INVESTIGATING DRIVERS OF COASTAL FLOODING TO ENHANCE THE RESILIENCY OF LOKO IʻA ALONG THE HILO HANAKAHI COASTLINE, HAWAIʻI

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ʻIke i ke au nui me ke au iki.
Knows the big currents and the little currents.
Is very well versed.
ʻŌlelo noʻeau #1209

Aloha. I chose this ʻōlelo noʻeau to signify one must know all to know everything. I am a steerswoman, who strives to be well-versed in and out of the waʻa, yet I know I can't fulfill this. I have navigated through many currents, big and small through life, the COVID pandemic, and now graduate school. Here is just one passing current of my life that I hope uplifts all the work and dedication of our lāhui today for our future.

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Abstract

Coastal ecosystem environments are undergoing stresses due to climate change, particularly in Hawaiʻi. Loko iʻa, traditional Hawaiian fishponds, require a balance of ocean and freshwater to sustain the ecosystem that lives within. With an increase in sea level, these sites become susceptible to higher water levels, salinity, and the introduction of invasive species. This study examines the environmental drivers of the water level variability experienced within the loko iʻa along the Keaukaha coastline during the summer 2023 and winter 2023-24 King Tide events. Given that Hawaii island only has two tidal stations for nearly 290 miles of coastline, water levels recorded by in-situ sensors were compared to the National Oceanic and Atmospheric Administration (NOAA) Hilo tide station to evaluate the accuracy of NOAA predictions in reflecting local conditions. Environmental variables like rainfall, wave height, wave period and direction, wind speed and direction, and water and air temperature were analyzed to determine their influence on the water level departures between the loko iʻa and NOAA. Results revealed that water levels measured at most loko iʻa were double or more than NOAA predicted values. In the summer, water levels departures were influenced by wave height (0.44%) and water temperature (0.89%), while in the winter, departures were influenced by wave height (2.27%) and by wave period (0.40%) and wind speed (0.35%). Wave action variables emerged as the dominant environmental factor influencing the loko iʻa water levels. This community-based research provides insight into how dynamic the coastlines of Keaukaha are and validates the observations of the loko iʻa kiaʻi, but also provides guidance into other environmental variables to assist in managing their sites for future sea levels.

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Introduction

Sea level rise (SLR) is currently and will continue to reshape coastlines, resulting in significant and lasting changes to coastal landscapes. Since 1993, the sea level has risen 104.7 ± 4.00 mm in the past 30 years as of June 2023 (Willis et al., 2023). Sea level change is driven by the melting of land-based ice sheets and mountain glaciers and the expansion of warming ocean water (Church et al., 2007; Lambeck et al., 2014; Cazenave & Moreira, 2022). The rate of SLR varies locally and differences in relative sea level are influenced by vertical land motion (e.g., subsidence or uplift), ocean currents, and short-term variations such as tides, storm surges, and waves (Kopp et al., 2014; Nicholls et al., 2021; Woodworth et al., 2019; Wöppelmann & Marcos, 2015; Church et al., 2007; Church & White, 2011). When considering local factors, the impact on coastlines can double or triple what is predicted (Nicholls et al., 2021; Marcos et al., 2019; Vitousek et al., 2017; Taherkhani et al., 2020). Understanding the local variations of sea level rise is critical for accurately predicting its impacts and developing effective coastal management strategies.

Populated coastal communities are already experiencing many negative impacts of SLR, especially across the Pacific (Nicholls et al., 2021). According to Part B of the 2014 Intergovernmental Panel on Climate Change (IPCC) Fifth Assessment Report, there is a strong agreement among climate scientists that SLR is one of the predominant threats to low-lying coastal areas and atolls (Nurse et al., 2014). Low-lying coastal areas and island communities threatened by large tidal fluctuations are estimated to experience an increase in flooding events annually and seasonally as storm surges continue to strengthen (Mimura, 1999; Nurse et al., 2014; Vitousek et al., 2017). Increasing sea levels are impacting many biological and cultural sites along the coasts. In Hawaiʻi, roughly 60% of the coastal native vegetation is highly disturbed by high wave energies, invasive species, road and urban development, and lava flows (Jacobi & Warshauer, 2017). There is also the concern of burials, artifacts, and historical homes along shorelines seen to be threatened in the oncoming years (Kane et al., 2012). Another significant issue arising with rising sea levels is saltwater intrusion into coastal groundwater systems, threatening freshwater resources. As future sea levels increase, the freshwater table rises, causing flooding further inland while also disturbing access to drinking water, irrigation used for crops and nearby coastal infrastructures (Mimura, 1999; Rotzoll & Fletcher, 2013; Marrack, 2015; Habel et al., 2017; Sweet et al., 2014; Habel et al., 2023). All these threats may force communities to migrate elsewhere or establish strategies to mitigate these issues.

Hawaiʻi Sea Level

To date, research has looked to further understand the impacts of future sea levels on Hawaiʻi's coastlines. Multiple studies have looked at the developed coasts with hard infrastructures (e.g. roads and wastewater infrastructure) at risk, such as those on Maui and Oʻahu (Habel et al., 2017; McKenzie et al., 2021; Cooper et al., 2013). Other studies have examined at how SLR will impact Native Hawaiian cultural and environmental resources like wetlands, anchialine pools and fishponds along the coast (Marrack, 2015; Kane et al., 2015; Marrack, 2016; Marrack et al., 2021; Steward et al., 2024). To model the impacts of future sea levels, these studies apply an array of techniques. Some research has measured local-based water measurements like extreme high tides, while others used regional-based scenarios from Sweet et al., 2022. This project hopes to contribute to SLR research done in Hawaiʻi by combining in-situ measurements and geospatial mapping with the integration of community-based knowledge.

For this study, we focused on extreme high tide events as a proxy to understand future sea level rise on the east side of Hawaiʻi island. These extreme high tide flooding events are called king tides, also known as perigean spring tides. These events are a natural phenomenon that occur twice a year in Hawaiʻi and have an estimated three-month duration (University of Hawaiʻi Sea Grant, n.d). King tides commonly occur during the summer and winter seasons on full and new moons when the sun, moon, and Earth align, causing a stronger gravitational pull which results in the highest high and lowest low tides of the year (EPA, 2011). Previous studies have used king tides as a proxy to determine coastal areas that will be impacted by future sea levels and quantify future coastal flood risk (McKenzie et al., 2021; Steward et al., 2024; Thompson et al., 2019; Lin et al., 2014). Here, king tides will be used to assist in understanding the variation in water levels reported between the local tidal station and local in-situ water levels recorded along the Keaukaha coastline, Hilo.

Currently, Hilo is experiencing a local relative sea level increase of 3.11 +/- 0.28 mm/year (NOAA, 2023). This is the second-highest rate within the Hawaiian Islands. However, it is not based on SLR alone. Previous research has found that land subsidence has also contributed greatly to the high rate (Caccamise et al., 2005; Yang and Francis, 2019). A study found that since Hawaiʻi island is located over the Pacific hotspot, there is an unstable rate of subsidence compared to the other Hawaiian Islands further from the hotspot (Parker, 2016). Another local influencer of sea level rise is the daily tides. Hawaii has a mixed semi-diurnal cycle, meaning two high tides and two low tides of unequal values occur every lunar day. The variation of the tides challenge researchers to determine long term trends in sea levels without having to separate the data. Also, for the nearly 266-mile coastline, there are only two harmonic tidal gauge stations for Hawaiʻi island. Tide station 1617433 is located in Kawaihae Harbor on the west side, while tide station 1617760 is in Kuhio Bay, Hilo on the eastern end (National Oceanic and Atmospheric Administration (NOAA), 2012). Tidal stations have been implemented in research to find new ways to understand future sea levels over the years. However, the predicted water level data is based on only a few variables, such as historical water levels and the moon's and sun's position (Parker, 2007). When it comes to the dynamic coastlines of Hawaiʻi, the accuracy of this tool is unknown, thus making it difficult to predict what environmental conditions and water levels will be experienced locally, especially concerning coastal management and protection of coastal cultural heritage sites.

Traditional Hawaiian Aquaculture

Hawaiian fishponds, or loko iʻa, are an important coastal cultural heritage site that is being impacted by rising sea levels. These are traditional aquaculture systems created by Native Hawaiians hundreds of years ago that use existing flow of waters and natural or man-made barriers (Apple & Kikuchi, 1975; Wyban, 2020). These fishponds are unique to Hawaiʻi and were designed to capture and raise fish sustainably. Loko iʻa are typically constructed along the shoreline using rocks, coral, and other natural materials to create a barrier that allows water to flow in and out. These brackish water ponds use the tides to bring ocean water, nutrients and new fish recruitments into the pond while flushing out waste and excess water. Designs of the loko iʻa differ based on the local environment. The three types in this study are the loko kuapā, loko wai and kāheka. The loko kuapā is a fishpond with a kuapā (seawall) that may consist of one or more makahā (sluice gate) (Apple & Kikuchi, 1975). This gate allows for fish recruitment and water exchange between the ocean and freshwater (Kikuchi, 1973). The loko wai are located further inland away from the shore and are mostly fed by groundwater springs with no direct access to the ocean (Kikuchi, 1973). Kāheka (natural pools) were not a part of the main loko types for loko iʻa, however, they still were able to provide an area to access ocean-based resources. These pools are naturally established along shallow rocky shorelines and are highly susceptible to wave action. Each type of fishpond experiences different exposure to the ocean causing SLR risk and management to differ from site to site.

Previous research has found that SLR can affect the salinity balance of similar ecosystems to loko iʻa, and cause groundwater to flood areas further inland (Habel et al., 2020; Marrack et al., 2015). Additionally, elevated water levels with an increase in wave energy may reduce the stability of the kuapā at some loko iʻa, which can lead to the spreading of invasive species or flood access to roadways (Steward et al., 2024; Marrack et al., 2021; Woodworth et al., 2019). Being that these places hold cultural knowledge and represent the history of the Hawaiian people, this project serves as an example for community-based research to study SLR.

The objective of this study is to investigate a frequently used SLR tool, the NOAA tidal station, to understand if it accurately depicts the water levels experienced along the Hilo coastline at various loko iʻa by comparing the tidal station to local water level sensor data. Using the king tides as a proxy for future sea levels, this study further investigated the environmental drivers of differences water levels recorded at the NOAA tidal station versus in-situ water level data at five different loko iʻa. This analysis was conducted over two seasonal periods to minimize variability in the data. The kiaʻi loko iʻa (fishpond managers) have previously mentioned concerns for environmental variables such as strong north swells, which will be considered in the analysis. This study uses the term "departure" to describe the differences in water levels between the in-situ sensor deployed in the loko and either the NOAA-verified or predicted measurement, as well as the difference between NOAA-predicted and verified measurements. This study aims to model summer and winter king tide water levels to determine the impact of selected environmental variables on the loko iʻa to assist kiaʻi loko iʻa in future management planning.

Materials & Methods

Study Area

This study took place on Hawaiʻi island along the Keaukaha coastline located in the ʻokana (subdivision) of Hilo Hanakahi in the ahupuaʻa (land division) of Wāiakea within the moku (district) of Hilo. Increased SLR significantly impacts this historically and culturally significant coastline. The homestead of Keaukaha consists of numerous Hawaiian families that utilize this coastline daily to perpetuate cultural practices such as fishing, diving, surfing, or loko iʻa stewardship. Data was collected at two transects along the Keaukaha coastline in Hilo (Figure 1). Each transect consists of three loko (ponds), which differ in proximity and direct exposure to the ocean and also vary by loko iʻa type.

Within Honohononui (Transect 1), three loko iʻa were present: Laehala, Hale o Lono, and Waiāhole (Figure 1). Laehala is classified as a kāheka, or a semi-exposed tidal pool partially protected by old lava flows from the direct ocean swell. Hale o Lono is a loko kuapā (rock walled fishpond) that was constructed with nearby rocks and loose coral rubble, allowing permeable water flow. Wāiahole is also considered a loko kuapā, however, water flow to and from the ocean is restricted to a single 1.2m culvert pipe underneath the main road. Since this loko still has direct connection with the ocean through a mākāhā (sluice gate), this loko is classified as a loko kuapā. The approximate location of all submerged in-situ sensors at each loko iʻa are represented by the dots in Figure 1.

The three loko iʻa at Transect 2 were Honokea, Kaumaui Makai, and Kaumaui Mauka (Figure 1). The organization Hui Hoʻoleimaluō are the caretakers of these loko iʻa within this transect. One sensor was deployed within the loko kuapā of Honokea near Waiuli, also called Richardson Beach Park, and two water sensors were located within the ʻili ʻāina (land inheritance) of Kaumaui. Within this ʻili ʻāina, there are currently six loko wai. The sensor labeled Kaumaui Makai was located at the pond closest to the ocean, while the Kaumaui Mauka sensor was submerged at the most inland pond. At Kaumaui, there is no direct connection of the loko to the ocean, so these loko are classified as a loko wai, concluding the ponds are dominated by freshwater fed through groundwater springs.

Figure 1. Location of the sites within the Hawaiian Islands (A). The study site was on the eastern coastline along Hilo Hanakahi, Keaukaha coastline (B). The sensors are represented by various colored dots located within the two transects. Within Honohononui (Transect 1), the loko iʻa are Laehala (orange), Hale o Lono (green) and Waiāhole (green). In Hui Hoʻoleimaluō (Transect 2), the loko iʻa are Honokea (green) and Kaumaui (purple). Additionally, the white dot shows the barometer's location.

Tidal Sensor Data

Water level data was collected during the summer and winter periods to assist in understanding the seasonal impacts of king tide flooding. Water level, conductivity, and water temperature were measured every 6 minutes using the Solinst Levelogger 5 LTC Water Level and Conductivity Loggers M10. Sensors were attached to a cement block and placed in adequate areas that remained submerged during the extreme low tides. A Solinst Barologger 5 Barometric Pressure Logger also collected atmospheric pressure and air temperature during the same months to compensate for the water level measurements. Water sensor deployment occurred for 76-106 days from June to September 2023 and 54 to 104 days from December to March 2023-2024 to capture the summer and winter king tide events. For the analysis, the data used were from days that overlapped between all the sites to ensure valid comparisons. As in Kainalu et al., GPS data points of the water sensors' locations in the ponds were captured to further assist in water level accuracy. During the winter in-situ data collection, rough conditions led to the loss of two sensor data, so sites Laehala and Honokea are not included in those results. The water level accuracy of these sensors is ±0.005 m with a resolution of 0.0006% (Solinst, 2023). In addition, the water temperature sensor accuracy is ±0.05 °C with a resolution of 0.003 °C.

Adjusting to Local Mean Sea Level

An orthometric adjustment (0.529 m) was applied to the elevation of each water sensor after comparing the calculated orthometric height (2.889 m) at the closest tidal benchmark to the LMSL orthometric value (2.360 m) based on the leveling network (National Geodetic Survey, 2022). Using the benchmark, the orthometric height was calculated using the Ellipsoid and Geoid height (Eq. 1).

$$\text{Eq 1. } Orthometric\ Height = Ellipsoid\ Height - \ Geoid\ Height$$

Water Level Analysis

Water level data recorded at the NOAA Hilo tidal station was downloaded via the NOAA Tides and Currents website in 6-minute readings of the survey periods (NOAA, 2012). Both predicted and verified levels were used in the accuracy analysis. Predicted water levels are given months in advance, while verified levels are compensated and typically released at the month's end. The predicted tides are calculated based on the historical tide data and the position of the sun and moon during a particular time. This included the changing speed of the tide from low to high and previous heights of the low and high tides (Parker, B. 2007). The verified tides use microwave radar sensors at the tidal station to measure the distance of the water surface from the sensor and then average one-second readings to six-minute averages (NOAA CO-OPs, 2023). In the analysis, the minimum, maximum, median, and average water level value, including the tidal range (maximum-minimum water level) at each in-situ water sensor, was compared to the predicted and verified readings from the NOAA Hilo tide gauge to improve understanding of how water levels vary along the coast and across the coastal plain.

All analyses were conducted with RStudio Statistical Software (Version 2024.04.2). To compare the NOAA-verified water level data to in-situ data, an Analysis of Variance (ANOVA) test was conducted. This data was not sorted to distinguish between low and high tides. After results were received, a Tukey's HSD was also conducted to find relationships between the in-situ data and the NOAA tidal gauge. Tidal exceedance days were determined by quantifying the number of days recorded over 0.382 meters (MHHW) at mean sea level, similar to Thompson et al. (2019).

Mixed Effect Modeling

Mixed effect modeling was used to understand what environmental factors caused the departures in the water levels between the NOAA-verified and the loko iʻa water level data while accounting for groups within the data. Water level departures were calculated by subtracting the loko water level from the verified NOAA tidal station. The fixed effects included regional and site-specific environmental data, such as rainfall, wind speed, wind direction, swell period, significant wave height, swell direction, air temperature, water temperature, and barometric pressure. Water temperature was the only site-specific environmental variable, since it was recorded by every sensor deployed in the loko. Rainfall data was taken at the Hilo International Airport, located within 4.15 km (~2.6 miles) of the water sensors (National Weather Service, 2024). Wind speed and direction data were downloaded from the NOAA tidal station (NOAA Tides and Currents, 2024). The swell period, significant wave height, and swell direction at 500-meter resolution were downloaded from the Pacific Island Ocean Observing System (PacIOOS) website (Cheung, 2010). Air temperature and barometric pressure were recorded at the Solinst Barometer at Transect 2. All of the environmental data were evaluated for correlations among the variables. If a high correlation was detected (≥ 0.7), a variance inflation factor was calculated and assessed to determine whether or not a variable should be removed from the model (Akogul, 2018). Additionally, random effects were included assuming groupings were within the data, since there were six individual sites and three loko iʻa types (kāheka, loko kuapā, and loko wai). Examining both the loko iʻa types and individual sites provided a better understanding of what may have influenced the water levels between loko iʻa types and what specifically affected the particular sites. Modeling analysis used maximum likelihood to evaluate the environmental data by sites and loko iʻa type. Model selection was based on the most parsimonious model since AICc values were within minimal decimal differences.

Results

Water Level Accuracy

Summer King Tides

During the summer king tide months (July to mid-September 2023), there was notable variability between the NOAA-verified and NOAA-predicted data measurements. The NOAA sensor verified 24 days in July where the water level exceeded the Mean Higher High Water (MHHW) at 0.382 meters (1.25 feet). August recorded 28 days, and September had 14 high water level days. However, the NOAA predictions stated there would be 18 tidal exceedance days in July, 22 days in August, and 9 days in September (Table 1). The tidal range was also 0.02 meters greater for the NOAA-predicted water levels. At the same time, the other summary statistics (mean, minimum, and maximum) of the NOAA-verified data were 0.11 to 0.12 meters (0.36 – 0.39 feet) higher than predicted (Table 2).

Table 1. These tables show the tidal exceedance days recorded by the water level sensors for the summer 2023 data.

Transect 1	Site	July	August	September	Total Days
1	Waiāhole	27	31	14	72 [1]
	Hale o Lono	28	31	14	73 [1]
	Laehala	28	31	14	73 [1]
2	Kaumaui Mauka	27	31	14	72 [1]
	Kaumaui Makai	24	24	12	60
	Honokea	6	9	2	17
	NOAA Predicted	18	22	9	49
	NOAA Verified	24	28	14	66

[1] These months recorded a higher number of tidal exceedance days where water levels were greater than 0.382 meters than the NOAA Verified.

Water sensors at Transect 1 recorded over 70 days during the summer when water levels exceeded the MHHW value of 0.382 meters, with August having the highest number of exceedance days (Table 1). Also, tidal ranges at Hale o Lono and Laehala exceeded the NOAA-verified tidal range (Table 2). On the other hand, transect 2 experienced the largest tidal ranges throughout the summer, with Kaumaui Mauka and Kaumaui Makai experiencing tidal ranges of 1.26 to 1.33 m (Table 2). Transect 2 results also showed August had the highest tidal exceedance days (Table 1). Loko iʻa Honokea experienced the fewest tidal exceedance days compared to all the other sites. Also, Honokea was the only loko to have a negative average water level value and lowest tidal range measurement (Table 2). By looking at the environmental data, a better understanding of Honokea's water dynamics will be understood.

Using the NOAA verified as the reference water level, sites were analyzed to understand if there were statistical differences between water level measurements. These results stated that most water levels were statistically different from the NOAA-verified measurements. At Transect 1, Laehala, Hale o Lono, and Waiāhole recorded significantly higher average water levels than the NOAA verified ($p < 0.001$) (Table 2). These sensors recorded higher water levels of 0.14 to 0.22 meters (0.46 - 0.72 feet) than the NOAA-verified data. At Transect 2, Kaumaui Mauka and Honokea water levels were determined to be significantly different from the NOAA verified. Kaumaui Mauka was the only sensor to measure higher average water levels (p-value <0.001), while Honokea recorded lower water levels than NOAA verified. Notably, Kaumaui Makai was the only site that was not significantly different from what NOAA verified ($p = 0.02$) (Table 2).

Table 2. These tables show the summary statistics of the water level sensors for the summer 2023 data.

Transect	Site	Mean	Minimum	Maximum	Tidal Range	P-value
1	Waiāhole	0.32	-0.12	0.82	0.94	< 0.001
	Hale o Lono	0.37	-0.16	0.99	1.15 [1, 2]	< 0.001
	Laehala	0.29	-0.23	0.90	1.13 [2]	< 0.001
2	Kaumaui Mauka	0.27	-0.53	0.80	1.33 [1, 2]	< 0.001
	Kaumaui Makai	0.12	-0.54	0.71	1.26 [1, 2]	0.022
	Honokea	-0.02	-0.41	0.52	0.93	< 0.001
	NOAA Predicted	0.03	-0.53	0.64	1.17	< 0.001
	NOAA Verified	0.15	-0.37	0.75	1.12	reference

[1] These sites recorded larger tidal ranges than NOAA predicted water levels

[2] These sites recorded larger tidal ranges than NOAA verified water levels

Winter King Tides

During the winter king tide survey months (January - mid March 2023 to 2024), NOAA predicted that there would be six tidal exceedance days in January, 10 days in February, and six in March (Table 3). However, NOAA tidal station verified 10 tidal exceedance days in January, 21 days in February, and eight in March (Table 3). There were noticeable departures where the verified experienced higher water levels than predicted. For example, the minimum water level recorded for NOAA-verified was -0.45 meters, while the predicted NOAA minimum was -0.55 meters (Table 4). On the other hand, the maximum water level between the NOAA measurements recorded showed a difference of 0.253 m, with NOAA-verified levels being higher than the NOAA-predicted values (Table 4).

Table 3. These tables show the tidal exceedance days recorded by the water level sensors for the winter 2024 data.

Transect	Site	January	February	[1]March	Total Days
1	Waiāhole	11	25	9	45 [1]
	Hale o Lono	13	29	13	55 [1]
2	Kaumaui Mauka	9	16	7	32
	Kaumaui Makai	13	29	12	54 [1]
	NOAA Predicted	6	10	6	22
	NOAA Verified	10	21	8	39

[1] These months recorded the highest amount of tidal exceedance days.

When looking at the in-situ data, Waiāhole, Hale o Lono, and Kaumaui Makai recorded over 45 days at or above MHHW (0.382 meters) during the winter, while NOAA verified only recorded 39 days and NOAA predicted 22 days (Table 3). Across all the loko iʻa, Kaumaui Mauka and Hale o Lono experienced maximum water levels exceeding one meter above mean sea level. In comparison, the verified NOAA data recorded a maximum water level of 0.85 meters (2.78 ft), while NOAA predicted the highest at 0.60 meters (1.97 ft). The other loko iʻa sites, Waiāhole and Kaumaui Makai, experienced lower maximum water levels than NOAA verified but were still higher than NOAA predicted values. At Transect 2, the largest tidal ranges were recorded, with Kaumaui Makai at 1.18 m and Kaumaui Mauka at 1.17 m (Table 3). Further analysis of the in-situ water levels to the NOAA-verified water levels determined that average water levels at Hale o Lono and Kaumaui Mauka recorded 0.28 to 0.35 meters higher. Only these two sites significantly differed between the site and the NOAA-verified data with p-values <0.001 (Table 4). Similar to the summer 2023 data, Kaumaui Makai had slightly departed from the water levels verified by NOAA, making it not significantly different (p-value = 0.075) (Table 4). Further data analysis will determine what environmental factors may contribute to water levels departing from the NOAA tidal station.

Table 4. These tables show the summary statistics of the water level sensors for the winter 2024 data.

Transect	Site	Mean	Minimum	Maximum	Tidal Range	P-value
1	Waiāhole	0.18	-0.42	0.70	1.12[1]	< 0.001
	Hale o Lono	0.45	-0.05	1.10	1.15[1]	< 0.001
2	Kaumaui Mauka	0.37	-0.16	1.01	1.17[1]	< 0.001
	Kaumaui Makai	0.10	-0.41	0.77	1.17[1]	0.075
	NOAA Predicted	-0.02	4-0.55	0.60	1.14	< 0.001
	NOAA Verified	0.11	-0.45	0.85	1.30	reference

[1] These sites recorded larger tidal ranges than NOAA predicted water levels

Environmental Factors Impact on Water Level Across Loko Iʻa Types

Summer King Tides

The two summer models resulted in some significant environmental variables that impacted the water level departure. Model 1 grouped the data by the loko iʻa types: kāheka, loko kuapā, and loko wai. It had a low variance (0.0015), meaning that the loko iʻa type did not explain much of the water level departure (Table 5). However, the most influential fixed effects on the loko iʻa types were significant wave height, wind speed, rainfall, and wave direction. Notably, wave height had the most critical influence on the water level, with every one-meter increase in height resulting in a 0.43% increase in water level departure within the loko iʻa (Table 5). The other three variables had a 0.13% to 0.17% influence on increasing the water level departures (Table 5).

Table 5. Coefficients from the mixed-effects Model 1 show the relationship between environmental predictors and absolute water level difference. Average wave height had the strongest positive effect, followed by wind speed, rainfall, and wave direction.

Group	**Variance**	**Standard Deviation**
Loko Type	0.001593	0.03992
Residuals	0.003225	0.05679

Fixed Effect	**Estimate**	**Standard Error**	**P-value**	**Percentage**
Intercept	1.37×10^{-01}	2.31×10^{-02}	0.0096 **	13.66%
Significant Wave Height	4.32×10^{-03}	6.26×10^{-04}	5.4E-12 ***	0.43%
Wind Speed	1.73×10^{-03}	5.78×10^{-04}	0.00275 **	0.17%
Rainfall	1.45×10^{-03}	6.46×10^{-04}	0.0242*	0.14%
Wave Direction	1.33×10^{-03}	5.80×10^{-04}	0.02201 *	0.13%

*Number of asterisks show variables that are statistically significant.

When examining relationships within individual loko iʻa types, the kāheka experienced a strong positive relationship with wave height, wind speed, and rainfall (Figure 2). Laehala was the only loko considered a kāheka. In contrast, loko kuapā, which included Hale o Lono, Waiāhole, and Honokea, experienced moderately positive relationships to wave height, wind speed, rainfall, and wave direction (Supplementary Figure 1 - S3). The loko wai sites showed no significant relationships with the variables selected in Model 1.

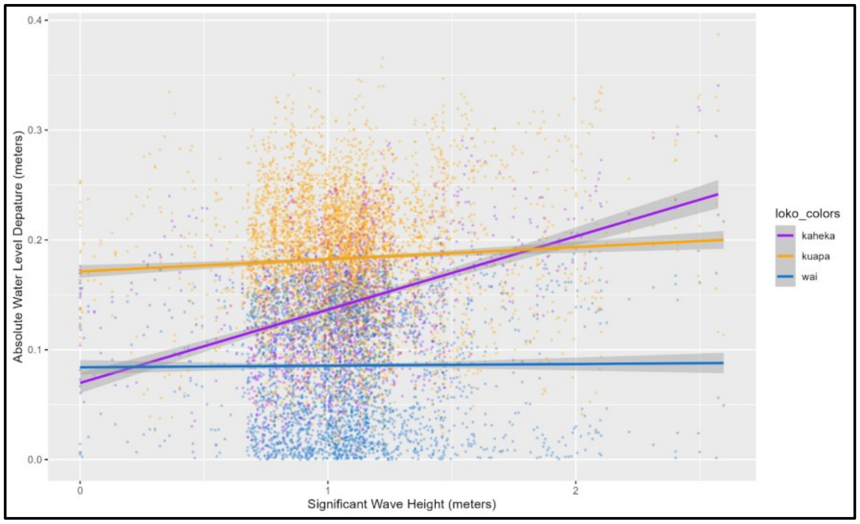

Figure 2. This regression illustrates the Model 1 relationship between significant wave height and the absolute water level difference between the NOAA-verified data and the loko iʻa. Model 1 grouped the data by the three loko iʻa types surveyed during Summer 2023. The kāheka (purple) exhibited a strong positive relationship, stating that as wave height increased, the water level departure also increased. Similarly, the loko kuapā (orange) also showed a slight positive relationship with increasing wave height. See supplementary for other variables regression plots. See Supplementary Materials for more regression plots of the other environmental factors.

Model 2 evaluated the water level departure by the individual loko iʻa. The variance in these results was higher than the loko iʻa type, suggesting that site-specific groupings explain the water level departures better (Table 6#). In Model 2, there were similar variables, with the addition of water temperature being a significant factor alongside wave height (Table 6#). Specifically, for every one-degree Celsius increase in water temperature, the water level would depart negatively by 0.89%, and every one-meter increase in wave height would lead to a 0.44% increase in water level departure (Table 6). The loko iʻa that were most influenced by the water temperature were Waiāhole, Kaumaui Mauka and Honokea (S4). Only Waiāhole had a strong negative relationship, meaning that as water temperature decreased, the water level departure between the NOAA values and the loko iʻa increased. Additionally, Laehala and Kaumaui Makai experienced slight negative relationships. The other variables, wind speed, wave direction, and rainfall, attributed to 0.12% to 0.26% of the water departures (Table 6). With the addition of water temperature in the second model, this model revealed additional relationships within the loko iʻa types. While the loko kuapā experienced a moderate positive relationship with water temperature, the loko wai had a strong negative relationship (Figure 3).

Table 6. Coefficients from the mixed-effects Model 2 show the relationship between environmental predictors and absolute water level difference. Water temperature again had the strongest positive effect, followed by significant wave height, wind speed, wave direction and rainfall.

Group	Variance	Standard Deviation
Site	0.003093	0.05562
Residuals	0.002183	0.04673

Fixed Effect	Estimate	Standard Error	P-value	Percentage
Intercept	1.44×10^{-01}	2.27×10^{-02}	0.000725 ***	14.39%
Water Temperature	-8.93×10^{-03}	1.57×10^{-04}	1.40e-08 ***	-0.89%
Significant Wave Height	4.44×10^{-03}	5.15×10^{-04}	< 2e-16 ***	0.44%
Wind Speed	2.62×10^{-03}	2.62×10^{-04}	2.33e-07 ***	0.26%
Wave Direction	1.32×10^{-03}	4.77×10^{-04}	0.005532 **	0.13%
Rainfall	1.20×10^{-03}	5.33×10^{-04}	0.024878 *	0.12%

* Number of asterisks show values variables that are statistically significant.

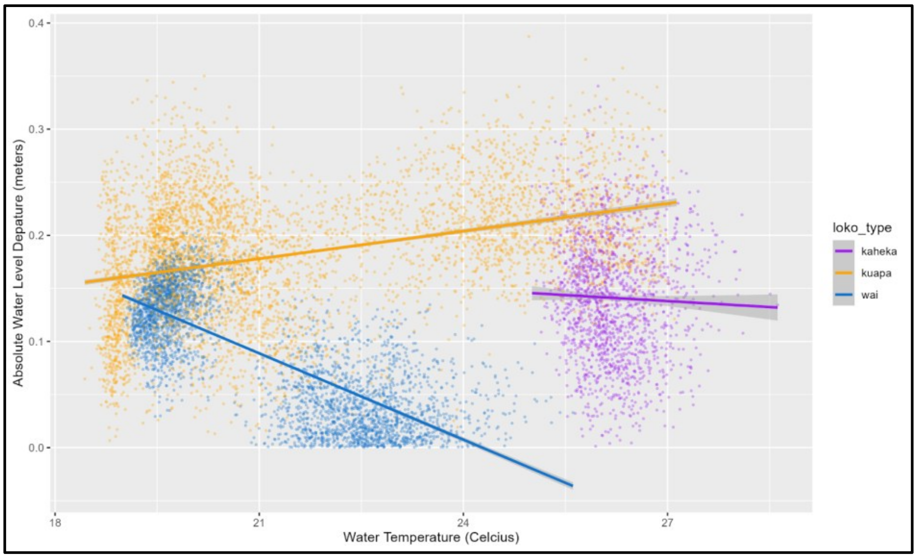

Figure 3. This regression represents the relationship between water temperature and the absolute water level difference between the NOAA-verified data and the loko iʻa. The loko wai (blue) shows a strong negative relationship, stating that as water temperature decreases, water departure increases. Additionally, the loko kuapā (orange) shows a moderate positive relationship; whereas water temperature increases, the water level departure also increases.

Winter King Tides

Due to the loss of a few sensors due to rough storm conditions, Model 3, which used the same structure as Model 1, only included two loko types. This led to a small variance (0.00004), indicating that this model poorly represented the data (Table 7). The residual variance (0.0164) was also high, inferring that the model poorly represented the data (Table 7). However, the results for this model consisted of water temperature, wave height and air temperature. When Model 4 was evaluated, there was a higher variance (0.016) and lower residual variance (0.002), suggesting a better explanation than Model 3. Like the summer analysis, Model 4 grouped the data by individual loko iʻa, and model selection was based on the most parsimonious model.

Table 7. Coefficients from the mixed-effects Model 3 show the relationship between environmental predictors and absolute water level difference. Average water temperature had the strongest positive effect, followed by wave height, and air temperature.

Group	Variance	Standard Deviation
Loko Type	0.0000423	6.48500E-03
Residuals	0.016410	0.1281170

Fixed Effect	Estimate	Standard Error	P-value	Percentage
Intercept	1.91E-01	5.16E-03	0.00117 **	19.08%
Water Temperature	4.67E-02	2.08E-03	< 2e-16 ***	4.67%
Significant Wave Height	2.79E-02	1.84E-03	< 2e-16 ***	2.79%
Air Temperature	-5.41E-03	1.87E-03	0.00388 **	-0.54%

* Number of asterisks show values variables that are statistically significant.

Model 4 determined that the influential environmental variables were wave height, swell period, wind speed, wave direction, and rainfall for the individual sites. Wave height was the variable that caused significant water level departures with every one-meter increase, leading to water level departing by 2.27% (Table 6). This relationship was strongest at the loko kuapā, Hale o Lono and Waiāhole, and Kaumaui Mauka, a loko wai (Figure 4). The swell period was the second most influential variable, which caused a 0.40% increase in water level for a second increase in the wave period. This variable had weak to moderate relationships across the loko iʻa types. Wave direction also influenced water level departures. While the summer saw more eastern swells, the winter had more northern swells, which departed water levels by 0.24%. Rainfall was added as a fixed effect for the winter data, causing a 0.22% increase in water level departure. This impact can be seen as a cause of slightly positive relationships at Waiāhole and Kaumaui Mauka and slightly negative at Kaumaui Makai (S5- S8).

Table 6. Coefficients from the mixed-effects Model 4 show the relationship between environmental predictors and absolute water level difference. Significant wave height again had the strongest positive effect, followed by wave period, wind speed, wave direction and rainfall.

Group	Variance	Standard Deviation
Site	0.016988	0.13034
Residuals	0.001867	0.04321

Fixed Effect	Estimate	Standard Error	P-value	Percentage
Intercept	1.910E-01	6.52E-02	0.042766 *	19.10%
Significant Wave Height	2.268E-02	2.27E-02	2.27E-02	2.27%
Wave Period	3.960E-03	7.14E-04	3.00e-08 ***	0.40%
Wind Speed	3.466E-03	6.53E-04	1.15e-07 ***	0.35%
Wave Direction	-2.363E-03	6.36E-04	0.000206 ***	-0.24%
Rainfall	2.189E-03	6.60E-04	0.000912 ***	0.22%

* Number of asterisks show values variables that are statistically significant.

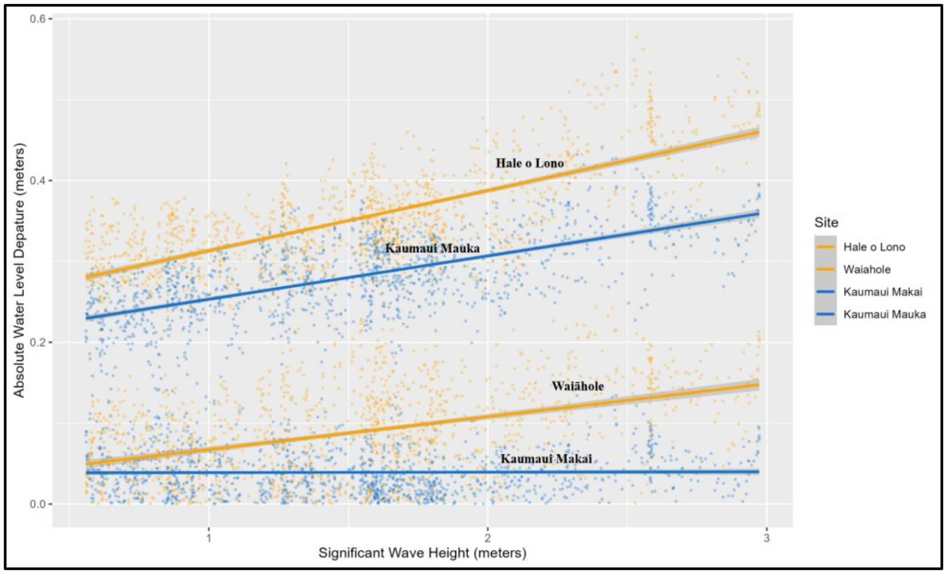

Figure 4. This regression illustrates the relationship between significant wave height and the absolute water level difference between the NOAA-verified data and the loko iʻa. The loko kuapā sites (orange) exhibited a strong positive relationship, stating that as wave height increased, the water level departure

also increased. Similarly, the loko wai Kaumaui Mauka (blue) also showed a strong positive relationship with water levels departing with wave height. See supplementary for other variables regression plots.

Seasonal Comparison

Based on observations, there were clear distinctions between the summer and winter king tide seasons. During the winter, multiple high surf events and intense weather produced higher-than-normal water levels on top of the high-water levels. However, there were more tidal exceedance days in the summer than in the winter. During the summer king tide season, transect 1 recorded an average of 72.6 tidal exceedance days, and Transect 2 had an average of 49.6 tidal exceedance days. The winter brought an average of 50 tidal exceedance days in Transect 1 and 43 days in Transect 2. There was also the loss of one sensor from each Transect. There were also interesting patterns within the summary statistics. For example, Kaumaui Mauka had a greater tidal range during the summer but experienced a higher maximum water level during the winter. Comparatively, when looking at the influential environmental variables and the two seasons, water temperature was the strongest influence for the summer water level departures, while wave height was the key influence during the winter. However, the other influential variables were similar with the addition of the wave period during the winter. The models determined that most variables influencing the water level departure in the loko iʻa coincide with ocean dynamics.

Discussion

In-Situ Water Data Assists Community-Level Research

This project demonstrated that recording in-situ water levels within each loko iʻa can significantly improve the understanding of the water dynamic influences of each. In this study, although the NOAA Hilo tidal station provided a valuable baseline for water levels in Hilo, several loko recorded significantly different levels. The results of this study saw discrepancies in the data between loko iʻa and the NOAA verified, but also discrepancies between the NOAA verified and predicted through both seasons. The predicted values from NOAA estimated lower water levels and fewer exceedance days than verified measurements. Also, during the 2023 summer king tide, four loko iʻa recorded higher water levels than the NOAA tidal station measurements. Likewise, during the winter king tide season, the in-situ sensor measurements averaged 46.5 days between the transects where the water levels exceeded MHHW. These differences in the data further support the importance of community-based research and monitoring of coastal water dynamics, particularly in island communities.

In a study on southern Pacific islands, researchers found that the water levels experienced after a storm were not accurately reflected by the tidal stations, showing discrepancies between the measured and actual conditions (Hoeke et al., 2013). The researchers stated this was common because these gauges were located in sheltered or far from the impacted regions (Hoeke et al., 2013; Thompson & Hamon, 1980). This is necessary to understand better how tidal stations correlate with water levels in different regions worldwide, enabling more effective preventive measures against dangerous flooding events in low-lying areas. Also, the resolution of the available data may not accurately represent the current issues experienced by SLR. Steward et al. (2024) used UAV imagery to model future flood impacts along an island coastline, producing a more accurate representation than LiDAR-derived flood models. The ability to do more research at a smaller scale quickly provides local information to the community. It is more reliable, which can lead to establishing resilient management practices in the face of climate change.

Furthermore, this study's results show a lag in some loko areas and a significant difference in the water level measurements being recorded along the coastline compared to what was predicted by the tidal station. This work stresses the importance of adding more tidal sensors along the coastline to allow for higher accuracy data for the community and management. Utilizing in-situ data to understand water levels within coastal communities could apply to coastal ecosystems worldwide. This work serves as a starting point for communities at risk of SLR, offering guidance on better monitoring their ocean conditions in the face of climate change.

A deeper understanding of the current influences on water levels has also demonstrated the importance of incorporating abiotic factors into assessing water level dynamics. Despite seasonal differences, wave height was a significant, influential environmental factor that impacted water level departure throughout this study. This is a well-documented wave action variable known to contribute to SLR. Other key elements of wave action include wave height, wave period, and wave direction, which also contribute to higher water levels. Additionally, wind speed and direction have been documented in previous studies also to drive up wave action, resulting in higher water levels (Marcos et al., 2019). Similarly, during the winter, there was more wave action due to multiple small craft advisory days posted by the National Weather Service. In SLR research, wave action is a common contributor to increasing rates of coastal erosion, causing higher high tide flooding and increasing the risk of storm surges (Barnard et al., 2015; Kane et al., 2012; Marcos et al., 2019).

Rainfall was another variable seen across both seasons but was prominent in the summer. Several studies have shown that increased rainfall exacerbates the impacts of SLR, leading to heightened flooding due to poor drainage to the ocean, which results in backflow into low-lying areas (Bloetscher et al., 2015; Gomez, 2021). Rainfall was not a surprising influence on water levels due to the average rainfall ranging from 2,750 - 3,550 millimeters (110 - 140 inches) that normally occurs on the windward side of Hawai‘i island (Giambelluca et al., 2013). However, with climate change, Frazier & Giambelluca (2016) have found an annual decrease in rainfall -26.5 mm per decade happening on Hawai‘i island. This decrease in rainfall can impact the balance of the brackish water environments necessary for sustaining loko iʻa, especially the groundwater-fed loko wai. More research could be done to examine how salinity levels in these loko iʻa fluctuate from season to season and year to year to identify changes in water quality. On the same note, water temperature was also a key environmental variable for the summer king tides. Usually, as water temperatures increase, thermal expansion of the ocean occurs, leading to higher water levels (Vermeer & Rahmstorf, 1990). However, in the loko wai, we found a strong negative relationship between water level and temperature, agreeing with the concept that loko wai are prominently fed by groundwater springs. We also saw a moderate positive relationship with water temperature at the loko kuapā sites, which are located closer to the ocean and may actually experience the impacts of thermal expansion. But for this study, we cannot conclude whether groundwater or distance from the shoreline could attribute to the influence of water temperature on water levels since these variables were not included in the analysis. This research has shown insight into the dynamic coastline of Keaukaha by understanding what environmental drivers impact water levels today. The work in this study supports what the kiaʻi loko have been experiencing on the ground throughout the year. Further research could build resilience-based strategies for individual loko iʻa across the state and Pacific to understand their coastal systems.

Future Sea Level Rise in Hilo

Hilo is already experiencing the impacts of SLR on its coastline. This study recorded significant maximum water level days at each loko iʻa. During the study, visual observations from the loko iʻa managers have seen firsthand the impacts these days have. Nevertheless, exceedance days are also expected to increase in frequency and intensity in the upcoming years, according to other research (Thompson et al., 2019; Taherkhani et al., 2020; Vitousek et al., 2017; Sun et al., 2023; Thompson et al., 2021). These tidal exceedance days can give insight into future sea levels. A range of local scenarios are currently designed for place-based adaptation to SLR. Some scenarios depict local relative SLR for Hilo as Low (0.3 m), Intermediate Low (0.5 m), Intermediate (1 m), Intermediate High (1.5 m), and High (2 m) (US Federal Interagency Task Force). While within the State, the Honolulu Climate Change Commission recommends using the Intermediate scenario (1 m) as the minimum scenario for all planning and design projects and the High scenario (2 m) for all planning and design of public infrastructure projects and other projects with a low tolerance for risk (Honolulu Climate Change Commission, 2022). However, the results of this study have shown that during king tide events, the Hilo coastline experiences water levels on average ranging from 0.644 meters to 0.90 meters during peak tidal seasons. Also, some loko iʻa, like Hale o Lono, experienced the highest water levels in both seasons. The physical structure of the loko kuapā at Hale o Lono allows for permeability of the rock wall between the freshwater and ocean.

However, during really high tides and wave action, there were multiple times when water was seen washing over the top of the wall as if it was not there. If SLR continues at the current rate, the water levels seen in this study are expected to be the mean sea level as early as 2060, following the Intermediate High scenario. This is meaningful to the kiaʻi loko iʻa to assess their goals and plans for future SLR management strategies.

Additionally, this study took place during an El Niño year, which is known to change weather and ocean conditions throughout the world (Lee & Wang, 2024). Other research done in Hawaiʻi found that El Niño can impact the local sea levels. The last El Niño in 2015 produced record high water levels 1-2 years following the anomaly (Long et al., 2020). The high-water levels caused by warmer oceans and weak trade winds increased beach and coastal erosion, flooded low-lying areas, and failed drainage infrastructures. So, it is possible that the water levels recorded in this study could be higher up to five years after El Niño. There is much to consider when studying SLR and understanding an area's coastal dynamic. However, this baseline research has started identifying the main drivers of the water levels, which can also allow kiaʻi to prepare in advance for these events to minimize the aftermath.

Delimitations and Ways of Improvement

This research has provided helpful insight into the water level characteristics of loko iʻa in Keaukaha. Regardless, there are still ways to improve this study. During data collection in the winter, the loss of a few tidal sensors reduced the accuracy of the seasonal comparison between water levels and environmental factors. However, this baseline study highlights the value of understanding what environmental variables influence the water level the most and should be investigated more frequently.

Additionally, this project does not consider the subsidence rate of Hawaiʻi Island nor groundwater flow when measuring environmental influence. Previous research has found that land subsidence on the island also contributes significantly to the high rate of SLR (Caccamise et al., 2005; Yang & Francis, 2019). Also, Hawaiʻi has active volcanoes, which add more mass to the island, simultaneously increasing the rate of island subsidence. Raspini et al. (2022) reviewed research and found a rise in research using interferometry to study land subsidence areas using satellite interferometry. With increasing satellite imagery quality and access, this method may provide helpful information for understanding land subsidence along a coastline.

Also, much research has looked into understanding the movement of groundwater in Hawaiʻi since it impacts many coastal communities. Studies have found groundwater alone can double the estimated SLR levels in predictive models and cause further damage inland in Hawaiʻi (Habel et al., 2023; Marrack, 2015; Rotzoll & Fletcher, 2013). For example, higher groundwater discharge impacts coastal infrastructures and increases the exposure to cesspool contamination (Habel et al., 2017; Marrack et al., 2021). Another study found that groundwater discharge is influenced by environmental factors like rainfall and intense storm events, further supporting this study's second objective (McKenzie et al., 2021). The gap in this study could be filled with further studies into the hydrological systems of each loko iʻa and installing accurate GPS points to calculate vertical land movement throughout the study time.

Comparatively, the environmental data was not recorded at every individual site. In reality, having individual sensors that record rainfall, wave action, and wind variables at each loko iʻa would not be feasible for the community members. However, by using a broader range of publicly available environmental data collected within a maximum three-mile radius of Keaukaha, the analysis effectively achieved the objectives of this study. Islands facing gaps in water level monitoring could also benefit from the methods outlined in this study to enhance local awareness and promote more community-based monitoring efforts.

Conclusion

In conclusion, water levels experienced throughout the loko iʻa along the Keaukaha coastline are not accurately represented based on the NOAA Hilo tidal station alone. Correspondingly, this study identified wave height and water temperature as the environmental variables with the strongest relationship with the departure in water levels across both king tide seasons. The methods from this study can provide valuable information to the coastal communities and other loko iʻa to plan for future sea-level impacts since no recent studies have identified the main drivers that impact water levels in loko iʻa systems. Additionally, by engaging with the community and the kiaʻi loko, this project fosters collaboration between the community and scientific research by integrating modern scientific tools to enhance traditional practices. As climate change changes, in-situ data collection techniques can provide the kiaʻi loko iʻa more accurate information about their dynamic coastline. Through this research, we emphasize the significance of small-scale, community-based studies to provide better information for sustainable and resilient actions in response to climate changes to assist in current and future resilience management.

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