UNDERSTANDING CHANGE: EXAMINING THE EFFECT OF *AHUPUAʻA* RESTORATION EFFORTS ON WATER CIRCULATION IN *LOKO IʻA O HEʻEIA*, A NATIVE HAWAIIAN FISHPOND

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

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To Ma and Pa, whose life-long support carried their daughter to be the first in the family to obtain a college degree.

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ABSTRACT

He‘eia National Estuarine Research Reserve (NERR), established as the 29th NERR in the U.S. national system in 2017, provides a living laboratory to better understand the complex relationships in areas where freshwater streams meet the sea. He‘eia Fishpond, located within He‘eia NERR boundaries, is an 88-acre, approximately 800-year old traditional Native Hawaiian fishpond that once provided sustenance for the communities in the area. However, a century of land-use change and introduction of non-native species have resulted in low productivity of food fish in He‘eia Fishpond. One of He‘eia NERR's missions include removing invasive species to restore the watershed to a system that reflects Indigenous knowledge and practices. In keeping with this mission, this project aimed to understand habitat change by measuring water circulation and flow related to invasive species removal efforts at He‘eia Fishpond. Efforts to restore the fishpond into a system that produces native food fish species for community sustenance is currently ongoing, led by a Native Hawaiian community non-profit group, Paepae o He‘eia, also the caretakers of He‘eia Fishpond. Water flux was measured at each of the six sluice gates (*mākāhā*), relative flow was measured within the fishpond, and the data was compared to water circulation data from a similar study conducted in the pond in 2018. As estuarine environments are highly dynamic in nature, understanding how the removal of invasive algae affects water circulation throughout the fishpond since 2018 may aid in addressing future coastal management issues and restoration actions for resource managers within the He‘eia NERR.

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1.0 INTRODUCTION

1.1 Estuaries: Where freshwater streams meet the sea

An estuary is defined as a semi-enclosed coastal body of brackish water, which has a free connection to the open sea (Pritchard 1967). The dynamics of estuaries are driven by both marine (tidal cycles, waves, in/outflux of seawater) and terrestrial (nutrients, in/out-flux of freshwater) influences, as well as physical and biological forcing from both sides. Within estuaries, there can be a strong salinity gradient of the waters from the land to the sea, as estuaries are found in places where freshwater inputs from terrigenous sources make contact with seawater from the ocean (Schlesinger & Bernhardt 2013). The mixing of fresh and saltwater occurs in the estuary's central channel, creating a transition zone where rapid biogeochemical processes and high productivity may occur (Burton 1988, Dagg et al. 2004). The turbulent mixing also generates abrupt changes in the environment's temperature, pH, nutrient concentrations, and other factors that influence the biogeochemical processes that take place there. Because these complex ecosystems are highly dynamic in nature, estuarine environments are one of the most challenging areas on Earth to study its biogeochemical processes.

Estuaries are one of the most productive areas in the world. The cycling and distribution of nutrients, in particular, is an essential component of a healthy estuarine environment. Many plants, animals, and humans rely on these ecosystems for food, habitat, and sustenance (NOAA 2016). Often referred to as the "nurseries of the sea" (USEPA 1993), estuarine environments provide vital nesting and feeding spaces for many aquatic flora and fauna.

FIGURE 1. He‘eia *ahupua‘a* (land division). Native Hawaiians are known to use sustainable practices of their natural resources. *Wai* (freshwater) trickles down the streams of the Ko‘olau mountains and into the *lo‘i kalo* (taro patches), providing community sustenance and filtering excess sediments and nutrients. *Wai* then makes its way into the *loko i‘a* (fishpond), allowing for a native fish community to thrive and sustain the people for generations. *Photo courtesy of Manuel Mejia*

1.2 Native Hawaiians and the *ahupua‘a* system

For centuries, Native Hawaiians have had a holistic understanding of the relationships between animals, environment, and humans, occurring from *mauka* (mountain) to *makai* (sea). They understood the responsibility of replenishing the natural resources from which they borrowed, from the crops they used for sustenance on land, to the water that eventually made its way back to the sea (Smith & Pai 1992). Although Native Hawaiians did not practice land ownership, they heavily relied on and developed a complex system of land tenure, known as the *ahupuaʻa* system. The main Hawaiian Islands were divided into several *ahupuaʻa*, which typically follow natural watershed boundaries such as mountain ridges and streams, that stretches from the mountain ridges on land to the outer bounds of coral reef systems in the sea (Kamakau et al. 1968).

Each *ahupuaʻa* contained the necessary resources needed to sustain the *ʻohana* (families) who live within the area. Holistic understanding of the relationships between natural resources were evident in the Native Hawaiians' use of fishponds (*loko iʻa*) and taro patches (*loʻi kalo*) in coastal environments, especially in Windward Oʻahu (**Figure 1**) (Kikuchi 1976). From diverting stream water to provide for copious taro patches in the wetlands to controlling sedimentation input that may end up in the fishpond, Native Hawaiians had a robust understanding of the physical, hydrodynamic, and biogeochemical processes of the watershed. Efficiently implementing this customary knowledge of place allowed them to persist and live for centuries prior to the arrival of western Europeans.

1.3 History of invasive species in within the Heʻeia *ahupuaʻa*

1.3.1 Red mangrove – *Rhizophora mangle*

Physical changes of land-use within the past century have led to land-management decisions that resulted in severe negative repercussions for the Heʻeia *ahupuaʻa* that are still evident today. The Heʻeia wetlands were once one of the largest areas of wetland taro cultivation in the island of Oʻahu (Handy, Handy & Pukui 1972). Starting in the mid-1800s, there was a transition in land-use from subsistence-based flooded taro agroecosystems (*loʻi kalo*) to a plantation-style commercial economy

(Kakoʻo ʻŌiwi 2010). While the flooded taro agroecosystems aided in regulating stream discharge rate and trapped excess sediment and nutrients, the new plantation-based economy accelerated excess erosion and siltation to the nearshore environment and surrounding Kāneʻohe Bay – harming coral reefs, adjacent coastal fisheries, and fishpond practices (Bahr et al. 2015, Moehlenkamp et al. 2019). In an attempt to control erosion and sedimentation brought on by the new sugar plantation, the red mangrove (*Rhizophora mangle*) was introduced to the island of Molokai in 1902 (Munro 1904), and introduced to Oʻahu in 1922 when they were planted in the Heʻeia estuary by the Hawaiian Sugar Planter's Association (Fosberg 1948, Wester 1981). Currently, the persistence of the invasive mangrove is still one of the biggest problems Heʻeia Fishpond faces today, and efforts to remove them have been on-going since the early 2000s (**Figure 2E**).

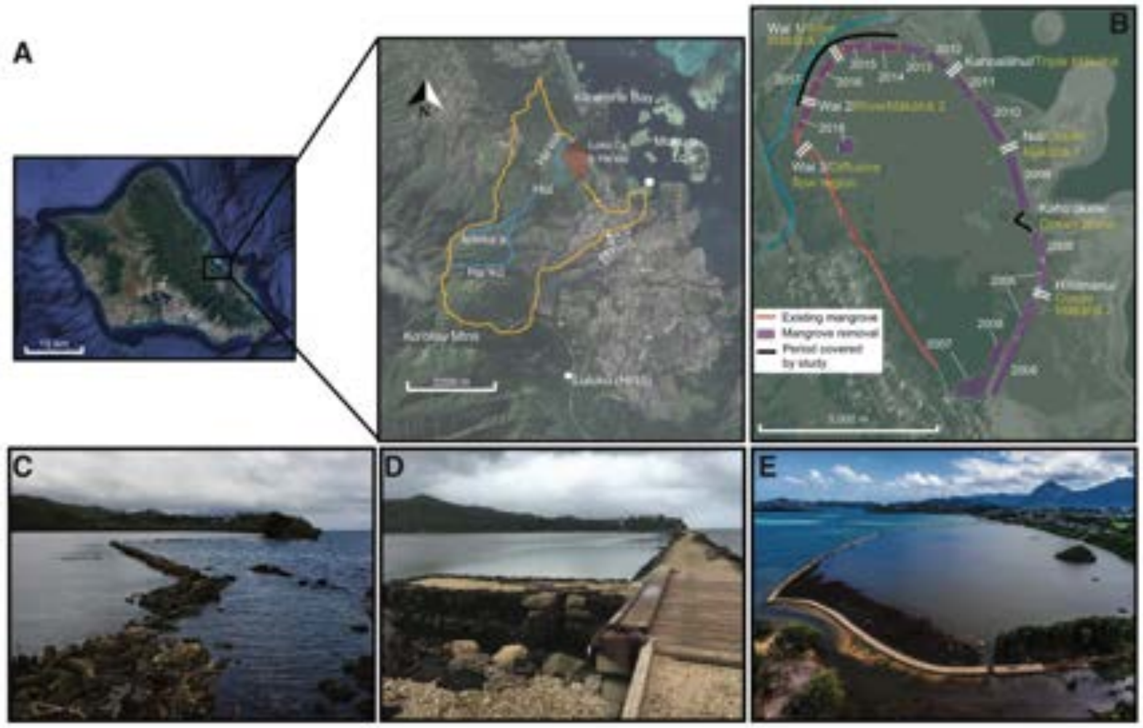

FIGURE 2. He‘eia Fishpond site. **(A)** The He‘eia *ahupua‘a*. The *ahupua‘a* is outlined in yellow, He‘eia stream is outlined in blue where it flows into He‘eia Fishpond, shaded in red, out into Kāne‘ohe Bay. **(B)** Shows the bio-cultural restoration outline from 2012-2018. Sluice gate locations that control freshwater and marine inputs into the pond are in yellow (Hawaiian names in white). Black line refers to areas worked on during the restoration periods. **(C)** Ocean Break, a large opening in the fishpond wall caused by the 1965 flood. It is currently rebuilt into *mākāhā* Kaho‘okele today. **(D)** Newly built sluice gate where Ocean Break used to be. **(E)** Invasive mangrove removal sites on the northern end of the fishpond. *Source: Moehlenkamp (2019)*

In many cases, mangroves are highly desirable in their native ecosystems as they provide shoreline protection, sediment stabilization, and nursery grounds for various animals in the area (Gedan et al. 2011). However, in the case of Hawaiʻi, the introduction of non-native mangroves has led to serious negative ecological and economic impacts (Chimner et al. 2006). The invasive red mangrove is found in almost all major Hawaiian islands. They have obstructed sluice gate structures, decreasing water volume flux and circulation of water in the fishpond and the streams that feed them (Allen 1998, Walsh 1967). Mangrove-dominated areas have high sediment rates and have become anoxic due to the excess bacterial decomposition of detritus (Allen 1998, Crooks 2002, Demopoulos & Smith 2010). As mangroves outcompete other native species in the area, their detritus becomes a sink for nitrogen and phosphorus and the excess sediment they trap cause poor water flow and decrease dissolved oxygen in its surrounding waters, which could potentially inhibit the rates of primary production in native Hawaiian fishponds (Walsh 1967). Because the red mangrove is non-native, native detritivores are unable to assimilate mangrove-derived nutrients and are not adapted to break down mangrove detritus (Demopoulos 2007).

Sediment loading from agricultural and urbanization sources has increased significantly since the 1800s. Dense mangrove root mass has resulted in an increased accumulation of terrigenous matter that extended outside the fishpond and onto the coral benthos (Vasconcellos 2007). Dense mangrove forests grew along the fishpond wall, resulting in increased salinity, organic matter, and turbidity that compromised the once native-dominated composition of the fishpond and moved towards an environment dominated by non-native species and invasive macro-algae.

Since 2001, the non-profit community organization Paepae o He‘eia has been earnestly restoring the prosperity of the Native Hawaiian fishpond, including removing invasive species, restoring the fishpond wall (*kuapā*) and other structures, and working to maintain a favorable environment for native food fish species such as Hawaiian striped mullet (*‘ama‘ama*). Thousands of volunteers have dedicated tens of thousands of hours toward the removal of mangrove and restoration over the years. As of 2018, approximately 1.46 km of the 2.13 km wall has been cleared of red mangrove via physical removal.

1.3.2 Invasive macroalgae

The Keapuka Flood of 1965 severely compromised the circulation and water volume flux patterns within He‘eia Fishpond, creating a 183 m opening in the northwestern sector of the fishpond wall adjacent to He‘eia Stream (Banner 1968). Historical tide data (NOAA Tides and Currents) show that the flood likely occurred during a perigean spring tide event, and might also explain the 56 m break (called "Ocean Break," **Figure 2C**) in the eastern seaward sector of the fishpond wall, likely from the build-up of internal pressure of the flood coupled with the extremely low tide outside the fishpond. These breaks of both the land- and seaside of the fishpond wall prevented He‘eia Fishpond from maintaining functionality and productivity. The pond's volume became unstable as it became even more tidally dominated, allowing for a dense mangrove forest to flourish and fragments of invasive macroalgae to enter and become well-established within the pond. Over time, the growth of invasive macroalgae contributed to more damage to the fishpond wall, effectively decreasing water exchange within the pond (Walsh 1967, Allen 1998).

Various species of invasive macroalgae populate the surrounding Kāneʻohe Bay. In particular, three invasive macroalgae species are present within Heʻeia Fishpond: prickly seaweed (*Acanthophora spicifera*), gorilla ogo (*Gracilaria salicornia*), and smothering seaweed (*Kappaphycus* sp.). The distribution of the algae during wet and dry seasons can be seen in **Figure 3**. Although the map and surveys were generated in 2012, the distribution can be perceived as accurate of the current state of the pond prior to the intense algae removal that took place from June 2019 to March 2020 (H. Kawelo & K. Kotubetey, personal communication). *A. spicifera* is the most widespread invasive alga in Hawaiʻi, first introduced in the 1950s most likely through unintentional introduction via barges (Doty 1961). *G. salicornia* and *Kappaphycus* sp., on the other hand, were both introduced in Hawaiʻi in the 1970s for the purpose of commercial cultivation (Cox 1999). Based on current observations, distribution of *G. salicornia* and *A. spicifera* are mostly concentrated near the fishpond wall facing Kāneʻohe Bay, with smaller clusters distributed throughout the pond.

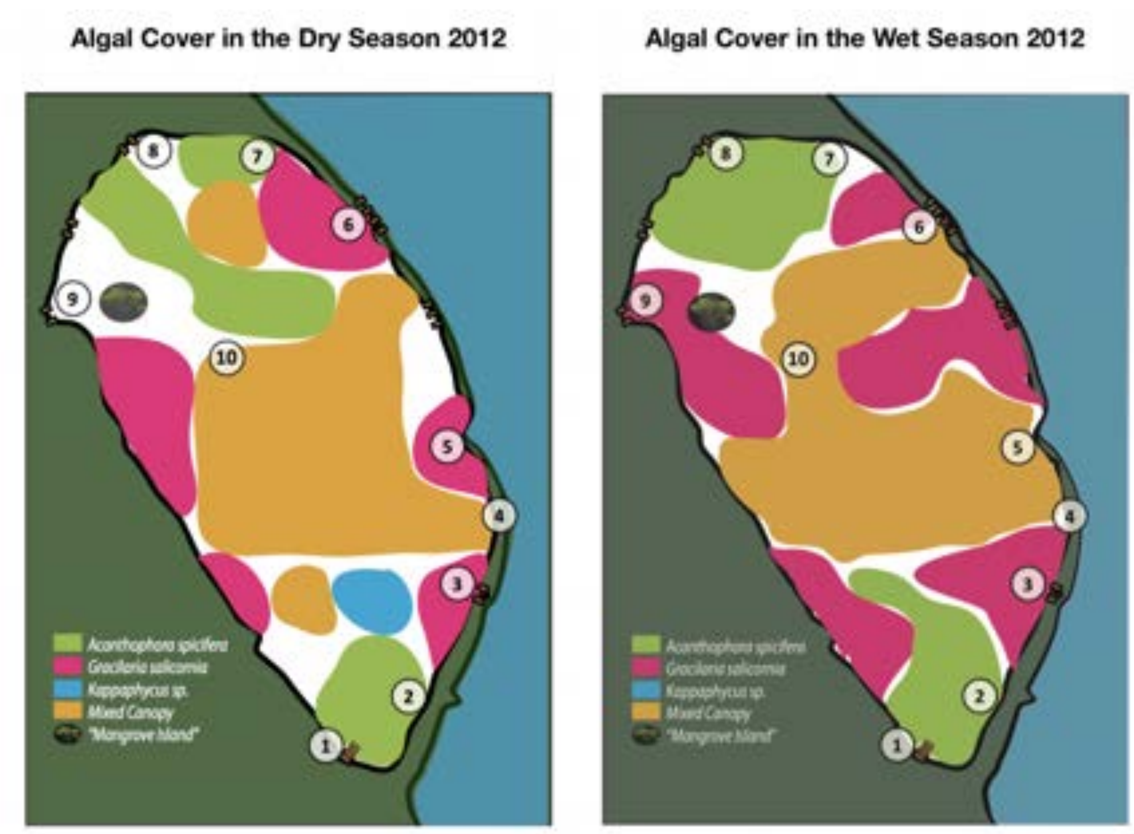

FIGURE 3. Invasive macroalgae distribution in He'eia Fishpond during wet and dry seasons of 2012. *A. spicifera* is consistent at the extreme northern and southern sectors of the pond. *G. salicornia* is consistent at locations adjacent to the mangrove forests near the shoreline and the fishpond wall facing Kāne'ohe Bay. *Source: Loko I'a Digital app*

Due to their phenotypic plasticity, high growth rates, and fragmentation capabilities, these invasive macroalgae have succeeded to spread and persist in the Hawaiian waters (Russell 1983, Kilar & Mclachlan 1986, Russell et al. 1992, Abbott 1999, Cox 1999). Fragments of these algae eventually made their way into He'eia Fishpond via high tides and established themselves throughout the area (Hawai'i Office of Planning 2016). The presence of invasive macroalgae are known to have detrimental effects to the overall health of the pond. Dense patches of the invasive seaweed damage the fishpond walls and clog the in/out flux of fresh and saltwater that flows through the pond, making it difficult to create a sustainable food chain and reestablish aquaculture production (Hawaiʻi Office of Planning 2016).

Throughout the surrounding Kāneʻohe Bay, remediation efforts have been done in an attempt to control the invasive macroalgae population. In collaboration with the State of Hawaiʻi Division of Aquatic Resources and the University of Hawaiʻi at Mānoa, physical removal of macroalgae has been done through the use of the Supersucker, a suction generated from a large pump system located on a barge (**Figure 4**). Bioremediation through the introduction of native sea urchins have also been found to be successful in controlling invasive macroalgae populations (Neilson et al. 2018) (**Figure 4**). Since June 2019, an intense period of physical removal of invasive macroalgae within Heʻeia Fishpond was undertaken by Paepae o Heʻeia using the Supersucker. This intense removal period was concluded at the end of March 2020.

FIGURE 4. Methods of invasive macroalgae removal in Kāne‘ohe Bay. Physical removal of algae through the use of the Supersucker (Left) and the introduction of native sea urchin species as a means of bioremediation (Right).

1.4 He‘eia National Estuarine Research Reserve

The National Estuarine Research Reserve (NERR) System consists of a network of 29 coastal sites across the United States designated to protect and study estuarine systems (NOAA OCM 2020). These Reserves are established through partnerships with the National Oceanic and Atmospheric Administration (NOAA) and respective coastal states. These sites provide researchers, policy makers, and caretakers of the land with “living laboratories” to better understand the unique relations that take place in areas where freshwater systems meet the sea. With over 1.3 million acres (over 500,000 hectares) of estuarine areas stewarded, NERR sites manage the site’s coastal stewardship, education, research, and long-term water quality monitoring (Winter et al. 2020).

The He‘eia NERR is the newest implemented Reserve, established as the 29th Reserve in the national system in 2017 (NOAA NOS 2017). Encompassing 1,385 acres (>550 hectares), He‘eia NERR consists of unique and diverse upland, wetland, stream, estuarine, coastal, and marine habitats within the He‘eia *ahupua‘a* (**Figure 5**). He‘eia

NERR is quite unique from other Reserves across the nation in implementing a management plan that takes on a “Traditional and Contemporary Approach”, which plans to integrate Indigenous ways of knowing and contemporary scientific research, monitoring, and sharing as a model for a sustainable estuary (Hawai‘i Office of Planning 2016). Through collective efforts with various site partners and the State of Hawai‘i, the designation of He‘eia NERR was determined appropriate in addressing the local challenges in improving land and water resources through their partnership with NOAA.

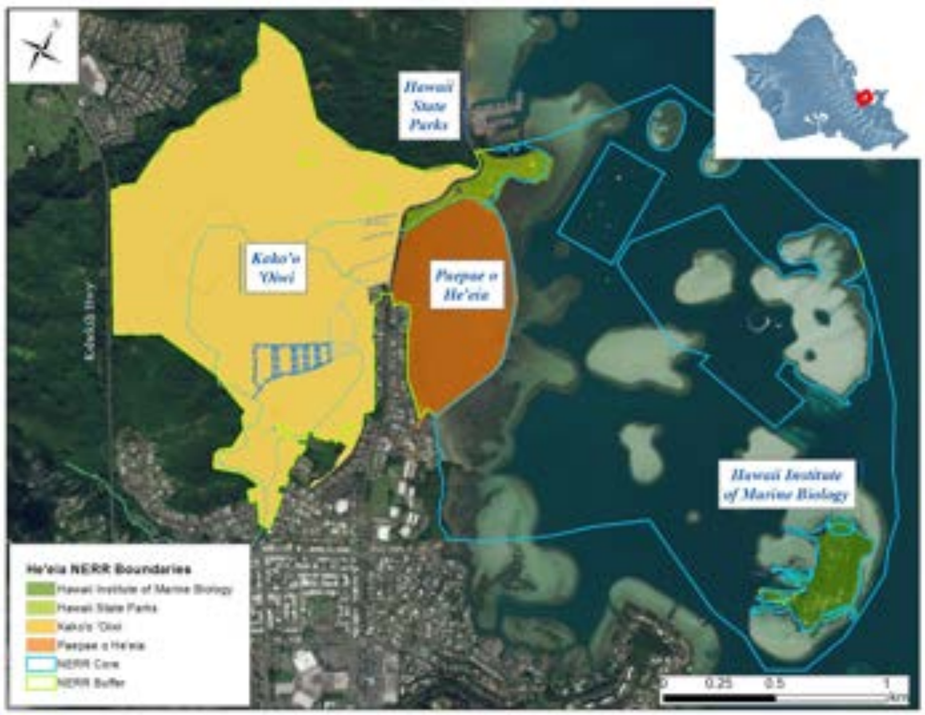

FIGURE 5. Entities within the He‘eia NERR boundaries and partnering organizations managing them. He‘eia State Park located to the north, wetlands of Hoi located south/west, *Moku o Lo‘e* (Coconut Island) to the east, surrounding marine waters with patch and fringing reefs, and *Loko i‘a o He‘eia* (He‘eia Fishpond) in the center. *Source: heeianerr.org/about-us/*

Priority coastal management issues within He‘eia NERR include invasive species, loss of habitat, erosion and sedimentation, non-point source pollution, urbanization and human activities in the area, water quality issues, agricultural development, and climate change impacts (Hawai‘i Office of Planning 2016). For this study, we were called upon by one of He‘eia NERR’s site partners, Paepae o He‘eia, to evaluate the circulation and water exchange dynamics of He‘eia Fishpond before and after the intense invasive algae removal that started in June 2019. The objective of this study is to understand how the removal of invasive species affect water circulation and flow within He‘eia Fishpond. Estuarine environments are highly dynamic in nature, and water circulation plays a significant role in the distribution of nutrients and microbial community throughout the pond, influencing food web dynamics and overall health of He‘eia Fishpond.

2.0 METHODS

2.1 Study Site: *Loko iʻa o Heʻeia* – Heʻeia Fishpond

Heʻeia Fishpond (*Loko iʻa o Heʻeia*) is a 0.356 km^2 Native Hawaiian fishpond located along the coast of Heʻeia Uli, bordering Kāneʻohe Bay on the windward side of Oʻahu (**Figure 6**). It is one of the largest fishponds in the Hawaiian Archipelago and is the second largest of at least 20 fishponds that were once active along the Kāneʻohe Bay shoreline (Henry 1975, Kikuchi 1976). Heʻeia Fishpond has been estimated to have been built over 600-800 years ago above the Malaukaʻa fringing reef (Kelly 2000). Characterized as a coastal wall fishpond (*loko iʻa kuapā*), it is entirely enclosed by a 2.5 km wall (*kuapā*) made up of a combination of basalt and fossilized coral (Henry 1975). The south and east *kuapā* is bordered by Kāneʻohe Bay, north bordered by Heʻeia Stream, and a historic man-made watercourse (*auwai*) that runs adjacent to the fishpond along the entire western bank.

FIGURE 6. *Loko iʻa o Heʻeia* is an 800-yr. old native Hawaiian fishpond situated in Kāneʻohe Bay. *Source: Nā Kilo Honua o Heʻeia.*

Sluice gates (*mākāhā*) are located throughout the fishpond in order to (1) control water flow in and out of the pond, and (2) protect target fish species from larger predators outside the pond. Heʻeia Stream is the main supplier of freshwater input and Kāneʻohe Bay is the main source of seawater (Apple & Kikuchi 1975, Kelly 2000). Historically, inland marshes upstream the fishpond were filled with taro patches which diverted water from He‘eia stream for crop irrigation. This system not only provided sustenance for the communities that tended for the land (*‘āina*), but also trapped excess sediment eroded from the land, ultimately reducing the sediment and nutrient load that enters the fishpond (Kikuchi 1976, Kelly 2000).

2.2 Measuring water flux at each *mākāhā*

To evaluate the flux of water that goes through sluice gates into and out of He‘eia Fishpond, Sontek Argonaut Shallow Water (SW) Profilers (Sontek, San Diego, CA, USA) with battery housings were deployed at each *mākāhā* for ~24 hr to capture a full tidal cycle (**Figure 6**). Deployments took place between June 15 - 20, 2019. Over the sampling period, one full spring tide was measured. Sontek Argonaut SW Profilers were oriented to face into the channel and placed at the bottom of each *mākāhā* floor between the sluice gate's interior/exterior edge. Instrumentation was mounted to a 0.7 x 0.7 m metal mooring and weighed down with ~30 kg weights. Measurements were recorded every 10 s with an average interval of 10 s. The blanking distance was set to the minimum of 0.07 m due to the shallow water column (~ <0.50 m). Water velocity (m s^{-1}) and water level measurements (m) were acquired to calculate water volume flux (WVF, m^3 s^{-1}) at each *mākāhā* using this equation:

$$\mathbf{\Phi = wdv} \qquad \textbf{(1)}$$

where Φ is WVF (m^3 s^{-1}), w is the respective *mākāhā* width (m), d is the water level vector (m), and v is water velocity through the respective *mākāhā* channel (m s^{-1}). For *mākāhā*

Kahoalāhui, water volume flux values were calculated by tripling the flow measurements taken at the southernmost *mākāhā* channel to reflect the three *mākāhā* units located at that station.

As each *mākāhā* was built with varying heights at time of construction, a different tidal cycle length (hr) was determined for each *mākāhā* to take this into account. Flood tidal cycle start and end times were defined as low slack water (LSW, WVF = 0 m^3 s^{-1}) tide stage and high slack water (HSW, WVF = 0 m^3 s^{-1}), respectively (Moehlenkamp 2018). For ebb tide cycles, start and end times were defined as HSW and LSW, respectively. LSW water levels for each *mākāhā* ranged widely from 0.08 m in Wai 1 to 0.64 m in Kahoʻokele. HSW water levels can also range widely from 0.5 m in Wai 1 to 1.1 m in Kahoʻokele. Peak WVF (m^3 s^{-1}) is defined as the highest WVF observed at each tidal cycle of each *mākāhā*. Cumulative flux per tidal cycle (m^3) is the total volume of water exchanged per tidal cycle, and was calculated using this equation:

$$\textbf{Cum. Flux = Mean WVF x Tidal Cycle Length} \qquad \textbf{(2)}$$

Where Cum. Flux is the cumulative flux per tidal cycle (m^3), Mean WVF (m^3 s^{-1}) is the average WVF at each tidal cycle of each *mākāhā*, and Tidal Cycle Length (hr) is the length of time a tidal cycle takes place. We multiply Equation 2 by 60x60 to reach the final unit of m^3.

To remove errors in the data retrieved from the Sontek Argonaut SW Profilers, we manually removed water level measurements (m) that deviated ± 0.05 the trend. As water level can be used as a proxy for tide levels (increase in water level indicate incoming tide, decrease in water level indicate outgoing tide), we referenced tide levels retrieved from NOAA.

2.3 Measuring relative water flow within He‘eia Fishpond

Clod cards have been widely used in marine habitats to correlate clod card weight loss with water motion, and shows the difference in water movement relative to other sites (Jokiel & Morrisey 1993). To measure water flow within He‘eia Fishpond, clod cards were deployed at 10 previously selected sites throughout the pond (**Figure 7**). Clod cards are solid blocks of calcium sulfate created by mixing a 10:9 ratio of Plaster of Paris:water, respectively. At each site, two pre-weighed, replicate clod cards were secured to a masonry brick at the fishpond floor for a ~24 hr. period. For control, the same setup was placed in a bucket filled with water from the pond in a shaded area, where water was motionless and consistent in salinity. Due to the wide salinity range within the pond, two control setups were conducted with waters from the north side (low salinity) and south side (high salinity) of the pond, respectively.

FIGURE 7. Deployment sites of Sontek Argonaut Shallow Water (SW) Profilers at each *mākāhā* (blue) and clod card site distribution (red) within He'eia Fishpond.

After retrieval, clod cards were rinsed with freshwater and dried in an oven for a couple of days until there were minimal changes in mass between daily readings. Three daily readings of each clod card were then measured and averaged to calculate post-weight. The diffusion index factor (DF) was then calculated:

DF = weight loss of field clods / weight loss of control clods **(3)**

A restoration project to remove invasive algae throughout He'eia Fishpond took place from June 2019 to March 2020. Uptake of algae via the Supersucker was the primary method of removal, and was led by a team at Paepae o He'eia. Selected areas of algae removal were based on visual observations by the fishpond stewards for where the majority of the algae was present. Approximately 100 ft x 200 ft grids were defined along the fishpond wall and removal of algae took place within each grid. Algae collected at each grid were weighed and sorted by species. Removal efforts primarily took place near the fishpond wall as invasive macroalgae was observed to be most abundant in those areas. The majority of algae collected were *G. salicornia* and *A. spicifera*. In order to determine whether algae abundance correlated with water flow at specific sites, we used the DF from clod cards as a proxy for relative water flow to the weight of algae collected from corresponding sites.

2.4 Comparison to 2018 water circulation study

Quantitative studies of water flow and circulation throughout He‘eia Fishpond were first conducted by Charles Young (2011), who laid the groundwork for future studies of water volume dynamics within the pond. For this study, methods used in this study were replicated from a study done by Moehlenkamp et al. (2019), which measured long-term effects of the removal of the invasive mangrove island and cattle egret absence on water circulation and flow within He‘eia Fishpond. Water fluxes at each *mākāhā* from Moehlenkamp’s study, conducted in 2018, were compared to calculated fluxes measured at corresponding sites.

3.0 RESULTS

3.1 Water volume flux dynamics in He‘eia Fishpond

3.1.1 Water flux at each *mākāhā*

The four *mākāhā* facing towards the ocean (Hīhīmanu, Kaho‘okele, Nui, Kahoalāhui; **Figure 2**) are observed to have bi-directional flow due to the semi-diurnal tidal cycle that takes place in Kāne‘ohe Bay. Wai 1, the first *mākāhā* in He‘eia Stream closest to the stream mouth, experiences bi-directional exchange of both seawater and freshwater from He‘eia Stream. Wai 2, further up He‘eia Stream towards the wetland, is observed to have a unidirectional flow of surface water into the fishpond. Wai 3, the river *mākāhā* located furthest upstream was not yet fully restored from past flood events and was not used in this study. Sampling period took place from June 15 to June 20, 2019. Tide data from NOAA Tide Predictions was used to determine the best dates for sampling and collecting water volume flux (WVF) measurements. Sampling period days were similar in predicted water levels and all within spring tides cycle.

Site-specific WVF ($m^3 s^{-1}$) of each of the six *mākāhā* were organized relative to water level (m) during Spring Flood and Spring Ebb tides (**Figure 8**). A positive WVF represents flux into the fishpond from Kāne‘ohe Bay and/or He‘eia Stream. A negative WVF represents flux out of the fishpond into Kāne‘ohe Bay.

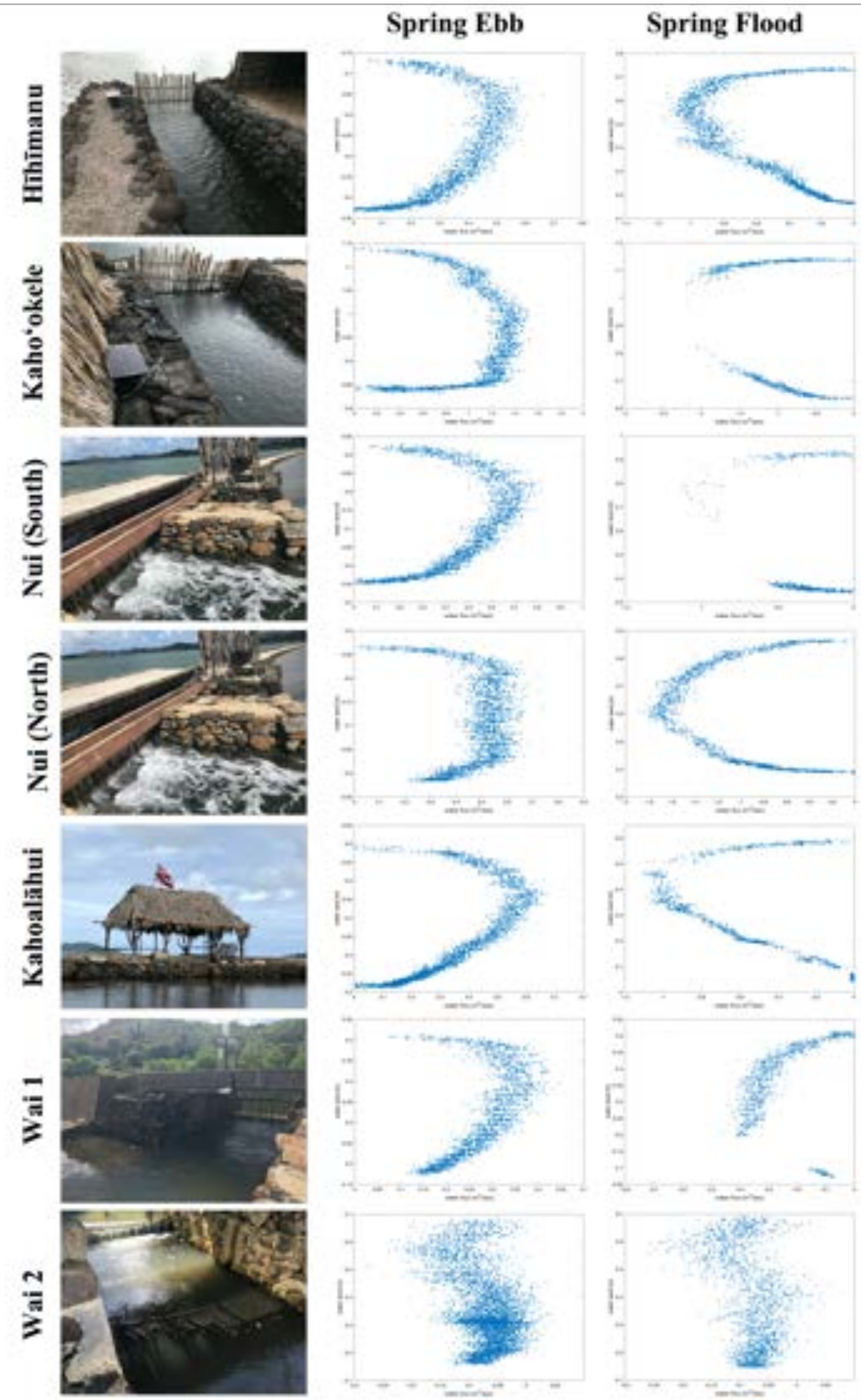

FIGURE 8. Water volume flux (m^3 s^{-1}) relative to water level (m) at each *mākāhā* over Spring flood and Spring ebb tidal cycles.

WVF measurements were used to calculate flow rates per tidal cycle through each *mākāhā* (**Table 1**). We found that peak WVF was highest during flood tides at all *mākāhā* with the highest in *mākāhā* Kahoʻokele (2.20 m^3 s^{-1}). Mean WVF is higher at Spring flood tide at Hīhīmanu, Kahoʻokele, Nui-North, and Kahoalāhui, with the highest mean WVF in Kahoalāhui (1.72 m^3 s^{-1}), indicating that most water exchange takes place at this *mākāhā*. Nui-South shows a higher mean WVF during Spring ebb tide. **Figure 9** shows relative water exchange at each *mākāhā* during Spring Flood and Spring Ebb tides.

On the other hand, the two river *mākāhā* Wai 1 and Wai 2 show similar mean WVF for both flood and ebb tides. For Wai 1, this may suggest uniform water exchange at both tidal cycles. Wai 2, however, has a positive mean WVF, indicating that water is primarily flowing into the pond. This can be explained as there is a wooden board in Wai 2 that allows water to flow into the pond only, unless water level in the pond is higher than the board (**Figure 8**, Wai 2). In addition, Spring flood tidal cycle lengths are generally shorter than their Spring ebb counterparts, with a mean tidal cycle length of 6.33 ± 0.84 hr and 7.01 ± 0.59 hr for Spring flood tide and Spring ebb tide, respectively. Overall, the combination of shorter-duration Spring flood tides and higher amounts of water volume exchange during Spring flood tides may suggest that Heʻeia Fishpond is still a flood-dominant system, as it was determined two years ago (Moehlenkamp et al. 2018).

TABLE 1. Water volume flux dynamics in He‘eia Fishpond in June 2019.

Mākāhā	Mean WVF [$m^3 s^{-1}$]	Peak WVF [$m^3 s^{-1}$]	Tidal Cycle Length [h]	Cum. Flux per Tidal Cycle [m^3]	WVF rate [$m^3 h^{-1}$]	Volume Exchanged per Tidal Cycle [m^3]	Relative WVF
Spring Flood				***120140***	***18066***	***120140***	100.00%
OM2 / Hīhīmanu	0.57	1.18	6.43	13175	2048	13175	10.97%
OB / Kaho'okele	1.07	2.20	7.68	29549	3846	29549	24.60%
OM1R / Nui-North	1.01	1.89	6.43	23377	3634	23377	19.46%
OM1L / Nui-South	0.32	1.14	6.42	7377	1150	7377	6.14%
TM / Kahoalāhui	1.72	1.10	6.55	40515	6186	40515	33.72%
RM3 / Wai 1	0.25	0.46	4.83	4383	907	4383	3.65%
RM2 / Wai 2	0.08	0.06	5.97	1763	296	1763	1.47%
Spring Ebb				***-90268***	***-12585***	***-90268***	100.00%
OM2 / Hīhīmanu	-0.33	-0.66	6.88	-8246	-1198	-8246	9.14%
OB / Kaho'okele	-1.01	-1.54	6.65	-24081	-3621	-24081	26.68%
OM1R / Nui-North	-0.48	-0.75	7.08	-12173	-1719	-12173	13.48%
OM1L / Nui-South	-0.45	0.82	6.93	-11354	-1638	-11354	12.58%
TM / Kahoalāhui	-1.04	-0.67	8.17	-30451	-3729	-30451	33.73%
RM3 / Wai 1	-0.27	-0.44	6.23	-6136	-984	-6136	6.80%
RM2 / Wai 2	0.08	-0.28	7.15	2172	304	2172	-2.41%

3.1.2 Comparison to Post-Mangrove Restoration Study (2018)

A similar study to quantify WVF in He‘eia Fishpond was conducted in 2018 by Moehlenkamp et al. (2019) in response to the large-scale removal of invasive mangrove throughout the pond. **Table 2** compares their findings to those of this study, which was done two years post-mangrove island removal.

At the time of their study, Moehlenkamp et al. (2019) found that more than half of the total water exchange was responsible by *mākāhā* Nui for both flood and ebb tides (relative WVF = 51.03% and 43.64% for flood and ebb respectively, **Figure 9B**), and found that He‘eia Fishpond was a flood-dominant system. Between Moehlenkamp's study and the time of this study, *mākāhā* Nui was reconstructed into two sections (measuring 2.46 m north side and 2.03 m south side), as opposed to one wide *mākāhā* (measuring 6.48 m) when it was originally built. We find that both *mākāhā* in Nui still play an important role in volume water exchange but has decreased in relative WVF since the last study (total 25.60% and 26.06% for flood and ebb spring tides, respectively, **Figure 9C**). We now find Kaho‘okele to play a similar role in relative water exchange to Nui in both Spring flood and ebb tides (24.60% and 26.68%, respectively). We find a ~three-fold increase in relative water flux in Kahoalāhui for both Spring flood and ebb tides in this study (33.72% and 33.73%, respectively), making it the site in which most water exchange occurs in and out of the *mākāhā*. In comparing site-specific WVF rates from the two studies, we see a ~37-48% decrease in total water volume exchanged per tidal cycle in He‘eia Fishpond, from 191,660 m^3 to 120,140 m^3 for flood tide and a decrease from 174,880 m^3 to 90,268 m^3 for ebb tide (**Table 2**).

TABLE 2. Changes in water volume flux rates post-mangrove removal (2018) and our study conducted in 2019. *Mākāhā* Nui measurements for Moehlenkamp et al. (2019) refer to when Nui was only one *mākāhā* (6.48 m); this study breaks down water volume exchange into the two *mākāhā* constructed in Nui at the time of study.

	Flood Tide					**Ebb Tide**				
	Moehlenkamp (2018)		*This study (2019)*			*Moehlenkamp (2018)*		*This study (2019)*		
Mākāhā	**Volume Exchanged per Tidal Cycle [m^3]**	**Relative WVF**	**Volume Exchanged per Tidal Cycle [m^3]**	**Relative WVF**	***Change in volume exchanged****	**Volume Exchanged per Tidal Cycle [m^3]**	**Relative WVF**	**Volume Exchanged per Tidal Cycle [m^3]**	**Relative WVF**	***Change in volume exchanged****
Hīhīmanu	7080	3.69%	13175	10.97%	*+86%*	-4780	2.73%	-8246	9.14%	*+72%*
Kaho'okele	54380	28.37%	29549	24.60%	*-46%*	-67520	38.61%	-24081	26.68%	*-64%*
Nui-North / Nui	97800	51.03%	23377	19.46%	*-69%*	-76320	43.64%	-12173	13.48%	*-69%*
Nui-South	-	-	7377	6.14%	-	-	-	-11354	12.58%	-
Kahoalāhui	24420	12.74%	40515	33.72%	*+66%*	-20220	11.56%	-30451	33.73%	*+51%*
Wai 1	7140	3.73%	4383	3.65%	*-39%*	-7600	4.35%	-6136	6.80%	*-19%*
Wai 2	840	0.44%	1763	1.47%	*+110%*	1560	-0.89%	2172	-2.41%	*+39%*
Mākāhā Total	**191660**	**100.00%**	**120140**	**100.00%**	***-37%***	**-174880**	**100.00%**	**-90268**	**100.00%**	***-48%***

*Percent change in volume exchanged per tidal cycle between this study and Moehlenkamp (2017)."+" indicates increase in volume exchanged for this study, and "-" indicates decreased exchange in volume.

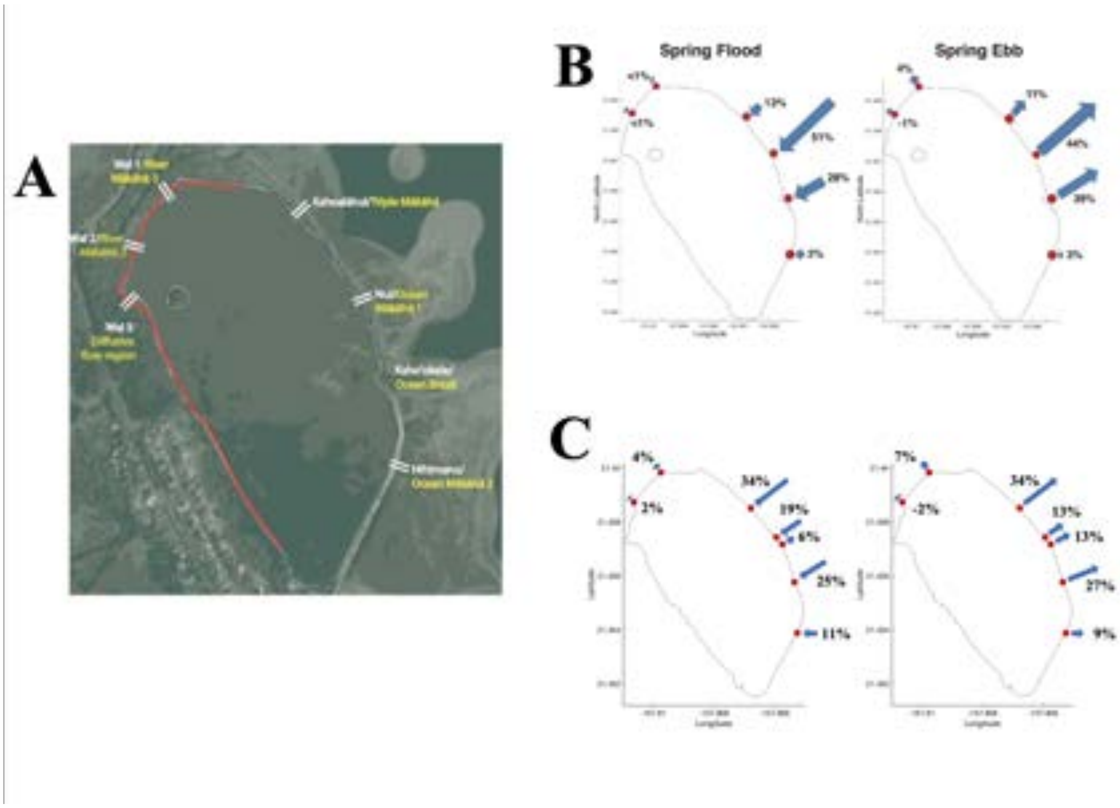

FIGURE 9. Relative Water Volume Exchange at each *mākāhā* during Spring Flood and Spring Ebb tides. **(A)** shows the location of each *mākāhā*, **(B)** shows relative water exchange rates from Moehlenkamp (2018), and **(C)** shows relative water exchange rates from this study (2019).

Overall, there is a slight increase in relative WVF at each *mākāhā* (other than Kaho‘okele and Nui) at the time of this study, suggesting that water flow is more distributed between each of the *mākāhā* than Moehlenkamp's study. We find the most obvious shift in water exchange in *mākāhā* Kahoalāhui, where we find a ~three-fold increase in relative exchange of water volume exchange in both Spring flood and ebb tide (12.74% to 33.72% and 11.56% to 33.73%, respectively). There is also about a ~three-fold increase in *mākāhā* Hīhīmanu's relative contribution to water volume exchange in

Spring flood and ebb tide (from 3.69% to 10.97% and 2.73% to 9.14%, respectively). The two river *mākāhā* - Wai 1 and Wai 2 - continue to have minor roles in water exchange in both studies (**Table 2**). In the summer of 2018, a water channel, referred to as "Horseshoe," was created in the northern side of the pond with the intention of redirecting more freshwater through the two river *mākāhā*. At the time of our study, we see a slight increase in relative water exchange for Wai 1 for Spring ebb tide (4.35% to 6.80%). Although Wai 2 continues to display a unidirectional flow of freshwater into the fishpond since the 2018 study regardless of tidal state, we find that there is an increase in relative water flux flowing into the pond (0.44% to 1.47% in flood tide). We also find that there is a ~two-fold increase in volume exchanged per tidal cycle for Spring flood and ebb tides (840 m^3 to 1763 m^3 and 1560 m^3 to 2172 m^3, respectively), which suggests that Wai 2 is contributing more freshwater input into He'eia Fishpond.

3.2 Relative water flow within the fishpond and invasive algae distribution pre-removal

3.2.1 Relative water flow measured using clod cards

Clod cards were used to determine relative water flow at different locations throughout He'eia Fishpond (**Figure 10**). Clod cards were deployed prior to the invasive algae removal project that took place from July 2019 to March 2020. We find that relative water flow is higher around the northern sector and sites adjacent to the shoreline of the pond, where there is an observed less presence of invasive algae at time of deployment. The southern sector and along the fishpond wall is shown to have the lowest relative flow adjacent to the fishpond wall facing Kāne'ohe Bay.

FIGURE 10. Clod card deployment sites show diffusion factor (DF) as a proxy for relative water flow. The higher the DF, the higher the water flow relative to other clod card sites. There is an observed lower relative water flow at sites adjacent to the pond wall.

3.2.2. Removal of invasive macroalgae in He‘eia Fishpond

A massive project to remove invasive macroalgae within He‘eia Fishpond took place from July 2019 to March 2020. Although algae removal sites were chosen based on observed areas of algae presence, the generated maps in **Figure 11** may not be completely representative of the algae distribution throughout the entire pond, as most sites were concentrated along the southern/southeastern sectors of the pond. The 2012 algae distribution map (**Figure 3**) may be a more accurate visualization of algae distribution at the time before the project. At the time of the invasive macroalgae removal project, collected algae was sorted by species and weighed accordingly within 100 ft x 200 ft grid sites within He'eia Fishpond. **Figures 11A and 11B** shows the abundance of *A. spicifera* and *G. salicornia*, the two most prominent invasive macroalgae in the pond, at each site. Throughout the entire large-scale removal project, 105,830 lbs of *G. salicornia* and 20,410 lbs of *A. spicifera*, for a total of 126,240 lbs of algae were collected. Overall, *G. salicornia* was the more abundant invasive macroalgae in the pond and was present at all grid sites (**Figure 11B**). *A. spicifera* was distributed mostly around the southern sector of the pond, and were not present in 7 of the 32 sites (**Figure 11A)**.

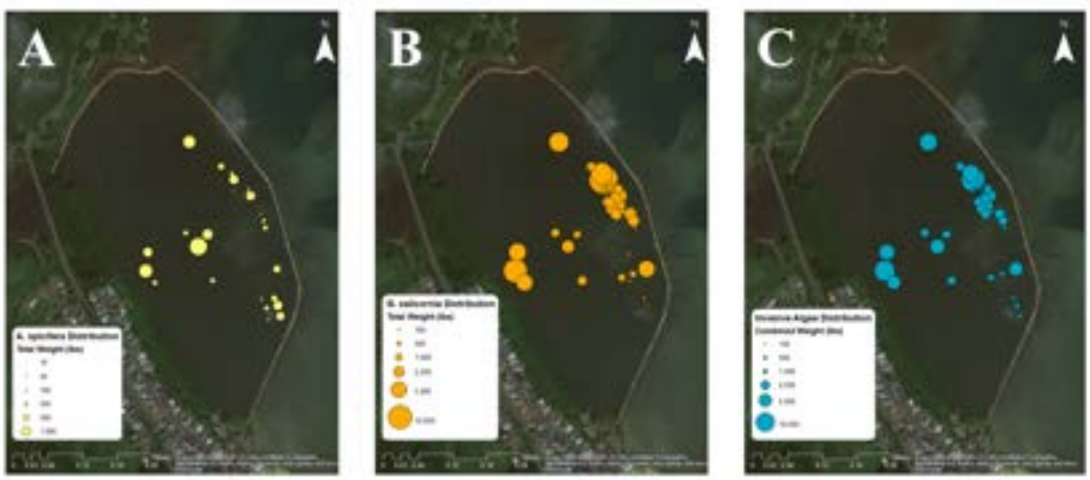

FIGURE 11. Invasive algae abundance at algae removal sites. Project took place from July 2019 to March 2020. **(A)** shows abundance (lbs.) of *A. spicifera*, **(B)** shows abundance (lbs.) of *G. Salicornia*, and **(C)** shows combined weight (lbs.) of all invasive algae collected at each removal site.

At the time the clod cards were deployed, large-scale invasive macroalgae removal had not yet taken place. When compared to the amount of invasive macroalgae removed, we find that the southern end of the fishpond, where we see high densities of both algae (**Figures 11C**), appeared to have lower relative flow than other parts of the pond (**Figure 10**).

4.0 DISCUSSION

4.1 Addressing changes in study objectives

The original intention of this study was to measure water volume flux and exchange before and after the large-scale removal of invasive macroalgae using the Supersucker within He‘eia Fishpond. However, due to the restrictions and risks from the COVID-19 pandemic, we were unable to complete the ‘after removal’ survey portion of the study, which was scheduled for April 2020. Instead, we decided to focus the study on comparing the data we collected to the water volume fluxes that were measured after mangrove island removal in 2018 (Moehlenkamp, 2019).

It is also important to take into consideration the differences of the two studies when comparing their findings. Moehlenkamp’s 2019 study measured water fluxes of four tidal cycles (Spring flood, Spring ebb, Neap flood, Neap ebb) at each *mākāhā* for 7-day sampling periods. This study observed water flux exchange at Spring flood and ebb tides at each *mākāhā* for ~24 hrs (one full tidal cycle) only. Thus, comparisons were made between their calculations for Spring tides. Also, at the time of this study, *mākāhā* Nui had been rebuilt into two *mākāhā* (2.03 m and 2.46 m), whereas during Moehlenkamp’s study Nui was only one *mākāhā* unit (6.48 m). Intense removal of mangroves upland of He‘eia Fishpond at Kāko‘o ‘Ōiwi had started during March 2018 and continued during the time of this study, and a water channel had been created at the northern sector of the pond in the summer of 2018 in hopes to channel more freshwater into the pond.

4.2 Changes in water flux two years post-mangrove removal efforts

Our results found a ~40% decrease in total volume exchange in this study compared to Moehlenkamp (2019)'s water volume fluxes. A plausible suggestion for this decrease could be the reconstruction of *mākāhā* Nui, which was rebuilt into two smaller *mākāhā* units. Moehlenkamp's 2018 study found that when Nui was one *mākāhā* unit (6.48 m), it accounted for approximately half of the water volume exchange in the pond for Spring flood and ebb tides (**Table 2**). We also know that the restoration of the Ocean Break *mākāhā* (known today as Kaho'okele) redistributed how much water is exchanged at each *mākāhā* (Moehlenkamp et al. 2019), so this might be what we are witnessing with the reconstruction of *mākāhā* Nui.

We also see an increase in freshwater flow into the pond from Wai 2 two years post-mangrove island removal (**Table 2**). As Wai 2 is observed to have a unidirectional flow into the pond from He'eia Stream, this may indicate that there is an increase of freshwater input into the pond. This may suggest that the water channel built in the summer of 2018, has been successful in redirecting freshwater from He'eia Stream into the two river *mākāhā*. As the overall health and productivity of estuarine environments such as He'eia Fishpond requires input of both freshwater and ocean water sources (Dagg et al. 2004, Burton 1988), this may suggest that the clearing of invasive mangrove forests has allowed more freshwater from He'eia Stream to be fed into the pond.

The calculations in this study only reflect a period of one Spring tidal cycle (~24 hr) in June 2019, and we expect additional studies with a longer sampling period with other tidal cycles and seasons represented may be needed to make further holistic comparisons and analyses. Future studies could also look into the residence time of the water in the pond. As restoration efforts continue within the fishpond and the surrounding uplands, we expect fluctuations in He‘eia Fishpond’s water volume exchange in response to these changes. Climate change may also alter fishpond circulation dynamics, as aperiodic freshwater input into the pond may increase during more intense storms, as well as increased seawater input through sea level rise and king tides. Thus it is important to continue to monitor changes in water volume flux and circulation in order to guide fishpond management.

4.3 Invasive algae distribution

Invasive macroalgae distribution and species type was mapped back in the wet and dry seasons of 2012 (**Figure 3**) and greatly represents the algae distribution in the pond for a long time, until a few months before the intensive algae removal described in this study, when large abundances of *G. salicornia* appeared (H. Kawelo & K. Kotubetey, personal communication, July 21, 2020). The 2012 map shows that regardless of the season, *A. spicifera* is more tolerant of freshwater than *G. salicornia* (Kilar & Mclachlan 1986), so that may explain why *A. spicifera* is present at the extreme northern and southern sectors of the pond year-round, around the river *mākāhā* and along the pier. *G. salicornia*, on the other hand, was observed to be present adjacent to the mangrove forests along the shoreline and near the fishpond wall facing Kāne‘ohe Bay, which is where the team at Paepae o He‘eia focused on removing the algae. *G. salicornia* has the tendency to tumble across the pond with the currents and entangle with each other and other species throughout the pond, obstructing flow (Cox 1999, Doty 1986). Because of this, it is hard to pinpoint exactly where they are located during different tidal cycles.

There is also an observed combination of macroalgae species throughout the middle of the pond. Compared to the distribution that was collected during the large-scale algae removal process, we find that *G. salicornia* continues to be persistent along the fishpond wall as it was back in 2012 (**Figure 3, Figure 11B**).

We found that *G. salicornia* are found in large clusters and surrounding the mouth of the ocean *mākāhā*. We suggest that as water flows in and out of the *mākāhā*, this causes fragmentation of the algae, allowing it to proliferate in the surrounding area and be found in such large amounts. As for *A. spicifera*, its low tolerance of salinity and wave exposure (Russell et al. 1992, Kilar & Mclachlan 1986) could be responsible for its continued presence in the northern sectors of the pond, near the river *mākāhā*, and southern sectors, near the fishpond pier.

4.4 Restoration efforts continue to make progress

He‘eia Fishpond has undergone large changes since the time of Moehlenkamp's study, including additional structural changes such as extension of the *kuapā* on the northwestern side and additional mangrove removal. In addition, the surrounding uplands in the He‘eia wetland, managed by Kāko‘o ‘Ōiwi, have continued to restore flooded-field agroecology (*lo‘i kalo*), native agroforestry, and further removed acres of mangrove trees. As of June 2020, most of the upland mangroves have been cleared and more water is being directed downstream, thus we expect these restoration activities to improve water circulation and freshwater access into the fishpond.

We hypothesize that there is a more even distribution of water flow between each *mākāhā* compared to Moehlenkamp's 2018 study, in response to the ongoing restoration efforts being done within the pond and the surrounding uplands. We also see an increase of freshwater input in the river *mākāhā* Wai 2, suggesting that there is more mixing of waters within the pond. Future studies can try to better understand the underlying processes and seasonal dynamics of such water diversions, so that the fishpond stewards can benefit from the information to manipulate water flow in the *mākāhā* to obtain favorable flow rates into the pond. Currently, the third river *mākāhā* Wai 3 has been constructed; however, the surrounding areas still need to be removed of debris in order to increase water flow, and the flow is highly dependent on water passage in the He‘eia wetland upstream, in Kako‘o ‘Ōiwi. This increased input of freshwater sources could contribute to the overall water exchange within the brackish waters of the pond, which would in turn increase productivity within He‘eia Fishpond.

5.0 CONCLUSION

Loko iʻa o Heʻeia provides us the unique opportunity to integrate western science and Indigenous ways of knowing in order to better understand the complex relations that take place where freshwater streams meet the sea. With the many restoration efforts that have been conducted and are currently ongoing, the dynamics of the fishpond will continue to change in response. This study shows that the water volume exchange dynamics of Heʻeia Fishpond respond to the structural changes being done within the fishpond and surrounding uplands. Through the combination of the findings of research collaborators and the deep-rooted Indigenous knowledge of how Heʻeia Fishpond functions, the fishpond stewards are provided with vital insight to create effective management plans. By understanding the underlying factors that drive the dynamics of the pond, we can continue to help to regulate water exchange through the *mākāhā* and increase productivity for the native biota within the pond, to work together towards the main goal of restoring the pond into the functioning Native Hawaiian *loko iʻa* it once was.

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