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By

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**Evaluating the impact of a stream restoration project on the
Waipā stream**

University of Hawai'i in Manoa



**UNIVERSITY
of HAWAII®
MĀNOA**

Analytical Note

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Title (English)	Evaluating the impact of a stream restoration project on the Waipā stream		
Summary (French)	<p>Mon stage s'est déroulé à l'université d'Hawaï'i, où je me suis concentrée sur l'évaluation de l'efficacité d'un projet de restauration d'un cours d'eau. Ce projet a été entrepris par la Fondation Waipā et se base sur la mise en œuvre de multiples solutions fondées sur la nature par le biais de bonnes pratiques de gestion, notamment la plantation d'espèces indigènes, l'élimination des porcs sauvages, le remplacement des fosses d'aisance, etc. Pour déterminer ses effets sur la santé des cours d'eau, j'ai analysé les données de la dernière décennie, en me concentrant particulièrement sur la turbidité et les bactéries fécales indicatrices. J'ai également essayé de déterminer le poids des différents facteurs sur ces variables cibles par le biais de la cartographie des systèmes et de la modélisation de la forêt aléatoire.</p>		
Summary (English)	<p>My internship took place at the University of Hawai'i where I focused on evaluating the efficiency of a stream restoration project. This project was undertaken by the Waipā Foundation and focused on implementing multiple nature-based solutions via BMPs including planting native species, feral hog removal, cesspool replacement, and more. To determine its effects on stream health, I analyzed data from the past decade, particularly focusing on turbidity and fecal indicator bacteria. I also tried to determine the weight that different factors had on these target variables via systems mapping and random forest modelling.</p>		
Key words (French, 5 max)	Restauration rivière, analyse de données, solutions fondées sur la nature, forêt aléatoire		
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COLLATION			
Number of...	Pages	Appendices	References
	76	2	24

Declaration of authorship

I declare that this report cannot be suspected of plagiarism because it constitutes the result of my personal work, explicitly distinguishing what I produced and what I borrowed from others. As such, the quotes are clearly identifiable and the sources (writings, images) which fed my reflection are referenced.

Je déclare que ce rapport constitue l'aboutissement d'un travail personnel et ne peut être suspecté de plagiat. Le travail présenté distingue explicitement ce que j'ai produit de ce que j'ai emprunté à d'autres. A ce titre, les citations sont clairement identifiables et les sources (écrits, images) qui ont alimenté ma réflexion sont référencées.

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1. Introduction

1.1 Context

1.1.1 Environmental context

In 2018, torrential rains fell on the islands of Oahu and Kaua'i. On April 13, an upper-level low crossed the region, creating a series of thunderstorms that moved over eastern Oahu, eventually arriving on the island of Kaua'i. The heaviest rainfall occurred in northern Kaua'i (where the Waipā area, which I study, is located), where rainfall of 1,262 in 24 hours was recorded between April 14 and 15. This is the highest 24-hour rainfall total ever recorded in the United States, surpassing the previous record of 43 in (1,100 mm) in Alvin, Texas, on July 25-26, 1979, set during Tropical Storm Claudette. [1]

The Wainiha River recorded a record flow during the event. The sudden rains caused landslides, mainly in isolated areas, as well as flash floods, leading to power cuts in Hanalei and Wainiha. The floods felled trees and power lines, eroded numerous bridges and roads, and swept away more than 500 houses, crops, beehives and livestock. Overall damage was estimated at over \$125 million. Damage to public buildings was estimated at \$19.7 million. Climate disruption has led to the loss of many seasonal patterns, making droughts and floods much more unpredictable. [1]

Despite the damage, there were no deaths or injuries. This is thought to be partly due to the close-knit nature of the local communities.

However, these rains cause a great deal of erosion, and the sediment from this is transported by rivers to the ocean, where the mud and silt that arrive with the floods are episodically resuspended, degrading the ecosystem.

In fact, the USGS uses aerial and satellite imagery to map the distribution and density of coral on the reefs. In addition, scientists have placed underwater instruments on the reefs to measure water clarity, waves, currents, temperature and light penetration, as well as sediment traps to quantify sediment accumulation rates and suspended particle concentrations. [1]

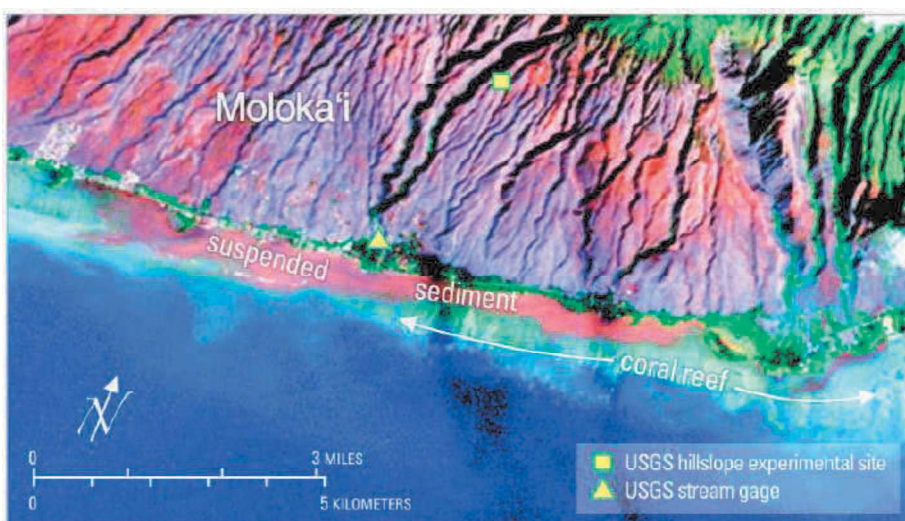


Figure 1 - Sediment movements on reefs. Source : USGS

Besides the rain, human activity also has an extremely negative impact on the health of river ecosystems, including the one in Waipā.

For instance, over the past two centuries, humans have drastically transformed rivers so that they could be used for new functions: enhancing navigation, energy production, agricultural production and settlement in former floodplain areas, drainage, etc. However, practices like pollution, nutrient enrichment, damming or overexploitation have had negative ecological repercussions such as increased erosion, decrease, and pollution of groundwater resources, increase in flood probability, decline in fisheries and biodiversity, as well as loss of esthetics and recreational functions. Indeed, dams fragment the river, interrupting the migratory route of many freshwater species. Deforestation increases the risk of flooding and prevents forests from performing the essential role of water purification. Urbanization and agriculture cause runoff of pesticides, fertilizers, industrial and household wastes which threatens native species. [2]

Climate change, too, is having its effect on the waterways, leading to a loss of quality of life and significant economic costs to make up for this. In Hawai'i, the increasing temperatures and disruption of rainfall frequency and intensity leads to changing habitat ranges and increases the threat of diseases, pests, and invasive species. Saltwater intrusion is becoming more common in freshwater. This also has implications for human health as climate change causes the water quality and availability to decrease and changes the frequency and intensity of tropical cyclones (hurricanes). [3]

A great deal of research has already been carried out to determine the impact of human activities on the entire aquatic ecosystem, from the mountains to the sea. Indeed, The Sustainable Development Goals 14 and 15 (Life on Land and Life below Water) explicitly aim at enhancing global ecological conditions of river landscapes, and river restoration is one of the main objectives in political agendas. [4]

These have led to recommendations for the following solutions: replacing invasive species with native plants to prevent erosion, estuarine watershed restoration plans, assessing the health of reefs to develop strategies to protect fish and their habitats from land-based sediments or other climatic stressors. These solutions have already been partially implemented: restoration of the fishpond has already begun, agroforestry is already playing a role in preventing erosion in the area, native plants are being replanted while invasive ones are being pulled out (although these grow back very quickly), etc. My main task during this internship has been to evaluate datasets to assess their effectiveness.

One of the tools used to regulate water quality is Hawai'i's Water Quality Standards. They define a legal basis to monitor the amount of pollution in Hawaiian waterways. The water quality standards depend on the type of body of water (e.g., embayment, open coastal, flowing stream, etc.) and on its designated use. They also include policies on how to avoid further degradation of these bodies of water. [5]

One of the indicators used in Hawai'i's Water Quality Standards is the bacteria *Enterococcus*. Enterococci are found in the feces of all warm-blooded animals. There is a high concentration of this bacteria in human feces, usually between 10^4 and 10^6 bacteria per gram wet weight. This means that they can signal fecal waste in bodies of water. The presence of Enterococci in streams and rivers usually comes from wastewater treatment plant effluent, leaking septic systems, stormwater runoff, sewage discharged or dumped from recreational boats, domestic animal and wildlife waste, improper land application of manure or sewage, and runoff from manure storage areas, pastures, rangelands, and feedlots. [6]

The state's list of impaired waterbodies shows that the Waipā Estuary does not meet state standards for Enterococcus and Turbidity, and Waipā Stream does not meet the standard for Enterococcus only (wet and dry season).

Table 1. KAUAI Inland Waters

Assessed Water Body	Water Body Type	Scope of Assessment	Water Body ID	Season	Enterococci	TN	NO ₃ -NO ₂	TP	Turbidity	TSS	Other Parameters	Category
Waimea	Stream	EN	2-4-04	Wet	-	Ac	Ac	Ac	V	Ac		2,3,5
Waimea	Estuary	EE	2-4-04-E	NA	-	-	-	-	V	NA		3,5
Wainiha	Stream	EN	2-1-14	Dry	-	Ac	Ac	Ac	Ac	Ac		2,3
Wainiha	Stream	EN	2-1-14	Wet	-	Ac	Ac	Ac	Ac	Ac		2,3
Waioli	Estuary	EE	HIW00163	NA	N	A	N	N	N _T	NA	NH ₄ (N) Chl <i>a</i> (A)	2,4a,5
Waioli	Stream	EN	2-1-18	Dry	N	N	A	A	N	A		2,5
Waioli	Stream	EN	2-1-18	Wet	N	A	A	A	N	-		2,3,5
Waiopili	Stream	EN	2-3-99	Dry	-	-	-	-	-	-		3
Waiopili	Stream	EN	2-3-99	Wet	N	-	-	-	N	-		3,5
Waipa	Estuary	EE	HIW00164	NA	N	A	A	A	N _T	NA	NH ₄ (A) Chl <i>a</i> (A)	2,4a,5
Waipa	Stream	EN	2-1-17	Dry	<u>N</u>	A	A	A	<u>A_T</u>	A _T		2,3,4a
Waipa	Stream	EN	2-1-17	Wet	<u>N</u>	-	-	-	<u>A_T</u>	-		2,3,5

Legend for Inland Waters

Scope of Assessment: EN = Entire network; EE = Entire estuary; ER = Entire reservoir; EW = Entire wetland; EL = Entire lake; E = Estuary
 Water Body Type: P = Pearl Harbor

Legend for Marine Waters

Water Body Type: B = Embayment; C = Open coastal; O = Oceanic; K = Kona marine waters

Legend for Inland or Marine Waters

Decision Codes: - = Insufficient data; A = Attained; Ac = Attained (with combined seasonal data); N = Not attained; Nc = Not attained (with combined seasonal data); N1 = Not attained (2x the standard); N1c = Not attained (with combined data, 2x the standard); V = Visual listing from 2001-2004; Y = Previous listing from 1998 or earlier; NA = Not applicable; Subscript _T denotes TMDL approved for parameter
 Category: 1 = All uses attained; 2 = Some uses attained; 3 = Not enough data to evaluate; 4a = Not attained but TMDL approved; 5 = At least one use not attained, TMDL needed
 N = Gray shading denotes assessment confirmed with new data
 N = Bold, italicized, underlined and shaded notations denote change from previous list
 = Red shading denotes disappearance of sample location due to volcanic activity

Figure 2 - 2024 303d Listing and Legend for Waipā Stream and Estuary

This is why restoration efforts will focus mainly on lowering the Enterococci levels and turbidity levels of the Waipā stream.

1.1.2 Societal context

Hawai'i's relatively stable climate enables the cultivation of macadamia nuts, coffee, orchids and other tropical plants, papaya, mango, cocoa, jackfruit, vanilla, ginger root, kava, goat's cheese, honey, hearts of palm and exotic fruits such as durian, rambutan, starfish, cherimoya, fig, lychee and dragon fruit. According to the USDA, in 2022, the state of Hawai'i had more than 7,300 farms working on 1,100,000 acres. On Kauai, following torrential rains, farmers were faced with the loss of almost a centimeter of topsoil as a result of intense flooding - which takes at least 100 years to form naturally. This is particularly problematic for a state where agriculture is essential to the economy. [7]

The Waipā area is also particularly rich in tradition and culture. There are two main cultural elements: the l'oi kalo and the fishponds.

Streams

Streams, called “wai” in Hawaiian, are essential to life and are considered sacred in Hawaiian culture. The division of the land in ahupua’as is defined by streams. Many battles were fought over the right to use the streams. In fact, the Hawaiian word for law is kānāwai, or “equal sharing of water.”

These streams provided the people living in the ahupua’a their wealth. Indeed, in Hawaiian, the term for abundance and prosperity is “Waiwai”. Streams are crucial to the Hawaiian way of life as they serve many purposes: in the mountainous part of the ahupua’a, they irrigate plants necessary to produce medicine, build canoes, make nets and fishing lines. In the plains, they are used to water food crops such as taro, banana, breadfruit, sugar cane, sweet potatoes, and yams. ‘Auwai are ditches used to divert water to the fields, then to direct the water back into the streams to allow fields downstream to be watered as well. Water was used very sparingly, and native Hawaiians only took what they needed. Due to the sacred nature of the streams, much care was taken to keep the streams clean and pollution-free. [8]

Streams are also essential to maintain l’oi kalo and fishponds.

L’oi kalo

Taro is a plant that was imported by the Polynesians 900 years ago. It thrived in the humid climate of the Hawaiian islands and became a staple in many traditional dishes. It can also be used as medicine and is a sacred part of Hawaiian culture. Indeed, legend has it that it sprouted from the body of the stillborn child of the sky god, Wakea, and the keeper of the stars, Ho’ohokukukalani, that had been buried in the ground. Humans are said to be descended from the second son of Wakea and Ho’ohokukukalani, and because of the order of birth, humans are sometimes considered genealogically inferior to taro in Hawaiian culture. Another testimony to the importance of taro is the fact that the word for family, “ohana” comes from the word ‘ohā which is used to describe the part of the taro plant that is underground.

Taro has a great number of uses. First of all, it is used for many dishes, the most famous being poi, a greyish-purple mash. Also, the leaf-stem juice and mud from the taro patches was used to dye kapa cloth and lauhala red and black. Of the 300 varieties of taro, some of them can be used for medicinal purposes. Others are given as offerings to the gods. Furthermore, they testified to the social ranking of the person eating it: the pink and purple royal taros were exclusively reserved for the high chiefs and royalty whereas the gray and white taros were consumed by commoners.

The l’oi kalo is a traditional farming and watering system used to grow taro. Lo’i kalo are generally found in areas where water sources are abundant, such as near rivers or streams. They consist of a series of terraces or shallow pits dug into the ground and lined with stones or other materials to retain water. Water is conveyed from the water source to the lo’i kalo, where it is used to irrigate taro plants. The lo’i kalo form a rich wetland ecosystem that is home to native plants and animals, including the pinao (Hawaiian dragonfly), ‘auku’u (black-crowned night heron) and ‘o’opu (goby fish). [9]

Fishponds

Fishponds (loko i'a) are generally located in the shallow areas of a reef, where freshwater streams meet the ocean, and surrounded by a basalt wall. This allows them to capture brackish water and stimulate beneficial eutrophication. Their distinctive gates called mākāhā, made of small tree branches forming a grid inside the channels that connect the pond to the sea allow fry to enter the pond and fatten up on abundant algae, but hold back adult fish that are then too large to pass through the grid and return to the open sea.

There are four main types of fishponds, serving different purposes : loko kuapā, the most common, are shallow areas of a reef flat surrounded by a low lava rock wall built out from the shore. Loko pu'uone are made from natural ponds near a beach or sandbar, which are then connected to the ocean via a channel, making the water within brackish. Next, the loko i'a kalo are simply created by the addition of fish to taro patches, which are covered in water. Finally, oko wai are inland freshwater ponds made in natural depressions from diverted streams or natural springs.

The pond has a dual purpose: as well as being a source of food, it has a strong spiritual value.

Hawaiian aquaculture was highly advanced compared to other aquaculture societies before the arrival of Europeans. However, the number of fishponds decreased dramatically in the 20th century because of Westernization, development and invasive mangrove. Until the contact with colonialists in the late 1700s, Hawai'i had a robust and self-sustaining food system. From the land and small farms, Hawaiians ate a variety of fish, root vegetables like taro, and fruits. Over the next 100 years, colonizers would introduce pigs, cattle, and goats, which tore at the landscape and decimated forested areas. The overthrow of the Hawaiian Kingdom by the U.S. military in 1893 gave way to the plantation era, which razed thousands of acres of land to create sugarcane and pineapple plantations. Today, over 80% of the food in Hawai'i is imported and a third of this goes bad before getting to its destination. The high prices of food (\$14 000 annually for a family of four) compensate for these losses. While Hawai'i could and did provide enough food for everyone, today 27% of Native Hawaiians are food insecure. [10]

One of the essential roles of the fishpond is teaching the art of "kilo", or careful observation. When young men are taught to fish, few words are used and they learn to understand the land and be able to identify any changes and threats, such as invasive species and gaps in the rock walls. This is an essential skill necessary to work with the land.

Traditionally, the fishpond was managed by the konohiki. He managed the construction of fishponds, monitoring the stock, protecting it from poachers, and maintaining the fishpond by organizing a team to remove the silt accumulating at the bottom of the pond. This was a highly respected position as it required knowledge in a variety of fields. Indeed, they needed to be educated in masonry and fishing, as well as possess an understanding of the ecosystem from tidal flows and watersheds to nutrients and micro-algae. Furthermore, they needed to have a strong connection to the land and to the rest of the community.

Furthermore, human activity is also detrimental to the health of the Hawaiian fishponds. In addition to plant pollutants such as invasive algae and mangrove, anthropogenic pressures like sediment runoff and oil from the highway disrupt the pH of the fishponds and prevent the fish

from swimming into the loko i'a. Plastic pollution also makes its way to the Hawaiian Islands from the Pacific Ocean gyre.

Today, there is a growing movement to restore fishponds to educate communities about culture and history. There are currently about 35 different community groups working at 49 different fishponds across the Hawaiian Islands. In 2012, the permitting process for working on fishponds was somewhat streamlined, reducing some of the regulatory barriers to restoration.

Since then, dozens of restoration projects have sprung up at fishpond sites across the Hawaiian Islands. In this way, fishponds are a means of reconnecting with ancestral traditions - whether or not a fishpond can be restored to the point of abundant food production, these projects often rekindle a sense of kuleana, or responsibility, to the land and the community. [11]

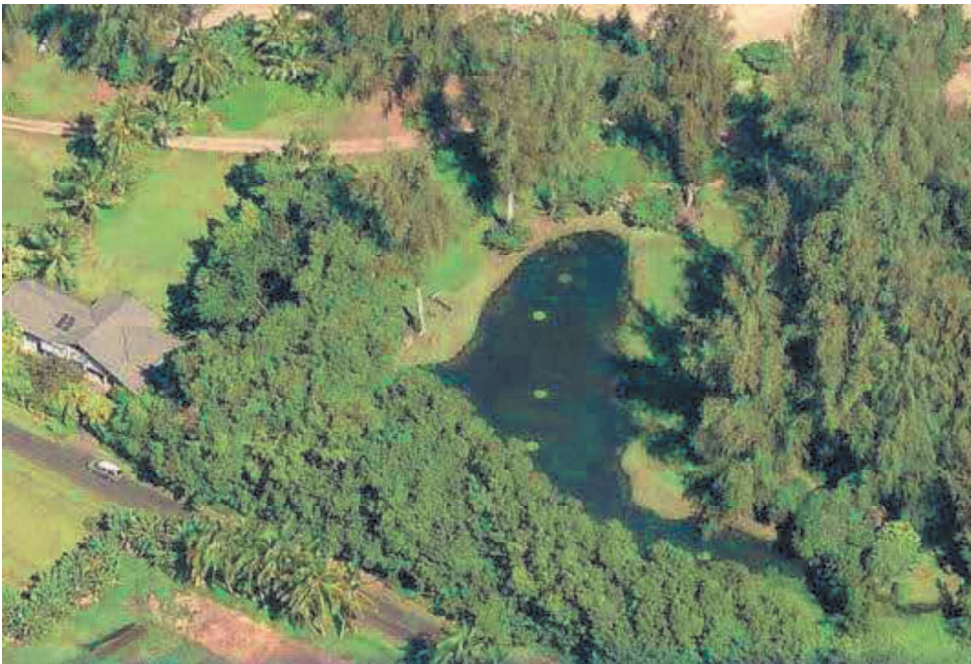


Figure 3 - Waipā fishpond. Source : Waipā Foundation

1.2 Nature based solutions

1.2.1 Definition and types of nature-based solutions

According to the U.S. Department of the Interior, a Nature-based Solution (NBS) is an action that incorporates natural features and processes to protect, conserve, restore, sustainably use, and manage natural or modified ecosystems to address socio-environmental challenges while providing measurable co-benefits to and benefit both people and nature. NBS implementation can be referred to as “green infrastructure” or “natural infrastructure.” [12]

In other words, nature-based solutions mimic natural processes and ecosystem services to enhance resilience, reduce risks, and provide multiple co-benefits, such as improving biodiversity, water quality, and human well-being. They are actions that focus on the protection, restoration or management of natural and semi-natural ecosystems, and are designed and implemented in a way that respects the rights, values and knowledges of local communities and Indigenous Peoples. When applied to environmental management, conservation, or sustainable land and water use, they are considered a type of BMP (Best Management Practice).

Nature-based solutions address five key societal challenges: climate change mitigation, climate change adaptation and disaster risk reduction, food security, water security and human health.

Generally, nature-based solutions can be divided into four categories : forestry practices, wetland-related practices, restorative agriculture, and ocean-based practices. [13]

1. **Forestry practices:** these focus on managing forests through different practices, including afforestation (planting trees where they were not before), reforestation (replanting trees where they have been cleared or degraded), agroforestry, and fire management. Indeed, forests provide many ecosystem services such as carbon sequestration, climate and air regulation, habitat provision, soil formation, cultural services like tourism and passing on spiritual values, biodiversity conservation, food and timber provisioning, and more.
2. **Wetland related practices:** these include revegetation with native plants, getting rid of invasive species (such as mangroves in Hawai'i), establishing vegetation buffers, etc. Wetlands play a crucial role in our ecosystems, which includes water supply and purification, flood control and water regulation, erosion control, groundwater recharge, biodiversity habitat and storm surge protection.
3. **Restorative agriculture:** these include cover cropping (planting crops during the off-season or between rows of main crops in order to prevent soil erosion, improve soil structure, fix nitrogen, and increase organic matter content in the soil, suppress weeds and reduce the need for chemical fertilizers), agroforestry, conservation tillage (soil cultivation method that leaves crop residue from the previous year on the field before and after planting the next crop), improved livestock management. The benefits of these practices are environmental (soil health, biodiversity, water quality), economic (productivity), social (community engagement, job creation, food security) and health-related (improved nutrition and less chemicals).
4. **Ocean based practices:** these include protection and rebuilding of stocks of marine fauna by restoring seagrass meadows or growing kelp or shellfish, ocean fertilization to encourage phytoplankton blooms, etc. The ocean is the world's largest carbon sink as well as a source of food, materials, tourism, research... It also plays an essential role in nutrient cycling, primary production and habitat provision. [14]

1.2.2 Literature reviews on nature-based solutions and their efficiency

Nature-based solutions have become increasingly popular over the past 20 years, both in adaptation and mitigation. NbS have been endorsed by major global assessments and reports (e.g., IPBES, IPCC, UN Climate Action Summit) and are increasingly seen as a way to reconcile economic development with ecosystem stewardship, while also transforming business practices toward sustainability. Funding from the EU and others has allowed research on NBS to increase dramatically, with the numbers of papers published on the subject rising from only three in 2015 to more than 250 in 2020.

The Paris Climate Agreement aims to keep global warming below 2°C, with efforts to limit it to 1.5°C, as exceeding this limit increases the risks of extreme weather and ecosystem collapse. The international community's actions between now and 2030 will be crucial in determining whether we can slow warming enough to avoid the most severe impacts of climate change. The

latest IPCC report highlights that nature-based solutions—such as reducing deforestation, restoring ecosystems, and better managing agricultural lands—are among the top five most effective strategies for reducing carbon emissions by 2030. Indeed, nature-based solutions could contribute approximately 30% of the global mitigation needed by 2030/2050 to meet the Paris Agreement's 1.5/2°C temperature goals. Furthermore, nature-based solutions could prevent 393 billion dollars' worth of damage by 2050 by reducing the risk of climate hazards by 26%.

However, the effectiveness and benefits of NbS have not been rigorously evaluated, raising concerns about their reliability, cost-effectiveness, and resilience compared to engineered alternatives. In order to widely adopt nature-based solutions, it is necessary to produce evidence of their effectiveness (including cost-effectiveness). Research on the topic is crucial to their development and implementation. This is particularly true for rivers, as most nature-based solutions focus on cities. More examples are needed to show how nature-based solutions integrate scientific, local and indigenous knowledge to establish a successful collaboration between different stakeholders. Indeed, one of the difficulties in implementing nature-based solutions is public acceptance, as many feel that nature-based solutions are less legitimate than technical solutions.

Thankfully, there is an increasing number of examples around the world proving that nature-based solutions are just as effective as technical solutions, while yielding the additional benefits of lower costs, more ecosystem services benefits, and higher biodiversity values. For instance, Urban Green Infrastructure has a similar effect in mitigating flood risks than conventional stormwater drainage, while creating significantly less runoff. [15]

Another challenge when implementing nature-based solutions is the collaboration between very different stakeholders such as municipalities, citizens, local authorities, and NGOs. The better the collaboration between them, the easier the implementation. When co-creating a project on a larger scale, more stakeholders must be considered, and this is one of the reasons why upscaling is difficult in this context. There is no “one-type-fits-all” type of governance for these kinds of project as each area has its own particularities.

Furthermore, climate mitigation policies may encourage NbS with low biodiversity value (e.g., afforestation with non-native monocultures), leading to maladaptation and undermining biodiversity-based resilience. [16]

1.3 Organizations involved

1.3.1 University of Hawai'i

The University of Hawai'i, known as UH, was founded in 1907. Today, it educates students and confers students associate, bachelor's, master's, and doctoral across six islands throughout the state of Hawai'i. The UH system's main administrative offices are located on the property of the University of Hawai'i at Mānoa in Honolulu CDP. [17]

I did my internship in the Oleson laboratory at the University of Hawai'i in Manoā. The Oleson laboratory is a multidisciplinary group that focuses on studying natural resource and environmental management problems. The aim is to develop the tools to effectively manage these ecosystems from mauka to makai (from reef to ridge) through many approaches

including quantification and valuation of ecosystem goods and services, data-driven and participatory modeling, value chain analysis, alternative economic welfare indicators, policy analysis, and decision science. The lab's research has been supported by NOAA, USGS, the Pacific Island Climate Adaptation Science Center, USDA, National Geographic Pristine Seas, the Moore Foundation, Ulupono Initiative, the Hawai'i State Department of Health, the Hawai'i Department of Economic Development, Business, and Tourism, and others.

At the head of the lab is my tutor Kirsten Oleson, an ecological economist, whose research focuses on improving natural resource and environmental management by integrating methods, approaches, and tools from economics, geography, natural science, decision science, and political science. The rest of the lab members include Post-docs, PhD students, Master's students, and research assistants. [18]

1.3.2 Waipā Foundation



Figure 4 - The Waipā Foundation

The Waipā Foundation is a nonprofit organization based in the island of Kaua'i in Hawai'i, which has stewarded the Waipā watershed for the past 20 years. The Waipā watershed is 1,600 acres of culturally and ecologically significant land located by Hanalei Bay in the Halele'a district. The land is owned by Kamehameha school and is being leased to the Waipā Foundation for its restoration, management, and preservation.

In accordance with its mission, the Foundation's core goals are to restore the deep connection between people and the land through experiential learning; to preserve and perpetuate Hawaiian culture, knowledge, values, and language through practice; to implement programs focused on culture, enrichment, education, and leadership to foster social, economic and environmental resiliency in the management of Waipā's natural and cultural resources.

To involve the community, the Waipā Foundation organizes youth programs, workshops and group visits to encourage hands-on learning and connection with the land. All ages are pushed to explore how native Hawaiian values and practices apply to modern life. For example, Poi Day

has taken place every Thursday for the past 30 years. It is a day where the community comes together to process cooked kalo into poi.

Moreover, the Waipā Foundation handles projects to improve the water quality and implement nature-based solutions for the management of the ahupua'a. The current projects are the stream restoration project, which I have been working on, and the coastline erosion project which has not yet been implemented. The funding of these projects comes from the U.S. Fish and Wildlife Service, the National Fish and Wildlife Foundation, NOAA, the State of Hawai'i Dept. of Health and the EPA, the Hawai'i Community Foundation, and Kamehameha Schools.

Overall, the Waipā Foundation is a key player in the conservation and cultural revitalization of the Waipā area, ensuring that the natural and cultural resources of the watershed are preserved and passed on to future generations in a sustainable and respectful manner.

2. Methodology

2.1 Research question

2.1.1 Question

When I first started my internship I did not yet have a very clear idea of what my research question should be. I started by familiarizing myself with the projects that were currently taking place. I also did extensive research on the ecosystems of Kauai from the mountain to the sea.

Based on this and on the data that I had available, I decided to focus on the following question:

Through aloha 'āina and mālama 'āina practices how has the Waipā Foundation influenced the resilience of the Waipā ahupua'a to disturbances or stressors, considering both natural hazards (e.g., storms, sea-level rise) and anthropogenic pressures (e.g., land development, pollution)?

2.1.2 Term definitions

Aloha 'āina : a Hawaiian phrase that translates to "love of the land". It is essential to Hawaiian culture and based on the idea that if you take care of the land, the land will take care of you. It also includes the sense of being connected to all living things, and the mutuality that exists between all things on spiritual, social, and scientific levels.

Mālama 'āina : a Hawaiian phrase that translates to "caring for and honoring the land" or "to care for what nourishes you".

Resilience: Resilience refers to the ability of a system, organization, community, or individual to adapt, recover, and bounce back from adversity or change. It encompasses the capacity to

withstand and absorb shocks, disruptions, or stressors while maintaining essential functions, structures, and processes.

Risk: Risk is the potential for loss, harm, or negative impact resulting from uncertain events, situations, or decisions. It involves the likelihood of undesirable outcomes occurring and the magnitude of their consequences. Risk = hazard x vulnerability

2.2 Stream restoration project

2.2.1 Objectives of the project

The Waipā Stream Restoration Project initiated in 2011 to address overgrowth of Hau Bush and other invasive vegetation in the Waipā Stream corridor where hau had grown into the stream causing sediment and plant debris to fill up the stream channel. This was aggravating flooding and degrading habitat for native stream life, as it created a barrier for migrating native fish and prawns that must pass through this section of the stream at least twice during their life cycle.

A holistic approach was implemented to manage and

The main objectives of this project are:

- Controlling this invasive overgrowth
- Improved drainage
- Flood mitigation
- Water quality enhancement
- Ecosystem restoration

Over the past years, much of the cleared hau material was chipped on-site to create mulch used for erosion control in the clearing areas. In flood-prone areas where mulching is not suitable, hau is being burned with the resulting charcoal and ash harvested for use in Waipā's gardens and taro loi. Approximately 1,000 feet of the stream channel has been cleaned of hau debris, and fish passage conditions in the project area have improved. Monitoring programs have been established to regularly measure streamflow and water quality at various points along the stream.

In over 12 years, all of the previously mentioned objectives were achieved to an extent, but there is still much work to be done to perpetuate this success and build from it to achieve greater goals at Waipā and beyond.

2.2.2 Nature based solutions implemented

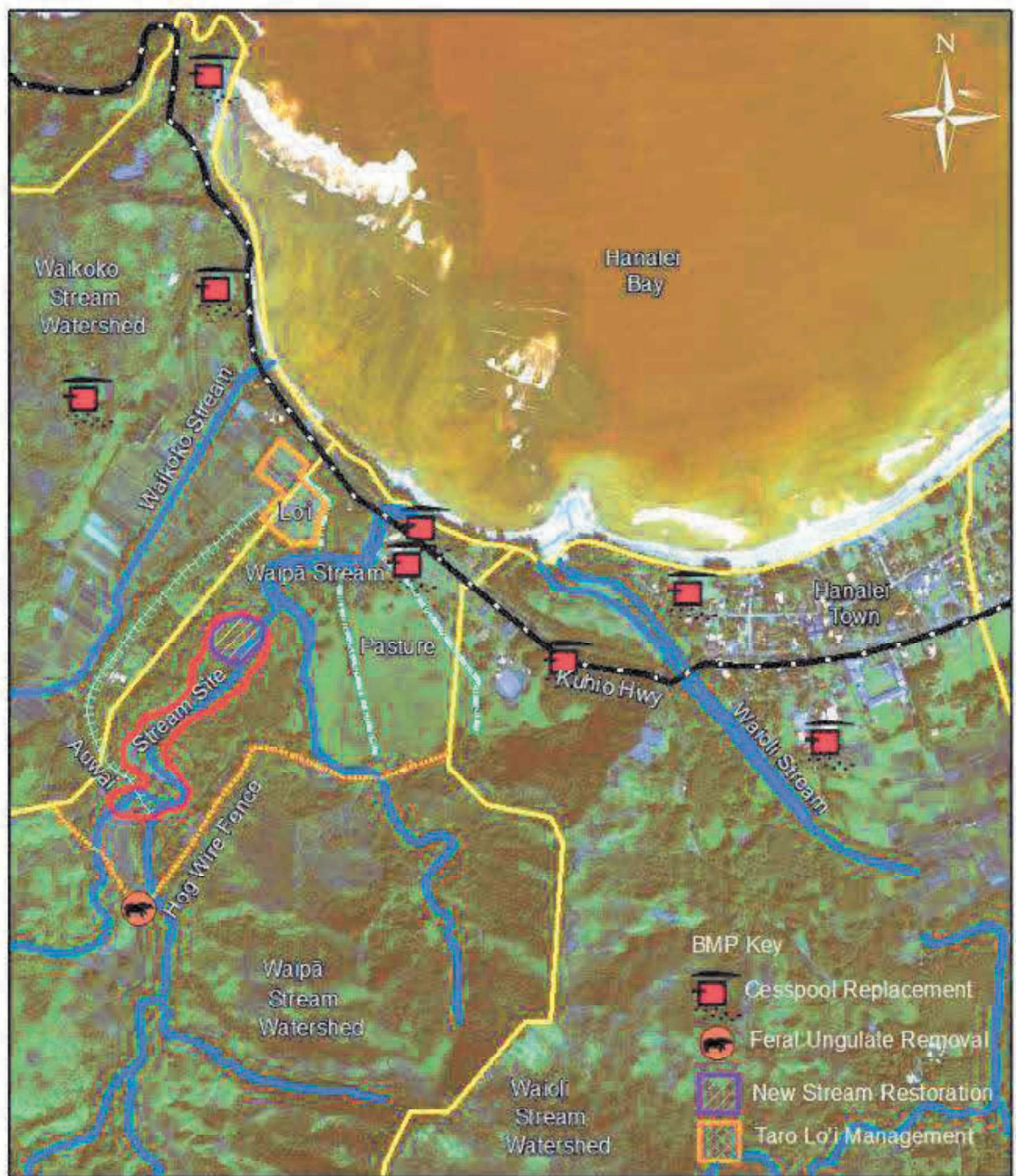
Many management practices were implemented for the management of the Waipā ahupua'a.

These BMPs include:

1. **Cesspool Replacements:** Cesspools within the Waioli, Waipā and Waikoko Stream watersheds were upgraded to suitable replacement systems, including conventional septic systems and alternative systems that utilize an Aerobic Treatment Unit (ATU). Indeed, cesspools often allow untreated sewage to seep into the surrounding soil and water, leading to contamination of groundwater, streams, and coastal waters. This is particularly true in the Hanalei area as the conditions make the likelihood of cesspools overflowing very high. Indeed, low ground elevations, a relatively high-water table, fast soil percolation rates, and extremely high rainfall that contributes to substantial

groundwater flux. Upgrading to septic systems or ATUs significantly reduces the release of harmful contaminants like pathogens, nitrates, phosphates, and other pollutants into the environment. These would be detrimental to both human and ecosystem health. [19]

2. **Feral Ungulate Removal:** the only feral ungulates present in the area are feral pigs, which are a nonnative species brought to the Hawaiian islands by the Polynesians 1500 years ago. Ever since, they have been causing native plant extinction, as well as soil erosion and soil compaction in their tracks. In Waipā, they damage the taro lo'i and areas where native vegetation is being replanted. The pigs are hunted or caught in traps, and the meat is used to feed community members at different events. [20]
3. **Taro Lo'i Management:** a lo'i kalo is a traditional Hawaiian irrigation system used for growing taro, a staple crop in Hawaiian culture. The practices implemented by the Waipā Foundation for their management is to close the lo'i outlets for at least a day after doing work that may create turbid water conditions, replacing wet-tilling with dry tilling, and giving the taro patches a break of at least 6 months after harvest before beginning a new planting cycle.
4. **Stream Restoration:** The stream restoration practices implemented were mostly in-stream habitat enhancement and bank stabilization along Waipā Stream. Much invasive vegetation, especially the Hau Bush and the fast-growing Albizia and Cecropia trees, has been removed with machetes or cane knives as well as hand-pulling and lawn-mowing.
5. **Constructed Wetlands:** Constructed wetlands are man-made ecosystems that double as treatment systems that use natural processes involving wetland vegetation, soils, and their associated microbial assemblages to improve water quality. The first constructed wetland established used native vegetation, while the second was low maintenance and simply used the vegetation that would develop naturally. Interestingly, the second proved to be much more effective in improving the water quality of the taro patch.
6. **Livestock Exclusion Fencing & Watering:** This refers to enclosures that are built to prevent livestock from accessing and damaging certain parts of the area. Indeed, grazing and trampling can deteriorate the water quality and vegetation growth. Because they are prevented from accessing certain bodies of water, it is important to "water" them by giving them access to throughs or tanks in their enclosure.
7. **Upland Erosion Control & Revegetation:** Grasses, shrubs and trees prevent erosion by stabilizing the soil with their roots. This way, less fertile soil is removed by the wind or water runoff, and sedimentation in downstream water bodies, which could damage aquatic, is decreased. In Waipā, native vegetation has been replanted and biodegradable fabrics and mulching have been placed on the ground to cover bare soil to protect soil health, habitats and water quality.



Blue Lines - Streams/Ditches, Black Lines- Roads, Yellow Lines - Watersheds

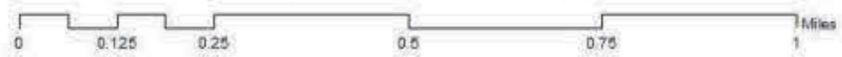


Figure 5 - Location of the stream restoration project. Source : WATER QUALITY MONITORING PLAN /QUALITY ASSURANCE PROJECT PLAN for the WATERSHED IMPLEMENTATION PROJECT FOR THE AHUPUA'A OF WAIPĀ by Matt ROSENER

2.2.3 Timeline of the stream restoration project

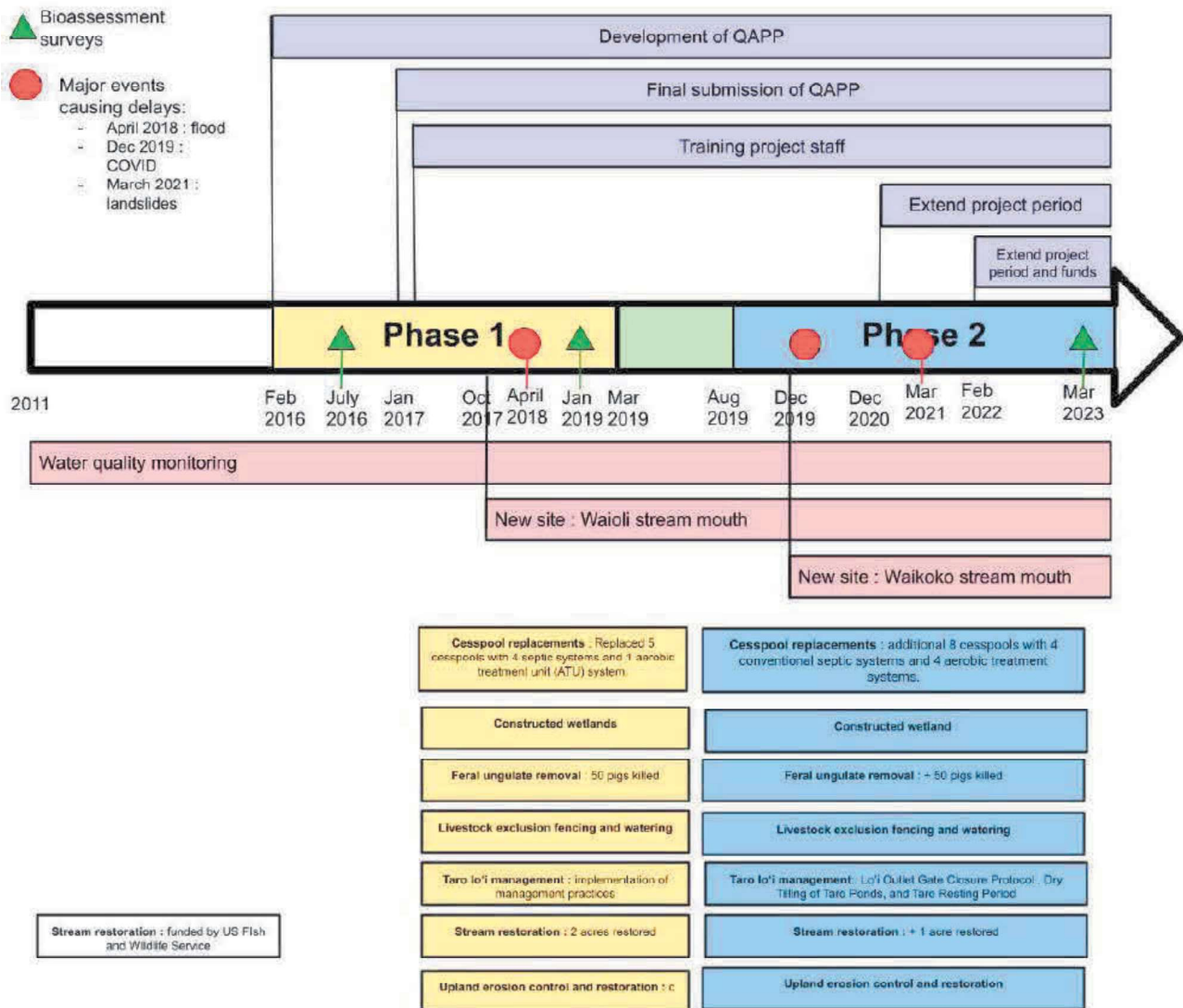


Figure 6 - Timeline of the stream restoration project

2.3 Approach of the methodology

2.3.1 Global methodology across projects

All the projects by the Oleson lab dealing with Evaluation Based Adaptations (EbAs) follow a similar approach. The main characteristic of this approach is its focus on feedback. Indeed, the plans of the projects are ever-changing to accommodate all of the inputs, especially from the local communities, collected along the line.

Each of the projects begins with a collaborative visualization. The goal of this collaborative visualization is to define the goals of each of the parties involved and come up with an objective that satisfies everyone. The co-development of the monitoring and evaluation of plans allows the local communities to define what they consider to be a success. Indeed, the Hawaiian community and Western scientists may prioritize different outcomes, which is why it is crucial

to get input from all parties every step of the way. The measures and evaluation of results are also done with the native community as they use different indicators to evaluate the health of an ecosystem. Of course, the analysis of the data collected is also shared with the community, so they remain involved and engaged with the project and so that they know what is being done with their land.

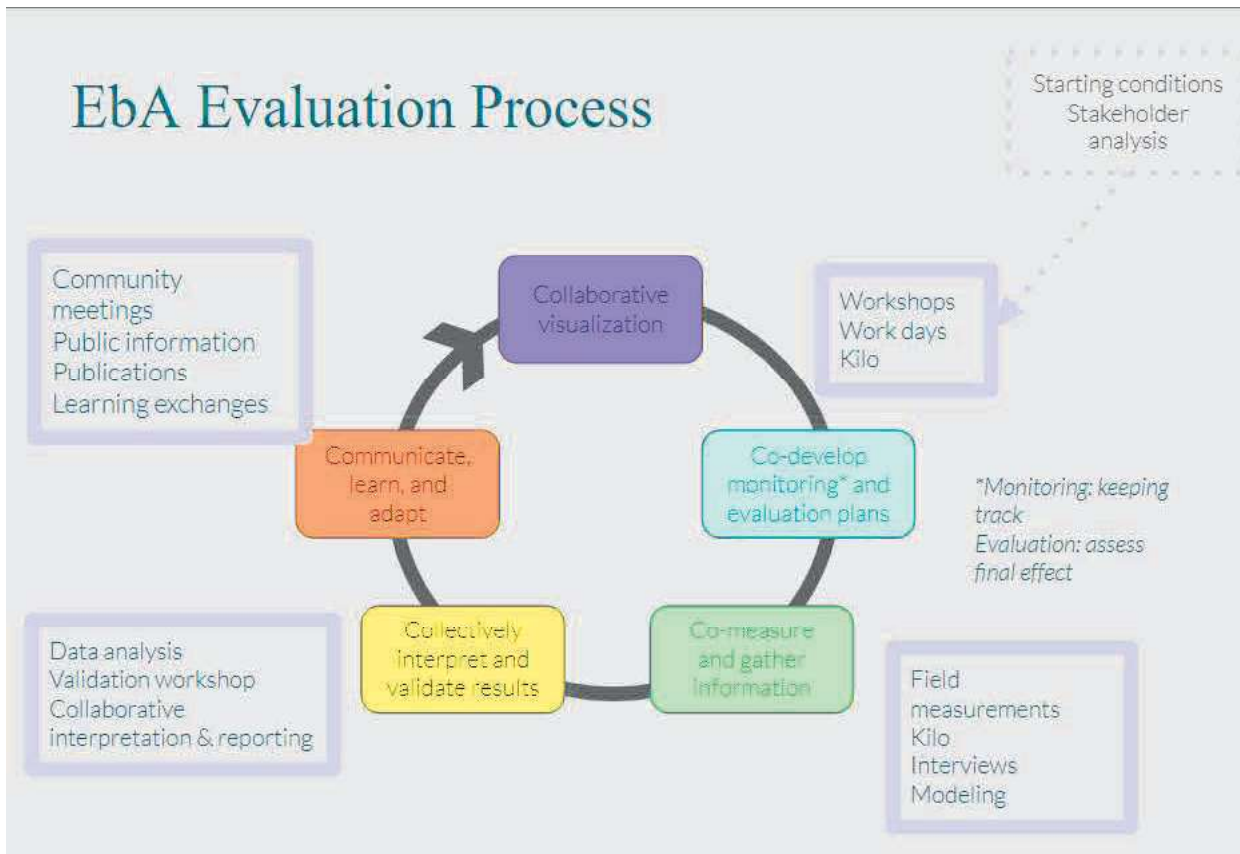


Figure 7 – EbA Evaluation Process. Source : University of Hawai'i

2.3.2 Systems map

One of my first missions upon arriving in Hawai'i and starting my work as an intern was to create a systems diagram to understand the complex interactions between different parts of the ecosystem. This allowed me to have a visual representation of what I was learning during my literature review, and to gain a clearer understanding of the big picture as well as the connections and cycles, illustrated by the feedback loops.

To make this map, I used Kumu.io software, which allows you to create complex causal diagrams.

The colors of the graph make it easier to read. They are based on the DPSIR structure (Drivers, Pressures, State, Impact, Response model of intervention), a causal framework used to describe interactions between society and the environment. It seeks to analyze and evaluate environmental problems by bringing together various scientific disciplines, environmental managers and stakeholders, and to solve them by integrating sustainable development.

I then used the systems map to gather information and feedback from the community at a local festival.

On May 4th, 2024, the Waipā Foundation organized a festival which brought together musicians, food vendors, small businesses, and stands to raise awareness about some of the organizations working to protect the environment on the island of Kauai. At one of those stands, my team and I asked festivalgoers to pick out a colored popsicle stick with a question pertaining to the environment in Kauai. The prompts on the popsicle stick (which can be found in the questionnaire in the annex) got the participants thinking and talking about their own experiences with the environment. From there, we encouraged them to contribute to the map by adding observations, identifying missing information or links, and highlighting anything that they believed was important. In order to make the activity less daunting, I had previously created a simplified version of the systems map which was quicker to explain for people who did not have the time or patience for a long and complex explanation of the different parts of the ecosystem. Both the original and the simplified version of the map were printed in poster format and taped down on a table to allow participants to write on them with Sharpie, or Post-It notes if they wished to add longer comments. After they added their contributions, if they seemed interested to learn more, we would also hand them a flyer that I created (which can also be found in the annex) which explained the different projects of the Waipā Foundation and had a QR code with a link to the questionnaire on Google Forms, where they could answer more questions if they were so inclined.

In the end, we had 58 participants (counted with a clicker) from a wide variety of backgrounds: we had tourists, locals, young, old, people who worked or volunteered in conservation, people who didn't believe in climate change, people who were interested in learning but didn't know very much about the topic for now... In the end, people didn't end up using the question prompts very much and they became more of an icebreaker than what they would end up speaking most about. People were also weary of writing on the systems map and often would tell us elaborate anecdotes or opinions but would write a single word on the map – we began to listen to them and take the notes ourselves.

The objective of this initiative was to gather data from the local community to better understand their perspectives on desirable outcomes and objectives, ensuring their input was integrated into the project planning and decision-making processes.

I analyzed the inputs of all the participants and wrote a report which summarized the main points expressed, starting with the ones that had come up most often. Their comments were separated into four categories: connection to place, challenges, solutions, and the systems map itself.

I then presented this report to a member of the Waipā Foundation so that the opinions and contributions could be taken into consideration in the next phases of the projects.

This also helped me gain a better understanding of the projects that had been implemented by the Waipā Foundation and what the community deemed to be important. One of the themes that came up frequently was flooding and water quality, and this weighed in on my decision to focus on the analysis of the impact of the stream restoration project on the water quality in the stream.

2.3.3 Results chains

To properly analyze the effects of the stream restoration, it was necessary to understand the expected outcomes of each of the activities of the project. For each of the seven BMPs implemented, I created a results chain highlighting the outputs, immediate outcomes, intermediate outcomes, and long-term impacts. This visual map of the cause-and-effect relationships within a project not only clarifies the logic behind these BMPs, associates each one to parameters to monitor, and facilitates communication but also identifies the risks and other factors having an impact on each of them.

Below is an example of the results chain for one of the BMPs: cesspool replacement

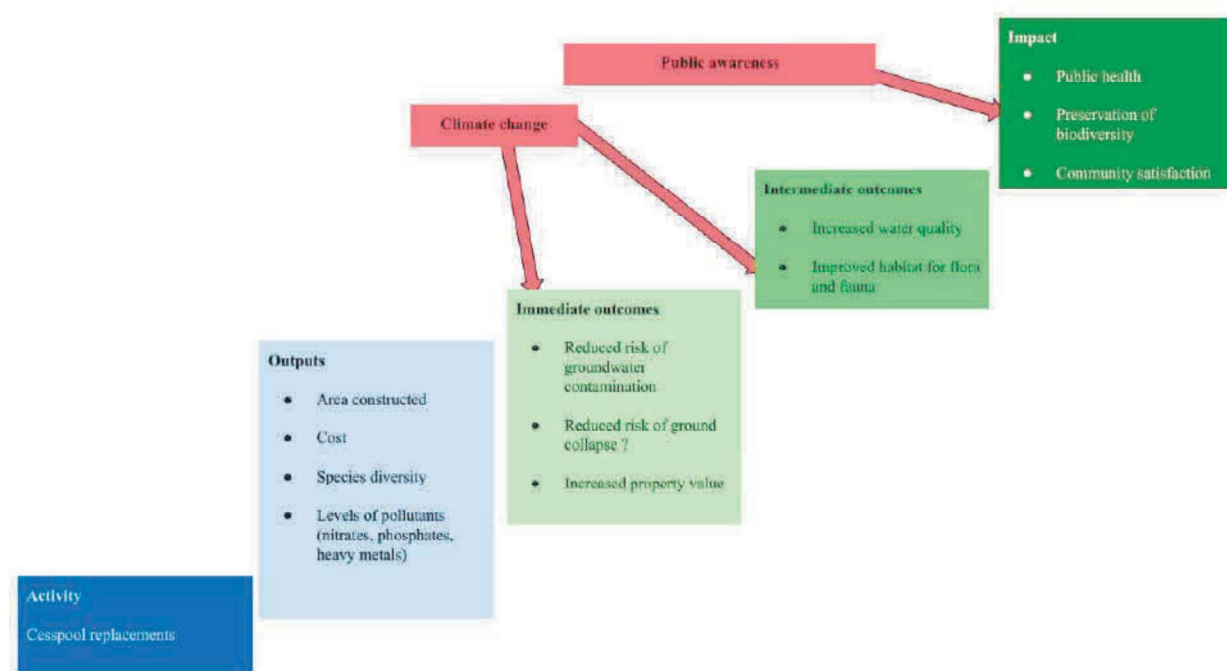


Figure 9 - Results chain of cesspool replacement

2.3.4 Data collection

The following data has been collected over the years :

- Rainfall
- Temperature

- Salinity
- pH
- Turbidity
- DO = dissolved oxygen
- Enterococcus - Fecal-Indicator Bacteria (MPN/100mL)
- Clostridium Perfringens - Fecal Indicator Bacteria (MPN/100mL)
- HS-IBI biodiversity index

The following table shows the frequency in the collection of most of these datasets :

Data	Notes	Dates	Frequency	Sites
Rainfall in Waipā	Some data missing	8/12/2011 - 4/12/2023	1-3 x / minute	Waipā Garden
Temperature		8/19/2013 - 3/8/2023 for steam gage	Three times a month	8
Salinity				
pH	pH probe tends to be taken and data is loses accuracy due to rain	7/26/2013 for 1st crossing 11/14'/2011 for Bamboo. Estuary gage and Boat crossing 2/13/2012 for ditch junction 01/18/2013 for Muliwai 10/04/2014 for waioli		
Turbidity		2012-2023 for Bamboo and Boat crossing	Three times a month	8

		2013-2023 for the rest		
DO = dissolved oxygen		2012-2023 for Bamboo and Boat crossing 2013-2023 for the rest	Three times a month	8
FIB		4/6/2017 - 8/3/2023	Every two weeks	5
HS-IBI index		2003-2023	4 measures : August 2003, July 2016, January 2019, March 2023	

Table 1 - Collection of datasets

The map below shows the location of the data collection :

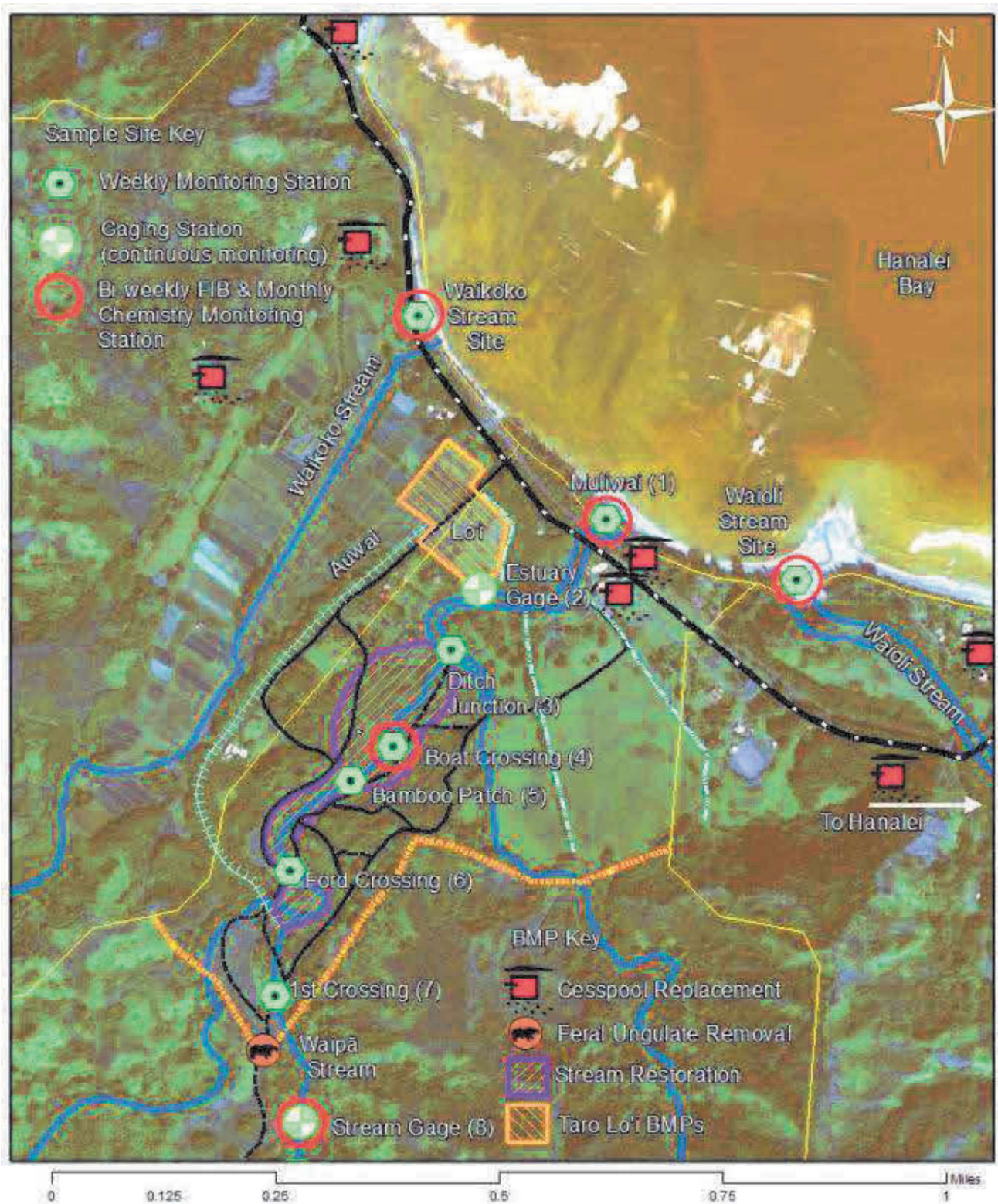


Figure 10 - Map of the stream restoration project data collection sites. Source : WATER QUALITY MONITORING PLAN /QUALITY ASSURANCE PROJECT PLAN for the WATERSHED IMPLEMENTATION PROJECT FOR THE AHUPUA'A OF WAIPĀ by Matt ROSENER

FIB (5) (red circles):

Monitoring sites :

- Waikoko
- Waipā stream
 - Muliwai
 - Stream gauge
 - Boat crossing
- Waioli stream
- Boat crossing

Monitored :

- Enterococcus
- Clostridium perfringens
- Chemistry monitoring (8) (green dots):

Monitoring sites :

- Waipā Stream :
 - Stream Gage
 - Boat Crossing
 - Muliwai
- Ditch Junction
- Estuary Gage
- 1st Crossing
- Ford Crossing
- Bamboo

Monitored :

- Temperature
- Salinity
- pH
- Turbidity
- DO

3. Results analysis

3.1 Exploratory research

3.1.1 Basic statistics for individual variables

For all of the data that I was provided, I decided to divide the data into three: before Phase 1, Phase 1 and Phase 2. For each of these datasets, I calculated the mean, the maximum, the minimum, the variance, and for temperature, the frequency of the water being above 20 C.

P1- Phase 1 of the project: February 2016 to March 2019

P2- Phase 2 of the project: March 2019 to March 2023

In this section, I will summarize the most interesting observations that I have come to when analyzing this data, and go into detail for some of the observations, but not all the ones that I have performed as that would be far too long.

Temperature

All sites (except Boat Crossing) showed a decrease in temperature during Phase 1 of the project.

Temperature average

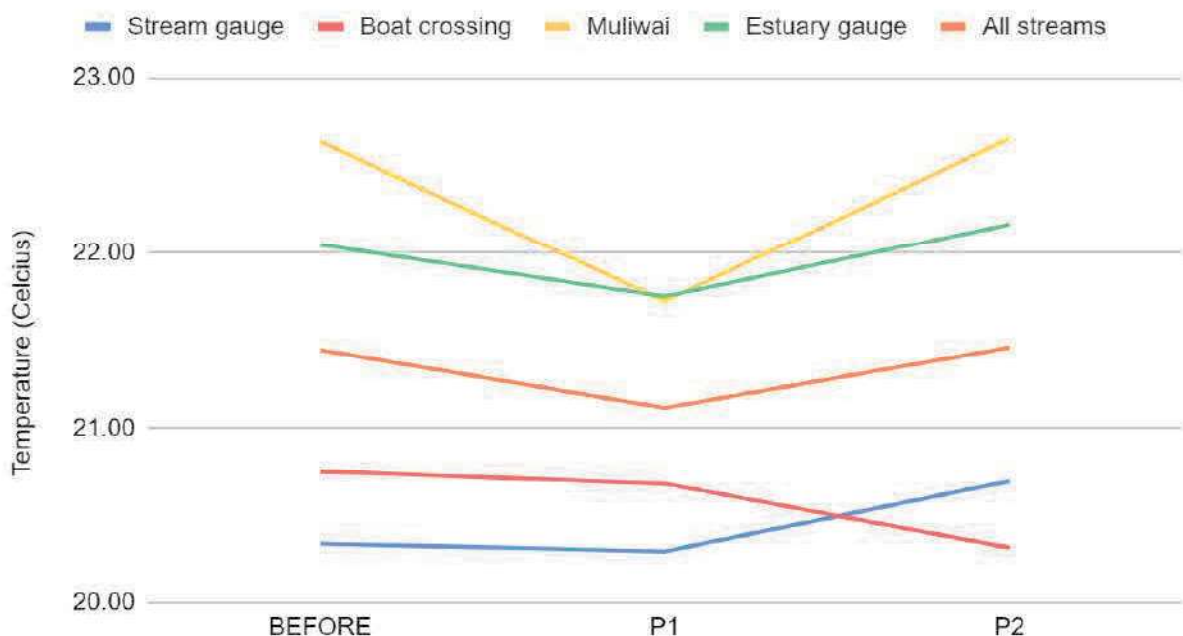


Figure 11 - Temperature average in P0, P1, P2.

As one might expect, the closer the measuring site to the sea, the higher the temperatures observed. The warmest site is Muliwai. This can be explained by the sparse vegetation around the sides, which provide less shade and the stagnancy of the water when the mouth is closed.

For the site Boat Crossing, the average and minimum temperatures decreased between P1 and P2, but the maximum temperature and variance went up. This is the site with the most variation, most likely because it is located right where the restoration efforts are. Indeed, the Hau Bush was removed around the Boat Crossing site in 2011-2012 but by the P2 period, outplanted vegetation had grown large enough to shade the stream there more., which explains the decrease in temperature.

pH

The graphs of the mean, maximum and minimum pH all show that cross the sites, the pH has overall been diminishing, but more so on the sites close to where stream restoration has taken place. Indeed, Stream Gage and Muliwai (situated respectively most upstream and downstream) are the same at 7.19 but the sites in the stream restoration area are lower - Bamboo at 7.04 and Boat Crossing at 7.02. We can ask ourselves if the lower pH levels can be attributed to the restoration work and if so, if this is a good or bad thing.

Maximum pH

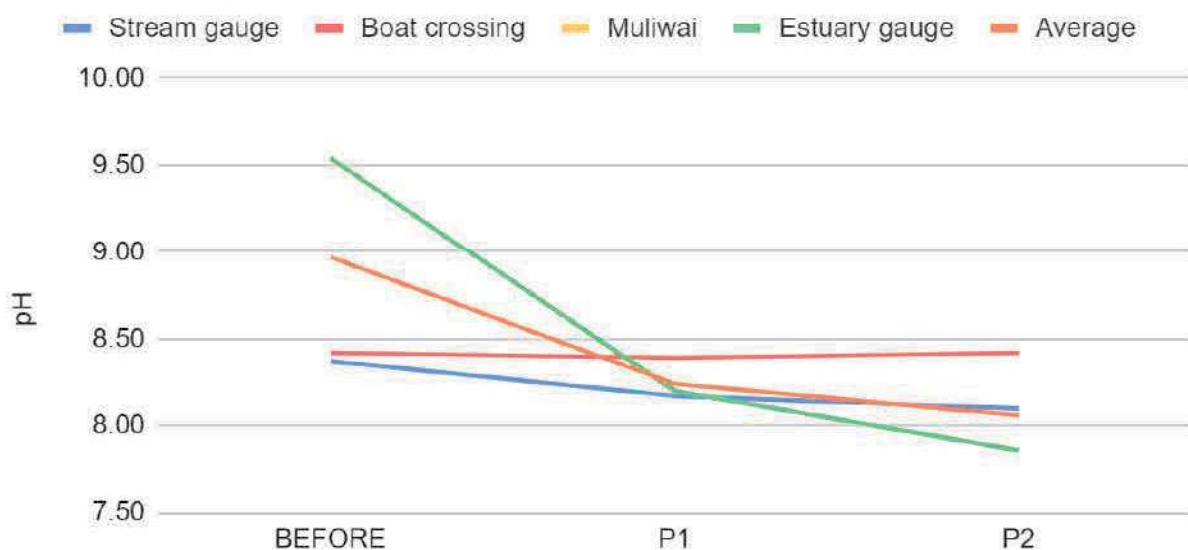


Figure 12 - Maximum pH in in P0, P1, P2.

We notice that Estuary gauge is the site with the steepest drop in maximum pH. This could be due to runoff due to its proximity with a taro patch, which could cause runoff.

Salinity

The overall salinity of all streams seems to decrease during Phase 1, possibly due to the consequences of the floods in April 2018 which would have flushed out all the salt and diluted the water, making it less salty.

Average Salinity

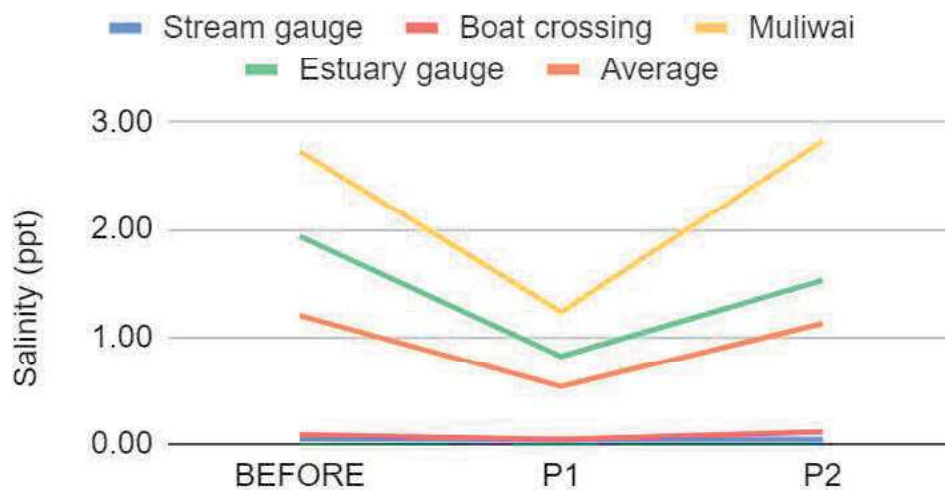


Figure 13 - Average salinity in P0, P1, P2.

As we would expect, the highest degree of salinity is found in the sites closest to the ocean. Indeed, Stream gauge and boat crossing have the lowest levels of salinity as they are highest in the mountains and thus furthest from the ocean. Both Muliwai and Estuary Gage sites are in the estuary, so they are usually brackish. The stream mouth often blocks up with a sandbar at the mouth and this affects water levels throughout the estuary. The Boat Crossing site is right at the transition point from the freshwater stream and the brackish estuary. When the stream mouth is closed, brackish water can be observed all the way upstream to the Boat Crossing site.

Maximum Salinity

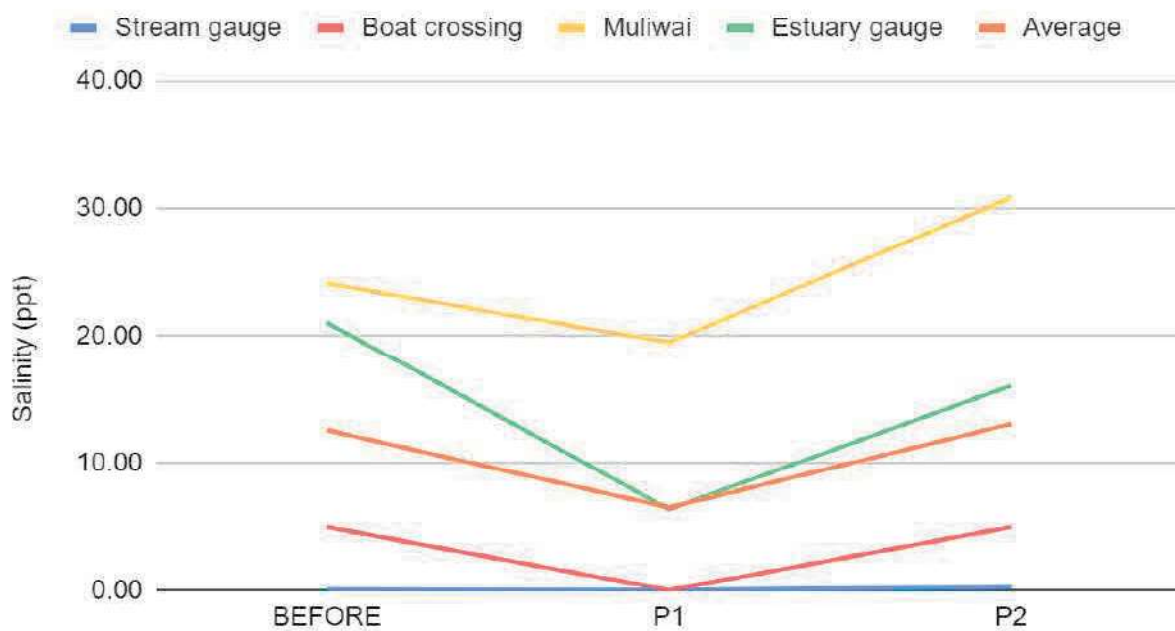


Figure 14 - Maximum salinity in P0, P1, P2.

The maximum salinity in the Boat Crossing site went from near zero to 3-4ppt from P1 to P2. This suggests the site is becoming more influenced by the estuary. Perhaps this could be

explained by the fact that after the 2018 flood maybe the stream mouth stayed open more consistently which would result in lower Salinity at the Boat Crossing.

Turbidity

The overall turbidity of all sites except Boat Crossing has decreased between phase 1 and phase 2. This is likely due to the 2018 floods which would increase turbidity in April of that year (during Phase 1). It is also worth noting that there is some bias in the data due to the impossibility of sampling the Stream Gauge site on flood days for safety reasons.

The graph that best shows the impact of the 2018 floods is the one that shows the maximum turbidity. Most of these maximum values in Phase 1 can be dated to April 2018.

Maximum turbidity

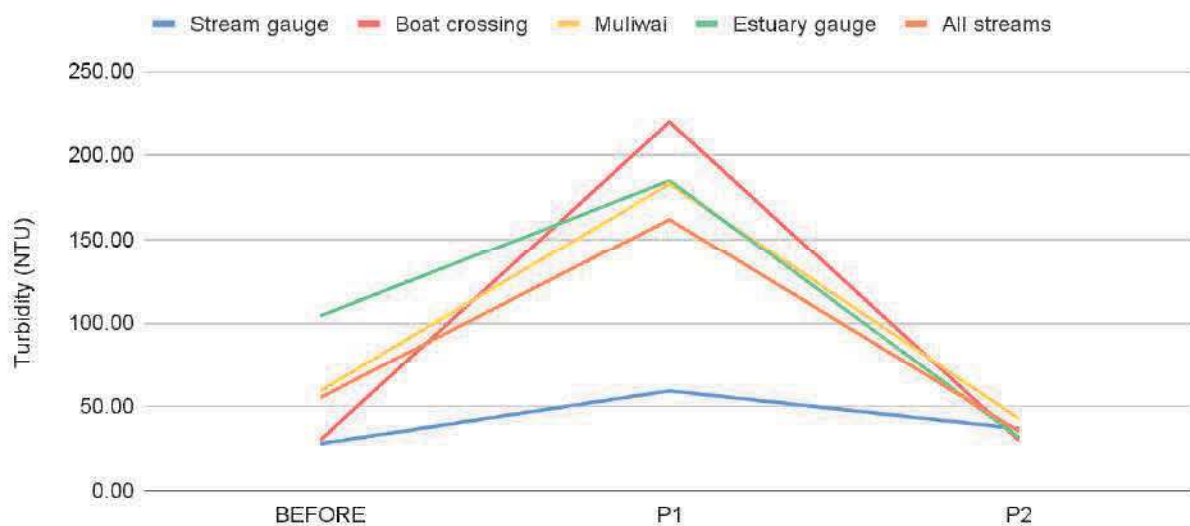


Figure 15 - Maximum turbidity in P0, P1, P2.

However, this decrease between Phase 1 and Phase 2 can also be partly attributed to the stream restoration efforts and the feral pig removal. As the invasive vegetation being removed has a very dense canopy and generally no understory vegetation. By removing and outplanting with grass shrubs and trees, the streamside areas have become much more resistant to soil erosion.

The change in turbidity is quite small, but Waipā Stream estuary is listed as water-quality impaired for turbidity and the data shows that only small decreases in turbidity levels are needed to attain the water quality standards of 1.5 NTU (geomean) in the estuary (year-round) and 2.0 NTU/5.0 NTU (dry/wet season) in the stream. These results are very encouraging.

3.1.2 Two-way correlations

I decided to see if I could find links between any two parameters measured. To do this, I checked the correlations between any pair of parameters: pH and temperature, salinity and DO, etc... I formatted the data for all of them and then ran a linear regression on them. I hoped to find some R^2 values that came close to 1.

One of the pairs I had highest hopes for was turbidity and rainfall. It gave me the following graph:

Turbidity/Rainfall correlation

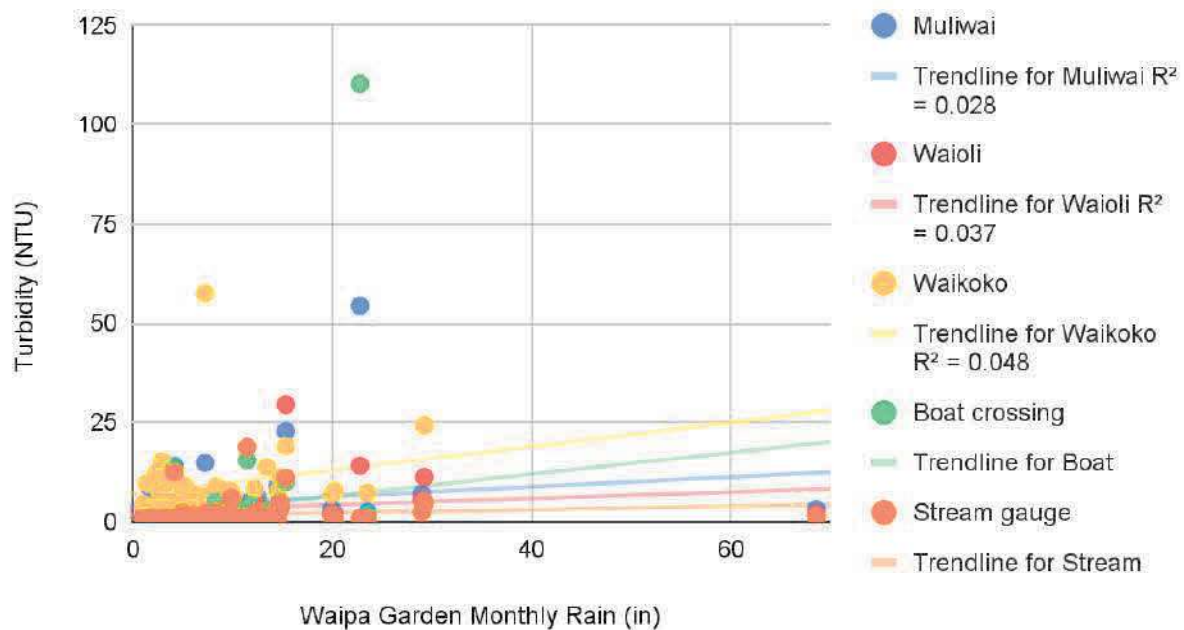


Figure 16 - Turbidity/rainfall correlation

We can see that for this graph, the R^2 are all far too small to be able to claim that there is a correlation between rainfall and turbidity.

Of the 21 potential pairs of parameters, none of them showed any sort of clear correlations. The R^2 value was always less than 0.2.

The highest correlation observed was between water temperature and dissolved oxygen. This is to be expected as cold water, with its slow-moving molecules, holds more dissolved oxygen than warm water. As water heats up, the molecules within it move faster, pushing some of the free oxygen atoms into the atmosphere. However, even then, the R^2 value is 0.17.

These low correlations are because many other factors must be taken into consideration when analyzing this data as they also impact the target variable.

3.1.3 Systems map of the data

To better understand the different links between the activities organized by the Waipā Foundation and the data collected, a systems map can be created.

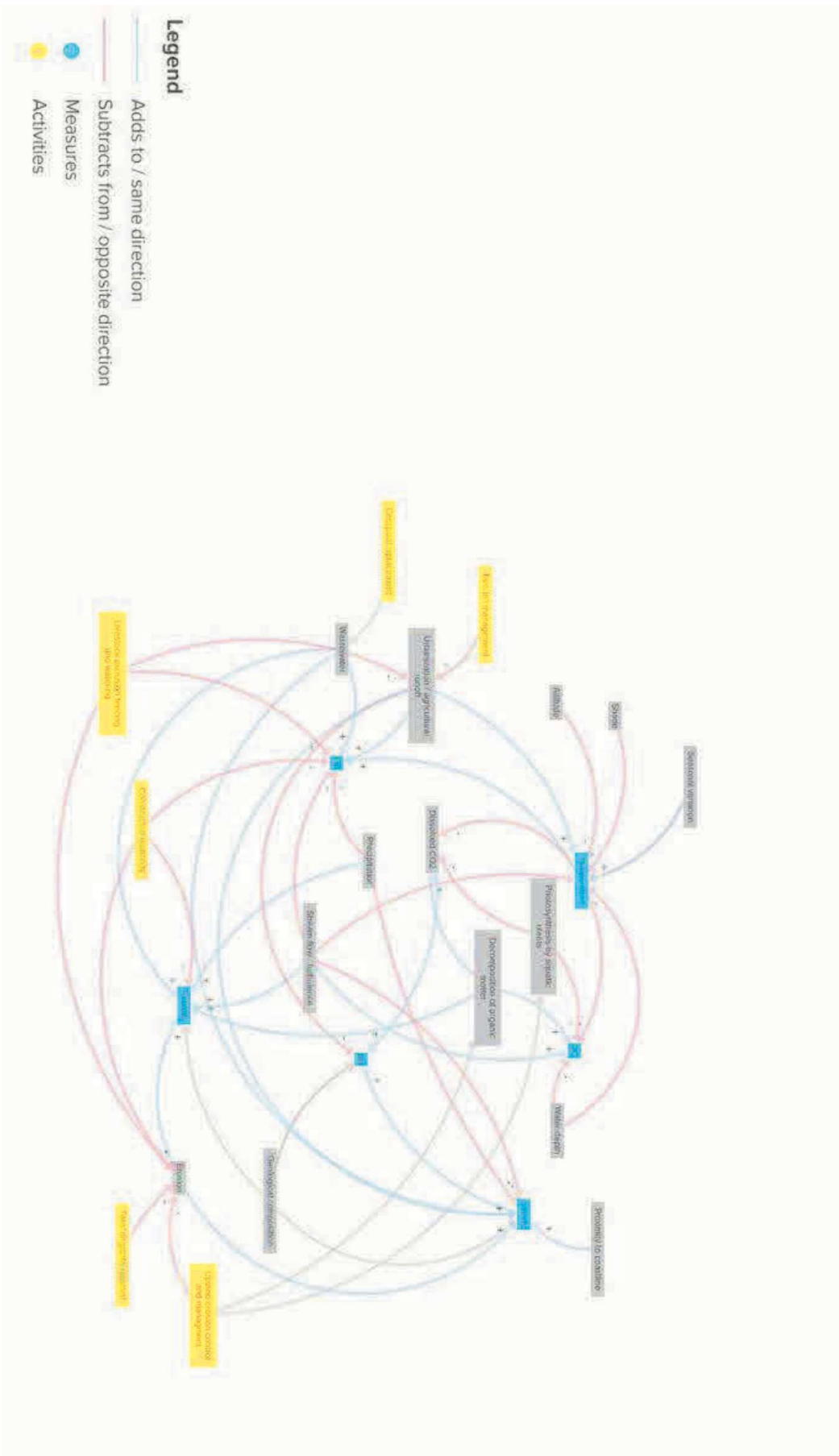


Figure 17 - Systems map of the data collected

<https://kumu.io/mariongfx/water-quality-connections#water-quality-relationships>

This map shows why the correlation factors are always so low: indeed, this map shows that every single element of data is impacted by a great number of factors.

For instance, we can see that it is absurd to hope to find a correlation between temperature and rainfall, as temperature is also dependent on seasonal variation, shade, water depth, dissolved oxygen, dissolved CO₂, stream flow, urbanization, etc.

3.2 Establishing the impact of the stream restoration project

3.2.1 Timelines

Rainfall

Daily rainfall has been collected since April 2017 in the Waipā Garden thanks to gauging stations monitoring continuously. The graph below summarizes the rainfall month by month.

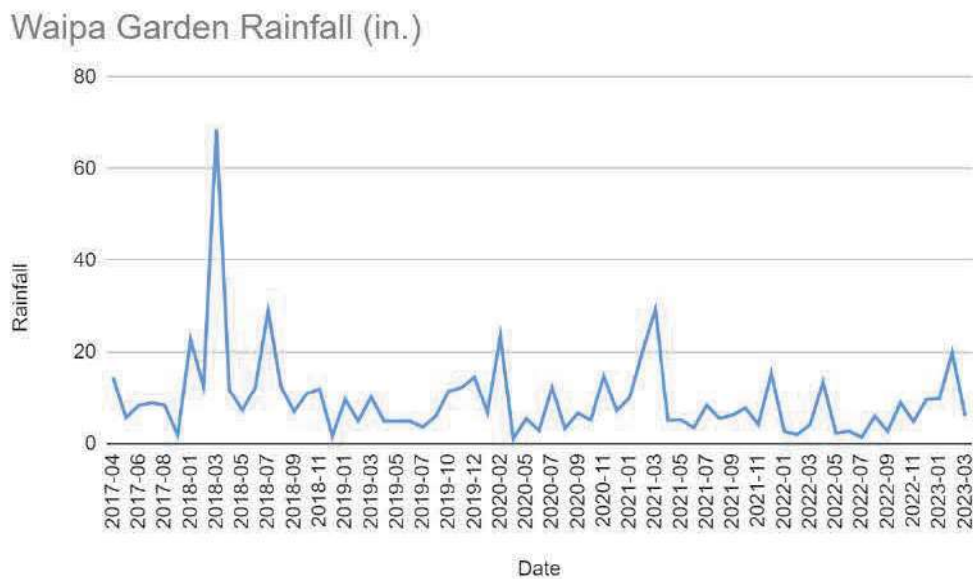


Figure 18 - Waipā Garden Rainfall from April 2017 to March 2023

We notice a very big spike in April 2018, which corresponds to the heavy downpour that flooded Kaua'i and set a national record for the most rainfall in a 24-hour period. With 49.7 inches at Waipā Garden, Kaua'i set the new record on April 14 and 15, 2018.

Enterococcus

Enterococcus Timeline

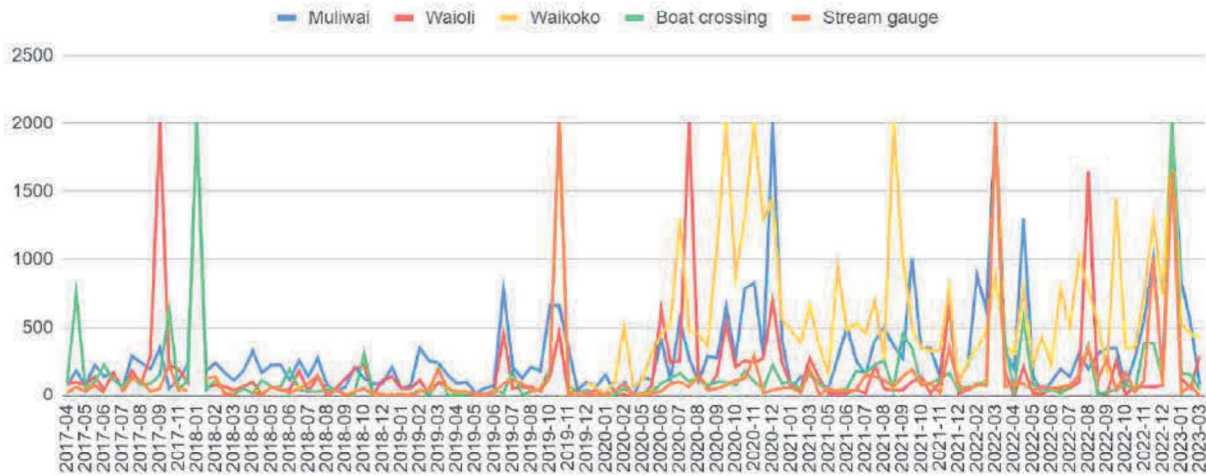


Figure 19 - Timeline of Enterococcus from 2017 to 2023

There is a clear decrease in the Enterococcus populations after early 2018, which is when the cesspool replacements and livestock fencing and watering began, which likely has as much to do with waterway sediments being flushed out during the 2018 flood than with the actual BMPs implemented. Indeed, the waterway sediments are expected to be ENT reservoirs based on directed testing and other investigations (Ali Boehm, Stanford). The fact that it is may be partly due to flushing is shown by the fact that after June 2019, it seems that the populations began to increase again, despite more cesspools being replaced and the efforts to keep the livestock in pens continuing.

Turbidity

In this graph, the turbidity for all sites on the Waipā stream were grouped together: this includes Muliwai, Boat Crossing and Stream Gauge. We can use Waioli and Waikoko as control variables as no stream restoration efforts were undertaken on these streams.

Turbidity Timeline

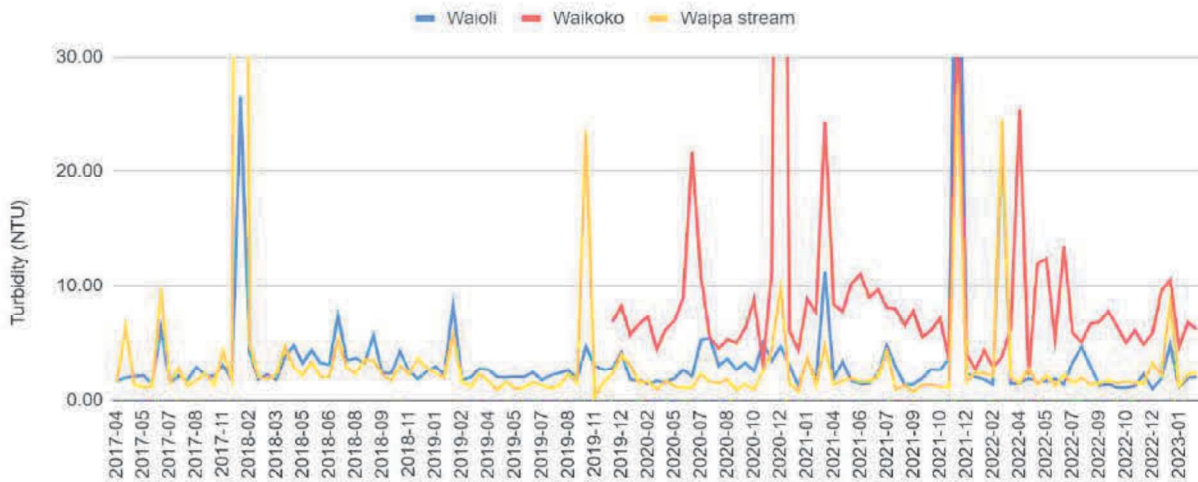


Figure 20 - Timeline of Turbidity from 2017 to 2023

We certainly notice a decrease in turbidity after January 2018, which is about a year after restoration actions began to be implemented. We can probably say that the restoration efforts have been at least somewhat effective in reducing stream turbidity. However, they began to increase again in October 2019, even though these activities continued to be undertaken in the second phase of the project, which began in August 2019. This is consistent with what was determined in the exploratory research part of this report.

3.2.2 One-way ANOVAs

Turbidity

We want to analyze whether or not the project appears to have had a significant impact on the turbidity levels. To do this, we want to compare the turbidity levels between different phases of the project for the sites Boat Crossing, Estuary Gage, Bamboo and Ditch Junction, which are the ones being impacted by the stream restoration project.

The data was separated in three phases:

- Phase 0 : before the start of the project in February 2016
- Phase 1 : February 2016- March 2019
- Phase 2 : March 2019-March 2023

We obtain the following graph :

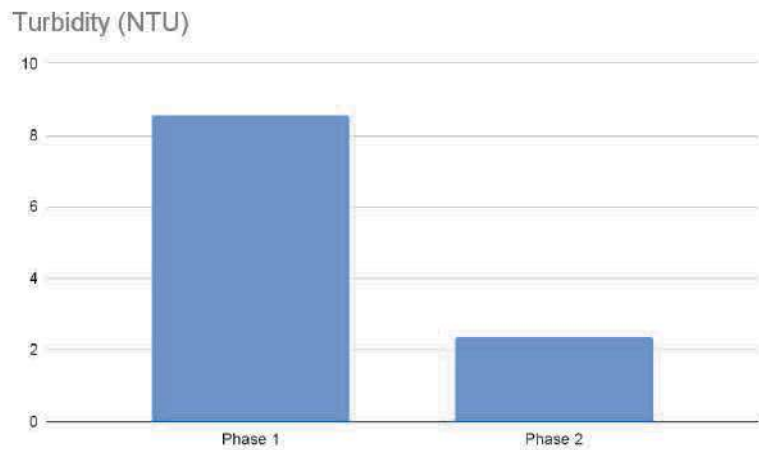


Figure 21 - Mean Turbidity in Phase 1 vs Phase 2

There appears to be significant differences between the different levels of turbidity in these phases. It would be expected that the turbidity levels would decrease with time thanks to the solutions implemented by the Waipā Foundation, which is indeed what we observe here.

To determine whether these differences are significant, we can perform an ANOVA-analysis in order to determine whether or not the variations in turbidity over the course of the project are indeed significant.

The null hypothesis would be that the mean turbidity level is the same across all phases and that any observed differences in turbidity across the dates are due to random variation and not because of a systematic effect of the dates.

An R-script allows us to calculate the following values:

Df	Sum Sq	Mean Sq	F value	Pr(>F)
2	10026	5013	20.79	1.27e-09

Table 2 - ANOVA statistics test for turbidity P1 vs P2

The p-value (or p-factor) in the context of ANOVA (and statistical tests in general) represents the probability of observing the data, or something more extreme, assuming that the null hypothesis is true. It depends on the degrees of freedom and the desired significance level (typically 0.05) and can be found in a table.

- Small p-value (typically ≤ 0.05): Indicates strong evidence against the null hypothesis → suggests that there is a significant effect.
- Large p-value (> 0.05): Indicates weak evidence against the null hypothesis → there is no significant effect.

Here, the p-value is 1.27e-9, which indicates the probability that the observed data would occur if the null hypothesis were true.

This means that there are indeed significant variations in turbidity linked to date. The levels of turbidity are clearly much lower in Phase 2 than they were in Phase 1, which shows that the

project has most likely significantly decreased the levels of turbidity in the water near the areas where the stream restoration is taking place.

HS-IBI

The report of the Waipā stream bioassessment has the measures of the HS-IBI scores, which is based on the biodiversity present at the site of the measure.

The Hawai'i Stream Index of Biological Integrity (HS-IBI) incorporates 11 metrics covering five ecological categories (taxonomic richness, sensitive species, reproductive capacity, trophic-habitat capacity, and tolerance capacity). The HS-IBI classifies streams from undisturbed (near-pristine) to severely impaired. This scale was created by sampling 39 sites (6 estuarine reaches) on 18 Hawaiian streams located on all major islands. [21]

This index has been measured in the upper, middle and lower stream at four different dates :

- August 2003
- July 2016
- January 2019
- March 2023

The results are reported in the table below:

A. Taxa Presence in Waipa Stream	Lower				Middle				Upper				
Fishes	Aug'03	Jul'16	Jan'19	Mar'23	Aug'03	Jul'16	Jan'19	Mar'23	Aug'03	Jul'16	Jan'19	Mar'23	
Poeciliidae - <i>Xiphophorus helleri</i> (swordtails)	13.2	6.5	0.8	35.8	N	N	N	1.8	N	N	N	N	
<i>Poecilia sphenops</i> (Mexican molly)	N	N	0.8	19.3	N	N	N	N	N	N	N	N	
Gobiidae: - * <i>Stenogobius hawaiiensis</i> (*o'opu naniha)	42.1	5.2	18.7	8.2	N	N	N	N	N	N	N	N	
* <i>Awaous guamensis</i> (*o'opu nakea)	4.4	3.3	20.3	6.6	33.0	20.8	43.6	27.7	81.8	72.4	66.0	59.3	
* <i>Sicyopterus stimpsoni</i> (*o'opu nopili)	N	N	8.4	0.2	0.9	11.4	50.8	7.8	3.0	8.6	5.2	1.6	
* <i>Eleotris sandwicensis</i> (*o'opu akupa)	1.8	8.5	12.8	2.7	4.5	0.4	3.3	2.9	N	N	N	N	
* <i>Lentipes concolor</i> (*o'opu-alamo'o)	N	N	N	N	N	N	N	N	3.0	6.9	6.1	0.3	
Kuhliidae: * <i>Kuhlia sandwicensis</i> (aholehole)	N	8.5	17.1	9.0	0.9	N	N	N	N	N	N	N	
Mugilidae: * <i>Mugil cephalus</i> (*ama'ama)	N	N	N	N	N	N	N	N	N	N	N	N	
Macroinvertebrates:													
Palaenonidae - <i>Macrobrachium lar</i> (Tahitian prawn)	36.8	64.7	21.1	17.3	60.7	67.3	41.3	61.3	6.1	12.1	22.8	32.4	
* <i>Macrobrachium grandimanus</i> (*ōpae-'ōcha'a)	1.8	3.3	N	1.0	N	N	N	N	N	N	N	N	
Atyidae - <i>Atyoida bislucata</i> (*opae-kala'ole)	N	N	N	N	N	N	N	N	6.1	N	N	0.8	
Neritidae - * <i>Neritina granosa</i> (hihiwai)	N	N	N	N	N	N	N	N	N	N	N	N	
B. Percent Native Species in Stream Assemblage	50.0	28.7	77.3	26.7	39.3	32.7	58.7	38.5	87.9	88.0	77.2	62.0	
C. Index of Biological Integrity (% of reference)	49.1	45.5	70.9	63.6	63.6	74.6	85.5	74.5	78.2	86.3	81.8	81.8	
D. Overall HS-IBI Mean ± Standard Error		57.3 ± 1.711				74.6 ± 1.121				82.0 ± 0.375			

Table 3 - HS-IBI table for the Waipā stream. Source : Kido et al. Waipā Stream Bioassessment Pt 3

The HS-IBI is a key element that allows us to analyze the health of the watershed, as it reflects the biodiversity in the stream.

The following timeline shows that there is an overall increase in the biodiversity index. It would be interesting to analyze if this increase is in fact significant.

Biodiversity index over time

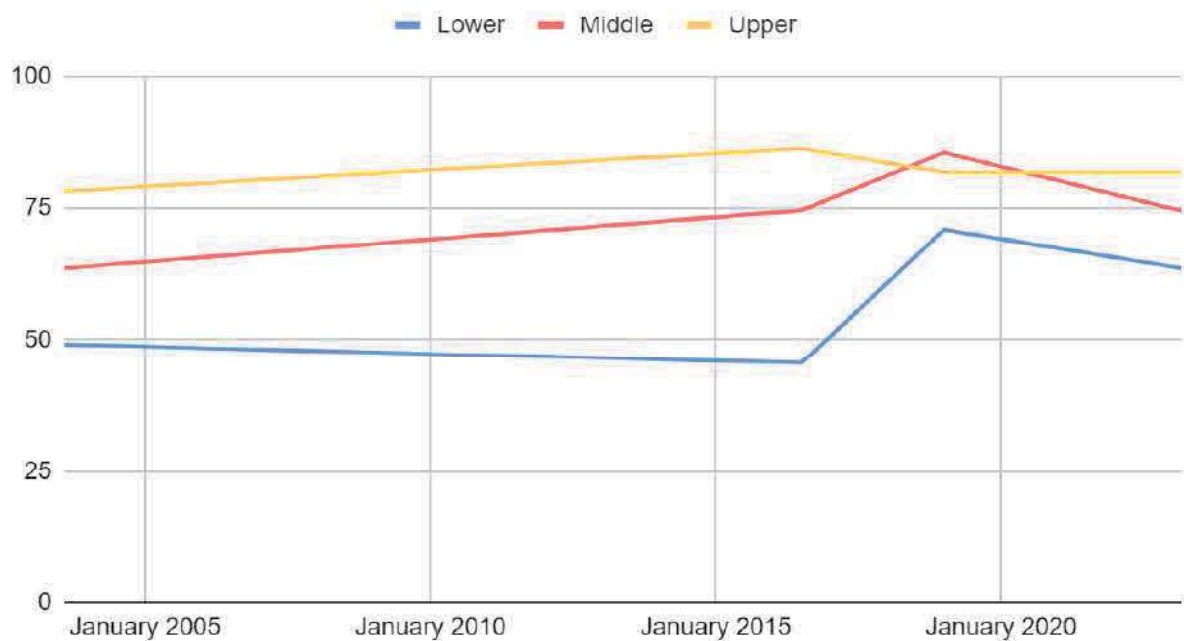


Figure 22 - Biodiversity index over time

The null-hypothesis would be that the mean biodiversity index is the same across all four dates and that any observed differences in the biodiversity index across the dates are due to random variation and not because of a systematic effect of the dates.

An ANOVA analysis can be used to determine whether the null hypothesis is correct or not.

The following table shows the p-values for the significance of the difference between two dates.

	2003	2016	2019	2023
2003	1			
2016	1	1		
2019	1	1	1	
2023	1	1	1	1
Overall p-value : 0.139				

Table 4 - p-values of HS-IBI in 2003, 2016, 2019 and 2023

All pairwise comparisons (Date_2003 vs. Date_2016, Date_2003 vs. Date_2019, etc.) have p-values of 1, indicating no significant differences between any pairs of dates.

The p-value for the date effect ($\Pr(>F) = 0.139$) is greater than the common significance level (e.g., 0.05), indicating that the differences in biodiversity index across the four dates are not statistically significant at the 5% level.

The ANOVA result suggests that there is no significant effect of the dates on the biodiversity index ($p = 0.139$). The pairwise comparisons further confirm this by showing that none of the dates differ significantly from each other after adjusting for multiple comparisons.

This lack of significance is due to the small sample size: indeed, for each of the dates, we only have three values. A more frequent calculation of the HS-IBI index would potentially allow us to have more conclusive evidence of a variation of the biodiversity throughout the dates, possibly thanks to the stream restoration project.

Thanks to the one-way ANOVA, we have been able to determine that the project phase does have a strong impact on turbidity. This most likely means that the project was successful. However, it is impossible to prove that the stream restoration has had a positive impact on the

3.2.3 Two-way ANOVAs

Now that we have studied the effect of project phase on our target variables, we can see if we can take into account a second variable in our data analysis : rainfall. Let us study the combined effect of rainfall and project phase on turbidity and FIB populations. For this analysis, rather than using an R-script, I chose to do the calculations “by hand” in an Excel spreadsheet in order to fully understand the method of the two-way ANOVA,

FIB (Enterococcus) :

Factors :

- Rainfall, separated into 4 quartiles based on the averages of all streams (the value for April 2018 being such a big outlier, it was removed).

Q1	4.885
Q2	7.24
Q3	11.895
Q4	29.24

 - 0-4.885 inches / month
 - 4.885-7.24 inches/month
 - 7.24-11.895 inches/month
 - 11.85-29.24 inches/month
- Phases
 - Phase 1: April 2017 - February 2019
 - Phase 2 : March 2019 - March 2023

Response variable : Enterococcus populations

The aim is to determine the extent of the impact of the two factors (rainfall and phase) on the quantity of the fecal-indicator bacteria Enterococcus in the stream.

The population of Enterococcus is measured in MPN*/100 mL in the following sites :

- Waikoko

- Waioli
- Muliwai
- Stream gauge
- Boat crossing

*Most Probable Number, a statistical method used to estimate the number of bacteria in a sample based on the principle of extinction dilution, which involves inoculating broth in 10-fold dilutions.

Null hypotheses :

- Null Hypothesis for Rainfall:
 - Statement: The ENT population means of the different quartiles of rainfall are equal.
 - $\text{meanENT}(\text{Rainfall Q1}) = \text{meanENT}(\text{Rainfall Q2}) = \text{meanENT}(\text{Rainfall Q3}) = \text{meanENT}(\text{Rainfall Q4})$
 - Interpretation: Rainfall does not have a significant effect on the response variable (Enterococcus population).
- Null Hypothesis for Timeline:
 - Statement: The ENT population means of the different phases are equal.
 - $\text{meanENT}(\text{Phase 1}) = \text{meanENT}(\text{Phase 2})$
 - Interpretation: The date does not have a significant effect on the response variable (Enterococcus population).
- Null Hypothesis for the Interaction between Rainfall and Timeline:
 - Statement: There is no interaction effect between rainfall and phases of the restoration project.
 - Interpretation: The effect of one factor does not depend on the level of the other factor

Analysis table :

The first thing we do is calculate the mean for each rainfall quartile/phase combination, as well as for each of the rainfall quartiles and each of the phases.

	P1	P2	
Q1	436.2625	226.2726786	263.3297059
Q2	119.4375	282.2398214	261.8895313

Q3	98.72916667	383.7069444	269.7158333
Q4	92.9239575	263.731	187.8167589
	151.7594295	281.0605851	

Table 5 - Mean for each rainfall quartile/phase combination for Enterococcus

Based on this we can calculate the sum of squares, degrees of freedom and mean squares, as well as the F-factors.

The F-factors allow us to test the null hypotheses.

- If the F-statistic is significantly larger than 1, it suggests that the variability between group means is larger than the variability within the groups, indicating a significant effect of that factor or interaction.
- If the F-statistic is close to or less than 1, it suggests that the variability between group means is not significantly larger than the variability within the groups, indicating no significant effect of that factor or interaction.

Source	Sum of Squares (SS)	Degrees of Freedom (df)	Mean Square (MS)	F
Rainfall	3589934.559	3	1196644.853	13.81574888
Phase	4227715.596	1	4227715.596	48.81068669
Interaction AB	402431.3201	3	603959.3709	0.5047106243
Error	5023643.82	58	86614.54863	
Total	3668142.8	65		

Table 6 – Statistical tests for Rainfall/Timeline/Enterococcus

Here, the F-factors for rainfall and the phase of the project are significantly larger than 1, meaning that both rainfall and the phase of the project have a strong effect on the response variable, which is the Enterococcus population.

However, the F-factor for the interaction between these two variables is smaller than one, so we can assume that rainfall and project phases are independent, as one could probably expect.

P-values :

Next, I calculated the p-values associated with each of the hypotheses.

Factor	p-value	Interpretation
Rainfall	0.000000144	very significant effect of rainfall on fecal bacteria levels
Phase	0.000000000013	very significant effect of the date
Rainfall/phase interaction	0.683	interaction between rainfall and date is not significant

Table 7 - p-values for Rainfall/Timeline/Enterococcus

We can see the null hypotheses for rainfall and phase can be rejected. Indeed, the probability of the decrease in Enterococcus bacteria being the same independently from rainfall and phase is extremely low (p-value). This means that both rainfall and date categories have highly significant effects on the number of fecal bacteria in the stream.

On the other hand, the null hypothesis stating that the two variables , rainfall and dates, do interact strongly with one another, can be rejected as the p-value for this shows that the probability of this correlation being purely random is 68%.

Analysis:

The populations of Enterococcus are heavily influenced by both the amount of rain and the phases of the project.

The mean value of the density of the bacteria decreases when the rainfall increases. This means that overall, the more rain there is, the less dense the bacteria population is. This seems logical as the rain will increase the dilution of the bacteria.

On the other hand, it is clear that there is an increase in the number of bacteria in the stream over the course of the project. Indeed, there is a significant increase in the Enterococcus population between Phase 1 and Phase 2. This is surprising as one would expect the actions undertaken, such as the replacement of cesspools, to cause a decrease in these populations. We must assume that other factors are at play here which also have an impact on these populations. Some of these factors could be temperature variations and agricultural runoff.

Turbidity

Let us perform the same analysis on the target variable turbidity.

Factors:

- Rainfall, separated into 4 quartiles based on the averages of all streams (the value for April 2018 being such a big outlier, it was removed).

Q1	4.885
Q2	7.24
Q3	11.895
Q4	29.24

- 0-4.885 inches / month
- 4.885-7.24 inches/month
- 7.24-11.895 inches/month
- 11.85-29.24 inches/month

- Phases
 - Phase 1: April 2017 - February 2019
 - Phase 2 : March 2019 - March 2023

Response variable : turbidity

The aim is to determine the extent of the impact of the two factors (rainfall and phase) on the turbidity of the water of the streams.

The turbidity is measured in NTU* in the following sites :

- Waikoko
- Waioli
- Muliwai
- Stream gauge
- Boat crossing

*Nephelometric Turbidity Units, the most common unit for turbidity measurement, are based on the scattering of light at a 90-degree angle from the incident light.

Null hypotheses:

- Null Hypothesis for Rainfall:
 - Statement: The turbidity means of the different quartiles of rainfall are equal.
 - $\text{meanTurbidity(Rainfall Q1)} = \text{meanTurbidity(Rainfall Q2)} = \text{meanTurbidity(Rainfall Q3)} = \text{meanTurbidity(Rainfall Q4)}$
 - Interpretation: Rainfall does not have a significant effect on the response variable (turbidity).
- Null Hypothesis for Timeline:
 - Statement: The turbidity means of the different phases are equal.
 - $\text{meanTurbidity(Phase 1)} = \text{meanTurbidity(Phase 2)}$
 - Interpretation: The date does not have a significant effect on the response variable (turbidity).
- Null Hypothesis for the Interaction between Rainfall and Timeline:
 - Statement: There is no interaction effect between rainfall and phases of the restoration project.

- Interpretation: The effect of one factor does not depend on the level of the other factor

Analysis table:

The first thing we do is calculate the mean for each rainfall quartile/phase combination, as well as for each of the rainfall quartiles and each of the phases.

	P1	P2	
Q1	4.27	4.15	4.17
Q2	3.76	4.74	4.62
Q3	3.83	4.89	4.47
Q4	3.93	6.32	5.26
	3.94	4.93	

Table 8 - Mean for each rainfall quartile/phase combination

Based on this we can calculate the sum of squares, degrees of freedom and mean squares, as well as the F-factors.

Source	Sum of Squares (SS)	Degrees of Freedom (df)	Mean Square (MS)	F
Rainfall	54.46380344	3	18.15460115	0.0003317420621
Phase	98.56269952	1	98.56269952	0.001801052688
Interaction AB	561953.9873	3	14.08038565	0.7755822082
Error	3174052.936	58	54725.05063	
Total	65.57582252	65		

Table 9 - Statistical tests for Rainfall/Timeline/Turbidity

Here, the F-factors for rainfall and the phase of the project are significantly smaller than 1, meaning that both rainfall and the phase of the project have little to no effect on the response variable, which is turbidity.

However, the F-factor for the interaction between these two variables is smaller than one, so we can assume that rainfall and project phases are independent, as one could probably expect.

P-values:

Factor	p-value	Interpretation
Rainfall	0.99999	no effect of rainfall on turbidity
Phase	0.9663	no effect of the date on turbidity
Rainfall/phase interaction	0.5124	interaction between rainfall and date is not significant

Table 10 – p-values for Rainfall/Timeline/Enterococcus

Both rainfall and date categories have no effect on the amount of turbidity in the stream. The interaction between rainfall and date categories does not significantly affect turbidity.

Analysis:

Turbidity levels are neither influenced by the amount of rain nor the phases of the project.

There is a slight increase in turbidity between phases 1 and 2 but according to the p-values, it is not significant enough to be attributed to the efforts made over the course of the stream restoration project. This is surprising as one would expect the actions undertaken, such as the removal of feral pigs and livestock fencing, to cause a decrease in turbidity. We must assume that other factors such as erosion are at play here and have an impact on turbidity levels.

There also appears to be no interaction between rainfall and the phases of the project.

3.3 Determining the weight of factors on target variables

3.3.1 Weight of factors on HS-IBI

The HS-IBI is an excellent indicator of stream health. Therefore, it would be relevant to determine which of the parameters measured (pH, salinity, temperature) have an impact on biodiversity. The parameters studied were:

- Rainfall
- pH
- Salinity
- Temperature
- DO

- Turbidity
- FIB

In order to do this, it is possible to create a linear multiple-factor regression to determine the weight of each of the parameters. Indeed, the regression allows us to find the coefficients in the following formula:

$$Y = a + b_1 X_1 + b_2 X_2 + \dots + b_k X_k$$

Equation 1 – Multiple variable regression

- Y is the target variable, in this case, the HS-IBI index.
- X1, X2, ..., Xn are the values of the different parameters measured.
- The coefficients (a, b1, b2, ..., bk) are what we are looking for, as they determine the impact that the parameters have on the HS-IBI.

These coefficients (a, b1, b2, ..., bk) are usually calculated with the method of least squares, which minimizes the sum of the squared prediction errors. The prediction errors or residuals are given by Y – (Predicted Y).

Unfortunately, we had no measures for the parameters (pH, salinity, temperature etc) in August 2003, so the HS-IBI for that time period could not be used. Furthermore, FIB was not measured before 2017, so the HS-IBI index for July 2017 was unused.

The only data kept was the HS-IBI, pH, rainfall, temperature, DO, salinity, turbidity, and FIB measured in January 2019 and March 2023. The remaining data was compiled in an [Excel Sheet](#).

A code on R allowed us to determine the weight of each of each of the parameters on the HS-IBI: :

Parameter	Coefficient	Interpretation	p-value	Significant ?
Intercept (a)	-644.22174	When all over variables are 0, this is the expected result.		
Temperature	23.34373	Each one-degree Celsius rise in temperature is associated with an increase of 23.34 units in the biodiversity index (IBI), taking into account the other model variables.	0.0474	Yes
Salinity	10.67691	Each unit increase in salinity is associated with an increase of 10.68 IBI units.	0.0462	Yes
DO	0.74604	Each unit increase in DO is associated with an increase of 0.75 IBI units.	0.0426	Yes

pH	29.96150	Each unit increase in pH is associated with an increase of 30 IBI units	0.0783	Almost
Turbidity	-15.00379	Each one-unit increase in turbidity is associated is associated with a decrease of 15.00 IBI units.	0.0509	Almost
FIB	0.11946	Each unit increase in FIB is associated with an increase of 0.12 IBI units	0.1114	No
Rainfall	4.20628	Each extra inch of rainfall is associated with an increase of 4.2 IBI units	0.1754	No
R ² =0.9972				

Table 11 – Weight coefficients for HS-IBI

The R² value is very close to one, which allows us to say that the model very accurately predicts the IBI as a function of temperature, salinity, DO, pH, turbidity, FIB and rainfall.

The calculation of the p-values by R allows us to determine which of the parameters influence IBI. Indeed, the p-value is the probability that the observed results would occur if the null hypothesis were true, the null hypothesis being that the parameter studied has no effect on the IBI.

We notice that the p-values for FIB and rainfall are much larger than 0.05 which means that there is a high probability (respectively 11 and 28% chance) that the IBI value would have been the same had the rainfall and FIB values been drastically different.

However, the p-values of temperature, salinity, and DO are less than 0.05, which means that the results are unlikely to have occurred by chance, so the null hypothesis can be rejected. This suggests that there is a significant effect or difference on the IBI depending on the value of temperature, salinity and DO.

To check if the weight of these different factors is significant, it is important to check the correlation of different variables. Indeed, if there is a strong correlation between two of the parameters, the b₁, b₂, ..., b_n factors can be off.

The correlation coefficient measures the strength and direction of the linear relationship between two variables. It ranges from -1 to 1, with the following interpretations:

- +1: Perfect positive linear relationship. As one variable increases, the other variable increases in a perfectly linear manner.
- -1: Perfect negative linear relationship. As one variable increases, the other variable decreases in a perfectly linear manner.

- 0: No linear relationship. Changes in one variable do not predict changes in the other variable.

	Temperature	Salinity	DO	pH	Turbidity	Rainfall	FIB
Temperature	1						
Salinity	0.1489000	1					
DO	-0.5147124	0.7474769	1				
pH	0.2150765	0.1130453	0.002685457	1			
Turbidity	0.6758053	0.7305773	-0.892320635	-0.076193690	1		
Rainfall	-0.3325951	-0.1169001	-0.056622537	-0.879811740	0.06813177	1	
pH	0.1933261	0.5523701	-0.672813161	-0.390124137	0.75780626	0.59088028	1

Table 12 – Correlation for HS-IBI

Many of these parameters have a high degree of correlation. This is problematic as it may indicate that there is a higher chance of having multicollinearity in the regression model, which would make the weight of the different parameters inaccurate.

In order to check this, we use the VIF coefficient. To measure them, a code on R was used.

- VIF = 1: No multicollinearity. The predictor is not correlated with other predictors.
- $1 < VIF < 5$: Moderate multicollinearity. Generally acceptable.
- $VIF > 5$: High multicollinearity. Indicates that the predictor is highly correlated with other predictors.
- $VIF > 10$: Very high multicollinearity. Suggests a serious problem, and the predictor should be considered for removal or further investigation.

The following values were calculated:

Temperature	Salinity	DO	pH	Turbidity	Rain	FIB
107.63086	100.91188	13.92581	44.48899	246.08065	164.85472	71.25386

Table 13 – VIF for HS-IBI

Unfortunately, all of the values here show a very high to extremely high multicollinearity. This invalidates the values for the weight of each factor previously calculated.

In order to solve the problem with multicollinearity, it would be necessary to remove all redundant parameters. Unfortunately, this means decreasing the quality of the model as we are losing key information.

3.3.2 Fecal indicator bacteria (Enterococcus)

Let us determine the weight of these different parameters on a different target variable, for which we have a lot more data.

First, the R-script calculated the following coefficients :

Parameter	Coefficient	Interpretation	p-value	Significant ?
Intercept (a)	1720.654	When all over variables are 0, this is the expected result.		
Temperature	-8.391	Each one-degree Celsius rise in temperature is associated with a decrease of 8.39 FIB units (MPN/100mL), taking into account the other model variables.	0.44048	No
Salinity	10.118	Each one-ppt rise in salinity is associated with an increase of 10.11 FIB units (MPN/100mL)	0.03561	Yes
Turbidity	13.822	Each one-NTP rise in turbidity is associated with an increase of 13.8 FIB units (MPN/100mL).	< 2e-16	Yes
DO	-85.980	Each one-percent rise in DO is associated with a decrease of 13.8 FIB units (MPN/100mL).	6.80e-10	Yes
pH	-103.730	Each one unit rise in pH is associated with a decrease of 103.7 FIB units (MPN/100mL).	0.00997	Yes

Rainfall	43.518	Each one-inch rise in rainfall is associated with an increase of 43.5 FIB units (MPN/100mL).	0.06901	No
R ² = 0.3047				

Table 14 - Weight coefficients for Enterococcus

The R² value is 0.3047. This indicates that approximately 30.47% of the variability in the target variable Enterococcus can be explained by the model.

Next, let's calculate the correlation between the different parameters.

	Temperature	Salinity	Turbidity	DO	pH	Rainfall
Temperature	1					
Salinity	0.35342202	1				
Turbidity	-0.01190919	0.1249896	1			
DO	-0.65841238	-0.37693678	0.03935844	1		
pH	0.06562532	0.10688941	-0.06658325	-0.04707953	1	
Rainfall	-0.11902241	-0.02730261	0.09592095	0.03466208	-0.09687721	1

Table 15 – Correlation for Enterococcus

All of the relationships observed have weak or very weak correlations. This indicates that there is little to no linear relationship between them. This is coherent with what was observed in the two-way analysis part of the report.

We can calculate the VIF values anyways just in case:

Temperature	Salinity	Turbidity	DO	pH	Rainfall
1.842641	1.225012	1.034860	1.850243	1.026326	1.033948

Table 16 – VIF for Enterococcus

All VIF values are well below 10, indicating no significant multicollinearity issues.

In conclusion, the model may only explain only 30% of the FIB population in the water, but it does so accurately. The parameters that have the biggest impact on the FIB population are

Given the significance and the size of the coefficients, the parameters that have the biggest impact on turbidity are :

- Dissolved oxygen
- pH
- Turbidity

We can draw a pie chart to be able to visualize the weight of each of the factors.

In order to do this, we have to consider that about 70% of the turbidity levels cannot be explained by the model. Of the 30% left, we have to calculate the proportion of each of the parameters that are indeed significant in the variations of turbidity and weigh them according to their coefficient. This give us the following pie chart :

Weight of factors explaining FIB population levels

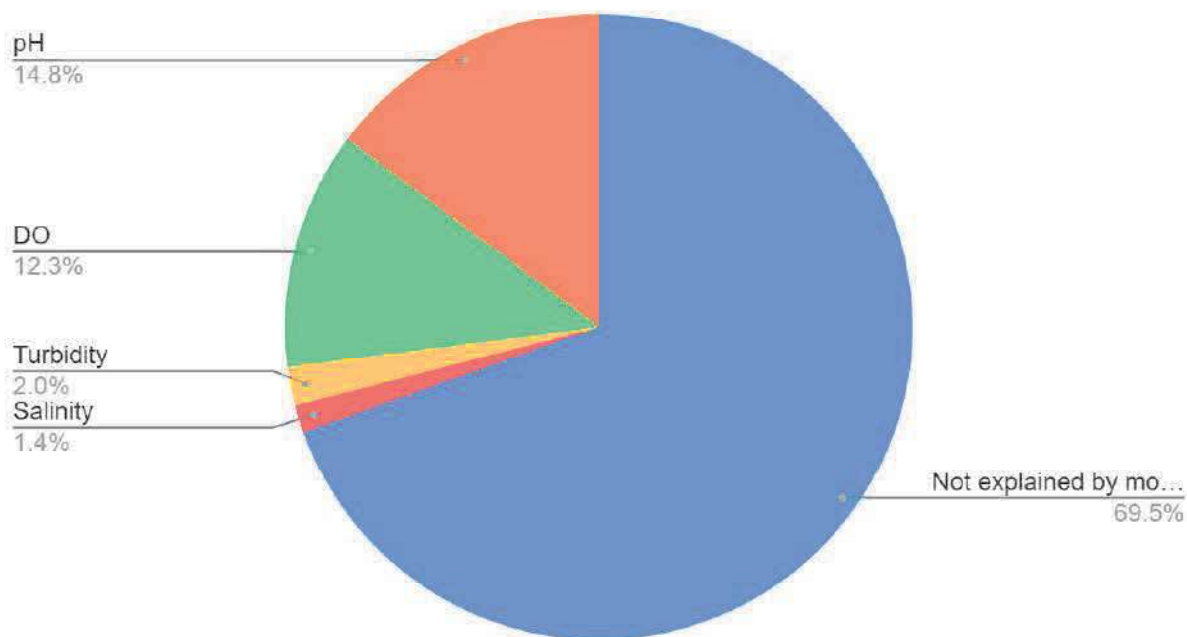


Figure 23 – Weight of the factors explaining FIB population levels

As we can see, most of the causes of the populations of Enterococcus in the river cannot be explained by the model. This is inevitable when studying such a complex ecosystem.

3.3.3 Turbidity

Let us study the parameters most influencing our last target variable: turbidity.

Parameter	Coefficient	Interpretation	p-value	Significant ?
Intercept (a)	3.518686	When all over variables are 0, this is the expected result.	0.7904	No
Temperature	0.013486	Each one-degree Celsius rise in temperature is associated with an increase of 0.13 NTP in turbidity, considering the other model variables.	<2e-16	Yes
Salinity	-0.291863	Each one-ppt rise in salinity is associated with a decrease of 0.29 NTP in turbidity.	0.3903	No
Turbidity	0.291355	Each one-NTP rise in turbidity is associated with an increase of 0.29 NTP in turbidity.	0.0528	Almost
DO	0.888932	Each one-percent rise in DO is associated with an increase of 0.8 NTP in turbidity.	0.0443	Yes
pH	-0.491721	Each one unit rise in pH is associated with a decrease of 0.49 NTP in turbidity.	0.6966	No
Rainfall	0.765469	Each one-inch rise in rainfall is associated with an increase of 0.76 NTP in turbidity.	0.3063	No
R ² = 0.2138				

Table 17 – Coefficients for turbidity

The R² value is 0.2138. This indicates that approximately 21% of the variability in the target variable can be explained by the model.

Let us check the correlation matrix:

	FIB	Temperature	Salinity	DO	pH	Rainfall
FIB	1					
Temperature	0.1729545	1				
Salinity	0.2229228	0.35342202	1			

DO	-0.3192748	-0.65841238	-0.37693678	1		
pH	-0.1056883	0.06562532	0.10688941	-0.04707953	1	
Rainfall	0.1053565	-0.11902241	-0.02730261	0.03466208	-0.09687721	1

Table 18 – Correlations for turbidity

Most of the correlations are the same as the ones found in the FIB part of the multiple-factor regression part of this report, as it is indeed the same dataset. The new correlations (the ones involving FIB) are all quite low which means that there is most likely no correlation.

The VIF values are the following :

Temperature	Salinity	FIB	DO	pH	Rainfall
1.842164	1.226490	1.170189	1.968016	1.038471	1.038194

Table 19 – VIF coefficients for turbidity

All VIF values are well below 10, indicating no significant multicollinearity issues.

In conclusion, the model may only explain only 21% of the turbidity levels, but it does so accurately.

Given the significance and the size of the coefficients, the parameters that have the biggest impact on turbidity are:

- DO
- Temperature

We can draw a pie chart to be able to visualize the weight of each of the factors.

In order to do this, we have to consider that about 79% of the turbidity levels cannot be explained by the model. Of the 21% left, we have to calculate the proportion of each of the parameters that are indeed significant in the variations of turbidity and weigh them according to their coefficient. The formulas can be found [here](#) and give us the following pie chart :

Weight of factors explaining turbidity

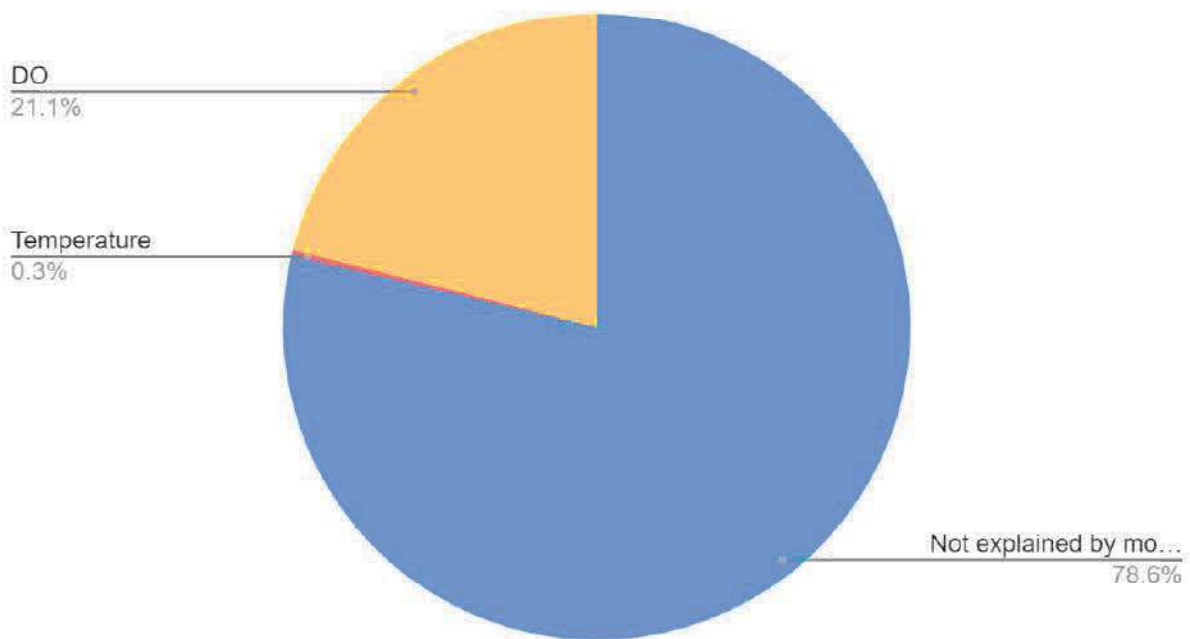


Figure 24 – Weight of the factors explaining turbidity

3.4 Random forest model

3.4.1 Principle

A random forest model is a machine-learning algorithm. It is one of the most commonly used algorithms as it usually produces great results, is easy to use and versatile as it combines regression and classification tasks.

Some of its benefits include :

- High accuracy
- Robustness to overfitting : the ensemble approach helps in diluting the effect of outliers by averaging multiple trees.
- Handles large datasets
- Versatility: works well with both categorical and numerical data
- Feature Importance : they provide a measure of the importance of each feature in the prediction process. This can be useful for feature selection and understanding which variables are most influential in the model

This last benefit is the one that we will be mainly interested in. We want to use a random forest model to calculate the weight of each of the parameters on turbidity.

A random forest model uses multiple decision trees to create a single output. A decision tree is a model that makes predictions by splitting the data into branches based on feature values (the

value of an individual measurable property or characteristic of the data). It continues splitting until it reaches a leaf node, which represents the prediction. In this case, the features are pH, rainfall, salinity, dissolved oxygen etc. These variables represent the nodes. This node will be split into two branches between feature values, for example >30 inches and <30 inches of rainfall.

Different decision trees may predict different turbidity output values depending on their structures and the feature values represented. The final prediction from the Random Forest is the average of all the tree predictions.

The weight of the factor, or feature importance, is calculated by the sum of the reduction in error that this distinction has caused across all the trees. Each time a tree makes a split based on a feature it reduces the error in predicting the target variable. This reduction in error is measured, and we attribute that improvement to the feature used at that split. For instance, continuing with the same example, if splitting on "rainfall above or below 30 inches" reduces the error by a significant amount, that feature gets a high score for that particular tree.

In a decision tree, further splits can occur based on the same feature if it helps to reduce the prediction error even more. This is a key aspect of how decision trees work—they keep splitting the data into smaller and more specific groups as long as it improves the model's accuracy. The process continues until a stopping criterion is met (e.g., maximum tree depth, minimum number of samples in a node). Or when further splits don't significantly reduce the error.

The reduction in error at each split is compared to the error that existed before the split was made. For example, if our first node is still rainfall below or above 30 inches, this will separate our data into two groups: more and less than 30 inches of rainfall. Each of these groups will have an average turbidity and this will be compared to the average turbidity that we had before the split, in other words the average turbidity of the entire dataset. If the new predictions (after the split) result in smaller errors on average, then this split is considered to have reduced the error. This process is repeated at every split in each decision tree. The feature that consistently contributes to significant reductions in error across many splits and trees is considered more important. The total reduction in error attributed to each feature is summed up and averaged across all the trees in the forest to determine the overall feature importance.

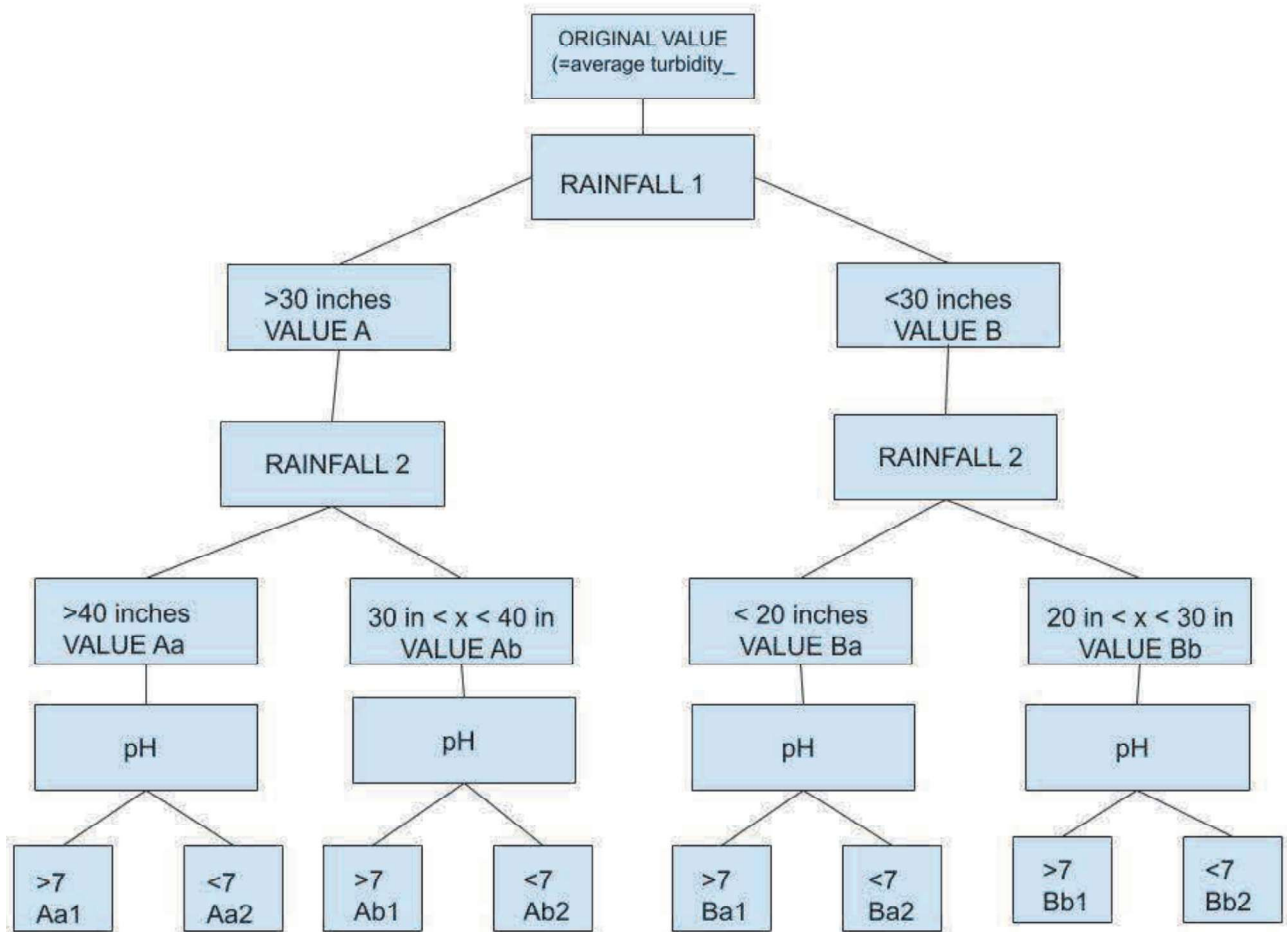


Figure 25 – Example of a part of a decision tree for turbidity

Above is an example of a decision tree for turbidity. Here, the features considered are rainfall (split into subcategories twice) and pH. A collection of these creates a random forest.

The data is divided between the training data and the testing data. The training data allows the random forest model to determine the relative importance of the factors and learn to predict accurately. Meanwhile the testing data is data that has been previously unseen by the model and tests the model to see if its predictions are accurate.

Each one of the decision trees is “trained” with a different subset of the data. Each of the data points are sampled with replacement. In other words, after a data point is selected from the original dataset to be part of a sample, it is “replaced” back into the dataset and can be chosen again. This means that the same data point can appear multiple times in the same sample. This technique is called “bagging”. Also, every decision tree does not consider every single one of the variables: the ones considered are chosen randomly. This reduces correlation between the trees of the forest and makes for more accurate predictions.

By averaging the predictions of multiple trees, Random Forest reduces the risk of overfitting compared to a single decision tree, which may become too complex and fit the training data too closely. Overfitting is a common problem in machine learning where a model learns the training data too well, capturing noise and details that are specific to the training data rather than general patterns that would apply to new, unseen data. As a result, the model performs very well on the training data but poorly on new data, as it has essentially “memorized” the training data instead of learning to generalize.

3.4.2 Application

I would have liked to run multiple tests on different target variables but a random forest model requires a lot of data and I did not have enough for FIB and HS-IBI.

Multiple tests were run on the data with different hyperparameters and features for turbidity. Most were done with a 70/30 split (70% of the data used to train the model, 30% to test it).

Model 1 : with historical events

The first test considered historical events (the 2018 floods, landslides, etc) and thus one of the distinctions in the data was “pre-2018” and “post-2018”, as well as “pre-landslide” and “post-landslide” (as seen in the Waipā Stream Restoration Timeline).

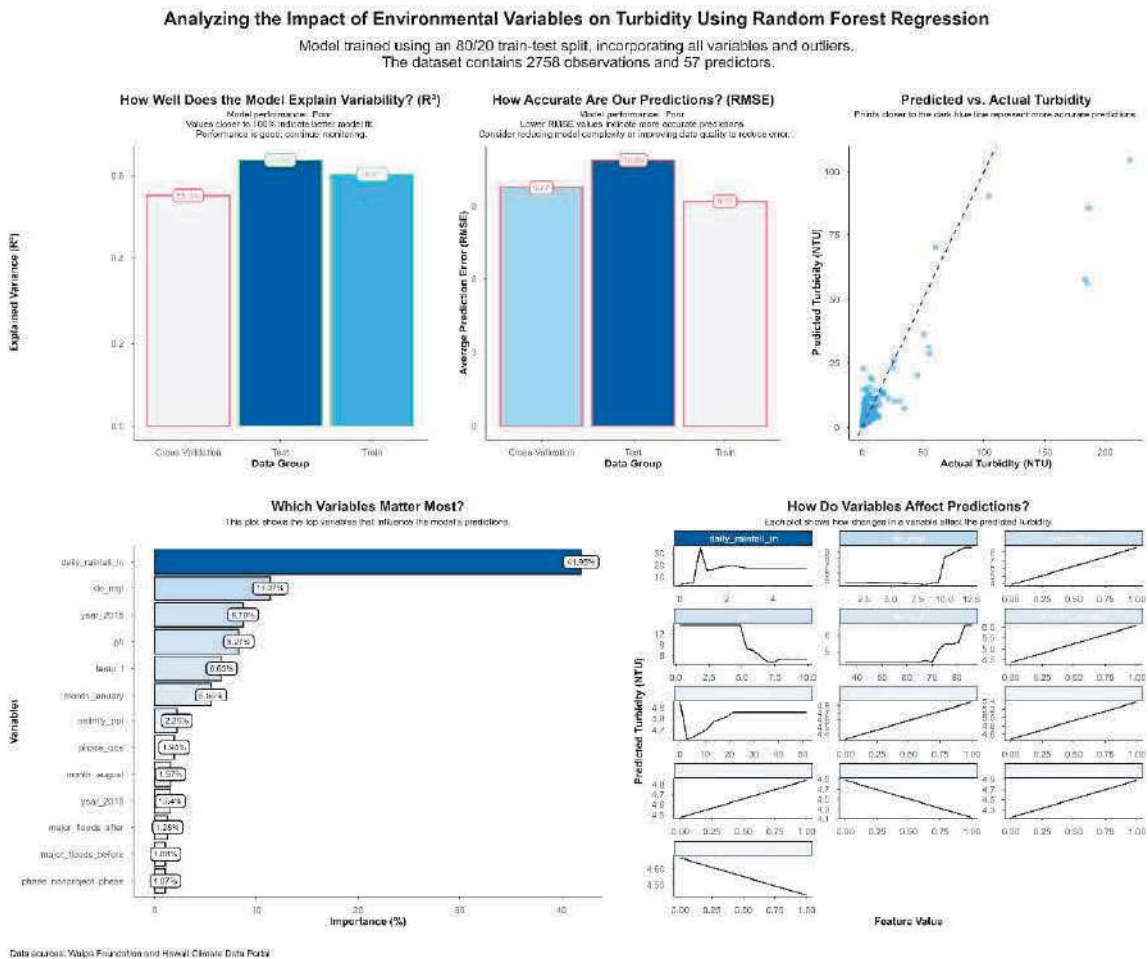


Figure 26 – Random Forest result considering ALL variables

We can see that the main factor having an influence on turbidity is rainfall. It is followed by dissolved oxygen and specific years like 2016. Other variables such as pH, temperature, and seasonal/monthly factors also play significant roles.

Indeed, the R^2 values show that while the linear model only explained about 30% of the turbidity, this one explains over 50% :

- R^2 Cross-Validation: $R^2 = 53.3\%$
- R^2 Test Data: $R^2 = 53.5\%$
- R^2 Train Data: $R^2 = 60.4\%$

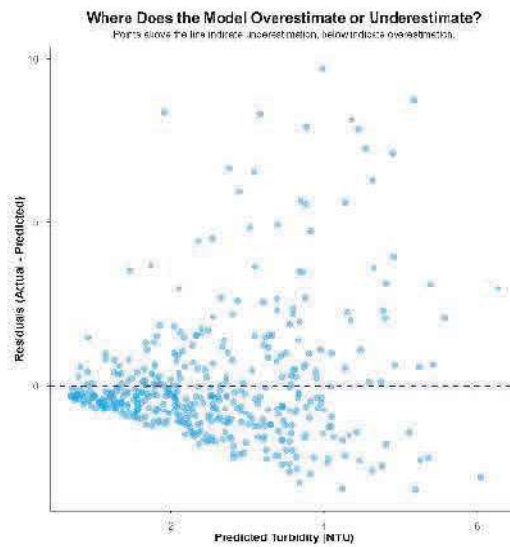
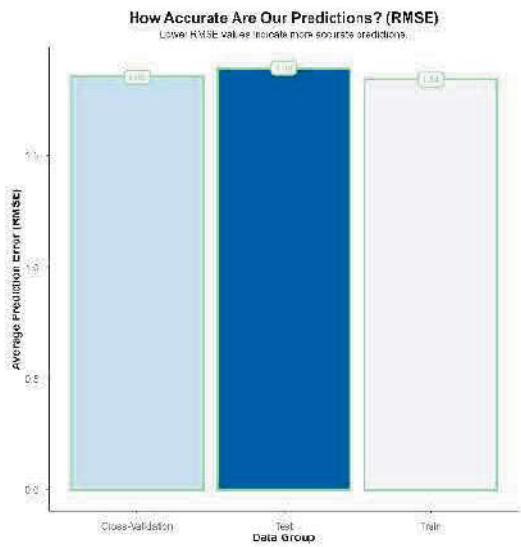
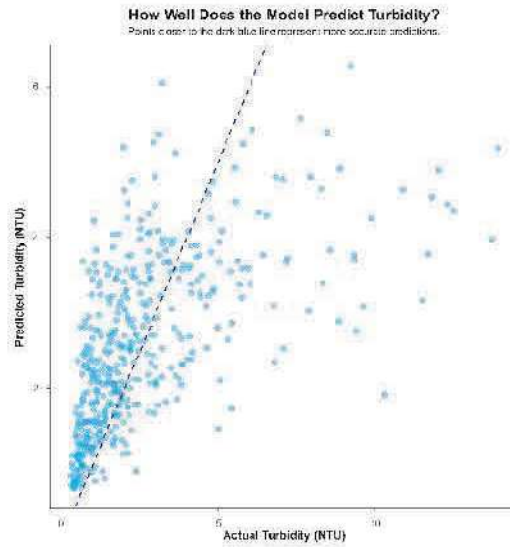
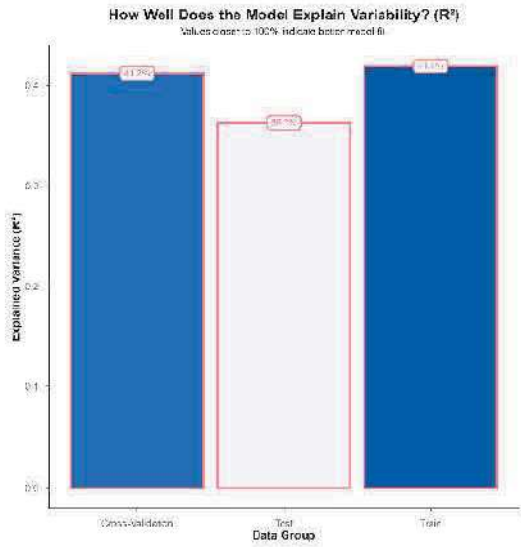
The R^2 values indicate that the model explains about half of the variance in turbidity. The similar R^2 for cross-validation and test data suggests that the model generalizes well, though there might be room for improvement, as indicated by the relatively low values. This model explains more of the turbidity than the linear regression model.

Model 2 : without historical events

Another model used exclusively the same parameters as the ones obtained with the linear regression, to compare the two models more accurately. When removing all other variables, we get the following results:

Analyzing the Impact of Environmental Variables on Turbidity Using Random Forest

Model trained using an 80/20 train-test split without outliers. Encoded year and season and removed major event variables. The dataset contains 2396 observations and 17 predictors.



Data sources: Waikato Foundation and Hawaii Climate Data Portal

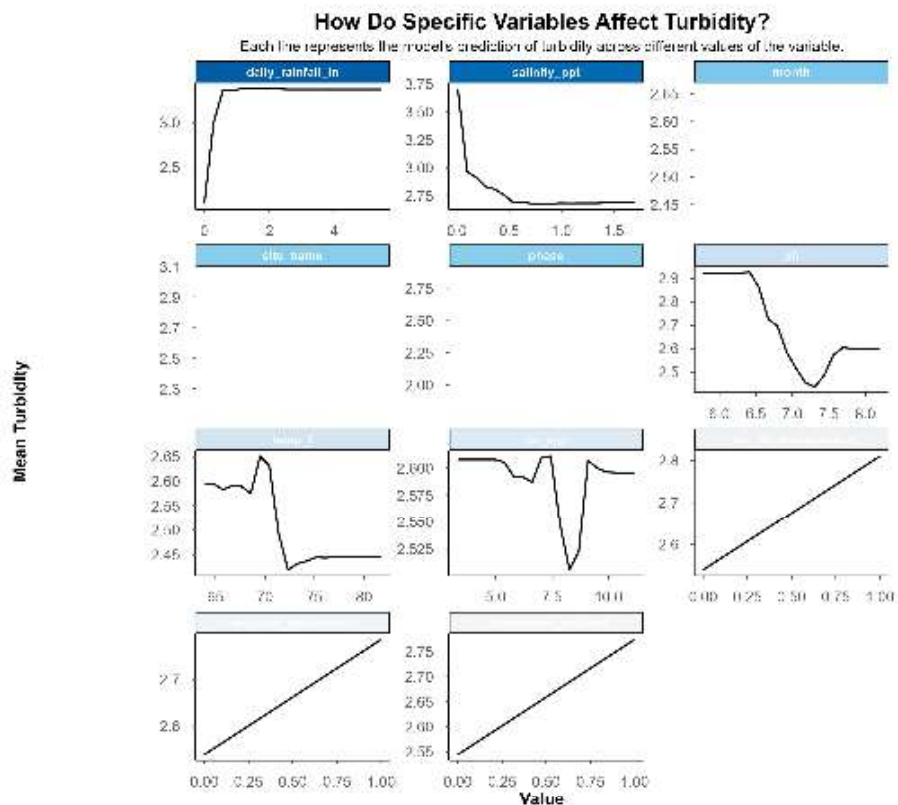
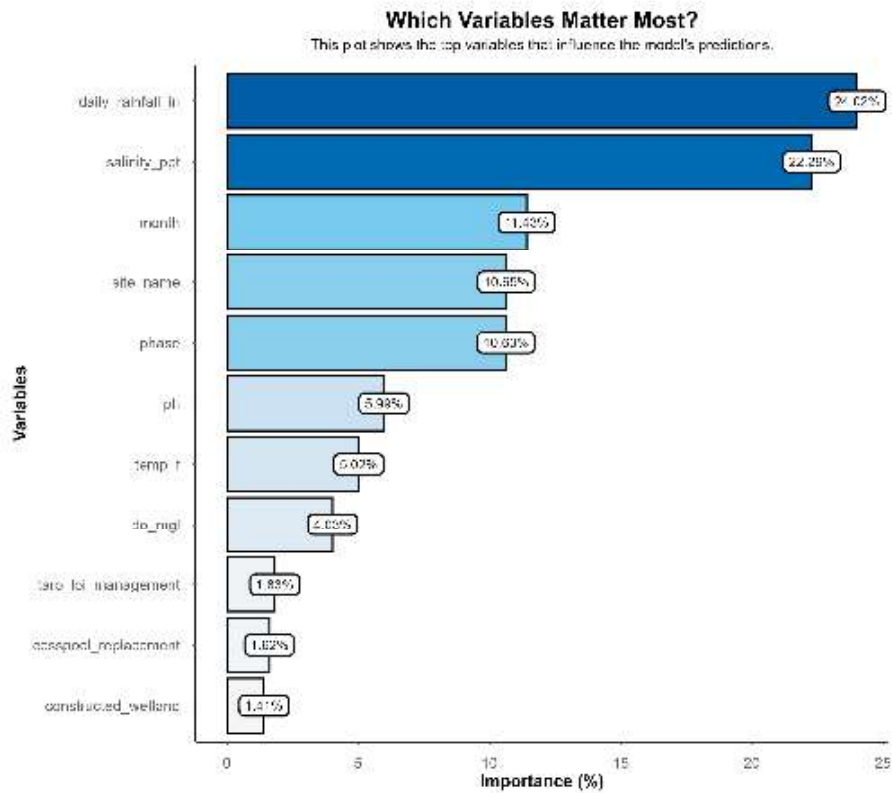


Figure 27 – Random Forest only considering quantitative parameters

- **R² Cross-Validation:** R² = 41.7%
- **R² Test Data:** R² = 50.2%
- **R² Train Data:** R² = 47.1%

The R² values suggest that the model explains around 42-50% of the variance in turbidity. These values indicate a moderate ability of the model to capture the underlying patterns in the data. The relatively close R² values between cross-validation, test, and train data indicate that the model is consistent and not overly prone to overfitting, but there's still a significant portion of unexplained variance.

This Random Forest model provides insights into how environmental variables influence turbidity. Daily rainfall and salinity are the dominant factors, significantly impacting turbidity levels. The model captures some of the variability in turbidity but leaves a substantial amount unexplained, as indicated by the R² values. The predictions are fairly accurate, but the model tends to underestimate higher turbidity levels.

We notice that these results are different from the ones obtained with the linear model. This can be explained by the fact that Random Forest can capture more complex, nonlinear relationships and interactions, which might lead to different (and sometimes more accurate) predictions compared to linear regression. However, this flexibility comes at the cost of interpretability. On the other hand, linear regression offers simplicity and interpretability but may fail to capture more complex patterns in the data. This is shown by the fact that the patterns comparing rainfall and turbidity in the bottom right corner of the image are rarely linear.

4. Discussion

4.1 Strong points of the study

I believe that one of the strongest points of this study is the combination of Hawaiian knowledge and Western knowledge. Indeed, one of the essential objectives lies in the consideration and consultation of the locals when elaborating and implementing BMPs.

It is essential to come in with an open mind and not rush in to try to “convert” the local communities with the Western way of doing things. Indeed, they often have their own reasons for managing the land the way that they do, which has been perfected over generations to be most adapted to the specific area. It takes many years of learning the traditional ways and forming a bond with the local communities before having the legitimacy to be able to make suggestions.

For this reason, one of the main things that I appreciated in the methods used was the efforts to include the local communities in all of the decision-making process, every step of the way. This allows us to determine what the objectives should be and figure out ways to make them happen. Indeed, the knowledge of the Hawaiian communities is extremely useful when dealing with environmental projects.

In the same vein, the study adopts a holistic approach by considering multiple facets of ecosystem health, including biological, chemical, and physical parameters. This comprehensive view ensures that the restoration efforts address not only the symptoms but also the root

causes of environmental degradation. The study focuses on the principles of resilience and sustainability, emphasizing the importance of long-term ecosystem health and the need to adapt management practices based on ongoing monitoring and feedback. This approach is critical for addressing the complexities of environmental restoration.

Another one of the strong points of this study is being able to study a project that is so many years in the making. It has been great being able to analyze more than ten years' worth of data to be able to really determine the changes implemented by the Waipā Foundation.

4.2 Limits

One of the main difficulties in this study is the complexity of the system. We are not dealing with a closed system with controlled experimental conditions allowing us to keep every variable stable besides the one we are targeting. The stream and its measures are subject to the elements, to landslides, to variations in temperature, to unexpected punctual runoff... proving causality in this case is extremely difficult. Moreover, all the BMPs have an impact on multiple variables as it is all quite interconnected. When we observe a variation in one of the parameters measures, not only is it difficult to prove its link to the stream restoration project, but also to prove which of the BMPs it can be attributed to.

One thing that could perhaps make this easier to prove is to choose to measure variables that are impacted mostly by a single BMP. For instance, soil compaction can be measured, and a decrease can likely be associated to feral hog removal and to the livestock exclusion fencing. Assuming that at this point of the project, all of the livestock is already fenced in and unable to roam free, the variations in this factor can be attributed for the most part to feral hog removal.

Another element that contributed to the difficulty in proving the effectiveness of the project is that some of the measures began after the start of the project, making it impossible to have a Before and After comparison. One of the things that made the study of the fecal-indicator bacteria so difficult is that I only had data from after 2017. The last day of my internship I was sent some measures of *Enterococcus* dated to 2013, which I was not aware existed, but by then it was a bit too late to figure out what I could do with it. I do wish it could have been sent to me sooner, but I am not sure that I would have been able to make that much of it seeing as I did not have the data from 2014-2017, meaning I could not make an uninterrupted timeline of it. This also means I would have had less data to use to study the "before" phase, making proving significance in the differences more difficult when running statistical tests.

I also ran most of my data analysis for fecal-indicator bacteria on *Enterococcus*. This is because it is the main bacteria that is used to determine the health of streams: the legal criteria to deem a stream as "healthy", the Hawai'i water quality standards, provides the maximum levels of *Enterococcus* that can be found in a stream or river and still consider it safe to swim and fish in.

However, studies have shown that *Enterococcus* is not in fact the greatest indicator of stream cleanliness. While *Enterococcus* is found in fecal matter it can also be found in sediment and

streambank soil along the nearby Hanalei River. This means that a stream that is not in contact with sewage can also have Enterococcus bacteria in it, making it an unreliable way to determine whether a stream is subject to an overflow of cesspools or other sources of human and animal feces. Looking back now, I feel that I should have done more research on the nature of Enterococcus and perhaps have performed more statistical tests on Clostridium Perfringes, though it would not have allowed me to determine if the stream restoration project allowed the stream to comply to Hawai'i water quality standards. [22]

I think it would have been nice to study more parameters, particularly those indicating stream health. For instance, some other variables that could be measured are nutrient levels, as they can lead to eutrophication, biological oxygen demand, algal blooms... Indeed, the only target variables that I used to determine the health of the stream were the populations of fecal-indicator bacteria, turbidity, and the biodiversity index (and in the case of the biodiversity index, given that there only 12 measures, the statistical tests did not allow me to prove the efficiency of the stream restoration project on biodiversity).

Indeed, more frequent measures of the biodiversity index would have been very beneficial as it is an excellent indicator of stream health. Twelve measures are not enough to go on to prove causality, but I also understand the difficulty in measuring the HS-IBI. It requires quantifying species diversity within a given area, using metrics that consider both the number of species (richness) and the relative abundance of each species (evenness). This certainly takes a lot more time and resources than a pH measures. For my research however this was a limiting factor.

Finally, the study was also limited by the lack of control groups on different levels of the nearby stream. It is interesting to compare the Waipā Stream, upon which the stream restoration efforts have been implemented, to the nearby streams of Waikoko and Waioli. However, while there are many gages and monitoring sites along the Waipā Stream, the only ones whose data we have access to on the Waikoko and Waioli streams are located right at the estuary. This means that while we have good sites for comparison between the estuary of the Waipā Stream (Muliwai) and other estuaries that were not impacted by the stream restoration project, but not for the sites higher upstream. Indeed, as shown in the Exploratory research part of the report, the conditions along the course of the stream are quite different, particularly for temperature and salinity. Comparing the parameters at Stream gage, located in the mountains, to the Waikoko stream mouth would be nonsensical. It would have been good to have the data for multiple sites along the stream to compare the variables of the Waipā stream's monitoring points in the mountains to Waikoko and Waioli's monitoring points in the mountains. I did express this to the Waipā Foundation and was informed that the other foundations in charge of the upkeep and monitoring of Waikoko and Waioli were unwilling to share their data, and that getting the information that they did have now had been quite a struggle already.

4.3 Comparison with other NBS in the world

Having become more prominent in recent years, nature-based solutions have been implemented all over the world.

Mangroves in Mexico, the Bahamas and Florida

An example of this is the use of mangroves for flood mitigation in Mexico, Florida and the Bahamas. Mangroves often serve as a first line of coastal defense during tropical storms. They have been shown to reduce wave height up to 66% over the first 100 meters of forest thanks to the roots, trunk, and canopy that dissipate wave energy and slow storm surge penetration. Also, mangroves have been shown to reduce erosion thanks to their deep root systems stabilizing the soil. These mangroves have provided more than \$17 billion in flood protection benefits.

Like the ecosystem in the Waipā region, mangroves serve a variety of purposes, both cultural and ecological. These range from fishing grounds, carbon storage, habitat for multiple species of animals to flood mitigation. [23]

One of the key differences between the Waipā stream restoration project and the mangroves in Mexico, Florida and the Bahamas is that mangroves are removed in Waipā. Indeed, while they must be protected in other parts of the world (between 1980 and 2005 alone, nearly 20% of global mangrove cover was lost due to direct and indirect impacts of human activities), they are considered invasive in Hawai'i.

Room for the River in the Netherlands

Another example of nature-based solutions is the Room for the River project in the Netherlands.

This program was created by the Dutch government due to the inability of traditional solutions such as relying solely on dikes and levees to combat the increasingly frequent and severe river flooding. Nature-based solutions were implemented: by giving rivers more space to flood freely, the floods and their impact on the surrounding communities are minimized. Also, in some areas, dikes were moved further inland to create more space for the river to expand during floods. Much like in the Waipā Stream Restoration project, floodplains and wetlands were restored to absorb more of the floods. This improved the habitat of local species and increased biodiversity. Again, like the Waipā stream restoration project, the program encouraged more sustainable land use practices, integrating agriculture, recreation, and nature conservation.

One of the main differences between the two projects lies in the scale. While Waipā's stream restoration project focuses on a small ahapua'a, Room for the River takes place along multiple rivers across the Netherlands. [24]

4.4 Perspectives

This study has allowed me to prove the efficacy of the stream restoration project on some of the variables. For instance, my data analysis showing the clear decrease in turbidity between Phase 1 and Phase 2 of the project will be featured on the Waipā Foundation's page. I hope that this concrete, quantitative proof will enable the Waipā Foundation to receive more grants and funding in the future so that they can continue the restoration efforts.

I have also shared my recommendations for the project and the monitoring with the Waipā Foundation and hope that these suggestions can be taken into consideration to improve the monitoring of the water quality, by integrating more measures, whether it be new types of measures or more frequent measures of the same things, such as the HS-IBI index.

In order to continue to influence the local communities, one of the things that would be beneficial would be the development of more educational programs and workshops for the local community, focusing on the importance of stream and ecosystem health, as well as the role of traditional Hawaiian practices in modern environmental management. More interest from the local communities would allow foundations like the Waipā Foundation to have more volunteers and to raise more awareness on the ecosystem challenges that are being faced in Waipā but also in the rest of Hawai'i.

I also hope that this project will inspire others to work with the local communities to preserve the environment in a way that benefits everyone and is respectful of everyone and their goals. I think that the collaboration between the Waipā Foundation and the University of Hawai'i is a wonderful model that should be recreated elsewhere in Hawai'i and any other places where traditional knowledge is still present. Applying similar nature-based solutions (NBS) to other streams or watersheds across Hawai'i and the Pacific Islands would be extremely beneficial to these areas. The successes at Waipā can serve as a model for other regions facing similar environmental challenges. The methodologies and lessons learned can be adapted to other contexts, with a focus on scalability and replicability.

5. Conclusion

The Waipā Stream Restoration Project has provided a comprehensive and insightful exploration into the application of nature-based solutions (NBS) for stream and ecosystem restoration. Over the course of this project, several Best Management Practices (BMPs) were implemented, including cesspool replacements, feral ungulate removal, stream restoration, constructed wetlands, livestock exclusion fencing, and upland erosion control. These interventions were designed to address key environmental challenges such as invasive species, water quality degradation, and flood risks, while also aiming to enhance the overall resilience of the Waipā ahupua'a.

The project's outcomes, as evidenced by the extensive data analysis, reflect both successes and areas for further improvement. One of the significant achievements of the restoration efforts was the observed decrease in turbidity levels, particularly in areas directly impacted by the stream restoration activities. The one-way ANOVA analysis confirmed that these reductions in turbidity were statistically significant, indicating that the BMPs implemented by the Waipā

Foundation have had a positive impact on stream water clarity. This is a crucial finding, as turbidity directly affects the health of aquatic ecosystems, influencing factors such as light penetration and the habitat suitability for various species.

Furthermore, the project successfully reduced the levels of Enterococcus bacteria in the stream, which is indicative of improved water quality and reduced contamination from fecal matter. The two-way ANOVA analysis highlighted that both the project phase and rainfall significantly influenced Enterococcus levels, suggesting that while the restoration efforts contributed to these improvements, external environmental factors such as rainfall also played a critical role. This underscores the complexity of ecosystem management, where multiple interacting variables must be considered to fully understand and predict outcomes.

However, the results also pointed to challenges and areas requiring ongoing attention. For instance, despite the efforts to improve biodiversity, the HS-IBI index, which serves as a key indicator of stream health, did not show significant improvement over the course of the project. This suggests that while water quality may have improved, the biological responses of the ecosystem may require more time or additional interventions to show measurable changes. The lack of significant changes in biodiversity could also be attributed to the limited sample size or the need for more frequent monitoring to capture the subtleties of ecosystem recovery.

The correlation analysis and the subsequent regression modeling further revealed the intricate relationships between various environmental parameters, such as temperature, salinity, and dissolved oxygen, and their impact on biodiversity. The high R^2 value in the regression model suggests that the selected parameters were strong predictors of the HS-IBI index. However, the presence of multicollinearity between these variables indicated that the interpretation of their individual effects should be approached with caution, and further research is needed to disentangle these complex interactions.

One of the standout aspects of the project was the integration of local community input through systems mapping and participatory approaches. This not only ensured that the restoration activities were culturally appropriate and aligned with the community's values but also enhanced the legitimacy and sustainability of the interventions. The use of collaborative visualization and community feedback helped to refine the project's objectives and adapt the strategies to better meet local needs.

In conclusion, the Waipā Stream Restoration Project illustrates the potential of nature-based solutions to address both ecological and societal challenges. The project's successes in improving water quality and engaging the community are commendable, yet the findings also highlight the need for a continued and adaptive management approach. Future restoration efforts should build on these insights, focusing on enhancing biodiversity, addressing the underlying causes of environmental stressors, and maintaining strong community involvement. By doing so, the Waipā Foundation can continue to contribute to the resilience and sustainability of the Waipā ahupua'a, serving as a model for similar initiatives in Hawai'i and beyond.

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Annex



Waipā Stream Restoration Project

The Waipā Stream Restoration Project initiated to address overgrowth of Hau Bush and other invasive vegetation in the Waipā Stream corridor that was aggravating flooding and degrading habitat for native stream life. A holistic approach was implemented to manage and control this invasive overgrowth while providing mutual benefits of improved drainage, flood mitigation, water quality enhancement, and ecosystem restoration. In over 12 years, all of these objectives were achieved to an extent, but there is still much work to be done to perpetuate this success and build from it to achieve greater goals at Waipā and beyond.

WAIPĀ FOUNDATION

Waipā Foundation's mission is to restore Waipā's vibrant natural systems and resources and inspire healthy, thriving communities connected to their resources, and lead by example.



In accordance with its mission, the Foundation's core goals are to restore the deep connection between people and the land through experiential learning; to preserve and perpetuate Hawaiian culture, knowledge, values, and language through practice; to implement programs focused on culture, enrichment, education, and leadership to foster social, economic and environmental resiliency in the management of Waipā's natural and cultural resources.

Waipā Coastline Erosion Project

This project will address ongoing coastal erosion and degradation of aquatic habitats of the Waipā coastline and reef system through nature-based solutions. We envision a project that assesses current and ongoing shoreline erosion at the project site, and after consultations with coastal process experts, a plan will be developed to transition the coastal strand on the project property from a plant community dominated by invasive vegetation to a native and cultural plant regime that allows for sand dune restoration to naturally occur. Our team is particularly interested in assessing how ongoing watershed management practices impact the nearshore coral reef habitats and health of Hanalei Bay.



PROJECT GOALS

The aim of our project is to support local communities doing ecosystem restoration to evaluate the performance of the activities as climate adaptation measures. Our work is funded by PacRISA, a NOAA Climate Adaptation Program project.



We are working with the Waipā Foundation towards a better understanding of the mechanisms linking different parts of the ecosystem from mauka to makai, in order to use this knowledge as the basis of the restoration efforts in the area.



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SYSTEMS MAP

QUESTIONS

CONNECTION TO PLACE

1. Can you describe your connection to Waipā (the 'āina, kai, and mauka)?
2. With which part(s) of the Waipā ahupua' ecosystem (resources, areas) do you feel needs to be protected and cared for?
3. What are the most significant elements of the ridge-to-reef ecosystem that should be prioritized in ecosystem-management projects?

SOLUTIONS

6. Throughout Hawai'i, are there any existing community-led initiatives or projects related to the mauka to makai ecosystem that you believe are successful or worth replicating?
7. What traditional knowledge or practices do you believe are essential for maintaining the health of the ahupua'a (ridge to reef ecosystem)?

CHALLENGES

4. What do you think are the main challenges or threats facing the Waipā mauka to makai ecosystem?
5. What are the main changes that you have observed in the mauka to makai ecosystem over time, and what do you think are some of the reasons for these changes?

SYSTEMS MAP

8. What would you add or change about this system map? Do you feel that some elements are missing?
9. With which of the elements on the systems map do you find the most important personally feel pilina and can you describe it?
10. Are you interested in engaging more with Waipā's Coastal Resilience Project?