

Predicting sea level rise impacts to coastal wastewater infrastructures and water quality along the Kailua-Kona shoreline

Ihilani Kamau
Master's Thesis Proposal
Tropical Conservation Biology and Environmental Science
University of Hawai'i at Hilo
200 W. Kawili St.
Hilo, HI 96720
Thesis Advisor: Dr. Tracy Wiegner
Research Committee: Dr. Steven Colbert and Dr. Lisa Marrack

Acknowledgements

I feel so blessed and am extremely grateful for everyone who has helped make this project possible. From the beginning of this project, I have been blessed with an amazing group of people who have helped me complete my master's thesis. They have helped me with planning out each step of the project, met with me weekly for updates, and were able to tag along for a few trips to Kona. I would like to thank Dr. Tracy Wiegner and Dr. Steven Colbert for helping me in every step of this project and guiding me throughout this process. I would also like to thank Dr. Lisa Marrack for playing a major role in this project by bringing in the SLR aspect and creating SLR projections in order to determine OSDS and WI at risk. Together we were able to use multiple indicators in order to identify sewage pollution hot spots, areas where OSDS and WI are at risk of inundation, and determine future water quality along the Kailua-Kona, Hawai'i shoreline.

There were many hours and many hands that helped make the field work go smoothly. Field days consisted of early morning drives over and back from Kona for sample collection and many hours in the lab for processing. Even with these long days, many volunteers contributed their time and skills to help make this project possible. Hi'ilei Kamau assisted in collecting and helping process the samples that were collected in this study. Joseph Nakoa assisted with the planning, field work, and processing in the early stages of this project. Three undergraduate students helped over the course of this project: Sierra Hall, Amber Skiwo, and Morgan Youngblood. Field and lab assistance was also provided by volunteers: Katie Cartee, Anna Ezzy, Walter Boger, Silas Piianaia, and Christian Colo. Dr. Karla McDermid and Lauren Pepper for helping me identify a few of the macroalgae species found at the shoreline.

I would also like to thank Jasmine Panelo, Zach Taylor, and Erik Johnson at the University of Hawai'i at Hilo's Analytical Lab for processing all of my samples. Thank you to the SDAV research lab at UH Hilo for helping us get high resolution differential GPS points in order to create the GW model. I would also like to thank Malia Kipapa and Kimo Chai from Kamehameha Schools and Paka Davis from Liliuokalani Trust for allowing us to collect data from their anchialine ponds. A big thank you to Auntie Cindi Punihaole and the Kohala Center for assisting in the dye tracer tests. I would like to thank Jon Kawamura from the Hawai'i Water Service for providing maps of the sewer system and Robert Whittier for meeting with us and answering questions regarding OSDS. I would also like to thank Jamison Gove for providing us with the GIS files for sewage effluent offshore. Thank you to the Hawai'i County, Waiwai Ola 'Ohana, and the Hawai'i Division of Aquatic Resources for meeting with us and providing feedback.

Finally, I would like to thank Pacific Islands Climate Adaptation Science Center (PI-CASC) for funding my master's thesis work. I am extremely blessed to have this opportunity and am grateful for all of the people, programs, foundations and communities that have helped make this project possible.

Mahalo nui loa.

Abstract

Sea level rise (SLR) poses a serious threat to coastal infrastructures. On-site sewage disposal systems (OSDS) and wastewater infrastructure (WI) are vulnerable, and when inundated, will result in human and ecosystem health threats. This study focused on the Kailua-Kona shoreline, Hawai‘i Island, where these two sewage sources are potentially impacting water quality. Study goals were to: 1) document and identify sewage pollution hotspots by assessing current water quality conditions, 2) map out and assess predicted SLR to determine what OSDS and WI are at risk of inundation. Sewage pollution hotspots were assessed using a dye tracer test and monthly water quality sampling at 12 stations from August 2022 to September 2023. At Kahalu‘u, dye traveled at 278 m/d, reaching the shoreline in < 6 hours. While *Enterococcus* spp. concentrations occasionally exceed water quality standards, *Clostridium perfringens* did not. *Staphylococcus aureus* was also detected, but Methicillin-resistant *S. aureus* was not. Nutrient concentrations were variable. Macroalgal $\delta^{15}\text{N}$ measurements, a stable isotope mixing model, and a sewage pollution score determined that groundwater is the dominant source of NO_3^- at our stations contributing 77%. However, the results did display a sewage influence on these stations. We examined six different SLR scenarios (2024 Mean higher high water (MHHW), 0.3, 0.6, 1, 1.5, 2 m) and at 0.3 m SLR, 58 OSDS will be at risk of inundation and at a 2 m SLR, this number doubles. We also found that the majority of WI is already being inundated during MHHW events (66 manholes, 79 mains). Our results show that Kailua-Kona is already impacted by sewage pollution and that this will continue to worsen with SLR if management actions are not taken. The entire shoreline from Kailua-Kona to Keauhou should be a Priority 1 area for cesspool conversion for Hawai‘i County, and sewer line setbacks are needed; our results can help guide this effort. Our findings illustrate that adaptive planning is needed to protect future water quality and increase coastal resilience in Hawai‘i, as well as elsewhere where coastal waters are impacted by OSDS and WI.

Table of Contents

Abstract.....	iii
Introduction.....	1
Methods.....	2
Site Description.....	2
Dye Tracer Test.....	3
Shoreline Station Selection and Sample Collection.....	4
Laboratory Analysis.....	4
Stable Isotope Mixing Model (SIMMR).....	5
Sewage Pollution Score.....	6
Statistical Analysis.....	6
Sea Level Rise Modeling.....	6
Results.....	9
Dye Tracer Test.....	9
Fecal Indicator Bacteria.....	9
Nutrients.....	9
Chlorophyll <i>a</i> , Turbidity, & pH.....	9
Macroalgae.....	9
Stable Isotope Mixing Model (SIMMR).....	10
Sewage Pollution Score.....	10
Sea Level Rise Modeling.....	10

Discussion.....	10
Dye Tracer Test.....	10
Shoreline Water Quality.....	11
Macroalgae.....	13
Stable Isotope Mixing Model (SIMMR).....	14
Sewage Pollution Score.....	14
Sea Level Rise Modeling.....	15
Conclusion.....	16
Tables.....	17
Figures.....	22
References.....	33

List of Tables

Table 1. Average ($\pm$ SE) of nutrient concentrations ($\mu\text{mol/L}$) for 12 shoreline stations from Kailua-Kona to Keauhou, Hawai‘i Island, from August 2022 to September 2023.....	17
Table 2. Species list of macroalgae and cyanobacteria collected from shoreline stations from Kailua-Kona to Keauhou, Hawai‘i Island.....	18
Table 3. Groundwater level data obtained from groundwater test wells in Kona, Hawai‘i Island.....	19
Table 4. Sea level rise (SLR) risk to on-site sewage disposal systems (OSDS) from the Old Kona Airport to Kahalu‘u, Hawai‘i Island.....	20
Table 5. Groundwater (GW) and surface inundation by seawater of sewage infrastructure at different sea level rise scenarios (2024 Mean Higher High Water (MHHW), 0.3 m, 0.6 m, 1 m, 1.5 m, 2 m) along the shoreline from Kailua-Kona to Keauhou, Hawai‘i Island.....	21

List of Figures

Figure 1. Map of 12 stations in Kona, Hawai‘i Island, sampled for monitoring sewage pollution and areas associated with the stations.....	22
Figure 2. Results of the dye tracer test conducted in Kahalu‘u, Kona, Hawai‘i Island with fluorescein concentration at three stations over a 10-d period.....	23
Figure 3. Average ($\pm$ SE) concentrations of sewage indicators and pathogens: (A) <i>Enterococcus</i> spp., (B) <i>Clostridium perfringens</i> , and (C) <i>Staphylococcus aureus</i> at shoreline stations in Kailua-Kona, Hawai‘i Island.....	24
Figure 4. Average ($\pm$ SE) $\delta^{15}\text{N}$ (‰) of macroalgae collected at 12 stations along the Kailua-Kona (north to south: Kailua-Kona to Keauhou) shoreline, Hawai‘i Island.....	25
Figure 5. Map of the average nutrient concentrations ($\text{NO}_3^- + \text{NO}_2^-$) along the 12 shoreline stations from Kailua-Kona to Keauhou, Hawai‘i Island.....	26
Figure 6. "Simmr" mixing model results displaying the proportion (%) of each N source: (A) sewage, (B) groundwater, and (C) ocean contributed to twelve shoreline stations along Kailua-Kona shoreline, Hawai‘i Island.....	27
Figure 7. Sewage pollution scores for 12 stations along the Kailua-Kona shoreline.....	28
Figure 8. Modeled sea level rise (SLR) risk of inundation of on-site sewage disposal systems (OSDS: purple dots) in Kailua-Kona, Hawai‘i Island, USA (north to south: Old Kona Airport State Recreation Area to Luna Pule Rd., Kahului Bay).....	29
Figure 9. Modeled sea level rise (SLR) risk of inundation of on-site sewage disposal systems (OSDS: purple dots) in Kailua-Kona, Hawai‘i Island, USA, (north to south: Holualoa, Stardust Ln to White Sands Beach Park, La‘aloa Ave.....	30
Figure 10. Modeled GW and surface ocean inundation of wastewater infrastructure (WI: sewer mains and manholes) at different sea level rise (SLR) scenarios in Kailua-Kona, Hawai‘i (north to south: Old Kona Airport State Recreation Area to Luna Pule Rd., Kahului Bay).....	31
Figure 11. Modeled groundwater and surface ocean inundation of wastewater infrastructure (WI: sewer mains and manholes) at different sea level rise (SLR) scenarios in Kailua-Kona, Hawai‘i Island, USA (north to south: Kahalu‘u Beach Park to Keauhou).....	32

Introduction

Sea level is rising and impacting coastal onsite sewage disposal systems (OSDS: cesspools, septic tanks, anaerobic treatment units) and other coastal wastewater infrastructures (WI) (sewer lines, treatment plants) integrity and effectiveness. The global sea level is expected to rise 0.3-1.0 m by 2100, with less conservative estimates ranging up to 2 m or greater (Sweet et al., 2017). This rise in sea level will facilitate the inundation of saltwater and brackish groundwater into wastewater systems (Shuler, 2021; Habel et al., 2024), which can compromise nearshore water quality, posing significant risks to both human and ecosystem health. The untreated sewage that can leach from these systems when inundated contains hazardous concentrations of nutrients, pathogens, endocrine disruptors, heavy metals, and other toxins (Wear & Vega Thurber, 2015). Annually, there are an estimated 50 million cases of respiratory illnesses and over 120 million gastrointestinal illnesses worldwide associated with swimming in sewage-contaminated waters (Shuval, 2003; Fleisher et al. 2010). Harmful chemicals found in these contaminated waters can also increase rates of coral disease and algal cover, reduce coral growth and reproduction, and increase coral bleaching which can result in mortality (Nalley et al., 2021). However, by reducing wastewater pollution there is the potential for the coral's mortality rates to decrease and encourage the persistence of coral reefs in these changing climates (Gove et al., 2023). Given the increasing effects of climate change, it is imperative to understand which infrastructures will be exposed and are vulnerable to sea level rise (SLR) in order to develop targeted investments and take protective actions such as upgrades, removal, or relocation of the infrastructures at risk (Hummel et al., 2018). This can be done with the combination of assessing current water quality conditions and analysis of SLR modeling maps with the location and construction details of OSDS and WI. Modeling multiple SLR scenarios can quantify the number of OSDS being inundated and therefore be used to identify areas of vulnerability (Habel et al., 2017; Habel et al., 2019).

Due to the complexity of determining sewage pollution hotspots, multiple indicators and methods are frequently used. Dye tracer tests are used to determine the connectivity between OSDS and WI to the nearshore waters (Glenn et al., 2013; Abaya et al., 2018a; Wiegner et al., 2021; Waiki et al., 2025). A multi-indicator approach has also been used to more accurately detect the presence of sewage pollution (e.g., Abaya et al., 2018a; Aguiar et al., 2023). This approach includes measurements of fecal indicator bacteria (FIB, i.e., *Enterococcus* spp. and *Clostridium perfringens*), nutrients, and $\delta^{15}\text{N}$ in macroalgae. *Enterococcus* spp. are widespread in tropical soils and streams resulting in high levels without any sewage pollution (Byappanahalli et al., 2012), so a secondary sewage indicator (*Clostridium perfringens*) is typically used. Additionally, a stable isotope mixing model using the $\delta^{15}\text{N}$ - and $\delta^{18}\text{O}$ - NO_3^- from water samples have been used to determine percent source contributions of each NO_3^- source (Parnell et al., 2013; e.g., Xue et al., 2009; Wiegner et al., 2021).

Vulnerable to the impacts of SLR, Hawai'i faces an urgent issue of wastewater management with its current and widespread use of cesspools. Cesspools are holes in the ground that are used to discharge raw, untreated human waste as well as other residential and commercial wastewater. Hawai'i was the last state in the U.S.A. to ban cesspools, with approximately 88,000 cesspools releasing over 200,000 m³/d of untreated wastewater (Carollo Engineers, 2021). In response to the concerns of untreated wastewater entering the nearshore waters and threatening human and coral reef health, the Hawai'i Department of Health (HDOH) banned construction of new cesspools in 2015. In 2017, the Hawai'i State Legislature passed Act 125, which requires that all cesspools in the State be converted, upgraded to a septic or aerobic

treatment unit (ATU), or connected to a sewer system by January 1, 2050 (Wada et al., 2021). However, the cost for a full upgrade and conversion can be as high as \$569 million dollars (Wada et al., 2021). These costs show the importance of prioritizing targeted areas that are highly susceptible to inundation and sewage pollution in order to adapt to SLR and increase coastal resilience.

The Kailua-Kona area on Hawai‘i Island is a coastal community with many OSDS and WI at risk of inundation due to SLR. HDOH has identified 6,500 cesspools in the coastal Kailua-Kona area along with the potential fluxes of nutrients to these waters due to these systems (HDOH, 2017). This region frequently hosts canoe paddling and triathlon events, and is a cultural hotspot due to a variety of historical sites, bringing thousands of locals and tourists to this shoreline year round (Wada et al., 2021). The ancient Royal Center at Kamakahonu, located at the north end of Kailua bay, served as Hawai‘i’s first capital where King Kamehameha I ruled the kingdom from 1812-1819 and a restored version can still be seen today (CMP, 2011). Although it is home to many coral reef colonies, it also has the second-highest prevalence of coral growth anomalies in West Hawai‘i, thought to be linked to sewage contamination (Couch et al., 2014; Redding et al., 2013). Previously seawater infiltration and sewage leaks have been documented along this shoreline. Chloride data from a sewage line in this area confirmed the presence of seawater showing that the sewage is not only leaking out, but seawater is also infiltrating the sewer line (Chandler-‘Iao per. comm.). Kailua Bay has also been temporarily closed due to high concentrations of FIB along with a phytoplankton bloom related to a sewer line leak (Jensen, 2020a,b). A $\delta^{15}\text{N}$ macroalgae analysis along Kailua-Kona’s coast determined that the nitrogen comes from a combination of both natural and anthropogenic sources (Smith et al., 2021), resembling values in other areas of Hawai‘i Island that were affected by OSDS. Based on the importance of this shoreline to the community and the ecosystem, and the history of sewage pollution in this area, community members reached out and expressed the need for water quality testing along this shoreline. While previous studies have modeled surface flooding and seawater intrusion from SLR, only a few have included groundwater inundation (GWI) (Habel et al., 2017). Previous studies on Hawai‘i island have been conducted to detect sewage pollution in Hilo (Nakoa, 2022; Waiki et al., 2025) and Puakō (Abaya et al., 2018a; Abaya et al., 2018b; Wiegner et al., 2021; Aguiar et al., 2023), but there is little information regarding sewage pollution along the Kailua-Kona shoreline. No models have included existing or future wastewater infrastructure that could be inundated from SLR and examined future water quality impacts with observational data.

The goals of this study are to: 1) document and identify sewage pollution hotspots along the Kailua-Kona shoreline by assessing the current water quality conditions and 2) map out and assess predicted SLR to determine what OSDS and WI are at risk of inundation. This study will provide a baseline of the current water quality conditions at the shoreline, identify possible sewage pollution hotspots, and address knowledge gaps regarding the impact of SLR on coastal OSDS and WI. This study will provide valuable insights for coastal communities worldwide whose nearshore waters are impacted by OSDS and WI due to SLR in order to increase coastal resilience.

Methods

Site Description

Kailua-Kona is located on the leeward coast of Hawai‘i Island, HI, USA. It is located on the flank of two active volcanoes, Hualālai and Mauna Loa, resulting in the land mostly

consisting of highly permeable basalt rocks with no major rivers or streams entering the ocean (Wada et al., 2021; Peterson et al., 2009). It is characterized by a tropical dry climate, with a mean annual rainfall of 575-870 mm and greater mean rainfall at higher elevations (Frazier & Giambelluca, 2017; Fackrell et al., 2020). Due to the region's geology, the water can infiltrate and form groundwater reservoirs at various elevations. In Kailua-Kona, high-level groundwater exists in perched aquifers above less permeable rock layers and is primarily replenished by rainfall at higher elevations (Fackrell et al., 2020). While the lower-elevation groundwater aquifers have a subterranean connection to the marine lens allowing for saltwater to mix in, creating brackish water immediately below the water table (Oki, 1999). These freshwater fluxes from the land to the sea occur as submarine groundwater discharge (SGD) rather than surface flow to the shoreline (Peterson et al., 2009). Historically, this SGD provided an important source of water and food through the use of loko i'a (fishponds) for the coastal communities (Gibson et al., 2022).

There are ~6,500 cesspools located in the coastal Kailua-Kona area, with an effluent discharge of 15 ML/d into the nearshore waters (Carollo Engineers, 2021). The northern part of this study site (north to south: Kailua pier to Keolonahihi State Historical Park) is a Priority Level 1 for cesspool conversion according to HDOH, as it has the second-highest concentration of OSDS on Hawai'i Island (Hawai'i Cesspool Hazard Assessment, 2022). However, the southern part of this study site (north to south: Keolonahihi State Historical Park to Keauhou) is currently at a Priority Level 2. Priority Level 1 areas are characterized as cesspools that have the greatest potential to impact human health and the environment and are directly adjacent to sensitive natural resources like coral reefs or drinking water aquifers, while Priority Level 2 areas are ranked below level 1 areas, but still pose a serious threat (Hawai'i Cesspool Hazard Assessment, 2022).

The Kealakehe Wastewater treatment plant (KWWTP) and the Keauhou Community Services, Inc.'s (KCSI) wastewater system are the two WWTPs that services this study area. The KWWTP services the northern part of this study site from Kailua-Kona area to Magic Sands. It is the only municipal WWTP in the area and it treats 6 ML/d of sewage from the North Kona sewerage system using aerated lagoons and disposing of the treated sewage into a percolation basin (Wada et al., 2021). While the southern portion of this study site including Kahalu'u Beach Park and Keauhou Bay is serviced by KCSIs wastewater system, which also serves about 1,500 residential, hotel, and commercial customer-equivalent units in Keauhou (Hawaii Water Service, per. com.). Based on these two different systems, the study shoreline for this project was split into two different regions of the Kailua-Kona area (Priority Level 1) and Kahalu'u to Keauhou (Priority Level 2).

Dye tracer tests

A dye tracer test was completed at a home and a public restroom near Kahalu'u Bay (1 cesspool, 1 sewer line) in August & October 2024, to determine their connectivity to shoreline springs. A non-toxic yellow-green fluorescein dye was used for this study. It was selected due to its low adsorption to basalt and vibrant color making it easy to observe even at concentrations orders of magnitude below levels harmful to marine life (Field et al., 1995; Glenn et al., 2013). Powdered fluorescein dye (Amresco Fluorescein Sodium Salt) was mixed with tap water at concentrations of 50-75 g per 20 L of tap water per hour and slowly added to the OSDS/pump station over a 10 hour period or until the dye appeared at the shoreline. Additional water was added throughout the day to flush down the dye and to calculate the initial dye concentration.

Water samples were collected from 7-8 coastal springs in the area, where the dye was expected to emerge. Samples were collected before, during and after the addition of the dye. During the first day of the dye tracer study, samples were collected every 2 hours in order to identify any fast flow pathways. After day 1, duplicate samples were collected from each spring in the morning and within an hour of the lowest low tide twice a day for up to nine days. Samples were collected in 125 ml amber HDPE bottles to prevent photo-degradation. Samples were stored on ice as they were transported to the lab and stored at 4 °C until analysis, within 1 month. In the lab, sample conductivity was measured using a Fisher Scientific Accumet AB200 conductivity meter and it was used to calculate the salinity of each sample. For the fluorescence analysis, samples were brought to room temperature, filtered (0.7- μ m, Whatman™ GF/F), and analyzed using a Turner AU10 fluorometer. Fluorescein standards were made by dilution from a 100,000 ppb stock solution to 10–200 ppb. The method detection limit is 0.1 ppb.

Shoreline station selection and sample collection

A shoreline salinity survey was conducted from June 29 to July 1, 2022, using a YSI ProSolo to document salinity and temperature and a Garmin GPS to mark these locations. From this survey and in collaboration with local stakeholders, 12 shoreline stations were chosen from the Kailua Pier to Keauhou based on having low salinity, importance to the community, and if they were areas of concern for sewage pollution (Fig. 1). There were large gaps between the sampling stations because some locations had very little detectable groundwater discharge and others were not accessible due to cliffs.

Water and macroalgal samples were collected on the lowest tides during each month on two consecutive days from August 2022 to September 2023. Low tides were targeted for sampling in order to minimize dilution of groundwater with seawater and optimize sewage detection. Early morning sampling was conducted to better capture FIB concentrations in groundwater at the shoreline springs, because sunlight reduces the survival of FIBs (Fujioka et al., 1981; Sinton et al., 2002). Triplicate water samples were collected at each station in sterile, acid washed, 1-L polypropylene plastic bottles and stored on ice during transport to the lab. Samples were processed within 6 h of collection. In the field, at each station, physicochemical parameters (temperature, salinity) were measured using a calibrated YSI ProSolo. Macroalgal samples were also collected at each station for $\delta^{15}\text{N}$ and %N analyses.

Laboratory Analyses

FIB and Pathogen Analyses

In the laboratory, each of the three sample bottles were analyzed for *Enterococcus* spp. and *Clostridium perfringens*. *Enterococcus* spp. was analyzed using the Enterolert MPN method and Quanti- Tray®/2000 from IDEXX Laboratories Inc. following the manufacturer's recommendations of 10 mL of the sample and 90 mL of sterile. This method is used by HDOH and its analytical range is from 1 to 2419 MPN/100 mL. Samples that fell below the detection limit and displayed no fluorescent blue wells are reported as 5 MPN/100 mL, half of the detection limit. *Clostridium perfringens* was enumerated by filtering 100 mL of the sample water through 0.45- μ m pore size cellulose nitrate filters (Whatman™), incubating them on mCP agar in an anaerobic jar at 45°C for 18-24 h, and then exposed to ammonium hydroxide for 30 s (Bisson and Cabelli, 1979). Pink colonies were counted and recorded as positive confirmation. At six of the 12 stations for four months of the study, we analyzed these water samples for *S. aureus* and MRSA. The water samples were filtered through a 0.45- μ m pore size cellulose nitrate filter (Whatman) and placed on BBL CHROMager *S. aureus* (Becton, Dickinson Co. MD) and BBL MRSA II Select media (Becton, Dickinson Co., MD), incubated at 37°C for 24 h, and

mauve/purple colonies were counted and recorded as positive confirmations (Goodwin & Pobuda, 2009; Viau et al., 2011). Colonies were re-streaked and incubated again for 24 h for additional confirmation. All samples were corrected for sample dilution.

Nutrient Analysis

Water from one of the three samples from each station was also analyzed for nutrient concentrations, turbidity, pH, Chlorophyll *a* (Chl. *a*), and $\delta^{15}\text{N}$ - and $\delta^{18}\text{O}$ - NO_3^- . For nutrient analysis, the sample water was filtered through a muffled (500 °C for 6 h) filter (GF/F Whatman™, 0.7- μm) and stored frozen until it could be analyzed at the University of Hawai‘i at Hilo (UH Hilo) Analytical Laboratory. Nutrients were analyzed on a Lachat Quikchem 8500, FIA for $\text{NO}_3^- + \text{NO}_2^-$ [Detection Limit (DL) 0.07 $\mu\text{mol/L}$, EPA 353.2], NH_4^+ [DL 0.36 $\mu\text{mol/L}$, EPA 349], PO_4^{3-} [DL 0.03 $\mu\text{mol/L}$, EPA 365.5], and total dissolved phosphorus (TDP) [DL 0.25 $\mu\text{mol/L}$, USGS I-4650-03, EPA 365.5], and H_4SiO_4 [DL 1 $\mu\text{mol/L}$, EPA 366]. Total dissolved nitrogen (TDN) and dissolved organic carbon (DOC) were analyzed on a Shimadzu TNM-1, TOC-V using high-temperature combustion, followed by chemiluminescent detection of nitric oxide (DL 5, 10 $\mu\text{mol/L}$, ASTM D5176, EPA 415.1) (Sharp et al., 2002). Turbidity and pH were measured in the laboratory with calibrated HACH 2100Q and an ORION STAR A325. Filters from the nutrient samples were stored frozen for Chl *a* analysis and analyzed using a Turner 10-AU fluorometer using EPA 445.0 method. For a $\delta^{15}\text{N}$ - and $\delta^{18}\text{O}$ - NO_3^- analysis, water samples filtered through a 0.4- μm nylon filter (Corning) and analyzed on a Thermo-Finnigan™ Delta V Advantage isotope ratio mass spectrometer (IRMS) with a Conflo III interface and a Costech™ ECS 4010 Elemental Analyzer. Isotope data were normalized to USGS standards (USGS32, USGS34, USGS35) and expressed as per mil (‰) Eq. (1).

$$\delta^{15}\text{N}, \delta^{18}\text{O} = [(R_{\text{sample}} - R_{\text{standard}})/R_{\text{standard}}] \times 1000, R = {}^{15}\text{N}/{}^{14}\text{N}, {}^{18}\text{O}/{}^{16}\text{O} \quad (1)$$

Macroalgae Analyses

A variety of macroalgae species were present along the coastline and differed among stations. Hence, we collected composite macroalgae samples at each station for $\delta^{15}\text{N}$ and %N analysis. Previous studies have found that the $\delta^{15}\text{N}$ from different macroalgal species collected at the same locations had similar values (Wiegner et al., 2016). Samples were placed into a ziploc bag with station water on ice during transportation to the laboratory. In the lab, the macroalgae were rinsed with deionized water, placed into the drying oven at 60 °C, until a constant weight was achieved. Prior to being placed in the drying oven, a subsample of each species present at each station was preserved as voucher specimens in 4% formalin. Macroalgae samples were identified to the lowest taxonomic based on morphological and anatomical characteristics using an Olympus BX41 compound microscope and identification books (Abbott, 1999; Abbott and Huisman, 2004). The remaining samples were dried at 60 °C, homogenized using a Wig-L-Bug grinding mill, and placed in 3.5 x 5-mm tin capsules. The macroalgal tissues were analyzed for $\delta^{15}\text{N}$ using a Thermo-Finnigan™ Delta V Advantage IRMS with a Conflo III interface and a Costech™ ECS 4010 Elemental Analyzer at the UH Hilo Analytical Laboratory. Data were normalized to USGS standard NIST 1547 and reported as %N and $\delta^{15}\text{N}$ vs N_2 in air.

Stable Isotope Mixing Model (SIMMR)

A stable isotope mixing model was used to determine the percent contribution of specific NO_3^- sources to the NO_3^- pool at each station. The "simmr" package in Rstudio (version 0.4.5) was used. This model uses Bayesian methods and NO_3^- concentration dependence to account for natural variation and uncertainty in the model (Parnell et al., 2013). Potential NO_3^- sources included were: sewage (n = 7), groundwater (n = 15), and ocean (n = 6). These source values

came from previous studies that were conducted from the same area as this study on Hawai‘i Island (Hunt, 2014; Abaya et al., 2018; Wiegner et al., 2021; Panelo et al., 2022).

Sewage Pollution Score

A sewage pollution score was calculated for each station using the method developed by Abaya et al. (2018a). The score was calculated using three sewage indicators FIB, $\delta^{15}\text{N}$ macroalgae, and nutrient concentrations Eq. (2). Each parameter had three levels (1 = low, level 2 = medium, level 3 = high) based on its concentration relative to HDOH standards or literature values. Each parameter was also assigned a weight based on its reliability as a sewage indicator, with the most reliable indicators having a weight of 3. However, at the time of writing, not all macroalgae $\delta^{15}\text{N}$ values were available, so low $\delta^{15}\text{N}$ was assumed when no data was available. Scores were calculated using Eq. (2) and placed into low (11-17), medium (18-25), and high (26-33) sewage pollution categories.

$$(C. \text{perfringens level} \times 3) + (\delta^{15}\text{N macroalgae level} \times 3) + (Enterococcus \text{ spp. level} \times 2) + (\text{NO}_3^- + \text{NO}_2^- \text{ level} \times 1) + (\text{NH}_4^+ \text{ level} \times 1) + (\text{TDP level} \times 1) \quad (2)$$

Statistical Analysis

Normality and equal variance assumptions were assessed using the Shapiro-Wilk and Levene's tests. If assumptions were not met, log or square root transformations were used, or a non-parametric test was conducted. A one-way analysis of variance (ANOVA) or a Kruskal-Wallis test was conducted to determine if there were potential differences in FIB and nutrient concentrations, as well as $\delta^{15}\text{N}$ in the macroalgae and $\delta^{15}\text{N}$ - and $\delta^{18}\text{O}$ - NO_3^- measurements among stations. A Tukey post hoc test (or Dunn's test), followed by a Bonferroni correction, was used to determine differences among stations. Additionally, the $\delta^{15}\text{N}$ values in macroalgae were compared to the potential NO_3^- sources to determine the origin of nitrogen in their tissues (Wiegner et al., 2016). All statistical analyses were conducted in R studio (version 4.3.0), with a significance level (α) set at 0.05.

Sea Level Rise Modeling

To predict sea level rise impacts to coastal wastewater infrastructure and water quality, we created high-resolution geospatial models of groundwater (GW) levels above local mean sea level at current and future SLR scenarios. Local wells and groundwater level loggers placed into anchialine pools were used to update the groundwater level model developed by Marrack et al. (2020). In West Hawai‘i, the GW table is elevated above the mean sea level, sloping up and away from the shoreline, and it moves in response to changes in ocean level (Okai, 1999). Raster surfaces representing the increase in the GW heights with the distance from the shore were created based on our field measurements. We then mapped approximate shoreline position and GW heights with future projections of SLR (MHHW, 0.3, 0.6, 1, 1.5, and 2m) expected for this region of the Pacific throughout this century (Sweet et al., 2020). In order to develop a risk framework for GW from sewage infrastructure, we compared the locations and depths of OSDS, sewer lines, and injection wells with models of future GW levels.

Groundwater Level Model

Previous work in West Hawai‘i immediately north of the study area showed that the relationship between average GW height in meters above MSL (H_{GW}) and distance from shore in meters (d) could be calculated as $H_{\text{GW}} = (0.010883d^{1/2} + 0.15234)$ ($R^2 = 0.8$; Marrack et al., 2021). The data and resulting curve support previous observations from the Kona area (Marrack, 2015), as well as theoretical models for homogeneous unconfined coastal aquifers with constant recharge from an inland source (Glover, 1959).

To compare the relationship to GW in the study area, GW levels were collected at four anchialine pools and six wells located between Kailua and Keauhou. GW level loggers (Rugged TROLL 100; In-Situ, Inc., Fort Collins, CO, USA) were deployed in three of the four pools and collected data at 15-minute intervals for three months from July 21, 2023 to Nov 1, 2023. The Old Airport pool goes dry at low tides and therefore was measured by hand over this time period. At each level-logger position, semi-permanent benchmarks were established by Ryan Perroy and the Spatial Data and Visualization Lab at UH Hilo using a Trimble R10-2 (Global Positioning System, GPS) differential receiver during July 21, 2023. These surveyed control points were used to calculate the mean GW level over sea level as well as examine the effect of tides on GW heights with high vertical resolution (< 4 cm).

Additional GW level data was obtained from GW test wells including four located in the Kaloko-Honokohau area and maintained by the United States Geological Survey (USGS) and two located in the Kahalu'u area and maintained by the State of Hawai'i Commission of Water Supply (Table 3). Other wells exist in this area, but they do not have regularly collected monitoring data available online. Mean GW levels from the three loggers along with the measurements from the additional seven GW sites were used to recalculate the equation for H_{GW} .

To map the increase of GW heights with distance from the shore, geospatial rasters were developed based on the equation for H_{GW} (Marrack et al., 2021). First, a 2-m resolution raster representing the Euclidean distance from the shoreline was created. Then, the mean GW height above local MSL was calculated by applying the GW height equation to each pixel within the Euclidean distance raster. A tidal efficiency component was then added to the GW raster to incorporate MHHW tidal effects on GW heights. Tidal effects decay with distance inland from shore, and can be represented by a tidal efficiency ratio, which is the ratio of mean daily GW tidal range at a site to mean daily ocean tidal range (Todd, 1980). The ratio is 1 at the shoreline and decreases to 0 inland, where there is no tidal effect. For this study, raster surfaces representing tidal influence during MHHW (0.364 m over MSL, Kawaihae tide gauge) were combined with the raster of GW heights above MSL to create the final GW models. GW models were created for each sea level scenario using the unique shoreline (MSL) predicted for that specific ocean water level. Additionally, GW elevations were increased for each sea level scenario by adding magnitude of sea level change to the GW raster.

Sea Level Rise

We used a modified “bathtub” approach to map sea level rise scenarios onto the topography of the study area. The commonly applied “bathtub” approach delineates flooding on any surface below a specific elevation on a coastal DEM. We modified this approach in two ways - we incorporated vertical uncertainty associated with the digital elevation model (DEM) and we added the GW raster to more realistically depict flooding in areas inland from the ocean.

To account for vertical uncertainty associated with the DEM, we employed the modified deterministic approach described by Gesch et al. (2020). The full vertical error (RMSE or LE95) is added to or subtracted from the sea level change, then these values are used to delineate the minimum and maximum projected inundation zones for that SLR scenario. Thus, the flooded area between these values has a confidence label based on the error probability distribution. For this study, we used the most current Lidar DEM product for the West Hawai'i coast from the 2018 - 2020 NOAA USGS Lidar DEM dataset (Office for Coastal Management, 2024). The DEM is 1m resolution and projected to the current geoid, GEOID 12B, which is offset from local mean sea level by approximately 0.5 meters in the State of Hawai'i. Based on recommendations from NOAA's National Geodetic Survey lead Ed Carlson (Pacific Rim Geospatial Conference

3/17/2023), the DEM was globally corrected for the Island of Hawai‘i by -0.474 m to get orthometric heights. The non-vegetated vertical accuracy is 0.21 m at the 95% confidence level or 0.11 m RMSE, and the vegetated vertical accuracy is 0.91 m at the 95% confidence level or 0.50 m RMSE.

For each sea level rise scenario, maps of projected inundation zones were created. The shoreline from Kailua to Keauhou is primarily rocky, therefore the non-vegetated vertical accuracy level (0.11 RMSE) was used to map coastal inundation. Because a specific shoreline was needed to create the GW level rasters, the upper level of flooding was used for each SLR scenario. Additional inland flooding at each scenario was mapped in locations where the GW elevations were greater than the DEM topography.

Water levels used in flood models included still water level (regional SLR, oceanographic processes, tides, and climate variability) and GW levels. Models do not include predictions of storm waves or erosion, and will not account for changes in GW recharge from changes in future rainfall.

Sewage Infrastructure Risk

We combined the GW level model with the SLR scenarios to determine which existing WI could be inundated due to SLR thus at greater risk of corrosion and leaking of sewage to the nearshore. A spatial analysis compared the locations and depths of OSDS, sewer lines, and injection wells with models of future GW levels.

The Hawai‘i County Planning Department provided a dataset of sewage infrastructure in the area of study. The GIS data included sewage mains and laterals, manholes and pumping stations. The sewage system in this location is gravity driven. In the GIS dataset, each sewage main or lateral has a *downelev* value which represents the lowest elevation of the pipe. For each SLR scenario, the pipes were categorized as at high risk if they were at or below the elevation of the GW raster (MHHW) in a particular location. This translates to a pipe being submerged at MHHW on a daily basis. For the manholes, the *invert* level, defined as the elevation of the inside - bottom or the “floor level” of the pipe, was used to determine risk.

To determine chronic risk to GW from septic systems and cesspools, we compared the depth of GW to the depth of cesspools. Cesspool position was estimated using the Hawai‘i State OSDS layer, which identifies OSDS in the centroid of each property (Whittier and El Kadi, 2014). There are no data on the depths of the cesspools in the GIS layer; however, a conversation with staff at the State of Hawai‘i Department of Health confirmed that cesspools in the study area typically range from 3 to 4.5 m deep (measurements are from ground surface to the deepest part of cesspool). A haphazard check of 10 individual records for cesspools located between shoreline and 12 m elevation relative to local mean sea level show that the cesspools are between 3 to 4.6 m deep in the study area. Hawai‘i State regulation (HAR 11-62) considers a cesspool to be flooded or impacted by SLR if the space between land surface of the cesspool and the GW is less than 4.4 m. For this study, we assume septic and cesspools to be impacted if there is less than 5.5 m between the surface topography (DEM) to the GW. The 5.5 m threshold includes 0.9 m of unsaturated space in the porous soils between the cesspool and the GW surface and the maximum recorded depth of cesspools in the coastal zone of the study area (4.6 m). For each SLR scenario, the OSDS were categorized as high risk if they were within a location where the DEM minus the GW raster (MHHW) was < 5.5 m. This translates to an OSDS being within the impact distance at MHHW on a daily basis. H_{GW} .

Results

Dye Tracer Test

Dye was detected at the Kahalu‘u shoreline within 5.5 hours after dye was initially added to the cesspool. The dye was first observed visually at one station (Fig. 2). Dye was also observed at other stations at lower concentrations: however, it was unclear whether the dye came from GW or if it was washed along the shoreline from the station, where the highest dye concentration was observed. Dye was also observed at an anchialine pool and was added on day 2 as a sampling station. Based on these times and the distance to the house, the flow rate for dye to travel from the cesspool to the shoreline was 278 m/d. Throughout the dye tracer test, concentrations at the other shoreline springs remained near background (0.17 ± 0.16 ppb), demonstrating no outside sources of fluorescein from the seawater were evident.

No dye was visually observed at the shoreline during the second dye tracer test conducted at the public restroom. It was determined that no significant dye presence was detected throughout the five days following the dye addition. Fluorescein concentrations remained within the range of background values, with the highest recorded concentration being 0.09 ppb.

Fecal Indicator Bacteria & Pathogens

Enterococcus spp. concentrations ranged from 18 to 286 MPN/100 mL and differed among stations (Fig. 3, $\chi^2 = 44.5$, $p < 0.001$), with station 12 having the highest concentration (286 MPN/100 mL). *Clostridium perfringens* concentrations were similar among the stations with the highest concentration being 2 CFU/100 mL and averaging (Average $\pm$ SE) 0.5 ± 0.1 CFU/100 mL (Fig. 3; $\chi^2 = 15.2$, $p = 0.17$). *Staphylococcus aureus* was present along the shoreline, with concentrations similar among the six stations sampled (93 ± 30 CFU/100 mL), ranging from 14 to 214 CFU/100 mL (Fig. 3, $\chi^2 = 1.18$, $p = 0.95$). *MRSA* was not detected at any of the stations.

Nutrients

Nutrient concentrations varied among stations for all parameters. $\text{NO}_3^- + \text{NO}_2^-$ concentrations ranged from 8.71 to 139 $\mu\text{mol/L}$ ($\chi^2 = 102$, $p < 0.001$) and TDN concentrations ranged from 18.9 to 148 $\mu\text{mol/L}$ ($\chi^2 = 114$, $p < 0.001$) (Table 1). For both of these parameters, station 6 and 7 had the highest concentrations (Table 1). NH_4^+ also differed among stations ($\chi^2 = 20.3$, $p = 0.04$), with concentrations ranging from 0.43-1.51 $\mu\text{mol/L}$ (Table 1). Based on these concentration ranges, $\text{NO}_3^- + \text{NO}_2^-$ is the dominant form of TDN, constituting about 94% of the total TDN. PO_4^{3-} concentrations ranged from 0.52 to 3.88 $\mu\text{mol/L}$ ($\chi^2 = 80.3$, $p < 0.001$) and TDP concentrations ranged from 0.92 to 3.24 $\mu\text{mol/L}$ ($\chi^2 = 60.3$, $p < 0.001$) (Table 1). H_4SiO_4 concentrations ranged from 46.5 to 272 $\mu\text{mol/L}$ ($\chi^2 = 65.9$, $p < 0.001$), with stations 5 and 10 having the overall highest concentrations (Table 1). DOC concentrations also differed among stations ($\chi^2 = 31.3$, $p = 0.001$), ranging from 79 to 127 $\mu\text{mol/L}$ with station 10 having the lowest concentration and station 12 having the highest (Table 1). Station 2 consistently displayed the lowest nutrient concentrations for $\text{NO}_3^- + \text{NO}_2^-$, NH_4^+ , TDN, PO_4^{3-} , TDP, and H_4SiO_4 (Table 1).

Chlorophyll a, Turbidity, & pH

Chlorophyll *a* concentrations differed among stations ($\chi^2 = 41.7$, $p < 0.001$). Station 3 had the highest concentration of Chl. *a* at 1.4 $\mu\text{g/L}$, while station 10 had the lowest concentration (0.3 $\mu\text{g/L}$). Turbidity and pH also differed throughout the stations ($\chi^2 = 35.5$, $p < 0.001$; $\chi^2 = 60.1$, $p < 0.001$), with turbidity ranging from 0.83 to 9.91 NTU and pH ranging from 7.8 to 8.2.

Macroalgae $\delta^{15}\text{N}$

The most prevalent macroalgal species along the shoreline were *Ahnfeltiopsis concinna*, *Chaetomorpha antennina*, and *Gelidium pusillum* (Table 2). Macroalgal $\delta^{15}\text{N}$ values significantly

differed among the stations, ranging from +2.7 to +5.4‰ (Fig. 4, $F = 7.88$, $p < 0.001$). Stations 2, 4, 6, 7, and 12 had the highest values, while stations 10 and 11 had the lowest. Percent N content in macroalgae also differed among stations ($F = 5.42$, $p < 0.001$), with station 8 having the highest values and station 5 having the lowest values (Fig. 4). All of the stations fell below the range indicated for sewage, with almost all of the stations falling within the range for groundwater (Fig. 4).

Stable isotope mixing model (SIMMR)

Of the three potential NO_3^- sources (sewage, groundwater, ocean) included in the mixing model, the dominant source was groundwater (Fig. 6). Based on the median estimate (50th quantile) across all twelve stations, groundwater contributed 77% of the NO_3^- . Station 5 had the highest GW contribution of 85%, with station 3 having the lowest of 37%. The ocean was the second most dominant source contributing 15% to the NO_3^- pool. Ocean contributions ranged from 11-25%, with station 5 having the lowest and station 3 having the highest contributions (Fig. 6). Sewage had the lowest contribution to the NO_3^- pool with 5.8%. Station 3 had the highest sewage contribution of 37% and station 5 displayed the lowest sewage contribution of 3% (Fig. 6).

Sewage Pollution Score

All 12 stations had low to medium sewage pollution scores, with an overall median of 17 (Fig. 7). Average sewage pollution scores at each individual station ranged from 16 to 18. Stations 3, 5, 9, 11, and 12 had the highest mean sewage pollution score of 18, placing these stations into the medium sewage pollution category. Stations 2 and 8 had the overall lowest sewage pollution score of 16.

Sea Level Rise Modelling

Using six different SLR scenarios (2024 MHHW, 0.3, 0.6, 1, 1.5, 2 m), maps were created to determine which OSDS and WI are at risk of inundation. Based on the 0.3 m SLR scenario (north to south: Old Airport to Kahalu‘u), approximately two OSDS are estimated to be inundated at the surface, 56 OSDS are at risk of inundation from GW with threshold depths < 4.4 m, and 77 OSDS with threshold depths < 5.5 m (Table 4, Fig. 8 & 9). At the 2-m scenario, this number increases significantly with nine OSDS being inundated at the surface, 92 OSDS at risk of inundation at threshold depths < 4.4 m, and 112 OSDS at threshold depths < 5.5 m (Table 4, Fig. 8 & 9). SLR scenario modeling also revealed that the majority of WI are already being inundated during MHHW events (66 mains, 55 manholes) along the Kailua-Kona shoreline (North to south: Kailua pier to Kahalu‘u) with an additional 13 mains and 11 manholes from Kahalu‘u to Keauhou (Table 5, Fig. 10 & 11). The number of inundated WI doubles at a 2-m SLR scenario, with 135 mains, 113 manholes inundated from groundwater, and 33 mains, 17 manholes flooded at the surface along Kailua Kona shoreline (Table 5, Fig. 10). With an additional 20 mains, 15 manholes inundated from GW and 10 mains, and seven manholes inundated at the surface during a 2-m SLR scenario just from Kahalu‘u to Keauhou (Table 5, Fig. 11).

Discussion

Dye Tracer Test

Dye tracer tests provide irrefutable evidence of the connectivity of OSDS and WI to nearshore waters (Glenn et al., 2013; Abaya et al., 2018a; Waiki et al., 2025). The dye tracer test conducted at Kahalu‘u Bay, demonstrated that sewage from OSDS in the area is reaching the shoreline. A groundwater flow rate of 278 m/d was measured in this study, which is faster than

any of the flow rate reported in previous dye tracer studies done on Hawai‘i Island. Keaukaha in Hilo ranged from 130 to 213 m/d (Waiki et al., 2025) and Puakō in South Kohala had flow rates two times slower, 137 m/d (Abaya et al., 2018a, Wiegner et al., 2021). Our flow rate is also much faster than the dye tracer test done in Lahaina, Maui, that determined the connectivity between WWTP and injection wells to the shoreline waters, with a maximum flow rate of 8.9 - 9.5 m/d (Glenn et al., 2013). This flow rate could be a result of various factors such as rainfall (Frazier & Giambelluca, 2017), hydrogeology (Whittier and El Kadi, 2014), and geology of the area. Higher rainfall can increase the flow rate of the dye, but it could also impact the concentration of the dye through dilution. Hydrogeology differs between these four locations and is impacting the flow rate of these tests due to flow barriers that could slow the flow down or streams that speed up the flow (Whittier and El Kadi, 2014). Another factor that could explain the different results between these areas is the geology of the study site. Although Kailua-Kona has fairly low rainfall and no major streams or rivers, this high flow rate could be due to the geology of the area such as underground fractures or lava tubes. However, additional dye tracer tests are necessary to determine the spatial extent of this fast flow rate. With this flow rate, sewage from cesspools along the coastline will only take a few hours to reach the nearshore waters. If this same flow rate extends farther inland, sewage from homes just above the Māmalahoa highway (1.5 km) would reach the shoreline in less than 6 days.

Shoreline Water Quality

Fecal Indicator Bacteria (FIB) are typically monitored to assess recreational waters and identify the potential risks of swimming in sewage polluted waters. When comparing the average values of *Enterococcus* spp. from this study to the HDOH beach action value (BAV) of 130 MPN/100 mL, eight out of twelve stations exceed this threshold 20 times within one year (HDOH, 2019). The average *Enterococcus* spp. concentrations exceeded the HDOH geometric mean water quality standard of 35 MPN/100 mL at ten out of the twelve stations. High *Enterococcus* spp. concentrations have also been measured on Hawai‘i Island in both Hilo (Nakoa, 2022) and at Puakō’s shoreline with values ranging from 324 to 19,018 MPN/100 mL (Wiegner et al., 2021). However, in a study done at multiple beaches in California the *Enterococcus* spp. concentrations were fairly low with an average concentration of 42 CFU/100 mL, which is equivalent to 42 MPN/100 mL (Goodwin et al., 2012). With the results of beaches in California exceeding the standard of 35 MPN/100 mL and the results from studies on Hawai‘i Island frequently exceeding the BAV, the odds of diarrhea, respiratory illness, and earache is elevated among swimmers compared to non-swimmers and beach users (Sinigalliano et al., 2010; Wade et al., 2010). Since these beaches are typically frequented by swimmers and surfers there is an increased health risk for those who use these waters. Based on a study by Sinigalliano et al. (2010) even with a mean *Enterococcus* spp. concentration of 71 CFU/100 mL, 4.75% of bathers reported gastrointestinal disease while 7.47% reported skin disease. Our results showed the months of August and November 2023 frequently having the highest overall *Enterococcus* spp. concentrations, possibly due to the higher wave action during these periods. Higher wave action could potentially increase the concentration of *Enterococcus* spp. in the environment by disturbing the sand at beaches, which then can release previously deposited bacteria and pathogens into the water (Goodwin et al., 2012), meaning that high *Enterococcus* is not strictly from sewage contamination. Therefore, in order to more accurately detect the presence of sewage pollution, *C. perfringens* was used as a secondary sewage indicator (Fujioka et al., 2015).

The average *C. perfringens* concentrations reported from this study was below the water quality standard of 5 CFU/100mL recommended by Fujioka et al. (2015) (Fig. 3). Additionally

using the Fung/Fujioka *C. perfringens* scale for sewage pollution, all 12 stations fell below the range indicative of non-point sewage contamination (> 10 CFU/100 mL) (Fung et al., 2007). The *C. perfringens* concentrations reported from this study were generally lower than those measured in Puakō (2-12 CFU/100mL, Abaya et al., 2018a; Wiegner et al., 2021). However, concentrations are comparable to those reported in a previous study done in Hilo that ranged from (0-2 CFU/100mL, Nakoa, 2022). *C. perfringens* concentrations in both Hilo and this study could be low concentrations due to dilution from freshwater or ocean water mixing, while Puakō could be more polluted and not as impacted by dilution from freshwater or the ocean. Another study done at a few beaches on the Mexican Pacific coast also found a similar pattern. They measured high values for *Enterococcus* spp. (149-157 CFU/100mL), but lower concentrations for *C. perfringens* ranging from 35 to 89 CFU/100mL (Curiel-Ayala et al., 2012). However, 95.8% of their samples measured exceeded the standard of 5 CFU/100mL, while the results of this study remained far below the standard.

Pathogens in nearshore waters are a significant public health risk, as recreational water users may be exposed to harmful infections through direct contact with contaminated water. Pathogens such as *S. aureus* and *MRSA*, both have been detected in raw sewage in Hawai‘i and other locations worldwide (Economy et al., 2019; Steadmon et al., 2024). This study showed that five out of the six stations had an average count above 100 CFU/100 mL, which is the level associated with increased infection rates among recreational pool water users (Favero et al., 1964). However, the overall average concentration for *S. aureus* exceeds this recommended value at only three out of the six stations with *MRSA* not being detected at any of the stations (Fig. 3). Although this portion of the study was conducted over a four-month period, the elevated concentrations of *S. aureus* observed in January may be associated with an increase in beachgoers during that time. Human skin sheddings is a potential source of *S. aureus* (Elmir et al., 2007; Goodwin et al., 2012), the stations recording the overall highest concentrations were located at Kahalu‘u and Keauhou Bay, which is areas that are typically frequented by large numbers of swimmers and surfers. The results of a study done in Mexico had similar conclusions, where 70% of their samples exceed the guideline value of 100 CFU/100 mL (Curiel-Ayala et al., 2012). Based on the results of their study and visual observations they also noted that higher *S. aureus* concentrations coincided with the highest tourist presence at the beach. Along with beachgoers potentially contributing to the *S. aureus* and the sand or other factor impacting *Enterococcus* concentrations, Mexico also faces the issue of sewage pollution in their shoreline waters.

Elevated nutrient concentration in coastal waters is also associated with sewage pollution (Lapointe et al., 2015; Abaya et al., 2018a). However, in our study nutrient concentrations significantly varied across all 12 stations, making it difficult to identify sewage hotspots from these measurements alone. Station 2 consecutively displayed the overall lowest nutrient concentrations for $\text{NO}_3^- + \text{NO}_2^-$, TDN, PO_4^{3-} , H_4SiO_4 , NH_4^+ and TDP. These low concentrations could be due to the physical mixing and dilution with seawater, since this station did not have a strong GW outflow (Prouty et al., 2017). These findings are comparable to a study done in Puakō that found an inverse correlation of nutrient concentrations with salinity, suggesting that these nutrients are more concentrated in freshwater sources (groundwater) and become diluted as they mix with seawater (Prouty et al., 2017; Abaya et al., 2018a). These findings are also comparable to a study done in Hilo, where GW-influenced areas had high nutrient concentrations and low $\delta^{15}\text{N}$ macroalgal values (Nakoa, 2022). Since station 2 did not have strong GW influence, it had low nutrient concentrations due to possible seawater dilution and high $\delta^{15}\text{N}$ macroalgal values

indicating possible sewage contamination. Station 5 appeared to have the highest PO_4^{3-} , TDP, NH_4^+ , and H_4SiO_4 concentrations. This nutrient enrichment is possibly due to groundwater discharge, which could potentially be a result of anthropogenic sources such as sewage pollution (Prouty et al., 2017).

$\text{NO}_3^- + \text{NO}_2^-$ is typically found in sewage. A previous study by Gove et al. (2023) modeled the offshore distribution of sewage effluent using a Gaussian decay function along the Kailua-Kona shoreline. Using the average $\text{NO}_3^- + \text{NO}_2^-$ concentrations by stations from this study and the effluent dispersal from Gove et al. (2023), areas with high nutrient concentrations were associated with areas of high effluent dispersal offshore (Fig. 5). However, based on the Gove et al. (2023) paper, their data did not extend as far south as this study. Associations between the modeled data and this study could not be determined for the Kahalu'u and Keauhou stations. The Holualoa stations (6 & 7) displayed the highest $\text{NO}_3^- + \text{NO}_2^-$ concentrations and were associated with the highest effluent dispersal possibly indicating some sort of sewage influence in this area. However, station 8 is also located within this high sewage effluent area, but it displayed low nutrient concentrations and had the lowest sewage pollution score (16). These results indicate that even though elevated nutrients are typically detected in sewage polluted areas (Amato et al., 2016), measuring nutrient concentrations alone as sewage pollution indicators is not adequate (Abaya et al., 2018). These comparisons also provide the opportunity for future work to be done at Kahalu'u and Keauhou to better understand the impact on those areas as well.

Macroalgae $\delta^{15}\text{N}$

Since nutrients can come from multiple sources that are not detectable based solely on concentrations, macroalgae $\delta^{15}\text{N}$ is a useful indicator in determining N sources. Its distinct stable N isotopic composition has also proven to be successful in identifying locations of shoreline sewage pollution (Dailer et al., 2010; Dailer et al., 2012; Abaya et al., 2018a; Nakoa, 2022; Waiki et al., 2025). Based on a previous study done by Abaya et al. (2018a), all of the stations in this study fell below the range indicated for sewage (+9.62 to +11.57‰) and fell within the GW and ocean range. However, a statewide assessment determined $\delta^{15}\text{N}$ in macroalgae values +6‰ to be indicative of sewage waters and values +4.0 - +5.9‰ were sewage-influenced (Smith et al., 2021). Based on these results, all of our stations still fell below the range for sewage (+6‰), with eight stations (stations 1-4, 6-8, 12) reported above the +4.0‰ threshold indicating a low to medium influence of sewage. This assessment measured the $\delta^{15}\text{N}$ and %N throughout Hawai'i Island. In this assessment, Holualoa (stations 6,7,8 in this study) had an average $\delta^{15}\text{N}$ value of +4.90‰, which was higher than the results of the average for this study shoreline (+4.27‰) and a %N value of 1.23% which was lower than the average found in this study (2.04%) (Smith et al., 2021). Although Holualoa is reported to have high $\delta^{15}\text{N}$ values based on this assessment, the results of this whole shoreline including Holualoa (stations 6,7,8) still fell below the range indicative of sewage.

Previous studies have also shown that macroalgae uptake N more rapidly under low NO_3^- concentrations (Fujita, 1985) and that $\delta^{15}\text{N}$ in macroalgal tissue can be underestimated by up to ~6‰ in waters with high NO_3^- concentrations above 10 $\mu\text{mol/L}$ (Swart et al., 2014). Based on the results of this study, the $\text{NO}_3^- + \text{NO}_2^-$ concentrations at all stations, except station 2, exceeded 10 $\mu\text{mol/L}$, suggesting that the $\delta^{15}\text{N}$ at majority of the stations could be underestimated. Monitoring macroalgae $\delta^{15}\text{N}$ has also proven useful in tracking the sources and movement of nitrogen in order to assess the impact of sewage effluent on coastal ecosystems in Australia (Costanzo et al., 2005). Although macroalgae $\delta^{15}\text{N}$ is useful in determining if there is a sewage influence, based

on this study it is also useful in determining the outcome of management decisions. Incorporating macroalgae $\delta^{15}\text{N}$ in sewage management has proven useful in determining the effectiveness of sewage upgrades (Costanzo et al., 2005). These findings are significant because it demonstrates the importance of water quality monitoring and solidifies the use of macroalgae $\delta^{15}\text{N}$ for sewage management.

Stable isotope mixing model (SIMMR)

The use of $\delta^{15}\text{N}$ - and $\delta^{18}\text{O}$ - NO_3^- data in mixing models allows for greater distinction among potential N sources, while accounting for isotope fractionation processes (Xue et al., 2009). In our study, a stable isotope mixing model was used to determine the percent contribution of sewage, groundwater (GW), and ocean to the NO_3^- pool at different stations along the Kailua-Kona shoreline. Several studies have used this method to determine percent contribution of different N sources, however only a few studies within Hawai'i used these stable isotopes in a mixing model (Wiegner et al., 2016; Wiegner et al., 2021; Nakoa, 2022; Waiki et al., 2025). Based on the results of this study, GW was the dominant source contributing more than half of the NO_3^- to the shoreline stations. Previous studies on Hawai'i island have shown similar results with GW contributing 38% NO_3^- and being the dominant source in Kapoho (Wiegner et al., 2016). In another study done in Pau'ao, they also determined that fresh GW was the dominant NO_3^- source to all water types (Panelo et al., 2022). These findings are interesting because even though these areas receive low to moderate annual rainfall (225-850 mm), a large contributor of the NO_3^- is through the GW. The NO_3^- sources from the mixing models agreed with findings from $\delta^{15}\text{N}$ in macroalgae sources, determining that GW is the dominant source. However, even with sewage making the smallest contribution, all of these results together suggest that there is some sort of sewage pollution occurring along this shoreline.

Sewage Pollution Score

All stations fell within the low to medium category, with stations 2 and 8 representing areas with the lowest score which corresponds to the low concentrations among the sewage indicators (nutrients & FIB). Stations 3, 5, 9, 11, and 12 had the overall highest average scores (18), which makes sense based on the history of these areas and the results of this study. Station 3 has experienced beach closures and public advisories due to sewage spills (Ruminski, 2020) and based on this study it also had the highest Chl. *a* concentrations. Stations 5 and 12 consistently had high nutrients or FIB concentrations, with station 12 having a manhole that is inundated at the surface during high tide. A dye tracer test confirmed the connectivity between coastal OSDS and the shoreline at station 9; however, station 11 is located approximately 250 m apart, possibly indicating the connectivity to other nearby OSDS and effluent being discharged at the shoreline. All of these results and previous history of these stations are consistent with the score that was calculated for each station.

Although these scores were high compared to the other stations, they ranked in the medium range. These results were unexpected for Kailua-Kona because of the amount of OSDS, the proximity of the houses to the shoreline and how quickly the dye entered the shoreline from the cesspool dye tracer test. However, similar results were found in previous studies done in Hilo and Puakō that found low-medium sewage pollution scores along the shoreline. Even with a fast GW flow based on a dye tracer test in Hilo, two studies identified medium sewage pollution scores (Nakoa, 2022; Waiki et al., 2025). The results of this study showed a similar variability of the scores in Hilo with a median score of 17 (Nakoa, 2022), where there was not much variability in the indicators. However, the results of a study done in Puakō calculated medium to high sewage pollution scores with slightly more variability, possibly due to the greater variability

in FIB, $\delta^{15}\text{N}$, and the nutrients (Abaya et al., 2018a). These sewage pollution scores provide a more comprehensive understanding of the sewage pollution along this shoreline. The addition of the dye tracer test and other sewage indicators just help to solidify these hot spots.

Throughout this study it was determined that the home where dye was added and nearby homes with OSDS are not currently included in the Hawai'i Department of Health GIS layer of On-site Sewage Disposal Systems (OSDS). In order to determine and plan for which OSDS should be prioritized for removal or sewer line setback, further studies are needed. Currently the Kailua-Kona area is prioritized as a priority 1 area for cesspool conversion (Mezzacapo & Shuler, 2021). However based on a statewide assessment homes located within the *Kahalu'u ahupua'a* [land division] to Keauhou, which is at the southern end of this study site are currently set at priority 2 area for cesspool conversion. Based on the results of this dye tracer study, Kahalu'u homes located within a few miles of the shoreline are currently impacting coastal water quality and human health along this shoreline. With the fast travel time to the ocean, the wastewater does not have enough time for biological processes to take place to break down the sewage before entering the nearshore waters. Therefore the results of this study should be used by the community, county, and state to modify those priority rankings so that cesspools with the greatest impact on coastal resources are removed first.

SLR Modeling

As sea level rise continues to threaten coastal communities worldwide, accurately assessing the vulnerability of coastal OSDS and WI through SLR modeling is crucial for effective planning and management. The Hawai'i Cesspool Prioritization Tool (HCPT) is a helpful tool that displays the prioritization level for each of Hawai'i's cesspools based on its impacts on the ecosystem and human health (Hawai'i Cesspool Hazard Assessment, 2022). However, the HCPT did note that there were problems with the accuracy and number of OSDS used in their model (Shuler et al., 2022). We found this true in the Kahalu'u area, where 74 cesspools were identified within 13 to 240 m of the shoreline. The addition of this data helped identify 47 OSDS that are currently at risk of inundation within the threshold of < 4.4 m and 66 OSDS within the threshold of < 5.5 m during MHHW. A large majority of these OSDS are already at risk of being inundated during MHHW and SLR will only increase the amount of OSDS being inundated in the future. These findings are similar to what was seen on Honolulu, Hawai'i, that found nearly 90% of OSDSs (particularly cesspools) are likely compromised during present-day king-tide events (Habel et al., 2020). These findings along with the dye tracer test and sewage pollution hot spots, highlights the need to re-evaluate the cesspool prioritization along this shoreline. While the HCPT is useful for island-wide prioritization, updated counts for OSDS are needed. Without these data, the tool may be underestimating the priority of certain areas.

Not only are OSDS at risk of inundation, but many WI are currently being inundated throughout this shoreline. During MHHW, 79 mains and 66 manholes are being inundated by GW. Groundwater inundation (GWI) is an often overlooked consequence of SLR (Habel et al., 2017); however, it can cause significant damage to coastal communities and infrastructures. The effects of SLR can be seen in American Samoa, where sewer lines are currently being inundated and manholes are being corroded (Shuler, 2023). Studies on Maui have been able to estimate the impacts of future SLR by determining areas of GWI in order to assess coastal vulnerability (Cooper & Chen, 2013; Cooper et al., 2013). Modeling SLR scenarios can provide a clear understanding of vulnerable areas that can then be prioritized for adaptive planning. Currently at Pago Pago harbor in American Samoa, 3.5% of the sewer lines are flooded, at a 1.5-m SLR 27%

is flooded, then for the worst case at a 2.4-m SLR, 32.5% of the sewer lines is flooded (Shuler, 2023). Based on the model in this study, the Holualoa area (Stations 6-8) was identified as the stretch of shoreline where WI are already being inundated by MHHW. Just like Pago Pago as different SLR scenarios are modeled, the number of WI being inundated also increases. Knowing this information can help the county prioritize these areas for upgrades or sewer line setbacks in order to prepare for the future. Overall incorporating future SLR projections into adaptation planning can help generate successful and efficient solutions in order to reduce risk and increase resilience (USGCRP, 2018).

Conclusion

Our study showed that a dye tracer test, multi-indicator approach, and sewage pollution scoring system is necessary in accurately detecting sewage pollution hot spots along the shoreline. Based on the sewage pollution scoring tool, which accounted for multiple sewage indicators (FIB, macroalgae $\delta^{15}\text{N}$, and nutrients), five out of the 12 stations (stations 3, 5, 9, 11, and 12) were determined as potential sewage pollution hotspots. The use of multiple indicators and methods helped overcome the limitations of individual indicators and identified areas impacted by sewage (Abaya et al., 2018a; Wiegner et al., 2021). The dye tracer test demonstrated that sewage is entering the nearshore waters from OSDS, with the fastest GW flow rate on Hawai'i island (Abaya et al., 2018a, Wiegner et al., 2021; Waiki et al. 2025). Additionally, stable isotopes of NO_3^- in a mixing model helped determine sewage as the dominant source of NO_3^- . Although some stations were determined as sewage pollution hot spots, the majority of these stations have some sort of sewage influence. This study also demonstrated that including SLR modeling scenarios can be useful in determining current impacts of inundation on OSDS and WI, which can help predict future water quality based on these conditions to better prioritize areas. Multiple SLR scenarios (2024 MHHW, 0.3, 0.6, 1, 1.5, and 2 m) determined that majority of the WI are currently being inundated at MHHW, while the low elevation OSDS continue to pose a risk to GW. Based on the current water quality conditions along this shoreline and the fact that majority of the OSDS and WI are currently inundated in the SLR models, future water quality will be severely degraded with SLR if management actions are not taken. Currently, only the Kailua-Kona area is prioritized as a Priority 1 area for cesspool conversion, while Kahalu'u to Keauhou is currently a Priority level 2 (Mezzacapo & Shuler, 2021). Based on the results of this study, Kahalu'u to Keauhou should also be a Priority 1 area for cesspool conversion for Hawai'i County. Cesspool conversions and sewer line setbacks are needed; these results can help guide this effort. The results of this study could also be used on a broader scale in other tropical locations in order to address the issue of sewage pollution and implement effective management plans. Monitoring water quality has proven to be useful in tracking sewage pollution in other places such as Australia (Costanzo et al., 2005) and incorporating SLR modelling can help guide the efforts of improving future water quality as well. Our findings illustrate that adaptive planning is needed to protect future water quality and increase coastal resilience in Hawai'i, but these methods could also be used in other places around the world where coastal waters are impacted by OSDS and WI.

Table 1: Average ($\pm$ SE) of nutrient concentrations ($\mu\text{mol/L}$) for 12 shoreline stations from Kailua-Kona to Keauhou, Hawai‘i Island, from August 2022 to September 2023. Superscript letters indicate significant groupings from Kruskal-Wallis and Dunn’s test ($\alpha=0.05$). Total Dissolved Nitrogen (TDN), Total Dissolved Phosphorus (TDP), and Dissolved Organic Carbon (DOC).

Station	$\text{NO}_3^- + \text{NO}_2^-$	NH_4^+	TDN	PO_4^{3-}	TDP	H_4SiO_4	DOC
1	$30.8 \pm 5.53^{\text{ab}}$	$0.67 \pm 0.12^{\text{ab}}$	$39.4 \pm 3.10^{\text{a}}$	$1.43 \pm 0.22^{\text{ab}}$	$1.55 \pm 0.33^{\text{abc}}$	$110 \pm 14.3^{\text{ab}}$	$87.9 \pm 8.30^{\text{ab}}$
2	$8.70 \pm 1.17^{\text{c}}$	$0.43 \pm 0.08^{\text{a}}$	$18.9 \pm 1.78^{\text{b}}$	$0.52 \pm 0.05^{\text{c}}$	$1.04 \pm 0.33^{\text{abc}}$	$46.5 \pm 5.76^{\text{c}}$	$101 \pm 4.67^{\text{a}}$
3	$101 \pm 10.1^{\text{def}}$	$0.97 \pm 0.16^{\text{ab}}$	$116 \pm 8.28^{\text{cd}}$	$2.58 \pm 0.26^{\text{ade}}$	$2.47 \pm 0.29^{\text{abd}}$	$217 \pm 31.4^{\text{ad}}$	$90 \pm 6.12^{\text{ab}}$
4	$85.9 \pm 6.80^{\text{def}}$	$0.94 \pm 0.22^{\text{ab}}$	$93.8 \pm 5.64^{\text{cd}}$	$1.95 \pm 0.22^{\text{ad}}$	$1.99 \pm 0.24^{\text{a-d}}$	$178 \pm 17.6^{\text{ad}}$	$100 \pm 9.52^{\text{ab}}$
5	$50.1 \pm 9.11^{\text{a-dg}}$	$1.51 \pm 0.41^{\text{ab}}$	$65.3 \pm 9.10^{\text{a-cc}}$	$3.88 \pm 0.76^{\text{a-e}}$	$3.24 \pm 0.57^{\text{a-d}}$	$273 \pm 61.9^{\text{a-d}}$	$95.1 \pm 4.73^{\text{ab}}$
6	$136 \pm 16.5^{\text{e}}$	$0.69 \pm 0.09^{\text{ab}}$	$140 \pm 14.51^{\text{d}}$	$2.26 \pm 0.40^{\text{abde}}$	$1.62 \pm 0.26^{\text{abc}}$	$142 \pm 24.3^{\text{abd}}$	$86.4 \pm 5.71^{\text{ab}}$
7	$139 \pm 16.4^{\text{ef}}$	$0.93 \pm 0.17^{\text{ab}}$	$148 \pm 15.60^{\text{d}}$	$2.10 \pm 0.37^{\text{ad}}$	$1.84 \pm 0.19^{\text{a-d}}$	$159 \pm 18.6^{\text{ad}}$	$108 \pm 6.67^{\text{a}}$
8	$29.4 \pm 7.70^{\text{a}}$	$0.93 \pm 0.23^{\text{ab}}$	$30.7 \pm 2.25^{\text{a}}$	$0.72 \pm 0.11^{\text{bc}}$	$0.92 \pm 0.17^{\text{c}}$	$67.4 \pm 6.66^{\text{bc}}$	$97 \pm 1.61^{\text{a}}$
9	$50.6 \pm 4.44^{\text{bg}}$	$0.98 \pm 0.23^{\text{ab}}$	$60.6 \pm 3.38^{\text{e}}$	$2.61 \pm 0.35^{\text{ade}}$	$2.12 \pm 0.19^{\text{abd}}$	$169 \pm 20.2^{\text{ad}}$	$91 \pm 4.59^{\text{ab}}$
10	$84.2 \pm 3.21^{\text{def}}$	$0.90 \pm 0.16^{\text{ab}}$	$91 \pm 3.49^{\text{cd}}$	$3.82 \pm 0.42^{\text{e}}$	$3.10 \pm 0.24^{\text{d}}$	$242 \pm 29.1^{\text{d}}$	$78.9 \pm 2.89^{\text{b}}$
11	$74.4 \pm 4.80^{\text{d-g}}$	$1.10 \pm 0.37^{\text{ab}}$	$84.5 \pm 4.17^{\text{cde}}$	$3.16 \pm 0.36^{\text{de}}$	$2.81 \pm 0.19^{\text{ad}}$	$202 \pm 20.5^{\text{ad}}$	$107 \pm 14.8^{\text{ab}}$
12	$71.9 \pm 5.57^{\text{dfg}}$	$1.11 \pm 0.12^{\text{b}}$	$77.3 \pm 5.03^{\text{ce}}$	$1.83 \pm 0.15^{\text{ad}}$	$1.62 \pm 0.12^{\text{bc}}$	$172 \pm 23.4^{\text{ad}}$	$128 \pm 12.4^{\text{a}}$

Table 2: Species list of macroalgae and cyanobacteria collected from shoreline stations from Kailua-Kona to Keauhou, Hawai‘i Island, from July - November 2022 and August - September 2023. Occurrence is the number of times the species were present at each station. Algae were identified to the lowest taxonomic level and are listed in order of greatest occurrence to least, alphabetically.

Phylum	Genus Species	Occurrence
Rhodophyta	<i>Ahnfeltiopsis concinna</i>	58
	<i>Gelidium pusillum</i>	9
	<i>Amancia glomerata</i>	2
	<i>Centroceras clavulatum</i>	2
	<i>Chrysymenia sp.</i>	1
	<i>Gelidiopsis variabilis</i>	1
	<i>Polysiphonia tuberosa</i>	1
Chlorophyta	<i>Chaetomorpha antennina</i>	16
	<i>Ulva fasciata</i>	6
	<i>Enteromorpha flexuosa</i>	4
	<i>Cladophora laetevirens</i>	3
	<i>Cladophorales socialis</i>	3
Cyanobacteria	<i>Lyngbya</i>	1

Table 3: Groundwater level data obtained from groundwater test wells in Kona, Hawai‘i Island. Four wells are located in the Koloko-Honokohau area and maintained by the United States Geological Survey (USGS) and two located in the Kahalu‘u area and maintained by the State of Hawai‘i Commission of Water Supply. Data Sources: Pacific Islands Climate Adaptation Science Center (PI-CASC), United States Geological Survey (USGS), Kaloko-Honokōhau National Historical Park (KAHO), and Commission on Groundwater Resources (CGWR).

Location	Annual GW level (m)	Distance From Shore (m)	Data Source
Old Kona Airport Pool	0.50	155	PI-CASC (2023)
Kamehameha School Pool Kahalu‘u	0.48	48	PI-CASC (2023)
Keauhou Pier Pool	0.47	76	PI-CASC (2023)
Lili‘uokalani Trust Pool	0.55	64	PI-CASC (2023)
KAHO Well 3	0.49	430	USGS (2013-2023)
KAHO Well 2	0.50	1021	USGS (2013-2023)
KAHO Well 1	0.45	521	USGS (2013-2023)
‘Aimakapā Fishpond	0.46	216	USGS (2013-2023)
Kahalu‘u Deep Monitoring Well 04	0.66	770	CGWR - State of Hawai‘i (2023)
Keōpū Deep Monitoring Well	0.76	2565	CGWR - State of Hawai‘i (2023)

Table 4: Sea level rise (SLR) risk to on-site sewage disposal systems (OSDS) from the Old Kona Airport to Kahalu‘u, Hawai‘i Island. Along each SLR scenario (2024 Mean Higher High Water (MHHW), 0.3 m, 0.6 m, 1m, 1.5 m, 2 m) the cumulative total of OSDS within a threshold (< 4.4 m, < 5.5 m) from ground surface to GW and any OSDS that will be inundated by surface flooding from the ocean is displayed.

Location	SLR Scenario	< 4.4m from GW	< 5.5m from GW	Surface inundation OSDS
Old airport to Kahalu‘u	2024 MHHW	47	66	0
	0.3m	56	77	2
	0.6m	57	86	2
	1m	64	96	3
	1.5m	78	102	7
	2m	92	112	9

Table 5: Groundwater (GW) and surface inundation by seawater of sewage infrastructure at different sea level rise scenarios (2024 Mean Higher High Water (MHHW), 0.3 m, 0.6 m, 1 m, 1.5 m, 2 m) along the shoreline from Kailua-Kona to Keauhou, Hawai‘i Island. Numbers in parenthesis are the cumulative total of infrastructures being inundated with rising sea levels.

Location	SLR Scenario	GW manhole	Surface inundation manhole	GW main	Surface inundation main
Kailua-Kona	2024 MHHW	55	0	66	0
	0.3m	13 (68)	0	14 (80)	0
	0.6m	8 (76)	0	6 (86)	0
	1m	12 (88)	1	15 (101)	1
	1.5m	7 (95)	10 (11)	17 (118)	11 (12)
	2m	18 (113)	6 (17)	17 (135)	21 (33)
Kahalu‘u-Keauhou	2024 MHHW	11	0	13	0
	0.3m	0 (11)	0	3 (16)	0
	0.6m	1 (12)	1	0 (16)	4
	1m	0 (12)	1 (2)	1 (17)	1 (5)
	1.5m	2 (14)	2 (4)	1 (18)	2 (7)
	2m	1 (15)	3 (7)	2 (20)	3 (10)

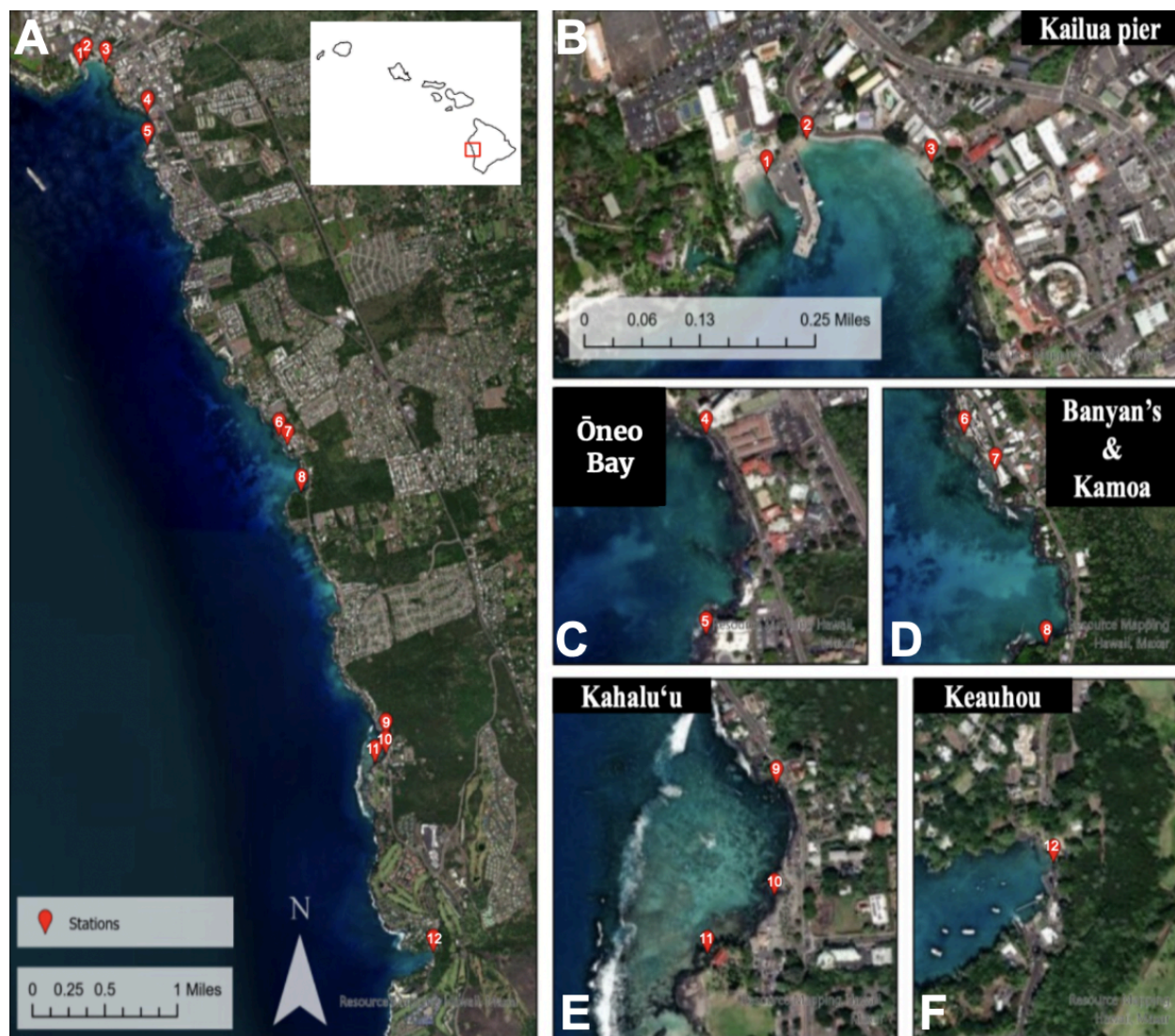


Figure 1: Map of 12 stations in Kona, Hawai'i Island, sampled for monitoring sewage pollution and areas associated with the stations. (A) shoreline map of all stations, (B) stations at Kailua Pier/Niumalu beach, (C) stations within Ōneo Bay, (D) stations at Banyans and Kamoā, (E) stations at Kahalu'u (North, Middle, South), (F) station at Keauhou.

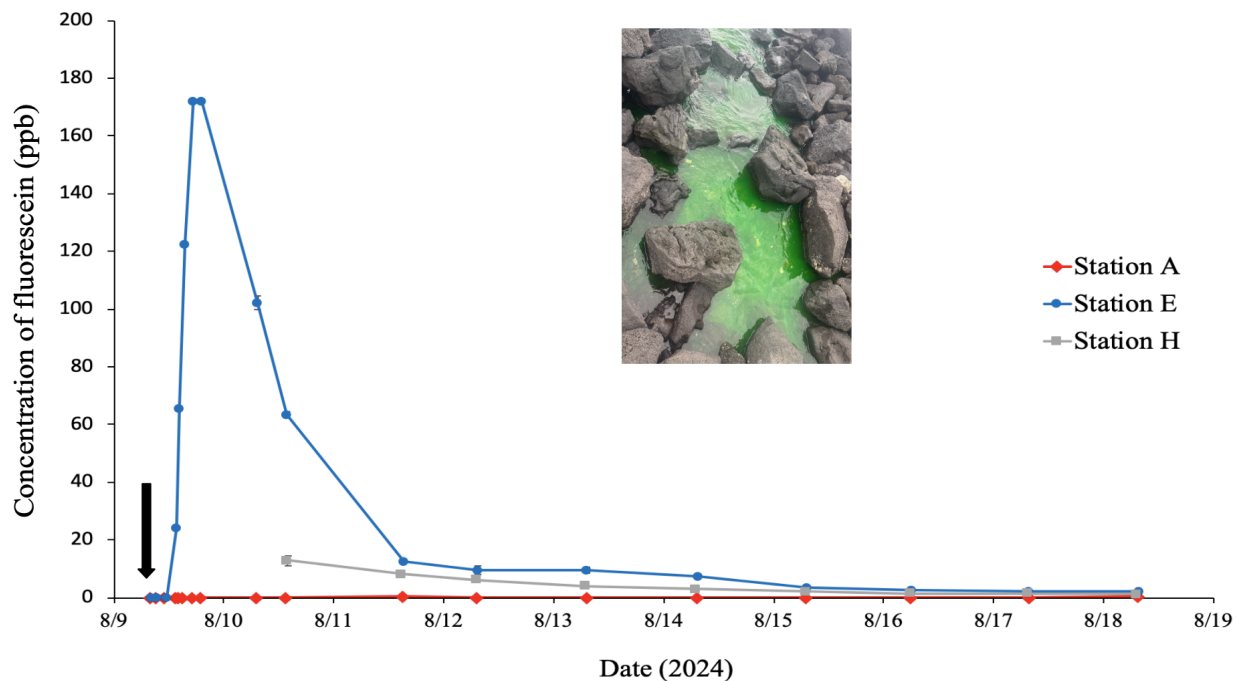


Figure 2. Results of the dye tracer test conducted in Kahalu‘u, Kona, Hawai‘i Island with fluorescein concentration at three stations over a 10-d period. Concentrations of fluorescein in the spring where the dye emerged (Station E) are compared with a nearby spring, where concentrations remained near background levels during the dye tracer test (Station A), and an anchialine pool where dye was also observed (Station H). For this dye tracer test, dye was added to the on-site sewage disposal systems (OSDS) at 8:15 am on August 9, 2024, as indicated by the arrow on the figure, and dye was first observed visually at Station E at 13:00 that same day. Photograph of the fluorescein that emerged at the shoreline spring (photo credit: I. Kamau).

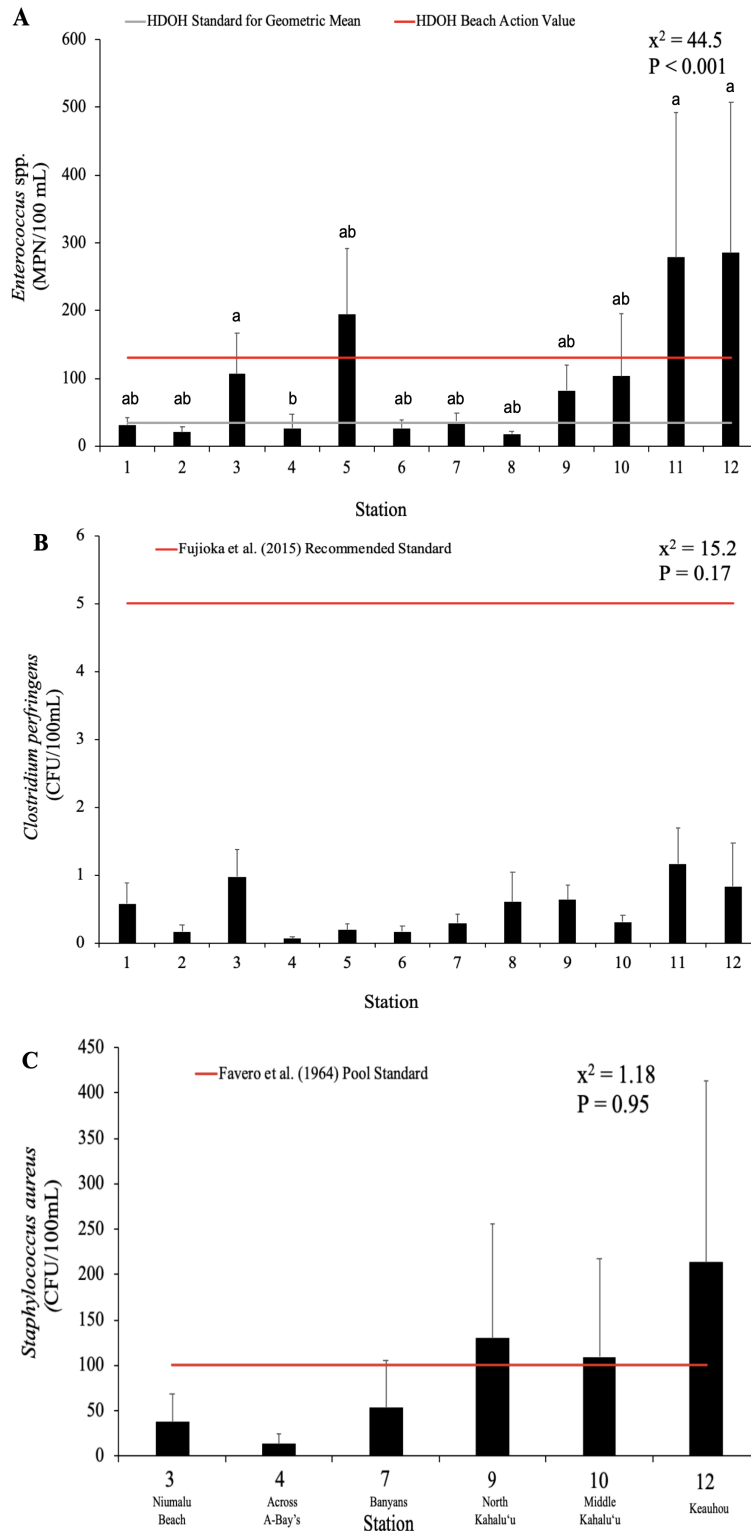


Figure 3. Average ($\pm$ SE) concentrations of sewage indicators and pathogens: (A) *Enterococcus* spp., (B) *Clostridium perfringens*, and (C) *Staphylococcus aureus* at shoreline stations in Kailua-Kona, Hawai‘i Island, from August 2022 to September 2023. Shown on figures are reference lines to water quality standards (A) Hawai‘i’s Department of Health (HDOH) geometric mean (gray; 35 MPN/100 mL) and Beach Action Value (red; 130 MPN/100 mL) for Enterococci at all 12 stations (HDOH, 2019). (B) A recommended marine recreational standard for *C. perfringens* in Hawai‘i (red; 5 CFU/100 mL) at all 12 stations (Fujioka et al., 2015). (C) *S. aureus* concentrations associated with increased skin infection rates among recreational water users in pools recommended by Favero et al. (1964) (red; 100 CFU/100mL) at 6 of the stations (overall lowest salinity). Results from Kruskal-Wallis and Dunn’s test (Fig. A) shown on figure ($\alpha = 0.05$).

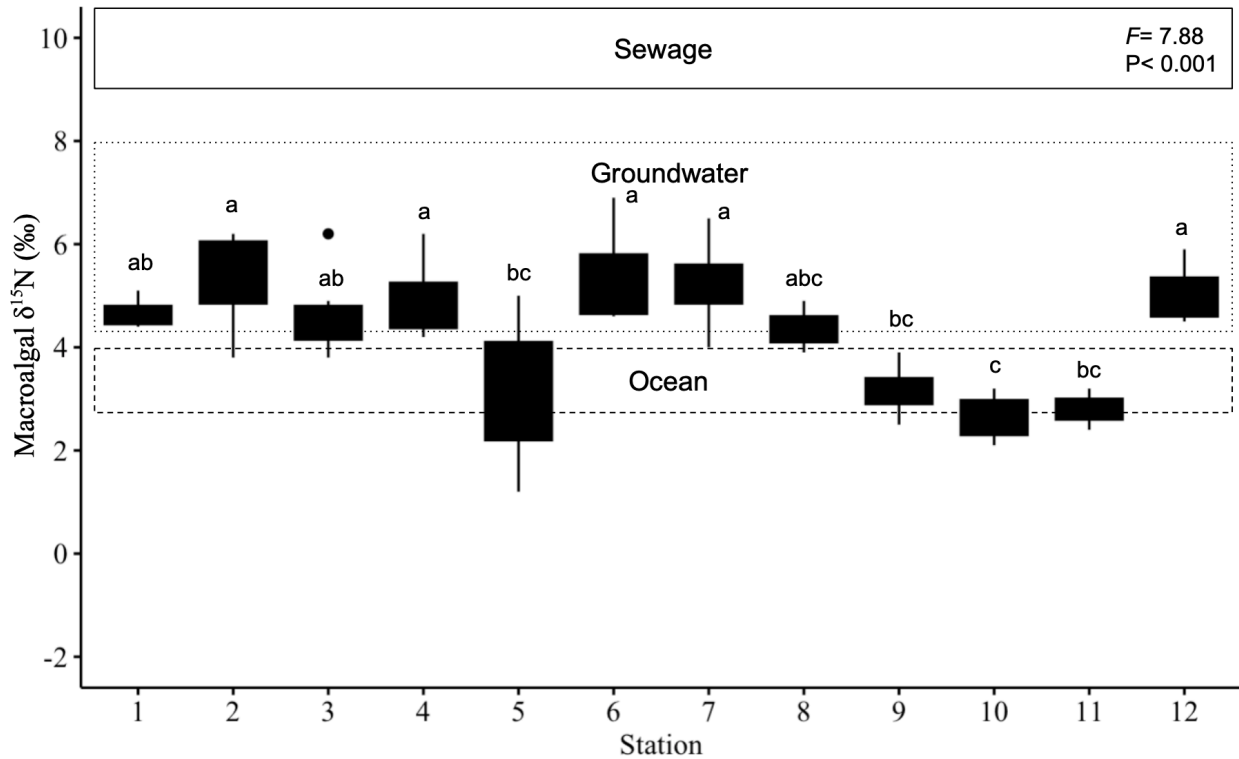


Figure 4. Average ($\pm$ SE) $\delta^{15}\text{N}$ (‰) of macroalgae collected at 12 stations along the Kailua-Kona (north to south: Kailua-Kona to Keauhou) shoreline, Hawai‘i Island, USA, from August 2022 to September 2023. Values are compared to potential NO_3^- sources to these coastal waters (sewage, ocean, groundwater). Ranges for sources are from Hunt, 2014; Abaya et al., 2018a; Wiegner et al., 2021; Panelo et al., 2022. Results from ANOVA and Tukey’s test are shown on figure. Different letters indicate a significant difference among the stations ($\alpha = 0.05$).

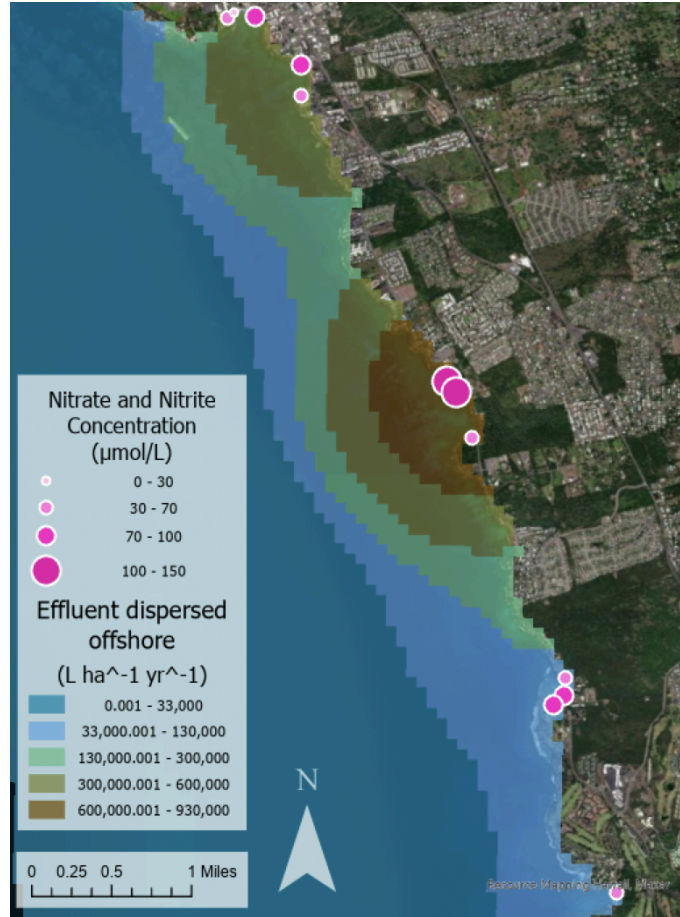


Figure 5. Map of the average nutrient concentrations ($\text{NO}_3^- + \text{NO}_2^-$) along the 12 shoreline stations from Kailua-Kona to Keauhou, Hawai‘i Island, from August 2022 to September 2023. Models of effluent dispersal offshore are displayed with light blue to dark orange shading representing low to high effluent input (Gove et al., 2023). This map is comparing the nutrient concentrations from the 12 stations in this study to the effluent dispersal offshore modeled using a Gaussian decay function based on a total effluent dispersal at the coastline and a total effluent by zones in the Gove et al. (2023) study.

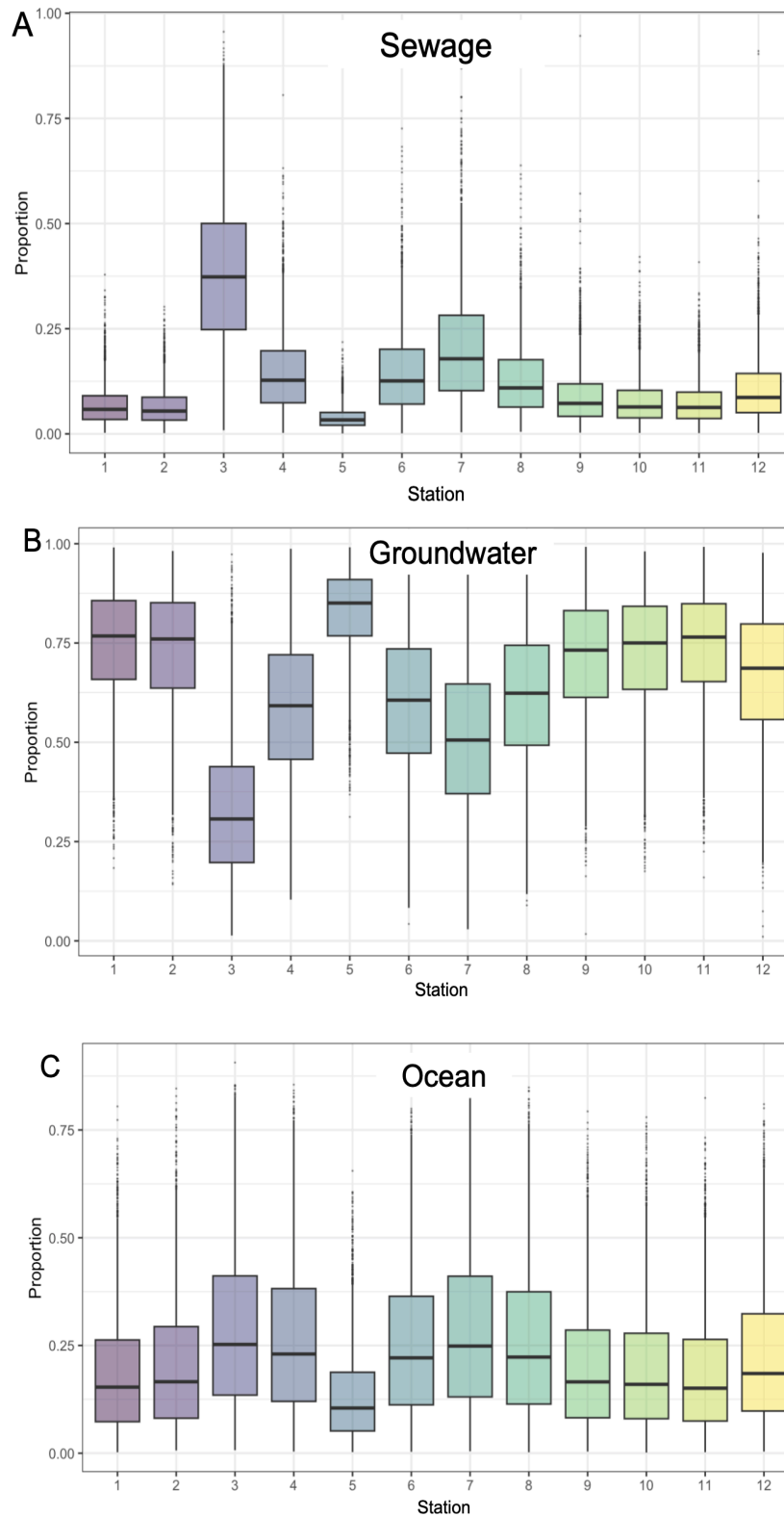


Figure 6. "Simmr" mixing model using $\delta^{15}\text{N}$ - and $\delta^{18}\text{O}\text{-NO}_3^-$ values at twelve shoreline stations along the Kailua-Kona shoreline, Hawai'i Island, from August 2022 to September 2023. Results displaying the estimated proportion (%) contribution of each N source: (A) sewage, (B) groundwater, and (C) ocean. Values for potential N sources (sewage, groundwater, and ocean) are from previous studies (Hunt, 2014; Abaya et al., 2018a; Wiegner et al., 2021; Panelo et al., 2022). Boxed area represents 25% and 75% credible quantiles, horizontal lines indicate the 50% quantile, and vertical lines and outliers indicate minimum (2.5%) and maximum (97.5%) proportion values.

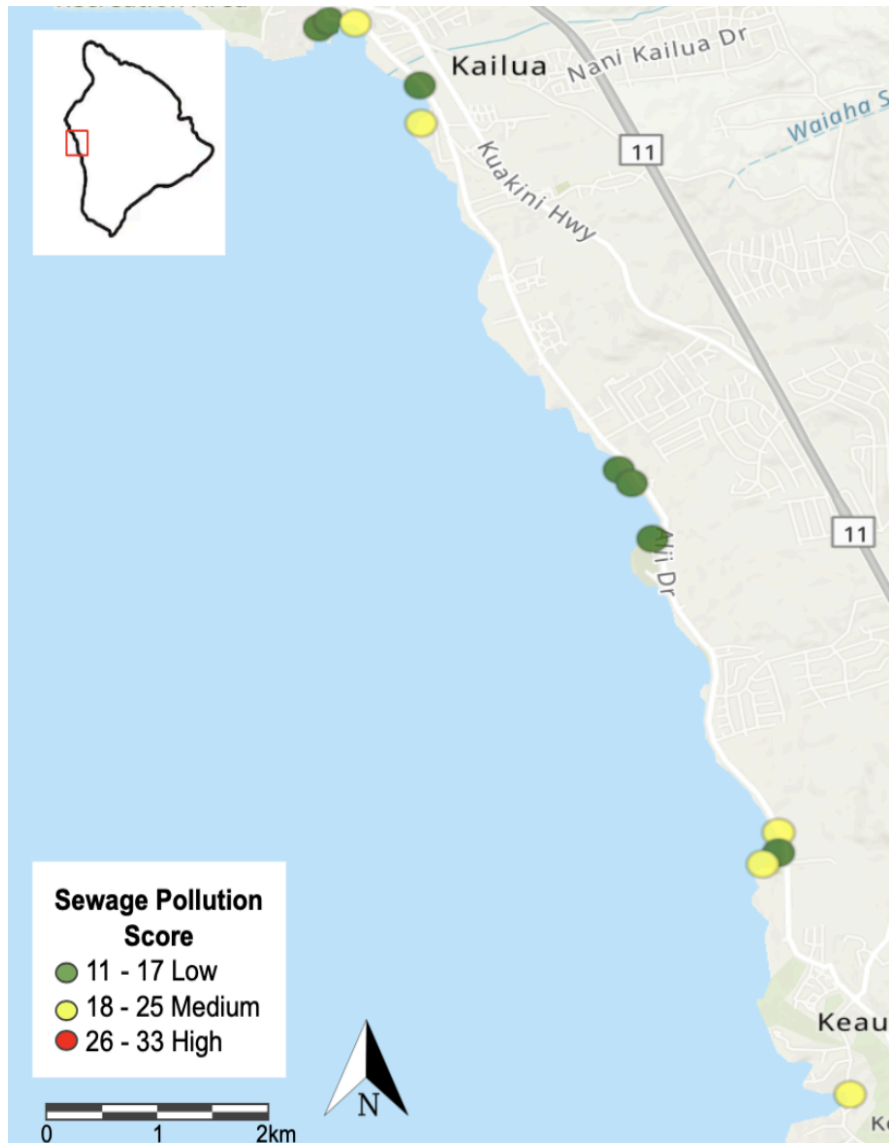


Figure 7. Average sewage pollution scores for 12 stations along the Kailua-Kona shoreline, Hawai‘i Island, were based on established and recommended water quality standards, literature values for sewage indicators, and measured values from this study (fecal indicator bacteria, $\delta^{15}\text{N}$ in macroalgae, and nutrients). Sewage pollution score categories are: low = 11–17; medium = 18–25; high = 26–33. Equation for this calculation of the sewage pollution score is provided in the Methods section.

Kailua Kona 0.3m SLR - OSDS threshold from GW

Kailua Kona 1m SLR - OSDS threshold from GW

Kailua Kona 2m SLR - OSDS threshold from GW

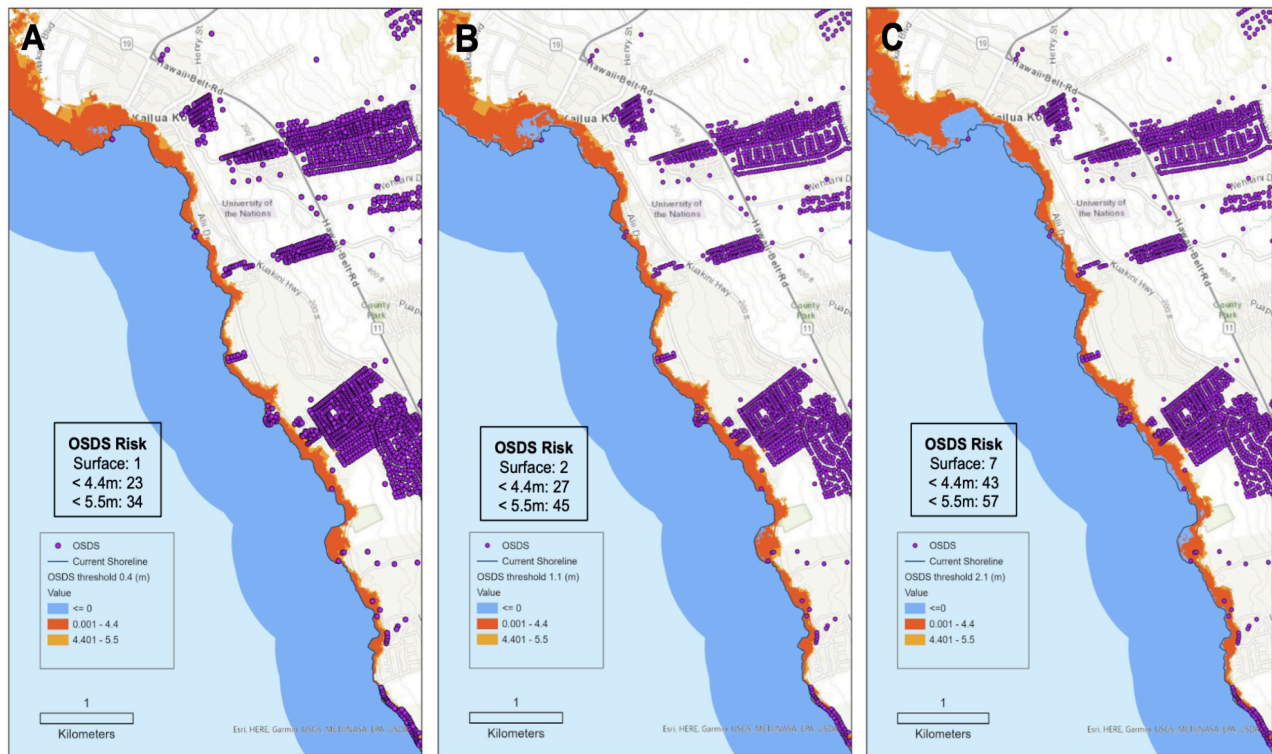


Figure 8. Modeled sea level rise (SLR) risk of inundation of on-site sewage disposal systems (OSDS: purple dots) in Kailua-Kona, Hawai'i Island, USA (north to south: Old Kona Airport State Recreation Area to Luna Pule Rd., Kahului Bay). SLR scenarios for (A) 0.3 m, (B) 1 m, and (C) 2 m are shown. The black box represents the cumulative total of OSDS that is inundated (Surface: blue) and at risk of inundation (<4.4 m: dark orange and <5.5 m: light orange; distance from ground surface to groundwater).

Kahaluu 0.3m SLR - OSDS threshold from GW

Kahaluu 1m SLR - OSDS threshold from GW

Kahaluu 2m SLR - OSDS threshold from GW

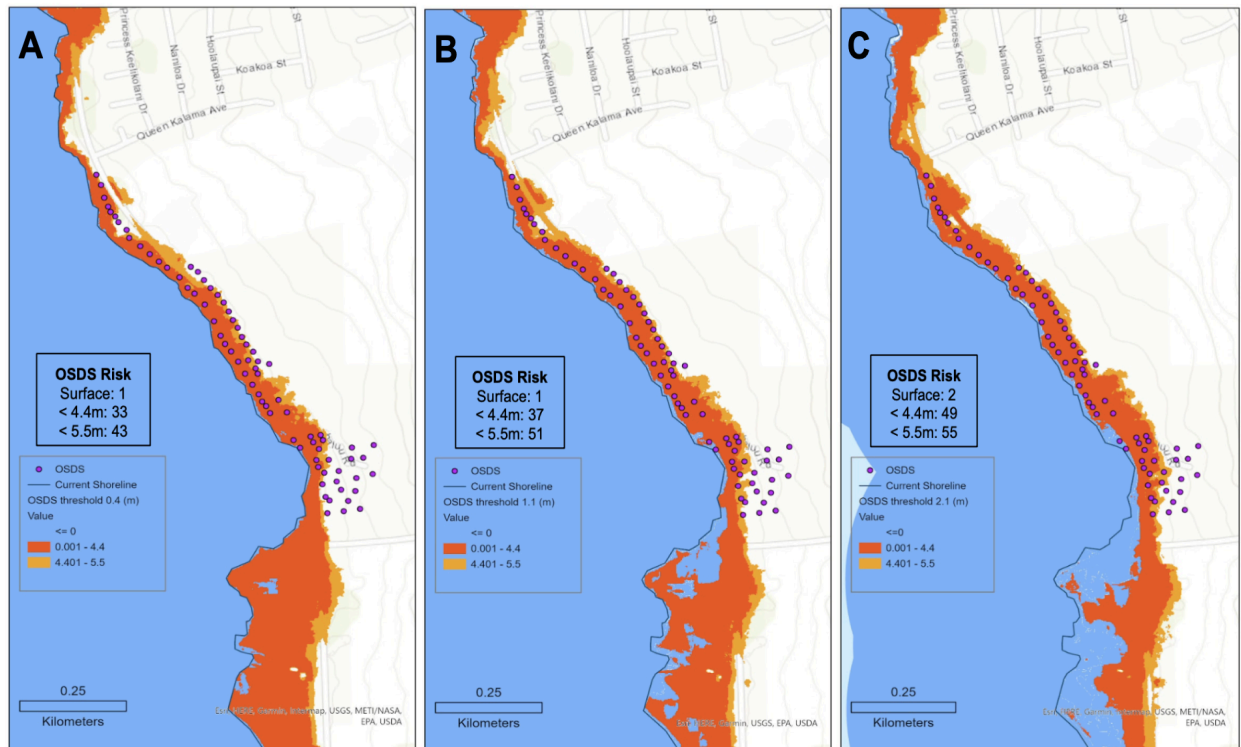


Figure 9. Modeled sea level rise (SLR) risk of inundation of on-site sewage disposal systems (OSDS: purple dots) in Kailua-Kona, Hawai'i Island, USA, (north to south: Holualoa, Stardust Ln. to White Sands Beach Park, La'aloa Ave.). SLR scenarios for (A) 0.3 m, (B) 1 m, and (C) 2 m are shown. The black box represents the cumulative total of OSDS that is inundated (Surface: blue) and at risk of inundation (<4.4 m: dark orange and <5.5 m: light orange; distance from ground surface to groundwater).

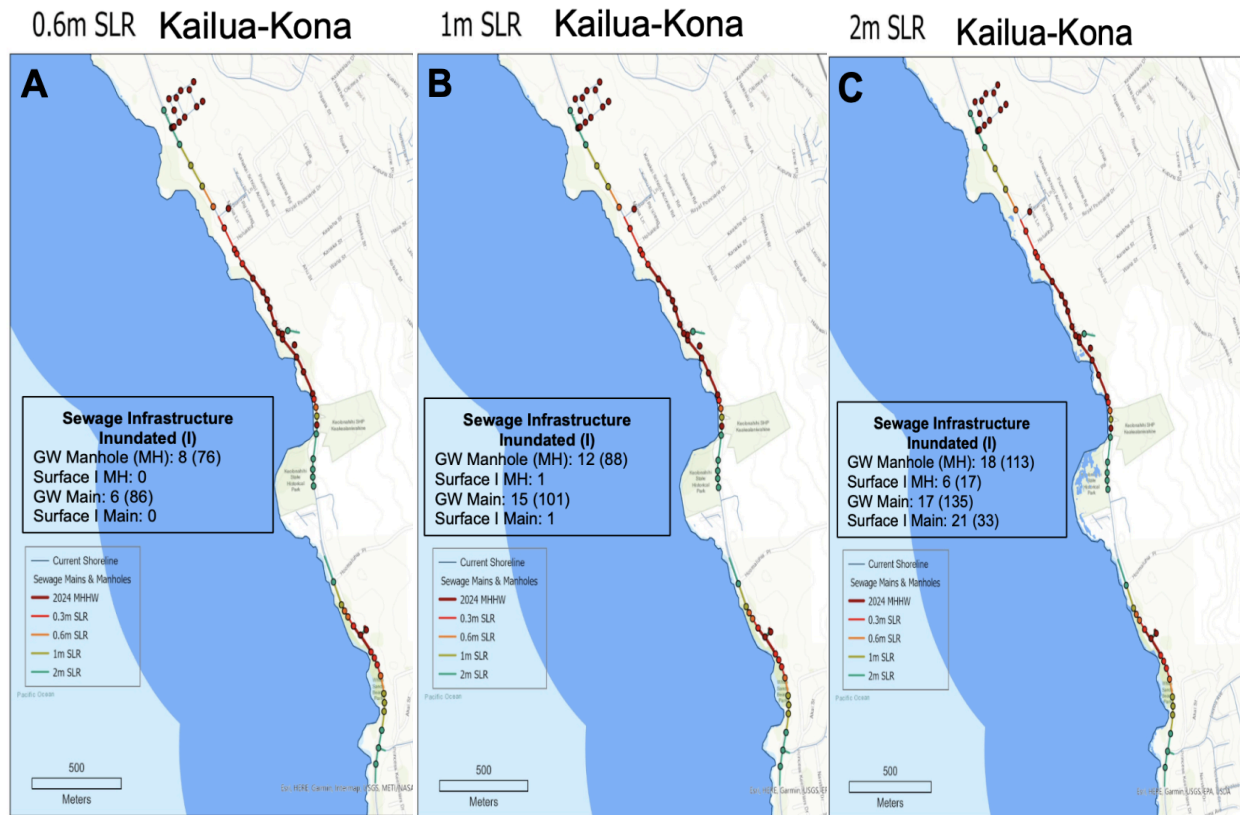


Figure 10. Modeled groundwater and surface ocean inundation of wastewater infrastructure (sewer mains and manholes) at different sea level rise (SLR) scenarios in Kailua-Kona, Hawai‘i Island, USA (north to south: Old Kona Airport State Recreation Area to Luna Pule Rd., Kahului Bay). SLR scenarios for (A) 0.6 m, (B) 1 m, and (C) 2 m are shown. The number of WI that will be inundated by GW and at the surface (parenthesis is the cumulative total) under each SLR scenario is displayed in the black box.

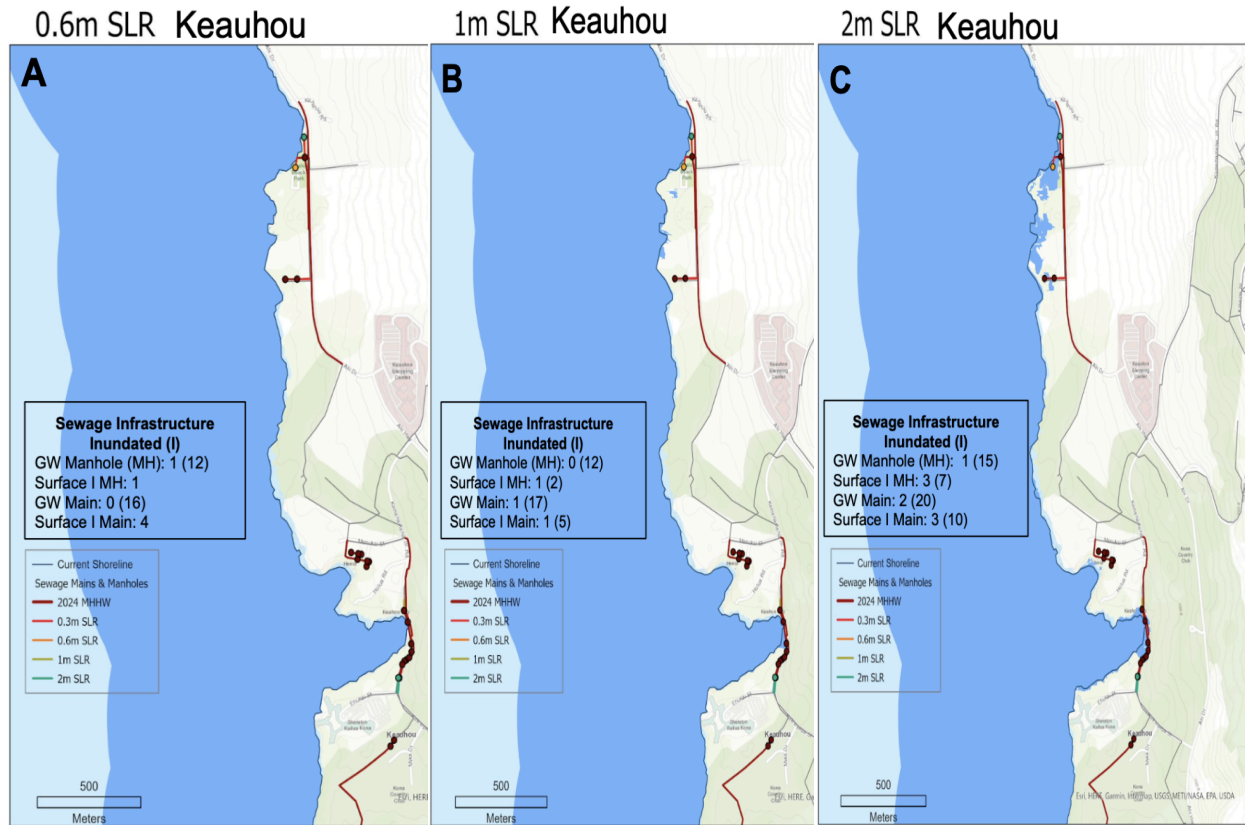


Figure 11. Modeled groundwater and surface ocean inundation of wastewater infrastructure (WI: sewer mains and manholes) at different sea level rise (SLR) scenarios in Kailua-Kona, Hawai‘i Island, USA (north to south: Kahalu‘u Beach Park to Keauhou). SLR scenarios for (A) 0.6 m, (B) 1 m, and (C) 2 m are shown. The number of WI that will be inundated by GW and at the surface (parenthesis is the cumulative total) under each SLR scenario is displayed in the black box.

Literature Cited:

- Abaya, L.M., Wiegner, T.N., Colbert, S.L., Carlson, K.M., Kramer, K.L., Most, R., Couch, C.S., 2018a. A multi-indicator approach for identifying shoreline sewage pollution hotspots adjacent to coral reefs. *Mar. Pollut. Bull.* 129, 70-80.
- Abaya, L.M., Wiegner, T.N., Beets, J.P., Colbert, S.L., Carlson, K.M., Kramer, K.L., 2018b. Spatial distribution of sewage pollution on a Hawaiian coral reef. *Mar. Pollut. Bull.* 130, 335-347.
- Abbott, I.A., 1999. *Marine red algae of the Hawaiian Islands*. Bishop Museum Press, Honolulu, Hawai'i.
- Abbott, I.A., Huisman, J.M., 2004. *Marine green and brown algae of the Hawaiian Islands*. Bishop Museum Press, Honolulu, Hawai'i.
- Amato, D.W., Bishop, J.M., Glenn, C.R., Dulai, H., Smith, C.M., 2016. Impact of submarine groundwater discharge on marine water quality and reef biota of Maui. *PLoS ONE* 11(11), e0165825.
- Barbier, E.B., Hacker, S.D., Kennedy, C., Koch, E.W., Stier, A.C., Silliman, B.R., 2011. The value of estuarine and coastal ecosystem services. *Ecological Monographs* 81(2), 169–193.
- Bisson, J.W., Cabelli, V.J., 1979. Membrane filter enumeration method for *Clostridium perfringens*. *App. Env. Micr.* 37(1), 55-66.
- Boehm, A.M., Shellenbarger, G.G., Paytan, A., 2004. Groundwater discharge: Potential association with fecal indicator bacteria in the surf zone. *Env. Sci. and Tech.* 38(13), 3558-3566.
- Carollo Engineers, 2021. Cesspool Conversion Technologies Research Summary Report. Prepared for the Hawai'i State Department of Health. <https://health.hawaii.gov/wastewater/files/2021/02/technicalfinalreportr.pdf>.
- CMP (Corridor Management Plan), 2011. *Royal Footsteps along the Kona Coast*. Ho'okuleana LLC.
- Cooper, H.M., Chen, Q., 2013. Incorporating uncertainty of future sea-level rise estimates into vulnerability assessment: A case study in Kahului, Maui. *Climatic Change* 121(4), 635–647.
- Cooper, H.M., Chen, Q., Fletcher, C.H., Barbee, M.M., 2013. Assessing vulnerability due to sea-level rise in Maui, Hawai'i using LiDAR remote sensing and GIS. *Climatic Change* 116(3), 547–563.
- Couch, C.S., Garriques, J.D., Barnett, C., Preskitt, L., Cotton, S., Giddens, J., Walsh, W., 2014. Spatial and temporal patterns of coral health and disease along leeward Hawai'i Island. *Coral Reefs* 33, 693-704.

- Costanzo, S.D., Udy, J., Longstaff, B., Jones, A., 2005. Using nitrogen stable isotope values ($\delta^{15}\text{N}$) of macroalgae to determine the effectiveness of sewage upgrades: Changes in the extent of sewage plumes over four years in Moreton Bay, Australia. *Mar. Pollut. Bull.* 51(1-4), 212-217.
- Costanzo, S.D., Udy, J., Longstaff, B., Jones, A., 2005. Using nitrogen stable isotope ratios ($\delta^{15}\text{N}$) of macroalgae to determine the effectiveness of sewage upgrades: changes in the extent of sewage plumes over four years in Moreton Bay, Australia. *Mar. Pollut. Bull.* 51, 212–217.
- Cruz-Trinidad, A., Aliño, P.M., Geronimo, R.C., Cabral, R.B., 2014. Linking food security with coral reefs and fisheries in the Coral Triangle. *Coastal Management* 42, 160–182.
- Curiel-Ayala, F., Quinones-Ramirez, E., Pless, R., Gonzalez-Jasso, E., 2012. Comparative studies on *Enterococcus*, *Clostridium perfringens* and *Staphylococcus aureus* as quality indicators in tropical seawater at a Pacific Mexican beach resort. *Mar. Pollut. Bull.* 10, 2193–2198.
- Dailer, M.L., Knox, R.S., Smith, J.E., Napier, M., Smith, C.M., 2010. Using $\delta^{15}\text{N}$ values in algal tissue to map locations and potential sources of anthropogenic nutrient inputs on the island of Maui, Hawai‘i, USA. *Mar. Pollut. Bull.* 60, 655-671.
- Dailer, M.L., Ramey, H.L., Saephan, S., Smith, C.M., 2012. Algal $\delta^{15}\text{N}$ values detect a wastewater effluent plume in nearshore and offshore surface waters and three-dimensionally model the plume across a coral reef on Maui, Hawai‘i, USA. *Mar. Pollut. Bull.* 64, 207–213.
- Department of Health, State of Hawai‘i, 2022. Prioritization Tool Report. Retrieved from <https://health.hawaii.gov/wastewater/files/2022/11/prioritizationtoolreport.pdf>.
- Economy, L.M., Wiegner, T.N., Strauch, A.M., Awaya, J.D., Gerken, T., 2019. Rainfall and streamflow effects on estuarine *Staphylococcus aureus* and fecal indicator bacteria concentrations. *J. Env. Qual.* 48(6), 1711-1721.
- Ellison, L.M., 2020. Geochemical and stable isotope source tracking of terrestrial nutrient pollution to the coastal waters of Waialua Bay, North Shore, O‘ahu. M.Sc. thesis, University of Hawai‘i at Mānoa, 90 pp.
- Elmir, S.M., Wright, M.E., Abdelzaher, A., Solo-Gabriele, H.M., Fleming, L.E., Miller, G., et al., 2007. Quantitative evaluation of bacteria released by bathers in marine water. *Water Research* 41, 3–10. <https://doi.org/10.1016/j.watres.2006.10.005>.
- Favero, M.S., Drake, C.H., Randall, G.B., 1964. Use of *Staphylococci* as indicators of swimming pool pollution. *Public Health Reports* 79(1), 61–70.
- Fleisher, J.M., Fleming, L.E., Solo-Gabriele, H.M., Kish, J.K., Sinigalliano, C.D., Plano, L., Elmir, S.M., Wang, J.D., Withum, K., Shibata, T., Gidley, M.L., Abdelzaher, A., He, G., Ortega, C., Zhu, X., Wright, M., Hollenbeck, J., Backer, L.C., 2010.

- The Beaches Study: Health effects and exposures from non-point source microbial contaminants in subtropical recreational marine waters. *International Journal of Epidemiology* 39(5), 1291–1298. <https://doi.org/10.1093/ije/dyq084>.
- Frazier, A.G., Giambelluca, T.W., 2017. Spatial trend analysis of Hawaiian rainfall from 1920 to 2012. *Intern. Jour. Climat.* 37(5), 2522–2531. <https://doi.org/10.1002/joc.4862>.
- Fung, D.Y.C., Fujioka, R., Vijayavel, K., Sato, D., Bishop, D., 2007. Evaluation of Fung double tube test for *Clostridium perfringens* and easyphage test for f-specific RNA coliphages as rapid screening tests for fecal contamination in recreational waters of Hawai'i. *J. Rap. Meth. Auto. Micro.* 15, 217–229.
- Fujioka, R., Hashimoto, H., Siwak, E., Young, R., 1981. Effect of sunlight on survival of indicator bacteria in seawater. *App. Env. Micro.* 41, 690–696.
- Fujioka, R.S., Shizumura, L.K., 1985. *Clostridium perfringens*, a reliable indicator of stream water quality. *J. Wat. Poll. Cont. Fed.* 57, 986–992.
- Fujioka, R., Solo-Gabriele, H., Byappanahalli, M., Kirs, M., 2015. U.S. recreational water quality criteria: A vision for the future. *Int. J. Env. Res. Pub. Health* 12(7), 7752–7776.
- Gesch, D., Palaseanu-Lovejoy, M., Danielson, J., Fletcher, C., Kottermair, M., Barbee, M., Jalandoni, A., 2020. Inundation exposure assessment for Majuro Atoll, Republic of the Marshall Islands using a high-accuracy digital elevation model. *Remote Sensing* 12(1), 154.
- Gibson, V.L., Bremer, L.L., Burnett, K.M., Keaka Lui, N., Smith, C.M., 2022. Biocultural values of groundwater-dependent ecosystems in Kona, Hawai'i. *Ecology and Society* 27(3), 18. <https://doi.org/10.5751/ES-13432-270318>.
- Glenn, C.R., Whittier, R.B., Dailer, M.L., Dulaiova, H., El-Kadi, A.I., Fackrell, J., Kelly, J.L., Waters, C.A., Sevajian, J., 2017. Lahaina groundwater tracer study- Lahaina, Maui, Hawai'i, Final Report. Prepared for the State of Hawai'i Department of Health, the U.S. Environmental Protection Agency, and the U.S. Army Engineer Research and Development Center.
- Goodwin, K.D., McNay, M., Cao, Y., Ebentier, D., Madison, M., Griffith, J.F., 2012. A multi-beach study of *Staphylococcus aureus*, MRSA, and enterococci in seawater and beach sand. *Water Research* 46, 4195–4207. <https://doi.org/10.1016/j.watres.2012.04.001>.
- Goodwin, K.D., Pobuda, M., 2009. Performance of CHROMagar Staph aureus and CHROMagar MRSA for detection of *Staphylococcus aureus* in seawater and beach sand—comparison of culture, agglutination, and molecular analyses. *Water Research* 43, 4802–4811.

- Gove, J.M., Williams, G.J., Lecky, J., Brown, E., Conklin, E., Counsell, C., Davis, G., Donovan, M.K., Falinski, K., Kramer, L., Kozar, K., Li, N., Maynard, J.A., McCutcheon, A., McKenna, S.A., Neilson, B.J., Safaie, A., Teague, C., Whittier, R., Asner, G.P., 2023. Coral reefs benefit from reduced land-sea impacts under ocean warming. *Nature* 621(7979), 536–542.
<https://doi.org/10.1038/s41586-023-06394-w>.
- Habel, S., Fletcher, C.H., Anderson, T.R., Thompson, P.R., 2020. Sea-level rise induced multi-mechanism flooding and contribution to urban infrastructure failure. *Scientific Reports* 10, 3796.
- Habel, S., Fletcher, C.H., Rotzoll, K., El-Kadi, A.I., 2017. Development of a model to simulate groundwater inundation induced by sea-level rise and high tides in Honolulu, Hawai‘i. *Water Research* 114, 122–134.
- Habel, S., Fletcher, C.H., Rotzoll, K., El-Kadi, A.I., Oki, D.S., 2019. Comparison of a simple hydrostatic and a data-intensive 3D numerical modeling method of simulating sea-level rise induced groundwater inundation for Honolulu, Hawai‘i, USA. *Env. Res. Com.* 1(4), 041005.
- Hardina, C., Fujioka, R., 1991. Soil: the environmental source of *Escherichia coli* and *Enterococci* in Hawai‘i's streams. *Env. Tox. W. Qua.* 6, 185–195.
- HDOH (Hawai‘i Department of Health), 2021. HAR 11-54.
<https://health.hawaii.gov/cwb/hawaii-administrative-rules-har/har-11-54/>
- HDOH (Hawai‘i Department of Health), 2017. Report to the 29th legislature state of Hawai‘i 2018 regular session relating to cesspools and prioritization for replacement. Report in response to Act 125, 2017 Regular Session (House Bill 1244, HD1, SD2, CD1).
- HDOH (Hawai‘i Department of Health), 2019. Hawai‘i beach monitoring program: revised December 31, 2019. Hawai‘i State Department of Health.
- Hummel, M.A., Berry, M.S., Stacey, M.T., 2018. Sea level rise on wastewater treatment systems along the U.S. coasts. *Earth’s Future* 6, 622–633.
<https://doi.org/10.1002/2017EF000805>.
- Hunt, C.D., Rosa, S.N., 2009. A multi-tracer approach to detect wastewater plumes from municipal injection wells in nearshore marine waters in Kihei and Lahaina, Maui, Hawai‘i. USGS Scientific Investigations Report 2009-5253.
- Jensen, C., 2020. High enterococci levels prompt advisory for waters near Kailua Pier. *West Hawai‘i Today*, 3 June 2020.
- Johannes, R.E., 1975. Pollution and degradation of coral reef communities. In: Wood, E.J.F., Johannes, R.E. (Eds.), *Trop. Mar. Poll.* Elsevier Scientific Publishing Company, Oxford, pp. 13–51.

- Johnson, A.G., 2008. Groundwater discharge from the leeward half of the Big Island, Hawai‘i. M.S. thesis, University of Hawai‘i.
- Knee, K.L., Street, J.H., Grossman, E.E., Boehm, A.B., Paytan, A., 2010. Nutrient inputs to the coastal ocean from submarine groundwater discharge in a groundwater-dominated system: Relation to land use (Kona coast, Hawai‘i, U.S.A.). *Limnol. Oceanogr.* 55, 1105–1122.
- Lapointe, B.E., Herren, L.W., Paule, A.L., 2017. Septic systems contribute to nutrient pollution and harmful algal blooms in the St. Lucie Estuary, Southeast Florida, USA. *Harmful Algae* 70, 1–22.
- Marrack, L., Wiggins, C., Marra, J.J., Genz, A., Most, R., Falinski, K., Conklin, E., 2020. Assessing the spatial-temporal response of groundwater-fed anchialine ecosystems to sea-level rise for coastal zone management. *Aq. Cons. Mar. Fresh. Eco.* 31, 853–869 (2021).
- McKenzie, T., Habel, S., Dulai, H., 2021. Sea-level rise drives wastewater leakage to coastal waters and storm drains. *Limnol. Oceanogr. L.* 6(3), 154–163.
- Mezzacapo, M., Shuler, C., Lander, M., 2022. 2022 Hawai‘i Cesspool Hazard Assessment & Prioritization Tool. <https://health.hawaii.gov/wastewater/files/2022/11/prioritizationtoolreport.pdf>
- Nakoa, J.W.P., III, 2022. Dilution of sewage pollution in the coastal waters of Hilo, Hawai‘i, U.S.A.: An area with high river and groundwater inputs. M.S. thesis, University of Hawai‘i at Hilo, Tropical Conservation Biology and Environmental Science Graduate Program.
- Nalley, E. M., Tuttle, L. J., Barkman, A. L., Conklin, E. E., Wulstein, D. M., Richmond, R. H., & Donahue, M. J. 2021. Water quality thresholds for coastal contaminant impacts on corals: A systematic review and meta-analysis. *Sci. Tot. Env.* 794, 148632. <https://doi.org/10.1016/j.scitotenv.2021.148632>
- Nicholls, R.J., Wong, P.P., Burkett, V.R., Codignotto, J.O., Hay, J.E., McLean, R.F., Ragoonaden, S., Woodroffe, C.D., 2007. Coastal systems and low-lying areas. In: Parry, M.L., Canziani, O.F., Palutikof, J.P., van der Linden, P.J., Hanson, C.E., (Eds.), *Climate Change 2007: Impacts, Adaptation and Vulnerability*. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, UK, pp. 315–356.
- Office for Coastal Management, 2024. 2018 - 2020 NOAA USGS Lidar: Hawaii, HI from 2010-06-15 to 2010-08-15. NOAA National Centers for Environmental Information. <https://www.fisheries.noaa.gov/inport/item/68082>.
- Oki, D.S., 1999. Geohydrology and numerical simulation of the groundwater flow system of Kona, island of Hawai‘i. US Geological Survey Technical Report No. 99–4073.

- Panelo, J., Wiegner, T.N., Colbert, S.L., Goldberg, S., Abaya, L.M., Conklin, E., Couch, C., Falinski, K., Gove, J., Watson, L., Wiggins, C., 2022. Spatial distribution and sources of nutrients at two coastal developments in South Kohala, Hawai‘i. *Mar. Pollut. Bull.* 174, 113142.
- Parnell, A.C., Phillips, D.L., Bearhop, S., Semmens, B.X., Ward, E.J., Moore, J.W., Jackson, A.L., Grey, J., Kelly, D.J., Inger, R., 2013. Bayesian stable isotope mixing models. *Environmetrics* 24, 387–399.
- Peterson, R.N., Burnett, W.C., Glenn, C.R., Johnson, A.G., 2009. Quantification of point-source groundwater discharges to the ocean from the shoreline of the Big Island, Hawai‘i. *Limnol. Oceanogr.* 54, 890–904.
<https://doi.org/10.4319/lo.2009.54.3.0890>
- Pinto, B., 1999. Characterization of ‘faecal streptococci’ as indicators of faecal pollution and distribution in the environment. *L. Appl. Micro.* 29, 258–263.
- Prouty, N. G., Swarzenski, P. W., Fackrell, J. K., Johannesson, K., & Palmore, C. D., 2016. Groundwater-derived nutrient and trace element transport to a nearshore Kona coral ecosystem: Experimental mixing model results. *J. Hydro. Reg. Stud.*, 5, 1–15. <https://doi.org/10.1016/j.ejrh.2015.12.058>
- Redding, J.E., Myers-Miller, R.L., Baker, D.M., Fogel, M., Raymundo, L.J., Kim, K., 2013. Link between sewage-derived nitrogen pollution and coral disease severity in Guam. *Mar. Pollut. Bull.* 73, 57–63.
- Reopanichkul, P., Carter, R.W., Worachananant, S., Crossland, C.J., 2010. Wastewater discharge degrades coastal waters and reef communities in southern Thailand. *Mar. Env. Res.* 69, 287–296.
- Ruminski, L., 2020. Sewage spill closes Kailua Bay. *West Hawaii Today*.
<https://www.westhawaii.com/2020/07/12/hawaii-news/sewage-spill-closes-kailua-bay/>.
- Sharp, J.H., Rinker, K.R., Savidge, K.B., Abell, J., Benaim, J.Y., Bronk, D., Burdige, D.J., Cauwet, G., Chen, W., Doval, M.D., Hansell, D., 2002. A preliminary methods comparison for measurement of dissolved organic nitrogen in seawater. *Mar. Chem.* 78(4), 171–184.
- Shuler, C., 2023. The hidden consequences of sea level rise: Assessing vulnerability of buried infrastructure to groundwater inundation in American Samoa. *J. Wat. Clim. Cha.* 14(12), 4860–4874. <https://doi.org/10.2166/wcc.2023.556>
- Shuval, H., 2003. Estimating the global burden of thalassogenic diseases: Human infectious diseases caused by wastewater pollution of the marine environment. *J. Wat. Hea.* 1, 53–64.
- Sinigalliano, C.D., Fleisher, J.M., Gidley, M.L., Solo-Gabriele, H.M., Shibata, T., Plano, L.R.W., Elmir, S.M., Wanless, D., Bartkowiak, J., Boiteau, R., Withum, K.,

- Abdelzaher, A.M., He, G., Ortega, C., Zhu, X., Wright, M.E., Kish, J., Hollenbeck, J., Scott, T., Backer, L.C., Fleming, L.E., 2010. Traditional and molecular analyses for fecal indicator bacteria in non-point source subtropical recreational marine waters. *Water Res.* 44, 3763–3772.
- Sinton, L.W., Hall, C.H., Lynch, P.A., Davies-Colley, R.J., 2002. Sunlight inactivation of fecal indicator bacteria and bacteriophages from waste stabilization pond effluent in fresh and saline waters. *App. Env. Micro.* 68(3), 1122–1131.
- Smith, C.M., Whittier, R.B., Amato, D.W., Dailer, M.L., Colbert, S.L., Shuler, C.K., Altman-Kurosaki, N.T., Vasconcellos, S., Markel, A.C., Ornelas, B., 2021. State-wide assessment of wastewater pollution intrusion into coastal regions of the Hawaiian Islands. Report prepared for the Hawai‘i State Legislature 2022, Hawai‘i State Department of Health, and the Cesspool Conversion Working Group.
- Steadmon, M., Takakusagi, M., Wiegner, T.N., Jones, M., Economy, L.M., Panelo, J., Morrison, L.A., Medeiros, M.C., Frank, K.L., 2024. Detection and modeling of *Staphylococcus aureus* and fecal bacteria in Hawaiian coastal waters and sands. *W. Env. Res.* 96(5), e11037.
- Swart, P.K., Evans, S., Capo, T., Altabet, M.A., 2014. The fractionation of nitrogen and oxygen isotopes in macroalgae during the assimilation of nitrate. *Biogeosciences* 11, 6147–6157.
- Sweet, W.V., Kopp, R., Weaver, C.P., Obeysekera, J.T.B., Horton, R.M., Thieler, E.R., Zervas, C.E., 2017. Global and regional sea level rise scenarios for the United States, NOAA Technical Report NOS CO-OPS 083, 75 pgs.
- Sweet, W.V., Genz, A.A., Obeysekera, J., Marra, J.J., 2020. A regional frequency analysis of tide gauges to assess Pacific coast flood risk. *Front. Mar. Sci.* 7:883.
- Viau, E.J., Goodwin, K.D., Yamahara, K.M., Layton, B.A., Sassoubre, L.M., Burns, S.L., Tong, H.I., Wong, S.H., Lu, Y., Boehm, A.B., 2011. Bacterial pathogens in Hawaiian coastal streams—associations with fecal indicators, land cover, and water quality. *Water Research* 45, 3279–3290.
- Wada, C.A., Burnett, K.M., Okuhata, B.K., Delevaux, J.M.S., Dulai, H., El-Kadi, A.I., Gibson, V., Smith, C., Bremer, L.L., 2021. Identifying wastewater management tradeoffs: Costs, nearshore water quality, and implications for marine coastal ecosystems in Kona, Hawai‘i. *PLoS ONE* 16(9), e0257125. <https://doi.org/10.1371/journal.pone.0257125>.
- Wade, T.J., Sams, E., Brenner, K.P., Haugland, R., Chern, E., Beach, M., Wymer, L., Rankin, C.C., Love, D., Li, Q., Noble, R., Dufour, A.P., 2010. Rapidly Measured Indicators of Recreational Water Quality and Swimming-Associated Illness at Marine Beaches: A Prospective Cohort Study. *Environmental Health* 9,66.

- Waiki, S. M. P., Colbert, S. L., Wiegner, T. N., Puniwai, N., Nakoa, III, J. W. P., Storie, N. M., Nelson, C. E., Overly, A. N., McDermid, K. J., Aguiar, D. K., 2025. Sewage pollution from onsite sewage disposal systems and an offshore wastewater treatment plant outfall in coastal waters of Keaukaha, Hawai‘i Island. *J. Hydro. Reg. Stud.* 57, 102122.
- Wear, S., Vega Thurber, R., 2015. Sewage pollution: Mitigation is key for coral reef stewardship. *Annals of the New York Academy of Sciences* 1355, 1355-30.
- Whittier, R.B., El-Kadi, A., 2014. Human health and environmental risk ranking of on-site sewage disposal systems for the Hawai‘i and Islands of Kaua‘i, Moloka‘i, Maui, and Hawai‘i. Final report prepared for the State of Hawai‘i Department of Health, Safe Drinking Water Branch.
- Wiegner, T.N., Edens, C.J., Abaya, L.M., Carlson, K.M., Lyon-Colbert, A., Molloy, S.L., 2017. Spatial and temporal microbial pollution patterns in a tropical estuary during high and low river flow conditions. *Mar. Pollut. Bull.* 114(2), 952–961.
- Wiegner, T.N., Mokiao-Lee, A.U., Johnson, E.E., 2016. Identifying nitrogen sources to thermal tide pools in Kapoho, Hawai‘i, U.S.A., using a multi-stable isotope approach. *Mar. Pollut. Bull.* 103, 63–71.
- Wiegner, T.N., Colbert, S.L., Abaya, L.M., Panelo, J., Remple, K., Nelson, C.E., 2021. Identifying locations of sewage pollution within a Hawaiian watershed for coastal water quality management actions. *J. Hydro. Reg. Stud.* 38, 100947.
- Xue, D., Botte, J., De Baets, B., Accoe, F., Nestler, A., Taylor, P., Van Cleemput, O., Berglund, M., Boeckx, P., 2009. Present limitations and future prospects of stable isotope methods for nitrate source identification in surface and groundwater. *Water Research* 43, 1159–1170.
- Zhao, Z., Yin, H., Xu, Z., Peng, J., Yu, Z., 2020. Pin-pointing groundwater infiltration into urban sewers using chemical tracer in conjunction with physically based optimization model. *Water Research* 175:115689.