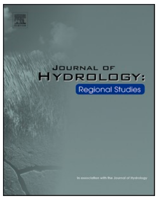
Journal of Hydrology: Regional Studies 57 (2025) 102122

Contents lists available at ScienceDirect

Journal of Hydrology: Regional Studies

journal homepage: www.elsevier.com/locate/ejrh



Sewage pollution from onsite sewage disposal systems and an offshore wastewater treatment plant outfall in coastal waters of Keaukaha, Hawaiʻi Island

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ARTICLE INFO

Keywords:
Wastewater
Fecal indicator bacteria
Stable nitrogen isotopes
Macroalgae
Dye tracer
cesspools

ABSTRACT

Study region: Keaukaha, Hawaiʻi.
Study focus: Onsite sewage disposal systems (OSDS) and the Hilo Wastewater Treatment Plant (HWTP) outfall are potentially impacting Keaukaha's coastal waters. We used dye tracer tests, water quality, δ^{15}N macroalgal, δ^{15}N- and δ^{18}O-NO$_3^-$ measurements along with stable isotope mixing models to assess connectivity of OSDS to coastal waters and characterize water quality at coastal OSDS-impacted springs, coral reefs, and from the HWTP. A citizen science survey tool evaluated the association of both the presence and intensity of sewage odor with weather, ocean, and river conditions.
New hydrological insights for the region: All measurements confirmed sewage presence in Keaukaha's coastal waters and coral reefs. OSDS-sewage reached shoreline springs within 20 h to 3 d. Measured flow rates ranged from 130 to 213 m/d, which were 15 times faster than state models

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Abbreviations: TDN, Total Dissolved Nitrogen; TDP, Total Dissolved Phosphorus; DOC, Dissolved Organic Carbon; CTD, Conductivity-Temperature-Depth; OSDS, On-site Sewage Disposal System; HDOH, Hawaiʻi Department of Health; FIB, Fecal Indicator Bacteria; SGD, Submarine Groundwater Discharge; HWTP, Hilo Wastewater Treatment Plant; WWTP, Wastewater Treatment Plants; ATU, Aerobic Treatment Units; USEPA, United States Environmental Protection Agency; MST, Microbial Source Tracking; Chl *a*, Chlorophyll *a*; IRMS, Isotope Ratio Mass Spectrometer; USGS, United States Geological Survey; ANOVA, Analysis of Variance; NOAA, National Oceanic and Atmospheric Administration; CDIP, Coastal Data Information Program; NCEI, National Centers for Environmental Information; NIST, National Institute of Standards and Technology; MPN, Most Probably Number; TimePrecip, Sum of precipitation from each 15-min interval; CFU, Colony Forming Units; HCPT, Hawaiʻi Cesspool Hazard Assessment & Prioritization Tool; N, Nitrogen; PSS-78, Practical Salinity Scale 1978; SCUBA, Self-Contained Underwater Breathing Apparatus; DL, Detection Limit; QR, Quick Response; BDL, Below Detection Limit; NWS, National Weather Service; *Pac*IOOS, Pacific Island Ocean Observing System.

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https://doi.org/10.1016/j.ejrh.2024.102122
Received 19 July 2024; Received in revised form 1 November 2024; Accepted 3 December 2024

for cesspool removal prioritization. Coastal OSDS-impacted springs had higher fecal indicator bacteria and nutrient concentrations than in the HWTP outfall plume. Benthic macroalgal $\delta^{15}N$ was indicative of sewage at the outfall and nearby reef, as well as along the shoreline. Reported sewage odors coincided with high bacterial count advisories and HWTP discharge events, demonstrating the effectiveness of human olfaction as a sewage pollution indicator. Our findings suggest that Hilo's prioritization category for OSDS removal should be elevated to Priority 1, and that the HWTP outfall should be relocated to a less culturally and ecologically sensitive area.

1. Introduction

Sewage enriched in inorganic nutrients, pathogens, endocrine disruptors, heavy metals, and other toxins are polluting coastal waters worldwide (Wear and Vega Thurber, 2015). Untreated and minimally-treated sewage are released into the environment from sewage spills and as effluent from onsite sewage disposal systems (OSDS, i.e., cesspools, septic systems), while treated sewage enters from aerobic treatment units (ATUs) and wastewater treatment plants' (WWTP) injection wells and outfalls. Annually, recreating in sewage-polluted waters results in ~ 120 million gastrointestinal diseases and 50 million cases of severe respiratory illness worldwide (Shuval, 2003). Consumption of filter-feeding organisms, like oysters, harvested from sewage-polluted waters causes 4 million cases of Hepatitis A and E, and 40,000 cases of chronic disability (Wear et al., 2021; Desdouits et al., 2023). Additionally, ~ 58 % of coral reefs are exposed to sewage pollution, with 104 out 108 coral-human inhabited topographies having issues (Wear and Thurber, 2015; Tuholske et al., 2021). This exposure negatively impacts coral reefs, with documented phase shifts from coral- to macroalgal-dominated ecosystems, increased prevalence and severity of coral disease, greater susceptibility to bleaching, elevated bioerosion rates, reduced coral growth rates, as well as decreased community diversity and species abundance (i.e., Lapointe, 1997; Sutherland et al., 2010; Redding et al., 2013; Vega Thurber et al., 2014; Prouty et al., 2017). These conditions slow the recovery of bleached corals, further impeding their resilience and recovery from other stressors (Carilli et al., 2009 Wear and Vega Thurber, 2015). While the myriad of sewage impacts to coral reefs are being documented, reef managers have generally not addressed the issue (Wear, 2016).

Due to the complex and variable composition of sewage, multiple approaches and indicators are used to document its presence. Dye tracer tests are used to determine the connectivity between both OSDS and injection wells to coastal waters (Hunt, 2007; Hunt and Rosa, 2009; Glenn et al., 2013). Commonly used sewage indicators include fecal indicator bacteria (FIB, i.e., *Enterococcus* spp., *Clostridium perfringens*), microbial source tracking (MST, i.e., human-associated *Bacteroides* markers), stable isotopes of nitrogen (N) in macroalgal tissue and NO_3^-, and nutrients. Smell can also be used to detect sewage pollution, but it has not been widely adopted as an indicator, although humans are able to distinguish between at least 1 trillion olfactory stimuli (Bushdid et al., 2014). While a single sewage indicator alone can be highly variable, the use of them in concert in a scoring tool allows for more accurate identification of sewage pollution hotspots and assessment of the pollution intensity (e.g., Abaya et al., 2018).

The State of Hawai‘i relies heavily on OSDS to dispose of sewage, with high densities of OSDS located close to the coast. There are approximately 110,000 OSDS statewide, with 49,000 classified as cesspools located on Hawai‘i Island (Whittier and El-Kadi, 2014; HDOH, 2017a). The Hawaiian Islands are made up of porous and highly permeable basalt rock, which allows untreated sewage from cesspools to rapidly seep into basal groundwater and be transported to coastal waters posing an immediate human health risk (Whittier and El-Kadi, 2014). Recognizing this issue, the Hawai‘i State Legislature passed Act 125 in 2017, which requires the replacement of all cesspools by the year 2050 (HDOH, 2015; HDOH, 2017a). However, in order to prioritize locations for removal, more water quality data are needed. Earlier sewage pollution research in Hawai‘i State focused on impacts from WWTP outfalls and injection wells on the islands of O‘ahu and Maui, with the latter resulting in a U.S. Supreme Court case that upheld the Clean Water Act requiring a permit to discharge pollution into navigable waters (Smith et al., 1981; Glenn et al., 2013; Supreme Court of the United States, 2020). OSDS have become the focus of research over the last decade, with studies being conducted on the islands of O‘ahu, Kaua‘i, and Hawai‘i, with many being conducted in the coastal community of Puakō, located in West Hawai‘i (i.e., Nelson et al., 2015; Kirs et al., 2016; Yoshioka et al., 2016; Abaya et al., 2018; Wiegner et al., 2021). While many communities in Hawai‘i State and elsewhere in the region are impacted by sewage from both WWTPs and OSDS, no study has examined the combined impact of both or isolated contributions from the two in order to make targeted and effective management decisions to improve water quality

One location on Hawai‘i Island receiving sewage inputs from these two sources is the Keaukaha region of Hilo. Although, there is a tremendous amount of community concern regarding sewage pollution, no study to date has documented it along this shoreline, where people recreate, subsistence fish and gather, and perform cultural practices, except at a few Hawai‘i Department of Health (HDOH) FIB monitoring stations. While earlier sewage studies in Hilo Bay examined the impacts of storm-driven OSDS inputs from rivers (Wiegner et al., 2013, 2017; Economy et al., 2019), this study specifically focuses on Keaukaha's coastal waters outside of Hilo Bay. The goals of this study were to: 1) ascertain the connectivity of OSDS to coastal waters, 2) characterize water quality at coastal OSDS-impacted springs, coral reefs, and from the HWTP (influent to outfall), and 3) document the presence and intensity of sewage odor and assess the association with weather, ocean, and river conditions. Study goals were accomplished using dye tracer tests, water quality, $\delta^{15}N$ macroalgal, $\delta^{15}N$- and $\delta^{18}O$-NO_3- measurements along with stable isotope mixing models, and a citizen science survey. This study provides some of the first water quality data for the Keaukaha region and they will serve as a baseline for future comparisons. These datasets are essential for evaluating the prioritization of cesspool removal for Hilo and potential improvements to water quality from cesspool removal and upgrades to the WWTP. Additionally, if neither of the latter occur, our measurements will help document changes in future water quality from sea level rise as OSDS and WWTP's sewer lines become inundated (McKenzie et al., 2021; Kiefer and Felton, 2024). Our novel focus and approach for studying sewage pollution provides a framework for researchers and natural resource managers who are challenged with assessing and addressing sewage pollution in their coastal waters, particularly in Hawai'i State and those on high volcanic islands in the Pacific.

2. Methods

2.1. Site description

This study was conducted along the Keaukaha coastline in the town of Hilo on the windward side of the Island of Hawai'i, Hawai'i, USA. (Fig. 1). Keaukaha sits on the east flank of Mauna Loa volcano, an area of highly permeable subaerial basalt lava flows (Takasaki, 1993). This area has a tropical climate, with a wet winter (Oct.-April) and a dry summer (May-Sept.), experiencing a mean annual rainfall ranging from 2751 - 3550 mm (Giambelluca et al., 2013). Our study area is representative of 31 % of the Pacific islands, which are high volcanic islands with coral reefs (Nunn et al., 2016). Two watersheds drain into this area, Keaukaha (6.56 km^2) and Leleiwi (8.51 km^2), with ~ 30 m maximum elevations. Combined land cover for the two watersheds is: 22 % native forest, 6 % native shrub, 22 % alien wet forest, 10 % alien grassland, < 1 % alien shrubland, 5 % cultivated agriculture, 8 % developed open space, 18 % low/med/high intensity development, and 7 % sparse/unvegetated (Jacobi et al., 2017). There are no perennial or ephemeral streams in this area; the only source of freshwater to the shoreline is through submarine groundwater discharge (SGD). Estimated SGD fluxes for this area are 4663,627 m^3/d (Hilo + Onomea aquifers; Engott, 2011). The Keaukaha coastline ranges from a rugged rocky shore, to black sand beaches with a few white sand pockets, and numerous freshwater springs. Keaukaha is Hawaiian for "passing current", and this area of Hilo is known for its *loko i'a*, fishponds, which are a cultural asset that many community members work to restore and maintain the cultural traditions of Hawai'i and its people. Located within Keaukaha is a *wahi pana*, special place, known as Puhi Bay. This *wahi pana* serves as a gathering place for families and is used for recreational and cultural activities, such as subsistence fishing to provide food for families. The neighborhood adjacent to Puhi Bay is the Keaukaha Homestead, originally known in 1924 as the Kūhiō Settlement, the second established Hawaiian Homestead in Hawai'i State, with 60 Native Hawaiian families who became lessees (DHHL, 2014). As of 2022, the Hawaiian Homestead population in Keaukaha was 1955, consisting of 497 families (Census Report, 2022).

Keaukaha's coastal waters are potentially impacted by sewage from OSDS and the HWTP outfall. Of the current 497 homes within the Keaukaha Hawaiian Homestead, 258 utilize OSDS and 239 are connected to municipal sewer lines (HDOH, 2017a,b). The HWTP is located just southeast of the Keaukaha region and is Hilo's only municipal WWTP. The HWTP has a design capacity of ~ 22,730 m^3/d, but currently operates and disposes ~13,638 m^3/d of secondary-treated, chlorinated sewage into the ocean (Tetra Tech, 2010). Ongoing since 2016, the United States Environmental Protection Agency (USEPA) and HDOH has fined Hawai'i County for the derelict state of the HWTP and illegal discharges into the ocean (Dobbyn, 2024). It was found that the HWTP no longer operates within USEPA standards under the Clean Water Act (Brestovansky, 2024). Effective March 26, 2024, Hawai'i County is under an administrative consent order with the USEPA to rehabilitate and replace corroded equipment, address deferred maintenance, and develop a program to systematically repair, rehabilitate, and replace aging infrastructure by 2035 or face penalties (USEPA, 2024). The administrative consent order also includes that Hawai'i County must expand sewer service, create a cesspool conversion plan and initiate it by 2026. Start date for operation of new and upgraded WWTP is 2035 (Dobbyn, 2024).

2.2. Study design

Dye tracer tests assessed the connectivity of OSDS to coastal waters, and were coupled with water and macroalgal sampling at coastal springs to evaluate water quality where dye emerged. HWTP (influent, effluent, and pre-outfall [manhole before outfall pipe starts]) and outfall plume samples were used to characterize water quality directly related to the HWTP. Comparisons between effluent and pre-outfall samples were used to evaluate how the sewer pipe microbial community may modify water quality of the effluent prior to discharge at the outfall (McLellan and Roguet, 2019; McLellan et al., 2024). Macroalgal samples from inside Puhi Bay were used to assess the presence of sewage on the reef. Lastly, a citizen science survey was conducted to document the presence and intensity of sewage odors encountered in Keaukaha and identify the association with weather, ocean, and river conditions.

2.3. Dye tracer tests

At four homes, dye tracer tests were conducted utilizing OSDS (3 cesspools, 1 septic tank) from June to October 2021, to determine their connectivity to shoreline springs. Fluorescein was selected as a dye for this study because it has very low adsorption to basalt and has a vibrant color that can easily be observed at concentrations orders of magnitude below the levels that would be harmful to marine life (Glenn et al., 2013). Powdered fluorescein dye (0.5–2.0 kg, Amresco Fluorescein Sodium Salt) was mixed with tap water at a concentration of 100 −200 g per 20 L of tap water per hour and slowly added to the OSDS over a 10 h period. Note, the mass of dye added with each subsequent dye tracer test decreased as it was determined that less dye was needed for measurable concentrations at shoreline springs. Ten hours was chosen for the dye addition to ensure its visualization at shoreline springs. Additional tap water was added throughout the day and its volume was recorded to calculate the initial dye concentration.

Water samples were collected at 12–13 coastal springs before, during, and after dye addition to determine where and when the dye emerged. If the point of maximum dye concentration was not identified at one of the initially sampled springs, additional springs were

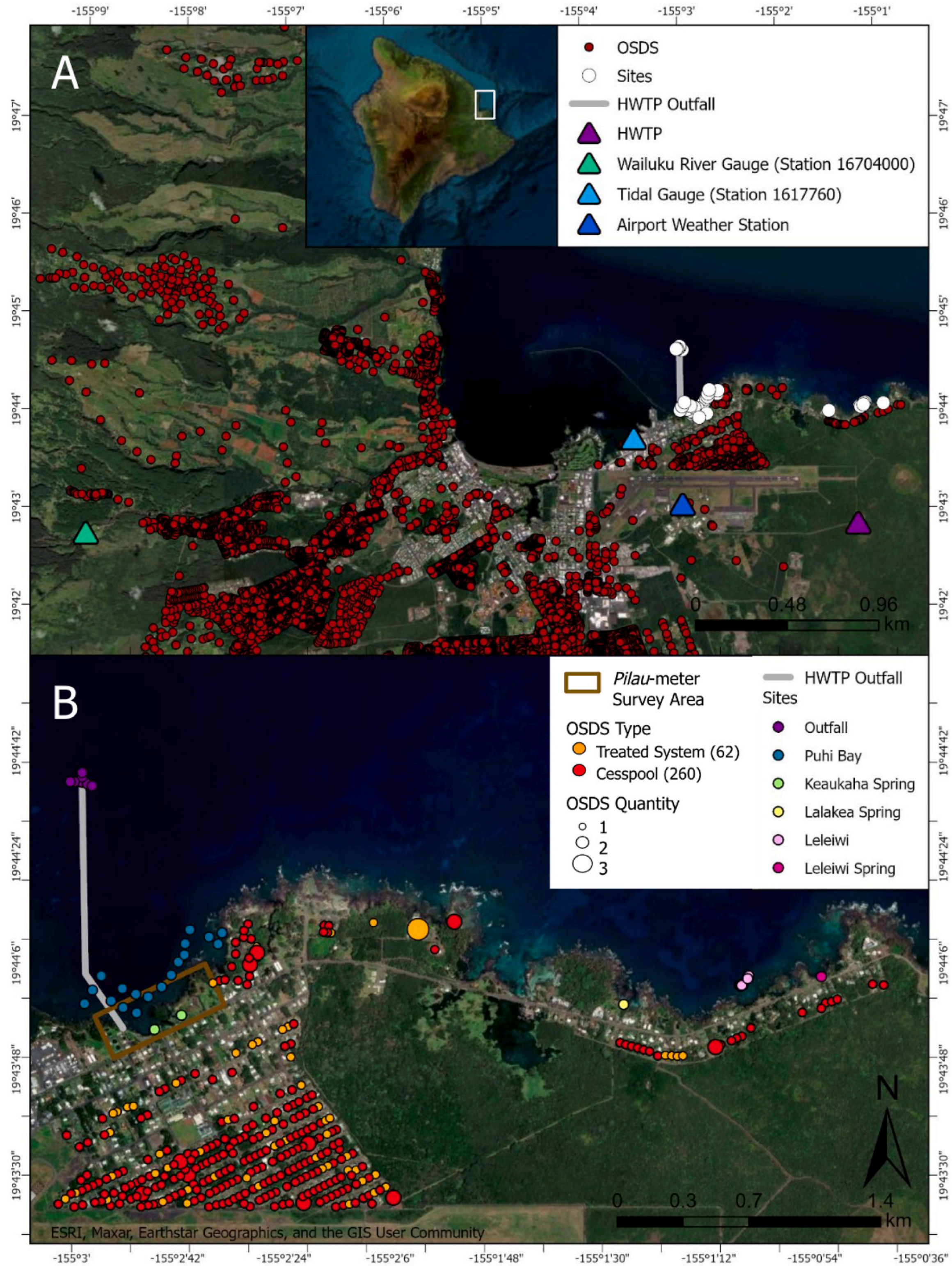

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Fig. 1. A) Map of all onsite sewage disposal systems (OSDS, red dots) in the greater Hilo, Hawaiʻi, area, including Keaukaha (far right). The inset is of Hawaiʻi Island, with the study location outlined. Also, displayed are the locations for the Hilo International Airport National Weather Service (NWS) station (#91285021504), National Oceanographic and Atmospheric Administration (NOAA) Hilo Bay tidal gauge (#1617760), United States Geological Survey (USGS) Wailuku River gauge (#16704000), and the Hilo Wastewater Treatment Plant and its outfall. B) Zoomed in area of Keaukaha with all OSDS displayed (red: cesspools, orange: septic tanks or aerobic treatment units, circle size proportional to number of OSDS at that location). Locations for the coastal spring samplings for the dye tracer tests, as well as for macroalgae sample collection are shown. Brown highlighted area shows where the citizen science *Pilau*-meter (bad smell) survey was conducted. Detailed information on where data were recorded by participants during the survey is located in Appendix V. Study period was from July 2020-May 2022.

sampled to see if the dye could be detected. Samples were collected in opaque amber high-density polyethylene bottles to prevent photodegradation, and stored at 4 °C until analysis, within 1 month of collection. During the first 12 h of the dye tracer study, samples were collected every 2 h to identify any fast-flow pathways. Then, two samples were collected at each spring within an hour of the lowest-low tide each day for up to 14 d after. Approximately 2 d after dye was visually observed at the coastal springs, the number of springs sampled was reduced to six to eight. For fluorescein analysis, samples were brought to room temperature, filtered (0.7-µm, Whatman™ GF/F), and analyzed using a Turner AU10 fluorometer. The method detection limit (DL) is 0.1 ppb. Sample conductivity was measured (Fisher Scientific Accumet AB200) and converted to PSS-78 salinity (UNESCO, 1981). Note, the EC50 for fluorescein for green algae is about 10 ppm, and much higher for fish and invertebrates (Field et al., 1995), while the maximum concentration measured at shoreline springs in our study was 0.05 ppm. Dilution of the dye from the OSDS to the shoreline springs was calculated using the ratio of the peak concentration of dye measured at the spring to the initial dye concentration added multiplied by 1×10^6. This dilution estimate is conservative as it was likely that we may have missed capturing the peak concentration at the shoreline.

2.4. Water quality and macroalgal sample collection and analyses

Water quality samples were collected at three coastal springs from the dye tracer tests (Lalakea only sampled once), the HWTP and its offshore outfall plume in sterile, acid-washed, polypropylene 1-L bottles. Coastal spring water samples were collected from July 2020 to October 2021 during the lowest morning low tide. This protocol was chosen because sunlight reduces FIB concentrations (Fujioka et al., 1981) and the proportion of SGD in coastal waters is highest during low tides (Ataie-Ashtiani et al., 2001; Robinson et al., 2007), allowing for accurate detection of sewage pollution. The HWTP influent, effluent, and pre-outfall samples were also collected monthly over the same time period. Water samples from the offshore outfall plume were sampled four times via boat in June and August 2021, above the halocline, where the plume has been previously observed (Birmingham et al., 2008). The warm, low-salinity outfall plume was identified using a Conductivity-Temperature-Depth (CTD) sensor (Xylem Castaway) and water samples were collected in a Niskin bottle at depths of 0.5, 1.0, 1.5, 2.0, and 2.5 m. All water samples were analyzed for FIB, nutrient concentrations, and δ^{15}N- and δ^{18}O-NO$_3^-$ Additionally, composite macroalgal samples were collected at the coastal springs, as well as at offshore stations via SCUBA and snorkel in Puhi Bay and other locations in Keaukaha, and analyzed for δ^{15} N and N content (%N) (Fig. 1).

Enterococcus spp., *C. perfringens*, and human-associated *Bacteroides* marker HF183 were quantified in triplicate water samples from the coastal springs, HWTP, and outfall plume. Sample processing occurred within 6 h of collection. *Enterococcus* spp. were analyzed using the Enterolert MPN method with QuantiTray/2000 from the IDEXX Laboratories, Inc. When no QuantiTray wells fluoresced blue, *Enterococcus* spp. concentrations were reported as 5 MPN/100 mL, half of the detection limit. *Enteroccocus* spp. concentrations are reported in this study as geometric means in order to be consistent with USEPA water quality criteria for *Enterococcus* spp. (USEPA, 2012). *Clostridium perfringens* concentrations were quantified using a membrane filtration technique, in which 100 mL of water were filtered through a 0.45-µm pore size cellulose nitrate membrane (Whatman™), placed on mCP agar plates, incubated in an anaerobic jar at 45°C for 18–24 h, followed by fumigation with ammonium hydroxide; pink colony forming units (CFU) were counted as positive detections (Bisson and Cabelli, 1979).

For human-associated *Bacteroides* marker HF183 analysis, 250–500 mL of water were filtered through a 0.22-µm mixed cellulose ester membrane filter (Millipore, USA) and stored frozen in Qiagen bead beating tubes (Cat. No.: 12888–100-PBT) until analysis. For DNA extraction, samples were thawed at room temperature 1–2 h. DNA extraction proceeded via the MP Bio FastDNA spin kit for soil following the manufacturer's instructions, with a modification: cells were mechanically lysed using a MP Biomedicals FastPrep-96 bead beater for 45 s at maximum speed, 6.5 m/s. DNA was stored at −40°C until sequencing. Detection of *Bacteroides* was performed using the established qPCR assay HF183 (Appendix I). 25-µL reaction mixtures containing 10 µL of Kapa Probe Force Master Mix (Cat. No. KK4301), 400 nmol/L of each specific primer, 200 nmol/L of each specific probe, and 1 µL of sample or standard DNA were amplified using an Eppendorf Realplex2 Mastercycler®. A 2-min hot start at 95°C was followed by 45 cycles of 95°C denaturing for 30 s, and 60°C elongation for 30 s. Standard curves were constructed from serial dilutions of synthetic DNA fragments. For each assay, eight dilution steps ranging from 50,000 - 10 gene copies per well were performed in triplicate on every run plate. R^2 values ranged from 0.96 to 0.99 and threshold cycle y-intercepts (a theoretical limit of detection) for these assays ranged from 37.1 to 38.5. Threshold values were controlled manually at 500 Relative Fluorescence Units.

For nutrient analyses, one of the triplicate water samples was filtered through a pre-combusted (500°C for 6 h) 0.7-µm pore size GF/F filter (Whatman™) and stored frozen until analysis at the University of Hawaiʻi at Hilo (UH Hilo) Analytical Laboratory. Water samples were analyzed on a Lachat Quikchem 8500, flow-injection autoanalyzer using standard methods and reference materials for: NO$_3^-$ + NO$_2^-$ [DL 0.07 µmol/L, USEPA 353.4], NH$_4^+$ [DL 0.36 µmol/L, USGS I-2525], PO$_4^{3-}$ [DL 0.03 µmol/L, USEPA 365.5], total dissolved phosphorus (TDP) [DL 0.25 µmol/L, USGS I-4650–03, USEPA 365.5], H$_4$SiO$_4$ [DL 1 µmol/L, USEPA 366]. Total dissolved nitrogen (TDN) was analyzed by high temperature combustion, followed by chemiluminescent detection of nitric oxide (DL 5 μmol/L, Shimadzu TOC-V, TNM-1) (Sharp et al., 2002). Turbidity was measured using a Hach 2100Q Turbidimeter.

For δ^{15}N- and δ^{18}O-NO_3^- analysis, water samples were filtered through a 0.45-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 at the UH Hilo Analytical Laboratory. Data were normalized to United States Geological Service (USGS) standards (USGS32, USGS34, USGS35). Isotopic signatures are expressed as standard (δ) values in units of parts per mil (‰) (Eq.1):

$$\delta = [((R_{sample}\text{-}R_{standard}))/R_{standard}] \times 1000‰ \tag{1}$$

where R is the ratio of the heavy isotope (^{15}N or ^{18}O) to the light isotope (^{14}N or ^{16}O). Isotope delta values are reported relative to atmospheric nitrogen gas for δ^{15}N and VSMOW-SLAP for δ^{18}O.

Composite macroalgal samples were collected and analyzed from each coastal spring where dye was confirmed and algae were present ($n = 2$), and from benthic ($n = 18$) stations for δ^{15}N and %N. Note, one coastal spring (Lalakea) did not have macroalgae present. Composite samples were used because the same species of macroalgae were not present at every station, and species varied among stations. Previous studies have used composite samples successfully to map out sewage pollution hotspots, including on Hawaiʻi Island (Derse et al., 2007; Dailer et al., 2012; Wiegner et al., 2016; Abaya et al., 2018). Additionally, previous studies found that δ^{15}N from different macroalgal species collected at the same location had similar δ^{15}N values (Derse et al., 2007; Wiegner et al., 2016; Nakoa, 2022). Benthic samples were collected via SCUBA and snorkeling with water depths ranging from 0.5 to 15 m, and were 25–70 m apart from each other. At Leleiwi, samples were collected opportunistically and were closer together than at the other locations.

Upon collection, macroalgal samples were placed on ice and transported to the laboratory, where they were rinsed with deionized water and dried at 60 °C. Prior to drying, small portions of each macroalgal species collected were photographed and identified using identification books (Abbott, 1999; Abbott and Huisman, 2004; Huisman et al., 2007). Dried samples were ground, and ~ 1–2 mg of tissue were placed in 4×6 mm tin capsules for δ^{15}N and %N analysis using a Thermo-Finnigan™ Delta V Advantage IRMS with a Conflo III interface and a Costech™ ECS 4010 Elemental Analyzer located at the UH Hilo Analytical Lab. Data were normalized to the USGS, standard NIST 1547.

2.5. Statistical analyses and stable isotope mixing models

Differences in water quality (FIB, nutrients, δ^{15}N and %N in macroalgae, and δ^{15}N- and δ^{18}O-NO_3^-) between two coastal springs near homes where dye tracer tests were conducted and dye was visually present were examined using either a two-sample *t*-test or a Mann-Whitney test depending on whether data for an individual parameter met the criteria for parametric analysis. The springs at Lalakea were not included in these analyses because visual presence of dye was absent and therefore only one sample was collected. A One-way Analysis of Variance (ANOVA) or a Kruskal-Wallis test was used to assess differences in water quality among the three different HWTP treatment stages, and among three different depths sampled within the outfall plume. A one-way ANOVA was also used to evaluate δ^{15}N algae among benthic regions sampled in Puhi Bay. When significant differences were detected, either a Tukey's HSD multiple comparisons test or a Dunn's test, both with a Bonferroni correction, were used to determine where the differences occurred. All statistical tests were analyzed in R (v. 4.0.3) with $\alpha = 0.05$. R codes for statistical tests used are: two- sample *t*-test (*t. test*), Mann-Whitney test (*wilcox.test*), one-way ANOVA (*aov*), Kruskal-Wallis test (*kruskal.test*), Tukey's HSD test (*Tukey.HSD*), and Dunn's test (*dunn.test*).

To identify N sources to the coastal springs and determine their relative percent contributions to the NO_3^- pool, δ^{15}N- and δ^{18}O-NO_3^- data were used to construct stable isotope mixing models using the "*simmr*" package in R (v. 0.4.5). This analysis was only conducted for Keaukaha and Leleiwi Beach Parks because the NO_3^- concentrations for Lalakea were below detection limit (DL 2 μmol/L) for the stable isotope analysis. The *simmr* package uses Bayesian methods and NO_3^-concentration dependence to account for natural variation and uncertainty in the model in order to estimate proportional contributions of each source to the NO_3^- concentration in each sample (Parnell et al., 2010; Parnell et al., 2013). Normality of δ^{15}N and δ^{18}O values was tested using the Shapiro-Wilk normality test (*shapiro. test*). Potential NO_3^- sources sampled were the HWTP pre-outfall effluent (HWTP, $n = 13$) and outfall discharge plume ($n = 4$), inland groundwater from drinking water wells (GW, salinity <1, $n = 7$), and ocean water ($n = 3$). Stable isotope data for OSDS on Hawaiʻi Island were obtained from Wiegner et al. (2016) and Abaya et al. (2018) consisting of cesspools, septic systems, and ATUs (OSDS, $n = 17$). NO_3^- stable isotope source values used in the mixing models were (mean ± SE): δ^{15}N-NO_3^- + 3.6 ± 7.4 ‰ and δ^{18}O + 4.48 ± 2.7 ‰ for the pre-outfall station (Nakoa, 2022), δ^{15}N-NO_3^- + 0.7 ± 0.6 ‰ and δ^{18}O + 2.5 ± 1.1 ‰ for inland groundwater (Nakoa, 2022), and δ^{15}N-NO_3^- + 13.1 ± 2.1 ‰ and δ^{18}O + 16.6 ± 5.2 ‰ for OSDS (Wiegner et al., 2016; Abaya et al., 2018). Ocean water and the outfall plume were not used as NO_3^- sources in this model because NO_3^- concentrations in these samples were below detection limits (DL 2 μmol/L). Bi-plots were created using average and corrected average values of δ^{15}N and δ^{18}O in NO_3^- for each potential source to remove any sources with substantial overlap from the mixing model. Mixing model results show N proportions of each N source as quantiles for the coastal springs where dye emerged from the dye tracer studies. The 50 % quantile was chosen to report for the mixing models because it provides the median contribution value of each source.

2.6. Sewage pollution scoring tool

A sewage pollution score was calculated for each spring using FIB (*Enterococcus* spp., *C. perfringens*), nutrient concentrations (NO_3^- +

NO_2^-, NH_4^+, TDP), and $\delta^{15}N$ macroalgal data. This score was initially developed for Puakō, a coastal community located on the leeward side of Hawaiʻi Island that falls under the HDOH open coastal water quality standards (HDOH, 2014; Abaya et al., 2018). The sewage indicators selected for the score have either HDOH water quality standards or well-established sewage pollution values in the literature (i.e., $\delta^{15}N$ macroalgae). For our study, we modified the score using HDOH nutrient concentration water quality standards for estuaries and embayments under wet conditions (Table 1; HDOH, 2014, 2020; Nakoa, 2022). This change was made because Hilo receives high annual rainfall, has rivers, and the estuary/embayment category is more accurate description for this location. No other part of the score was modified for our study. Each indicator was assigned a level based on its measured value in our study and where it fell relative to water quality standards or literature values, with low values indicative of lower pollution levels (1 = low, 2 = medium, 3 = high). Once each indicator was assigned a level (levels 1–3), it was multiplied by a weight factor (weights 1–3 according to Abaya et al., 2018), with the most reliable sewage indicators from the literature having the greatest weight. *Clostridium perfringens* and $\delta^{15}N$ macroalgae had the greatest weights (weight = 3), as these indicators are more specific to sewage pollution, more integrative of environmental conditions, and do not fluctuate to the same degree as *Enterococcus* spp. and nutrient concentrations. The equation for calculating the sewage score was: (*C. perfringens* level x 3) + ($\delta^{15}N$ macroalgal level x 3) + (*Enterococcus* spp. level x 2) + (NO_3^-+NO_2^- level x 1) + (NH_4^+ level x 1) + (TDP level x 1). Sewage pollution score categories were: low (11−17), medium (18−25), and high (26−33). More details on the sewage score can be found in Abaya et al. (2018). A sewage pollution score was not calculated for the coastal spring at Lalakea because no macroalgae were present to sample.

2.7. Citizen science odor survey, the *Pilau*-meter

A Google Form survey called the *Pilau*-meter (Hawaiian word for stink, rotten, foul), was developed to document the presence and intensity of the odor encountered around Puhi Bay using a citizen science approach (Appendix II). The idea to incorporate observations of smell in our study arose from comments at Keaukaha community meetings regarding the “stink” that has occurred in their neighborhood for decades. We wanted a community-based way of collecting data recording the phenomena and combining it with water quality data. The assumption of the community is that the odor arises from the HWTP and sewer lines, and may coincide with when sewage is released into Puhi Bay or fractures in the sewer line pipes occur. The survey consisted of 13 questions that addressed information such as: date, time, demographics, types of odors, severity of odor, and environmental conditions (Appendix II). The survey began in June 2021 and concluded in March 2022. A random, volunteer opportunistic survey method was used taking advantage of community willingness to participate in understanding sewage pollution in their waters. Flyers with QR codes accessing the *Pilau*-meter were posted at Puhi Bay and shared in-person with beachgoers during the weekends. The representativeness of our data is limited to the demographics of Keaukaha and context of our study, as this is a water-based community with a reliance on the water for sustenance, recreation, and cultural practices. Our survey could be modified for other physical and demographic contexts in which odor is an issue. The study protocol was approved by the Institutional Review Board at the University of Hawaiʻi, Protocol #: 2021–00694 on 12/02/2021.

To assess potential associations between odors recorded during surveys and environmental conditions at that time, weather, ocean, and river data from June 2021 to March 2022 were obtained from the National Oceanographic and Atmospheric Administration’s (NOAA) National Center for Environmental Information (NCEI) Hilo Airport’s National Weather Service (NWS) station #91285021504, the NOAA Hilo Bay tide gauge #1617760, the Coastal Data Information Program (CDIP) Pacific Island Ocean Observing System (*Pac*IOOS) Hilo Bay wave buoy #188, and the USGS Wailuku River gauge #16704000. Wave data were only available from November 2021 to March 2022. HDOH water quality advisories were also analyzed for association with the presence of

Table 1
Sewage indicators used to evaluate water quality along the Hilo coastline, Hawaiʻi. These indicators were ranked based on their measured concentrations relative to Hawaiʻi Department of Health (HDOH) standards and literature values (levels: low = 1, medium = 2, high = 3), multiplied by a weight factor (1−3) based on the reliability of that parameter as a sewage indicator, and summed for a final sewage pollution score. The greatest weight (weight = 3) was given to the most reliable sewage indicators. The sewage pollution score was modified from using open coastal waters standards for nutrients (HDOH, 2014; Abaya et al., 2018) to those for estuaries and embayments under wet conditions (Nakoa, 2022). The latter is more representative of the water characteristics and weather conditions for Hilo.

Levels					
Sewage Indicator	**Weight Factor**	**Low**	**Medium**	**High**	**Reference**
C. perfringens (CFU/100 mL)	3	0.00–10.00	10.01–100.00	100.01 +	Fujioka et al., (2015)
Macroalgal $\delta^{15}N$ (‰)	3	0.00–5.99	6.00–10.99	11.00 +	Abaya et al., (2018)
Enterococcus spp. (MPN/100 mL)	2	0.00–35.00	35.01–129.99	130.00 +	HDOH, (2020)
NO_2^- + NO_3^- (µmol/L)	1	0.00–0.60	0.61–1.43	1.44 +	HDOH, (2014)
NH_4^+ (µmol/L)	1	0.00–0.43	0.44–0.93	0.94 +	HDOH, (2014)
TDP (µmol/L)	1	0.00–0.81	0.82–1.61	1.62 +	HDOH, (2014)

different odors.

Observations from the *Pilau*-meter and all environmental conditions data (wind speed/direction/gusts, air temperature/pressure, precipitation, water temperature, tide height/time/time from low tide, wave height/peak period/peak direction/average period, river discharge/gauge height) were combined into one dataset in Python to examine potential associations between them. Environmental conditions data were resampled in Python into 15-min intervals, except for high and low tides, which were resampled at 6-min intervals for better resolution of tide data. Time precip. was created by calculating the sum of precipitation over the previous 6 h from each 15-min interval (Appendix III). Time from low tide was calculated as the time before and after low tide (Appendix III). Correlation analysis examined possible associations between the three most commonly reported odors (good/normal, fishy, sewage) and their intensity with environmental conditions (Appendix III).

3. Results

3.1. Dye tracer tests

Dye from all four dye tracer tests was detected at the shoreline at two to three coastal springs near each test location (Fig. 2). Dye from the dye tracer test conducted at Lalakea lacked visual presence at the shoreline because of lower dye concentrations and consequently water quality parameters were measured only once at this spring. However, dye was detected in Lalakea's water samples using a fluorometer. Dye reached the shoreline from 20 h to 3 d, which is a conservative estimate, calculated from the difference in time from the start of the dye addition to the OSDS until the first observed appearance at the shoreline (Table 2). The flow rate for dye to travel from the OSDS to the shoreline ranged from 130 to 213 m/d (Table 2). The maximum sewage fraction at the shoreline spring based on dye dilution ranged from 2.4 to 28.9 ppm (Table 2).

3.2. Coastal springs' water quality

Concentrations of sewage indicators varied between coastal springs where dye emerged from the dye tracer tests. While the human-associated *Bacteroides* marker HF183 was not detected at any of the coastal springs, FIB (*Enterococcus* spp. and *C. perfringens*) and most nutrient concentrations (NH_4^+, TDP, PO_4^{3-}, H_4SiO_4, and DOC) were similar between coastal springs at the two beach parks. *Enterococcus* spp. concentrations ranged from 5 to 6546 MPN/100 mL and those for *C. perfringens* ranged from 0 to 1 CFU/100 mL (Table 3). In

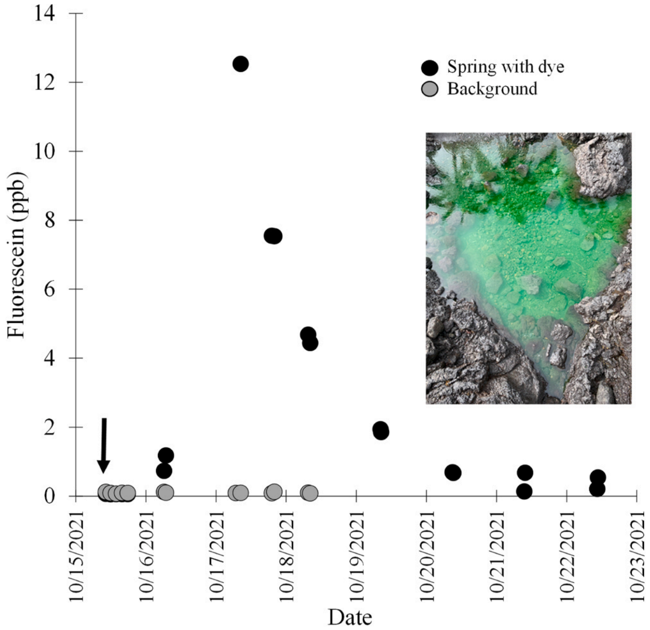


Fig. 2. Example of results from a dye tracer test conducted in Keaukaha, Hilo, Hawai'i, with fluorescein over a 6-d period. Concentrations of fluorescein in the spring where the dye emerged are compared with those at a nearby spring, where concentrations remained at background levels during the dye tracer test. For this dye tracer test, dye was added to the onsite sewage disposal system at 9:25 am on 10/15/2021 as indicated by the arrow on the figure, and dye at the spring was first observed at 6:14 am on 10/16/2021. Photograph of the fluorescein that emerged at the shoreline spring (photo credit: S. Waiki).

Table 2
Sewage travel time, flow rate, and maximun sewage fraction at the shoreline springs based on dye dilution from four dye tracer tests conducted between June and October 2021, in Keaukaha, Hawai'i. Dye tracer tests were conducted on two types of onsite sewage disposal systems (OSDS): cesspools and septic tanks.

Spring location	OSDS type	Start date	Travel time (d)	Flow rate (m/d)	Maximum sewage fraction (ppm)
Keaukaha Beach Park	Cesspool	06/14/2021	3.2	129.9	3.2
Leleiwi Beach Park	Cesspool	07/19/2021	0.8	178.4	28.9
Lalakea	Cesspool	10/15/2021	0.9	213.3	16.4
Keaukaha Beach Park	Septic Tank	07/05/2021	1.9	157.4	2.4

contrast to FIB, concentrations for most dissolved N species significantly differed among the coastal springs at the two beach parks, with Keaukaha Beach Park having significantly higher values of $NO_3^- + NO_2^-$, TDN, and $\delta^{15}N\text{-}NO_3^-$ (Table 3).

At the coastal springs, 15 algal species were collected, including (ordered based on their highest occurrence): *Polyopes hakalauensis* (Rhodophyta), *Chondrus retortus* (Rhodophyta), *Ahnfeltiopsis concinna* (Rhodophyta), *Rhizoclonium riparium* (Chlorophyta), *Gelidiella myrioclada* (Rhodophyta), diatom sp.(Ochrophyta), *Ulva compressa* (Chlorophyta), *Ahnfeltiopsis flabelliformis* (Rhodophyta), *Pyropia vietnamensis* (Rhodophyta), *Ahnfeltiopsis pygmaea* (Rhodophyta), *Colpomenia sinuosa* (Ochrophyta), *Ulva flexuosa* (Chlorophyta), *Gelidium pusillum* (Rhodophyta), *Hypnea spinella* (Rhodophyta), and *Ulva clathrata* (Chlorophyta). The $\delta^{15}N$ in macroalgal tissue present at coastal springs ranged from + 0.7 to + 4.4 ‰, while %N ranged from 1.22 % to 2.94 %, and both significantly differed between the two beach parks (Table 3). The macroalgal $\delta^{15}N$ was more enriched in ^{15}N at Keaukaha Beach Park, while Leleiwi's macroalgae had a higher %N content (Table 3).

NO_3^- in the coastal spring waters of Keaukaha was a mixture of NO_3^- from OSDS, HWTP, and groundwater. The highest OSDS contribution to the NO_3^- pool was at Keaukaha Beach Park (20.8 %, Fig. 3). Leleiwi had a much smaller percentage (4.8 %; Fig. 3). Likewise, the highest HWTP contribution to the NO_3^- pool was at Keaukaha (26.1 %) with the contribution at Leleiwi being much lower (9.0 %) (Fig. 3). Groundwater was an important source of NO_3^- to the two beach parks' springs, contributing 42.2 % and 85.1 % at

Table 3
Mean ± SE and [range] of sewage indicators measured at three of the shoreline springs where dye was confirmed from dye tracer tests in June - October 2021 in Keaukaha, Hawai'i. Results from two sample-t and Mann-Whitney tests are shown in the table. * denotes significant differences between springs sampled for cesspools at Keaukaha and Leleiwi Beach Parks ($\alpha = 0.05$). n = sample size. BDL= NO_3^- concentrations below analytical detection limits for $\delta^{15}N$- and $\delta^{18}O\text{-}NO_3^-$ analyses. NA= no data available for shoreline springs. Note, dye from the Lalakea dye tracer test lacked visual presence at the shoreline due to lower concentrations and consequently, water samples quality were only collected once and no macroalgae was present to sample. Hence, a sewage pollution score was not calculated for Lalakea. No samples were collected at the septic tank dye tracer test spring at Keaukaha Beach Park. Also, samples collected for human-associated *Bacteroides* HF183 analysis were all below detection limits and are not reported in the table.

Coastal springs' location	Keaukaha Beach Park	Leleiwi Beach Park	Lalakea
OSDS type	Cesspool	Cesspool	Cesspool
n	5	17	1
Enterococcus spp. (MPN/100 mL)	8 ± 2 [5–30]	405 ± 252 [5–9804]	17
C. perfringens (CFU/100 mL)	0 ± 0 [0]	0 ± 0 [0–1]	1
$NO_3^- + NO_2^-$ (μmol/L)	39.11 ± 5.21 * [28.49–57.82]	22.49 ± 1.55 * [13.30–42.07]	31.39
PO_4^{3-} (μmol/L)	2.14 ± 0.31 [1.64–3.37]	1.89 ± 0.13 [0.75–3.43]	2.24
H_4SiO_4 (μmol/L)	313 ± 50 [138–340]	348 ± 31 [144–580]	420
NH_4^+ (μmol/L)	1.21 ± 0.21 [0.59–1.69]	1.54 ± 0.66 [0.18–11.70]	3.35
TDP (μmol/L)	2.4 ± 0.3 [1.7–3.6]	2.5 ± 0.2 [1.7–4.2]	2.4
DOC (μmol/L)	44 ± 4 [37–54]	43 ± 5 [5–68]	5
TDN (μmol/L)	54 ± 11 * [32–86]	33 ± 4 * [19–75]	66
$\delta^{15}N\text{-}NO_3^-$ (‰)	3.88 ± 0.68 * [2.50–5.40]	−1.46 ± 1.33 * [−9.50–5.20]	BDL
$\delta^{18}O\text{-}NO_3^-$ (‰)	−1.68 ± 1.19 [−3.80–1.10]	−1.76 ± 1.23 [−13.20–3.80]	BDL
Macroalgal %N	1.72 ± 0.22 * [1.22–2.26]	2.37 ± 0.05 * [1.96–2.94]	NA
Macroalgal $\delta^{15}N$ (‰)	3.70 ± 0.23 * [3.00–4.40]	1.16 ± 0.09 * [0.70–2.10]	NA
Sewage pollution score	16.8 ± 0.3 (low)	16.6 ± 0.3 (low)	NA

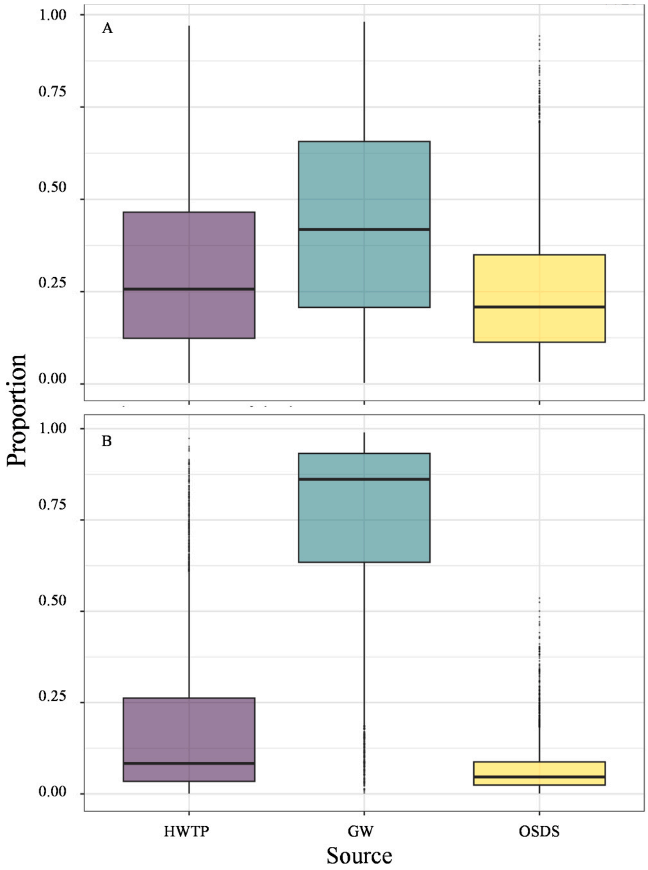


Fig. 3. Estimated proportion contribution from Bayesian stable isotope mixing model "*Simmr*" using δ^{15}N- and δ^{18}O-NO_3^- values from shoreline springs, A) Keaukaha Beach Park and B) Leleiwi Beach Park, where dye emerged from the dye tracer tests conducted in Keaukaha, Hilo, Hawai'i, from July 2020 - October 2021. Potential NO_3- sources include: sewage from the Hilo Wastewater Treatment Plant (HWTP: pre-outfall), groundwater (GW: freshwater), and onsite sewage disposal systems (OSDS). Boxed areas represent the 25 % and 75 % credibility quantiles with the horizontal black line as the median or 50 % credible quantile for each source. The 50 % quantile was chosen to report for the mixing models because it provides the median contribution value of each source. Vertical black lines represent error bars for the minimum (2.5 %) and maximum (97.5 %) proportion values.

Keaukaha and Leleiwi, respectively (Fig. 3).

Sewage pollution scores were comparable between Keaukaha and Leleiwi Beach Parks' coastal springs. Both had sewage pollution scores of 17, falling into the low sewage pollution category (Table 3).

3.3. HWTP and sewage outfall plume

Fecal indicator bacteria and nutrient concentrations varied among influent, effluent, and pre-outfall samples from the HWTP. *Enterococcus* spp. and *C. perfringens* concentrations in influent samples were an order of magnitude higher than effluent samples (Table 4). However, *C. perfringens* concentrations in pre-outfall samples were similar to influent samples, but both were higher than effluent concentrations (Table 4). The human-associated *Bacteroides* marker HF183 was also detected in the influent, effluent, and pre-outfall samples from the HWTP, and influent concentrations were significantly higher by an order of magnitude than those in the effluent and pre-outfall locations ($p < 0.0001$; Table 4). $NO_3^- + NO_2^-$, PO_4^{3-}, and TDP concentrations significantly increased from influent to effluent, and were similar between effluent and pre-outfall (Table 4). In contrast, DOC concentrations significantly decreased from influent to effluent, and were similar in effluent and pre-outfall samples (Table 4).

Within the HWTP outfall plume, FIB and nutrient concentrations were relatively low. The average *Enterococcus* spp. and *C. perfringens* concentrations were < 12 MPN/100 mL and 1 CFU/100 mL, respectively (Table 5). FIB concentrations were similar across all depths sampled within the outfall plume (Table 5). Nutrient concentrations were similar across all depths, except for H_4SiO_4, which significantly decreased from < 1 m to 2–3 m (Table 5).

Within Puhi Bay, only benthic macroalgal samples were collected; extensive water quality sampling which was done at the other locations in this study were not conducted. Seven species were collected, including (ordered based on the highest occurrence): *Portieria hornemannii* (Rhodophyta), *Amansia glomerata* (Rhodophyta), *Schizothrix mexicana* (Cyanobacteria), *Asparagopsis taxiformis*

Table 4

Geomean (± SE) and [range] of *Enterococcus* spp. and mean (± SE) and [range] of sewage indicators measured in influent, effluent, and pre-outfall samples obtained from Hilo Wastewater Treatment Plant (HWTP), Hilo, Hawai'i, from August 2020 – October 2021. Results from one-way analysis of variance or Kruskal-Wallis are shown on the table, with different letters denoting significant differences based on either a Tukey's HSD or Dunn's tests, followed by a Bonferroni correction ($\alpha = 0.05$). n = 16 samples for influent and effluent, and n = 15 for pre-outfall., † = 14 samples. £ = 10 samples.

HWTP location	Influent	Effluent	Pre-Outfall
Enterococcus spp. (MPN/100 mL)	65,466 ± 67,065^a [5289–942,367]	187 ± 12,541^b [11−201,111]	1385 ± 220,732^b [51−3,331,356]
C. perfringens (CFU/100 mL)	200 ± 59^a [0−767]	6 ± 2^b [0−25]	31 ± 9^a [0−128]
Human-associated *Bacteroides* HF183 (CN/100 mL)	96,134 ± 44,249^a [9223 – 303,903]	4345 ± 1000^b [2667 – 8819]	4865 ± 1442^b 1775 – 9066]
$NO^{3-} + NO_2^-$ (μmol/L)	6.92 ± 2.36^a [0.25–40.07]	91.71 ± 14.79^b [7.85–244.33]	145.25 ± 18.87^b [2.83–286.35]
PO_4^{3-} (μmol/L)	28.13 ± 3.16^a [9.21–54.52]	44.73 ± 3.66^b [12.31–64.42]	46.39 ± 3.15^b [29.60–63.88]
H_4SiO_4 (μmol/L)	438 ± 32 [101−674]	413 ± 39 [175−733]	430 ± 37 [148−683]
NH_4^+ (μmol/L)	590.85 ± 38.86 [302.65–875.71]	558.63 ± 44.27 [251.34–920.96]	514.09 ± 34.11 [351.02–747.63]
TDP (μmol/L)	35.6 ± 4.1^a [11.8–67.8]	55.3 ± 3.7^b [15.5–76.5]	58.5 ± 3.2^b [37.5–80.0]
DOC (μmol/L)	1687 ± 211^a [166–3003]	451 ± 42^b [228−743]	412 ± 44^b [155−681]
TDN (μmol/L)	1038 ± 85 [559–1686]	1020 ± 81 [680–1743]	968 ± 86 [607–1707]
$\delta^{15}N\text{-}NO_3^-$ (‰)	10.09 ± 2.98† [0.40–25.10]	9.10 ± 2.75† [−4.10–33.10]	3.56 ± 2.14† [−7.30–12.50]
$\delta^{18}O\text{-}NO_3^-$ (‰)	8.60 ± 0.97† [2.30–12.30]	8.46 ± 2.25 £ [1.10–26.70]	4.49 ± 0.79 [−2.00–8.10]

Table 5

Mean (± SE) and [range] of sewage indicators measured in depths of < 1, 1–2, and 2–3 m within the treated outfall sewage plume produced by the Hilo Wastewater Treatment Plant, Hilo, Hawai'i, June and August 2021 (4 d). Results from one-way analysis of variance or Kruskal-Wallis are shown on the table, with different letters denoting significant differences based on either a Tukey's HSD or Dunn's tests, with a Bonferroni correction ($\alpha = 0.05$). Also, samples collected for human-associated *Bacteroides* HF183 marker and $\delta^{15}N$- and $\delta^{18}O$ NO_3^- analyses were all below detection limits and are not reported in the table. Dissolved organic carbon (DOC) data are not available for this effort. n = 4.

Depth (m)	< 1	1–2	2–3
Enterococcus spp. (MPN/100 mL)	8 ± 2 [5−20]	12 ± 3 [5−41]	6 ± 1 [5−10]
C. perfringens (CFU/100 mL)	0 ± 0 [0−1]	1 ± 0 [0−2]	1 ± 0 [0−6]
$NO_3^- + NO_2^-$ (μmol/L)	2.18 ± 1.01 [0.57–4.60]	1.90 ± 0.41 [1.02–3.19]	0.87 ± 0.16 [0.44–1.17]
PO_4^{3-} (μmol/L)	0.25 ± 0.23 [0.02–0.72]	0.57 ± 0.29 [0.02–1.66]	0.16 ± 0.15 [0.02–0.60]
H_4SiO_4 (μmol/L)	24 ± 7^a [12–35]	17 ± 2^a [10–23]	8 ± 0^b [6–10]
NH_4^+ (μmol/L)	3.20 ± 1.40 [1.53–5.97]	4.70 ± 1.47 [1.82–9.80]	4.29 ± 1.23 [2.37–7.88]
TDP (μmol/L)	1.2 ± 0.6 [1.1–1.3]	1.8 ± 0.4 [0.7–3.2]	2.0 ± 0.9 [1.0–4.6]
TDN (μmol/L)	15 ± 3 [12−21]	15 ± 2 [9−18]	18 ± 2 [13−21]

(Rhodophyta), *Dictyota ceylancia* (Ochrophyta), *Caulerpa racemosa* (Chlorophyta), and diatoms (Ochrophyta). The $\delta^{15}N$ values of macroalgae collected ranged from + 2.5 to + 5.5 ‰ (Fig. 4). Macroalgae collected from the HWTP outfall (+4.4 ± 0.5 ‰) and within Puhi Bay (+4.6 ± 0.5 ‰) had significantly higher $\delta^{15}N$ values than at Leleiwi Beach Park (+3.6 ± 0.8 ‰) (Fig. 5A). %N content of the macroalgae ranged from 0.21 – 5.05 %, and was similar among the three locations sampled (Fig. 5B).

3.4. The Pilau-meter

Eighty-five observations were recorded with the *Pilau*-meter survey from June 2021- March 2022. The majority of participants were 18–29 years old (77 %), residents of Hawai'i Island, excluding Keaukaha (59 %; 15 % Keaukaha), come to Puhi Bay one to two times per week (60 %) for diving (47 %) and swimming (36 %), and the majority were college educated (70 %) (Appendix IV). The

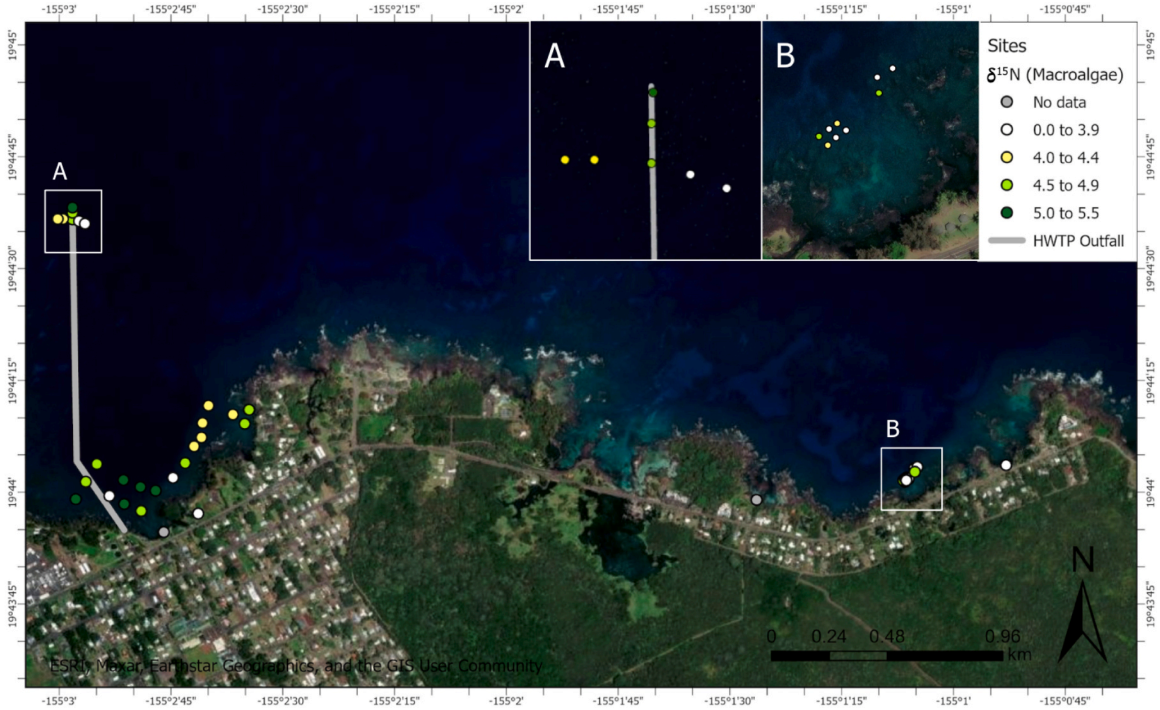


Fig. 4. Map δ^{15}N macroalgal samples collected along the Keaukaha shoreline, including those collected at A) the Hilo Wastewater Treatment Plant Outfall and offshore in Puhi Bay, and B) Leleiwi Beach Park, Hilo, Hawaiʻi. Samples were collected June 2021 to May 2022.

three odors most observed were good/normal, fishy, and sewage. Good/normal odors comprised 65 % of observations (n = 55), fishy 17 % (n = 14), and sewage 13 % (n = 11) (Appendix V). Strong odors (severity of 5) were reported the least amount of times (1.2 %), while odors with the lowest severity (1) were reported most often (55 %) (Appendix V). There was a significant, positive correlation between good/ normal odors and sea surface and air temperatures (Table 6). Fishy odors were not correlated with any environmental conditions (Table 6). In contrast, sewage odors were significantly correlated with wave period, particularly waves coming from the North (Table 6). The time of day and time from low tide were not significant indicators of any type of smell within this study. The *Pilau*-meter documented the presence of sewage odors during times HDOH released public advisories for high bacterial counts (06/24/2021) and wastewater discharge (01/28/2022) at Puhi Bay.

4. Discussion

4.1. Dye tracer tests

While many sewage indicators have confounding factors that complicate their interpretation, dye tracer tests provide irrefutable evidence of the connection between the sewage sources (OSDS, WWTP) and the coastal waters of interest (HDOH, 1984; Yates, 1985; Glenn et al., 2013). In our study, dye tracer tests demonstrated that raw, untreated sewage from OSDS from homes in Keaukaha reached coastal waters within 20 h - 3 d, with minimum flow rates ranging from 130 to 213 m/d (Table 2). Flow rates measured in Keaukaha were, in some cases, two and up to two orders of magnitude faster than those measured in other locations within Hawaiʻi State (Puakō: 3 – 137 m/d, Abaya et al.,. 2018; Wiegner et al., 2021; Lahaina: 8.6 – 9.5 m/d, Glenn et al., 2013). Differences in time of travel and flow rates among locations on Hawaiʻi Island and State reflect differences in permeability and groundwater recharge among sites. Estimates of hydraulic conductivity of dike-free basalts vary by two to three orders of magnitude on each island in the State of Hawaiʻi (Rotzoll and El-Kadi., 2008). Dye tracer tests on Hawaiʻi Island were all done in aquifers of young lava flows (< 8 ky) from Mauna Loa and Kīlauea (Sherrod et al., 2021), where highly permeable structures, like vertical fractures, are commonly observed at the surface and the aquifer is in the same lava flow from the OSDS to the shoreline. When groundwater crosses different lava flows, it can encounter lower permeability zones that result in much slower times of travel and flow rates, such as those observed in Lahaina (Glenn et al., 2013).

A modeling study by the HDOH used a 2-y time of travel to estimate OSDS that pose the greatest risk in nutrient loading to the coastal environment, and in Hilo, the 2-y time of travel was 6–8 km inland from the shoreline (Whittier and El Kadi, 2014). However, using the mean of flow rates measured in our study (170 m/d), it would only take 47 d for sewage from OSDS located 8 km inland to reach the shoreline, approximately 15 times faster than the predicted 2-y travel time. This suggests OSDS farther inland also contribute to nutrient loading risk to the coastal environment. In the first iteration of the HDOH cesspools and prioritization report (HDOH,

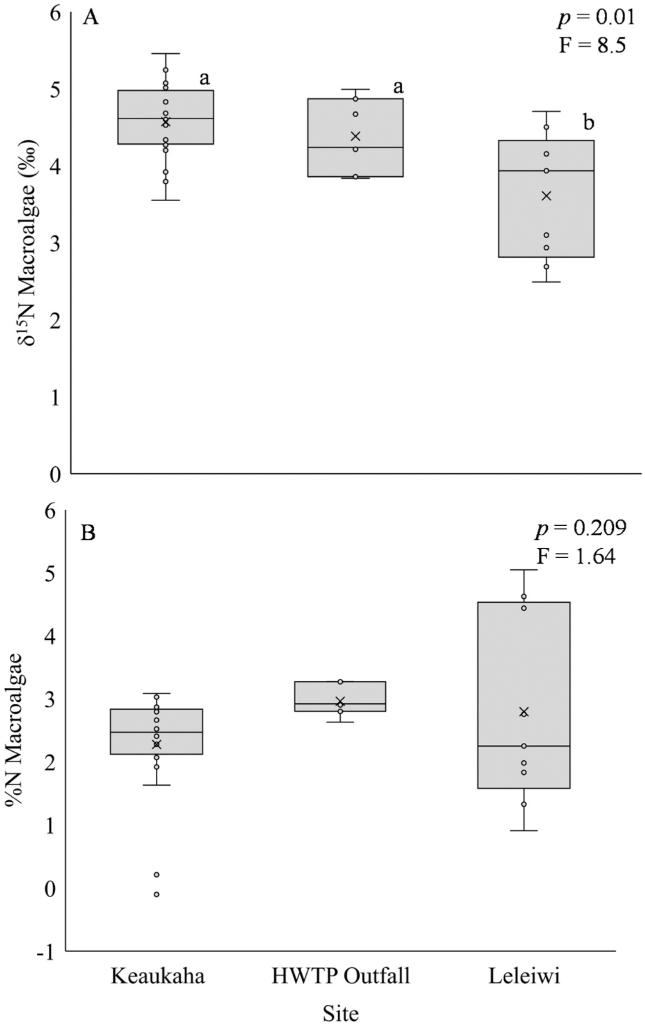


Fig. 5. Box and whisker plots for A) $\delta^{15}N$ and B) %N of benthic macroalgae collected from February to May 2022 in Keaukaha, Hilo, Hawaiʻi Keaukaha and Leleiwi Beach Parks and Hilo Wastewater Treatment Plant (HWTP) outfall). Results of a one-way analysis of variance test are shown on the figure, bars with differing letters were significantly different based on Tukey HSD, $\alpha = 0.05$.

2017a), the Keaukaha region was classified as a Priority 3 area, the second lowest priority for cesspool upgrade or conversion. In Priority 3 areas, potential impacts to sensitive waters may include coral reefs, impaired waterways, waters with endangered species, or other vulnerabilities and a pronounced sewage contamination hazard (HDOH, 2017a; Mezzacapo and Shuler, 2021). More recently, the Hawaiʻi Cesspool Hazard Assessment & Prioritization Tool (HCPT) shifted three areas in Hilo, including Keaukaha, to a Priority 2 area (Mezzacapo and Shuler, 2021). Priority 2 areas have a significant contamination hazard (Mezzacapo and Shuler, 2021). However, given that our recent dye tracer test measurements documented travel times and flow rates faster than areas listed as Priority 1 (Puakō, Kailua Kona, West Maui), the priority level for Hilo region should be re-evaluated, especially because there is insufficient time for biological processes in the environment to further reduce harmful bacteria in OSDS effluent that impact water quality and pose a risk to human and coral reef health (HDOH, 2017a; Mezzacapo and Shuler, 2021).

The HCPT purposely excluded water quality observation datasets as HDOH requested the development of a tool that could be applied statewide and was not limited to or biased to locations where studies had been previously conducted (Mezzacapo and Shuler, 2021). Our study provides essential ground truthing that should be used to refine the prioritization for Keaukaha, and possibly for other locations statewide, where site specific data are available. Additionally, two factors in the HCPT model that may have led to a less accurate characterization of Keaukaha are precipitation and sea level rise zones. In the HCPT, it is assumed that areas with high rainfall are less impacted by OSDS pollution because recharge is greater than effluent discharge, and that will result in the sewage pollution being sufficiently diluted to not pose as great of a risk to human and environmental health. While the dilution part of this is true, and our data support this assumption with our relatively low FIB concentrations and low $\delta^{15}N$ macroalgal values, our dye tracer tests demonstrated that the sewage from OSDS was rapidly transported to the coastline. The building codes for cesspools require that the bottom of the OSDS are at least 4.4 m below the land surface (Mezzacapo and Shuler, 2021). Ideally, the codes would take into account

Table 6

Results from correlation analysis examining associations between odors (good/ normal, fishy, sewage) recorded during the *Pilau*-meter (bad smell) survey and the weather, ocean, and river conditions at that time at Puhi Bay, Hilo, Hawai‘i, June 2021- March 2022. Bold front is used to indicate significant correlations (α = 0.05). Time precip. was calculated from the sum of precipitation over the previous 6 h from each 15-min interval recorded at the National Weather Service (NWS) weather station at the Hilo Airport (#91285021504, Appendix III). Time from low tide was calculated as the time before and after low tide recorded at the National Oceanographic and Atmospheric Administration (NOAA) tide gauge (#1617760, Appendix III). Hilo Bay wave buoy data are from Coastal Data Information Program (CDIP) Pacific Island Ocean Observing System (*Pac*IOOS) station #188. River discharge for the Wailuku River (Wailuku R.) is from the United States Geological Service (USGS), station #16704000.

Environmental conditions	Good smell		Fishy smell		Sewage smell		Data source
	r	*p*	*r*	*p*	*r*	*p*	
Wind speed (m/s)	0.020	0.885	−0.230	0.428	−0.326	0.327	NOAA Tide Gauge
Wind speed (m/s)	−0.095	0.493	0.396	0.161	0.188	0.579	NWS Hilo Airport
Wind direction (deg)	−0.197	0.153	0.438	0.117	0.263	0.434	NOAA Tide Gauge
Wind direction (deg)	−0.078	0.574	0.412	0.143	0.348	0.294	NWS Hilo Airport
Wind gust (m/s)	0.083	0.550	−0.098	0.740	−0.324	0.331	NOAA Tide Gauge
Air temperature (°C)	**0.310**	**0.023**	−0.253	0.384	−0.237	0.482	NOAA Tide Gauge
Air temperature (°C)	0.197	0.154	−0.208	0.476	−0.271	0.421	NWS Hilo Airport
Air pressure (mb)	−0.200	0.147	−0.056	0.848	0.466	0.149	NOAA Tide Gauge
Air pressure (mHg)	−0.185	0.179	−0.043	0.885	0.448	0.167	NWS Hilo Airport
Time precip.	−0.129	0.354	0.079	0.788	0.104	0.760	NWS Hilo Airport
Water temperature (°C)	−0.187	0.175	−0.495	0.072	−0.269	0.424	NOAA Tide Gauge
Tide (m)	0.141	0.308	0.502	0.067	−0.078	0.819	NOAA Tide Gauge
Time from low tide	0.173	0.216	0.375	0.186	−0.145	0.671	NOAA Tide Gauge
Sea surface temperature (°C)	**0.418**	**0.011**	−0.108	0.818	−0.353	0.492	Hilo Wave Buoy
Significant wave height (m)	−0.049	0.775	−0.324	0.478	0.082	0.877	Hilo Wave Buoy
Wave peak period (s)	−0.081	0.639	0.074	0.874	**0.832**	**0.040**	Hilo Wave Buoy
Average wave period (s)	0.076	0.660	0.082	0.861	0.002	0.997	Hilo Wave Buoy
Wave peak direction (deg)	−0.031	0.857	−0.026	0.955	0.766	0.076	Hilo Wave Buoy
River discharge (m^3/s)	−0.083	0.551	−0.432	0.123	−0.361	0.275	USGS Wailuku R.
River gauge height (m)	−0.112	0.418	−0.464	0.095	−0.362	0.274	USGS Wailuku R.
Time of day (h)	0.194	0.161	0.281	0.331	0.403	0.219	

mean sea level, and at least, be interpreted as 4.4 m above mean sea level, which is ~ 500 m inland. Note, within 200 m of the shoreline, the surface of the water table is observed as tidally-influenced brackish anchialine ponds. Groundwater levels are also expected to be higher than mean sea level with a hydraulic gradient increasing away from the shoreline (Rotzoll and Fletcher, 2013; Marrack, 2015). Therefore, it is likely that many of the bottoms of coastal OSDS are already below mean sea level and those further inland may flood with groundwater during tidal variations. This condition allows for sewage to enter groundwater directly, extracting additional pollutants from the sewage sludge. Similar low-lying communities with low priority ranking are found across Hawai‘i, and the number of OSDS inundated with groundwater will increase with sea level rise (Habel et al., 2020; Marrack et al., 2021, McKenzie et al., 2021).

4.2. *Coastal springs' water quality*

Our coastal spring sampling characterized water quality at springs where dye emerged. Our *Enterococcus* spp. (ENT) and *C. perfringens* (CP) concentrations (ENT: 8 – 405 MPN/100 mL; CP: 0 – 1 CFU/100 mL) are comparable to those reported earlier for a statewide cesspool conversion assessment (ENT: BDL – 3270 MPN/100 mL, Smith et al., 2021) and in nearshore waters on the north shore of Kaua‘i Island where sewage pollution is an issue (ENT: 20 – 4160 MPN/100 mL; CP: BDL – 14 CFU/100 mL, Knee et al., 2008). However, our concentrations were generally lower than those measured at Puakō (18–2777 MPN/100 mL; 2–12 CFU/100 mL), another location on Hawai‘i Island intensively studied for sewage pollution (Abaya et al., 2018; Wiegner et al., 2021), and Hilo Bay during storms (10–10,670 MPN/100 mL; 0–45 CFU/100 mL) (Wiegner et al., 2017; Economy et al., 2019). The human-associated *Bacteroides* marker HF183 was below the detection limit at both coastal springs, and this finding is similar to those reported for Malibu, California, where HF183 was detected in OSDS samples, but not in groundwater wells (Izbicki et al., 2012). In comparison, HF183 has been detected at Puakō and Hilo Bay (Wiegner et al., 2017; Wiegner et al., 2021). High groundwater discharge along the Keaukaha shoreline is likely diluting OSDS effluent, resulting in the overall lower concentrations of the three FIB in comparison to other locations.

In contrast to our measured FIB concentrations, nutrient concentrations at the springs fall within the range reported for other nearshore waters in Hawai‘i and elsewhere affected by sewage pollution (Lapointe et al., 1990; Miller- Pierce and Rhoads, 2016; Abaya et al., 2018; Wiegner et al., 2021; Kealoha et al., 2024). While these concentrations may be a sign of potential sewage pollution, they do not provide information on the source(s) of nutrients. We used δ^{15}N and %N in macroalgal tissue, as well as stable isotopes of NO_3^- (δ^{15}N-NO_3^- and δ^{18}O-NO_3^-) in mixing models to provide percent contribution of different sources to the NO_3^- pool (Hunt, 2007; Wiegner et al., 2016; Wiegner et al., 2021; Panelo et al., 2022). δ^{15}N of macroalgal (+0.7 to +4.4 ‰) and δ^{15}N-NO_3^- values at the same springs (-1.46 to +3.88 ‰) had comparable values and were consistent with values measured in an earlier study in Keaukaha (Smith et al., 2021). Values for both the macroalgae and NO_3^- fall within the range for sewage-influenced locations within Hawai‘i State (Smith et al., 2021), albeit on the lower side, and closer to δ^{15}N-NO_3^- values we measured for groundwater and the pre-outfall effluent (Table 4). Using a conceptual model that employs δ^{15}N and %N macroalgal measurements to identify major sources of N to coastal waters, our measurements suggest that natural and agricultural N sources dominate along the Keaukaha shoreline (Amato et al., 2016; Smith et al., 2021). Mixing models using δ^{15}N- and δ^{18}O of NO_3^- further confirm groundwater as the dominant NO_3^- source to springs at Keaukaha and Leleiwi Beach Parks. The δ^{15}N- NO_3^- value from groundwater wells in the Keaukaha watershed are + 0.7 ± 0.6 ‰, within the range for both agricultural fertilizer inputs and nitrogen-fixing vegetation, like *Falcataria falcate* (albizia) and *Trema orientalis* (gunpowder tree), both of which occur in the watershed; the latter is more likely the source as wet alien forest comprises 22 % of the land cover, and cultivated agriculture 5 % (Jacobi et al., 2017).

Using data from our sewage indicators in a sewage pollution score, we were able to compare sewage pollution levels in Keaukaha to other locations on Hawai‘i Island (Abaya et al., 2018). The coastal springs had low sewage pollution scores. This finding conflicts with our dye tracer tests results which showed that sewage from OSDS reached the shoreline within hours to days. The discrepancy is likely from the high weight placed on *C. perfringens* concentrations and δ^{15}N in macroalgal tissue in the sewage pollution score, which are both thought to be strong indicators of sewage pollution. At our springs, these parameters both had low values. High groundwater discharge as measured in our dye tracer tests likely diluted the *C. perfringens* concenrations (Table 2). It is also apparent that the δ^{15}N of the NO_3^- was diluted when comparing upland well to coastal spring values from Puakō to Hilo. At Puakō, the upland wells had δ^{15}N-NO_3^- of + 4.8 ‰ as compared to + 0.7 ‰ in Hilo (Abaya et al., 2018; Nakoa, 2022). Therefore, when assuming an equivalent flux of sewage to groundwater at the two locations, a lower δ^{15}N-NO_3^-, and thus the δ^{15}N of macroalgae, would be expected for Hilo. Additionally, macroalgae using NO_3^- from other sources like fertilizers or nitrogen-fixing vegetation instead of sewage could be lowering their δ^{15}N values. It is unlikely that a chemical or biological process is affecting the transport and concentrations of *C. perfringens* and NO_3^- at the shoreline springs as the groundwater is traveling through fractured basalt and is oxic when it emerges at the shoreline. Our result show that in an area of high groundwater discharge a sewage pollution score is not enough for evaluating the sewage pollution, dye tracer tests are needed.

4.3. *HWTP and sewage outfall plume*

Hilo is the first location to our knowledge that has been studied for water quality impacts from both OSDS and a WWTP, although the situation is common throughout Hawai‘i State, as well as the greater Pacific Island region and elsewhere. Influent from the HWTP had the highest *Enterococcus* spp. and *C. perfringens* concentrations compared to the treated effluent and pre-outfall samples. Untreated wastewater FIB concentrations range from 10,000 – 100,000 MPN/100 mL for *Enterococcus* spp. and 1000 – 100,000 MPN/100 mL for *C. perfringens* (Tchobanoglous et al., 2003). *Enterococcus* spp. concentrations in our influent samples fall within this range, as the geometric mean was 65,467 ± 67,065 MPN/ 100 mL. *Clostridium perfringens* concentrations averaged 200 ± 59 CFU/100 mL, an order of magnitude lower than previous studies (Tchobanoglous et al., 2003; Kirs et al., 2016). Additionally, the human-associated *Bacteroides* marker HF183 was present in all samples from all three stages of wastewater treatment and its concentrations were comparable to those in wastewaters at other WWTPs in Hawai‘i, but lower than those measured in other world cities (Table 4; Kirs et al., 2016; McLellan et al., 2024). We found that the secondary treatment and chlorination process used at the HWTP reduced FIB concentrations in wastewater prior to discharge at the outfall 350, 33, and 22 times for *Enterococcus* spp., *C. perfringens*, and human-associated *Bacteroides* marker HF183, respectively.

Nutrient concentrations in sewage can change with sewage treatment, increasing or decreasing depending on the treatment method employed. The HWTP’s sewage treatment does not include a nutrient reduction step, and consequently some nutrient concentrations increased (NO_3^- + NO_2^-, PO_4^{3-}, and TDP) during the sewage treatment process (influent to pre-outfall), while others decreased (DOC) (Table 4). Sewer pipe systems provide environments for microbial communities to thrive due to aqueous medium, lack of light, high nutrient concentrations, less variable temperatures, and fluctuating oxygen levels (McLellan and Roguet, 2019; McLellan et al., 2024). Our study further supports the idea that microbes in the sewer line further modify the effluent before being discharged. We found that pre-outfall samples collected from the pumping station onshore (~ 3.5 km from the HWTP) had higher concentrations of *C. perfringens* compared to effluent samples.

Offshore outfalls dispose of treated sewage away from nearshore waters and allow for further mixing and dilution from ocean currents. In our study, water offshore above the sewage outfall had *Enterococcus* spp. and *C. perfringens* concentrations concentrations below HDOH recreational water standards (HDOH, 2014). Similar results were reported for Māmala Bay, Oahu, and Avalona Bay, California, where low FIB concentrations (< 10 MPN/100 mL) of *Enterococcus* spp, total coliform, fecal coliform, and *Escherichia coli* were measured directly over wastewater outfalls (Fujioka et al., 2001; Boehm et al., 2003). Dilution and mixing of the plume upon release into the environment, as well as the momentum of the effluent discharge exiting the diffusers or the buoyancy of the discharged effluent likely results in the low FIB concentration (Wu et al., 1994; Birmingham et al., 2008). Water stratification also appears to affect the mixing and ultimate dilution of the effluent being discharged at the outfall pipe. At Ipanema Beach in Rio de Janeiro, Brazil, the effluent in the outfall plume was trapped below the thermocline and dilution was low (35−1), whereas in unstratified conditions, the plume surfaces and the dilutions increased significantly to more than 100–1 (Carvalho et al., 2002). The dilution factor in our study was 35–1. Some of the N in the treated sewage from the outfall appears to be taken up by the macroalgae. Some of the highest δ^{15}N values measured in Puhi Bay were from macroalgae collected off of the outfall pipe; however, there were also high values in close proximity to the shoreline, which may have been influenced by sewage from OSDS (Fig. 5).

4.4. Pilau-meter

Incorporating the sense of smell into scientific research provides additional data on environmental landscapes (Gostelow et al., 2001; Henshaw, 2013; Quercia et al., 2015). Hawaiʻi State rules regulating water quality recognize the contribution of odor to water pollution, as it is defined as “such contamination or other alteration of the physical, chemical, or biological properties of any state of waters, including…odor of waters” (HI Rev Stat, 2023). Citizen scientists in our study were clearly able to distinguish several different smells, including good/normal, sewage, fishy, and diesel/exhaust. Good air quality days occurred with warm air temperatures, while sewage odors were observed when waves were coming from the North. Greater energy of waves breaking in Puhi Bay, which is opens to the north, may lead to greater aerosol production which may carry the odors (Van Eijk et al., 2011). In our study, the presence of sewage odors coincided with two water quality advisories posted by HDOH for Puhi Bay. Sewage smells were reported on the *Pilau*-meter on June 17, 2021 and June 21, 2021, and a few days thereafter (June 24, 2021), an advisory for high bacterial counts in Puhi Bay was posted by HDOH. Sewage smells were also reported on the *Pilau*-meter on January 29, 2022 and January 30, 2022. During this time, HDOH posted an advisory to avoid waters near Puhi Bay because untreated wastewater from the HWTP was discharged into the waters during a power outage (January 28, 2022 - January 31, 2022). Additionally, sewage odors detected on these days during our study could also have been caused by the HWTP pumping station, which is located on the Hilo-side of Puhi Bay, in the same vicinity that the sewage odors were recorded. Results from our study further this new field of research and demonstrate that human olfaction provides important information about places, and that detection of odors can be associated with environmental conditions. The latter warrants further investigation, including sea surface temperature, water temperature, tidal height, and wave peak direction in Keaukaha.

5. Conclusion

Our study shows that dye tracer tests in conjunction with water quality measurements are necessary for documenting nearshore sewage pollution. Together, they provide irrefutable evidence of the environmental problem that poses a human and ecosystem health threat. While FIB and nutrient concentration measurements were relatively low along the Keaukaha shoreline in comparison to other areas impacted by sewage pollution on Hawaiʻi Island and elsewhere, our dye tracer tests confirm that sewage from OSDS in Keaukaha reaches the shorelines within 20 h – 3 d. This is a faster travel time than previously reported in other areas of Hawaiʻi, which are ranked as a higher priority by Hawaiʻi State for cesspool conversion (Mezzacapo and Shuler, 2021). Our results suggest that the Hilo region, which includes Keaukaha, should become a Priority 1 area for cesspool conversion.

We also showed that wastewater treatment at the HWTP is reducing FIB concentrations, and that concentrations are further reduced as the treated effluent is diluted with seawater at the outfall. The USEPA administrative consent order will further improve sewage treatment at the HWTP. Corroded equipment must be rehabilitated and replaced, including sedimentation tanks, clarifiers, the chlorination facility, effluent and disinfection monitoring systems, standby power, anaerobic digestors, solid handling and dewatering facilities, and construction of supervisory control and data acquisition system (County of Hawaiʻi, 2024). New equipment will include a secondary treatment facility, bioreactors and blowers, waste sludge station, alkalinity feed system, snail removal facility, and with the future possibility of a cogeneration facility and biosolids dryer (County of Hawaiʻi, 2024). Hawaiʻi County is also under order to expand sewer service and our findings have resulted in Keaukaha being prioritized for this. However, one item not included in the administrative consent order or being considered by Hawaiʻi County due to cost is to relocate the outfall to an area where its potential impact to human and ecosystem health is less. This item is one of the most frequent requests of the Keaukaha community and relocation of the outfall would greatly improve community relations with Hawaiʻi County. Additionally, the *Pilau*-meter demonstrated that human olfaction could detect when issues arose with the HWTP that resulted in HDOH advisories for high FIB levels in Puhi Bay and wastewater discharge. Engaging the community to report when they smell sewage to HDOH and HWTP could be used as an early warning system before issues are realized and signage posted, potentially reducing waterborne health issues.

When comparing sewage pollution entering Puhi Bay from the outfall and OSDS, the most immediate water quality and health concerns are from the OSDS. FIB and other sewage indicators are highest along the shoreline, and lowest within the outfall plume. To arrive at our conclusion, a variety of approaches and indicators were needed, illustrating the complexity of assessing sewage pollution. Also, different types of solutions need to be implemented to reduce sewage pollution from both OSDS and a WWTP. In Keaukaha, transitioning homes away from OSDS and connecting to an expanded sewer line will likely occur simultaneously with improvements to the HWTP. Future research will document improvements to water quality from these infrastructure projects. Findings from our study have both local and worldwide implications for detecting sewage pollution in nearshore waters, as well as how geographic locations are prioritized for OSDS conversion in Hawaiʻi State.

CRediT authorship contribution statement

Shayla Waiki: Writing – review & editing, Writing – original draft, Visualization, Supervision, Methodology, Investigation, Data curation, Conceptualization. **Steven Colbert:** Writing – review & editing, Writing – original draft, Visualization, Supervision, Software, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Tracy Wiegner:** Writing – review & editing, Writing – original draft, Visualization, Supervision, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Noelani Puniwai:** Writing – review & editing, Writing – original draft, Methodology, Conceptualization. **Joseph Nakoa:** Writing – review & editing, Writing – original draft, Visualization, Supervision, Methodology, Investigation, Formal analysis, Data curation, Conceptualization.

Nicolas Storie: Writing – review & editing, Writing – original draft, Data curation. **Craig Nelson:** Writing – review & editing, Writing – original draft, Supervision, Methodology, Funding acquisition, Formal analysis, Conceptualization. **Ashlynn Overly:** Writing – review & editing, Writing – original draft, Visualization, Supervision, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Karla McDermid:** Writing – review & editing, Writing – original draft, Resources, Methodology, Investigation, Funding acquisition, Formal analysis, Conceptualization. **Devon Aguiar:** Writing – review & editing, Writing – original draft, Supervision, Methodology, Investigation, Formal analysis, Data curation, Conceptualization.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in the paper.

Acknowledgements

Thank you Keaukaha Community Association (P. Kahawaiolaʻa), Leleiwi Community Association (K. Anthony), Hilo Wastewater Treatment Plant (D. Ombac), boat captain (K. Hauanio), summer interns and volunteers (D. Kealoha, K. Villafuerte, F. Reil, B. Enright, and W. Boger), University of Hawaiʻi at Hilo Analytical Lab (E. Johnson, T. Holtzki, and J. Panelo), R. Perroy, L. Morrison, S. McLellan, and E. Karth. Funding for this project was provided by: University of Hawaiʻi Sea Grant College Program, Hauʻoli Mau Loa Foundation, USGS Pacific Island-Climate Adaptation Science Center, Pacific Internship Program for Exploring Science (PIPES), and Kamehameha Schools), Students of Hawaiʻi Advanced Research Program (SHARP, National Institute of Health Research (NIH) Initiative for Scientific Enhancement Award No. R25GM11347), and University of Hawaiʻi at Hilo Marine Science and Environmental Science/Geography Departments. This paper is funded in part by a grant/cooperative agreement from the National Oceanic and Atmospheric Administration, Project R/IR-54 which is sponsored by the University of Hawaiʻi Sea Grant College Program, SOEST, under Institutional Grant No., NA18OAR4170076 from NOAA Office of Sea Grant, Department of Commerce. The views expressed herein are those of the author (s) and do not necessarily reflect the views of NOAA or any of its subagencies. UNIHI-SEAGRANT-4947. Sea Grant publication 4947.

Appendix A. Microbial source tracking assay used in this study

Assay Target	Assay Name	Gene Target	Nucleotide Sequences		Standard	Reference
Human Bacteroidales	HF183	16S rRNA	Forward	ATCATGAGTTCACATGTCCG	IDT gBlocks dsDNA sequence AB242142.1 (Green et al., 2014). 16S rRNA sequence for *Bacteroidales dorei* strain DSM 17855.	Haugland et al., (2010); Green et al., (2014)
			Reverse	CTTCCTCTCAGAACCCCTATCC		
			5'Nuclease Probe	6-FAM™/CTAATGGAA/ZEN™/CGCATCCCCAT/IB®FQ/		

Appendix B. *Pilau*-meter survey. Questions and possible answers are shown

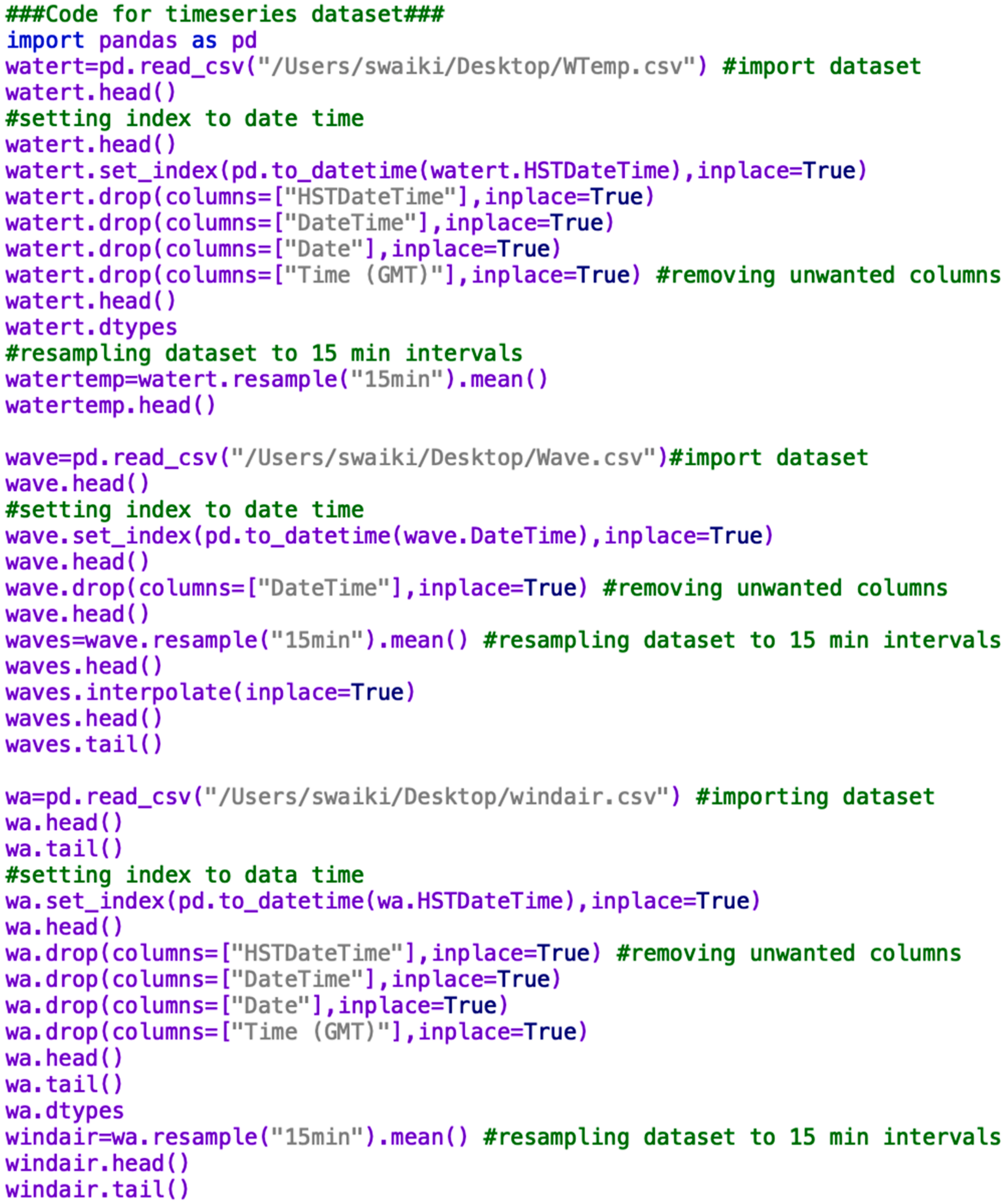
Pilau-meter Questions	Possible Answers
Your observation takes place on what day? Your observation takes place at what time?	

(*continued on next page*)

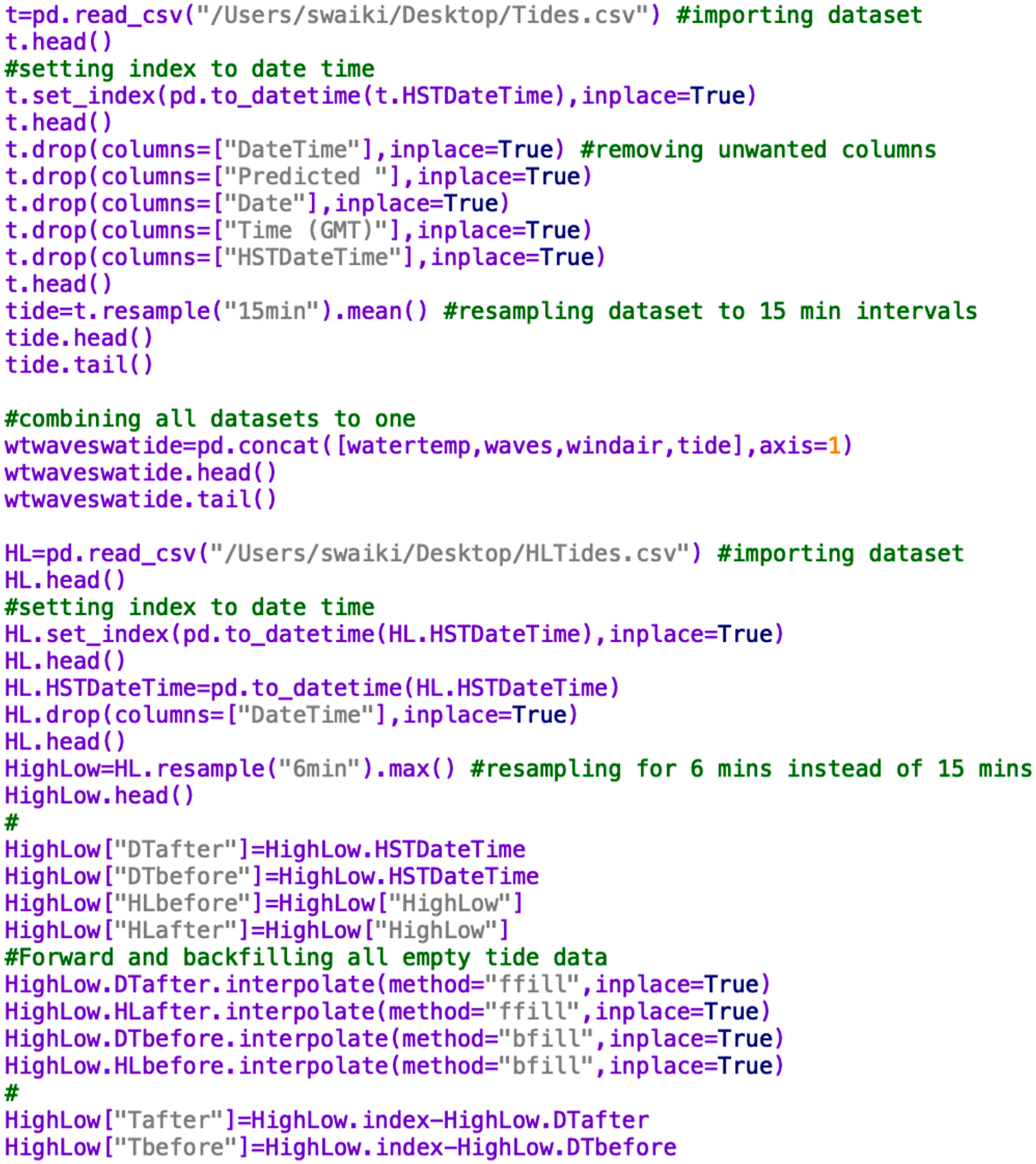
(*continued*)

What are the environmental conditions like at the time you are completing this survey?	Sunny
	Overcast/Cloudy
	Rainy
	Windy
	Low Tide
	Other
	Slight breeze
Which region are you reporting from (refer to above map)?	Region 1- PACRC to First Gate, Hilo Side
	Region 2- First Gate at Puhi Bay to Community Tent
	Region 3- Community Tent to Second Gate at Puhi Bay (Middle, by side road)
	Region 4- Second Gate to Restrooms and Parking Lot
	Region 5- Restroom to Gate by Chocks
What type of smell is it?	Sewage
	Sulfur
	Fishy
	No Smell
How severe is the smell?	1- no detectable odor
	2- not too stink
	3- getting stink
	4- stink
	5- extremely stink
Are there any other observations of this situation you would like to report?	
What is your age?	18–29 years old
	30–39 years old
	40–49 years old
	50 + years old
Where do you live? (Please select the best description.)	Keaukaha Community
	Local to Hawaiʻi Island (excluding Keaukaha community)
	Neighbor Island
	Out of State/ Country
How often do you go to Puhi Bay?	Once or twice a week
	Every other week
	Once a month
	Once every 3 months
	Once every year
What brings you to Puhi Bay?	Diving
	Swimming
	Fishing
	Paddling
	Working
	Other
If you selected "Working" as your answer to the question above, what is your occupation?	
What is your educational level?	High School
	Community College
	University- Undergraduate
	University- Graduate

Appendix C. Python code for *Pilau*-meter correlation with environmental variables

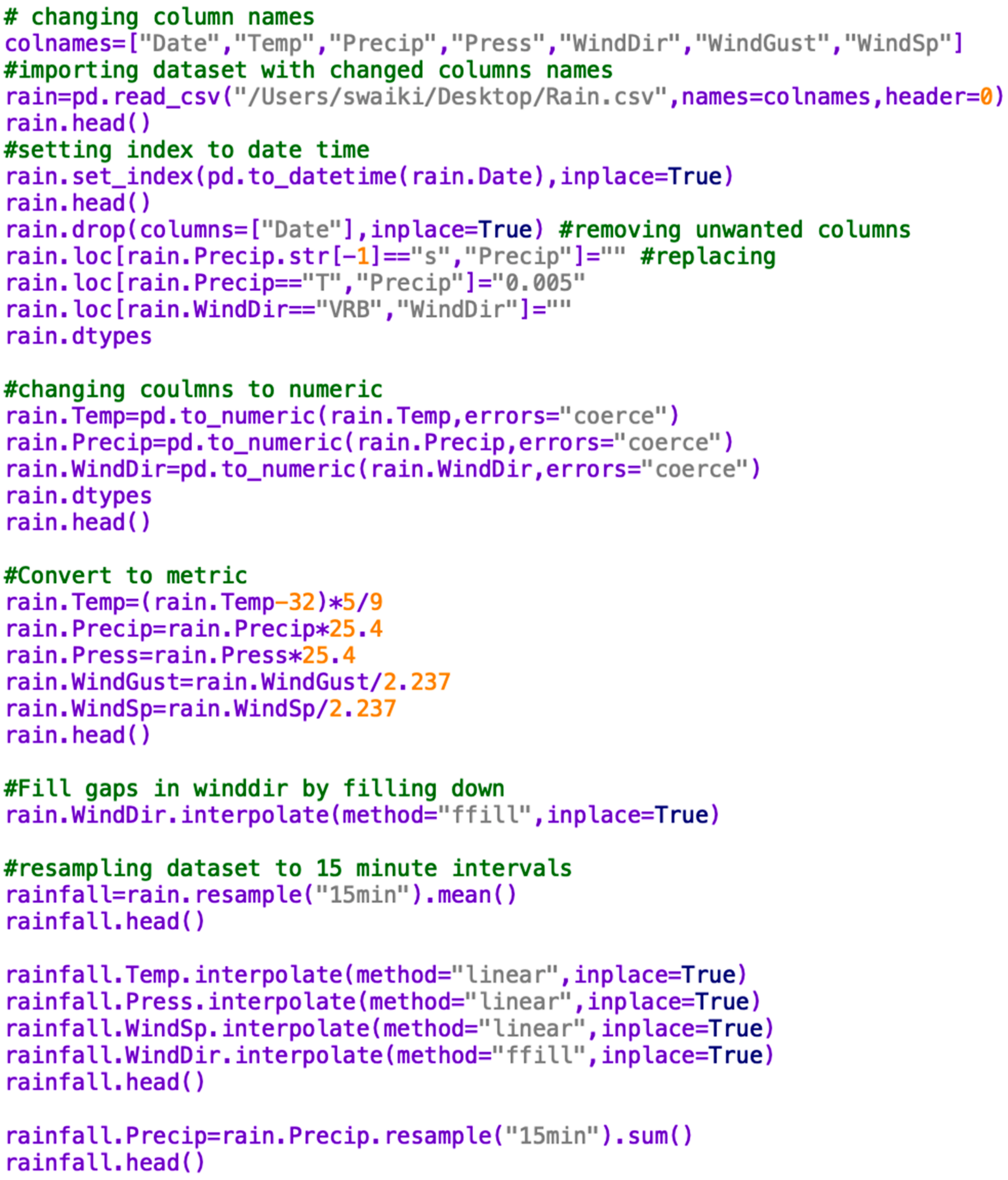


```
###Code for timeseries dataset###
import pandas as pd
watert=pd.read_csv("/Users/swaiki/Desktop/WTemp.csv") #import dataset
watert.head()
#setting index to date time
watert.head()
watert.set_index(pd.to_datetime(watert.HSTDateTime),inplace=True)
watert.drop(columns=["HSTDateTime"],inplace=True)
watert.drop(columns=["DateTime"],inplace=True)
watert.drop(columns=["Date"],inplace=True)
watert.drop(columns=["Time (GMT)"],inplace=True) #removing unwanted columns
watert.head()
watert.dtypes
#resampling dataset to 15 min intervals
watertemp=watert.resample("15min").mean()
watertemp.head()

wave=pd.read_csv("/Users/swaiki/Desktop/Wave.csv")#import dataset
wave.head()
#setting index to date time
wave.set_index(pd.to_datetime(wave.DateTime),inplace=True)
wave.head()
wave.drop(columns=["DateTime"],inplace=True) #removing unwanted columns
wave.head()
waves=wave.resample("15min").mean() #resampling dataset to 15 min intervals
waves.head()
waves.interpolate(inplace=True)
waves.head()
waves.tail()

wa=pd.read_csv("/Users/swaiki/Desktop/windair.csv") #importing dataset
wa.head()
wa.tail()
#setting index to data time
wa.set_index(pd.to_datetime(wa.HSTDateTime),inplace=True)
wa.head()
wa.drop(columns=["HSTDateTime"],inplace=True) #removing unwanted columns
wa.drop(columns=["DateTime"],inplace=True)
wa.drop(columns=["Date"],inplace=True)
wa.drop(columns=["Time (GMT)"],inplace=True)
wa.head()
wa.tail()
wa.dtypes
windair=wa.resample("15min").mean() #resampling dataset to 15 min intervals
windair.head()
windair.tail()
```



```
t=pd.read_csv("/Users/swaiki/Desktop/Tides.csv") #importing dataset
t.head()
#setting index to date time
t.set_index(pd.to_datetime(t.HSTDateTime),inplace=True)
t.head()
t.drop(columns=["DateTime"],inplace=True) #removing unwanted columns
t.drop(columns=["Predicted "],inplace=True)
t.drop(columns=["Date"],inplace=True)
t.drop(columns=["Time (GMT)"],inplace=True)
t.drop(columns=["HSTDateTime"],inplace=True)
t.head()
tide=t.resample("15min").mean() #resampling dataset to 15 min intervals
tide.head()
tide.tail()

#combining all datasets to one
wtwaveswatide=pd.concat([watertemp,waves,windair,tide],axis=1)
wtwaveswatide.head()
wtwaveswatide.tail()

HL=pd.read_csv("/Users/swaiki/Desktop/HLTides.csv") #importing dataset
HL.head()
#setting index to date time
HL.set_index(pd.to_datetime(HL.HSTDateTime),inplace=True)
HL.head()
HL.HSTDateTime=pd.to_datetime(HL.HSTDateTime)
HL.drop(columns=["DateTime"],inplace=True)
HL.head()
HighLow=HL.resample("6min").max() #resampling for 6 mins instead of 15 mins
HighLow.head()
#
HighLow["DTafter"]=HighLow.HSTDateTime
HighLow["DTbefore"]=HighLow.HSTDateTime
HighLow["HLbefore"]=HighLow["HighLow"]
HighLow["HLafter"]=HighLow["HighLow"]
#Forward and backfilling all empty tide data
HighLow.DTafter.interpolate(method="ffill",inplace=True)
HighLow.HLafter.interpolate(method="ffill",inplace=True)
HighLow.DTbefore.interpolate(method="bfill",inplace=True)
HighLow.HLbefore.interpolate(method="bfill",inplace=True)
#
HighLow["Tafter"]=HighLow.index-HighLow.DTafter
HighLow["Tbefore"]=HighLow.index-HighLow.DTbefore
```

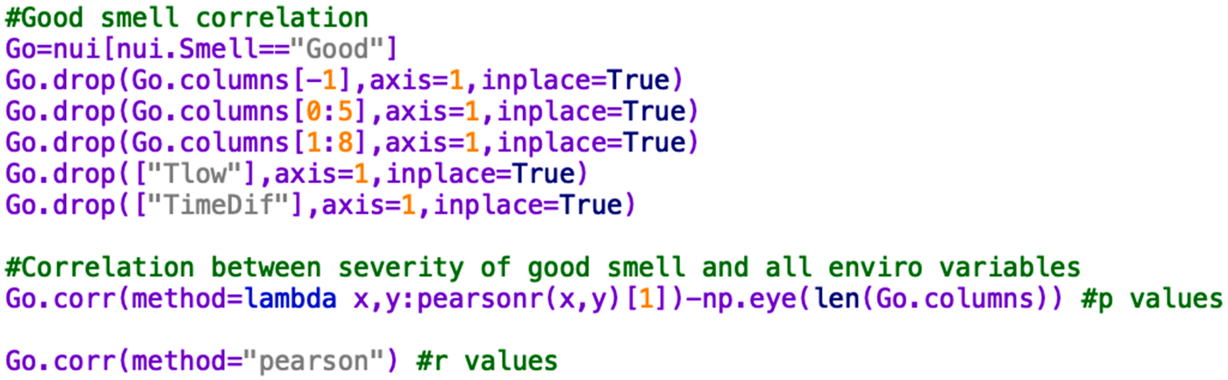
```
#Creating a time before or after low tide column
HighLow["Tlow"]=HighLow.Tafter[HighLow.HLafter=="L"]
HighLow["Tlow"].loc[HighLow.HLbefore=="L"]=HighLow.Tbefore.loc
[HighLow.HLbefore=="L"]
HighLow.Tlow.interpolate(method="ffill",inplace=True)
HighLow.head()

HighLow.interpolate(method="bfill",inplace=True)
HighLow.tail()
HighLow.head()
HighLow.drop(columns=["HSTDateTime"],inplace=True) #removing unwanted columns
HighLow.drop(columns=["Predict"],inplace=True)
HighLow.drop(columns=["HighLow"],inplace=True)
HighLow.drop(columns=["DTafter"],inplace=True)
HighLow.drop(columns=["DTbefore"],inplace=True)
HighLow.drop(columns=["HLbefore"],inplace=True)
HighLow.drop(columns=["HLafter"],inplace=True)
HighLow.drop(columns=["Tafter"],inplace=True)
HighLow.drop(columns=["Tbefore"],inplace=True)
HighLow=HighLow.resample("15min").nearest()
HighLow.head()

#combining datasets
wtwaveswatideHL=pd.concat([watertemp,waves,windair,tide,HighLow],axis=1)
wtwaveswatideHL.head(30)
wtwaveswatideHL.tail(30)

riv=pd.read_csv("/Users/swaiki/Desktop/River.csv") #importing dataset
riv.head()
#setting index to date time
riv.set_index(pd.to_datetime(riv.DateTime),inplace=True)
riv.head()
riv.drop(columns=["DateTime"],inplace=True) #removing unwanted columns
riv.drop(columns=["Discharge"],inplace=True)
riv.drop(columns=["Gage height"],inplace=True)
riv.head()
river=riv.resample("15min").mean() #resampling dataset to 15 min intervals
river.head()

wtwaveswatideHLriver=pd.concat([watertemp,waves,windair,tide,HighLow,river]
                              ,axis=1) #combining datasets
wtwaveswatideHLriver.head(50)
wtwaveswatideHLriver.head()
wtwaveswatideHLriver.tail()
```



```
# changing column names
colnames=["Date","Temp","Precip","Press","WindDir","WindGust","WindSp"]
#importing dataset with changed columns names
rain=pd.read_csv("/Users/swaiki/Desktop/Rain.csv",names=colnames,header=0)
rain.head()
#setting index to date time
rain.set_index(pd.to_datetime(rain.Date),inplace=True)
rain.head()
rain.drop(columns=["Date"],inplace=True) #removing unwanted columns
rain.loc[rain.Precip.str[-1]=="s","Precip"]="" #replacing
rain.loc[rain.Precip=="T","Precip"]="0.005"
rain.loc[rain.WindDir=="VRB","WindDir"]=""
rain.dtypes

#changing coulmns to numeric
rain.Temp=pd.to_numeric(rain.Temp,errors="coerce")
rain.Precip=pd.to_numeric(rain.Precip,errors="coerce")
rain.WindDir=pd.to_numeric(rain.WindDir,errors="coerce")
rain.dtypes
rain.head()

#Convert to metric
rain.Temp=(rain.Temp-32)*5/9
rain.Precip=rain.Precip*25.4
rain.Press=rain.Press*25.4
rain.WindGust=rain.WindGust/2.237
rain.WindSp=rain.WindSp/2.237
rain.head()

#Fill gaps in winddir by filling down
rain.WindDir.interpolate(method="ffill",inplace=True)

#resampling dataset to 15 minute intervals
rainfall=rain.resample("15min").mean()
rainfall.head()

rainfall.Temp.interpolate(method="linear",inplace=True)
rainfall.Press.interpolate(method="linear",inplace=True)
rainfall.WindSp.interpolate(method="linear",inplace=True)
rainfall.WindDir.interpolate(method="ffill",inplace=True)
rainfall.head()

rainfall.Precip=rain.Precip.resample("15min").sum()
rainfall.head()
```

```
rainfall["TimePrecip"]=rainfall.Precip.rolling(24).sum()
rainfall.head(50)

#Fully combined timeseries data
wtwaveswatideHLriverrain=pd.concat([watertemp,waves,windair,tide,HighLow,river,
                                    rainfall],axis=1)
wtwaveswatideHLriverrain.head(80)



#Reding in Pilau-meter responses
pilau=pd.read_csv("/Users/swaiki/Desktop/Pilaumeter.csv")
pilau.head()
pilau.set_index(pd.to_datetime(pilau.Timestamp),inplace=True)
pilau.head()
pilau.drop(columns=["Timestamp"],inplace=True)
pilau.head()

#Fixing input so that only one of each region remains in the responses
pilau.loc[pilau.iloc[:,3]=="Region 1- PACRC to 1st gate at
          "Puhi Bay (Hilo side)"
          ,"Which region are you reporting from?"]="Region 1"
pilau.loc[pilau.iloc[:,3]=="Region 2- 1st gate at Puhi Bay to community tent"
          ,"Which region are you reporting from?"]="Region 2"
pilau.loc[pilau.iloc[:,3]=="Region 3- Community tent to 2nd gate at Puhi Bay
          (Middle, by side road)","Which region are you reporting from?"]=
          "Region 3"
pilau.loc[pilau.iloc[:,3]=="Region 4- 2nd gate to restrooms and parking lot",
          "Which region are you reporting from?"]="Region 4"
pilau.loc[pilau.iloc[:,3]=="Region 5- Restrooms to gate by Chock‘s",
          "Which region are you reporting from?"]="Region 5"

#Combining pilau meter responses and timeseries dataset
nui=pd.merge_asof(pilau,wtwaveswatideHLriverrain,left_index=True
                  ,right_index=True)

#Creating new column TimeDif
nui["TimeDif"]=nui.index.to_series().diff()

nui["Hour"]=nui.index.to_series().dt.hour+nui.index.to_series().dt.minute/60

#Creating a new column for time before and after low tide in hours
nui["TimeLow"]=abs((nui.Tlow.dt.days+nui.Tlow.dt.seconds/(24*3600))*24)
```

```
#Creating new smell column in dataset and determing the category they belong
#in
nui["Smell"]="Good"
nui.loc[nui.iloc[:,4]=="Fishy","Smell"]="Fishy"
nui.loc[nui.iloc[:,4]=="Sewage","Smell"]="Sewage"
nui.loc[nui.iloc[:,4]=="Sulfur","Smell"]="Sewage"
nui.loc[nui.iloc[:,4]=="A bad smell I cannot describe","Smell"]="Sewage"
nui.loc[nui.iloc[:,4]=="Exhaust","Smell"]="Exhaust"
nui.loc[nui.iloc[:,4]=="Exhaust/gas","Smell"]="Exhaust"

#Grouping 2 different options into one
nui.loc[nui.iloc[:,6]=="18-28 years old","What is your age?"]="18-29 years old'
nui.loc[nui.iloc[:,6]=="19-29 years old","What is your age?"]="18-29 years old'

#Finding dups
#nui[nui.TimeDif<"00:05:00"]

#Stats
from scipy.stats import pearsonr
import numpy as np

#Sewage smell correlation
st=nui[nui.Smell=="Sewage"]
st.drop(st.columns[-1],axis=1,inplace=True)
st.drop(st.columns[0:5],axis=1,inplace=True)
st.drop(st.columns[1:8],axis=1,inplace=True)
st.drop(["Tlow"],axis=1,inplace=True)
st.drop(["TimeDif"],axis=1,inplace=True)

#Correlation between severity of sewage smell and all enviro variables
st.corr(method=lambda x,y:pearsonr(x,y)[1])-np.eye(len(st.columns)) #p values

st.corr(method="pearson") #r values

#Fishy smell correlation
fi=nui[nui.Smell=="Fishy"]
fi.drop(fi.columns[-1],axis=1,inplace=True)
fi.drop(fi.columns[0:5],axis=1,inplace=True)
fi.drop(fi.columns[1:8],axis=1,inplace=True)
fi.drop(["Tlow"],axis=1,inplace=True)
fi.drop(["TimeDif"],axis=1,inplace=True)

#Correlation between severity of fishy smell and all enviro variables
fi.corr(method=lambda x,y:pearsonr(x,y)[1])-np.eye(len(fi.columns)) #p values

fi.corr(method="pearson") #r values
```



```
#Good smell correlation
Go=nui[nui.Smell=="Good"]
Go.drop(Go.columns[-1],axis=1,inplace=True)
Go.drop(Go.columns[0:5],axis=1,inplace=True)
Go.drop(Go.columns[1:8],axis=1,inplace=True)
Go.drop(["Tlow"],axis=1,inplace=True)
Go.drop(["TimeDif"],axis=1,inplace=True)

#Correlation between severity of good smell and all enviro variables
Go.corr(method=lambda x,y:pearsonr(x,y)[1])-np.eye(len(Go.columns)) #p values

Go.corr(method="pearson") #r values
```

Appendix D. Demographics of *Pilau*-meter participants

Demographics	Repsonse	Percent	Count
What is your age?	18–29 years old	76.9	50
	30–39 years old	15.4	10
	40–49 years old	4.6	3
	50 + years old	3.1	2
Where do you live? (Please select the best description.)	Local to Hawai'i Island (excluding Keaukaha community)	59.1	39
	Out of State/ Country	21.2	14
	Keaukaha Community	15.2	10
	Neighbor Island	4.5	3
How often do you go to Puhi Bay?	Once or twice a week	60	30
	Once every year	14	7
	Every other week	10	5
	Once a month	10	5
	Once every 3 months	6	3
What brings you to Puhi Bay?	Diving	46.7	21
	Swimming	35.6	16
	Fishing	6.7	3
	For picnic	2.2	1
	Whale/ dolphin watching	2.2	1
	Hang out	2.2	1
	Cruising	2.2	1
	Lounging	2.2	1
If you selected "Working" as your answer to the question above, what is your occupation?	Fisherman		1
	Security guard		1
What is your educational level?	University- Undergraduate	52	26
	University- Graduate	18	9
	Community College	16	8
	High School	14	7

Appendix E. Summary of *Pilau*-meter responses, percent of responses and count of responses for a particular question

Pilau-meter Questions	Response	Percent	Count
Your observation takes place during what day? (Month)	June	38.8	33
	Feburary	29.4	25
	March	16.5	14
	January	12.9	11
	August	1.2	1
	April	1.2	1
Your observation takes place at what time? (24 Hour time)	11	17.6	15
	12	16.5	14
	16	9.4	8
	10	8.2	7
	15	5.9	5

(*continued on next page*)

(*continued*)

Pilau-meter Questions	Response	Percent	Count
	6	5.9	5
	9	4.7	4
	13	4.7	4
	19	4.7	4
	14	3.5	3
	8	3.5	3
	20	2.4	2
	7	2.4	2
	21	2.4	2
	3	2.4	2
	22	2.4	2
	4	1.2	1
	18	1.2	1
	17	1.2	1
What are the environmental conditions like at the time you are completing this survey?	Sunny	35.3	36
	Overcast/Cloudy	25.5	26
	Low tide	17.6	18
	High tide	11.8	12
	Windy	4.9	5
	Rainy	3.9	4
	Slight breeze	1.0	1
Which region are you reporting from?	Region 2	54.8	46
	Region 3	20.2	17
	Region 1	17.9	15
	Region 4	3.6	3
	Region 5	3.6	3
What type of smell is it?	Good	65.5	55
	Fishy	16.7	14
	Sewage	13.1	11
	Exhaust	4.8	4
How severe is the smell?	1	54.8	46
	2	26.2	22
	3	10.7	9
	4	4.8	4
	5	1.2	1

Data availability

Data will be made available on request.

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