SEA LEVEL RISE EXPOSURE OF CULTURAL SITES IN KOʻOLAUPOKO

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I certify that I have read this thesis and that, in my 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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For all the Pacific Island nations people who have been displaced by Sea Level Rise.

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ABSTRACT

This study assesses the exposure of Hawaiian cultural sites in the Koʻolaupoko region of Oʻahu to Sea Level Rise (SLR). Koʻolaupoko is home to numerous culturally significant sites and storied places (Wahi Pana), including but not limited to heiau, fishponds, paddling hālau, fishing shrines, loʻi kalo, pōhaku, and iwi kūpuna, many of which are situated along the coastline. Using a newly created Hawaiian Cultural Site layer, SLR exposure models from the Climate Resilience Collaborative, and Geographic Information System (GIS) tools, the exposure of selected sites was mapped at each predicted foot of sea level rise from 1-4 ft (2020-2100). The analysis indicates that a significant number of these Wahi Pana are located within areas projected to experience chronic flooding, erosion, and increased wave action. The results suggest that at 4 ft of SLR, more than half of the identified cultural sites may be at risk of inundation, and exposure to Wahi Pana at just 1 ft SLR. This research highlights the need for adaptive strategies that integrate cultural preservation with coastal management, ensuring that these important sites are protected for future generations. Additionally, collaboration with local communities and cultural practitioners is essential for developing resilient and culturally sensitive adaptation plans.

Keywords: Sea Level Rise, Cultural Sites, Hawaiian Cultural Sites, Hawai‘i

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1.0 INTRODUCTION

1.1 Sea Level Rise

Sea level rise is a global phenomenon caused by a combination of land ice melting into the ocean and thermal expansion of the ocean. It is a direct result of global temperatures rising from increased greenhouse gases in the atmosphere caused by anthropogenic activity. This increase in temperature results in ice, stored on land, to melt, adding water to the ocean and raising sea levels. In addition to melting ice, the ocean has absorbed 90% of the heat already added to Earth from greenhouse gasses (NASA Global Climate Change 2023). When water is heated, it expands. Thermal expansion of seawater contributed to 38% of sea level rise between 1901 to 2018 and will continue to be a major contributing factor (IPCC 2023).

Sea level rise has and will amplify the damage caused by coastal erosion, astronomical tides, and storm surge. Without adaptation measures, 48% more land and 52% more of the global population will be at risk of flooding in 2100 compared to 2020 (Kirezci et al., 2020). This is because about half the world's population lives within 100 km of a coastline (Erlandson, 2010). Currently, 600-million people live in low elevation coastal zones that will likely be impacted by the projected 1-meter increase in sea level by 2100 (Kirezci et al., 2020;Setter et al., 2023).

A common misconception is that sea level rise simply causes passive flooding of coastal areas by the ocean. While this is true, sea level rise also impacts the nearby coastal areas through groundwater inundation. In coastal areas, groundwater and seawater are connected (Habel et al., 2024). Groundwater inundation occurs when rising sea levels cause the water table below ground to rise, leading to wetland formation and surface

flooding. This process allows ocean water to mix with groundwater, and interact with underground infrastructure, potentially exposing the ocean to pollution from septic tanks, sewage drains, and underground fuel tanks (Habel et al., 2024). These pollutants have a detrimental impact on aquatic ecosystems. Pollution from wastewater puts excess nutrients into the aquatic ecosystem, which can lead hypoxic (low dissolved oxygen) conditions that can kill aquatic organisms (Whittier & El-Kadi, 2009). As sea levels continue to rise, it poses both visible and hidden threats to coastal communities and ecosystems, affecting the land, water, and coastal resources.

1.2 On-site Sewage Disposal Systems (OSDS) in Hawai‘i and MRSA infection rates

On-site sewage disposal systems are for homes and buildings that are not connected to a wastewater treatment plant. These include cesspools and septic tanks. A cesspool is a pit in the ground where raw sewage is stored to decompose naturally. A septic tank is an underground tank used to treat sewage on-site. On O‘ahu alone, there is an estimated release of almost 7.2 million gallons per day of untreated sewage effluent (Whittier & El-Kadi, 2009). This effluent can produce groundwater nutrient concentration that exceeds the EPA drinking water limit (Whittier & El-Kadi, 2009). Soil is the main filtration for OSDS. However, in coastal areas, soil does not provide adequate filtration (Whittier & El-Kadi, 2009). Untreated sewage effluent can also contain harmful pathogens and bacteria. The state of Hawai‘i has twice the MRSA infections than the national average, and this could be linked to OSDS effluent mixing with groundwater and reaching coastal areas where people swim (Economy et al., 2019). Kāne‘ohe, Kailua, and

Waimānalo are all low-lying areas where OSDS will likely be exposed to groundwater inundation and static flooding.

1.3 Hawaiian Cultural Sites

As sea level rise continues to threaten coastal regions worldwide, the impact on local cultural and historical sites becomes increasingly significant. Hawai‘i has a projected intermediate scenario of about 4 feet (1.2 m) of sea level rise by the end of the century (HSCC 2022). In Hawai‘i, the coastal environment is a part of many residents' everyday lives, and a large part of the culture's identity is tied to the ocean. Because of this, many modern and ancient Hawaiian cultural sites are located near the ocean, including but not limited to Paddling Hālau, Fishponds (loko i‘a), Fishing shrines (ko‘a), Heiau, Lo‘i kalo, Pōhaku and Iwi Kūpuna. In this paper, these cultural sites are referred to as Wahi Pana. Wahi Pana are storied places that are important to cultural practices and traditions in Hawai‘i and are not limited to the ones discussed in this paper. As most Wahi Pana are spiritually significant, they are also considered sacred and are treated with utmost respect. It is important to identify which of these Wahi Pana will be affected by sea level rise to prioritize their adaptation and location of restoration.

Outrigger Paddling is a popular Polynesian sport that many residents in Hawai‘i either dedicate their lives to or participate in for fun. It became popular in the 1970s at the time of the Hawaiian Renaissance and has played an important role in preserving Hawaiian Culture in modern times. There are about 40 canoe clubs just on the island of O‘ahu, and many more on the outer islands. Most of these clubs have a Hālau, a place of learning, near the ocean to store their canoes and gather their members for practice or

social events. Many of these places have already been impacted by sea level rise which is affecting storage of canoes and access to these locations.

Another significant resource are fishponds, which were created by the Kanaka Maoli as a form of aquaculture. They are located along the coast in shallow water, with stone walls built around them to keep the fish in. They have gates along the walls that allow smaller fish to come in from the ocean and hide from larger predators. Eventually, the fish grow too big to leave the pond through the gate and can then be harvested for food. When the Europeans arrived in Hawai‘i, there were almost 500 fishponds throughout the islands. Altogether they had the potential to produce 900 metric tons of fish per year (McCoy et al., 2017). With the arrival of Europeans, many of the fishponds became inactive, were destroyed, or filled in to become residential areas. Many fishponds today are managed by community organizations like Paepae o He‘eia and Waikalua Loko I‘a that educate the public about traditional Hawaiian fishpond practices. This education and collaboration strengthens connections within the community and also maintains Hawaiian traditions. Today, there are very few left, but they play an important role in the revitalization of Hawaiian cultural practices.

Sea level rise poses two threats to these fishponds. The first one is nutrient overload through groundwater contamination and inundation. If there are septic tanks or sewage pipes located upland from the fishpond, there is potential for eutrophication within the pond. This would be devastating as eutrophication leads to the formation of dead zones and aquaculture could no longer continue in this area. The second threat is direct marine inundation affecting the integrity of the fishpond. If fish and other

organisms can enter and exit the pond over the rock walls, the main function of the fishpond is lost.

Loʻi kalo are wetland taro (*Colocasia esculenta*) fields that cultivate kalo which is a culturally significant plant and dietary staple in Hawaiʻi. According to Hawaiian moʻolelo (stories) the kalo plant is the older brother of the first Kanaka Maoli (Native Hawaiian). In addition to being their ancestor, the kalo plant was the main source of starch for Kanaka Maoli before the arrival of the Europeans. These wetland systems also allow management of terrestrial runoff, as this water can be trapped in the wetland system allowing suspended sediments to settle before being released downstream towards the ocean. These are some of the reasons why Kanaka Maoli have continued to care for and cultivate this crop. Today, many loʻi kalo are managed by community organizations, much like those that manage fishponds, that teach traditional practices and strengthen connections within the community.

There are also spiritually significant sites that are affected by sea level rise. Fishing shrines (koʻa) are usually rock structures where Kanaka Maoli would place offerings to Kūʻula, the fish god. It is said that his spirit is housed in certain stones and that he directs fishermen to them through dreams (James, 1991). If these stones are taken care of, the caretaker is rewarded with good fishing and a healthy life. The purpose of placing an offering was either to pray for a good catch or thank Kūʻula for a good catch that day. These sites are either found on the beach or in the shallow water near fishing spots. Sea level rise may chronically flood and impact these places through increased wave activity, making them more difficult to access.

Similar to Koʻa, but on a much bigger scale are Heiau. Heiau are places of worship where offerings are made, and certain rituals and ceremonies are performed. They are large rock structures either built to be a platform or a walled enclosure. Heiau are dedicated to different gods depending on the purpose of the heiau (agricultural, healing, peace, fertility, etc.). This type of Wahi Pana hold a lot of mana (spiritual power) and thus are considered sacred.

As Wahi Pana constructed by rocks are spiritually significant, large rocks can be spiritually significant themselves as well. Pōhaku is the Hawaiian word for "rock" and is the name of the category this study places these spiritually signifcant pōhaku into. Pōhaku can have its own spirit, contain the spirit of someone who has passed away, or house the spirit of one of the gods. In many moʻolelo (stories) these pōhaku are preserved versions of the heroes in these stories. As these pōhaku contain a spirit, they are considered living and thus treated with respect, sometimes receiving offerings as well.

In Hawaiian culture, one's spirit remains in their bones. Because of this, burials, bones, and burial sites are sacred. Traditionally, Kanaka Maoli did not have one designated place for burials. One could be buried at a Heiau, in a cave, in the sand dunes, or another location where the remains would not be bothered. Coastal erosion has already unveiled some of these bones in Hawaiʻi's beaches and will likely continue to do so. With this will come many ethical issues of where to place them, and how to do so with respect.

1.4 Koʻolaupoko

The region of this study is located on the east side of Oʻahu in the moku (district)

of Koʻolaupoko. Within the moku, Kanaka Maoli further divided the land into ahupuaʻa which start at the top of the mountain and extend to the ocean. People living within an ahupuaʻa would work together to harvest, hunt and cultivate food, and then trade products with each other and people from other ahupuaʻa. Koʻolaupoko includes the ahupuaʻa of Waimānalo, Kailua, Kāneʻohe, Heʻeia, Kahaluʻu, Waiheʻe, Kaʻalaea, Waiāhole, Hakipuʻu, and Kualoa. This region was known historically for its abundance of loʻi kalo (irrigated terraces), fishponds and heiau (Landgraf, 1994). Before the Māhele, which introduced the concept of private property to Hawaiʻi in 1848, Koʻolaupoko was the primary population center on Oʻahu. This district, and many places within it were considered sacred, which is why there are so many significant sites in this area. After the Māhele, however, many of these sites were destroyed for construction and their meaning was forgotten. Today, Kanaka Maoli are revitalizing the culture through bringing back the language, spiritual ceremonies, and traditional agricultural and spiritual practices. With this has come the revival of Wahi Pana for their historical purposes. This is why identifying the coastal landscape changes in this region is important, and why this study aims to quantify how many Wahi Pana will be exposed to these changes in the coming years.

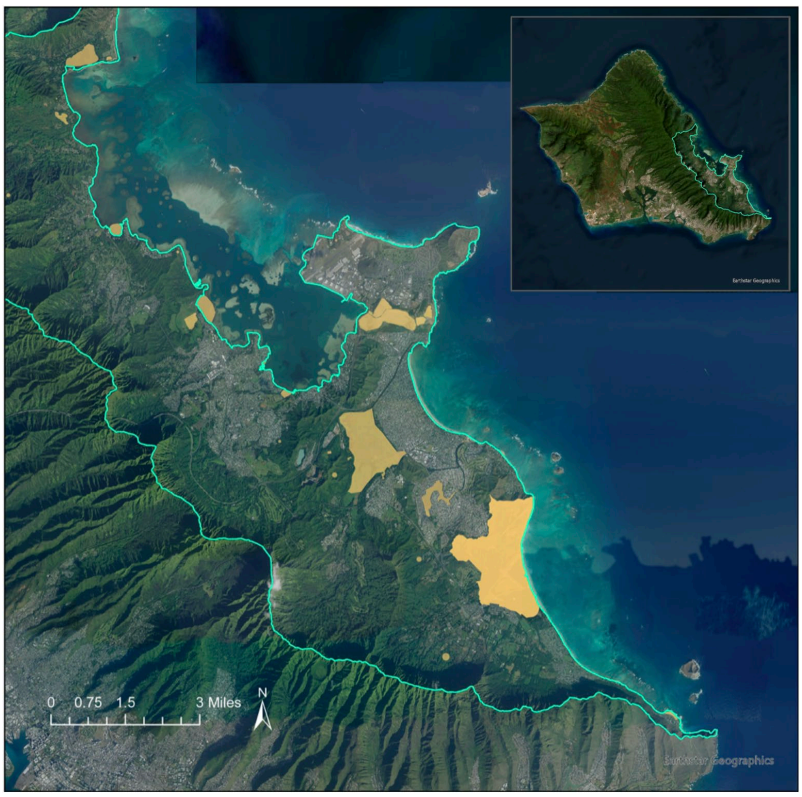

Figure 1. Map of Koʻolaupoko Study Region with Wahi Pana

Satellite image of Koʻolaupoko on Oʻahu with wahi pana highlighted in light orange with full view of Oʻahu in top right corner.

2.0 METHODS

In this study, a GIS layer of coastal Hawaiian cultural sites (Wahi Pana) within Koʻolaupoko was created and then overlayed with SLR exposure models of static flooding, groundwater inundation, coastal erosion, drainage backflow, and high-wave flooding. The exposure of Wahi Pana is quantified in 1 ft increments of SLR between 1-4 ft SLR. The methodology of these steps is outlined in this section.

2.1 Gathering Information

The first step was to identify the Wahi Pana within Koʻolaupoko. This includes Paddling Hālau, Fishponds (loko iʻa), Fishing shrines (koʻa), Heiau, Loʻi kalo, Pōhaku and Iwi Kūpuna. The Kipuka database is a geographical information system created by the Office of Hawaiian Affairs (OHA) (Office of Hawaiian Affairs, 2023). This database contains an interactive map that has a wide range of information about land grants, ownership, and divisions, but also has a layer for historical sites. Although this database is useful, it does not have detailed information about the significance of the sites, or pictures to help visualize them. These layers are also not available to the public. So, in order to evaluate their exposure to sea level rise, the Hawaiian Cultural Site layer used in this project was created, with the data from Kipuka as a main contributor.

Before the layer was developed, low-lying Wahi Pana were put into an excel sheet with information about their coordinates, location, a description, and a source that contains more information about the site. Many of the sites on the Kipuka Database were either unnamed, had vague descriptions, or appeared to no longer exist. For the purpose of clarity, these were left out of the new cultural site layer.

The Koʻolau ʻĀina Inventory was also a valuable resource for verifying current sites and adding any that were missing (Noho Papa Hawaiʻi, 2023). The Wahi Pana on their maps did not have exact locations, but with cross-referencing from Kipuka their locations were estimated. Several Wahi Pana from this resource were historically present, but have since been destroyed and are absent. For this reason, they were left out of the layer.

Additional wahi pana incorporated into the database from *Ancient Sites of O'ahu: a guide to Hawaiian archaeological places of interest* book (James, 1991). This resource was helpful to find sites that Kipuka didn't include, and to apply the Historical Context of the Ko'olaupoko region and many of the sites. *Sites of Oahu* by Elspeth P. Sterling and Catherine C. Summers was also examined to be a source of information, but did not prove to be helpful to this study as the descriptions resembled short jotted down notes, and the locations of the sites were relational to places that no longer exist (Sterling & Summers, 1993). For the location of modern outrigger paddling clubs, the names of canoe clubs were found using the O'ahu Hawaiian Outrigger Canoe Racing Association website, and individual club websites were used to determine the location of these sites (*OHCRA - Oahu Hawaiian Outrigger Racing Association*, 2024).

As most of the information and the status of these sites that are available is more than 20 years old, visits were made to these sites to determine their current state. Many of the fishponds that are listed in the Kipuka Database are filled in and are now residential areas. Other fishponds are still there, but are now private property, while others are being revitalized for community use. Other Wahi Pana are no longer there, and some Wahi Pana are overgrown. The fishponds that are filled in, and the sites that are no longer there were not used in the study. The private fishponds are included as they are still in place and possibly still used by the community on a smaller scale.

2.2 Creating Hawaiian Cultural Site Layer

Once the Wahi Pana database was collected and verified, the sites were added into a new layer using ArcGIS Pro. Polygons of each Wahi Pana were created and

information about each site was added into an attribute table. The information in the attribute table included the area of the Wahi Pana, moku (district), mokupuni (island), place name, and typeology. Sites that did not have the precise location available or had sensitive locations were represented with circular features. These represent the general area of the site.

2.3 Evaluating SLR using the Intermediate Sea Level Rise Scenario

This study uses local SLR projections from the 2022 NOAA Interagency Task Force Scenarios, using the Intermediate scenario which predicts 1 ft SLR by 2050, 2 ft by 2080, 3 ft by 2090, and then 4 ft by 2100 (Sweet, W. et al. 2022). The Intermediate scenario assumes that greenhouse gas emissions will increase slightly until 2050, and then decline but not reach net zero by 2100 (IPCC, 2023). This results in a projected global temperature increase of approximately 2.7º C by 2100 (IPCC, 2023). For higher accuracy, a local sea level rise projection based on the Honolulu tide gauge was applied (PSMSL ID: 155).

2.4 Analysis of SLR Exposure to Wahi Pana

For the analysis of flooding exposure to the Wahi Pana, flooding and erosion layers from the Climate Resilience Collaborative (CRC) were collected and overlaid with the Wahi Pana layer. Layers were available for erosion, high-wave flooding, groundwater inundation, drainage backflow, and static flooding. Compound flooding, which is when heavy rainfall and a high tide occur at the same time, was not available at the time of the study. Each type of exposure had 4 layers for each foot of sea level rise that were overlaid

one at a time with the Wahi Pana layer. These present the intermediate scenario of sea level rise for Hawai‘i, reaching approximately 4 ft by 2100.

While looking at the exposure to Fishponds, a slightly different method was used as it is already connected to the ocean. Overlap between high-wave driven flooding and static flooding layers with the fishpond walls were recorded as SLR exposure.

The first exposure analyzed was erosion. These layers were in the GeoJSON format, but were converted to polygons to be displayed on the ArcGIS Map. Once they were in polygon format, the Intersect tool was used to create a new layer that had polygons of all the overlapping areas. The attribute table of this layer was then used to identify which Wahi Pana were exposed.

For high-wave and static flooding, the layers came as TIF files that were able to be directly imported into ArcGIS Pro. For these layers, each site was individually examined to determine sea level exposure.

The groundwater and drainage backflow layers were also in TIF formats, but did not have transparent backgrounds. To make these layers easier to work with, the raster calculator tool was used to set the background values as NoData values so they would be transparent. After this, each site was individually examined to determine sea level exposure. To determine the percentage of Wahi Pana exposed, the exposed sites were counted in each scenario and that number was divided by the total number of Wahi Pana.

3.0 RESULTS

3.1 Results Summary

Fifty three wahi pana are included in this study. As shown in Table 1, there are 13 fishponds, 16 heiau, seven paddling hālau, three koʻa, two iwi kūpuna, three loʻi kalo, three pōhaku, and six in a category classified as "other". Within the "other" category there is a voyaging academy, springs, a fishing village, and a puʻuhonua (place of refuge). Wahi Pana are distributed evenly throughout the district, but have a slightly higher concentration on the Mōkapu Peninsula as it is historically sacred land. Results show varying levels of exposure to the coastal Wahi Pana included in this study based on typology. By 2100 at 4 ft SLR, 13 fishponds, two heiau, six paddling hālau, three koʻa, two iwi kūpuna, one loʻi kalo, and four other wahi pana will be exposed to potentially damaging SLR impacts.

Table 1. Exposure of Wahi Pana by typology

Type	**1 ft**	**2 ft**	**3 ft**	**4 ft**	**Total**
Fishponds	13	13	13	13	13
Heiau	2	2	2	2	16
Paddling Hālau	5	5	6	6	7
Koʻa	3	3	3	3	3
Iwi Kūpuna	2	2	2	2	2
Loʻi Kalo	0	1	1	1	3
Pōhaku	0	0	0	0	3
Other	4	4	4	4	6

3.2 Results by Exposure type

3.2.1 Exposure from Coastal Erosion

The coastal erosion layers provided by the CRC mark the future erosion hazard zones for sandy beaches on O‘ahu. At 1 foot of sea level rise (SLR), approximately 13% of Wahi Pana are projected to be exposed to shoreline erosion. This exposure increases slightly to 15% at 2, 3, and 4 feet of SLR.

3.2.2 Exposure from High-Wave Flooding

The wave driven flood layer shows the annual high wave-driven flooding. At 1 and 2 feet of SLR, 54% of the Wahi Pana are projected to experience wave-driven flooding. This increases slightly to 57% at 3 and 4 feet of SLR.

3.2.3 Exposure from Groundwater Inundation

The groundwater inundation layer shows locations where the groundwater will rise above the ground surface, forming a wetland. For this SLR exposure, 46% of Wahi Pana are expected to be exposed at 1 foot of SLR. At 2 feet, this exposure rises to 57%, and at 3 and 4 feet, it reaches 59%.

3.2.4 Exposure from Drainage Backflow

The Drainage Backflow layer shows flooding caused by the backflow of the ocean into the drainage system and onto land. Drainage Backflow had the least impact. At 1 and 2 ft SLR,

7% of Wahi Pana are exposed to Drainage Backflow. At 3 ft SLR, 20% are exposed, and at 4 ft, 26% of Wahi Pana are exposed.

3.2.5 Exposure from Static Flooding

The Static Flooding layer shows direct flooding from the ocean at the highest tide of the day. Static flooding at 1 ft SLR exposed 35% of Wahi Pana to inundation, while 37% were exposed at 2 ft, 50% at 3 ft, and 52% at 4 ft SLR.

Table 2. Exposure of wahi pana organized by exposure type

Exposure Type	**1 ft**	**2 ft**	**3 ft**	**4 ft**	**Total Sites**
High-Wave	29	29	31	31	53
Static	22	24	27	29	53
Groundwater	12	18	19	19	53
Drainage Backflow	4	4	11	14	53
Erosion	7	8	9	9	53

3.3 Visualization of Exposure

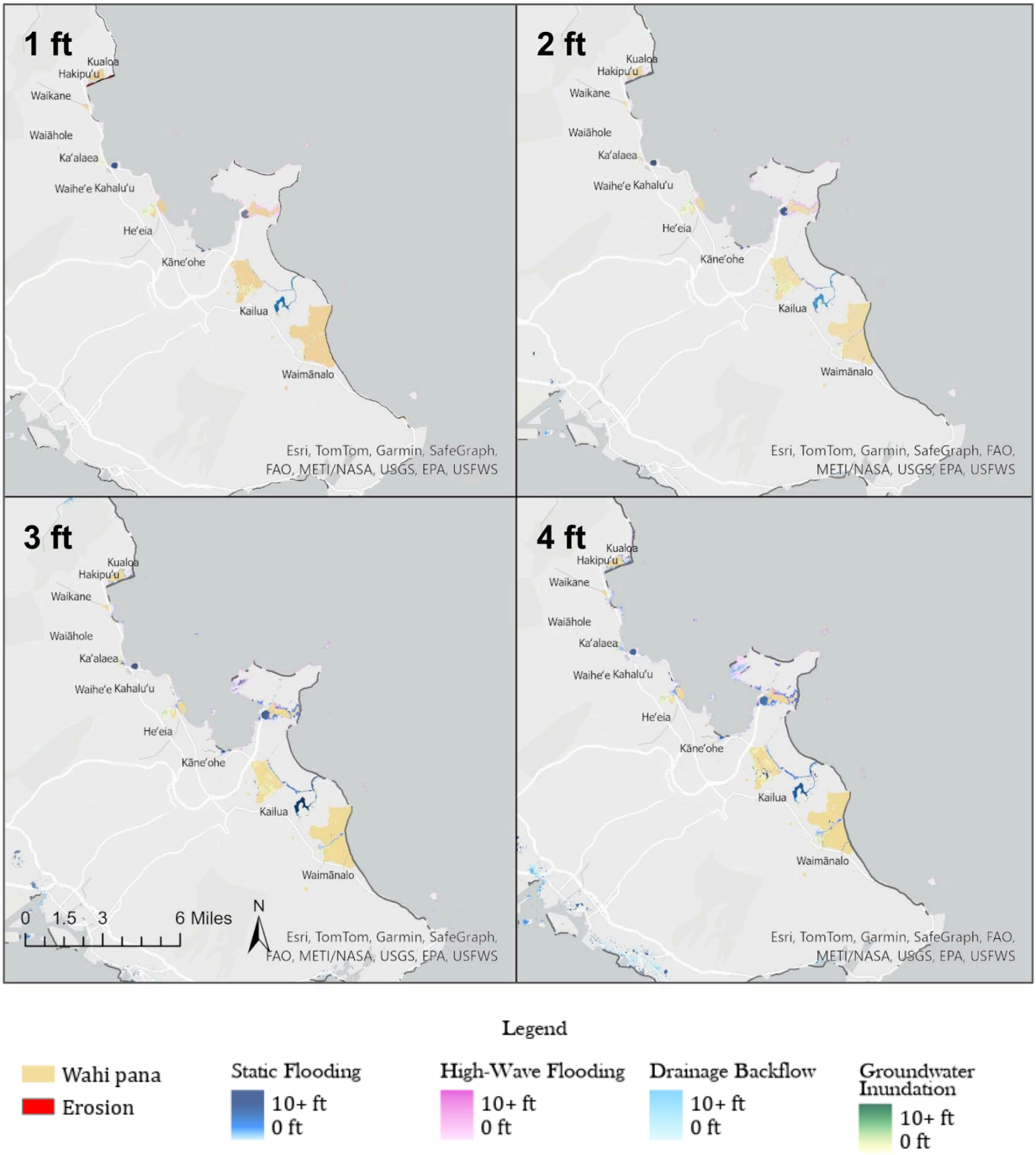

Figure 2. Map of Koʻolaupoko at 1- 4 ft SLR

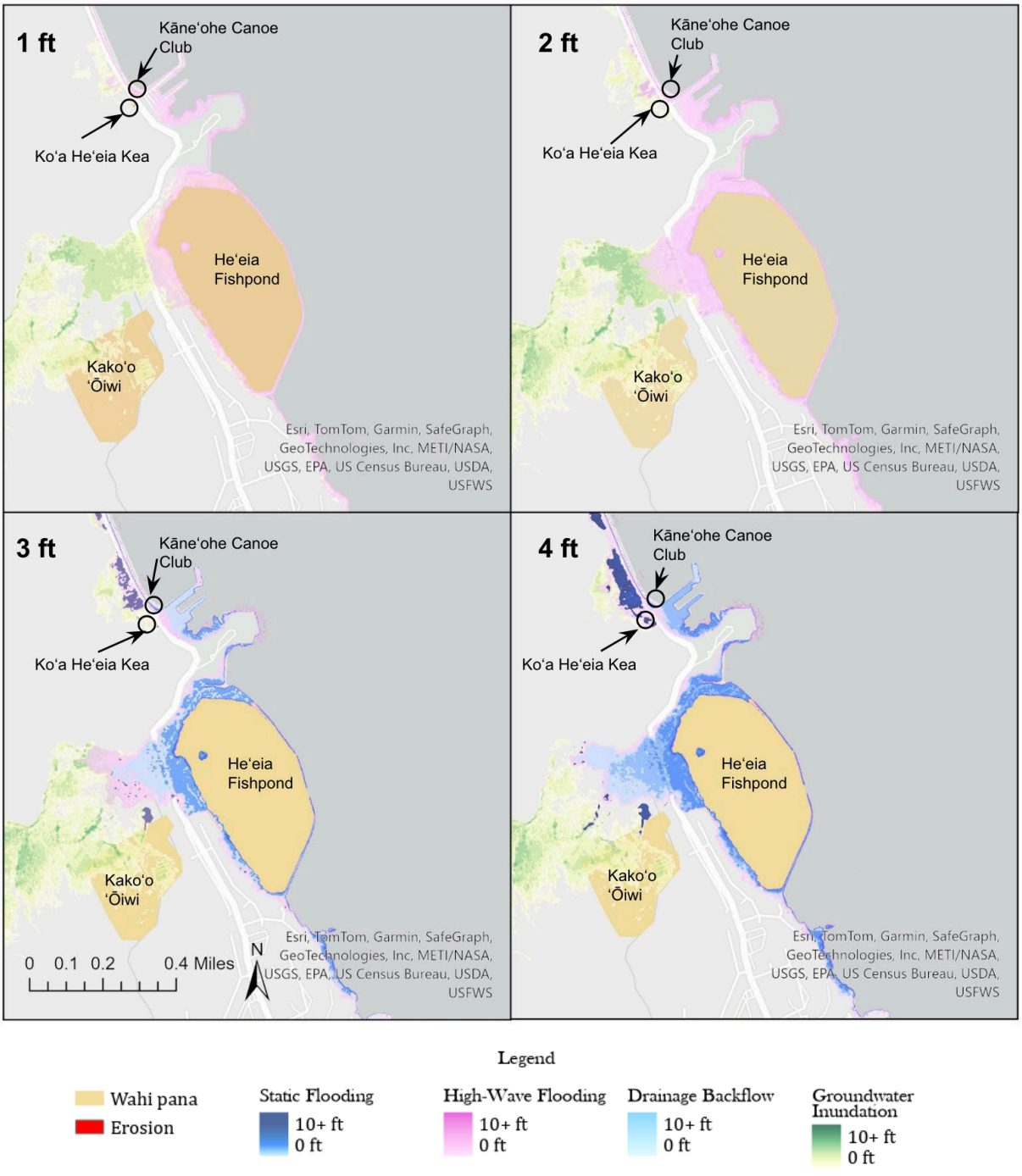

Figure 3. Heʻeia Fishpond, Kakoʻo ʻŌiwi, Koʻa Heʻeia Kea, and Kāneʻohe Canoe Club at 1-4 ft SLR

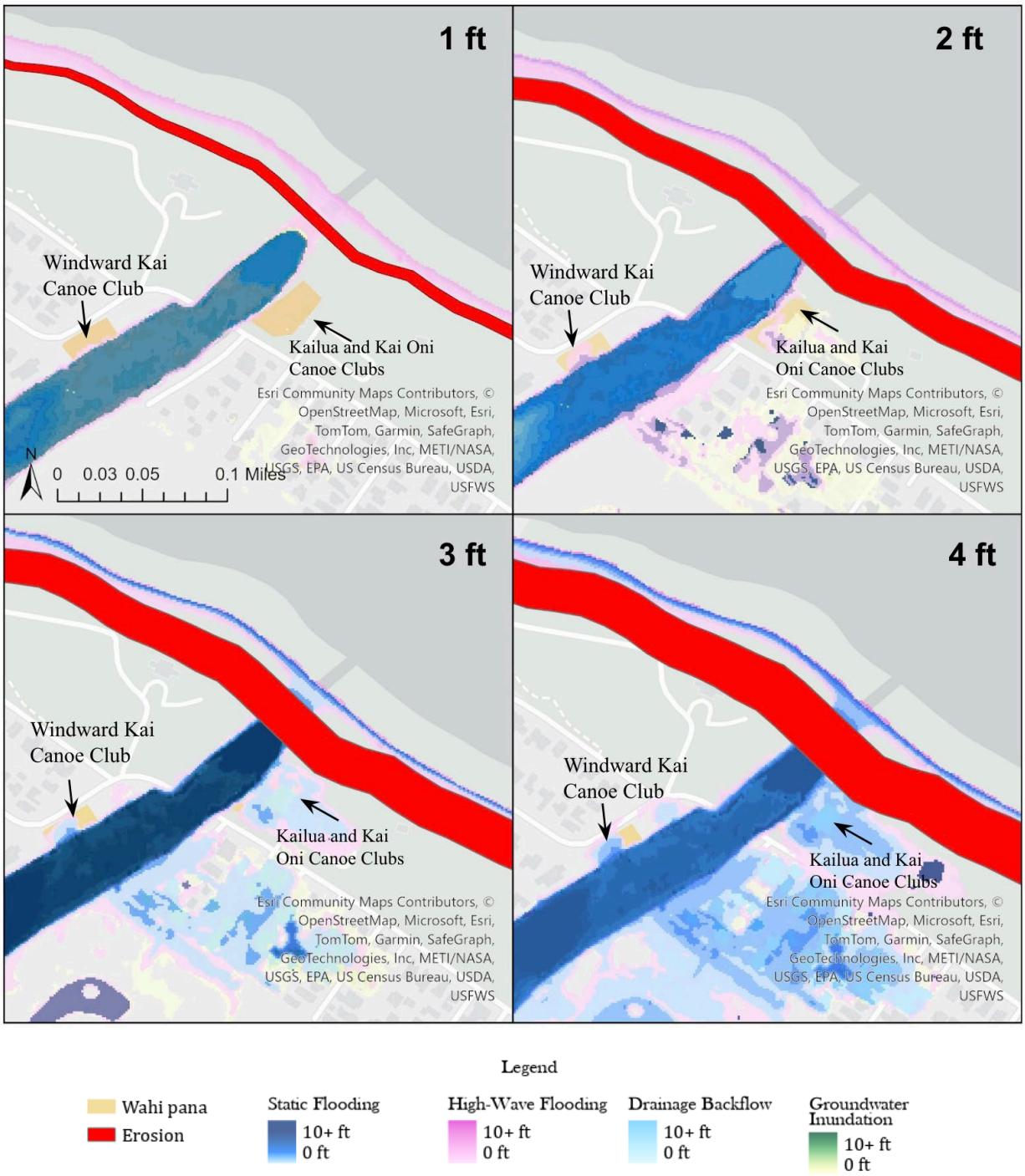

Figure 4. Kailua, Kai Oni, and Windward Kai Canoe Clubs at 1-4 ft SLR

4.0 DISCUSSION

4.1 Impact of SLR on Wahi Pana in Koʻolaupoko

Sea level in the intermediate scenario is projected to rise gradually until the mid-century in 2050, and then rapidly through the end of the century in 2100. In Hawaiʻi, 1 ft SLR is expected by 2050, 2 ft by 2080, 3 ft by 2090, and then 4 ft by 2100 (Sweet, W. et al. 2022). In addition to rising rapidly towards the end of the century, static flooding at 3 and 4 ft SLR appears to cover significantly more land than at 1 and 2 ft scenarios. In relation to Wahi Pana, 29 will face SLR exposure at 1 ft SLR, 30 at 2 ft SLR, and 31 for both 3 and 4 ft scenarios. Many of these Wahi Pana are being actively restored and, in some cases, expanded. This research has the potential to guide and prioritize the location of future restoration.

4.2 Impacts of different factors of SLR

This study differs from many other SLR studies as it evaluates five different exposures caused by SLR. Many studies of coastal impacts solely focus on static flooding because this layer can be generated with relatively few computing and data resources compared to layers such as wave-driven flood and coastal erosion. However, using only static flooding does not show the full extent of flooding caused by SLR or consider the unique impacts that different SLR exposures have on infrastructure. This study examines these unique impacts and considers how they will affect each category of Wahi Pana.

4.2.1 Coastal Erosion Impacts

In this study, coastal erosion looks at the receding of sandy beach environments. In erosion hazard zones, removal of sand and land is predicted. This is an issue for

several reasons. Currently, sandy beaches absorb wave energy from the ocean and protect land infrastructure from marine flooding. They also provide access to the ocean and are a public space for recreation, food gathering, and Hawaiian cultural practices. Paddling clubs often use the beach for storage of canoes as well, and erosion will likely require them to relocate their canoes. Both Lanikai Canoe Club and Na Koa Lani Canoe club are predicted to be exposed to erosion starting at 1 ft SLR.

Traditionally, Kanaka Maoli have also used sand dunes as burial sites. Coastal erosion has exposed iwi kūpuna (burials) in the past and is likely to continue as SLR increases, rates of coastal erosion continue, and unknown sites are revealed (Kane et al., 2012). Only two burial sites were identified in this study, one of which is projected to be exposed to coastal erosion at 1 ft SLR by 2050. If a lineal or cultural descendant of the iwi wishes to have the iwi kūpuna moved or preserved in place, approval from the Oʻahu burial council is required. If iwi are accidentally discovered, it must be reported to the State Historic Preservation Division (SHPD) and law enforcement. From there, the island burial council, lineal descendants, and Native Hawaiian groups collaborate to determine an appropriate course of action (SHPD, 2009).

4.2.2 Static Flooding Impacts

Static flooding is the most known consequence of SLR, occurring when the level of the ocean rises, flooding the surrounding coastal areas. Static flooding also affects low-lying areas that are not directly connected to the ocean. This results in either permanent or daily flooding of these zones, during the higher high tide, as Hawaiʻi has a mixed tide cycle (Climate Resilience Collaborative, 2024). This flooding impacts low-lying infrastructure, and also coastal Wahi Pana like koʻa, fishponds (loko iʻa), and

paddling hālau. By 2100, at 4 ft SLR, three identified koʻa are projected to be exposed to static flooding. As koʻa are usually rock structures, they may either become submerged or be eroded by wave action. All of the identified fishponds in this study are predicted to be impacted by 4 ft of SLR. This means that the average water level or high tide will exceed the walls of the fishpond, unless adaptations are made to increase their height above the ocean surface. Paddling Hālau will be impacted mainly through the storage of the waʻa (canoes) as they need to be stored on land. This study predicts that six canoe clubs in Koʻolaupoko will be exposed to static flooding by 2050 at 1 ft of SLR.

4.2.3 High-Wave flooding impacts

The entire coast of Oʻahu is exposed to high waves annually. As sea level rise increases, the area of land exposed to wave run-up will also increase. This is because reefs significantly decrease wave energy and height, and as the sea level rises further from the reef, it becomes less efficient at dissipating the wave energy. In this study, high-wave flooding is predicted to have the greatest exposure to Wahi Pana with 31 of 53 sites exposed by the end of the century. Although this exposure is temporary during high-wave events, wave energy has the potential to cause significant damage to Wahi Pana.

Wave energy resulting from rising sea levels has the potential to damage the structures that constitute loko iʻa, heiau, and paddling hālau. Loko iʻa have rock walls and mākāhā (sluice gates) that keep the system safe from predators. Wave energy can collapse these walls and break the mākāhā, allowing bigger organisms to enter or escape. Heiau and paddling hālau have structures separate from the ocean, but if exposed, wave energy could cause damage to or collapse these structures. If canoes are on the beach during a high wave event, they could be pulled out and damaged by hitting a rocky sea

bottom as the waves pass. Wave energy also has the potential to disrupt and remove koʻa, iwi kūpuna, and Loʻi kalo. As mentioned earlier, koʻa could be removed from its position by wave action. During high surf events, sand is removed from the beach and pulled back into shallow water. As new, deeper parts of sand dunes are exposed there will likely be exposure of iwi kūpuna to the ground surface.

4.2.4 Groundwater inundation impacts

Groundwater inundation is flooding caused by groundwater emerging from the ground surface or into underground infrastructure. This results in the formation of wetlands and the unearthing of buried pollutants. In this study, all the types of Wahi Pana have predicted exposure to groundwater inundation except for fishponds as groundwater is naturally present in these environments. Current wetlands are expected to have an increase in the volume of groundwater available, but because the groundwater is hydrologically connected to saltwater from the ocean, current wetlands will likely become more brackish. In wetlands used as loʻi kalo, this could negatively affect the crops although they can survive in environments with salt, it significantly reduces their growth rate and biomass (Lloyd et al., 2021).

Two heiau, three koʻa, six paddling hālau, and two iwi kūpuna sites are predicted to be exposed to groundwater inundation by the end of the century. These Wahi Pana are not meant to be submerged. This creates challenges with access to these Wahi Pana, and preserving their overall condition. There is also no protocol to address this, and relocating them from the flood hazard zone would be a complex issue.

4.2.5 Drainage Backflow Impacts

Drains rely on changes in elevation to transport stormwater and runoff to their outflow areas. In Hawai‘i, the outflow area is the ocean, and our drains are connected to it. As sea levels rise, water will backflow into these drainage systems, reducing their capacity to manage stormwater effectively. Water will pool near the drain, which is called drainage backflow. Water that runs into drains often comes from rain events that wash away chemicals from roads and other surfaces. Drainage backflow causes this water to be stagnant and allows chemicals to remain in areas that are near humans.

In this study, eight fishponds, four paddling hālau, and one iwi kūpuna site are predicted to be exposed to drainage backflow. This could negatively impact fishponds as the marine environment could be exposed to chemical pollutants that are detrimental to the health of the fish and other organisms. As the goal of a fishpond is to feed the community, the fish in this environment need to be healthy and fit for consumption. The storage of canoes and the health of paddlers would be the main concern for drainage backflow exposure to paddling hālau. Paddlers must enter the water to get into their canoes. This usually happens in the water adjacent to where the canoe is stored. Depending on the depth of the water, paddlers can be either ankle height or waist deep in the water adjacent to the hālau to get in and out of the canoes. If the water from drainage backflow contains harmful pathogens or skin-irritating chemicals, these could negatively impact the paddlers who enter them. Drain water exposure to iwi kūpuna could be considered desecration of their place of rest.

4.3 Considerations for analyzing SLR impacts on Fishponds

As Fishponds are already connected to the ocean and inundated, the analysis of these Wahi Pana were different from the rest. High surf advisories during extreme tides have collapsed fishpond walls and broken mākāhā in the past, and are likely to be the issues that fishpond stewards will face with future sea level rise (Steward et al., 2024). Even if wave events do not collapse the walls, submergence of the walls and the potential introduction of new organisms from overtopping waves harms the integrity of the fishpond (Kikuchi, 1976; Steward et al., 2024). For this reason, only high-wave and static flooding were examined with respect to fishponds, as those directly impact the fishpond walls and mākāhā.

4.4 Mitigation of SLR to Wahi Pana

Sea level will rise for centuries to millennia (IPCC 2023). Even with the reduction and removal of greenhouse gasses from the atmosphere sea levels will rise and remain elevated for thousands of years. As this is a global issue, every country and major industry must work together and make agreements to reduce further greenhouse gas emissions. However, sea level rise is happening now and impacting coastlines around the world. Locally, there are multiple ways of temporarily reducing the impacts of SLR. The two most sustainable strategies are maintaining coral reef health, and coastal dune restoration.

Corals are important because they protect the land from storm surge and flooding. Reefs have been shown to reduce wave energy by 97% and wave height by 84% (Ferrario

et al., 2014). As sea levels rise, the health of coral reefs will be essential to protection of current coastline structures and Wahi Pana. A healthy reef is more effective at slowing storm surge as the branches from corals provide more friction and help to reduce wave energy (Quataert et al., 2015). It is also important because corals need to grow at the same rate as sea level rise in order to be at an optimal depth. If a reef becomes submerged too deeply, its ability to reduce wave energy diminishes.

Much like coral reefs, beaches and sand dunes protect in-land environments from SLR, coastal erosion and storms. Dune plants help keep the dune structure by catching wind-blown sand and allowing it to build up over time (University of Hawai‘i Sea Grant College Program, 2022). They also keep the sand in place during high wind and wave events, allowing dune recovery afterwards (University of Hawai‘i Sea Grant College Program, 2022). The biggest threat to dune plants is human foot traffic. Minimizing this traffic is the best way to solve this issue. A simple way to do this is by designating beach access areas and discouraging access to where dune restoration is occurring. This can be done by roping off dune restoration sections with wooden posts and rope. If there are man-made obstructions or invasive plants that prevent the natural sand movement, it is also important to remove these with consideration of the impacts that removal will have (University of Hawai‘i Sea Grant College Program, 2022).

4.5 Limitations of the Study

Another environmental factor that has a major impact on coastal and inland flooding is precipitation. When heavy rain events occur at the same time as astronomical tides, this has a compounding effect. It is also important because Hawai‘i is experiencing less frequent rain, and an increase in low intensity rain events (Chu et. al 2010). This is

the outcome of Climate Change, and this pattern is expected to intensify in the future. This causes prolonged dry periods, leaving the land vulnerable to severe flooding and soil erosion during sudden heavy rain. Compound flooding was not modeled. Therefore, rain-induced flooding, which is common in Koʻolaupoko, the windward wet side of the island, is not accounted for. These results may therefore represent conservative estimates of overall flood impact and timing.

Due to problems with accessibility, many of the locations of heiau, koʻa and iwi kūpuna were approximated. For this reason, evaluations of exposure to these Wahi Pana are less certain than those for the other Wahi Pana. The results only reflect direct exposure to SLR but do not consider how access, or components of each site will be impacted.

4.6 Next Steps

The next steps of this research would be to include compound flooding data and look at it with the current Wahi Pana and also those at higher elevations in Koʻolaupoko. Eventually, all Wahi Pana on the island and in the state could be evaluated as well. With community interest and feedback, a more in-depth evaluation of specific Wahi Pana could be done to determine specific exposure of facilities and access to these locations.

5.0 CONCLUSION

This study examined SLR exposure to Wahi Pana in Koʻolaupoko using the Intermediate scenario of 4 ft SLR by the end of the century. As 53 coastal Wahi Pana were examined, 58% of them are expected to face exposure by 2100. Although 2100 is about 80 years from now, 55% of Wahi Pana will be exposed by 2050, and SLR is already happening. To best prepare for SLR, mitigation strategies and plans for Wahi Pana adaptation or movement should be considered now to ensure minimal impact to coastal Wahi Pana.

As fishponds, paddling hālau, koʻa, and iwi kūpuna are consistently located along the coast, they face the highest rates of exposure to SLR. Erosion, static flooding and wave-driven flooding are most harmful to the integrity of these structures, while groundwater and drainage backflow are most harmful to the health of the ecosystems and people who use it. Wahi Pana are of great importance because of the indigenous identity they give to the land they are on. Every place has its own unique culture that makes it different from everywhere else. Culture is what gives people their sense of identity, and this is why it is important to maintain Hawaiian culture and identity in Hawaiʻi. Part of this includes preserving and protecting Wahi Pana that set the islands apart from Polynesia and the rest of the world. Cultural sites occupy a central role in the moʻolelo (stories) and generational knowledge of societies, contributing greatly to cultural identity, community unity, and a sense of place (Carmichael et al., 2018).

This study assesses and predicts the extent of sea level rise. However, incorporating insights and perspectives from the stewards of these places could make these predictions more accurate and better aligned with their needs. With collaboration, then beneficial decisions and courses of action can be made to adapt to the changing coastal environment.

APPENDIX

Table 3. List of Wahi Pana assessed in the study

Name	**Ahupua‘a**	**Source**	**Description**
Haununāniho (Hunananiho) Pu‘uhonua	Waimānalo	https://kipukadatabase.com/kipuka/HistoricSites.html?ObjectID=905&g=points&b=7#view2	Small hill that was once a place of refuge.
Waimānalo Canoe Club	Waimānalo	https://waimanalocanoeclub.org/	Paddling Halau for Waimanalo Canoe Club where boats and other equipment are stored.
Kaupō (Koanapou) Fishing Village	Waimānalo	Ancient Sites of O‘ahu: a guide to Hawaiian archaeological places of interest, Van James	Modern Hawaiian Fishing village.
Pōhaku Pa‘akikī	Waimānalo	*Landgraf, Anne Kapulani, and Kalani Meinecke, Na Wahi Pana o Koolau Poko = Legendary Places of Koolau Poko*	Large sacred rock where local sweet potato farmers would offer ‘awa to Kamohoali‘i
Pāhonu Pond	Waimānalo	http://www.waimanalolimuhui.org/pahonu/	Ancient Turtle Pond for the Ali‘i still maintained by the community.
Pohakunui Heiau	Waimānalo	https://kipukadatabase.com/kipuka/HistoricSites.html?ObjectID=904&g=points&b=2#view2	Rectangular wall structure with division wall and terrace inside.
‘Iniki‘ōlohe heiau	Waimānalo	https://www.nohopapa.com/kkai	Shrine for moi and uhu
Unnamed Ko'a Waimānalo	Waimānalo	https://www.nohopapa.com/kkai	Ko‘a
Ka‘elepulu Fishpond	Kailua	https://kaelepulupond.org/	Brackish water wildlife habitat that was once an

			important freshwater pond.
Bellows Field Archaeological Area	Kailua	https://kipukadatabase.com/kipuka/HistoricSites.html?ObjectID=180&g=polygons&b=7#view2	Air force training area and recreation site. Many Hawaiian burials and ancient artifcats found here.
Windward Kai Canoe Club	Kailua	https://www.instagram.com/windward_kai/	Paddling Halau for the Windward Kai Canoe Club.
Kailua Canoe Club	Kailua	https://kailuacanoeclub.com/	Paddling Halau for Kailua and Kai Oni Canoe Club.
Kai Oni Canoe Club	Kailua	https://www.kaioniathletics.org/	Paddling Halau for Kailua and Kai Oni Canoe Club.
Kawainui Terraces & Marsh	Kailua	https://dlnr.hawaii.gov/wildlife/sanctuaries/kawainui/	Marshland that was once a fishpond and loʻi kalo of great significance.
Ulupō Heiau	Kailua	https://www.kauluakalana.org/	140 by 180 foot heiau with rock walls up to 30 feet tall.
Lanikai Canoe Club	Kailua	https://www.lanikaicanoeclub.org/	Paddling Halau for Lanikai Canoe Club, canoes stored on the sand and at the park.
Kānepolu	Kailua	Ancient Sites of Oʻahu: a guide to Hawaiian archaeological places of interest, Van James	Rock formation is believed to be a fishing shrine, is named after a legendary man from the time of King Kamehameha III.
Nā Pōhaku o Hauwahine	Kailua	http://www.koolau.net/NPEG/NaPohaku_Intro.html	Park area with rock formations. Site of the moʻo that protects Kawainui.
Pahukini Heiau	Kailua	https://www.civilbeat.org/2019/11/denby-fawcett-rescuing-a-12th-century-	One of the largest religous sites on the East Side, located

		heiau-from-a-garbage-dump/	within the fence of a landfill.
Ulupō Nui	Kailua	https://www.kauluakalana.org/	Restoration and education area for Kauluakalana.
Alala Heiau	Kailua	https://www.nohopapa.com/kkai	Site of former heiau where Kanepolu rock formation is.
Mokapu Iwi Kūpuna	Kailua	https://kipukadatabase.com/kipuka/HistoricSites.html?ObjectID=3984&g=points&b=7#view1	Burial exposed by Hurricane Fernanda
Kanahau Heiau	Kailua	https://kipukadatabase.com/kipuka/HistoricSites.html?ObjectID=903&g=points&b=2#view2	Destroyed during construction of highway, one terrace remaining.
Holomakani Heiau	Kailua	http://www.koolau.net/Holomakani.html	One intact wall that has multiple terraces, not confirmed location of heiau
Halekou fishpond	Kāneʻohe	Ancient Sites of Oʻahu: a guide to Hawaiian archaeological places of interest, Van James	26 acre fishpond a part of the Nuʻupia ponds
Kaluapuhi fishpond	Kāneʻohe	Ancient Sites of Oʻahu: a guide to Hawaiian archaeological places of interest, Van James	17 acre fishpond a part of the Nuʻupia ponds
Paʻakai fishpond	Kāneʻohe	Ancient Sites of Oʻahu: a guide to Hawaiian archaeological places of interest, Van James	Salt pond used for salt cultivation, Nu'upia ponds
Heleloa fishpond	Kāneʻohe	Ancient Sites of Oʻahu: a guide to Hawaiian archaeological	1.15 acre fishpond a part of the Nuʻupia ponds

		places of interest, Van James	
Nu‘upia Ponds	Kāne‘ohe	Ancient Sites of O‘ahu: a guide to Hawaiian archaeological places of interest, Van James	Total of 8 ancient fishponds and salt ponds. Is said to be the creation site of man, large amounts of Hawaiian burials were found here.
Kanohuluiwi Pond	Kāne‘ohe	https://kipukadatabase.com/kipuka/#view6	Small ancient fishpond, still used for fishing.
Waikalua Fishpond	Kāne‘ohe	https://www.thepaf.org/waikalua/	Active Fishpond with strong community engagement.
Ahukini Heiau	Kāne‘ohe	https://ulukau.org/cgi-bin/hpn?e=d-0hpn--00-0-0--010---4------0-0l--1en-Zz-1---20-about---00031-001-10escapewin-00&a=d&c=hpn&cl=CL2.1&d=HASHb09d5fc727e024dd971e02	One of the five temples attributed to Olopana, rectangular containing platforms and terraces.
Kawaewae Heiau	Kāne‘ohe	https://ulukau.org/cgi-bin/hpn?e=d-0hpn--00-0-0--010---4------0-0l--1en-Zz-1---20-about---00031-00110escapewin-00escapewin-00&cl=CL1.11.2.27&d=HASH01636cbd8ee7707dc49629ee&x=1	One of the five temples attributed to Olopana, rectangular containing platforms and terraces.
He‘eia Fishing Shrine	He‘eia	https://kipukadatabase.com/kipuka/#view6	3 platforms and 2 upright rocks representing Kane and Kanaloa
Lu o Wai o Kanaloa	He‘eia	https://kipukadatabase.com/kipuka/#view6	Brackish well about 10 ft deep

Ulupaʻu Heiau	Heʻeia	https://kipukadatabase.com/kipuka/#view6	Heiau believed to be dedicated to Hina and Ku, was later a location of a Catholic church.
Puʻu Hawaiʻiloa Spring	Heʻeia	https://kipukadatabase.com/kipuka/#view6	Spring located near the top of Puʻu Hawaiʻiloa
Na Koa Lani Canoe Club	Heʻeia	https://www.facebook.com/NaKoaLaniOCC/	Paddling Halau for Na Koa Lani Canoe Club.
Heʻeia Kea Shrine	Heʻeia	https://kipukadatabase.com/kipuka/HistoricSites.html?ObjectID=3639&g=points&b=7#view2	Basalt Boulder overgrown by vegetation.
Kāneʻohe Canoe Club	Heʻeia	https://www.kaneoheecanoeclub.org/	Paddling Halau for Kaneohe Canoe Club.
Heʻeia Fishpond	Heʻeia	https://paepaeoheeia.org/	Large active fishpond with immense community involvement.
Kākoʻo ʻŌiwi	He'eia	https://kakoooiwi.org/	Loʻi Kalo Farm with high community engagement
Leleahina Heiau	Heʻeia	https://www.pacificworlds.com/heeia/native/native3.htm	110 by 115 ft heiau dedicated to Goddess Hina.
Kahouna (Kahaluʻu) Fishpond	Kahaluʻu	https://www.hulagardenhawaii.com/	Ancient Fishpond that is now a private restaurant and lūʻau venue.
Keahiakahoe Canoe Club	Kahaluʻu	https://www.keahiakahoe.org/home.html	Paddling Halau for the Keahiakahoe Canoe Club.
Kalaealahiki Heiau	Kahaluʻu	https://www.nohopapa.com/kkai	Former Heiau destroyed by building of a road.
Unnamed Heiau Kahaluʻu	Kahaluʻu	https://www.nohopapa.com/kkai	Rock allignment of former heiau, possible burial.
Kānehūnāmoku Voyaging Academy	Kaʻalaea	https://www.kanehunamoku.org/	Polynesian Voyaging Academy

Kaawakoa heiau	Waikane	https://kipukadatabase.com/kipuka/HistoricSites.html?ObjectID=160&g=polygons&b=2#view2	Location of former heiau, no stones remaining.
Kukuianiani heiau	Waikane	https://kipukadatabase.com/kipuka/HistoricSites.html?ObjectID=160&g=polygons&b=2#view2	Ancient Heiau with 2 terraces remaining
Waikane wetland fields	Waikane	https://kipukadatabase.com/kipuka/HistoricSites.html?ObjectID=560&g=polygons&b=7#view2	Wetland used for loʻi kalo, previously used to grow rice.
Moliʻi fishpond	Hakipuʻu	https://www.fisheries.noaa.gov/tide-table-profiles-kualoa-ranch	Early royal fishpond that is still commercially used to this day to grow oysters, shrimp and talapia.
Puakea Heiau	Hakipuʻu	https://ulukau.org/cgi-bin/hpn?e=d-0hpn--00-0-0--010---4------0-0l--1en-Zz-1---20-about---00031-00110escapewin-00escapewin-00&cl=CL1.11.2.27&d=HASH011e9df886244a6c5614ead7&x=1	Three terrace structure with some walls remaining, possible puʻu honua.
ʻĀpua pond	Kualoa	Ancient Sites of Oʻahu: a guide to Hawaiian archaeological places of interest, Van James	Small pond east of Moliʻi pond, not much known about it.

Table 4. Wahi Pana Exposure to Shoreline Erosion

Name	**1 ft**	**2 ft**	**3 ft**	**4 ft**
Waikalua Fishpond		√	√	√

Bellows Field Archaeological Area	√	√	√	√
Kaupō (Koanapou) Fishing Village	√	√	√	√
Na Koa Lani Canoe Club	√	√	√	√
ʻĀpua pond	√	√	√	√
Lanikai Canoe Club	√	√	√	√
ʻIniki‘ōlohe heiau	√	√	√	√
Unnamed Ko‘a Waimānalo	√	√	√	√

Table 5. Wahi Pana Exposure to High-Wave Flooding

Name	**1 ft**	**2 ft**	**3 ft**	**4 ft**
Kawainui Terraces & Marsh	√	√	√	√
He‘eia Fishing Shrine	√	√	√	√
He‘eia Kea Shrine			√	√
Moli‘i fishpond	√	√	√	√
Kahouna (Kahalu‘u) Fishpond	√	√	√	√
Keahiakahoe Canoe Club	√	√	√	√
Kanohuluiwi Pond	√	√	√	√
Waikalua Fishpond	√	√	√	√
Nu‘upia Ponds	√	√	√	√

Kaʻelepulu Fishpond	√	√	√	√
Bellows Field Archaeological Area	√	√	√	√
Kaupō (Koanapou) Fishing Village	√	√	√	√
Windward Kai Canoe Club	√	√	√	√
Kailua Canoe Club	√	√	√	√
Na Koa Lani Canoe Club	√	√	√	√
Kāneʻohe Canoe Club	√	√	√	√
Pāhonu Pond	√	√	√	√
Halekou fishpond	√	√	√	√
Kaluapuhi fishpond	√	√	√	√
Paʻakai fishpond	√	√	√	√
Heleloa fishpond	√	√	√	√
ʻĀpua pond	√	√	√	√
Heʻeia Fishpond	√	√	√	√
Lanikai Canoe Club	√	√	√	√
ʻInikiʻōlohe heiau	√	√	√	√
Kākoʻo ʻŌiwi			√	√
Kānehūnāmoku Voyaging Academy	√	√	√	√
Unnamed Ko'a Waimānalo	√	√	√	√
Kalaealahiki Heiau	√	√	√	√

Mokapu Iwi Kūpuna	√	√	√	√
He'eia Fishing Shrine	√	√	√	√

Table 6. Wahi Pana Exposure to Groundwater Inundation

Name	**1 ft**	**2 ft**	**3 ft**	**4 ft**
He‘eia Fishing Shrine		√	√	√
He‘eia Kea Shrine			√	√
Keahiakahoe Canoe Club	√	√	√	√
Bellows Field Archaeological Area	√	√	√	√
Kaupō (Koanapou) Fishing Village	√	√	√	√
Windward Kai Canoe Club	√	√	√	√
Kailua Canoe Club	√	√	√	√
Na Koa Lani Canoe Club	√	√	√	√
Kāne‘ohe Canoe Club	√	√	√	√
Lanikai Canoe Club		√	√	√
‘Iniki‘ōlohe heiau	√	√	√	√
Kāko‘o ‘Ōiwi	√	√	√	√
Kānehūnāmoku Voyaging Academy		√	√	√
Unnamed Ko'a Waimānalo		√	√	√

Kalaealahiki Heiau		√	√	√
Mokapu Iwi Kūpuna	√	√	√	√
He'eia Fishing Shrine	√	√	√	√
Ulupō Nui	√	√	√	√

Table 7. Wahi Pana Exposure to Drainage Backflow

Name	**1 ft**	**2 ft**	**3 ft**	**4 ft**
Kawainui Terraces & Marsh	√	√	√	√
Moli‘i fishpond				√
Keahiakahoe Canoe Club			√	√
Nu‘upia Ponds			√	√
Ka‘elepulu Fishpond	√	√	√	√
Bellows Field Archaeological Area	√	√	√	√
Windward Kai Canoe Club	√	√	√	√
Kailua Canoe Club			√	√
Kāne‘ohe Canoe Club			√	√
Halekou fishpond			√	√
Heleloa fishpond			√	√
‘Āpua pond				√
He‘eia Fishpond			√	√
Kalaealahiki Heiau				√

Table 8. Wahi Pana Exposure to Static Flooding

Name	**1 ft**	**2 ft**	**3 ft**	**4 ft**
Kawainui Terraces & Marsh		√	√	√
He‘eia Fishing Shrine	√			√
Moli‘i fishpond	√	√	√	√
Kahouna (Kahalu‘u) Fishpond	√	√	√	√
Keahiakahoe Canoe Club	√	√	√	√
Nu‘upia Ponds	√	√	√	√
Ka‘elepulu Fishpond			√	√
Bellows Field Archaeological Area	√	√	√	√
Kaupō (Koanapou) Fishing Village	√	√	√	√
Windward Kai Canoe Club	√	√	√	√
Kailua Canoe Club		√	√	√
Pāhonu Pond	√	√	√	√
Halekou fishpond	√	√	√	√
Kaluapuhi fishpond	√	√	√	√
Pa‘akai fishpond	√	√	√	√
Heleloa fishpond	√	√	√	√
‘Āpua pond	√	√	√	√
He‘eia Fishpond	√	√	√	√
Na Koa Lani Canoe Club		√	√	√
Kāne‘ohe Canoe Club	√	√	√	√
Kanohuluiwi Pond	√	√	√	√
Waikalua Fishpond	√	√	√	√

Lanikai Canoe Club			√	√
ʻIniki‘ōlohe heiau			√	√
Kānehūnāmoku Voyaging Academy	√	√	√	√
Unnamed Ko'a Waimānalo	√	√	√	√
Kalaealahiki Heiau	√	√	√	√
Mokapu Iwi Kūpuna	√	√	√	√
He‘eia Kea Shrine				√

LITERATURE CITED

Carmichael, B., Wilson, G., Namarnyilk, I., Nadji, S., Brockwell, S., Webb, B., Hunter, F., & Bird, D. (2018). Local and Indigenous management of climate change risks to archaeological sites. *Mitigation and Adaptation Strategies for Global Change*, *23*(2), 231–255. https://doi.org/10.1007/s11027-016-9734-8

Chu, P.-S., Chen, Y. R., & Schroeder, T. A. (2010). Changes in Precipitation Extremes in the Hawaiian Islands in a Warming Climate. *Journal of Climate*, *23*(18), 4881–4900. https://doi.org/10.1175/2010JCLI3484.1

Climate Resilience Collaborative. (2024). Climate Viewer Documentation Page. *Climate Resilience Collaborative*. https://www.soest.hawaii.edu/crc/index.php/climate-viewer-documentation-page/

Economy, L. M., Wiegner, T. N., Strauch, A. M., Awaya, J. D., & Gerken, T. (2019). Rainfall and Streamflow Effects on Estuarine *Staphylococcus aureus* and Fecal Indicator Bacteria Concentrations. *Journal of Environmental Quality*, *48*(6), 1711–1721. https://doi.org/10.2134/jeq2019.05.0196

Erlandson, J. (2010). As the world warms: Rising seas, coastal archaeology, and the erosion of maritime history. *Journal of Coastal Conservation*, *16*, 1–6. https://doi.org/10.1007/s11852-010-0104-5

Ferrario, F., Beck, M. W., Storlazzi, C. D., Micheli, F., Shepard, C. C., & Airoldi, L. (2014). The effectiveness of coral reefs for coastal hazard risk reduction and adaptation. *Nature Communications*, *5*(1), 3794. https://doi.org/10.1038/ncomms4794

Habel, S., Fletcher, C. H., Barbee, M. M., & Fornace, K. L. (2024). Hidden Threat: The Influence of Sea-Level Rise on Coastal Groundwater and the Convergence of Impacts on Municipal Infrastructure. *Annual Review of Marine Science*, *16*(1), null. https://doi.org/10.1146/annurev-marine-020923-120737

IPCC, 2023: Summary for Policymakers. In: Climate Change 2023: Synthesis Report. Contribution of Working Groups I, II and III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [Core Writing Team, H. Lee and J. Romero (eds.)]. IPCC, Geneva, Switzerland, pp. 1-34, doi: 10.59327/IPCC/AR6-9789291691647.001

James, V. (1991). *Ancient sites of O'ahu: A guide to Hawaiian archaeological places of interest*. Bishop Museum Press.

Kane, H. H., Fletcher, C. H., Romine, B. M., Anderson, T. R., Frazer, N. L., & Barbee, M. M. (2012). Vulnerability Assessment of Hawai'i's Cultural Assets Attributable to Erosion Using Shoreline Trend Analysis Techniques. *Journal of Coastal Research*, *28*(3), 533. https://doi.org/10.2112/JCOASTRES-D-11-00114.1

Kikuchi, W. K. (1976). Prehistoric Hawaiian Fishponds. *Science*, *193*(4250), 295–299.

Kipuka—OHA. (n.d.). Retrieved July 10, 2024, from https://kipukadatabase.com/

Kirezci, E., Young, I. R., Ranasinghe, R., Muis, S., Nicholls, R. J., Lincke, D., & Hinkel, J. (2020). Projections of global-scale extreme sea levels and resulting episodic coastal flooding over the 21st Century. *Scientific Reports*, *10*(1), Article 1. https://doi.org/10.1038/s41598-020-67736-6

KO'OLAU 'ĀINA INVENTORY. (n.d.). Nohopapa. Retrieved October 4, 2024, from https://www.nohopapa.com/kkai

Landgraf, K. (n.d.). *Nā wahi pana o Ko'olau Poko: Legendary places of Ko'olau Poko*.

Lloyd, G. R., Uesugi, A., & Gleadow, R. M. (2021). Effects of Salinity on the Growth and Nutrition of Taro (Colocasia esculenta): Implications for Food Security. *Plants*, *10*(11), Article 11. https://doi.org/10.3390/plants10112319

McCoy, D., McManus, M. A., Kotubetey, K., Kawelo, A. H., Young, C., D'Andrea, B., Ruttenberg, K. C., & Alegado, R. 'Anolani. (2017). Large-scale climatic effects on

traditional Hawaiian fishpond aquaculture. *PLOS ONE*, *12*(11), e0187951. https://doi.org/10.1371/journal.pone.0187951

Nerem, R. S. et al. Climate-change–driven accelerated sea-level rise detected in the altimeter era. Proc. Natl. Acad. Sci. 115, 2022–2025 (2018).

Noho Papa Hawai'i. (2023). *Ko'olau 'Āina Inventory* (p. 384). https://www.nohopapa.com/kkai

Office of Hawaiian Affairs. (2023). *Kipuka—OHA*. https://kipukadatabase.com/

OHCRA - Oahu Hawaiian Outrigger Racing Association. (n.d.). OHCRA - Oahu Hawaiian Outrigger Racing Association. Retrieved December 4, 2024, from https://www.OHCRA.com

Quataert, E., Storlazzi, C., van Rooijen, A., Cheriton, O., & van Dongeren, A. (2015). The influence of coral reefs and climate change on wave-driven flooding of tropical coastlines. *Geophysical Research Letters*, *42*(15), 6407–6415. https://doi.org/10.1002/2015GL064861

Setter, R. O., Han, R. X., Tavares, K.-D., Newfield, C., Terry, A., Roberson, I. M., Tarui, N., & Coffman, M. (2023). Managing retreat for sandy beach areas under sea level rise. *Scientific Reports*, *13*(1), Article 1. https://doi.org/10.1038/s41598-023-38939-4

State Historic Preservation Division. (n.d.). *Burial Sites Program*. Retrieved November 4, 2024, from https://dlnr.hawaii.gov/shpd/about/branches/ibc/burial-sites-program/

Sterling, E. P., & Summers, C. C. (1993). *Sites of Oahu* (Repr). Bishop Museum Press.

Steward, K. K., Ninomoto, B. K., Kane, H. H., Burns, J. H. R., Mead, L., Anthony, K., Mossman, L., Olayon, T., Glendon-Baclig, C. K., & Kauahi, C. (2024). Highlighting the Use of UAV to Increase the Resilience of Native Hawaiian Coastal Cultural Heritage. *Remote Sensing*, *16*(12), Article 12. https://doi.org/10.3390/rs16122239

Sweet, W. et al. Global and Regional Sea Level Rise Scenarios for the United States: Updated Mean Projections and Extreme Water Level Probabilities Along U.S. Coastlines. 111

https://oceanservice.noaa.gov/hazards/sealevelrise/noaa-nos- techrpt01-global-regional-SLR-scenarios-US.pdf (2022).

University of Hawai‘i Sea Grant College Program. (2022). *Hawai‘i Dune Restoration Manual*.

Whittier, R. B., & El-Kadi, A. I. (n.d.). *HUMAN AND ENVIRONMENTAL RISK RANKING OF ONSITE SEWAGE DISPOSAL SYSTEMS*.