean, though there are two larger bodies of water separating it from the ocean. Kanewai Spring flows into Kanewai Fishpond which then flows into Paiko Lagoon (see Figure 14). Kanewai spring is lined with a basalt rock wall and is slightly oval in shape. The spring is overgrown with various trees sheltering it from strong winds (Figure 15). It has a surface area of 48 m^2 and an average depth of 0.9 m. There is a small channel that connects Kanewai Spring to Kanewai Fishpond. The channel is blocked by a narrow permeable basalt rock wall structure about 0.2 m wide, restricting the flow of water between the fishpond and the spring. Kanewai Fishpond is connected to Paiko Lagoon by a 2 m wide *`auwai*. At the connecting point of Kanewai Fishpond and the *`auwai*, a sheet of plywood blocks the interchange of water between Paiko Lagoon and Kanewai Fishpond (Figure 16). At high tide, saltwater from Paiko lagoon spills over the top of the plywood sheet providing an influx of saltwater to Kanewai Fishpond. As the tide drops, the water in Kanewai Fishpond slowly drains out between the spaces where the plywood sheet and the walls of the *`auwai* meet. This setting creates a fast influx of saltwater with a slower out flux of water from Kanewai Fishpond before the next high tide introduces more saltwater. Paiko Lagoon is connected directly to the ocean by way of a natural shallow channel about 15 m wide.

Figure 14. Overview of Kanewai Spring, Kanewai Fishpond, and Paiko lagoon with CTD-Diver locations shown with an X, Google Earth, 2010.

Figure 15. Kanewai Spring, April 2010. Photo: J. Kennedy.

Figure 16. Plywood barrier separating Kanewai Fishpond (bottom) from Paiko Lagoon (top). Photo: J Kennedy.

3.2 Sampling methods

Sampling of both locations took place between April 2010 and April 2011. Two radon time series deployments (section 3.2.1) took place at Lucas Spring, while three radon time series deployments took place at Kanewai Spring. Rainfall records from the Niu Valley rain gauge were retrieved from the National Weather Service (www.weather.gov/hawaii) for the period listed. The initial research plan was to use radon measurements to determine groundwater discharge rates at Lucas Spring and Kanewai Spring both before and after the sewer line rehabilitation project took place. The rehabilitation project was repeatedly delayed, so within our project time frame, radon measurements only occurred in the spring and summer of 2010, both of which were before the rehabilitation project. The use of compact (22 mm x 135 mm), conductivity, temperature, and depth (water level) data loggers (Schlumberger Water Services Inc. CTD-Diver, DI 271) provided the opportunity to monitor post-work changes in water flux variations at both locations using conventional salt balance modeling (section 3.4) based on observed salinity fluctuations from the pre-rehabilitation radon deployments. The CTD-Divers also provided important information on the effect tidal fluctuations had on each location.

3.2.1 Radon time series monitoring

In order to derive groundwater discharge rates to the fishponds over time, time-series measurements of radon, water level and salinity were performed. The first radon time series deployment at Lucas Spring occurred from April 7 – 10, 2010, while the second time series was deployed August 12 – 26, 2010. The radon time series deployments for Kanewai Spring were conducted April 2 – 4, July 14 – 17, and August 12 – 26, 2010. The method used for each continuous radon analysis was based on previous work done by Burnett and Dulaiova (2003) and Dimova and Burnett (2011).

Radon in the surface water was analyzed by a commercially available radon monitor (RAD-7, manufactured by Durridge, Inc). Water from mid water column at Kanewai Spring and bottom depth at Lucas Spring was pumped into an air-water exchanger via a small bilge pump. The purpose of the air-water gas exchanger is to release radon into a closed air loop that is then fed into the radon-in-air monitor. The RAD-7 analyzes the radon activity at pre-set intervals and is able to perform automated repeated measurements. The radon in the closed air loop reaches equilibrium with the radon in the water depending on the water temperature. The radon water activity can then be derived from the measured radon in air value. Since the radon activity ratio of water to air is determined by water temperature, a multi-parameter sonde was used in conjunction with the RAD-7. A YSI multi-parameter sonde (model 6920V2-2, YSI Inc.) was used for all radon time series setups and placed at the same depth and location as the bilge pump. The YSI sonde measured temperature (^{o}C), specific conductivity (mS/cm), salinity, depth (m), pH, chlorophyll-a, and dissolved oxygen (% saturation and mg/L) every 5 minutes. The data from the RAD7 and the YSI was retrieved upon completion of each time series analysis.

3.2.2 Salinity and water level analysis for tidal influence on spring discharge

Changes in salinity and water level were monitored in both Lucas Spring and Kanewai Spring in order to study the influence of the tidal cycle on groundwater discharge. We deployed four CTD-Divers for an extended period of time at four locations (Figure 14): Lucas Spring – 5 months, Kanewai Spring – 3 months, Kanewai Fishpond – 3 months, and the mouth of Paiko Lagoon – 2 months. The Paiko Lagoon diver captured the uninhibited ocean tidal fluctuation. Each diver was secured to a brick and set to record conductivity (mS/cm), temperature (^{o}C), and water depth (m) every 30 minutes. Conductivity was later converted to salinity using the following equation, where C is conductivity (Williams, 1986):

$$\text{Salinity} = (C^{1.0878})*(0.4665) \qquad (1)$$

The divers for Paiko Lagoon and Lucas Spring were deployed on November 11, 2010. The divers for Kanewai Fishpond and Kanewai Spring were deployed one day later on November 12, 2010. Due to a protective equipment failure, the diver located at Paiko Lagoon was permanently removed on December 31, 2010 with valid data collected intact.

The divers Kanewai Spring and Kanewai Fishpond were removed on February 10, 2011 while the diver located at Lucas Spring remained in place until April 2, 2011.

3.3 Radon model description

The use of continuous radon measurements for quantifying groundwater discharge stems from the basic idea that groundwater is highly enriched in radon while surface waters have no sources of radon other than groundwater and diffusion from the bottom substrate. By accounting for the radon inventory in the surface water one can calculate the radon-enriched groundwater flux required to sustain the measured surface water inventory. The major losses of radon from these spring systems are radioactive decay (half-life 3.8 days) and evasion to the atmosphere. Sources would be diffusion and groundwater discharge. Groundwater discharge rates can be determined by a flux-by-difference approach using a mass balance equation that accounts for all these sources and sinks of radon in the springs (Charette et al., 2008). Figure 17 illustrates a simple box model diagram depicting the conceptual model that the following calculations are based on.

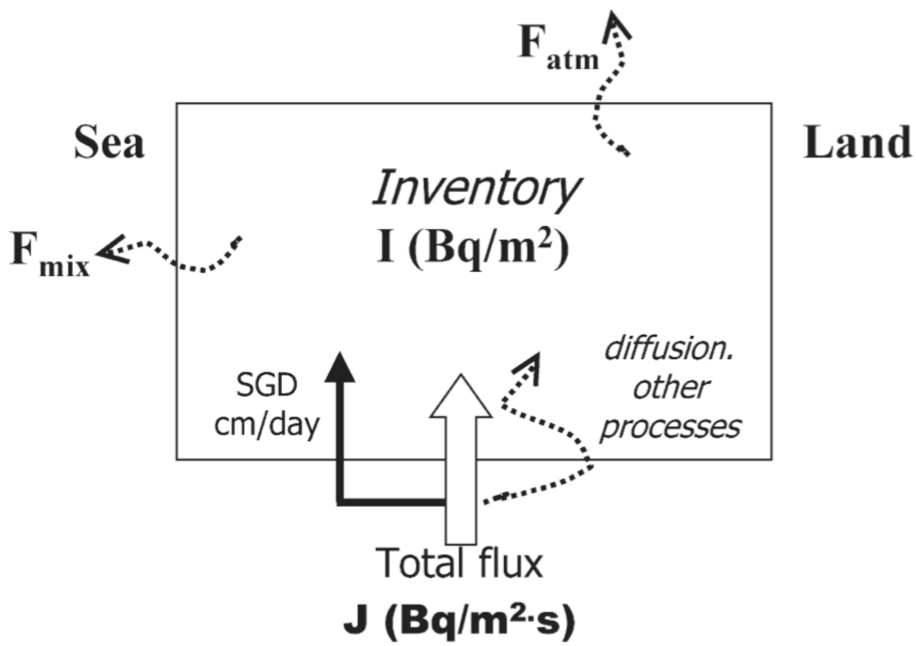

Figure 17. Box model diagram of radon sources and sinks in the coastal environment (from Burnett and Dulaiova, 2003). All the same source and sink terms were applied except losses to the ocean by mixing as our springs are not directly connected to the ocean.

3.3.1 Radon losses by evasion to the atmosphere

Radon losses to the atmosphere are fluxes driven by the air-water radon activity gradient and the gas transfer coefficient in the water. To calculate evasion rates we used radon activity measured by the RAD-7 and temperature and salinity measured by the multi-parameter sonde. The diffusive flux of radon gas across the air-water boundary was calculated using the following equation from Macintyre et al., (1995):

$$F_{atm} = k(C_w - \alpha C_a) \quad (2)$$

where F_{atm} (dpm/m^2*min) is the diffusive flux based on the activity gradient between the water and air, k (m/min) is the gas transfer coefficient, C_w (dpm/m^3) is the activity of radon in the water, C_a (dpm/m^3) is the activity of radon in the air and α is the temperature (T) dependent equilibrium activity ratio, also known as the Ostwald solubility coefficient, which is calculated using the following equation (Burnett and Dulaiova, 2003):

$$\alpha = 0.105+0.405e^{-0.0502T} \quad (3)$$

The gas transfer coefficient for radon, k, was determined based on the gas transfer velocity dependence on the Schmidt number of other known gases (Macintyre et al., 1995). The Schmidt number (Sc) for radon was calculated as the ratio of the kinematic viscosity of water, v (cm^2/sec), and the molecular diffusion coefficient, D (cm^2/sec), of the radon gas (Macintyre et al., 1995):

$$Sc = v/D \quad (4)$$

The kinematic viscosity of water is the absolute or dynamic viscosity (μ_{sw} (kg/m*sec)) divided by seawater density (ρ_{sw} (kg/m^3)) and was determined using work done by Isdale et al. (1972):

$$v = \mu_{sw}/\rho_{sw} \quad (5)$$

The diffusion coefficient, D, was calculated based on work done by Peng et al. (1974) Once the Schmidt number for radon was determined, the following formula was used to find k.

$$k_{Rn}/k_{CO2} = (Sc_{Rn}/Sc_{CO2})^{-0.5} \quad (6)$$

Since both study sites were sheltered from strong winds a k_{CO2} value of 0.8 cm/hour was used in determining the k value for radon since Macintyre et al. (1995) state that k is independent of wind speeds below 3 m/s.

3.3.2 Radon decay

A radon inventory was calculated by multiplying the water depth with the average radon activity during each deployment period. Time periods over which the average radon inventory was constant were selected. To sustain this constant inventory, the flux of radon rich groundwater must be equal to radon losses by radioactive decay.

$$I = F_I * (1-e^{-\lambda t})/\lambda \qquad (7)$$

where I (dpm/m^2) is radon inventory, F_I ($dpm/m^2\ day^{-1}$) is the radon flux that is required to sustain the measured radon inventory, λ (0.182 day^{-1}) is the radon decay constant, and t is time.

3.3.3 Groundwater flux calculation

By summing radon losses by evasion (F_{atm}) and radioactive decay (F_I) the total radon flux that has to be balanced by groundwater discharge is found.

$$F_{Rn\ total} = F_{atm} + F_I \qquad (8)$$

Inputs by diffusion and from ^{226}Ra dissolved in the water are negligible (Dimova and Burnett, 2011). Finally, groundwater flux (m^3/m^2/day) was determined by dividing the total radon flux by the groundwater radon activity (dpm/m^3). The groundwater flux rate is then multiplied by the surface area of the basin giving a groundwater discharge rate (m^3/day) into the fishpond. This calculation assumes that the water in the pond is well mixed and the radon measurement is a good representative of activities across the whole pond. Due to the shallow depth, small water volume and long residence time, this is a valid assumption

3.4 Salinity mass balance model

Due to observed changes in the salinity of both locations, a salt mass-balance approach was also used to calculate discharge rates. We took advantage of the fact that at peak spring high tide, Kanewai Spring was inundated by seawater in one individual spike. The salinity of the spring was then assumed to decrease at a rate equivalent to the groundwater discharge rate. We calculated the groundwater discharge based on the time required to achieve a minimum salinity in the pond. The following equation was used to calculate the amount of groundwater needed (V_{GW}) to account for the change in the observed drop in salinity after seawater inundation due to spring tides or the tsunami of March 11, 2010 at Lucas Spring (Dulaiova et al., 2010).

$$V_{GW} = (S_F V_S - S_I V_S) / (S_{GW} - S_F) \quad (9)$$

S_I represents the initial salinity, S_F is the final salinity, S_{GW} is the salinity of the groundwater discharging into the fishpond, and V_S is the volume of the fishpond. Flux rate, Q (m^3/day), was then calculated based on the amount of time (t) during which salinity values dropped from maximum to minimum.

$$Q = V_{GW}/t \quad (10)$$

4 Results

4.1 Lucas Spring

4.1.1 Lucas Spring 7-10 April, 2010 deployment

The Lucas Spring deployment in April 2010 lasted a total of 3 days during which only one fourth of the surface area was filled with water. Our objective was to monitor salinity, water level, and radon activities in Lucas Spring over time to discern any fluctuations due to tidal or meteorological forcing. Due to the low water level in Lucas Spring, we deployed the YSI multi-parameter sonde and the radon intake pump at the deepest location (0.17 m) to provide adequate water coverage. This location was about 25 m inland from the *`auwai* and located underneath the overhang of the house. Due to the irregularity of the bottom, an estimated average water depth of half of the deepest location was used for water volume calculations. For these calculations we used exact measurements of the dimensions of Lucas Spring and estimated a volume of 7.7 m^3.

Over the 3-day deployment the salinity ranged between 19.9 and 20.4. During this deployment, radon activity ranged from a low of 340 decays per minute per cubic meter of water (dpm/m^3) to a high of 3590 dpm/m^3, both the radon and salinity were tidally modulated though they cycled on a 24-hour period (Figure 18). However, water level in Lucas Spring cycled on a 12 hour period, with the water level only changing ~2-3 cm during each semidiurnal tidal induced fluctuation (Figure 19). Because there was no observable surface water flux between Lucas Spring and the ocean, tidal fluctuations in Lucas Spring were likely due to the underground hydrological connection of Lucas

Spring to the coastal aquifer. Figure 18 shows the regularity of both the change in salinity and the corresponding peak of radon activity whenever the salinity dropped. This is an indication of radon-rich and lower salinity groundwater discharge.

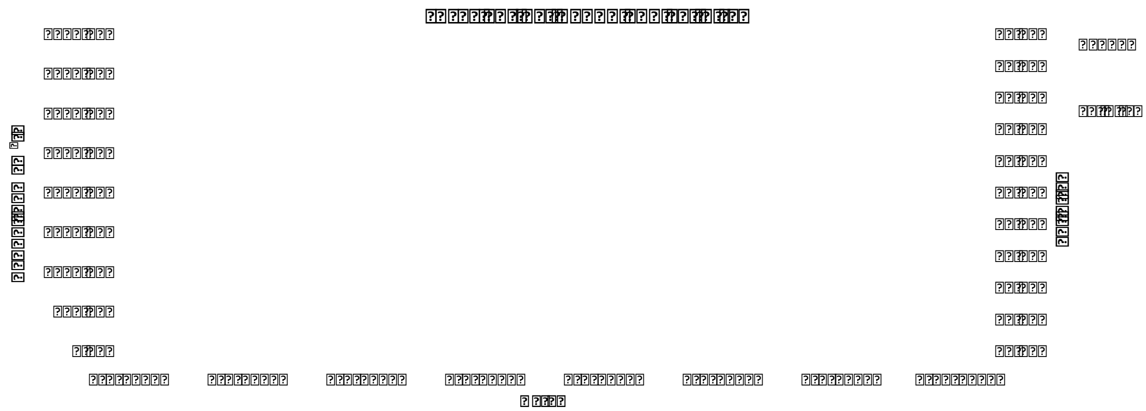

Figure 18. Lucas Spring April 2010 deployment radon activity and salinity.

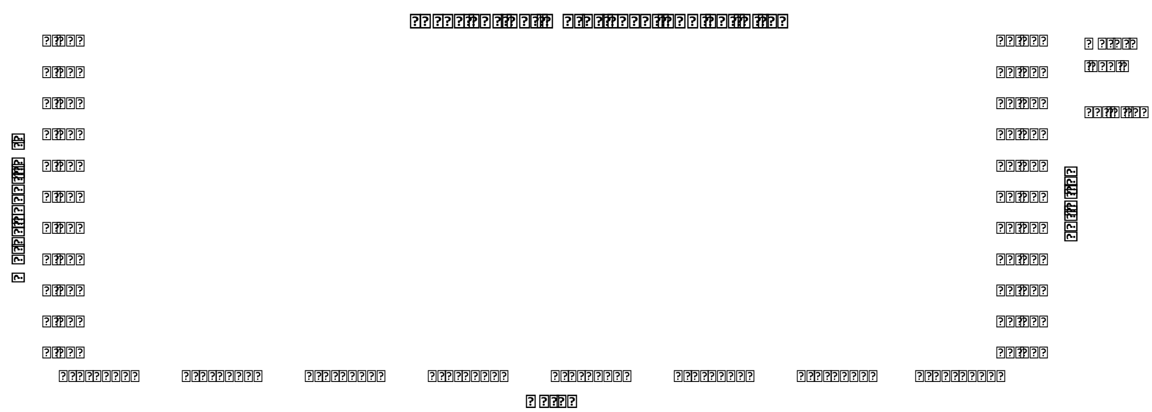

Figure 19. Lucas Spring April 2010 deployment water level and salinity.

These measurements recorded a decrease in average radon starting late April 9, indicating a slight shift in groundwater discharge. The radon balance (Eq (8)) was used to derive water flux into Lucas Spring. With an average radon activity for the period of April 7 – 9 of 1740 dpm/m^3 and a depth of 0.08 m, a radon inventory of 145 dpm/m^2 was calculated, and for the same time period the calculated losses to the atmosphere using Eq (2) were 417 dpm/m^2 day^{-1}. Radon loss due to radioactive decay was calculated using Eq

(7). These two terms represent radon losses, which have to be compensated for by radon flux into Lucas Spring by groundwater discharge. To compensate for radon losses by radioactive decay and atmospheric evasion a flux of 1290 dpm/m^2 day^{-1} of radon is required to sustain the calculated inventory. With a groundwater radon end-member of 168000 dpm/m^3, a water discharge of 0.71 m^3 day^{-1} is required in the period of April 7 – 9. However, at the end of the deployment period April 9 – 10 the radon inventory drops to 116 dpm/m^3 with losses to the atmosphere at 333 dpm/m^2 day^{-1}, leaving 1026 dpm/m^2 day^{-1} of radon to be compensated by groundwater giving a discharge rate of 0.56 m^3 day^{-1}.

The groundwater radon end-member activity was based on groundwater well measurements that were completed in the area (Holleman, in prep). From the time series record it is obvious that the total water level in Lucas Spring fluctuates only by 2-3 cm due to ocean tides. It is assumed that at lower low tide the hydraulic pressure allows the pond to fill with lower salinity high radon groundwater. Conversely, it is also assumed that at higher high tide, higher salinity low radon water is pushed into Lucas Spring from the ocean side of the coastal aquifer. One has to therefore distinguish between diurnal groundwater fluxes vs. long-term net groundwater discharge into the pond. Radon was used to calculate the average net fluxes and the salinity record was used to obtain groundwater discharge rates on a diurnal time scale due to tidal fluctuation. From the three observed drops in salinity, three groundwater discharge rates were calculated, 0.73 m^3 day^{-1}, 1.10 m^3 day^{-1}, and 0.64 m^3 day^{-1} for an average groundwater discharge rate of 0.82m^3 day^{-1} during dropping tide. Some of this water recharges back to the aquifer at each higher high tide to sustain a constant average water level. No significant precipitation events occurred prior to or during this deployment.

4.1.2 Lucas Spring 12-27 August, 2010 deployment

During this 15-day deployment, the entire area of the Lucas Spring was filled and had an average water depth of 0.18 m. Salinity started out at 25.7 and showed an increasing trend with a peak salinity of 27.0 four days later. The overall trend then leveled off until August 21, when the salinity record began a decreasing trend with a low of 24.9 at the end of the deployment (Figure 20). Water level showed similar semidiurnal fluctuations to the April 2010 deployment with changes of ~2-3 cm that tracked the local ocean tidal frequency. Radon activity also showed similar diurnal fluctuations as were observed in April 2010 (Figure 21). Radon activity started at an initial minimum value of 580 dpm/m^3 on August 12 and reached a maximum value of 4470 dpm/m^3 on August 22, 2010. The largest increase in radon was by 3500 dpm/m^3 that occurred within a 3-hour time span on August 22. Radon activity was averaged over two separate periods (Aug 12 – 17 and Aug 18 – 27) due to a distinct increase in activity on August 17. Average radon activity for the period of August 12 – 17 was 1680 dpm/m^3, an inventory of 294 dpm/m^2, and losses due to atmospheric evasion at 368 dpm/m^2 day^{-1}, giving a groundwater discharge rate of 4.7 m^3 day^{-1}. The average radon activity for the period of August 18 – 26 was 2280 dpm/m^3, an inventory of 397 dpm/m^2 and losses due to atmospheric evasion at 492 dpm/m^2 day^{-1}, giving a groundwater discharge rate of 6.3 m^3 day^{-1}. Two specific salinity drops on August 24 and August 26 were used to calculate a groundwater discharge rate of 12.2 m^3 day^{-1} and 7.3 m^3 day^{-1}. No significant precipitation events occurred prior to or during this deployment.

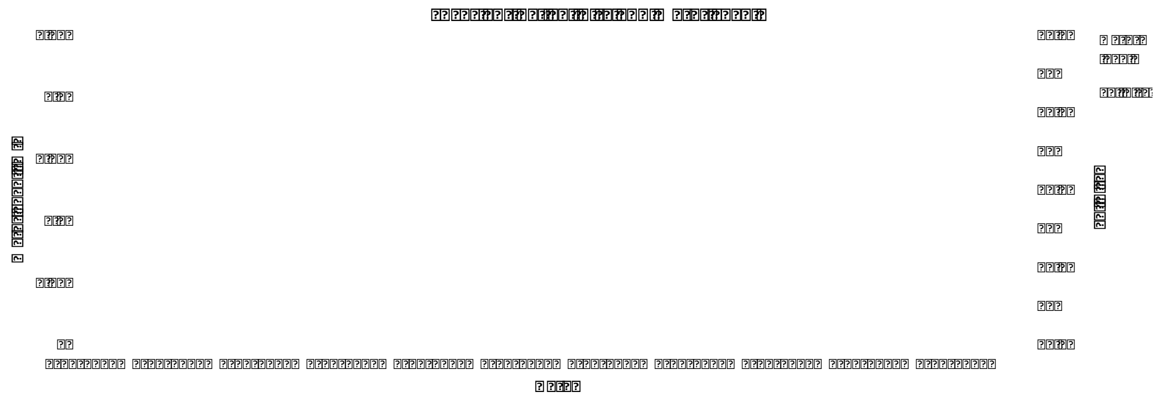

Figure 20. Lucas Spring August 2010 deployment, water level and salinity.

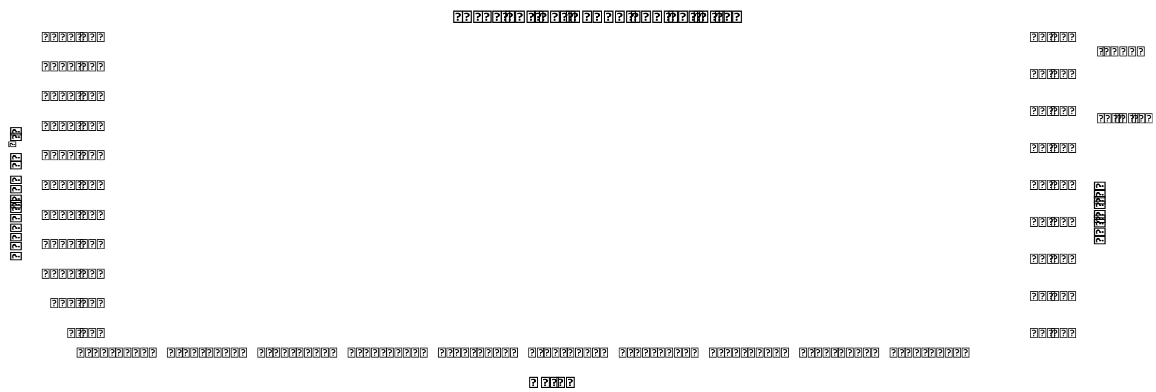

Figure 21. Lucas Spring August 2010 deployment, radon activity and salinity.

4.1.3 Lucas Spring CTD-Diver time series

The final measurements at Lucas Spring were restricted to the use of a CTD-Diver and spanned a period of nearly 5 months, between November 2010 and April 2011. The CTD-Diver was deployed 2 weeks after the sewer line rehabilitation project was completed. Throughout this period, the salinity in Lucas Spring showed an overall decreasing trend from an already low initial value of 9.1 on November 11, 2010, to a sustained baseline salinity approaching ~ 2 by mid-December. Two major anomalies in salinity punctuate that record, one due to a significant rainfall event on December 19, 2010 that coincided with spring tide inundation, and the other due to a tsunami which struck Hawai`i on March 11, 2011 (Figure 22 and Figure 23). Due to both salinity anomalies as well as the completion of the sewer line rehabilitation project at the end of October 2010, the data from this diver will be discussed further in section 5 below.

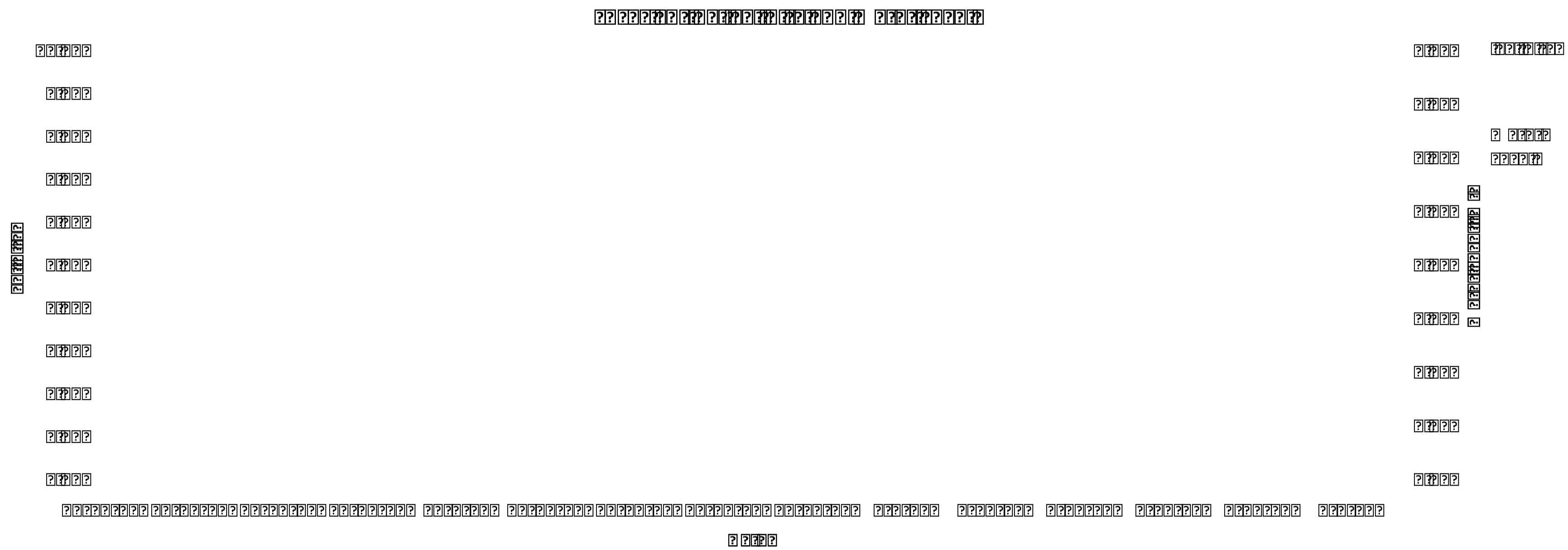

Figure 22. CTD-Diver time series data of Lucas spring from November 11, 2010 to February 10, 2011 showing changes in salinity and water level after the sewer line rehabilitation project was completed at the end of October 2010.

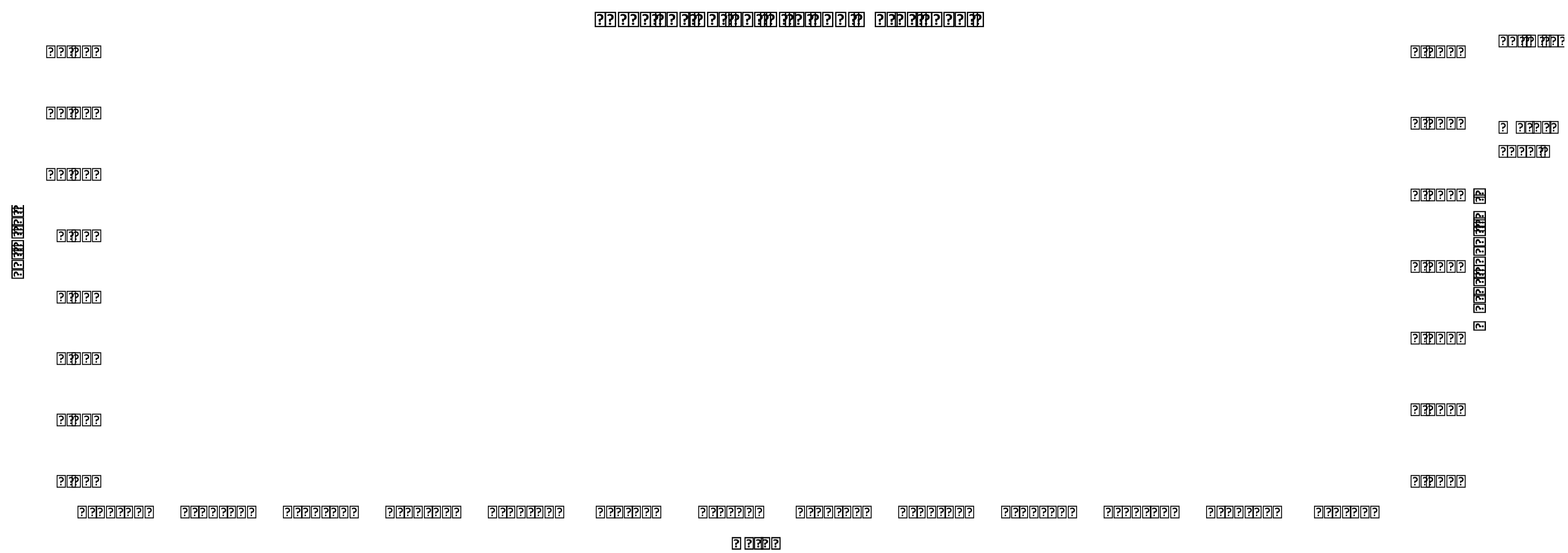

Figure 23. CTD-Diver time series data from February 10, 2011 to April 2, 2011 showing changes in salinity and water level with the impact from the March 11 tsunami that hit Hawai`i clearly seen in the salinity spike.

4.2 Kanewai Spring

4.2.1 Kanewai Spring 2-4 April, 2010 deployment

The initial deployment at Kanewai Spring took place over a period of 2 days. During this period the salinity of Kanewai Spring fluctuated slightly between 2.8-2.9 (Figure 24). Water depth averaged 0.9 m and the water level fluctuated ~4-5 cm on a 12-hour period, coinciding with the semidiurnal tidal cycle. Radon activity ranged between 36000 - 64000 dpm/m^3. The lowest radon activity was observed shortly after the initial deployment while the peak activity was observed 12.5 hours later (Figure 25). With an average radon activity of 51080 dpm/m^3, a radon inventory of 45970 dpm/m^2, and losses to the atmosphere at 11960 dpm/m^2 day^{-1}, a groundwater discharge rate of 82 m^3 day^{-1} was calculated. No significant changes in salinity occurred during the April 2010 deployment at Kanewai Spring, so no salinity mass balance calculations were completed for comparison to the radon model calculation. No significant precipitation events occurred prior to or during this deployment.

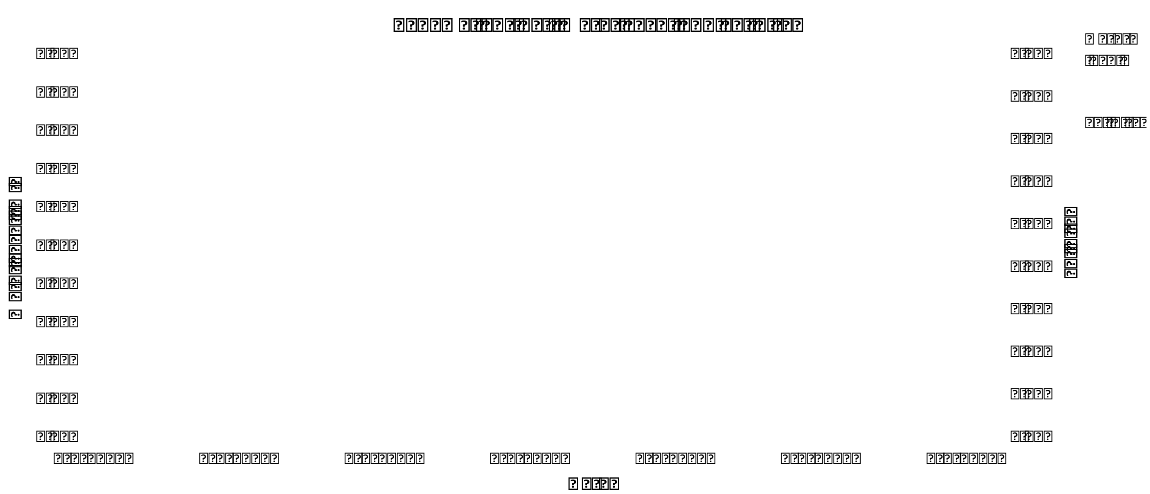

Figure 24. Kanewai Spring April deployment, salinity and water level.

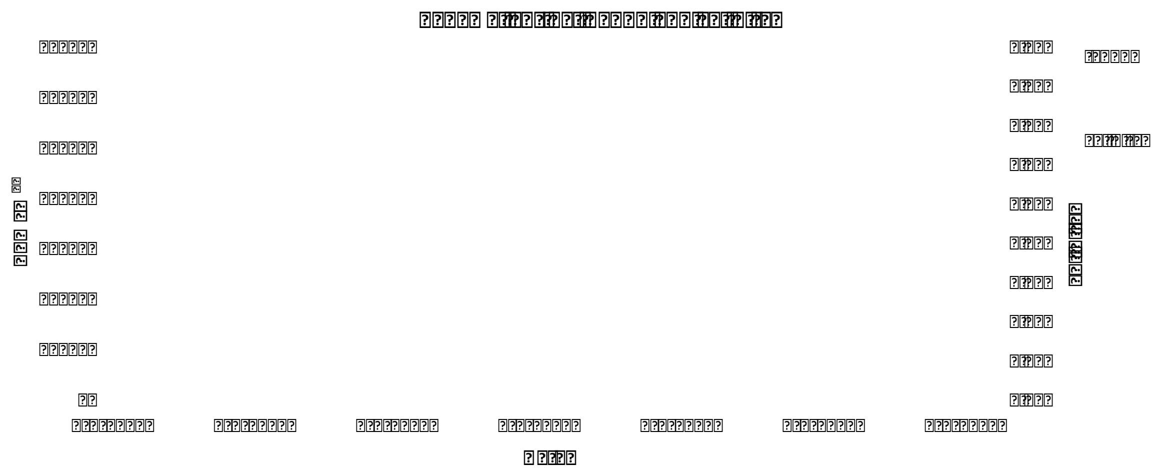

Figure 25. Kanewai Spring April deployment, salinity and radon activity.

4.2.2 Kanewai 14-17 July, 2010 deployment

The July deployment at Kanewai Spring took place over a period of ~3 days. The initial salinity of the spring was an extremely high 31 and increased to 33.5 the first night. Water level and temperature also peaked at the same time as the peak in salinity, indicative of an influx of seawater. After the initial peak, the salinity gradually dropped to 20 by the end of the time series analysis (Figure 26). The water level of Kanewai Spring fluctuated with a 12 hour period coinciding with the ocean tide and an amplitude of ~4-5 cm. Radon levels in Kanewai Spring started off low, 21000 dpm/m^3 and initially dropped to 11800 dpm/m^3, coinciding with the peak in salinity. This may have been due to flooding of Kanewai Spring with ocean water from Kanewai Fishpond. After this relatively low initial radon activity, radon levels consistently increased and leveled off around 95000 dpm/m^3 for about the last 12 hours of the time series deployment (Figure 27). The radon activity averaged over the entire period gave a groundwater discharge rate of 70.1 m^3, slightly lower than the first time series analysis. However due to the dramatic increase in radon activity, three separate groundwater discharge rates were also calculated based on the change in radon activity: July 14-15, 15-16, and 16-17 resulting in discharge rates of 30.4 m^3 day^{-1}, 68.2 m^3 day^{-1}, and 151.4 m^3 day^{-1} respectively. Using the drop in salinity from its peak of 33.5 to the final minimum salinity of 20, 56 hours later, a groundwater discharge rate of 16.0 m^3 day^{-1} was calculated using an end member salinity of 2.8 (based on the April deployment). This estimate is significantly lower than the one obtained from the radon mass balance. This may be due to the uncertainty in our groundwater end-member salinity and radon activity. Salinity seemed to be leveling out at about 6.5 during the later August deployment so the same calculation was also done using an end member salinity of 6.5 resulting in a groundwater discharge rate 20.5 m^3 day^{-1}. This estimate was still much lower than the radon derived discharge and we can conclude that in this setting for this short time period salinity is not the best tracer because there might be some interaction between Kanewai Spring and the high salinity water of Kanewai Fishpond that we cannot account for. No significant precipitation events occurred prior to or during this deployment.

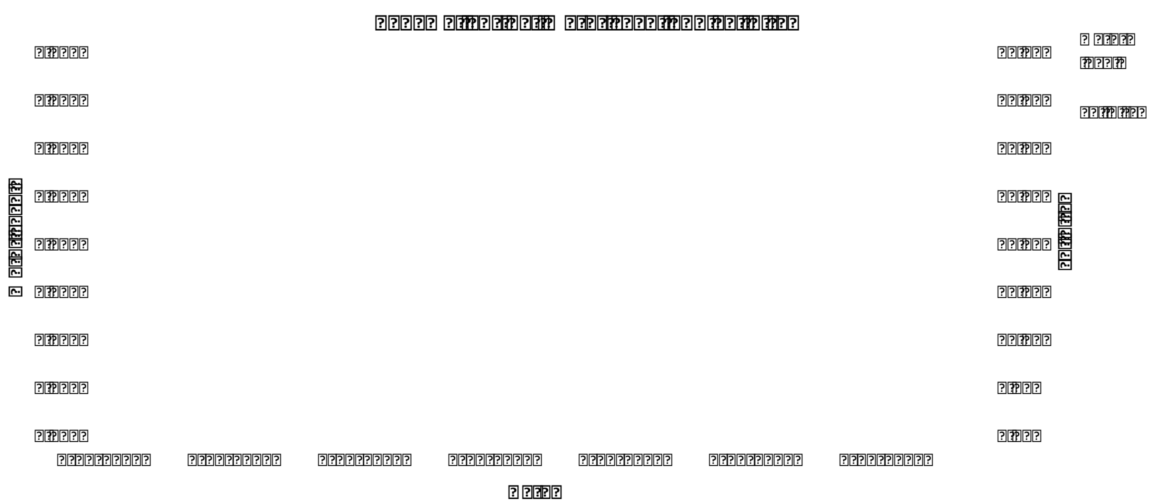

Figure 26. Kanewai Spring July deployment, salinity and water level.

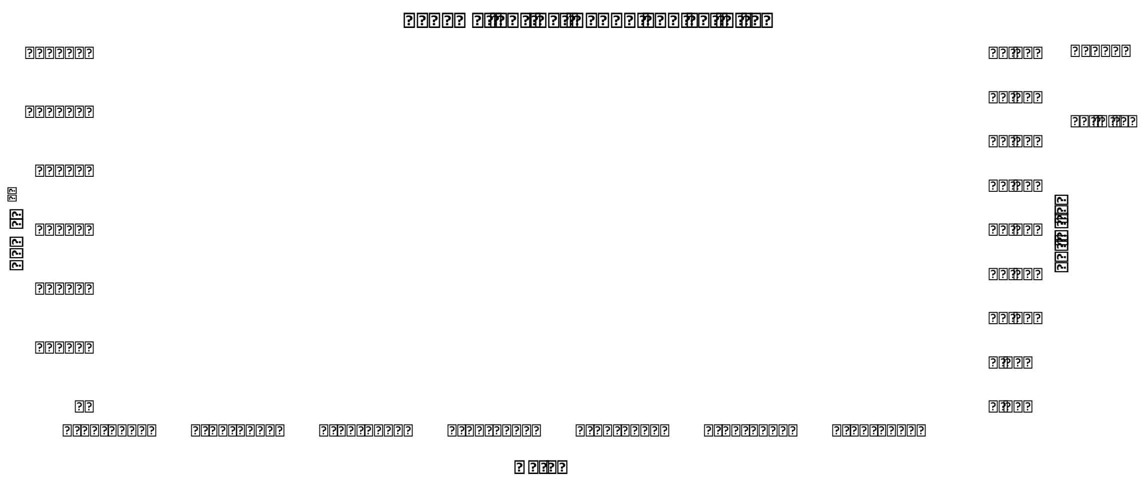

Figure 27. Kanewai Spring July deployment, salinity and radon activity.

4.2.3 Kanewai 12-26 August, 2010 deployment

The August deployment at Kanewai Spring lasted 14 days. The initial salinity of Kanewai Spring was 25.3 and peaked 4 hours later at 25.9. From this point, the salinity dropped for the next 8 days, leveling off at 6.5 before a fluctuating increase to 22.1 and subsequent decline that occurred over the last 6 days, with a salinity of 9.5 upon completion of the time series deployment (Figure 28). Figure 28 also shows how the water level of Kanewai Spring fluctuated with the semidiurnal ocean tide about 4-5 cm in a 12-hour period. Radon levels of Kanewai Spring started off low but quickly increased over the first day as the salinity dropped. Radon activity leveled off on the second day and then fluctuated between 100000 – 125000 dpm/m^3 for the next 4 days (Figure 29). A peak radon activity level of 157000 dpm/m^3 was observed on August 17, 2010. During the next four days, radon levels fluctuated more drastically with a net decrease to ~100000 dpm/m^3 when a blockage to the airline occurred on August 21 at 11:50 am invalidating the rest of the time series radon data. Radon levels were averaged from August 13 – 21, with an average radon activity of 117740 dpm/m^3 resulting in an average groundwater discharge rate of ~188 m^3 day^{-1}. In addition, a salinity mass balance calculation was done for the drop in salinity from the initial deployment salinity of 25. A groundwater discharge rate was calculated from the initial salinity peak to when it leveled off 5 days later to ~ 6.50, providing a discharge rate of ~158 m^3 day^{-1}. No significant precipitation events occurred prior to or during this deployment.

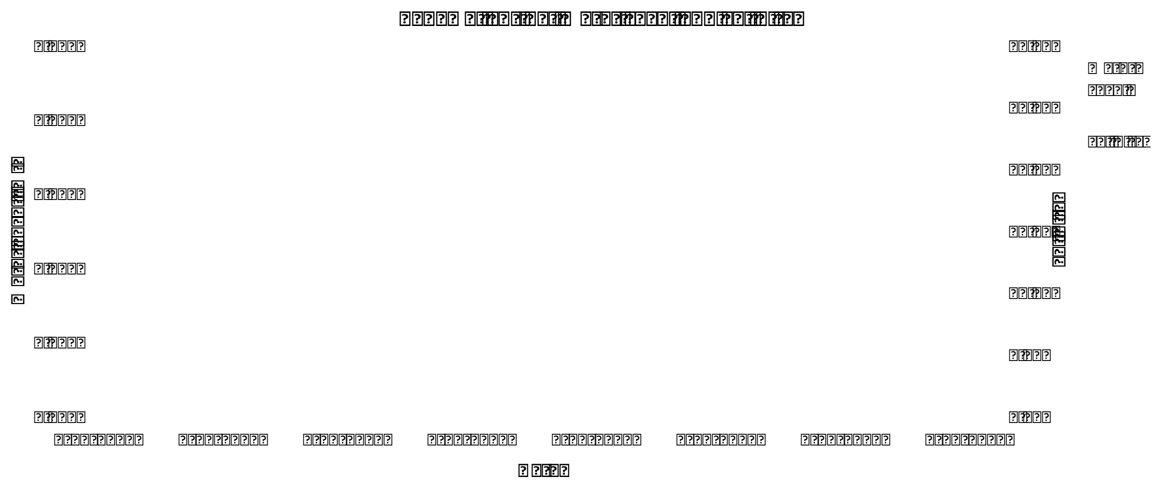

Figure 28. Kanewai Spring August deployment, salinity and water level.

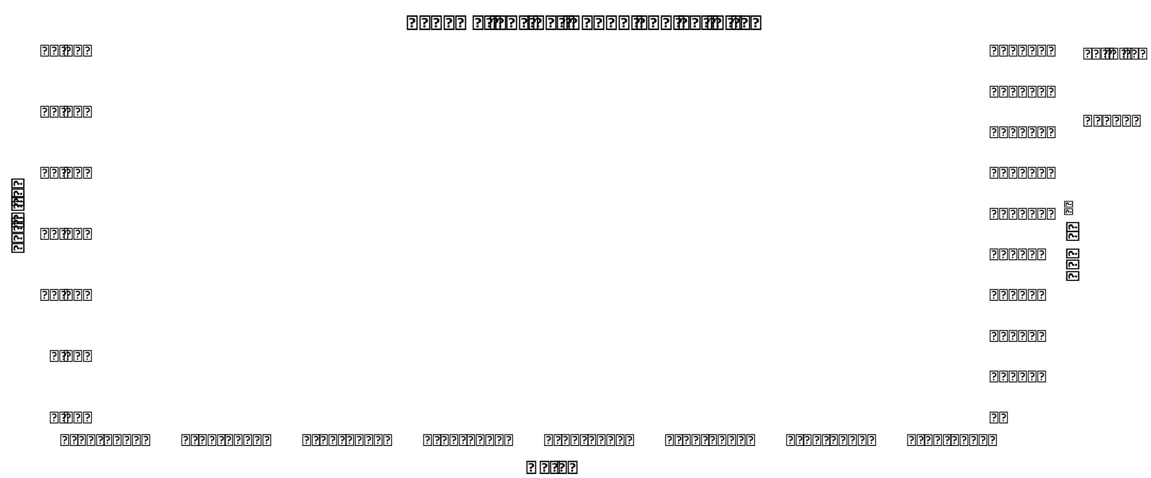

Figure 29. Kanewai Spring August deployment, radon activity and salinity.

4.3 CTD-Diver time series: Kanewai Spring, Kanewai Fishpond, Paiko Lagoon

CTD-Diver deployment for Kanewai Spring, Kanewai Fishpond, and Paiko Lagoon revealed some key coastal dynamics of the research area. The Paiko Lagoon diver recorded open ocean tide for comparison to what was occurring at the two research locations. A clear increase in tidal amplitude was recorded at the Paiko Lagoon site every two weeks, consistent with spring and neap tide fluctuations. The same increase in tidal amplitude could be seen in the Kanewai Fishpond and Kanewai Spring water level data (Figure 30). The data revealed that only during peak spring high tide does the water level of Kanewai Fishpond increase enough to flood Kanewai Spring with a subsequent increase in salinity of Kanewai Spring (Figure 31). The change in water level would also increase from an amplitude of ~ 4-5 cm to ~10-15 cm during the spring tide flooding of Kanewai Spring (Figure 32). The salinity of Kanewai Spring fluctuated between a high of 34 and a low of ~7. The salinity of Kanewai Spring did drop to a low of ~6 at the beginning of February at the end of the deployment. The 3 month long CTD-Diver time series revealed the consistency with which Kanewai Spring was flooded by high saline ocean water, allowing for the salinity mass-balance calculations to be completed. Table 1 shows all calculated flow rates based on both radon and salinity, which will be discussed in more detail in section 5.

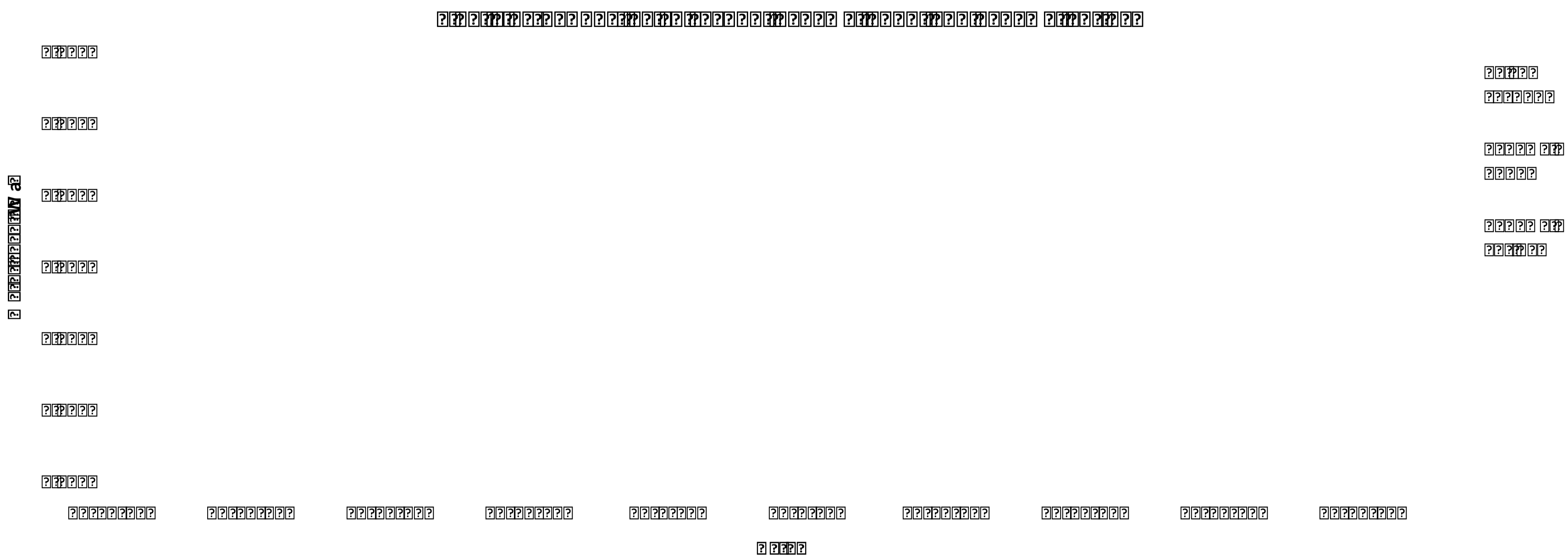

Figure 30. CTD-Diver time series data showing water level fluctuations due to spring tide events of Paiko Lagoon, Kanewai Fishpond, and Kanewai Spring

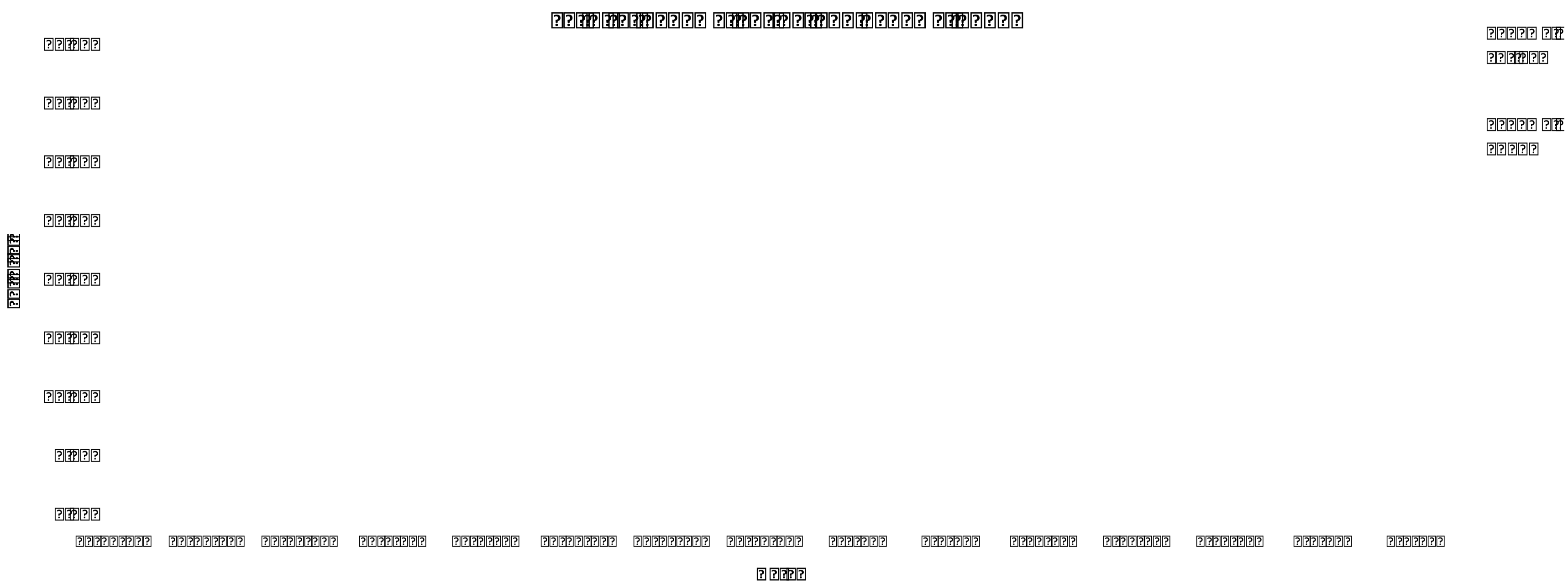

Figure 31. CTD-Diver time series data showing that the salinities of Kanewai Spring would match those of Kanewai Fishpond during peak spring high tides when Kanewai Fishpond would flood Kanewai Spring.

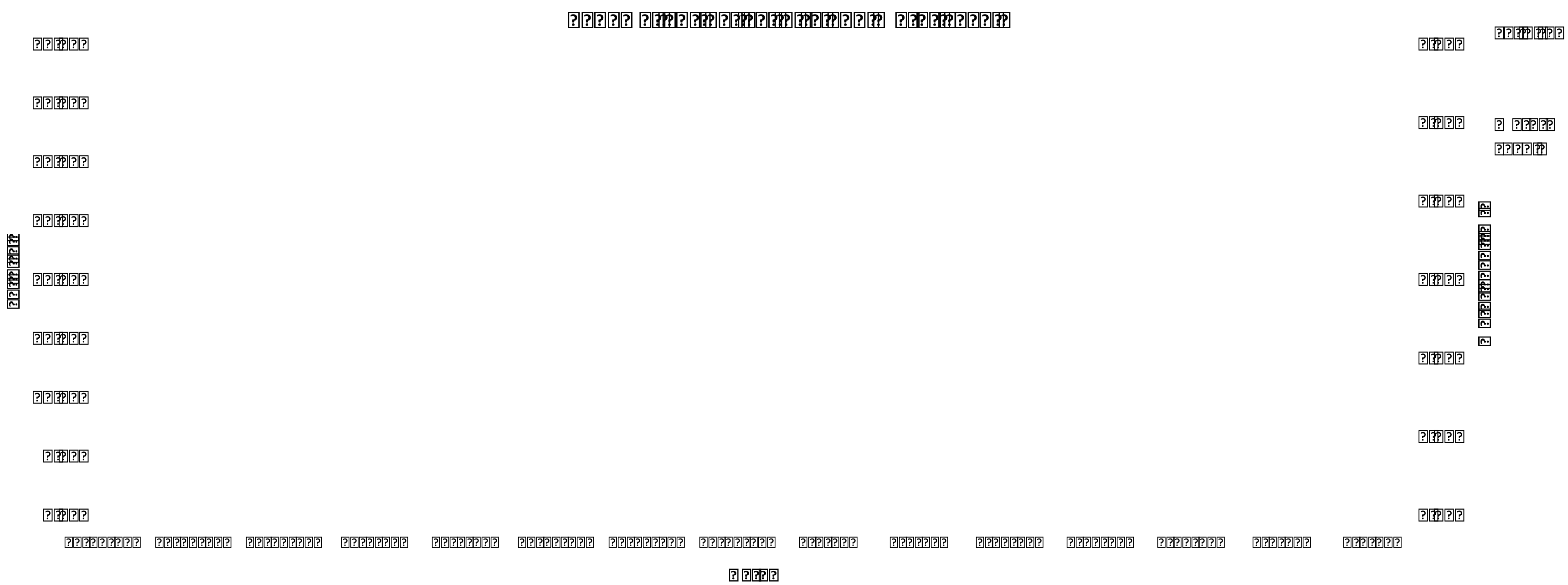

Figure 32. CTD-Diver time series data of Kanewai Spring showing the increase in salinity in conjunction with the increased water level amplitudes that coincide with peak spring high tides.

Table 1. Groundwater discharge rates ($m^3\ day^{-1}$) and monthly average rainfall (mm) at the two spring sites. Post-sewer line rehabilitation values are shaded.

		Radon mass-balance		Salinity mass-balance		Rainfall
	Date	Low	High	Low	High	Monthly Avg
Lucas Spring	Apr '10	0.6	0.7	0.6	1.1	26.7
	Aug '10	4.7	6.3	7.3	12.2	35.3
	Nov '10	-	-	35.8	114.5	95.5
	Mar '11	-	-	139.3	-	75.9
Kanewai Spring	Apr '10	-	82.0	-	-	26.7
	July '10	30.4	151.4	16.1	20.5	36.8
	Aug '10	-	188.3	36.1	157.8	35.3
	Nov '10	-	-	18.1	27.3	95.5
	Dec '10	-	-	22.9	33.1	272.5
	Jan '11	-	-	26.3	41.3	104.9

5 Discussion and Conclusion

The primary objective of this research was to determine before and after groundwater discharge rates to Lucas Spring, a spring clearly impacted by the road widening and sewer line rehabilitation projects, and Kanewai Spring, as a comparison site, which did not appear to be impacted by the construction. Although technical limitations allowed the collection of radon measurements to only take place before the rehabilitation project. The use of the Schlumberger CTD-Divers provided the opportunity to monitor post-work changes in water flux variations at both locations as a function of conventional salt balance modeling. In addition, the availability and thus longer-term deployment of the CTD-Divers also proved advantageous in providing a better overall grasp of the important impact of tides on the hydrology at both research locations.

5.1 Lucas Spring

The water volume of Lucas Spring changed dramatically throughout the entire research period of April 2010 to April 2011. Lucas Spring had an initial water volume of 7.7 m^3 during the April 2010 deployment, with only one fourth of the surface area covered with water, the remainder being desiccated to mud (Figure 33). Prior to the August deployment at Lucas Spring, the *`auwai* leading to the ocean had been partially dug out, allowing ocean water into Lucas Spring during some high tide events (Figure 34). The August deployment thus showed a dramatic change in water level with an estimated water volume of 64 m^3, covering all previous muddy areas of Lucas Spring. The increased salinity of the August deployment (~26 vs. ~20 in April, see Figure 19 and Figure 20), the visual observation of the *`auwai*, and the fact that the August radon inventories were of the same order of magnitude as those in April (150 and 350 dpm/m^2, respectively) all suggest strongly that this increase in water volume was mostly a result of increased surface flooding from the ocean.

Figure 33. Lucas Spring, April 2010. Photo: J. Kennedy.

Figure 34. Lucas Spring *`auwai* after being dug out (Photo: C. Cramer) and Lucas Spring July deployment Photo: J. Kennedy.

As noted above, this study's final deployment using CTD-Divers at Lucas Spring took place after the sewer line rehabilitation project was finished. The sealing of the sewer line took about 2 weeks to complete and began October 12, 2010. Due to the accessibility of the research locations, The CTD-Diver was deployed on November 11, 2010, approximately 2 weeks after the rehabilitation work was completed. The initial salinity reading on November 11 of 9.1 at Lucas Spring revealed a dramatic drop in salinity when compared to the April and August deployments (~20 and ~26 respectively), and the water level of Lucas Spring also increased from 0.08 m to an average depth of 0.4 m, giving an estimated volume of ~140 m^3. Although precipitation events must also be taken into account (see below), these values suggested that the sealing of the sewer line had indeed restored some flow of groundwater to Lucas Spring.

5.2 Precipitation events

The Niu Valley rain gauge showed a cumulative precipitation of 46.0 mm for the month of September 2010, slightly above the 30.0 mm average of the previous six months. The month of October 2010 had a cumulative precipitation of 10.2 mm. The salinity of Lucas Spring showed a dramatic drop over the month of November and into December (Figure 22). The month of November did have an increase in precipitation, although the salinity of Lucas Spring had already been fluctuating at remarkably low salinities of 4-5 even before the first significant precipitation event occurred, which was a 6-hour cumulative rainfall total on Nov 25, 2010 of almost 15.2 mm. A week after this precipitation event, the salinity fluctuations began to diminish and eventually leveled off below 3 about two weeks later when the next precipitation event occurred.

The next precipitation event took place on December 10, with a 12-hour rainfall total of ~50 mm (Figure 35); one day later a small spike in water level was observed at Lucas Spring. The one-day lag suggested that it was increased hydraulic head and not surface water runoff that impacted Lucas Spring. Interestingly, only a very small drop in salinity (0.3) was observed with the December 10 precipitation event, though the small salinity fluctuations prior to this event diminished greatly, suggesting that the precipitation and corresponding increase in hydraulic head overrode any tidally induced impacts of ocean water on the coastal aquifer at Lucas Spring.

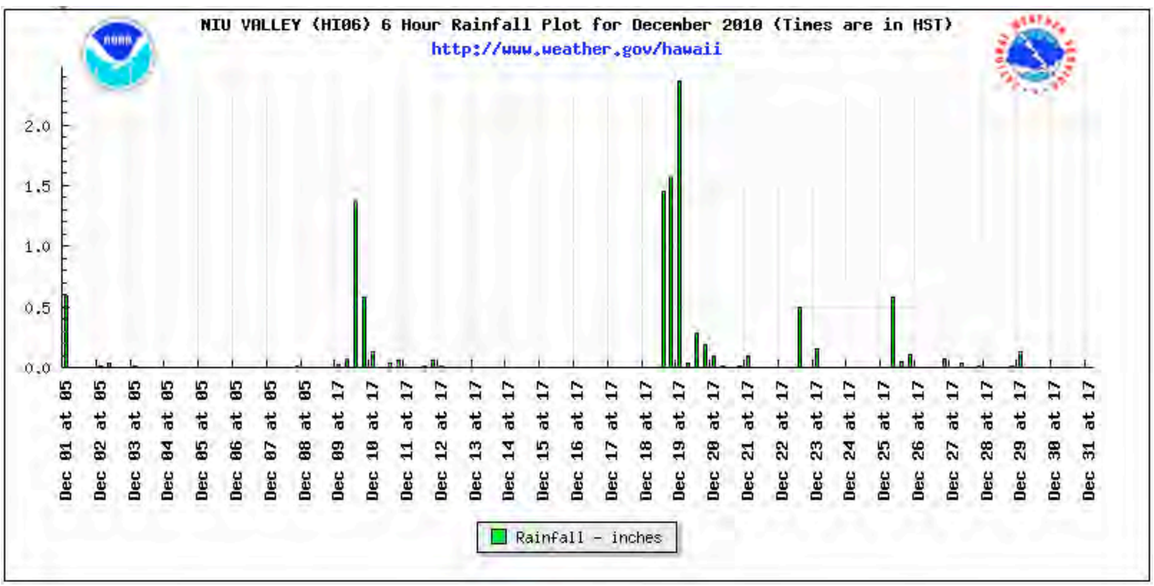

Figure 35. Niu Valley rain gauge 6-hour rainfall plot for December 2010 (www.weather.gov/hawaii).

The most notable precipitation event was a storm that occurred on December 19, 2010. The rain gauge in Niu Valley recorded two consecutive 6-hour rainfall totals ~40 mm, with a third 6-hour rainfall total immediately following totaling ~65 mm (Figure 35). The next day, a spike in water level at Lucas Spring was observed, followed by an increase in salinity. One might assume that the salinity of Lucas Spring would drop due to the amount of freshwater from the storm; however, the opposite occurred and the salinity increased, consistent with an influx of ocean water through the *`auwai*. CTD-Diver data from Paiko Lagoon, Kanewai Fishpond and Kanewai Spring revealed peak spring high tides at the same time period as the storm event. These combined events complicate differentiation between how much the rise in water level is due to increased hydraulic head from the storm and how much is from ocean water coming through the *`auwai*.

After the late December spring high tides, the salinity of Lucas Spring dropped consistently to just under 3 before a third precipitation event occurred with rainfall amounts of ~35 mm on January 12, 2011, and just over 50 mm on January 13, 2011 (Figure 36). A slight salinity drop to ~2 was observed at Lucas Spring one day later, which was accompanied by about a 0.1 m increase in water level that lasted for about 2 days. The salinity then leveled off at ~2 for the next 2 months until the tsunami of March 11, 2011.

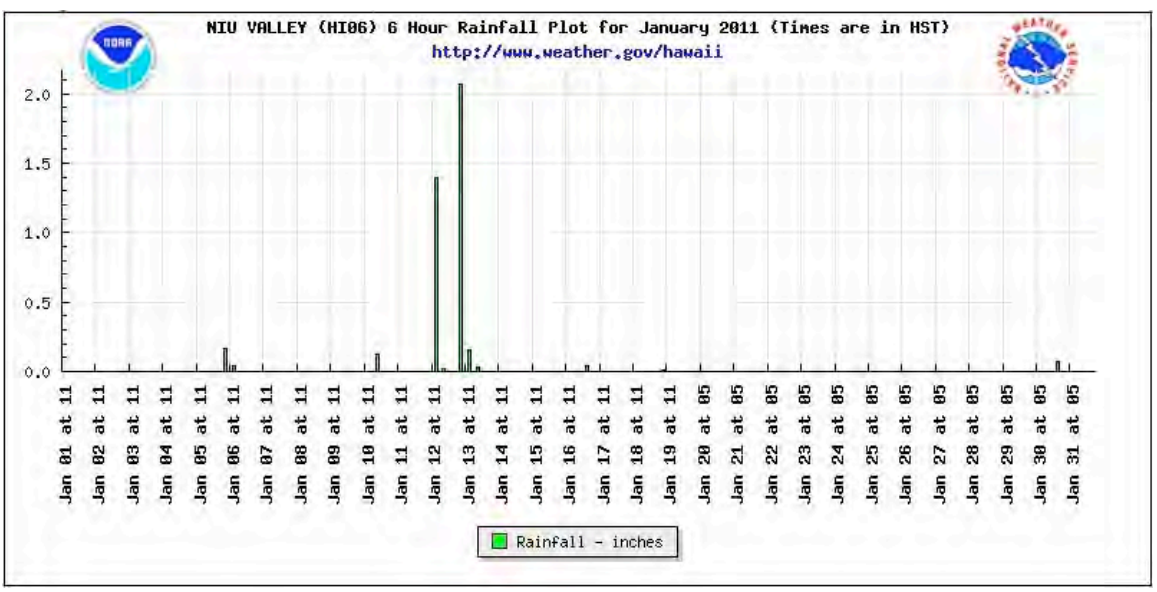

Figure 36. Niu Valley rain gauge 6-hour rainfall plot for January 2011 (www.weather.gov/Hawai`i).

Due to salinity changes during the 5-month deployment, the salt mass-balance approach (see Methods) was used to calculate a final groundwater discharge rate into Lucas Spring. In order to use this approach one must first determine the end-member salinity of the water that was discharging into the spring. During the first two deployments in April and August 2010, no clear salinity minimum was detected; this was expected due to the assumption that barely any water was flowing into the spring. The CTD-Diver provided a salinity minimum of 1.2 before the tsunami of March 11, 2011 hit Hawai`i. This provided the only clear representation of end member salinity for Lucas Spring that could be used when calculating the discharge rate using equation (9). During the tsunami, the water level of the pond rose 4.6 cm and the salinity increased from 1.3 to 11.8 in a span of 40 minutes (Figure 23). The sudden one time spike in salinity from the tsunami provided the perfect opportunity to then calculate a groundwater flux using the salinity mass-balance approach. Using this approach, the calculated groundwater discharge into the pond was a high 139 m^3 day^{-1}, which represents two orders of magnitude increase in groundwater discharge in comparison to April and August 2010 (both <1 m^3 day^{-1}).

5.3 Kanewai Spring

The April 2010 deployment at Kanewai spring showed salinities fluctuating in a narrow range between 2.8-2.9. The July deployment showed a vast difference from the April deployment with salinity reaching as high as 33.5 and only a low of 19.8 at the end of the deployment. The third deployment in August showed an even greater range with values ranging from a high of 25.8 and leveling off at a low of 6.5 before increasing again. Even the 3 month CTD-Diver deployment revealed that most salinity minimums never dropped below 6.5 with a few sporadic values dropping down to ~6 at the end of the deployment period. This shows that the salinity in Kanewai Spring is greatly influenced by the salinity of groundwater and water infiltrating from the fishpond. Since it is hard to determine exact groundwater salinity end-members for our salinity mass balance, we assumed a possible range of salinities based on the lowest salinities observed throughout our study period as a lower limit and where the salinity leveled out during the diver deployment as a higher limit. The two end member values of 2.8 and 6.5 were used to calculate a discharge rate providing a high and low range of groundwater discharge into the spring.

5.4 Overall trends in groundwater fluxes

Table 1 (Results section) shows the values of all SGD fluxes calculated using both radon and salinity. The groundwater flux rates into Lucas Spring show a clear increase when a pre- and post-rehabilitation project fluxes are compared. Both the April 2010 radon and salinity mass balance calculations reveal similar values. The Salinity mass-balance calculations for August are slightly higher than the radon mass-balance calculations. The November 2010 flux rates show a definite increase in groundwater discharge into Lucas Spring, in line with the assumption that the sewer line rehabilitation project did return some flow of groundwater to the conduit that feeds Lucas Spring. The nearly constant low salinity values for a two-month stretch in conjunction with the salinity mass-balance calculation from the tsunami salinity spike and subsequent drop back to extremely low levels further suggest that the sewer line rehabilitation project diverted water back to Lucas Spring. Our estimates show an increase of ~130 m^3 day^{-1}

which is 4% of the estimated 3,780 m^3 day^{-1} that was previously calculated to leak into the sewer lines before the rehabilitation project took place.

The calculated groundwater fluxes for Kanewai Spring do not show the same increase as in Lucas Spring. The Kanewai Spring radon mass-balance calculations show doubling of groundwater discharge from April to August 2010, before the sewer line rehabilitation project started. The salinity mass-balance calculations for August are much higher than the values calculated for July, November, December, and January. The August salinity mass-balance discharge rates are the only flow rates at Kanewai Spring that correspond with the radon mass-balance discharge rates for the same time period. This could be due to the fact that the salinity of the August deployment leveled out at 6.5, revealing the clearest end member salinity of the research period. The November, December and January flux rates, though much less than the August flow rate, show a progressive increase that is in line with the increased precipitation for that period. However, the salinity mass-balance flow rate calculations do not provide enough evidence to show that the sewer line rehabilitation project had any positive impact on the groundwater discharge at Kanewai Spring.

5.5 Conclusions

The results indicate that groundwater discharge to Lucas Spring increased after the sewer rehabilitation project by about two orders of magnitude, while discharge to Kanewai Spring over the same time period did not increase at the same magnitude. This may indicate that the rehabilitation project restored some groundwater conduits that are feeding Lucas Spring. To further test this theory we looked at sewer flow data obtained from HDR Inc., showing before and after sewer line rehabilitation dry-weather flow rates for the Niu Valley wastewater pump station. Figure 37 shows two dry-weather flow rates within the sewer system, with the January 2005 representative of the pre-rehabilitation scenario and the December 2010 flow rate showing the flow rate after the rehabilitation project was complete. The data reveals about a 2650 m^3 day^{-1} decrease in the flow rate after the sewer line rehabilitation project was completed. This data reveals that about 70% of the estimated 3,780 m^3 day^{-1} of groundwater is no longer infiltrating into the sewer line. All of the data suggests that the sewer line rehabilitation project did indeed restore some groundwater flow to the subterranean aquifer conduits, some of which feed Lucas Spring. Because only 4% of the restored flow of 2650 m^3 day^{-1}in Lucas Spring was accounted for, the rehabilitation project probably also enhanced groundwater discharge to the coastline or other nearby springs.

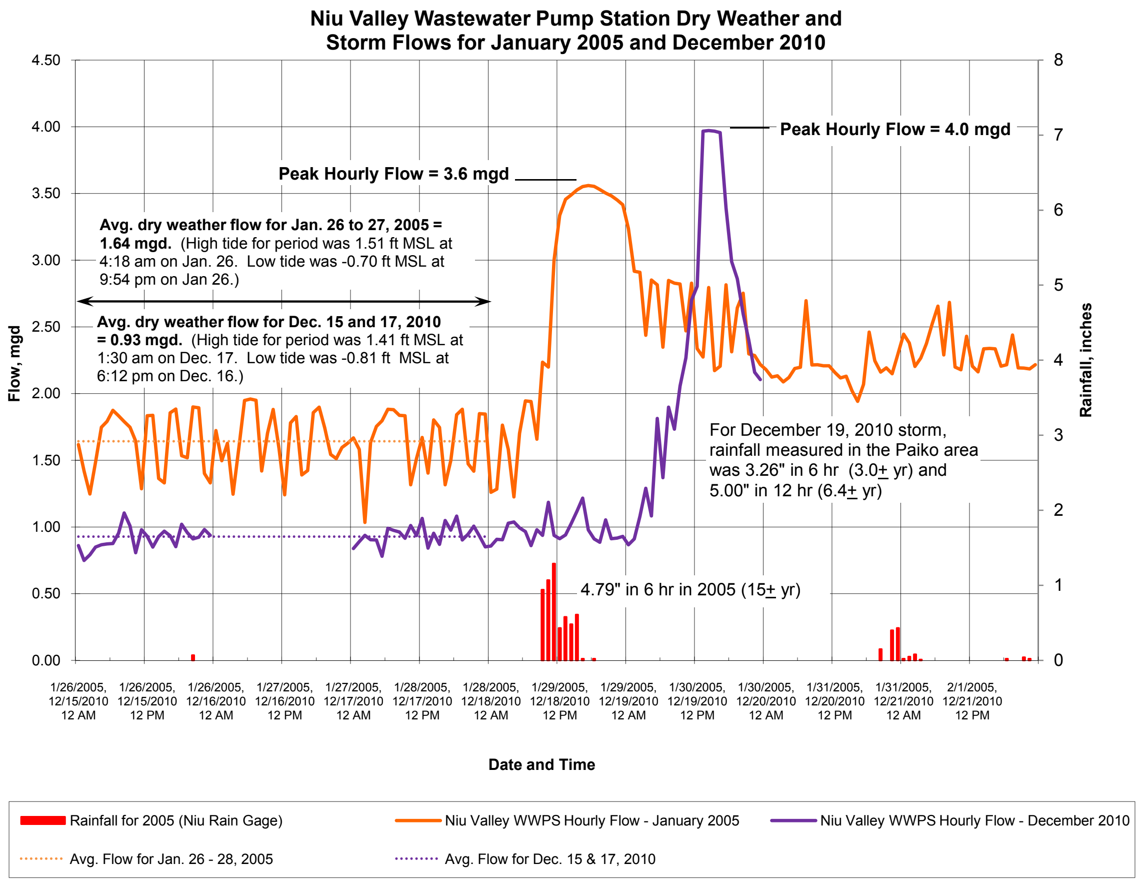

Figure 37. Dry-weather flow rates from the Niu Valley Wastewater Pump Station, showing flow rates from January 2005 and December 2010 (Abe, HDR Inc.).

Historically, both Lucas Spring and Kanewai Spring had an estimated 750 m^3 day^{-1} flux of groundwater. Fluxes observed at Kanewai Spring were on the order of 150 m^3 day^{-1} and the groundwater discharge in Lucas Spring after the restoration project was ~140 m^3 day^{-1}. Both these fluxes are significantly lower than the historic spring flow, representing only 18% of the 750 m^3 day^{-1}. This means that either not all water has been redirected back to Lucas Spring or that there is much less groundwater available as the aquifer has been stressed over the past few decades because of groundwater withdrawal for the public. Nevertheless, we can conclude that the sewer line rehabilitation project improved the flux into Lucas Spring and that the road-widening project on Kalanianaole Highway did indeed have an immediate and lasting effect on the groundwater discharge of the area. Lucas Spring has sat abandoned since 1994, but with the data suggesting that ~18% of the original flow of groundwater has been returned to the fishpond, and with the volume of water in the fishpond increasing from ~8 m^3 in April 2010 to ~190 m^3 in January 2011, there is now the chance that this location will once again be able to benefit the community through the continued preservation and restoration efforts of Maunalua Fishpond Heritage Center.

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Errata:

P.16 ‘most are on the verge of being taken away..’ Change word *most* to *many*.

P.17 Change to: *was founded in 2007*.

P.22 ‘Kanewai is listed as on the Historic Register’
Change to: *Kanewai meets the criteria to be on the Historic Register and is listed as Site 50-80-01166 on the State Inventory of Historic Places.*