BACTERIAL POLLUTION SOURCING AND OCEANIC TRANSPORT ON THE SOUTH SHORE OF KAUA'I

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

THESIS ADVISOR

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Dr. James Potemra
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For my Papa.

ACKNOWLEDGMENTS

This project would not have been possible without the help of my family and friends who have continuously supported me throughout my time at the University of Hawai'i at Manoa. I would also like to thank my thesis advisor, Dr. Jim Potemra, for dedicating his time and energy to guide me through the completion of this project. I wish to also thank Dr. Carl Berg from Surfrider Foundation for offering his advice and insights on the water quality issues observed during the study. I'd like to extend my thanks to Dr. Michael Guidry and Dr. Margaret McManus, my academic advisors, for their help in keeping me on track each semester. I'd also like to thank Dr. Marek Kirs for taking the time to review my thesis, as well as the GES office staff and many other GES faculty members for their assistance with many various matters over the years.

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ABSTRACT

Water quality problems have been plaguing the south shores on the island of Kaua'i in recent years. In the past, issues with water quality have been attributed to agricultural runoff and sedimentation. This study serves to verify past findings by analyzing data provided by water testing completed by volunteers from the Blue Water Task Force established by the Kaua'i Chapter of the Surfrider Foundation. In order to accomplish this goal, we determined the extent of bacterial pollution at each of the sites included in the study and identified individual cases of high bacteria levels. Time series of enterobacteria collected at nine sites along the south shore of Kaua'i show no clear seasonality but rather are marked by seemingly sporadic extreme events. We then coaligned the enterobacteria dataset with precipitation, near-shore currents and wave activity. These datasets were coaligned in order to look for possible correlations. Ultimately, no correlations were found which suggest that the water quality issues that have been observed cannot be accredited to local precipitation or near-shore oceanographic processes. Instead these pollution problems may be driven by irrigation runoff, sewage leaks, or a number of other local drivers. Further research and monitoring will be necessary to continue to provide the public with accurate information regarding the quality of their recreational waters.

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1.0 INTRODUCTION

1.1 Background

Life on Earth would cease to exist without water, but the overall quality of water plays a major role in determining how useful this resource actually is. Although it is estimated that 71 percent of the surface of the Earth is covered by water (Perlman, 2016), global water security has become progressively jeopardized due to water pollution, lack of sanitization, faulty infrastructure, and many other components (Pacific Institute, 2013). A water pollutant can be classified as a "physical, chemical, or biological factor causing aesthetic or detrimental effects on aquatic life and on those who consume the water" (Goel, 2006). Since clean water is a vital component for human life and health, economic systems, and ecosystem functionality, improving coastal water quality has become an increasingly important focus of conservation efforts around the world.

Surfrider Foundation is one of the many organizations that have dedicated their time and efforts to enhance the quality of water for both recreational and functional purposes. Surfrider is a non-profit organization that functions at local, regional, and national levels, relying on the joint efforts of local activists and environmental experts to reach a common goal: protecting our oceans and beaches. While this goal may seem broad, Surfrider associates plan to achieve this goal by focusing on five main factors: 1) beach access, 2) ocean protection, 3) coastal preservation, 4) plastic pollution, and 5) clean water. Through the efforts put forth by the Surfrider Foundation, it became obvious that there have been ongoing water quality disturbances on the south shore of Kauai in recent years. The purpose of this study is to establish the true extent of these water quality issues as well as determining the source of the fecal pollution that has been recorded.

Since all the observation sites are in the near-shore (beach) , spikes in bacterial counts were hypothesized to be due to a variety of factors, including local precipitation, flooding and runoff, near-shore ocean circulation, wave activity and winds. In the past, it has been determined that water quality issues on Kaua'i were caused by agricultural runoff and sediments (El-Swaify, 1999) and since agriculture is still a large part of life on Kaua'i, this study will analyse precipitation data as a means of bacterial input to our study sites that have recorded bacteria levels well over the regulations established by the United States Environmental Protection Agency (EPA).

In 2015, the United States EPA updated the Recreational Water Quality Criteria that offered a basis for establishing water quality standards in the State of Hawai'i (Department of Health, 2014). These regulations were established and updated in support of the Clean Water Act, amended in 1972. The 2015 update sets water quality criteria with the purpose of protecting the public from "exposure to harmful levels of pathogens" (Department of Health, 2014). These water quality standards are based on levels of enterococci bacteria contamination. Enterococci bacteria are a type of bacteria found in human and animal feces and indicate the presence of fecal bacteria in aquatic environments (Surfrider Foundation, 2018). Fecal indicating bacteria (FIB) are used to identify bacteria that can cause infections and other illnesses for those that come into contact with them. Therefore, regulations for recreational water-use require that enterococci concentrations do not exceed a geometric mean of 35 Colony Forming Units (CFUs) per one hundred milliliters over a thirty day period (DOH, 2014). Enterococci content may also be measured in terms of the Most Probable Number (MPN). CFU and MPN units are based on two different sample collection methods and an experiment was conducted to evaluate the relationship between both methods. The experiment ultimately determined that there is a positive correlation between CFU and MPN units, although MPN measurements are typically higher than those calculated by CFU (Cho et al., 2010).

The Clean Water Initiative created by Surfrider Foundation includes a program entitled Blue Water Task Force (BWTF) which is a volunteer-operated water quality monitoring and advocacy program. BWTF has water quality testing laboratories across the United States and U.S. Territories, including three located in the main Hawaiian Islands. The Surfrider Chapter located on the island of Kaua'i samples 22 surf spots, beaches, and stream mouths on a monthly basis, five of which have displayed chronic levels of bacterial pollution in recent years. Since determining the chronic levels of pollution at these Kauai beaches, Surfrider Foundation has been an advocate for the display of proper warning signs and taking preventative action.

1.2 Area Description

1.2.1 Island History

Formed approximately 5.1 million years ago, the island of Kaua'i is the oldest of the Main Hawaiian Islands. The island was formed from magma spilling out of the Hawaiian hotspot and through the Pacific Plate. The life cycle of Hawaiian volcanoes includes various stages including: an initial alkaline, a pre-shield stage, a shield stage, a second alkaline and postshield stage, and a rejuvenated stage. The island of Kaua'i currently consists of lavas from the shield, postshield, and rejuvenated stages (Cousens & Clague, 2015). Along with various forms of lava, Kaua'i also exhibits ten of the twelve soils orders due to the age of the island and an extensive exposure to conditions causing weathering (Deenik & McClellan, 2007). While there are ten soil orders present on Kaua'i, Table 1.1 shows that the island is largely composed of Oxisols, Mollisols, and Inceptisols.

Table 1.1 Total coverage of each soil order (in acres) on Kaua'i (Deenik & McClellan, 2007).

Soil order	*Kaua'i*
Andisol	14,499
Aridisol	4,616
Entisol	4,093
Histosol	6095
Inceptisol	21,307
Mollisol	24,867
Oxisol	76,638
Spodosol	4105
Ultisol	14,381
Vertisol	3,069

Each of the soil orders found in Kaua'i have unique physical and chemical properties that affect the stability and productivity of the soil. Oxisols, for example, are extremely weathered soils that are usually infertile. Oxisols are especially infertile in areas that receive high amounts of rainfall, such as the windward coast of Kaua'i. Due to the high level of infertility of Oxisols, the application of fertilizers is necessary to increase soil productivity. Inceptisol soils are normally quite productive, but tend to be more acidic when found in older and wetter landscapes (Deenik & McClellan, 2007). Inceptisols found in wetland landscapes were desired for the development of taro lo'i, while the more acidic inceptisols were used to produce pineapples.

Fertilization of inceptisol soils is necessary in order to produce crops that are intolerant of high levels of acidity (Deenik & McClellan, 2007). Out of the three prominent soils found in Kaua'i, mollisols are the only order known to be highly productive due to its natural composition. Mollisols were used to support the early sugarcane industry in Kaua'i and are still used to produce other vegetable crops (Deenik & McClellan, 2007).

In addition to soils with the properties to support crop growth, Kaua'i (nicknamed the Garden Island) also has a 365 day growing season (Kaua'i Chamber of Commerce, 2012). Due to these conditions, agriculture has always been a crucial part of the economy on the Garden Island. The importance of the agriculture industry began in 1835 when Ladd and Company established the first cash profit sugarcane plantation in the Hawaiian Islands in Koloa, Kaua'i (Takaki, 2008). Following the Koloa Plantation, the Kilohana Plantation and Lihue Sugar Company were founded, along with seven other plantations on the island of Kaua'i and several others on neighboring islands (Saito & Campbell, 2004). Although sugarcane is no longer produced on Kaua'i in large scales, the establishment of these sugar plantations marked the beginning of a new generation of agriculture in the Hawaiian Islands.

Today, agriculture remains an essential component of the economy on Kaua'i. Local farmers now produce a wide variety of crops ranging from tropical plants and fruits to coffee beans and hardwoods (Kaua'i Chamber of Commerce, 2012). In order to establish proper land use management techniques, the State Land Use Law (Chapter 205, Hawai`i Revised Statutes) was created in 1961. This law requires that all land within the State of Hawai'i be classified as Agricultural, Conservation, Rural, or Urban (State of Hawaii Land Use Commission, 2018). According to the Land Use Commission, more than half of the island of Kaua'i is designated as agricultural and conservation land. Figure 1.1 shows the Land Use District Boundaries for the study site.

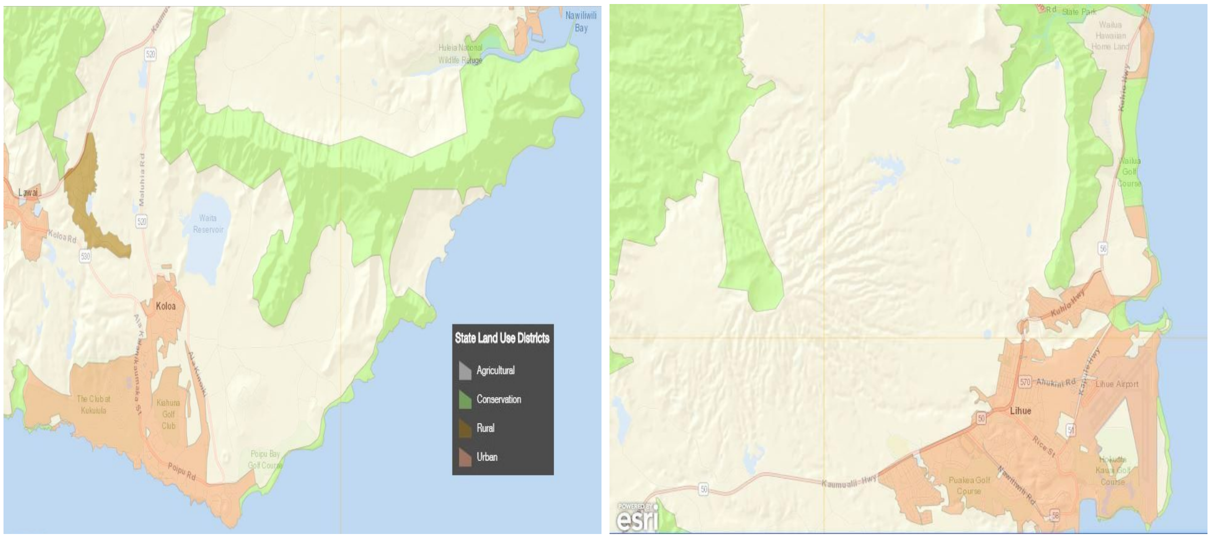

Figure 1.1 State of Hawaii Land Use District Boundaries Map for South/Southeast Kauai (HI State GIS, 2018). Grey indicates Agricultural districts, green indicates Conservation districts, brown indicates Rural districts, and red indicates urban districts.

Since agricultural lands occupy such a large portion of Kauai, water quality concerns in the past have been attributed to sediments and agricultural runoff in areas such as Hanapepe Bay, Nawiliwili Bay, and Waimea Bay (El-Swaify, 1999).

In recent years, water quality on Kaua'i has been jeopardized due to contamination by fecal bacteria, although the actual source of this fecal bacteria remains unidentified. If in fact, water quality has been affected by sediments and runoff, studies have shown that soils are the most likely source for naturally occuring fecal indicator bacteria (FIB) (Hardina & Fujioka, 1991). Based on the study accomplished by El-Swaify in 1999 in areas around the island of Kaua'i, this study will serve to validate that runoff has been a main source of fecal bacteria input to the South Kaua'i coast. The goal of this project will be achieved by using precipitation data as a proxy for runoff to determine correlations between runoff and bacterial contamination at the selected study sites.

1.2.2 Study Site Description

The study area for this project encompasses five sites that have shown chronic levels of FIB as well as neighboring sites that have showed various lower levels of bacteria concentrations. These sites are located on the south to south-east facing shores between the towns of Līhuʻe and Poʻipū. PK's Surf Spot (Site 1) and Hanamaulu Stream (Site 9) are 11.56 miles apart. Included in the study site is Mahaulepu, an area that has been under severe scrutiny after both locals and researchers have strongly expressed their opposition to a proposed industrial level dairy farm (Friends of Mahaulepu, 2017). Figure 1.2 displays a topographical map of the island of Kauai in which each of the nine study sites are marked by colored marks representing the number of high bacterial events (defined later in section 2.1.1) observed throughout the study period.

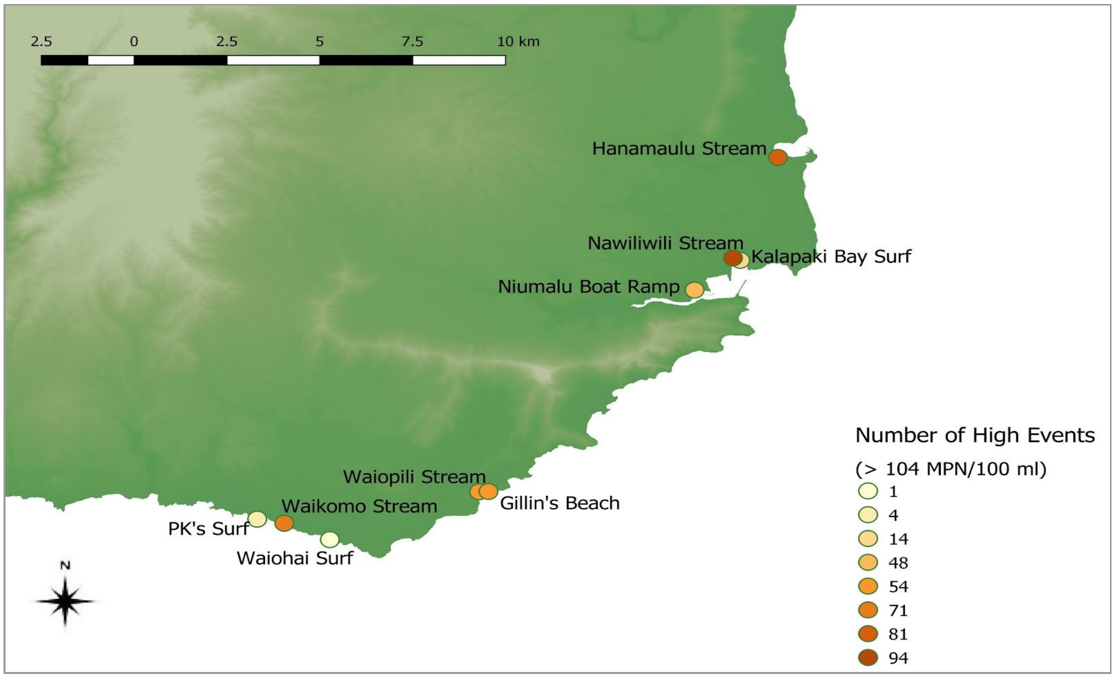

Figure 1.2 Study site locations on the island of Kaua'i categorized by observed number of medium (36-104 MPN/100 ml), and High (>104 MPN/100 ml) bacterial events.

The nine sites selected for this study are located along the windward shore of Kaua'i and are composed of six separate watersheds:Waikomo, Mahaulepu, Hanamaulu, Nawiliwili, Pu'ali, Hule'ia, and Mahaulepu (Parham et al., 2008). Windward Kaua'i receives a moderate amount of annual rainfall with areas ranging from 880 mm on the coast to 2000 mm towards the center of the island. Rainfall is typically higher along the coast from October to March, known as the "wet season" in Kaua'i. During the summer and early fall, rainfall tends to decrease along the coast (Giambelluca et al., 2013). Figure 1.3 shows mean annual rainfall for the study area.

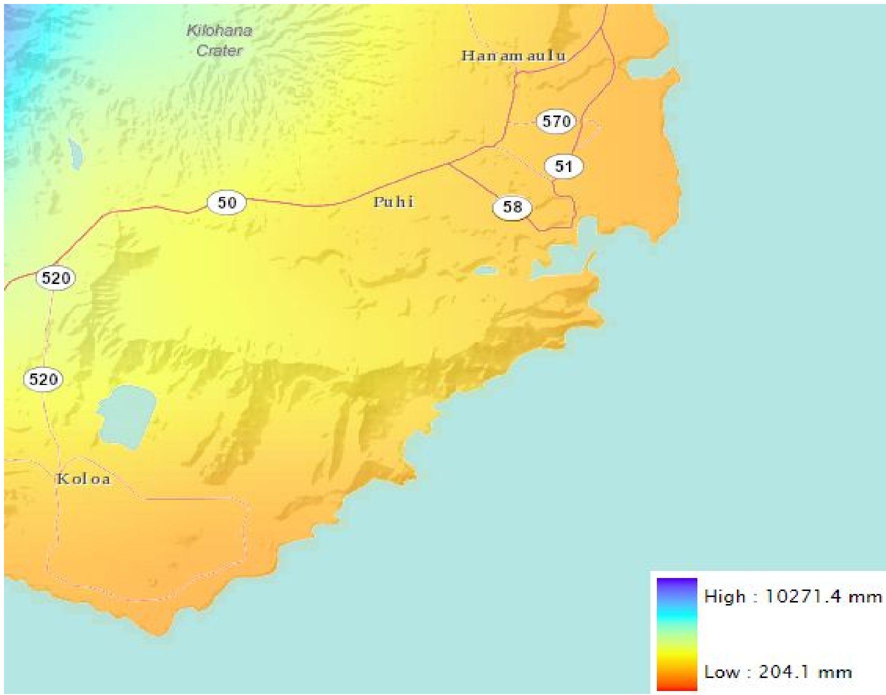

Figure 1.3 Mean annual rainfall in South Kaua'i (Rainfall Atlas of Hawai'i, 2011. UH).

Along with annual rainfall, the island of Kaua'i experiences year round wave activity. Wave patterns surrounding the island depend on seasonal changes and the presence of trade winds or Kona Storms. Winter storms in the South Pacific generate summer swells on the south shore. Kona Storms are storms generated to the southwest of the islands and occur during a small portion of the year. Northeast waves are generated by tradewinds consistently throughout the year. Wave activity was studied in order to observe the influence that waves have on flushing enterobacteria from coastal waters (Delpey et al., 2014). Seasonal wind and wave activity are represented schematically in Figure 1.4.

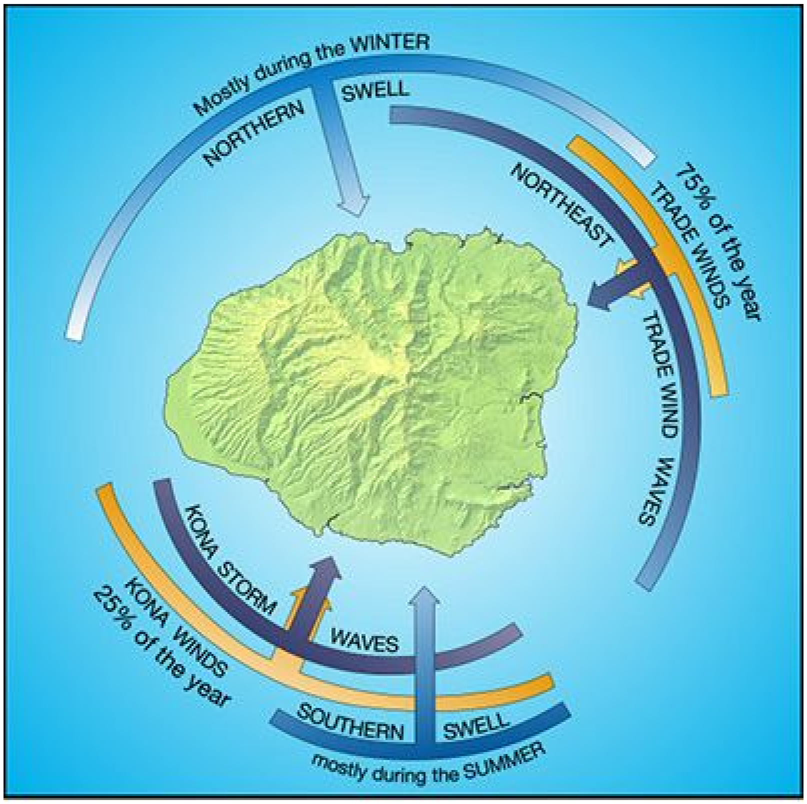

Figure 1.4 Kaua'i seasonal wave dynamics (Blay, 2013).

Due to a lack of direct observations, numerical model forecasts were used to analyze nearshore ocean currents and their potential role in transporting fecal bacteria along shore. Figure 1.5 depicts the velocity of oceanic currents the forecast model created by PacIOOS. Based on the model, currents typically travel up north towards the southernmost portion of the study area before diverging to the east and west near Waikomo Stream. These currents then continue to move northwards along the coastline, eventually continuing around the east coast to reach Kilauea on the north shore before converging with the western currents and travelling offshore. Since many of the chronically polluted sites are located on the northern end of the study area, it is possible that ocean currents are actively involved with the dispersal of bacteria and transporting this bacteria along shore. A better understanding of the properties and characteristics of enterobacteria will be necessary to ultimately determine whether or not ocean currents have an effect on the concentration of bacteria at various nearshore sites.

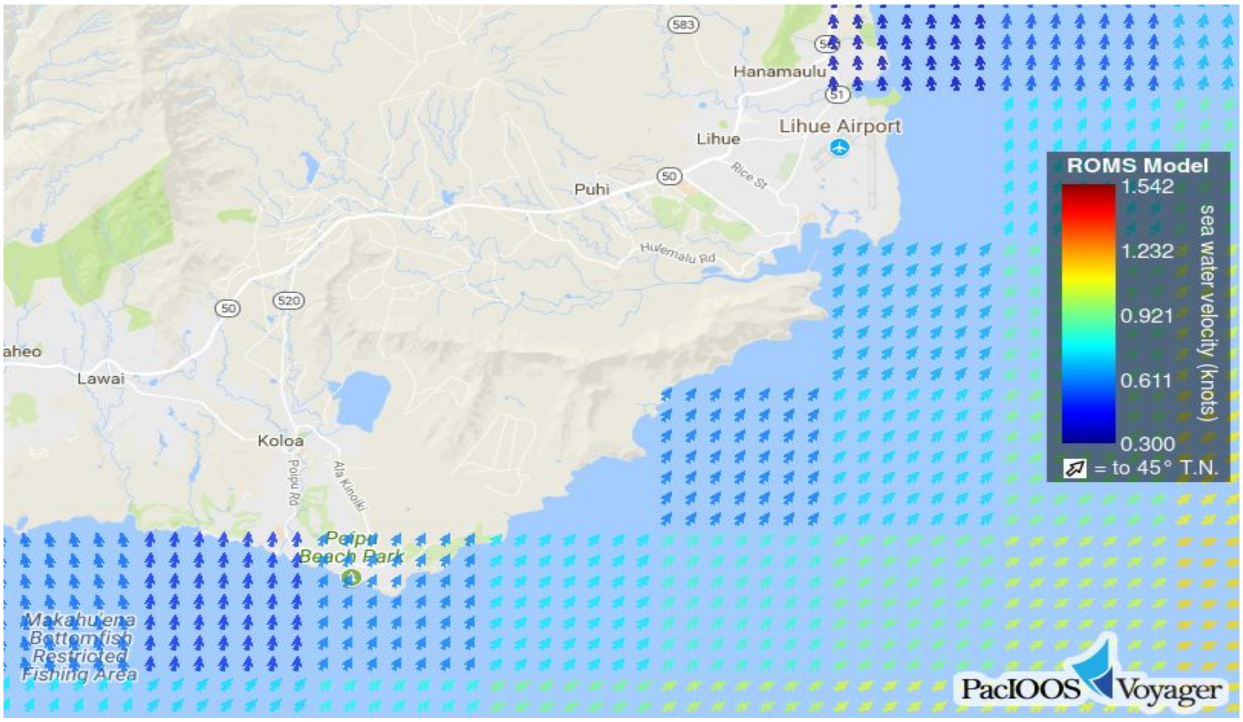

Figure 1.5 Example output from a computer generated simulation of the velocity of ocean current. Direction is given by the arrows and velocity is determined using the color legend (PacIOOS, 2018).

1.3 Project Objectives

The overall goal of this project is to examine water quality issues on the south shore of the island of Kaua'i by partnering with Surfrider Foundation's Blue Water Task Force program. First, the data were analyzed to understand the basic variability both in time and spatially. Next, a diagnostic study was performed that focused on certain geophysical parameters that possess the potential to impact water quality. In order to achieve this goal, the extent of the pollution issue at each site was determined through identifying individual events of high levels of bacterial contamination, assessing land-use patterns, establishing correlations between precipitation and nearshore wave activity, and observing nearshore oceanic circulation patterns as a dispersal mechanism for bacteria. New knowledge provided by this study will be especially useful as a tool for making informed decisions regarding development and land-use changes as well as for establishing a guideline for forecasting future water quality disturbances.

2.0 METHODS

2.1 Datasets

2.1.1 Site Selection and Sample Collection

Datasets for nine sites on the south and south-east shores of Kaua'i were selected for this study. The data were collected by the Blue Water Task Force Program of Surfrider Foundation and can be found online at the Blue Water Task Force Kauai Chapter website. Five sites were selected based on their history of chronic levels of enterococci bacteria, while four other sites were selected due to their close proximity to the contaminated sites. The sites consists of stream mouths, beaches, and popular surf spots.

The Blue Water Task Force conducts monthly sampling using Enterolert® (IDEXX Laboratories, Inc., Westbrook, ME) tests to measure bacteria levels in water samples from each site. Using this measurement method, bacterial counts are available within 24 hours of collection. Once the results were made available, samples were categorized by Low (0-35 MPN/100 ml), Medium (36-104 MPN/100 ml), and High (>104 MPN/100 ml) bacteria levels.

2.1.2 Precipitation Data

The precipitation dataset were obtained from a numerical model developed by the University of Hawai'i entitled "Weather Research and Forecasting (WRF) Regional Atmospheric Model: Main Hawaiian Islands" (Chen, 2010). Data can be found online using the ERDDAP data server published by the Pacific Islands Ocean Observing System (PacIOOS;

http://pacioos.org/erddap). The data encompass the entire range of the Hawaiian Islands, but data was only used for the latitude and longitude range of the study sites: 21.80 to 22.00 °N and 159.40 to 159.33 °W. Output from the model are made available as 7-day hourly forecasts at a 6 km resolution by Professor Yi-Leng Chen.

2.1.3 Wave Data

Numerical model output was also used to provide wave data for this study. Output from the University of Hawai'i "Simulating WAves Nearshore (SWAN) Regional Wave Model: Kauai" were obtained online using the same ERDDAP data server published by PacIOOS. Output are based on a regional wave model 7-day output with a 5-day hourly forecast for the island of Kaua'i at a 500m resolution and were provided to PacIOOS by Dr. Kwok Fai Cheung. The dataset encompasses the entire island of Kaua'i (including Ni'ihau), but data was only used for the latitude and longitude range of the study sites.

2.2 Analysis

To analyze BWTF enterococci measurements, the number of samples categorized as Medium and High were counted for each of the nine sites. The number of Medium and High events were used to assess and compare the extent of the bacterial pollution issue at each site.

Both the WRF and SWAN datasets were expressed in multiple latitude and longitude coordinate points. In order to use the correct data at each of the BWTF sites, the WRF and SWAN date were organized by coordinates that could be compared to the coordinates of each individual BWTF sites. Table 2.1 provides the coordinates used for each site and the coordinates used from each reference dataset.

Once the WRF and SWAN datasets were organized and assigned to a BWTF site, the entire dataset for the respective BWTF site was compared to both the WRF and SWAN datasets as potential driving factors. Specific point correlations were established between bacteria counts and both precipitation and wave activity. Each extreme event of bacterial contamination was analyzed individually to assess whether or not precipitation and wave activity had an effect on bacteria levels.

Table 2.1 Site coordinates and dataset coordinates used for each site.

SITE NO.	SITE NAME	SITE COORDINATES (N,W)	WRF COORDINATES (N,W)	SWAN COORDINATES (N,W)
1	PK's Surf Spot	21.880290, 159.476004	21.87, 159.43	21.88, 159.46
2	Koloa Landing, Waikomo Stream	21.879042, 159.468959	21.87, 159.44	21.87, 159.46
3	Waiohai Surf Spot	21.874047, 159.457074	21.87, 159.45	21.87, 159.45
4	Waiopili Stream	21.888651, 159.418196	21.93, 159.43	21.88, 159.42
5	Gillin's Beach	21.888754, 159.415748	21.93, 159.43	21.88, 159.45
6	Niumalu Beach Boat Ramp	21.950227, 159.362051	21.98, 159.31	21.95, 159.36
7	Nawiliwili Stream	21.960029, 159.352063	21.98, 159.31	21.96, 159.35
8	Kalapaki Bay Surf Spot	21.959316, 159.350161	21.98, 159.37	21.95, 159.35
9	Hanamaulu Stream	21.990723, 159.340339	21.98, 159.31	21.99, 159.34

3.0 RESULTS

3.1 Enterobacteria

The results of the water-testing completed by Blue Water Task Force show that there are varying levels of enterobacteria found at each site. Few sample sites regularly display low levels of pollution, while most of the sites frequently experience contamination levels that exceed standards established by the EPA. Figure 3.1 displays a time series of water-testing results at each of the nine sites included in this study.

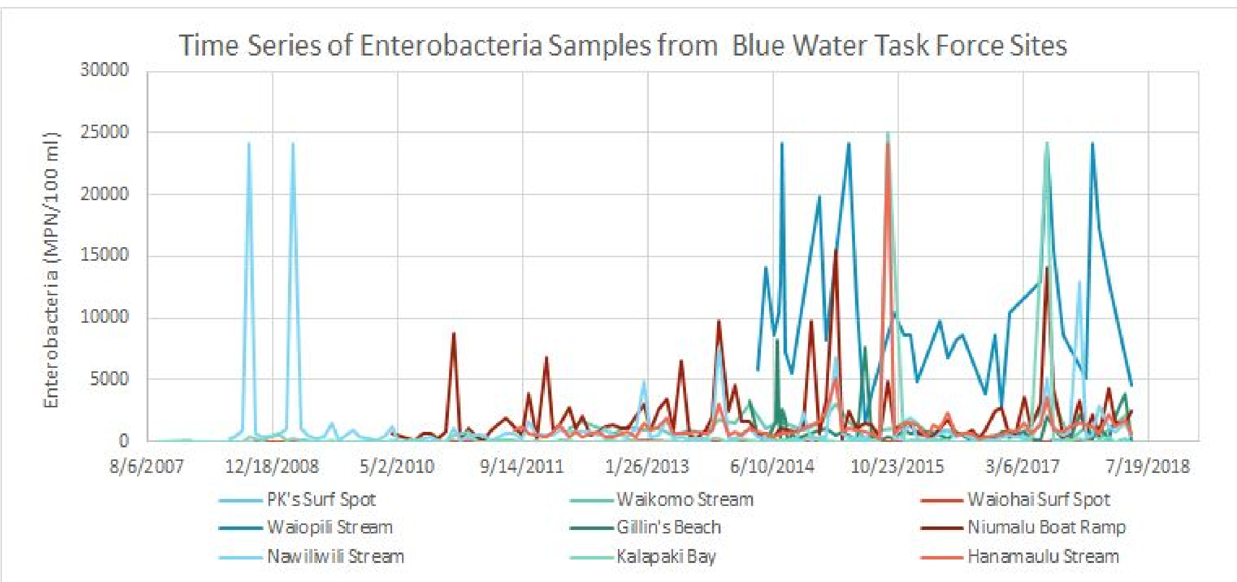

Figure 3.1 Time series of Enterobacteria samples from nine Kaua'i sites.

Five of the study sites have shown chronic levels of contamination in recent years. These sites include Hanamaulu Stream, Waikomo Stream, Nawiliwili Stream, Niumalu Boat Ramp, and Waiopili Stream. According to Surfrider Foundation, enterococci concentrations at Waiopili Stream are 10 times higher than the four other chronic sites, although this does not necessarily mean that the health risk is higher if the bacteria source is not sewage. Water samples from these sites have consistently recorded bacterial concentrations well over the 104 MPN/100 ml threshold for the High Bacteria category. These High concentrations have be observed since monitoring began at each site.

Gillin's Beach and Kalapaki Bay Surf Spot exhibit fluctuating pollution levels. These two sites consistently have recorded bacterial concentrations that are categorized as Low, Medium, and High. These two sites are especially concerning as the bacterial fluctuations they experience have an incredibly large range. The lowest recorded sample at both Gillin's Beach and Kalapaki Bay was 0 MPN, while the highest recorded sample was 8164 MPN/100 ml at Gillin's Beach on 6/9/2014 and 25000 MPN/100 ml at Kalapaki Bay on 9/12/2015.

PK's Surf Spot and Waiohai Surf Spot, consistently exhibit low levels of pollution with few exceptions throughout the years. PK's Surf Spot has recorded one Medium event and four High events, while Waiohai Surf Spot has has only experienced one High event. Both of these sites are popular, offshore surf spots that are in close proximity to nearshore areas with frequent pollution problems.

Most of the sample sites found on the northern end of the study area experience lower bacteria concentrations in the summer months. Kalapaki Bay is an exception to this observation as no seasonal trends are evident at this location. The Mahaulepu sites, Gillin's Beach and Waiopili Stream, experience lower concentrations in the winter months. Both sites experience the highest number of High bacteria events in the month of June. Seasonal trends are nonexistent at the three southernmost study sites. The two surf spots, Waiohai and PK's, have five combined High events in different months throughout the year. On the other hand, Waikomo Stream often experiences High bacteria events throughout the year but the number of events vary drastically from month to month. Figure 3.2 provides a clear depiction of the seasonal variability of bacteria concentrations at each site throughout the year.

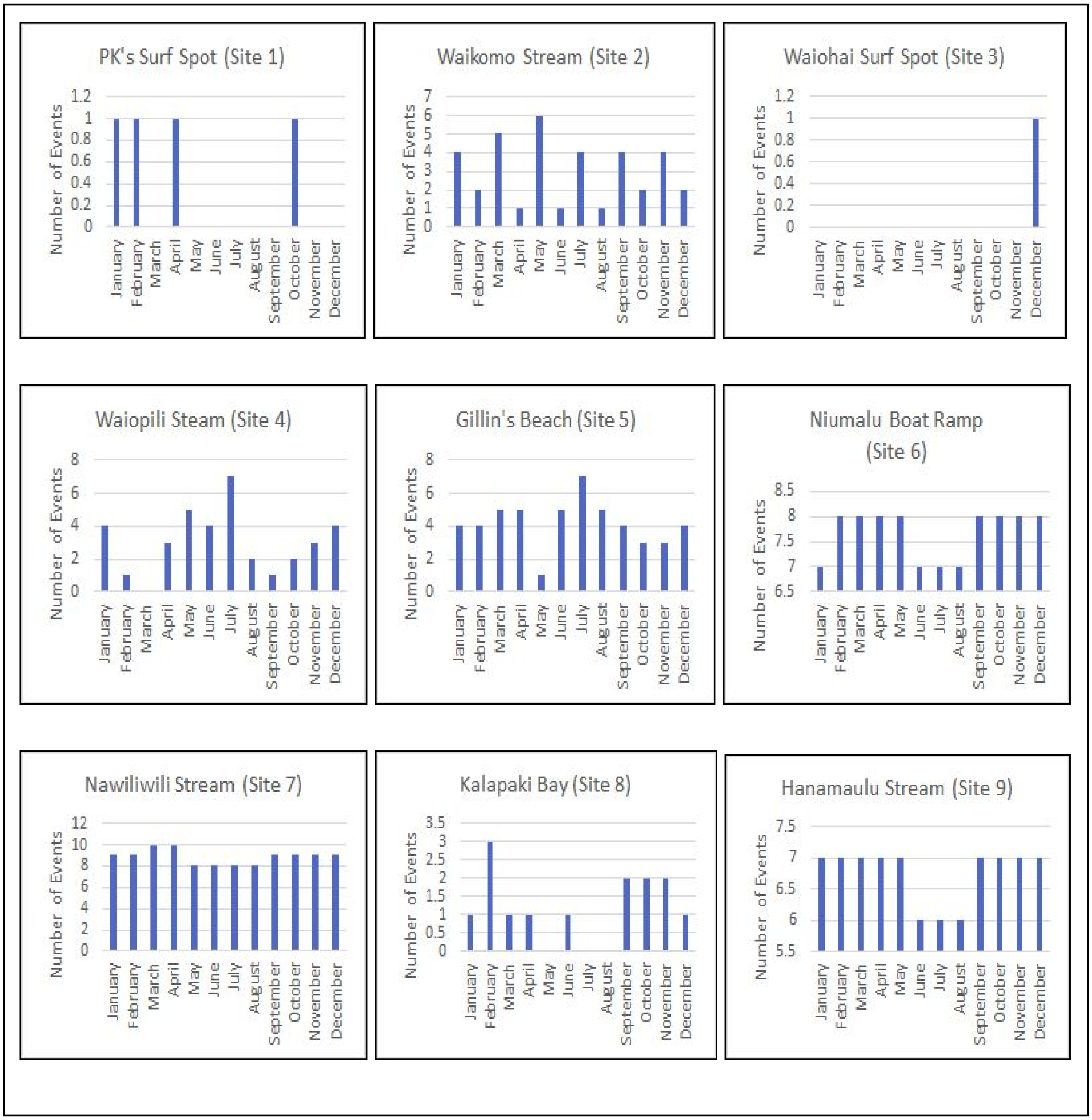

Figure 3.2 Total number of high bacteria events (MPN > 104/100 ml) per month from 2008 to 2018 at each site.

3.2 Precipitation

Since there is no clear signal or coherence in the bacterial counts either spatially (Figure 1.2) or temporally (Figure 3.1), an event-wise correlation was done between extreme bacterial events and high rain events. Figures 3.3 to 3.11 show the enterobacteria and precipitation time series datasets plotted against each other for each site. The graphs display peaks in enterobacteria levels that are generally sporadic events with no evidence of an annual cycle although precipitation is typically higher in the summer months and with little variation between sites. Individual analysis of each peak bacterial event shows no coherence with precipitation levels. The alternative is also true as high precipitations events are not associated with high levels of bacteria.

Figure 3.3 displays the coaligned datasets for enterobacteria and precipitation at PK's Surf Spot (Site 1). Bacteria levels at this offshore site are much lower than other areas included in the study with the highest recorded enterobacteria value reaching just over 200 MPN/100 ml. As seen in the graph below, the highest recorded enterobacteria value has no association with high precipitation. PK's Surf Spot has recorded only four events of bacterial levels over 104 MPN/100 ml and none of these events correlate with events of excessive rainfall.

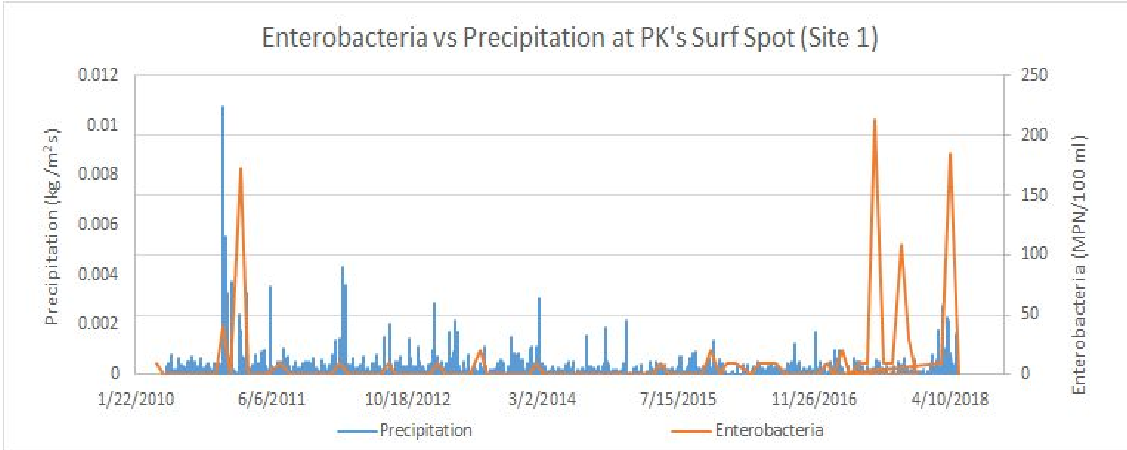

Figure 3.3 Enterobacteria data from BWTF compared to precipitation data from WRF at Site 1.

Figure 3.4 displays the coaligned datasets for enterobacteria and precipitation at Waikomo Stream (Site 2). Waikomo Stream is one of the five chronically polluted sites. It is important to note the change in range along our secondary y-axis in this figure. The lowest enterobacteria levels recorded at range from 104 to 1000 MPN/100 ml with extreme events reaching 25000 MPN/100 ml on 9/12/2015 and 24196 MPN/100 ml on 6/10/2017. Data at Waikomo Stream includes 71 events in which bacteria levels exceeded 104 MPN/100 ml. These events have shown no correlations with the precipitation dataset from the Weather Research and Forecasting Atmospheric Model.

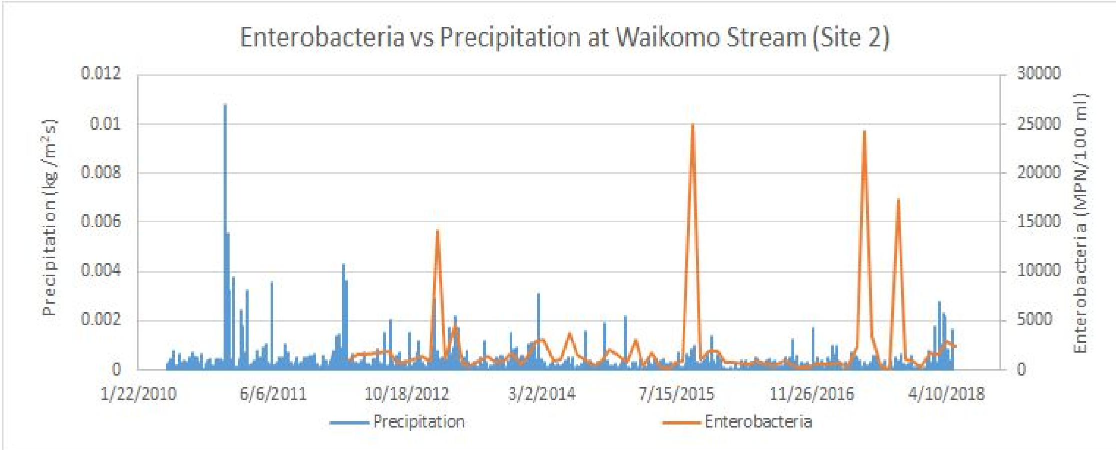

Figure 3.4 Enterobacteria data from BWTF compared to precipitation data from WRF at Site 2.

Figure 3.5 displays the coaligned datasets for enterobacteria and precipitation at Waiohai Surf Spot (Site 3). Waiohai is another offshore surf spot that typically has low levels of bacteria. Throughout the study, there has only been one event in which bacteria levels have exceeded 104 MPN/100 ml. At the time of this high bacterial event, the precipitation level is at one of the lowest observed levels, therefore precipitation cannot be a driving factor of the increased bacterial levels.

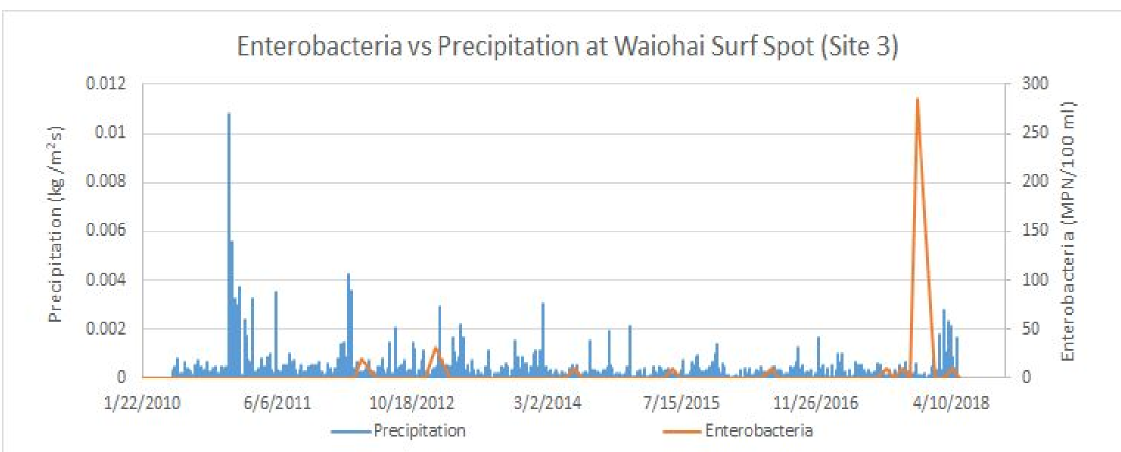

Figure 3.5 Enterobacteria data from BWTF compared to precipitation data from WRF at Site 3.

Figure 3.6 displays the coaligned datasets for enterobacteria and precipitation at Waiopili Stream (Site 2). Waiopili is another one of the five sites that have displayed chronic pollution problems. The study included 54 events of high bacterial concentrations at Waiopili Stream, the lowest recorded value being 1421 MPN/100 ml on 6/13/2015. Typically, enterobacteria concentrations at Waiopili Stream exceed 5000 MPN/100 ml and show no evidence of being related to precipitation levels.

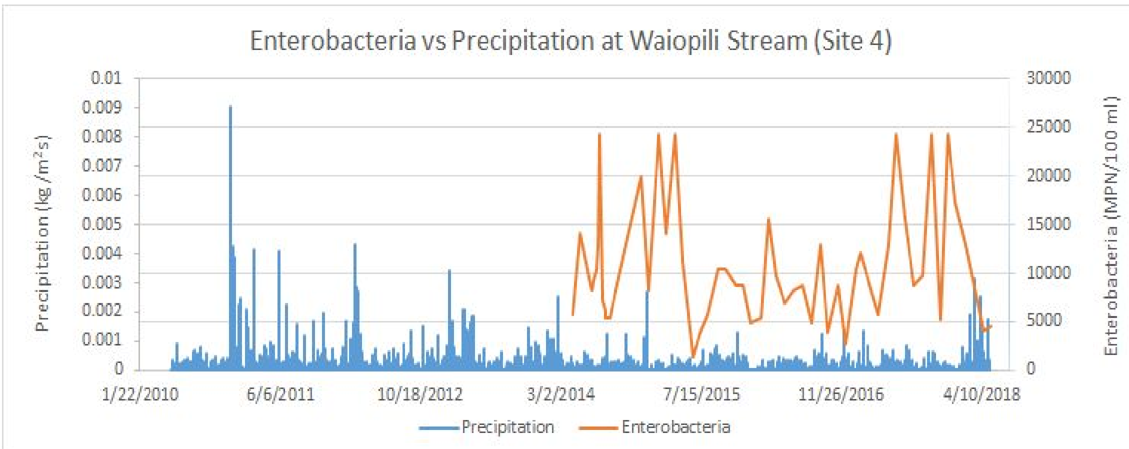

Figure 3.6 Enterobacteria data from BWTF compared to precipitation data from WRF at Site 4.

Figure 3.7 displays the coaligned datasets for enterobacteria and precipitation at Gillin's Beach (Site 5). Gillin's Beach has also observed 54 instances of high bacterial concentrations during the study, but values range from 104 to 8000 MPN/100 ml. These high bacterial events show no coherence with precipitation data.

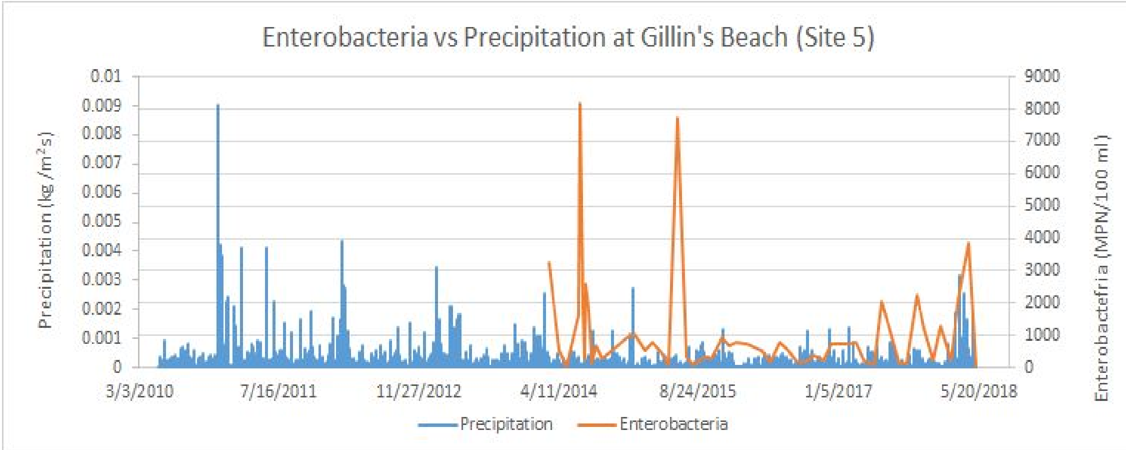

Figure 3.7 Enterobacteria data from BWTF compared to precipitation data from WRF at Site 5.

Figure 3.8 displays the coaligned datasets for enterobacteria and precipitation at Niumalu Boat Ramp (Site 6). Niumalu is another chronically polluted site that has 48 recorded high bacterial events included in the study. Bacterial concentrations at Niumalu fluctuate rapidly between 200 to 9000 MPN/100 ml with two events reaching above 14000 MPN/100 ml on 2/14/2015 and 6/10/2017. Bacterial events under 2000 MPN/100 ml generally show more of a correlation with precipitation levels, but precipitation cannot be used to justify events of extreme pollution at Niumalu Boat Ramp.

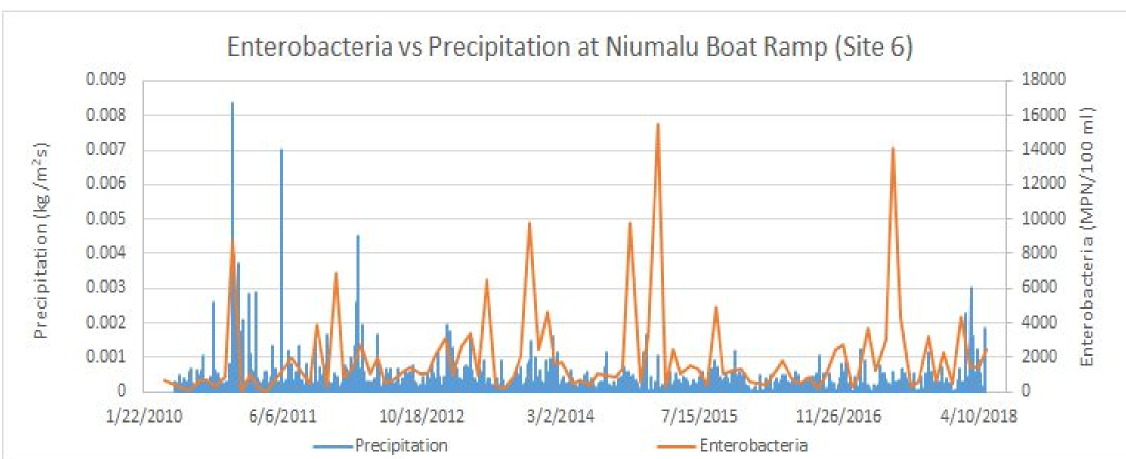

Figure 3.8 Enterobacteria data from BWTF compared to precipitation data from WRF at Site 6.

Figure 3.9 displays the coaligned datasets for enterobacteria and precipitation at Nawiliwili Stream (Site 7). Our study includes 94 events of high bacterial concentrations at Nawiliwili Stream. It is important to recognize the timeline in which these measurements take place as water quality monitoring by BWTF began at Nawiliwili Stream in 2008. While the additional monitoring time does add several events to the overall total of high bacterial events, Nawiliwili has continued to display consistent pollution problems since monitoring began ten years ago. Enterobacteria concentrations at Nawiliwili usually range from 104 to 4000 MPN/100 ml with few instances of concentrations that reach 12000 and 25000 MPN/100 ml on 9/12/2015, 9/14/2008, 3/14/2009, and 10/14/2017. These instances of extreme pollution show no correlation with precipitation, while lower levels of pollution better correlate with precipitation levels.

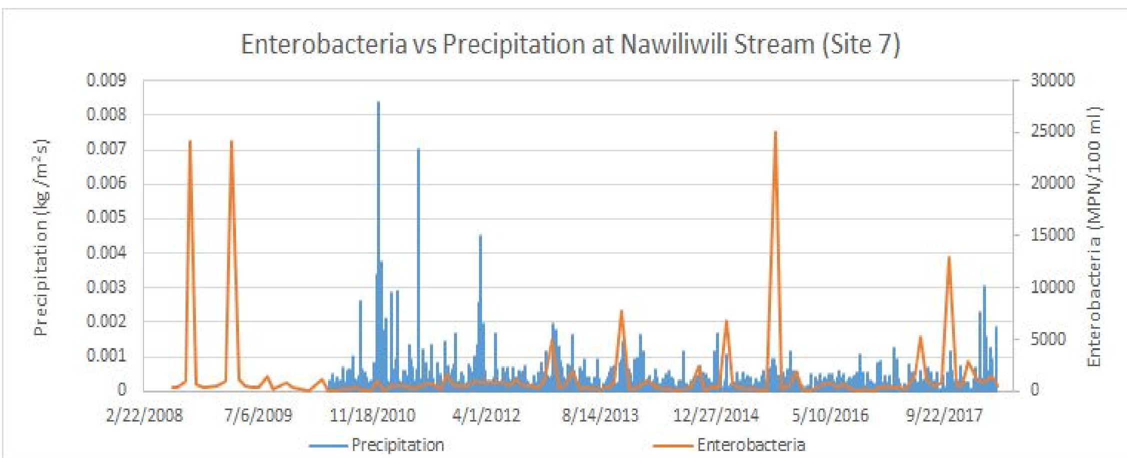

Figure 3.9 Enterobacteria data from BWTF compared to precipitation data from WRF at Site 7.

Figure 3.10 displays the coaligned datasets for enterobacteria and precipitation at Kalapaki Bay Surf Spot (Site 8). Kalapaki Bay has observed 14 high bacterial events throughout this study, making this spot the most frequently polluted surf spot included in the study area. This can be attributed to the close proximity of the spot to multiple areas that are chronically polluted. Kalapaki Bay typically records lower levels of pollution, but events of high bacterial concentrations span from 104 to 500 MPN/100 ml with only two instances of events that reach above 24000 MPN/100 ml on 9/12/2015 and 6/10/2017. Individual cases of extreme pollution at Kalapaki Bay cannot be attributed to precipitation levels.

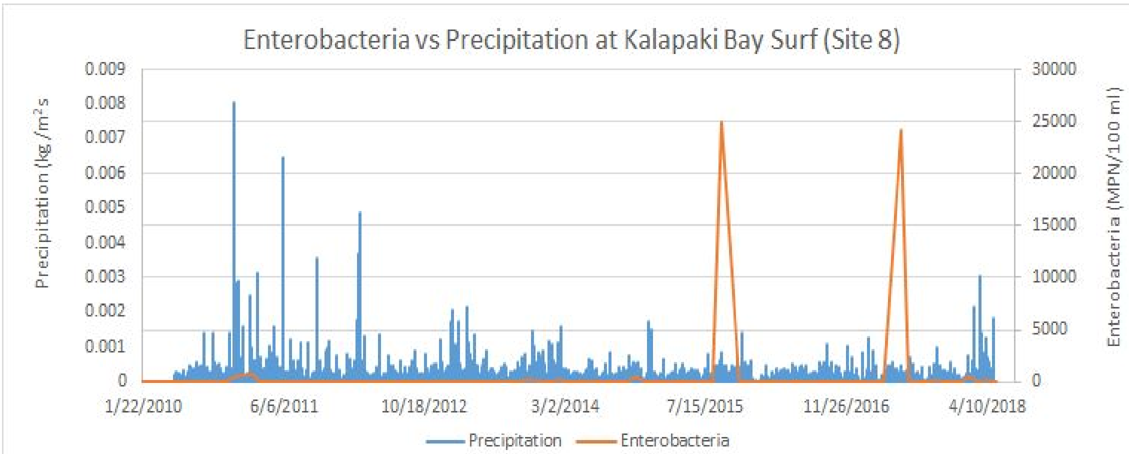

Figure 3.10 Enterobacteria data from BWTF compared to precipitation data from WRF at Site 8.

Figure 3.11 displays the coaligned datasets for enterobacteria and precipitation at Hanamaulu Stream (Site 9). Hanamaulu is the last chronically polluted included in the study with 81 recorded events of high bacterial concentrations. At Hanamaulu Stream, bacterial concentration range from 200 to 4000 MPN/100 ml with an occurence of bacterial concentrations reaching 24196 MPN/100 ml on 9/12/2015. Extreme bacterial events at Hanamaulu are not associated with precipitation levels.

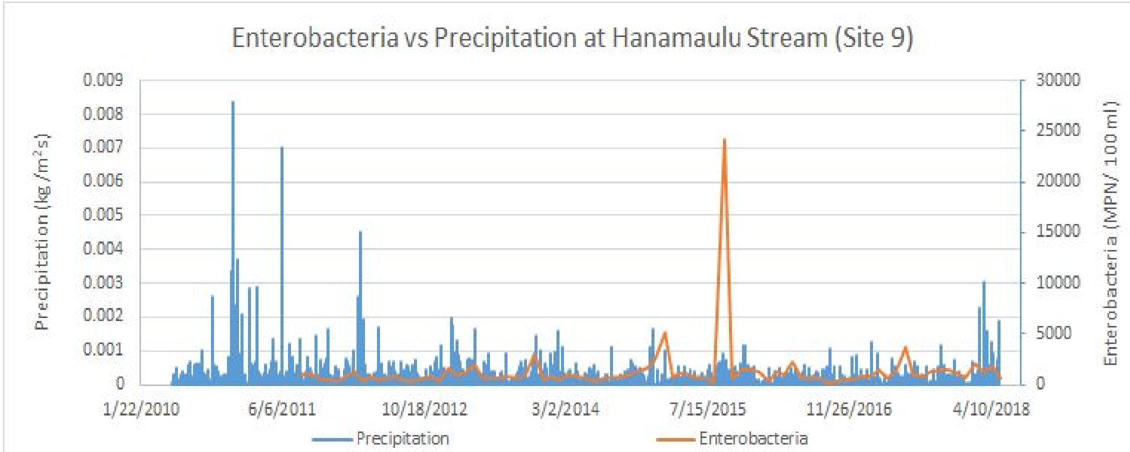

Figure 3.11 Enterobacteria data from BWTF compared to precipitation data from WRF at Site 9.

3.3 Wave Activity

Figures 3.12 to 3.20 show the enterobacteria and mean wave period time series datasets plotted against each other for each site. Once again, the peaks in enterobacteria occur sporadically throughout the time series, although wave activity varies between sites and exhibits some seasonal trends based on summer swells in the south and trade waves on the eastern sites. Since the mean wave period was used to measure wave energy, there are two possible outcomes for correlations between enterobacteria levels and mean wave period. One outcome being that high wave frequency will drive resuspension and increase bacterial concentrations.The second outcome being that high wave frequency will serve to flush bacteria from the site. Ultimately, the graphs show no direct coherence between wave activity and enterobacteria levels for either outcome, although some error was observed in the SWAN model output at the Gillin's Beach and Hanamaulu sites.

Figure 3.12 displays the coaligned datasets for enterobacteria and mean wave period at PK's Surf Spot (Site 1). While there were some errors observed in model output in the early years of forecasting, recent years have been much more successful. Wave activity is generally low at this site ranging from 6 to 12 seconds between waves. This data does not correlate with enterobacteria concentrations as low and high bacterial events have been recorded while wave energy was low.

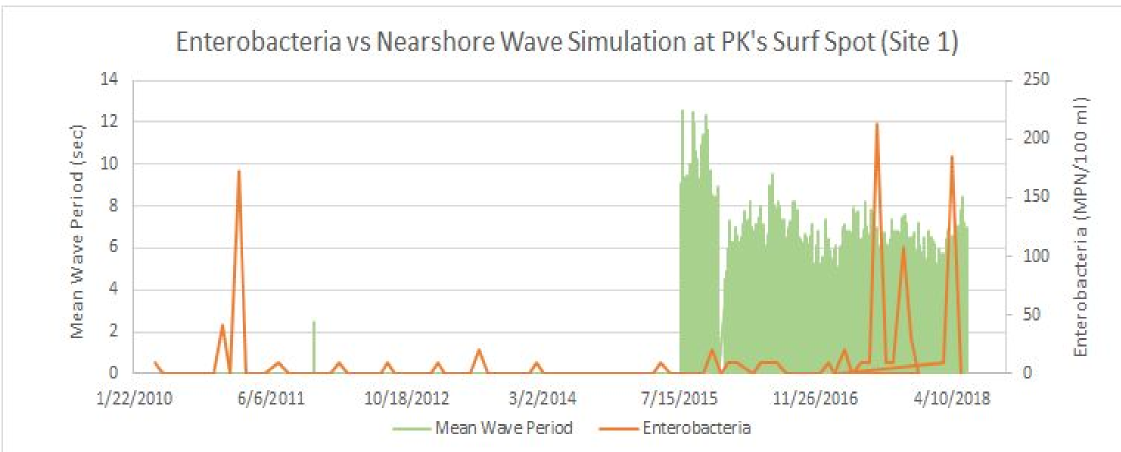

Figure 3.12 Enterobacteria data from BWTF compared to wave activity data from SWAN at Site 1.

Figure 3.13 displays the coaligned datasets for enterobacteria and mean wave period at Waikomo Stream (Site 2). The mean wave period at Waikomo Stream ranges from 1 to 15 seconds. There are some instances in which enterobacteria concentrations are low while wave energy is high, but there is no clear coherence between mean wave period and enterobacteria concentrations.

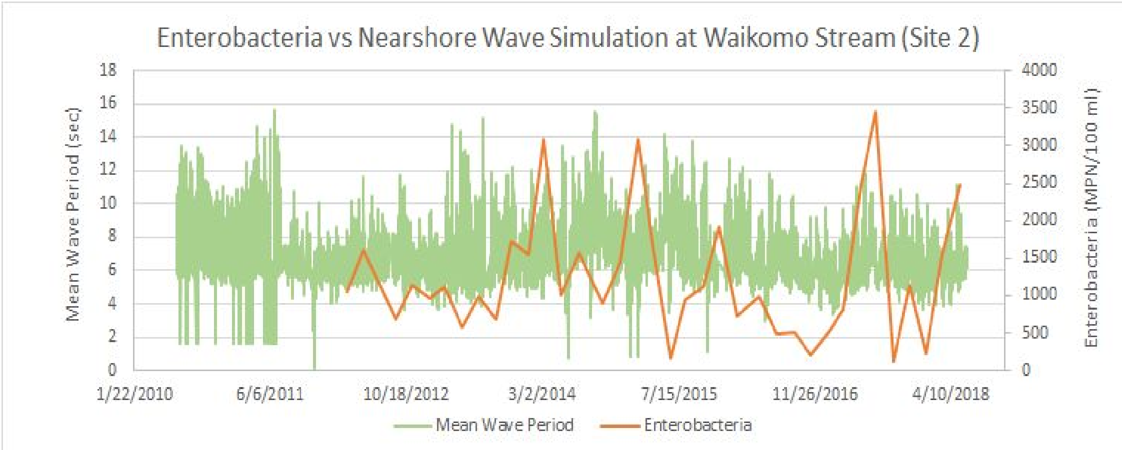

Figure 3.13 Enterobacteria data from BWTF compared to wave activity data from SWAN at Site 2.

Figure 3.14 displays the coaligned datasets for enterobacteria and mean wave period at Waiohai Stream (Site 3). Waiohai Stream experiences fluctuations in mean wave period from 1 to 15 seconds and only one event of high enterobacteria concentration. The many events of low bacterial concentrations occur during periods of high and low wave energy suggesting that there is no relation between wave energy and enterobacteria concentrations at Waikomo Stream.

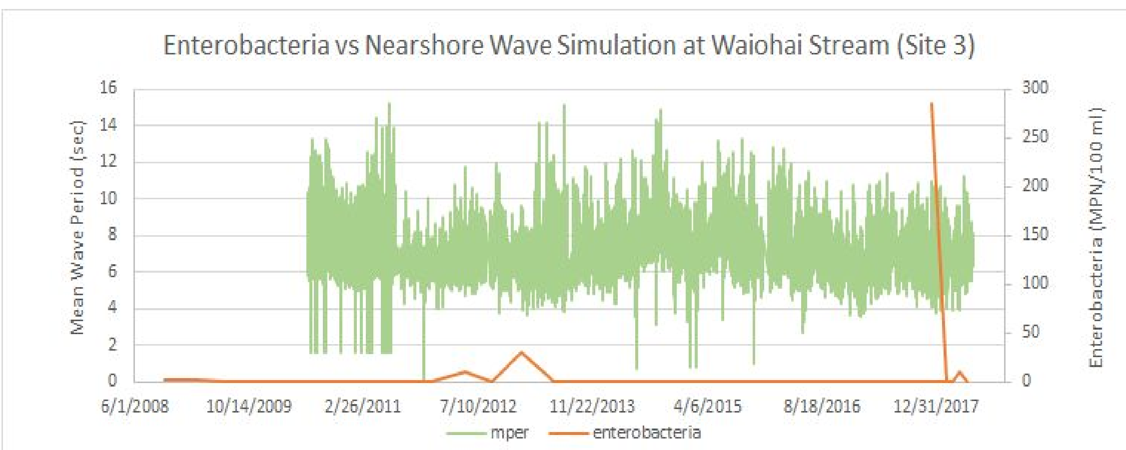

Figure 3.14 Enterobacteria data from BWTF compared to wave activity data from SWAN at Site 3.

Figure 3.15 displays the coaligned datasets for enterobacteria and mean wave period at Waiopili Stream (Site 4). Waiopili is one of the chronically polluted site and mean wave energy at Waiopili ranges from 1 to 15 seconds. The lowest recorded value of enterobacteria concentration and Waiopili correlates to a mean wave period of 11 seconds while other high bacterial events correlate with mean wave periods ranging from 4 to 6 seconds. Ultimately, there is no clear coherence between mean wave period and enterobacteria concentrations at Waiopili Stream.

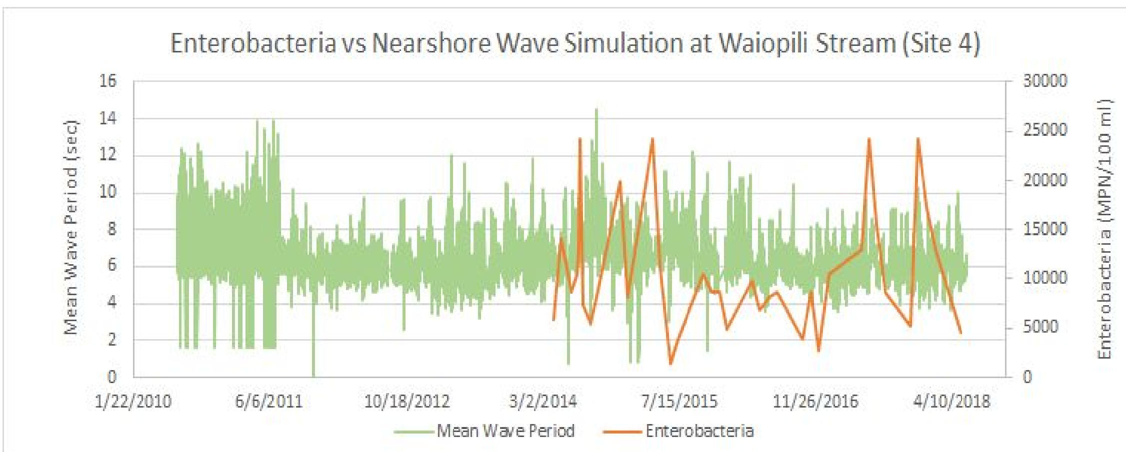

Figure 3.15 Enterobacteria data from BWTF compared to wave activity data from SWAN at Site 4.

Figure 3.16 displays the coaligned datasets for enterobacteria and mean wave period at Gillin’s Beach (Site 5). The available SWAN model output had missing values at Gillin’s Beach and many NaN values were recorded (likely due to problems with the daily forecast) which inhibited an accurate analysis of the relationship between enterobacteria concentrations and mean wave activity at this site.

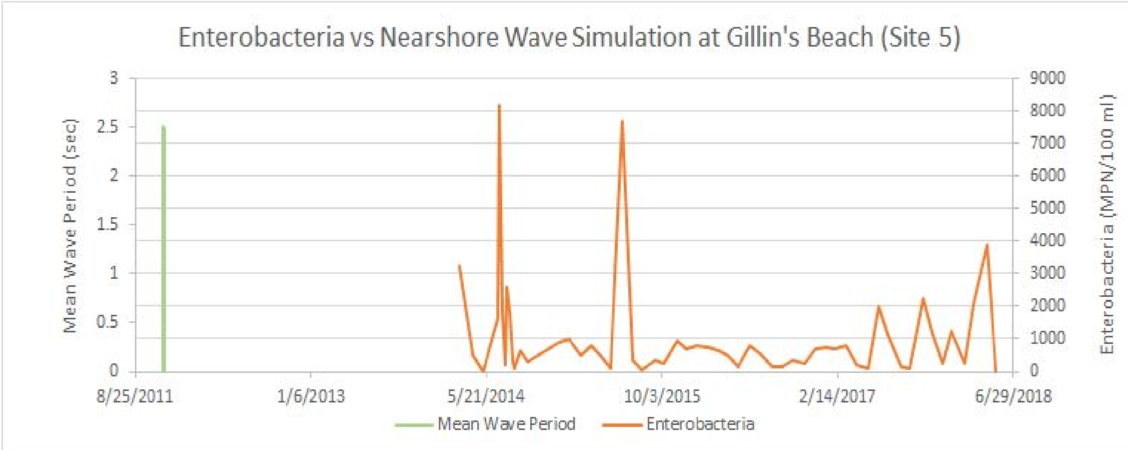

Figure 3.16 Enterobacteria data from BWTF compared to wave activity data from SWAN at Site 5.

Figure 3.17 displays the coaligned datasets for enterobacteria and mean wave period at Niumalu Stream (Site 6). Niumalu is another one of the chronically polluted sites included in this study. Wave activity at Niumalu ranges from 4 to 13 seconds and displays no clear coherence with enterobacteria concentration levels.

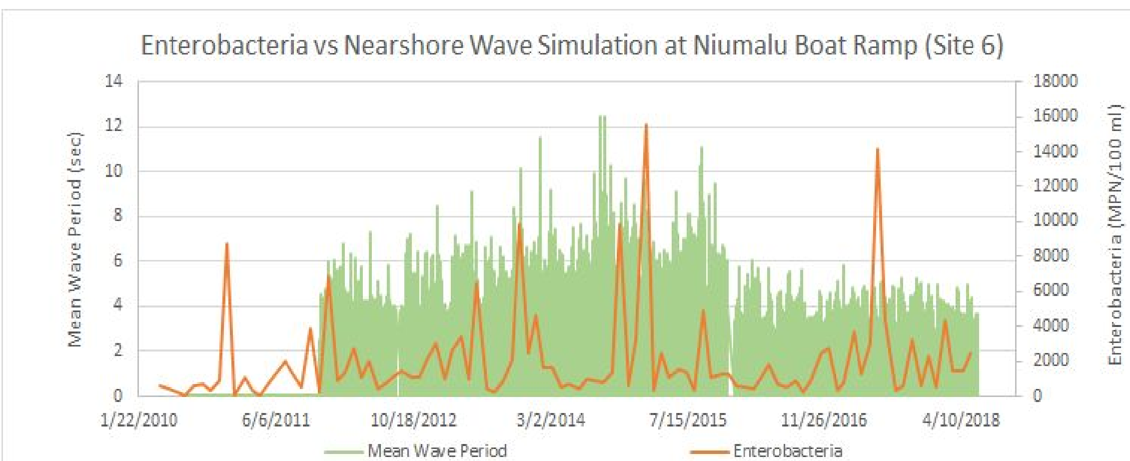

Figure 3.17 Enterobacteria data from BWTF compared to wave activity data from SWAN at Site 6.

Figure 3.18 displays the coaligned datasets for enterobacteria and mean wave period at Nawiliwili Stream (Site 7). Wave activity data was not consistently made available for

Nawiliwili Stream until 2015. A peak enterobacteria event correlates with a mean wave period of 12 seconds, however many of the lower intensity bacterial events also correlate with events of low wave energy. These results suggest that there is no direct relation between wave energy and enterobacteria concentrations at Nawiliwili Stream.

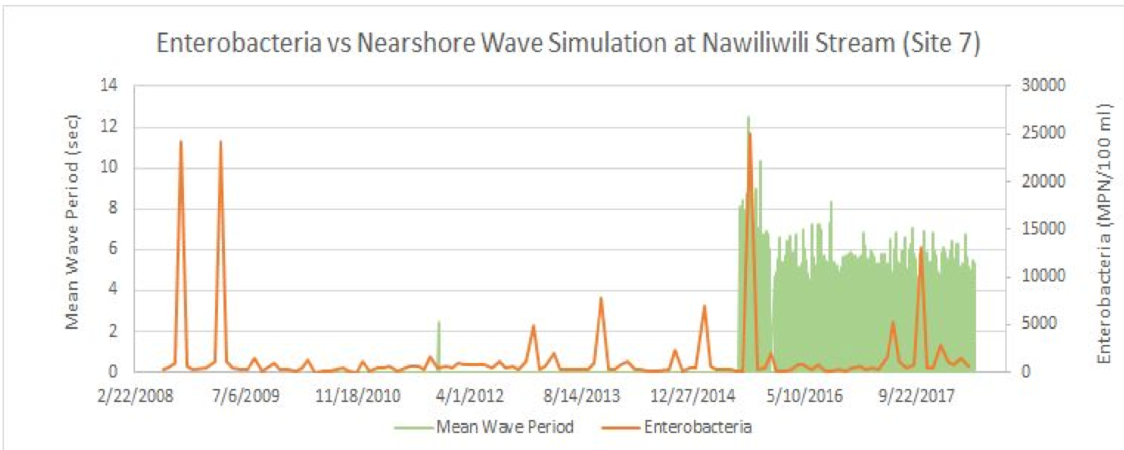

Figure 3.18 Enterobacteria data from BWTF compared to wave activity data from SWAN at Site 7.

Figure 3.19 displays the coaligned datasets for enterobacteria and mean wave period at Kalapaki Bay (Site 8). Kalapaki Bay is the most frequently polluted surf spot included in the study. Mean wave period at Kalapaki ranges from 4 to 13 seconds with no clear correlations with enterobacteria levels as high and low levels of enterobacteria concentrations occur when the mean wave period is above 6 seconds.

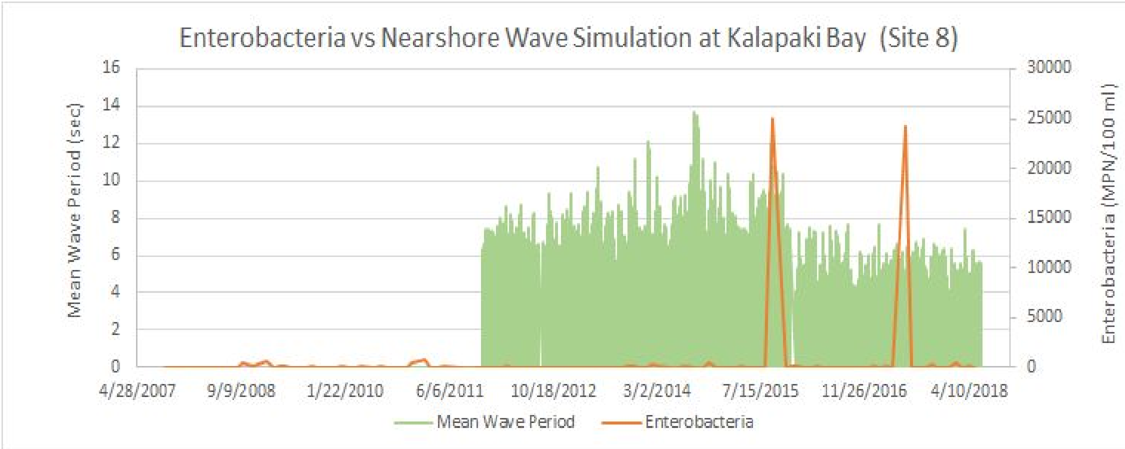

Figure 3.19 Enterobacteria data from BWTF compared to wave activity data from SWAN at Site 8.

Figure 3.20 displays the coaligned datasets for enterobacteria and mean wave period at Hanamaulu Stream (Site 9). Similarly to the SWAN model outputs at Gillin's Beach, many NaN values were recorded at Hanamaulu which prevented the completion of an accurate analysis of the relationship between enterobacteria concentrations and mean wave activity at this site.

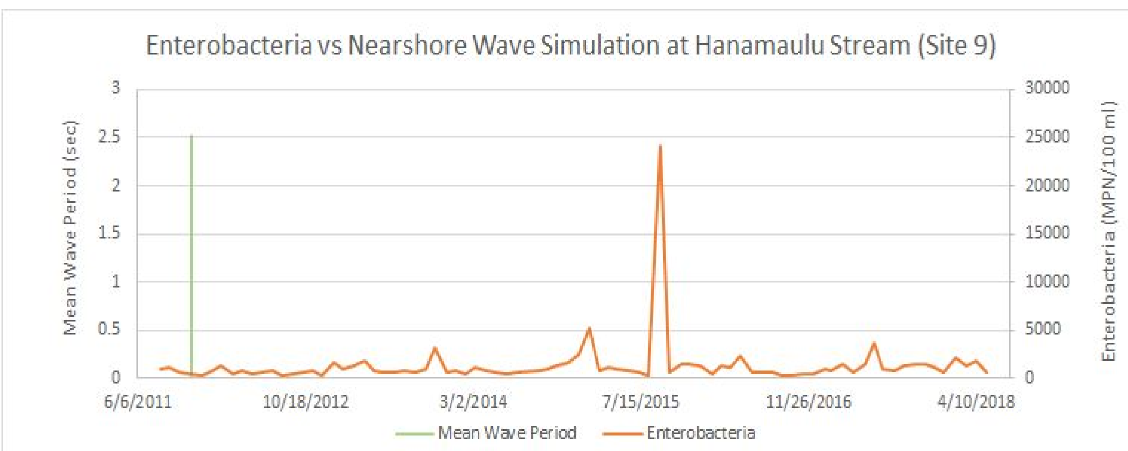

Figure 3.20 Enterobacteria data from BWTF compared to wave activity data from SWAN at Site 9.

4.0 DISCUSSION

An analysis of the occurrence of high enterobacteria concentration events at each site suggests that there are no seasonal trends. When compared to precipitation and wave activity data, there are no direct correlations with the extreme cases of bacterial concentrations that have been observed at each site. High concentrations of enterococci are present during periods of both low and high wave activity suggesting that enterococci concentrations are not dependant on bay flushing or bacterial resuspension prompted by wave energy (Delpey et al., 2014). However, there are cases in which precipitation relates to low-intensity enterococci concentrations. While these events are considered low-intensity compared to other events of severe pollution, they are still classified as high bacterial concentration due to the fact that the recorded value is greater than 104 MPN/100 ml. It is likely that precipitation does play a role in the distribution of bacteria to a certain extent since enterococci bacteria are naturally found in the soils that line freshwater streams in Hawai'i (Byappanahalli et al., 2012a). Regardless of the natural occurrence of enterococci, there must be another driving force to explain the extreme concentrations of 25000 MPN/100 ml that have been documented.

Due to the fact that enterococci are commonly found to occur naturally, the practicality of monitoring enterococci concentrations to indicate the presence of human or animal fecal matter has been a controversial topic in recent years (Lebreton, et al., 2014). While enterococci can be found to be present in large concentrations in human and animal feces, the presence of enterococci can occur in the absence of actual fecal matter (Byappanahalli et al., 2012b). This is largely the root of disagreements between the State of Hawai'i Department of Health, Surfrider

Foundation, and many concerned residents as all parties have different opinions regarding the source of enterococci bacteria and the severity of pollution.

The overall results of this study have several implications regarding the matters that have been directly addressed throughout this project. Firstly, there is a possibility that the resolution of datasets used to analyze precipitation and wave activity were too low to properly observe watershed and offshore characteristics throughout the study site. Datasets with higher resolutions may have been able to provide better insights on the environmental forcings that are contributing to the poor water quality observed on south Kaua'i. As observed with the SWAN wave activity dataset, the functionality of this model is not yet finalized. Once completed, this model may be better suited for an analysis of this sort. Secondly, runoff that has been affecting water quality in Kaua'i may not be caused solely by rainfall, making our precipitation dataset a poor proxy for runoff.

Given little correlation between rain and wave events to high bacterial counts, instead it may be that agriculture-induced runoff due to irrigation techniques may have a large impact on coastal water quality, especially in areas downstream of cattle ranches. Data based on agriculture-induced runoff will be necessary in the future to assess the possibility of fecal pollution due to this. Instead, agriculture-induced runoff due to irrigation techniques may have a large impact on coastal water quality, especially in areas downstream of cattle ranches. Data collections based on agriculture-induced runoff will be necessary in the future to assess the possibility of fecal pollution due to this. Thirdly, it is possible that runoff may not be contributing to the poor water quality at all. Land use changes and faulty infrastructure may lead to sewage or cesspool leaks that can contaminate groundwater that discharges to coastal regions.

Since there are many possible sources that have the potential to increase enterobacteria concentrations, the pollution problems on the shores of South Kauai can be classified as non-point source pollution. Being classified as non-point source pollution means that the water pollution becomes much more difficult to predict, manage, and control. However, proper monitoring can still provide useful insight to better protect the community from dealing with the health issues and other consequences associated with enterobacteria.

5.0 CONCLUSION

Overall, we were unable to find significant evidence to support the hypothesis that the water quality issues on south Kaua'i are driven by precipitation or wave activity. Study sites have shown different seasonal trends in enterobacteria levels that have proved to be unassociated with both precipitation and wave activity. Unfortunately, this leads us to believe that, although fecal bacteria can occur naturally in tropical soils (Hardina & Fujioka, 1991), the elevated levels of fecal bacteria observed in the study site must be due to inefficient land-use practices or other anthropogenic forces. Based on this conclusion, we have determined that there are several implications for future research. Since climatological factors have been disregarded as a main driver of fecal bacterial input and dispersal, using computer generated models or other means of predicting high pollution events is no longer a viable option. This implies that the frequency of water testing at each site will have to increase in order to provide much more precise information to the public. Monitoring by Blue Water Task Force is currently operated by volunteers on a monthly basis. It is also necessary to further analyze the practicality of monitoring enterococci concentrations as an indicator of fecal matter. Since Blue Water Task Force is a non-profit and volunteer operated organization, public outreach and education to raise awareness will be the biggest asset to researchers and activists working to find a solution to these water quality crises. Once again, clean water is an absolutely essential component for human life and health, economic systems, and ecosystem functionality, and it is crucial that improving water quality continues to be a significant conservation goal at the global level.

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