

# **The Interplay of Oceanic and Terrestrial Forces on the Hydrology of a Loko Wai‘ōpae**

A FINAL REPORT SUBMITTED TO THE DEPARTMENT OF EARTH SCIENCES,  
UNIVERSITY OF HAWAI‘I AT MĀNOA, IN PARTIAL FULFILLMENT OF THE  
REQUIREMENTS FOR THE DEGREE OF

**MASTER OF SCIENCE**

IN

**EARTH AND PLANETARY SCIENCES**

**MAY 2024**

BY

**YUNXUAN ZHONG**

**COMMITTEE:**

**HENRIETTA DULAI**

**SCOTT ROWLAND**

**EMILIO HERRERO-BERVERA**

## **Abstract**

This research investigates the dynamic hydrologic interactions within a Loko Wai‘ōpae in the Keahuolū Ahupua'a of North Kona, Hawai‘i, that is characterized by tidal influences and terrestrial groundwater inputs. The study primarily focuses on how tidal cycles and rainfall impact water levels and salinity, crucial factors that define the ecological balance and sustainability of this sensitive ecosystem.

Utilizing a combination of field measurements and analytical techniques, this research evaluates the periodicity and interdependencies of tidal heights, water levels, and salinity. Data collected from November 2019 to March 2021 show daily and semimonthly tidal effects, as well as the impact of rainfall events on salinity and water level.

Tidal forces play a dominant role in modulating water levels, with a clear time-lagged correlation to ocean tides. There is an attenuation effect, where water level changes are not in direct proportion to tidal variations, suggesting a moderated influence of ocean tides due to the geological characteristics of the site. Conversely, salinity levels, although influenced by tides, display a more complex response pattern due to the mixing of seawater and freshwater inputs.

# 1 Introduction

Loko wai‘ōpae, in Hawaiian, refers to the unique type of brackish water ecosystem known as an anchialine pool, found along coastal zones with subterranean connections to the sea (Keliipuleole, 2022). Anchialine environments are created when containment structures, either through the dissolution of karst or the formation of lava tubes via volcanic activity, enable the sustained presence of water bodies with mixed salinity levels (Mylroie & Mylroie, 2011). Consequently, they are found only in regions where limestone or recent volcanic lava is present near the sea, including the Caribbean, Indo-Pacific, and Hawai‘i. Remarkably, over half of the world's loko wai‘ōpae habitats are located in the Hawaiian Islands, with more than 600 pools spread across Hawai‘i Island, Maui, and O‘ahu, underlining the islands' crucial role in conserving these distinct ecosystems (Brock, 1985; Chai, 1993).

Because they stand at the crossroads between ocean and land, the interplay of marine and terrestrial forces significantly impacts these ponds, defining their unique water characteristics. The salinity range of these ponds, from about 2 ppt to 34 ppt, supports diverse and highly specialized flora and fauna, characterized by their ability to endure environmental extremes and they exhibit high rates of endemism (Iliffe & Kornicker, 2009; Bailey-Brock & Brock, 1993). Tidal actions introduce seawater, affecting salinity and water levels, while terrestrial inputs, such as rainfall and groundwater, influence freshwater supply and salinity balance. This delicate interaction between sea and land is essential for maintaining the conditions of each loko wai‘ōpae.

With distinct locations and hydrological traits, tidal rhythms lead to significant and varying changes in the physical and geochemical features of each loko wai‘ōpae (Craft et al., 2008). The tidal influence is evident on both daily and semimonthly scales. Daily, high and low tides facilitate varying exchanges between the sea and these ponds. At high tide, seawater raises salinity and water levels in the ponds with seawater intrusion; whereas at low tide, seawater in the ponds is drained back into the ocean, lowering both. Semimonthly, spring and neap tides, aligned with lunar cycles, further influence these dynamics. Spring tides, during full and new moons, amplify gravitational interactions, resulting in higher and lower tides. In contrast, neap tides, occurring during the moon's quarter phases, see a reduced gravitational pull, leading to milder tidal fluctuations (Daher et al., 2021).

Rainfall, on the other hand, significantly influences the freshwater input into loko wai‘ōpae, particularly crucial for balancing the delicate salinity levels that support its unique biodiversity. When rainfall occurs, it typically leads to an increase in a pond's water level and a corresponding decrease in salinity. It is important to note, however, that rainfall in the study area often falls at higher elevations rather than directly over the pond itself. As a result, the primary way that rainfall influences the pond is through raising the freshwater head in the surrounding aquifer, which then promotes the flow of more freshwater into the pond, which is responsible for the delay in salinity adjustments following rainfall events.

The focus of this study is a specific loko wai‘ōpae located in the Keahuolū Ahupua‘a in the North Kona District of Hawai‘i Island. This research aims to look into the hydrologic dynamics of the pond, highlighting the interplay between the tidal rhythms and terrestrial inputs such as

groundwater flow and rainfall. By examining the influence of these factors on water parameters such as salinity and water level, the study seeks to offer insights into the resilience and vulnerability of these unique ecosystems to environmental changes especially considering climate change and sea level rise.

The study is significant for several reasons, each contributing to a comprehensive understanding of these unique ecosystems. Firstly, the research explored the complex interplay between terrestrial and marine forces that are dominating the pond's water parameters. With the pond acting as a window to expose the local aquifer, its sensitivity to tidal changes and precipitation illuminates the complexity of seawater-surface water interactions in coastal environments of a volcanic island. The potential findings are pivotal for enhancing our understanding of groundwater flow patterns, recharge mechanisms, and the profound influence of geological structures on water resources.

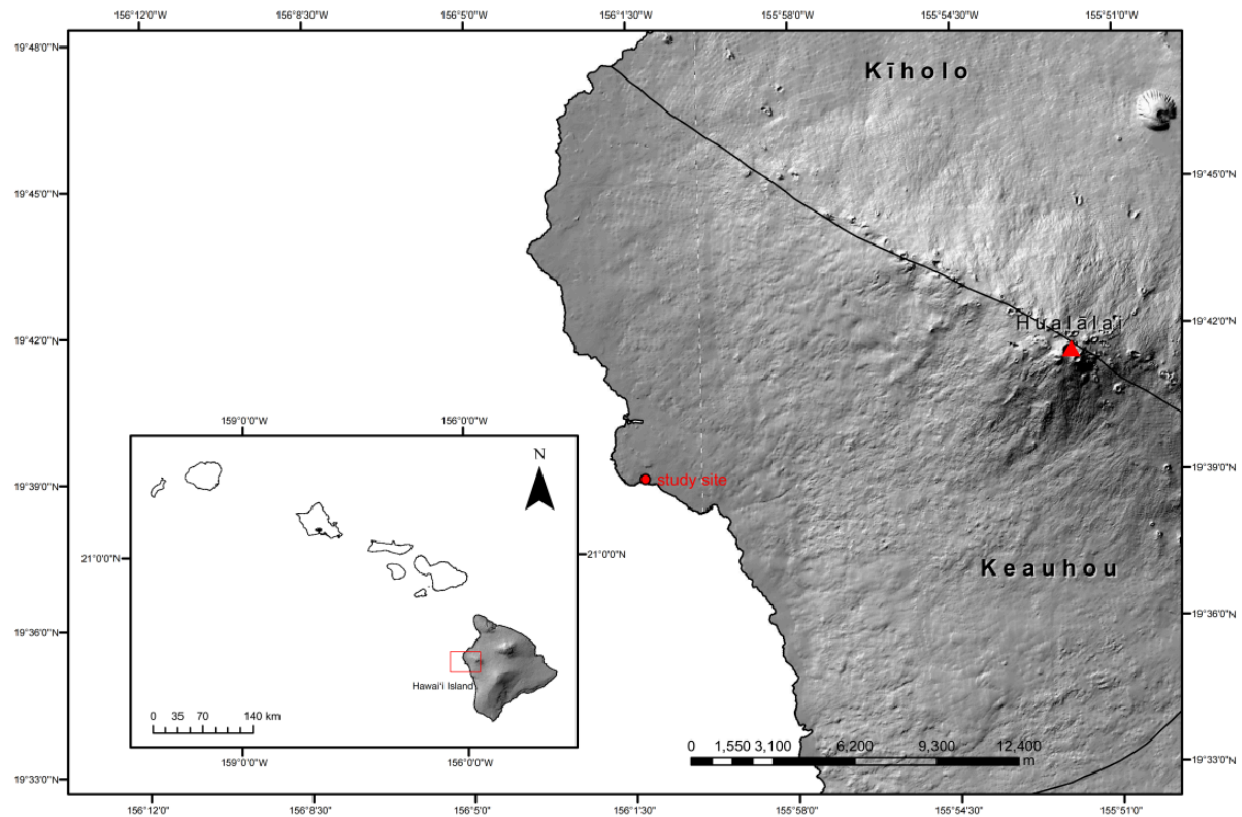
Moreover, the ponds, characterized by their distinct hydrological and ecological properties, are of great biological and conservation interest. These ecosystems often harbor unique species that have adapted to the specific conditions of anchialine environments. For instance, certain species that are found within these ponds exhibit remarkable tolerance to variations in salinity, a characteristic that has evolved over time due to the unique interface between freshwater and seawater within these systems (Iliffe & Kornicker, 2009). Despite their adaptability to current conditions, the future survival of these species is under potential threat due to climate change-induced factors such as higher temperatures, more evaporation, and sea-level rise. The

excessive intrusion of sea water into these habitats may alter salinity levels beyond the tolerance of the species, showing a risk to their continued existence.

## 2 Methods

### 2.1 Site Description

The loko wai'ōpae (19.64915°N, 156.02060°W) is located in the coastal lowlands of the Keahuolū Ahupua'a in the North Kona District, Hawai'i Island at Keahuolu Point, traditionally known as Hi'iakanoholae, on the flank of Hualālai volcano on the northwest side of the island of Hawai'i (Table 1). The pond is roughly 50 meters away from the coastline of Halepa'o Bay. The area of the pond is 253.89 m<sup>2</sup> and average depth is 0.19 m.



**Figure 1. Map of the Loko Wai'ōpae Location**

The climate of the Kailua-Kona region is semi-arid tropical, with warm, dry conditions prevailing year-round and an average annual rainfall of around 481 mm (Lau & Mink, 2017). Situated on the leeward side of the northeast trade winds, the area commonly experiences minimal precipitation, mainly at higher elevations. The study site benefits from sea breezes that increase cloud cover along the coast, which in turn mitigates radiation exposure and reduces evaporation rates. However, unlike the typical dry summer and wet winter pattern of leeward lowlands, the study area exhibits a seasonal rainfall trend with wet summers and less-wet winters, attributed to sea-breeze rains and the occasional Kona storms, which can bring heavy rainfalls during the winter months (Lau & Mink, 2017).

Hualālai volcano is a young and active volcano, which is primarily composed of porous basalt, with lesser quantities of andesite and trachyte (Langenheim and Clague, 1987). The geological surface unit at the study location is termed Qh2, which comprises basaltic lava flows dating to approximately 1,500-3,000 years ago (Sherrod et al., 2021). The fracturing, porosity, and permeability characteristics of these lava flows, coupled with the scant rainfall received in the leeward lowlands, significantly reduces surface runoff in this region. Consequently, groundwater acts as the essential connection between land-based water sources and the ocean in this area.

The main features of the lava flows contributing to their high permeability are (1) clinker zones associated with ‘a‘ā flows, (2) voids along the contacts between flows, (3) cooling joints normal to flow surfaces, and (4) lava tubes associated with pāhoehoe flows. The hydraulic conductivity is greatest parallel to the downslope direction of the lava flows, and is least perpendicular to the

layered sequence of lava flows (Oki, 1999). The most recent estimate of horizontal hydraulic-conductivity in the region is about 12,000 ft/d (Oki et al, 2021).

The aquifer type at the site is a coastal freshwater-lens system, which consists of an unconfined, lens shaped body of brackish water floating on denser, underlying saltwater that is in direct connection with the ocean. Water level in the loko wai‘ōpae readily responds to tidal fluctuations (Myloie & Myloie, 2011). This corroborates observations of transmission of the tidal signal to water wells hundreds to thousands of feet inland and is an indication of the high hydraulic conductivity (K) within the dike-free flank lava flows that comprise the region (Oki et al., 2021).

## 2.2 Data Collection

Salinity in the pond was measured using a CTD Diver (vanEssen Inc) installed on the SGD Sniffer, an autonomous, floating, underwater gamma-spectrometer (Dulai et al., 2016) with a sensor for measuring salinity and temperature added to its frame at ~0.2 m below water surface. This system was designed for coastal deployment and was placed in the pond from November 2019 to April 2022 (Figure 2). Salinity was measured at 15-minute intervals.



**Figure 2. The SGD Sniffer Deployed in the Loko Wai‘ōpae since 2019**

Additionally, a CTD Diver was employed for water level measurements. Fastened to a bedrock using cable ties, this device gathers total pressure data at 15-minute intervals, which, by subtracting barometric pressure, allows us to get water level. This technique ensured in-situ tracking of water level fluctuations that could be used to analyze pond depth and tidal fluctuations. Deployed alongside the SGD Sniffer since 2019, the CTD Divers captured detailed time-series data of water level and salinity. Measurements were taken every 15 minutes, from November 18, 2019, to April 1, 2021.

We obtained ocean tide height time-series data from the NOAA website (NOAA, 2019-2021), representing ocean water level data with a temporal resolution of one hour. Due to the unavailability of real-time data from the nearest tide station to the pond in Kailua-Kona, tide data from the Kawaihae station, located 48 km north of the study site, were utilized. The selection of a 20-minute tidal time difference correction between Kawaihae and Kailua-Kona was based on an analysis of NOAA Tide Predictions for both locations. This analysis revealed that peak tides at Kawaihae consistently occurred approximately 20 minutes later than those predicted for Kailua-Kona. Given that the Kawaihae station provides real-time data, we adjusted these data by advancing them by 20 minutes to accurately reflect the tidal conditions in Kailua-Kona. Tide height data sets could be accessed through <https://tidesandcurrents.noaa.gov/stationhome.html?id=1617846>.

The rainfall data utilized in this research were sourced from the nearby Keahole Airport station (PHKO) in Kailua-Kona, Hawai'i, provided by the National Centers for Environmental

Information (NCEI), accessed through the NCEI website at

<https://www.ncdc.noaa.gov/customer-support/certification-data>.

## 2.3 Data Preprocessing

Salinity data collected by the SGD Sniffer, together with the CTD Diver's pressure readings, were initially organized in an Excel sheet and subsequently analyzed in R Studio. The data from the CTD Diver, which reflected the water pressure at the bottom of the pond, were converted into water level measurements through calculations that incorporated the subtraction of local atmospheric pressure obtained from the Keahole Airport station (PHKO). These adjusted water level figures were then used as a variable for further analysis.

In refining the dataset, missing values were systematically addressed. For time-series data where a pattern or trend was observable, missing values were filled using linear interpolation between available data points before and after the missing entry. Outliers were defined as data points that lay beyond 1.5 times the interquartile range (IQR) above the third quartile and below the first quartile. This statistical method, known as the Tukey method, is commonly used to detect outliers in data. Such points were considered to significantly deviate from the majority of the dataset and were, therefore, excluded from the analysis.

## 2.4 Data Analysis

The data analysis for this research was performed using scripts available in a public GitHub repository, which can be accessed at <https://github.com/YunxuanZhong/method> for detailed replication and review.

### *Frequency analysis*

Frequency analysis plays a crucial role in understanding the periodicity of the variables by identifying the dominant frequencies within a time series dataset. The principle behind frequency analysis lies in decomposing a signal into its constituent frequencies, thereby facilitating the identification of recurring patterns within the data. In this study, Fast Fourier Transform (FFT) was chosen due to its efficiency in computing the discrete Fourier transform (DFT) and its inverse (Bouchaleun, 2019). The FFT algorithm transforms a sequence of values into components of different frequencies, thus enabling the detection of dominant cycles in tidal records, salinity, and water level data.

FFT was applied to the tidal height data, as well as salinity and water level data collected from the pond. The goal was to detect significant cyclic patterns that correspond to tidal influences in water parameters. The process involved subtracting the mean from each dataset to focus on the fluctuations around the mean value, thereby enhancing the analysis's sensitivity to periodic trends. For each dataset, the output of the FFT represents the magnitude of each frequency within the data. The output could be used to identify the dominant frequencies in the data, with the highest magnitudes. These frequencies were indicative of the most pronounced periodic behaviors, highlighting the cyclic patterns. This approach ensured an analysis of how tidal

movements impact the pond's dynamics through observable periodic patterns in water level and salinity.

### *Cross-correlation Analysis*

Cross-correlation analysis was employed to explore the relationship between the ocean tidal heights and both the salinity and water levels in the pond. This statistical method measures the similarity between two time-series datasets as a function of the displacement of one relative to the other, thereby elucidating any potential time lags or leads between them (Oświecimka et al., 2014). By calculating the cross-correlation function (CCF) between tide height data and environmental parameters (salinity and water level), it was possible to quantify the degree of correlation and identify the time lag at which the correlation peaked.

### *Attenuation Calculation*

In the attenuation analysis, a time lag between tide heights and water levels was identified through cross-correlation, pinpointing the strongest correlation to adjust for temporal shifts. Differences between consecutive tide heights and water levels were calculated, and the ratio of these differences during tide rising periods was calculated. This ratio shows the extent to which water level responses are dampened relative to ocean tide changes. By averaging these ratios, a single measure of the attenuation was obtained, providing insight into how external tidal forces influence the pond's water levels. This method allows for a focused examination of the dynamic interaction between tidal inputs and the pond's hydrological response.

## *Exploratory Analysis*

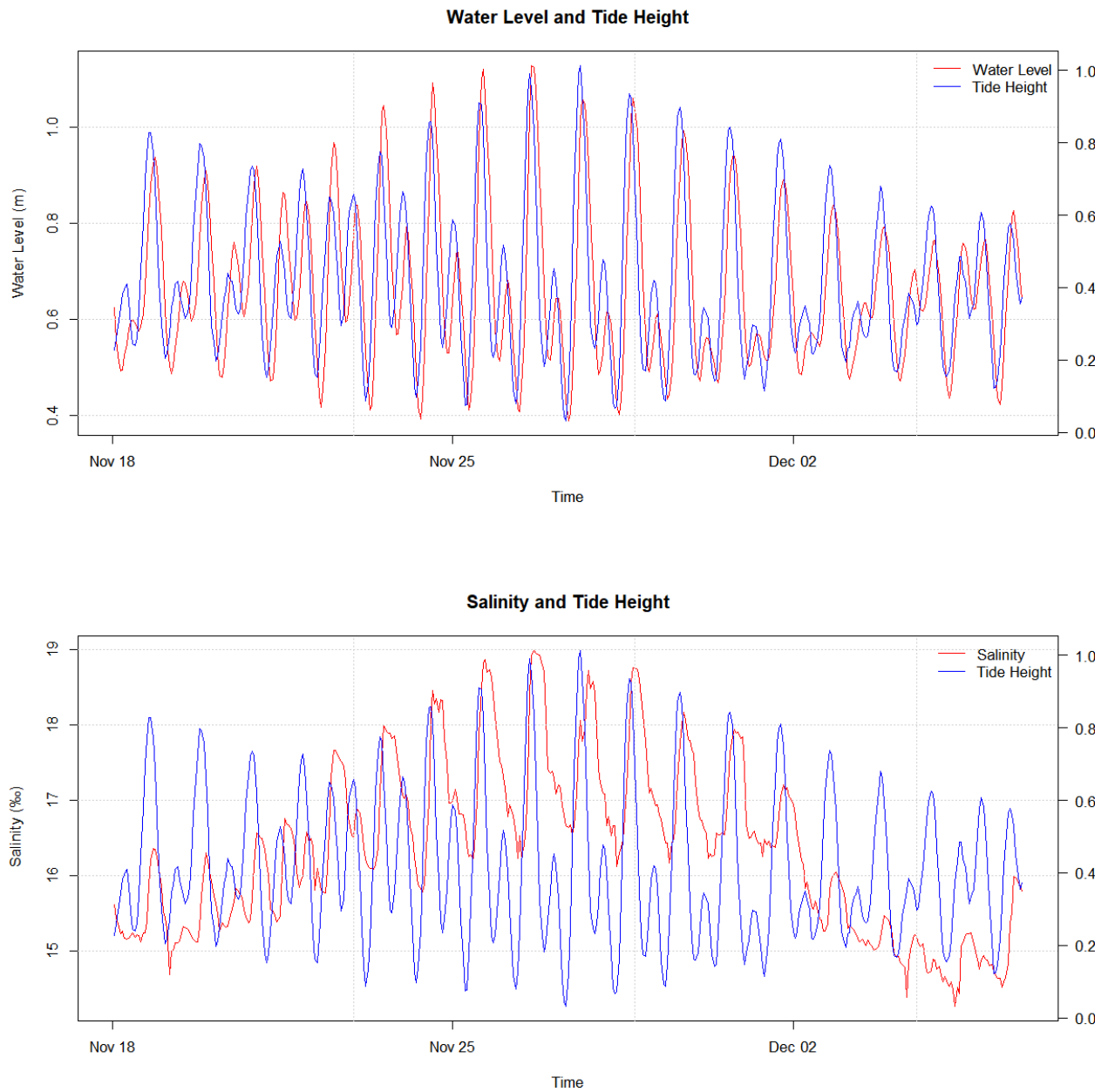
A variety of exploratory methods were utilized to examine the impact of rainfall on the ratio of salinity to water level in the pond. Initially, a correlation matrix assessed relationships among all parameters, including precipitation, salinity, and water level. Series of visualizations, such as time series plots, scatter plots, box plots, and histograms, were created to explore trends and patterns over time, offering insights into responses to rainfall events. Recognizing the lasting effect of rainfall on water parameters in the pond, a 48-hour period following each rainfall event was designated as a "rainy" condition to capture extended impacts. An F-test examined variance differences, and a t-test assessed mean differences in the ratio of salinity change to water level change between rainy and non-rainy periods. These statistical tests rigorously investigated rainfall's influence on the salinity/water level ratio, providing a comprehensive understanding of its effects on the dynamics of the pond.

## 3 Results

### 3.1 Cross-correlation Analysis

To assess how environmental factors, specifically ocean tides and the hydrological connection with the ocean, are influencing the conditions within the loko wai‘ōpae, I conducted a cross-correlation analysis on water level and salinity, each compared with the tide height over a period of a month. This analysis aimed to understand the interdependencies between ocean tidal changes and the water parameters of the pond.

The initial analysis focused on the correlation between water level and tide height. The time series plot shows that despite a slight offset, i.e. a delay in peaks, the two parameters exhibit almost identical amplitudes (Figure 3A). For the study site, water levels are influenced not only by the daily tidal cycle, resulting in daily shifts, but also exhibit fluctuations on a monthly scale. During the spring tide periods, when tide heights are higher, the water level noticeably increases. Conversely, during neap tide periods, it decreases.



**Figure 3. Tidal Cycle Dynamics in the Loko Wai'ōpae**

A: Water level fluctuations (red line) alongside ocean tide levels (blue line) during the tidal cycle of November/December 2019.

B: Salinity variations (red line) alongside ocean tide levels (blue line) over the same tidal cycle period.

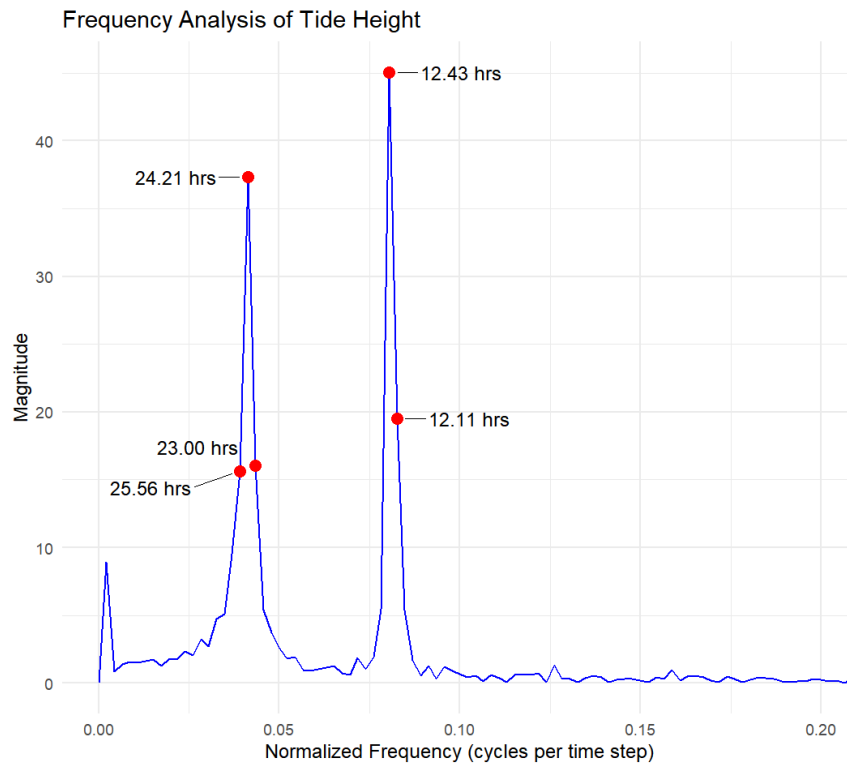
To quantify the relationship between water level and tide height, the Cross-Correlation Function (CCF) in R was utilized. The CCF is a statistical tool that measures the correlation between two time series at different lags. Mathematically, the lag at which the maximum correlation coefficient is observed indicates the actual time lag between the series. In this case, the analysis of the CCF revealed that the maximum correlation coefficient of 0.96 occurred at a lag of 2 hours. This strong positive correlation signifies a substantial impact of tidal changes on the water level. The 2-hour lag, as indicated by the shift in the CCF, represents the pond's response time to the external oceanic forcing.

Figure 3B shows the correlation between salinity in the pond and tide height. Although the correlation is not as strong as that between pond height and tide height, salinity is largely influenced by the tidal cycle, exhibiting daily shifts and variations over a semimonthly tidal period. The maximal correlation coefficient was 0.47, reflecting a moderate positive correlation. At the point of maximum correlation, there was a 3-hour time lag. This delay presented the complex processes of salinity adjustment, including the mixing of waters between the pond and groundwater as well as actual aquifer salinity conditions.

From the findings, it is evident that ocean tidal height plays a vital role in governing the water level and salinity in the pond, with the former more closely tracking the tidal patterns. The robust correlation between water level and tide height suggests that the water level variations within the loko wai‘ōpae are predominantly governed by the oceanic tidal forces.

## 3.2 Frequency Analysis

In the study, a frequency analysis was conducted to understand the periodicity in the behavior of tide height, water level, and salinity in the loko wai‘ōpae. The frequency analysis of tide height, utilizing Fast Fourier Transform (FFT), revealed significant periods that signify the natural oscillation of tides. Notably, the 24.21-hour and 12.43-hour frequencies have the most obvious magnitudes, presented on the magnitude vs. frequency spectrum plot as 2 dominant peaks (Figure 4).

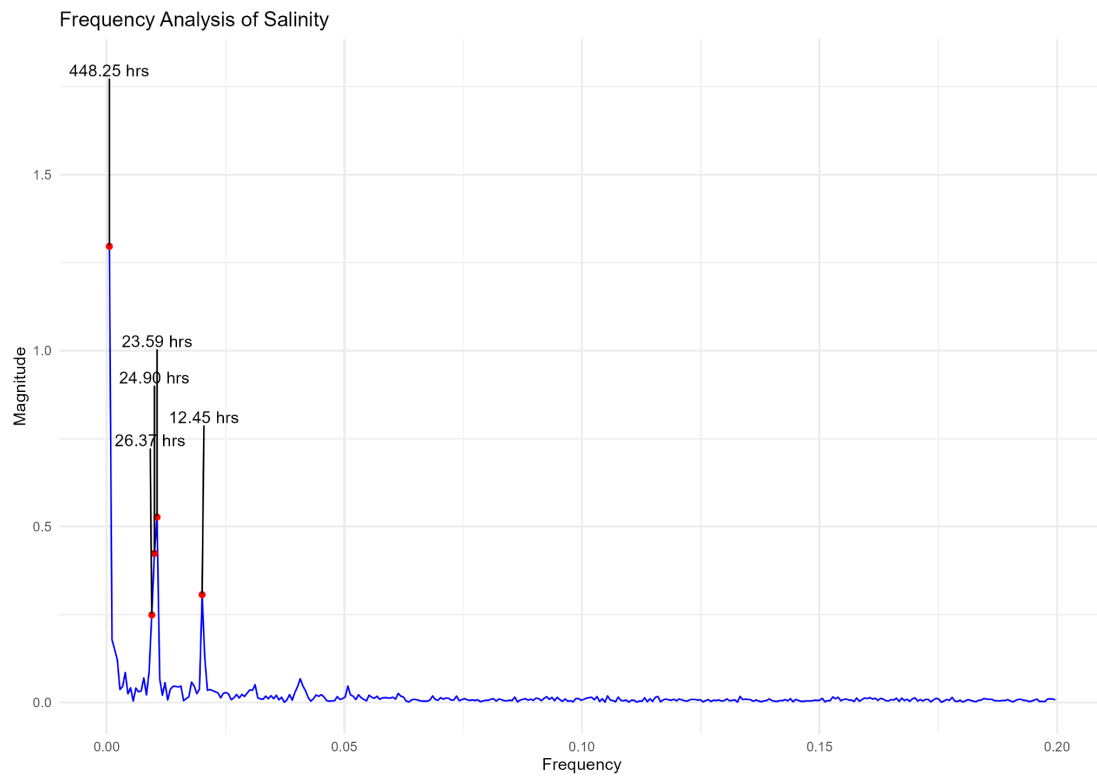
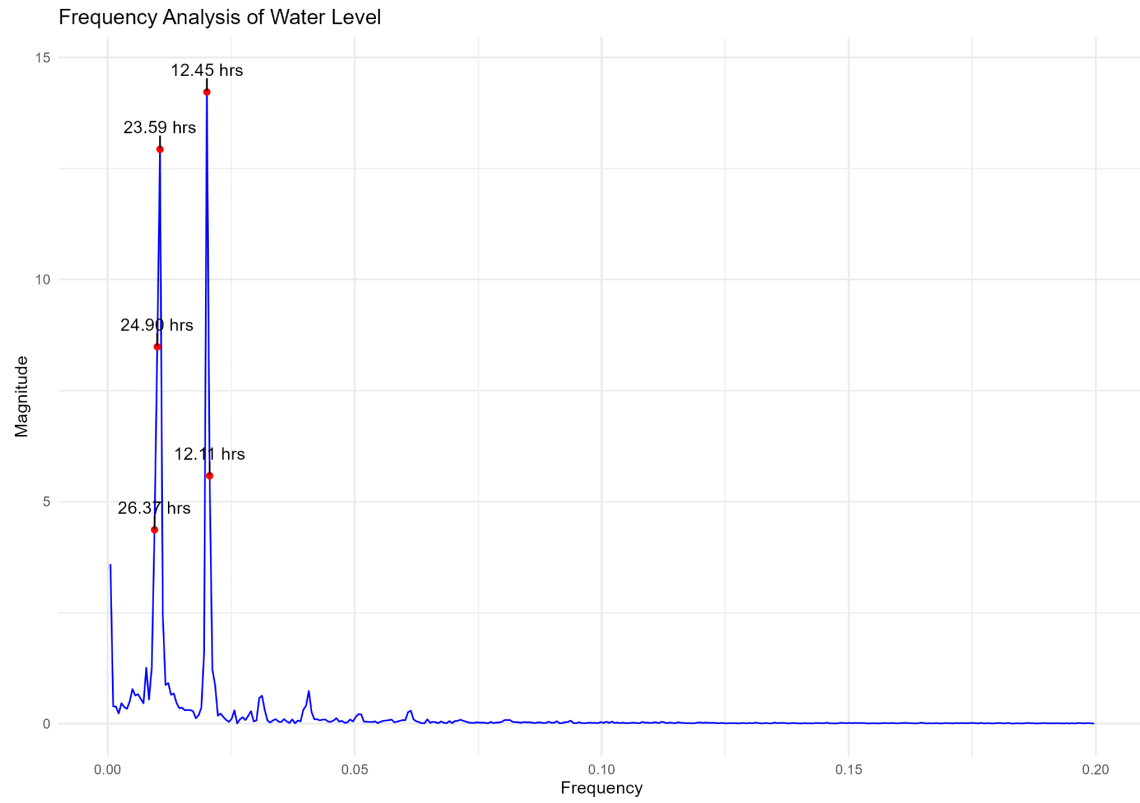


**Figure 4. Frequency Analysis of Ocean Water Levels**

Prominent peaks in the frequency domain (red dots) indicate a strong tidal signature in the ocean water levels, correlating with expected tidal frequencies.

In the measurements for water level and salinity, the time unit (sampling interval) was 15 minutes. After utilizing FFT, the water level exhibited dominant periods at 49.81 time units (12.45 hours) and 94.37 time units (23.59 hours). This finding emphasizes the semi-diurnal and diurnal patterns that correspond closely with the tidal frequencies, further highlighting the strong linkage between the tidal forces and the water level in the pond (Figure 5A).

Salinity exhibited dominant periods at 49.81 time units (23.59 hours) and 94.37 time units (12.45 hours) as well (Figure 5B). The alignment of salinity cycles with the semi-diurnal and diurnal patterns further illustrates the tight coupling between the tidal patterns and the salinity fluctuations in the pond. The salinity spectrum also reveals a cycle of 448.25 hours, approximately 18.7 days. We have not been able to identify any natural or human activities that this cycle may correspond to.



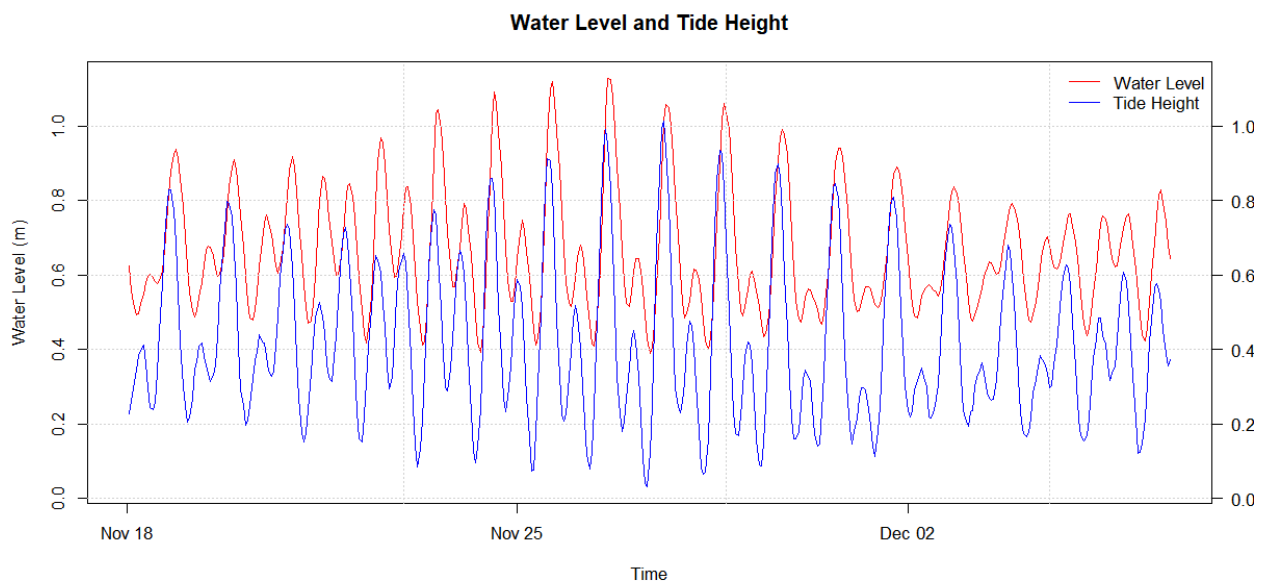
**Figure 5. Frequency Analysis of Water Level and Salinity Indicating Tidal Influence**

A: Water Level Frequency Analysis. The red dots identify peak frequency components that highlight the periodic nature of water level changes, suggesting a strong correlation with tidal patterns.

B: Salinity Frequency Analysis. The red dots mark dominant frequency components that underline the oscillations in salinity, indicative of the tidal influence on salinity levels.

### 3.3 Attenuation Calculation

Despite the high correlation between water level and tide height, these two parameters do not change in perfect unison. In the normalized time series plot that is presenting the curves for the two parameters, the y axis of the two have different scales, showing that the tidal effect is somehow diminished through hydrologic processes (Figure 3A). To plot the curves with the same range, a unnormalized time series plot was created(Figure 6), which can further suggest this diminished effect with a smaller range in the change of water level than tide height.



**Figure 6. An Unnormalized Time Series Plot with the Curves of Water Level and Tide Height**

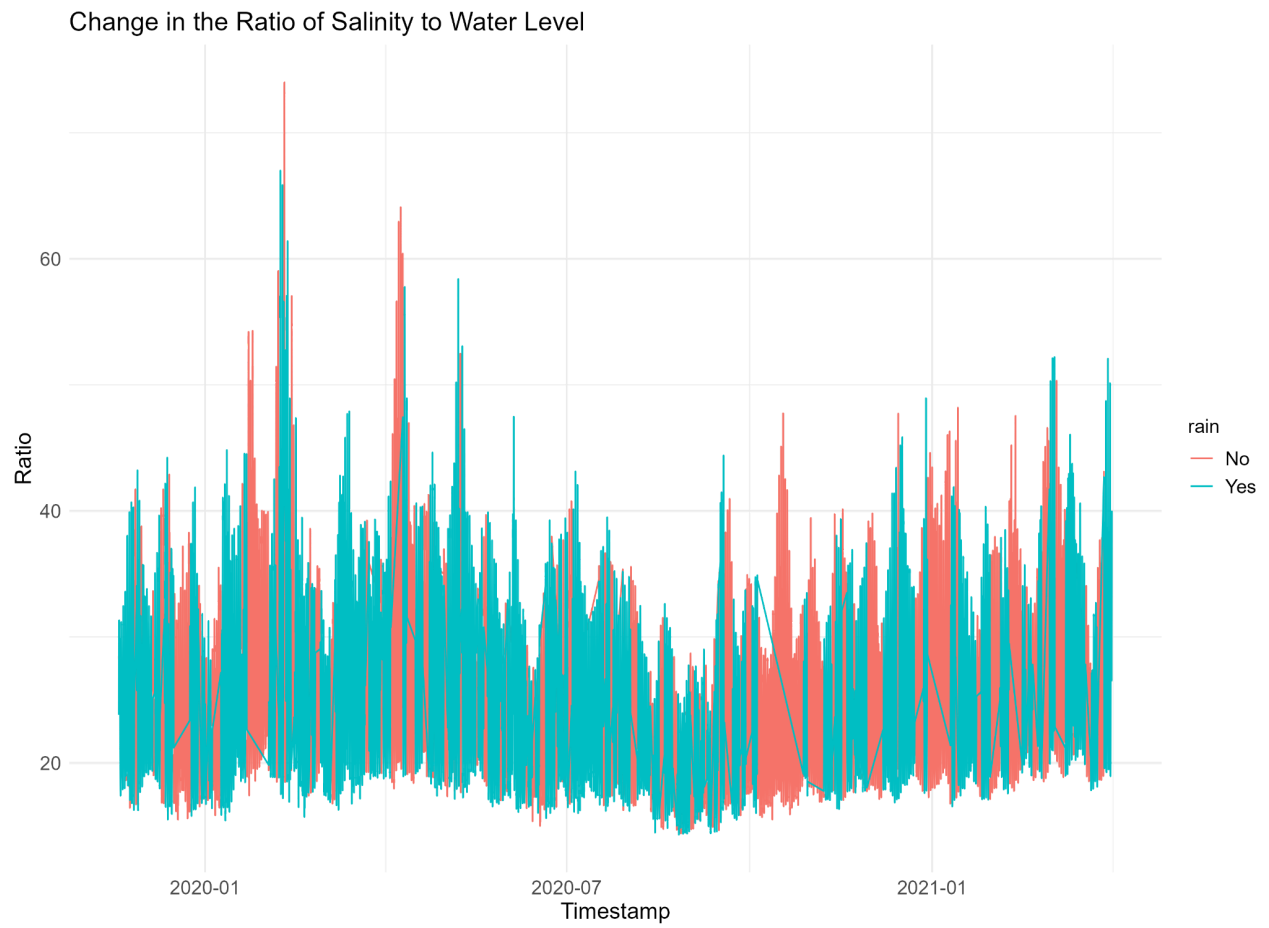
To further understand how water level response is modulated by changes in tide heights, the attenuation effect was taken into consideration. The attenuation calculation revealed that for every meter rise in tide height, the water level in the pond increases by approximately 0.638 meters, suggested by the attenuation ratio of 0.638. This attenuation ratio is essential for understanding the water dynamics within the pond, as it reflects the extent to which tidal forces are absorbed by the aquifer's characteristics.

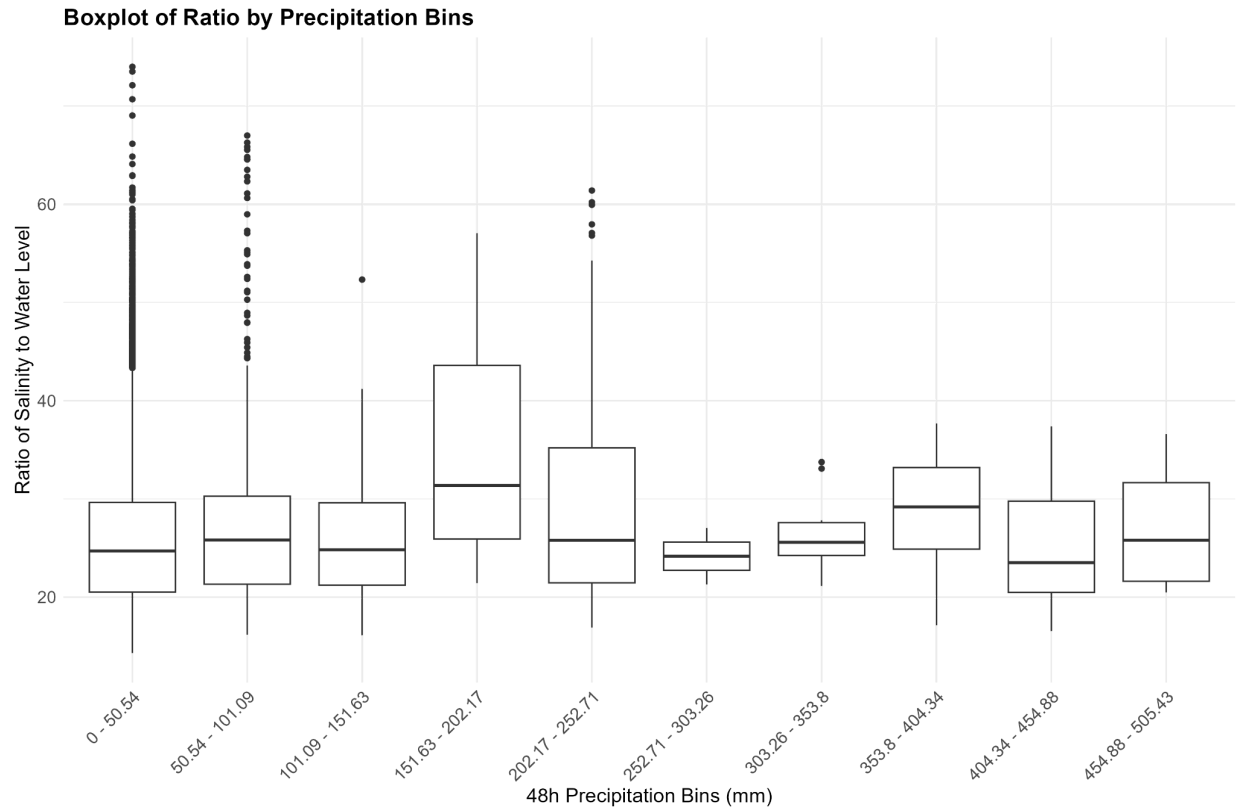
### 3.4 Rainfall effect

In this section, I study the impact of rainfall on the pond salinity. Potential impacts are via direct precipitation on the pond, surface runoff, and groundwater flow. Because salinity is also tidally driven (see above), in this analysis we normalize salinity by dividing it by water level to remove the tidal effects. In other words, we are looking for deviations from the positive salinity-water level pattern produced by the tides. The goal is to determine whether precipitation events, particularly within a 48-hour window following rain, affect salinity and water level, as the results suggest that this time frame is most relevant. We used 17 months of data for this analysis (Nov, 2019 - March, 2021).

Rainfall Window Analysis visualized different periods within and outside the 48-hour window following rain events. Because patterns are not obvious in the time series plots (Figure 7A), I divided the water level normalized salinities, i.e. salinity/water level ratios into bins based on the amount of rainfall within 48 hours and generated a box plot. Each bin represents a 50 mm precipitation range (Figure 7B). The binned data show that during the post-rain window, the

salinity/water level ratio range tended to decrease with decreasing precipitation, suggesting that rainfall introduces a diluting effect on the pond's salinity relative to water level increases.





**Figure 7. Exploratory Analysis of Rainfall Effect**

A: Change in the ratio of salinity to water level with periods of rain highlighted in blue color.

B: Boxplot of Ratio by Precipitation Bins, categorizing the data into bins based on 48-hour precipitation amounts.

Statistical Tests provided evidence of rainfall's influence:

- The F-test confirmed significant variance differences in the salinity/water level ratio between rain and non-rain periods, with a p-value of  $2.452e-11$ , which is far below the 0.05 threshold.
- The T-test also showed a significant mean difference in this ratio between the two conditions, indicating a measurable effect of rainfall on the pond's hydrological balance, with a p-value of  $2.836e-06$ .

In conclusion, the decrease in this ratio following rain events highlights the diluting impact of freshwater input on pool salinity, counterbalancing the saline influx from tidal activities.

## 5 Discussion

The analysis conducted in this study shows the impact of tidal cycles on water levels and salinity in the loko wai‘ōpae. To present these effects more clearly under different scenarios (king tide, spring tide and neap tide) within tidal cycles and to extend the research to a broader ecosystem perspective, nine days were selected as representative samples during the study period. These included three regular neap tide days, three regular spring tide days, and three king tide days, which are characterized by the highest tidal range within the year. Utilizing the tidal differences on these specific days, along with the average depth of the pond, I calculated the daily changes in pond water volume. These calculations were then used to estimate the extra nutrient fluxes resulting from the seawater’s incursion and subsequent outflow afterwards.

The observations are presented in Table 1. The differences between water level fluctuations and salinity changes during spring tides, neap tides, and particularly king tides, is substantial. The application of ANOVA for test significance has confirmed that the differences in water level and salinity changes across these three scenarios are statistically significant, with p-values less than 0.05. This provides a clear indication of the profound impact that different periods of the tidal cycle can have on the pond, affecting both water levels and salinity.

	Date	high WL (m)	low WL (m)	$\Delta$ WL (m)		$\Delta$ PV (m <sup>3</sup> )	high S (ppt)	low S (ppt)		$\Delta$ S (ppt)	N(g/d)	P(g/d)	Si(g/d)	
KT 1	01/12/20	1.23	0.39	0.84		213	20.34	17.34		3.00	210.58	48.07	3866.47	
KT 2	08/18/20	1.22	0.49	0.73		185	18.21	15.01		3.20	183.01	41.78	3360.14	
KT 3	12/15/20	1.2	0.37	0.83		211	20.60	17.37		3.23	208.07	47.50	3820.44	
					avg	203				avg	3.14	200.55	45.78	3682.35
ST 1	12/14/19	1.14	0.38	0.76		193	18.94	14.51		4.43	190.53	43.49	3498.23	
ST 2	04/11/20	0.95	0.29	0.66		168	18.28	15.12		3.16	165.46	37.77	3037.94	
ST 3	07/23/20	1.13	0.41	0.72		183	19.35	16.49		2.86	180.50	41.20	3314.11	
					avg	181				avg	3.48	178.83	40.82	3283.43
NT 1	12/05/19	0.71	0.62	0.09		23	15.21	13.93		1.28	22.56	5.15	414.26	
NT 2	04/22/20	0.74	0.45	0.29		74	15.94	14.28		1.66	72.70	16.60	1334.85	
NT 3	07/14/20	0.81	0.66	0.15		38	16.54	15.00		1.66	37.60	8.58	690.44	
					avg	45				avg	1.53	44.29	10.11	813.19

**Table 1. Hydrological Parameters for Nine Sample Days in the Pond**

'KT' denotes King Tide days, 'ST' denotes regular Spring Tide days, and 'NT' denotes regular Neap Tide days. Nutrient flux estimations are derived from the differences in the pond's water volume on each respective day and groundwater nutrient levels from Hudson 2017.

These findings are important in the context of global warming, because most models (provide references) forecast rising sea levels. It is not difficult to imagine how loko wai'ōpae like the one in this study could face the threat of flooding more regularly. Such inundations could lead to potential negative consequences, such as the introduction of invasive species that may thrive in altered water conditions. Moreover, as salinity levels increase, native species may struggle to adapt.

Additionally, the increase in pond water volume observed during each tidal cycle carries with it a significant nutrient load. As detailed in Table 1, the influx of subsurface seawater introduces nitrogen and phosphorus, which are key elements that fuel the growth of native algae and support the pond's primary productivity. The potential rise in sea levels and the increasing frequency of extreme weather events due to climate change could amplify the nutrient levels, similar to what is observed during king tides. If climate anomalies cause an excessive elevation in nutrient levels, this could lead to eutrophication and subsequent algal blooms, which could disrupt the delicate balance of the pond's inhabitants.

## **6 Conclusion**

This study has investigated the dynamic interplay of oceanic and terrestrial forces within the loko wai‘ōpae of Keahuolū Ahupua'a. The findings reveal the dominant influence of tidal cycles on water parameters (water level and salinity), demonstrating a significant correlation with tidal cycles. The delayed responses of pond water level and salinity reflect the pond's hydrodynamic character. Rainfall events, especially those with more precipitation, could affect the ratio of salinity to water level, offsetting the tidal effect.

The implications of these findings are critical especially in the context of climate change scenarios with increased sea levels and frequency of extreme weather events. These changes could threaten the biodiversity and ecological functionality of the pond. Since the study has shown how profoundly tidal cycles influence the pond's dynamics, an unusual rise in sea levels could lead to the pond's inundation, relocation, or even disappearance. At the same time this would disrupt the salinity balance and could lead to an influx of excess nutrients. Addressing these potential challenges is essential for the future preservation and management of this delicate ecosystem.

Disclaimer: this report was prepared with assistance of a translation application  
YOUDAO.

## **7 Reference**

Keliipuleole, Keku‘iapōiula. AIA KE KUMU WAIWAI MA MAKALAWENA:  
ANALYSIS OF THE NATURAL RESOURCES WITHIN THE MAKALAWENA  
LOKO WAI‘ŌPAE COMPLEX. University of Hawai‘i at Manoa, 2022.

Myroie, J. E., & Myroie, J. R. (2011). Void development on carbonate coasts: Creation  
of anchialine habitats. *Hydrobiologia*, 677(1), 15.

Brock, R. E. (1985). An assessment of the conditions and future of the anchialine pond  
resources of the Hawaiian Islands. Environmental Assessment Company.

Chai, D. K. (1993). Biophysical Inventory and Assessment of Anchialine Pools Along the  
Waiakea Coast, Hilo, Hawai‘i. University of Hawai‘i at Manoa.

Iliffe, T., & Kornicker, L. (2009). Worldwide diving discoveries of living fossil animals  
from the depths of anchialine and marine caves. *Smithsonian Contributions to Marine  
Science*, 38, 269–280.

Bailey-Brock, J. H., & Brock, R. E. (1993). Feeding, reproduction, and sense organs of  
the Hawaiian anchialine shrimp *Halocaridina rubra* (Atyidae).

Craft, J. D., Russ, A. D., Yamamoto, M. N., Iwai, T. Y., Hau, S., Kahiapo, J., Chong, C. T., Ziegler-Chong, S., Muir, C., Fujita, Y., Polhemus, D. A., Kinzie, R. A., & Santos, S. R. (2008). Islands under islands: The phylogeography and evolution of *Halocaridina rubra* Holthuis, 1963 (Crustacean: Decapoda: Atyidae) in the Hawaiian archipelago. *Limnology and Oceanography*, 53(2), 675–689.

<https://doi.org/10.4319/lo.2008.53.2.0675>

Daher, Houraa, et al. “Long-Term Earth-Moon Evolution With High-Level Orbit and Ocean Tide Models.” *Journal of Geophysical Research. Planets*, vol. 126, no. 12, 2021, p. e2021JE006875-n/a, <https://doi.org/10.1029/2021JE006875>.

Lau L S, Mink J F. *Hydrology of the Hawaiian Islands*[M]. University of Hawaii Press, 2017.

Langenheim V A M, Clague D A. The Hawaiian-Emperor volcanic chain; part II, stratigraphic framework of volcanic rocks of the Hawaiian Islands[J]. *Volcanism in Hawaii*, 1987, 1: 55-84.

Sherrod, D. R., Sinton, J. M., Watkins, S. E., & Brunt, K. M. (2021). *Geologic map of the State of Hawaii* (Scientific Investigations Map No. 3143). U.S. Geological Survey.

<https://doi.org/10.3133/sim3143>

Oki, Delwyn S. Ground-Water Resources in Kaloko-Honokohau National Historical Park, Island of Hawaii, and Numerical Simulation of the Effects of Ground-Water Withdrawals. U.S. Geological Survey, 1999.

Oki, Delwyn S. Numerical Simulation of the Effects of Groundwater Withdrawal and Injection of High-Salinity Water on Salinity and Groundwater Discharge, Kaloko-Honokōhau National Historical Park, Hawai'i. U.S. Department of the Interior, U.S. Geological Survey, 2021.

Dulai, Henrietta, et al. "Autonomous Long-Term Gamma-Spectrometric Monitoring of Submarine Groundwater Discharge Trends in Hawaii." *Journal of Radioanalytical and Nuclear Chemistry*, vol. 307, no. 3, 2016, pp. 1865–70, <https://doi.org/10.1007/s10967-015-4580-9>.

BOUNCHALEUN A. An Elementary Introduction To Fast Fourier Transform Algorithms[J]. 2019.

Oświęcimka P, Drożdż S, Forczek M, et al. Detrended cross-correlation analysis consistently extended to multifractality[J]. *Physical Review E*, 2014, 89(2): 023305.

National Oceanic and Atmospheric Administration. (2019). Tides and currents. Retrieved from <https://tidesandcurrents.noaa.gov/>