David Lassner
President

UNIVERSITY of HAWAIʻI

DEPT. COMM. NO. 82

November 24, 2021

The Honorable Ronald D. Kouchi,
President and Members of the Senate
Thirty-First State Legislature
Honolulu, Hawaiʻi 96813

The Honorable Scott Saiki, Speaker
and Members of the House of Representatives
Thirty-First State Legislature
Honolulu, Hawaiʻi 96813

Dear President Kouchi, Speaker Saiki, and Members of the Legislature:

For your information and consideration, the University of Hawaiʻi is transmitting a copy of the Report on the State-wide Assessment of Wastewater Pollution Intrusion into Coastal Regions of the Hawaiian Islands (Act 132, Session Laws of Hawaiʻi 2018 and Act 170, Session Laws of Hawaiʻi 2019) as requested by the Legislature.

In accordance with Section 93-16, Hawaiʻi Revised Statutes, this report may be viewed electronically at: https://www.hawaii.edu/offices/government-relations/2022-legislative-reports/ .

Should you have any questions about this report, please do not hesitate to contact Stephanie Kim at 956-4250, or via e-mail at scskim@hawaii.edu.

Sincerely,

David Lassner
President

Enclosure

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UNIVERSITY OF HAWAI'I SYSTEM REPORT

REPORT TO THE 2022 LEGISLATURE

Report on the State-wide Assessment of Wastewater Pollution Intrusion into Coastal Regions of the Hawaiian Islands

Act 132, SLH 2018
Act 170, SLH 2019

October 2021

STATE-WIDE ASSESSMENT OF WASTEWATER POLLUTION INTRUSION INTO COASTAL REGIONS OF THE HAWAIIAN ISLANDS

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October 1, 2021

Prepared for the Hawaiʻi State Legislature, Hawaiʻi State Department of Health, & the Cesspool Conversion Working Group

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E maliu mai i nā limu, nāna e moʻolelo mai.

“Give your attention to the limu, look at the story they tell.”

Acknowledgements

The research team for this project gratefully acknowledges the staff of the Water Resource Research Center, Jonalyn Mokiau and Barbara Guieb, for their support of this project, especially during the challenging period of COVID-19 restrictions. Additional fiscal support was provided by the staff at the Office of the Vice Provost for Research and Scholarship, University of Hawaiʻi at Mānoa. Many others, including Alicia Mohandro, Jodie Rosam, Shayla Waiki, and Sierra Stamer, assisted in field efforts and laboratory activities. We also thank Dr. Kanesa Seraphin and colleagues who attempted to set up a field team on Kauaʻi when COVID-19 restrictions impacted our teamʻs ability to travel during our sampling efforts. After the data were collected and analyzed, our interactions with the staff Department of Health, State of Hawaiʻi gave valuable feedback which improved this Act 132 Final Report. Similarly, presentations to and feedback from the Cesspool Conversion Working Group, convened by Christin Reynolds, led to feedback that helped improve this Act 132 Final Report. Mahalo nui loa to all.

EXECUTIVE SUMMARY

Introduction

Pursuant to Act 132, Session Laws of Hawai'i (SLH) 2018 and Act 170, SLH 2019, the University of Hawai'i is submitting the Legislative Report on the State-Wide Assessment of Wastewater Pollution into Coastal Regions of the Hawaiian Islands. Act 132, SLH 2018, required the University of Hawai'i, in cooperation and consultation with the Department of Health, to conduct a comprehensive state-wide study of wastewater contamination in nearshore marine areas. Act 132, SLH 2018 also required the submittal of a report of findings and recommendations, including any proposed legislation, to the Cesspool Conversion Working Group and Legislature no later than October 1, 2019. Act 170, SLH 2019 amended Act 132, SLH 2018 to extend the date for submittal of a report to the Cesspool Conversion Working Group and Legislature to no later than twenty days prior to the convening of the Regular Session of 2022.

Background

The potential for residential "onsite sewage disposal system" or OSDS wastewater to impact human health and coastal ecosystems is a cause of increasing concern throughout the State of Hawaiʻi (Abaya et al., 2018; Amato et al., 2016; Amato et al., 2020; Dailer et al., 2010). In 2016-2017, these concerns and federal EPA guidelines prompted the State of Hawaiʻi Department of Health to ban the installation of new cesspools and the Hawaiʻi State Legislature to provide financial assistance for upgrades of existing cesspools in sensitive areas (Act 120) and require the upgrade of the more than 88,000 cesspools in the state by 2050 with wastewater disposal systems that provide a higher level of wastewater treatment (Act 125). Field studies of the relationship between wastewater discharge to the groundwater and the resulting nutrient and contaminant loading in the coral reef communities has been studied on the local scale in Kahaluʻu and Puakō (Abaya et al., 2018) and Waialua and Waimanalo (Amato et al., 2020) and at the island wide scale for Maui (Dailer et al., 2010) and Oahu (Amato et al., 2020). A state-wide assessment of these relationships, however, has never been attempted. Previous groundwater modelling studies have used computer simulations to estimate impact of residential OSDS wastewater on the coastline on a state-wide scale (Whittier and El-Kadi 2009; Whittier and El-Kadi 2014). With the funding provided though Act 132 (2018), the University of Hawaiʻi collaborated with the State of Hawaiʻi, Department of Health to measure wastewater pollution using both field and modeling methods in the coastal waters of four major Hawaiian Islands: Kauaʻi, Oʻahu, Maui, and Hawaiʻi Island. The objective of this project was to provide data that will assist the State of Hawaiʻi in prioritizing areas for cesspool upgrades.

Methods

This study used a combination of coastal sampling, groundwater models, and geographical information system (GIS) analyses to determine the extent and magnitude of wastewater discharges to the nearshore waters of Kauaʻi, Oʻahu, Maui and Hawaiʻi. Nitrogen (N) was chosen as an indicator for sewage-derived wastewater because it is abundant in wastewater, it negatively impacts aquatic ecosystems, it is generally nonreactive in groundwater, and previous studies indicate that it is an effective N-based wastewater tracer in Hawaiʻi (Abaya et al., 2018; Amato et al., 2016; Amato et al., 2020; Dailer et al., 2010; Hunt and Rosa 2009) and throughout the tropics (Fong et al., 2003; Garrison et al., 2007; Shuler et al., 2019). Modeling of groundwater N expanded upon the previous modeling done by Whittier and El-Kadi (2009 and 2014) by producing estimates of nitrogen transport (N-flux estimates) per segment of coastline, using a method that tracks dissolved nitrogen particles from both OSDS and wastewater injection wells to the coastline. These nitrogen-flux estimates were used to select 2-kilometer (km) swaths of coastline for intertidal seaweed surveys. Study swaths were chosen for seaweed sampling based primarily on the nitrogen-flux estimates of wastewater-derived nitrogen in the groundwater adjacent to the shoreline, as well as other factors, including seaweed species availability, safety issues, and coastline access. The predicted wastewater influence of these swaths spanned a gradient from relatively high to low wastewater intrusion. Along each 2-km swath, individual sites were selected for seaweed sampling every 100 m for a total of 20 sites per swath. Multi-person, expert teams were established and trained in Standard Operating Procedures, for each island. At each site, one or more of a selected set of seaweed species were collected in triplicate, spaced apart by 1 meter. Seaweed samples were returned to labs on each island, cleaned, dried, and analyzed for the amount of nitrogen in a seaweed as a percentage of mass (%N) and the isotopic value of that nitrogen ($\delta^{15}N$).

Common seaweeds provide a useful indicator of nitrogen and have been used for over a decade to detect wastewater in coastal environments around the globe (Dailer et al., 2010 and references within). When N is abundant in nearshore waters, seaweed have the ability to store N in their tissues which causes their overall percent tissue nitrogen (%N) to increase. Because seaweed are continuously absorbing nutrients to grow, the composition of the nitrogen in the tissue reflects the average nitrogen conditions over several days to weeks (Dailer et al., 2012). In addition, the isotopic ratio of nitrogen in seaweed tissues can be used to determine the dominant nitrogen source because N from different sources tend to have different isotopic ratios. Isotopic nitrogen ratios of ^{15}N:^{14}N are expressed as the $\delta^{15}N$ signature or value, which is a measure of the abundance of the heavy Nitrogen-15 isotope (^{15}N) in relation to the the lighter nitrogen isotope ^{14}N. Wastewater is generally enriched in ^{15}N because bacteria preferentially uptake the lighter isotope of ^{14}N leaving the wastewater enriched in the heavier isotope of ^{15}N, consequently increasing its $\delta^{15}N$ value (Heaton 1986). Chemical fertilizer, naturally occurring and atmospheric nitrogen have nearly equal amounts of ^{15}N and ^{14}N, consequently resulting in low (near 0‰) $\delta^{15}N$ signatures. Evaluation of the seaweed $\delta^{15}N$ value in tandem with the percent of N in the sample (%N) gives insight into both the dominant source of that N ($\delta^{15}N$) and relative amount of coastal N loading (%N) in coastal waters where collected (Amato et al., 2016, Amato et al., 2020; Dailer et al., 2012). Seaweed samples therefore indicate the relative amount of N loading (%N) and the dominant source of that nitrogen ($\delta^{15}N$) in coastal waters where collected. Naturally derived nitrogen is characterized by low seaweed $\delta^{15}N$ and %N, agriculturally-derived nitrogen is characterized by low seaweed $\delta^{15}N$ and high %N, and wastewater-derived N is characterized by high seaweed $\delta^{15}N$ and moderate to elevated %N (Amato et al., 2016).

To compare the field collected seaweed data to the modeled wastewater-derived nitrogen flux, previous groundwater models (Whittier and El-Kadi, 2009; 2014) were updated to provide estimates of nitrogen discharge from OSDS and wastewater injection wells to the ocean as kilograms of nitrogen per km of shoreline. In addition, the density of OSDS within 1 km of the coastline was calculated using GIS analysis and expressed as the number of OSDS units per km^2. For all swaths, nitrogen-flux and OSDS density were evaluated alongside the seaweed nitrogen parameters ($\delta^{15}N$ and %N) to compare the areas wastewater influence predicted by the model and detected through seaweed samples. The swath averages for these four parameters were ranked to visualize trends in the data (Figure 2). Swath average seaweed $\delta^{15}N$ values were plotted with swath average OSDS density to statistically establish wastewater influence designations of wastewater dominant, wastewater influenced and little to no wastewater detected (Figure 3). Average seaweed $\delta^{15}N$ and %N values were then plotted against each other for each swath to illustrate N source trends (Figure 4).

Results

On a state-wide scale, data from seaweed samples and model predictions indicate that there are coastal regions on all the four Main Hawaiian Islands that are exposed to wastewater-derived nitrogen (Figure ES-1). In Figure ES-1, the map's color shading indicates the severity of wastewater influence (red for wastewater dominant, yellow for wastewater influenced, green for little to no wastewater detected) for both swath location names as well as the wastewater N-flux arcs. This color scheme is also consistent with the ranked data in the state-wide assessment (Figure ES-2). The modeled wastewater N-Flux arcs are similarly shaded with green for areas of little to wastewater N being discharged to the coast, yellow for moderate amounts of wastewater N being discharged, and red for areas of high wastewater N discharge to the coast.

For each swath, the swath average from four parameters (seaweed $\delta^{15}N$ values, seaweed %N values, wastewater nitrogen-flux, and OSDS density) were ranked to produce a comparative assessment. Swaths were then designated into one of the three following categories of wastewater influence: 1) wastewater dominant, 2) wastewater influenced, and 3) little to no wastewater detected (Figure ES-2). Swaths with dominant wastewater detection are shown on the state-wide assessment as the top one-third of ranked swaths and generally contain red to orange colored variable ranks from 1-13 (Figure ES-2). Swaths in the wastewater dominant category generally have very good agreement between the results from seaweed samples and modeled predictions of wastewater influence across all islands studied. This state-wide evaluation indicates that the following areas of coastal wastewater nitrogen flux are of the greatest concern: the northeast coast of Hawaiʻi Island up to Hāmākua, the west side of Hawaiʻi Island from the Natural Energy Laboratory of Hawaiʻi Authority to Hōlualoa, the east portion of central Maui both north and south coastlines, several stretches of coastline on Oʻahu, and the Poʻipū, Nāwiliwili, and Kapaʻa coastlines of Kauaʻi. The wastewater dominant swaths in rank order are:Waialua, Hauula, Nawiliwili, Wailoa, S. Kihei, Kaaawa, Wailea, Kapaa, and Waiohai. Additionally, other areas identified by the modeling efforts as high wastewater intrusion could have been included but they were not sampled due to the lack of access or COVID-19 travel restrictions. However, because of OSDS densities, these sites warrant further examination.

Average seaweed $\delta^{15}N$ values per swath were plotted as a function of the average OSDS density per swath, which allowed for the statistical designation of the wastewater influence categories (Figure ES-3). Initial data exploration suggested that modeled OSDS density had a nonlinear and saturating relationship with $\delta^{15}N$, so the data was modeled according to the nonlinear function that best fit the data. In this analysis, swaths with average seaweed $\delta^{15}N$ values of 6.0‰ and higher are dominated by wastewater (shown as circles in Figure ES-3; islands are noted by color of symbol) based on the best fit parameter estimation of the saturation point for these data (model correlation: r = 0.45. The best fit parameters for a was 6.3761 (95% CI = (6.0009, 6.7694), p <2E-16) and b was 0.5231 (95% CI = (0.2990, 0.8612), P = 1.69e-05), where a describes the asymptote of the function and b described the value of OSDS density at which average $\delta^{15}N$ is halfway to its asymptote. This analysis also provided statistical designation for the second category of wastewater influence as swaths with average seaweed $\delta^{15}N$ values ranging from 4.0 to 5.9‰ (shown as squares in Figure ES-3). Swaths with average seaweed $\delta^{15}N$ values from 3.9‰ and below were designated as little to no wastewater influence (shown as triangles in Figure ES-3). Site designations were confirmed as statistically distinct from each other using linear mixed effects models (F(2, 28.927) = 69.07, P = 9.659e-12).

Swaths in the wastewater influenced category (shown as squares in Figure 3) are often characterized by two distinct patterns of nitrogen input: 1) only significant wastewater inputs or 2) the nitrogen loading sources are a mixture of wastewater and agricultural (chemical) fertilizers. Thus, some of the swaths in this category may have results that diverge between the modeled wastewater loading predictions and the seaweed $\delta^{15}N$ and %N values. This mismatch of results can occur for a variety of well-recognized reasons, including the influence of fertilizer from proximal large-scale agriculture, as well as other land use and land cover occurrences. For instance, Figures ES-2 and ES-4 confirm that the coastal groundwater nitrogen-fluxes of two swaths on the north shore of Maui adjacent to old sugar cane fields are dominated by legacy agricultural fertilizer-based nitrogen.

Swaths with little to no wastewater detected from all analyses are found at the bottom of the state-wide ranked comparison and colored green. These swaths generally have very good agreement between the results of seaweed parameters and model predicted low estimates of wastewater influence. The major source of nitrogen to these swaths was generally predicted and confirmed to be from natural sources (Figure ES-4). Figure ES-5 illustrates that case in point for Makua, by displaying the spatial relationships of the local land-use showing almost no development inland of the coast, and the results from the model prediction of low wastewater nitrogen flux and the seaweed $\delta^{15}N$ values showing little to no wastewater detected.

At the island scale, significant positive relationships were found between modeled predictions of nitrogen-flux and OSDS density with seaweed $\delta^{15}N$ and %N values. A case in point for high levels of wastewater predicted and subsequently detected, Figure ES-6 illustrates the obvious land-use with numerous OSDS in the narrow coastal plain in Ka‘a‘awa, and moderate to high levels of wastewater predicted and then detected by the very elevated seaweed $\delta^{15}N$ values in this area.

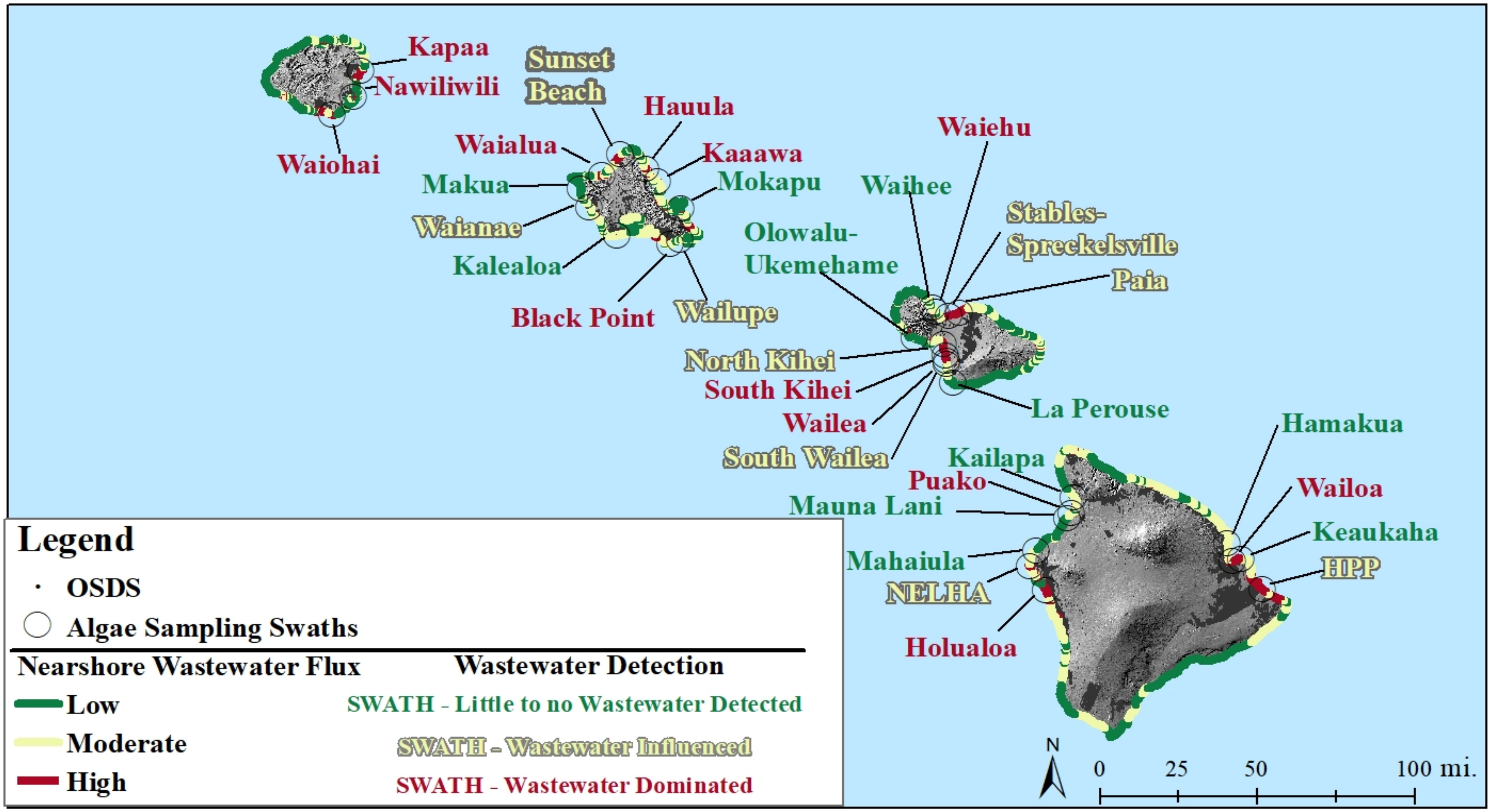
Conclusions

Wastewater discharge to coastlines was significant on all the Main Hawaiian Islands included in this study. Groundwater models evaluated the groundwater transport of wastewater nitrogen from onsite sewage disposal systems (OSDS) and wastewater injection wells to coastal waters. The modelling work in this study determined that cesspool nitrogen is the source of about 80% of the wastewater nitrogen discharging into coastal waters state-wide, and accounted for 83% of the wastewater nitrogen discharging into coastal waters on O‘ahu, for 86% of the wastewater nitrogen discharging into coastal waters on Kaua‘i, for 89% of the wastewater nitrogen discharging into coastal waters on Hawai‘i Island, and for 76% of the wastewater nitrogen discharging into coastal waters on Maui. All four of the Main Hawaiian Islands surveyed in this study had swaths designated as wastewater dominant sites. This state-wide evaluation and comparison of surveyed swaths indicates that the modeled N-flux and mapped OSDS density results are good predictors of wastewater-derived N in coastal water as supported by the seaweed $\delta^{15}N$ and %N results (Figure ES-3). A recently published study using similar methods on Oʻahu also came to the same strong conclusions (Amato et al., 2020). This result is further supported by significance linking seaweed data and OSDS density (Figure ES-3).

It is clear from the state-wide ranking (Figure ES-2) that the model results are particularly good at predicting relative wastewater inputs in the wastewater dominant and little to no wastewater detected areas. This suggests that one could extrapolate this relationship to areas that were not surveyed for seaweed parameters in this study. For example, modeled N-flux and OSDS density values may assist with estimation of the relative impact of wastewater sources for many other areas suspected of substantial wastewater, including additional sites Kauaʻi which were not thoroughly evaluated in this study because of travel issues related to the COVID-19 pandemic. The strong agreement between the model results and the seaweed nitrogen parameters suggests that modeled N-flux and mapped OSDS density can be used to identify the highest priority regions for cesspool upgrades if logistical or physical conditions preclude direct field sampling.

Fine scale sampling of seaweeds provides an integrated look at the available N in coastal waters at the resolution of meters of coastline. While these results do not provide a complete picture of coral reef health, they suggest that there is a significant risk in the wastewater dominant and influenced categories. In addition, these results cannot be used to indicate health risks to humans, as the N in seaweed is only an indicator of the presence of wastewater and not a direct measure of the harmful components in wastewater, such as pathogens. Future studies should include other parameters that provide additional information on risk to coral reef and human health.

In summary, this study documents that groundwater modeling and OSDS density can be used to estimate the wastewater impact to coastal areas of Hawaiʻi. Coastal areas designated here as wastewater dominant should be given a high priority for OSDS upgrades. In areas designated as influenced by wastewater, additional information may be needed to verify that wastewater is the major source of N in these areas. Current efforts are underway to use the results of this study in conjunction with other data sets to assist with cesspool upgrade prioritization (Mezzacapo and Shuler, 2021). Finally, coastal seaweed assessments can provide a quick, inexpensive and effective tool to monitor coastal wasters as cesspool conversions and other wasterwater changes occurr (Barr et al., 2013; Costanzo et al., 2005; Smith et al., 2016).



from model and seaweed survey results.

The modeled wastewater N-flux is shown in three color coded ranges with low flux (0.000 – 0.001 kg/m/d) shown in green, moderate flux (0.0011-0.015 kg/m/d) shown in yellow, high flux (0.0151 – 0.0294 kg/m/d) shown in red. Seaweed sampling swaths are shown as circles and the color of their name reflects their wastewater influence category. Individual OSDS units are shown as small black dots. The swath labels are shown in three color coded categories, wastewater dominant (in red), wastewater influenced (in yellow) and little to no wastewater detected (in green). In some places, the OSDS are so numerous that their black dots coalesce to form irregularly shaped, black regions on each island.

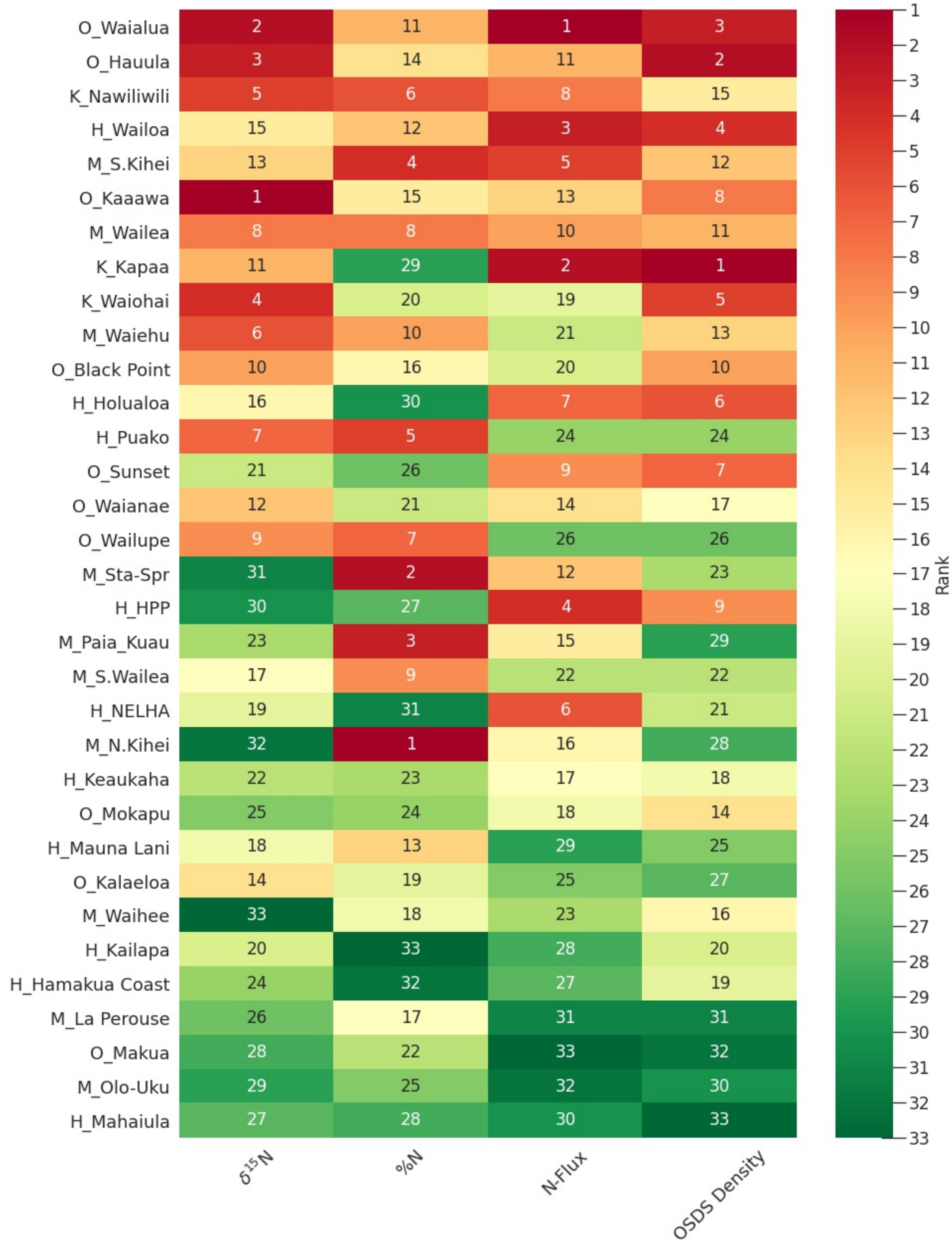


Figure ES-2. State-wide ranking of wastewater detected, organized by swath. Columns are seaweed $\delta^{15}N$ values, seaweed %N values, modeled wastewater N-flux, and OSDS density. Swaths (rows) are ranked in order from most to least wastewater detected or modeled. This analysis was not weighted for any one parameter. The first letter of the swath name indicates the island where the swath was located (K= Kaua‘i, O= O‘ahu, M= Maui, H= Hawai‘i Island).

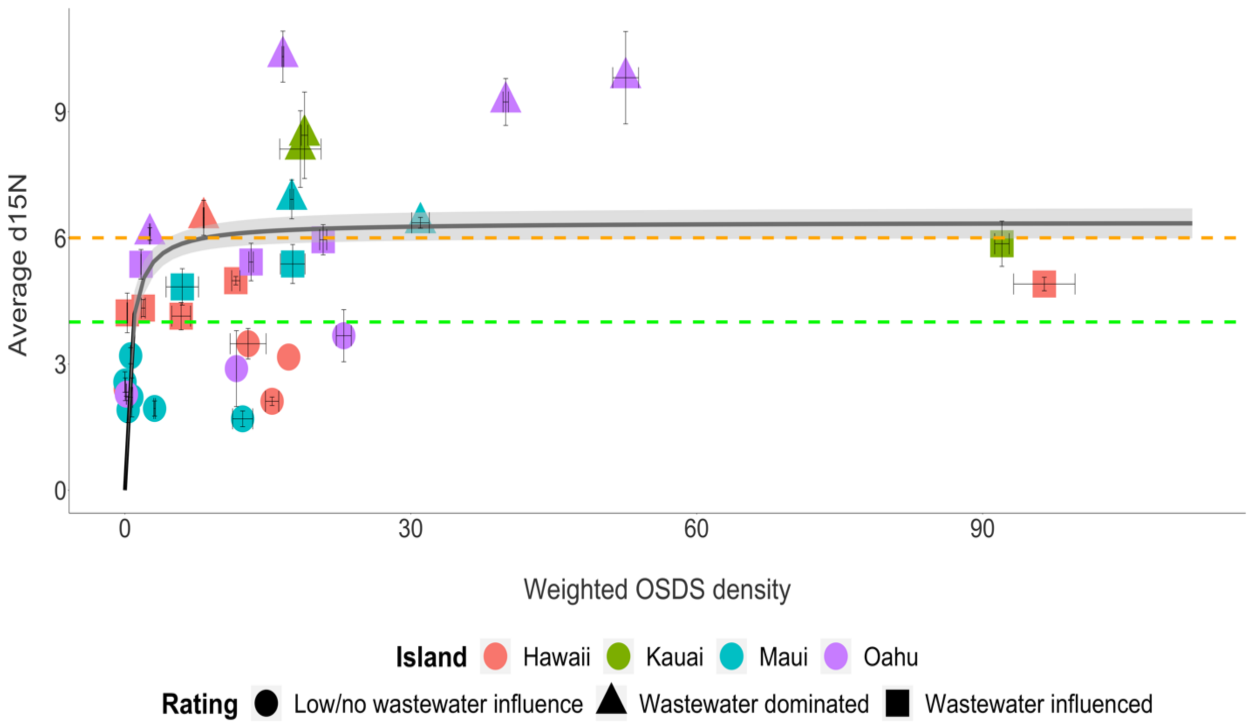
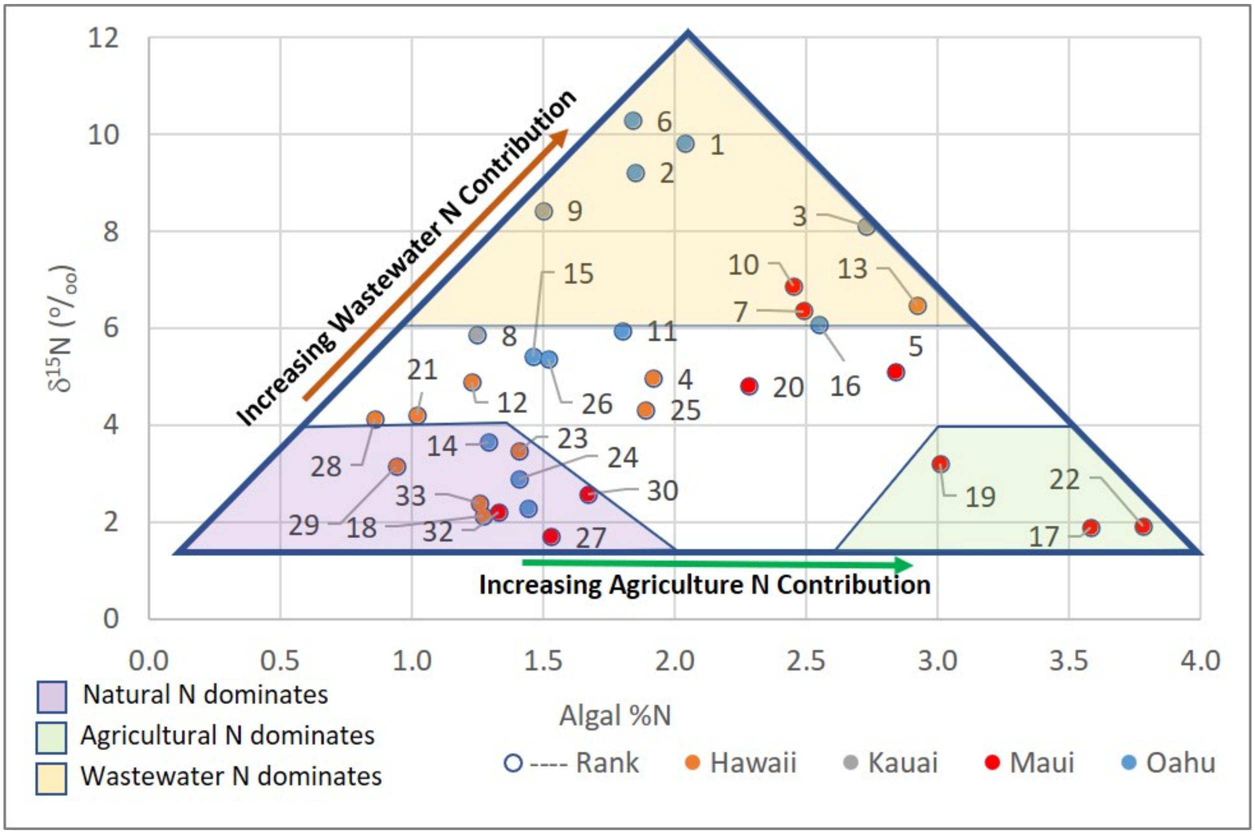


Figure ES-3. Mean seaweed $\delta^{15}N$ values plotted as a function of modeled OSDS density.

The relationship between OSDS density and seaweed δ15N values was evaluated with the Michaelis-Menten function with best-fit parameters derived from non-linear least squares (a = 6.3761 (95% CI = (6.0009, 6.7694), p <2E-16); b = 0.5231 (95% CI = (0.2990, 0.8612), P = 1.69e-05). The shaded area was constructed from 95% Confidence Intervals (CI) of the estimated parameters. Points represent the mean seaweed $\delta^{15}N$ values for a given swath, with vertical error bars representing Standard Error (SE) of seaweed $\delta^{15}N$ values and horizontal error bars representing SE of OSDS density. Color represents island (red = Hawai'i Island, green = Kaua'i, blue = Maui, purple = O'ahu) and shape represents wastewater influence designation (circle = wastewater dominant, square = wastewater influenced, triangle = little to no wastewater detected).



ES-4. A conceptual model links dominant nitrogen (N) sources with wastewater rank for each swath.

Each swath's data averages are graphed based on average seaweed values of %N (x-axis) and $\delta^{15}N$ (y-axis). Each swath is also depicted as a colored dot that indicates the island where the swath is located. Each dot has an associated rank number that correlates to the overall rank from Figure ES-2. This conceptual model depicts three ranges of N source dominance: Natural nitrogen, Agricultural nitrogen, and Wastewater nitrogen. Swaths with natural nitrogen sources are within or near the purple triangle and are characterized by low seaweed values of $\delta^{15}N$ and %N. Swaths with natural nitrogen sources are within or near the purple triangle and are characterized by low seaweed values of $\delta^{15}N$ and %N. Swaths with agricultural fertilizer nitrogen sources are within or near the green triangle and are characterized by low seaweed $\delta^{15}N$ values and high seaweed %N values. Swaths with wastewater nitrogen sources are within or near the yellow triangle and are characterized by high seaweed $\delta^{15}N$ values and elevated seaweed %N values. Swaths within the white area of the triangle represent a mixture of nitrogen sources with no dominant type but are considered distinct from control sites which only have natural nitrogen sources.

Figure ES-5. O'ahu- Makua swath. The Makua swath shows low seaweed δ^{15}N values and low predicted wastewater nitrogen flux to the coastline.

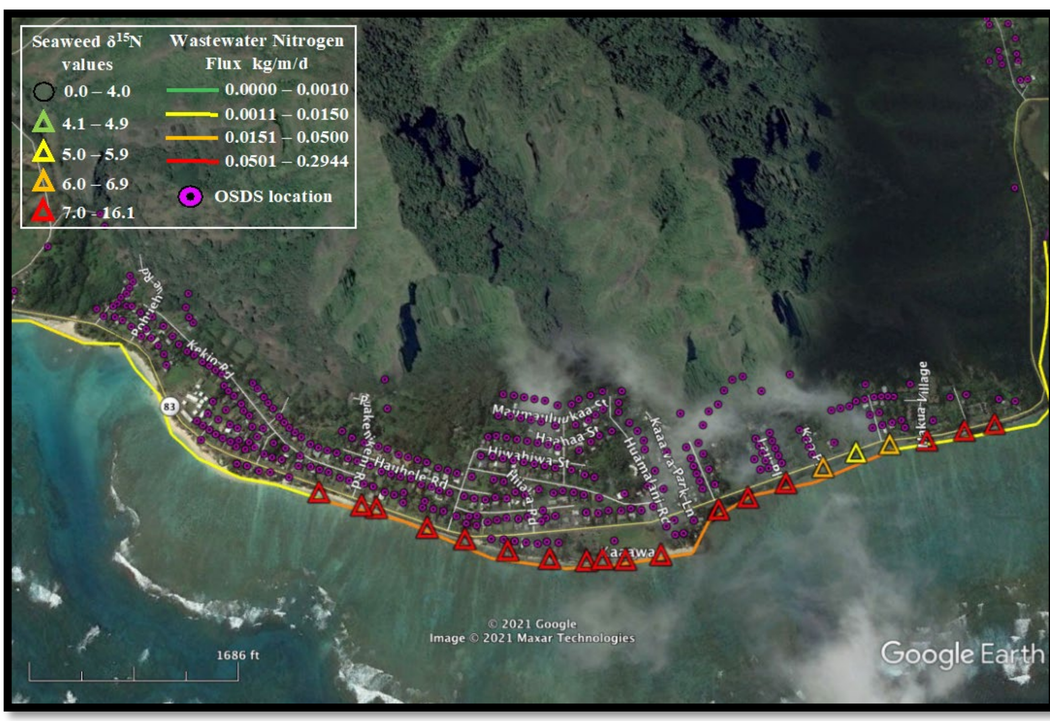


Figure ES-6. O'ahu- Ka'a'awa swath. The Ka'a'awa swath shows high seaweed δ^{15}N values (in red and orange triangles) and moderate to high predicted wastewater nitrogen flux to the coastline via the continuous color gradient, as kilograms of wastewater nitrogen per meter of coastline per day.

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SECTION 1 INTRODUCTION

1.1 Background

As of December 2020, over 91,000 cesspools are actively used to dispose wastewater into the ground across the Main Hawaiian Islands. In 2017, the legislature for the State of Hawaiʻi passed Act 125, thereby establishing the legal framework that mandates cesspool conversions by 2050. To support the cesspool conversion mandate, this project conducted a physically based sampling program coupled with a theoretical assessment of assumed wastewater influence, based on prevalence of cesspools and other sources of coastal wastewater pollution across the four most populated Hawaiian Islands. Theoretical wastewater influences were estimated using a groundwater modeling framework that predicted the severity of sewage pollution from cesspools and other terrestrial-based sources of coastal wastewater pollution to the marine environment.

Wastewater discharge to nearshore coastal waters presents many risks to marine ecosystems and the humans that rely on them. Excessive nutrients, medicines, and other chemicals commonly found in wastewater can stress reef organisms causing illness and changes in aquatic communities. On tropical reefs, decades of research have shown that wastewater input is one of the most damaging and widespread stressors to these important resources worldwide. Wastewater discharge to coastal waters has been directly associated with increases in human illness, coral death, bloom forming seaweed species, bio-erosion rates, declining fish stocks and an overall loss of health (Maragos 1972; Smith et al., 1981; Kinsey, 1985; Lapointe et al., 2005; Dailer et al., 2012; Prouty et al., 2017).

Recent studies have shown that wastewater discharge to the shoreline from contaminated coastal aquifers as submarine groundwater discharge (SGD) is related to lowered reef diversity and excessive growth of weedy seaweeds. (Dailer et al, 2010; Dailer et al., 2012; Amato et al., 2016). OSDS-derived wastewater also enters the coastline via streams and rivers at many chronically polluted areas across the state of Hawaiʻi. On Oʻahu, direct discharge of wastewater (and cessation thereof) to Kāneʻohe Bay serves as a textbook example of the impacts of wastewater nitrogen (N) on Hawaiian reefs (Smith et al., 1981). Although these direct discharges to the bay have been mitigated, more than 116,000 cesspools and other Onsite Sewage Disposal Systems (OSDS) in Hawaiʻi present a similar yet ubiquitous source of sewage that may impact nearly every shoreline in the state. The State of Hawaiʻi Department of Health is aware of this issue and has posted permanent warning signs at locations such as Kahuluʻu, Oʻahu, but work at many levels is needed to change the fundamental problems of wastewater contamination in coastal waters.

1.2 Act 132 and University of Hawaiʻi study as a legislative response to coastal wastewater intrusion

The Hawaiʻi State Legislature addressed the serious health and environmental impacts of cesspool pollution during the 2017 regular session by passing Act 125. Act 125 requires the replacement of all cesspools by 2050 and directed the State of Hawaiʻi, Department of Health (DOH) to:

> …. Investigate the number, scope, location, and priority of cesspools State-wide that require upgrade, conversion, or connection based on each cesspool's impact on

public health. The Department of Health shall also work in collaboration with the Department of Taxation to assess the feasibility of a grant program to assist low-income property owners with cesspool upgrade, conversion, or connection. The Department of Health shall submit a report of its findings and recommendations, including any proposed legislation and recommended administrative action, to the legislature no later than twenty days prior to the convening of the regular session of 2018 29th Legislature.

Upon reviewing the 2018 Department of Health cesspool report, many questions remained about cesspools in Hawaiʻi, including their impact on the environment, prioritization for cesspool replacement, and the cost of replacement. To address these data gaps the 2018-2019 Legislative session passed Act 132.

The purpose of Act 132 as it relates to filling the data gaps is to:

(1) Establish a cesspool conversion working group to develop a long-range, comprehensive plan for cesspool conversion state-wide of all cesspools by 2050; and

(2) Commission a state-wide study of sewage contamination in nearshore marine areas to further supplement the studies and reports conducted by the Department of Health related to cesspools.

This report fulfills the second requirement of Act 132 listed above.

1.3 State-wide coastal wastewater influence assessement methods

The main goal of this project was to determine which regions of the state are most likely to be influenced by terrestrial-derived wastewater pollution in an attempt to assist the State with cesspool prioritization efforts. To accomplish this, this study focused on areas of concern across Oʻahu, Hawaiʻi Island, Maui and Kauaʻi where the presence of wastewater pollution had been modeled in previous studies (Whittier and El-Kadi, 2009; 2014).

Data generated for this state-wide assessment consist of two fundamentally distinct types. The first data set is derived through modeling efforts that estimated wastewater-derived N loading per meter (m) of shoreline calculated as flux. The wastewater-derived nitrogen sources considered were on-site sewage disposal systems (including cesspools) and wastewater injection wells. Not considered in these models was the application of recycled water and any leaks that may occur in sewer lines. Because nitrogen (N) is one of the most prevalent elements in wastewater and is also linked to changes in reef health, groundwater models were modified to estimate wastewater-derived N discharge to the coastline from OSDS for the entire coastlines of Hawaiʻi Island, Maui, Oʻahu, and Kauaʻi. In addition, the density of coastal OSDS (defined as OSDS units located within 1 km of the coastline) was calculated for each sampling swath. The density of OSDS is calculated as units per square kilometer (km^2) and was related to each sampling swath through a geographic distance weighting function.

The second data set was designed to detect wastewater in the coastal environment, following internationally recognized, standard methods. Seaweed growing in nearshore waters were collected to serve as a bioindicator of anthropogenic impact as they are known to incorporate nitrogen from wastewater and other sources into their tissues. Seaweeds were collected following thorough procedures that were repeated across all islands and in similar seasons, to provide an initial state-wide assessment of coastal wastewater influence. At 10 or more regions for Hawaiʻi Island, Maui, and Oʻahu, specific seaweed species were collected at a fine scale across a 2-kilometer distance. COVID-19 related travel restrictions limited our work on Kaua‘i to sampling three regions. Seaweed samples were then analyzed for the presence of wastewater nitrogen using a stable isotope approach. Ultimately we aimed to relate to the modeled nitrogen loads and OSDS densities with seaweed nitrogen parameters.

The modeling approach for this study was to (1) incorporate the new hydrologic data that were acquired since the completion of the 2009 and 2014 studies (Whittier and El-Kadi, 2009; 2014) into the island wide groundwater models, (2) refine the estimated wastewater flux and nutrient loading rates to include injection well-derived N, and (3) map the distribution of wastewater effluent and nutrient loading across short segments of coastline for the four main Hawaiian Islands. This approach allows for the extension of our conclusions of the nearshore sewage impact from areas physically sampled to the entire coastlines of Hawai‘i Island, Maui, O‘ahu, and Kaua‘i. This is possible by statistically relating the modeled nearshore wastewater nitrogen inputs to the assessed seaweed nitrogen parameters generated by sampling the seaweeds at those same coastal regions.

SECTION 2 METHODS

2.1 Modeling the coastal impact of sewage pollution

The previous models were developed for cesspool and other residential sewage disposal system environmental impact on drinking water (Whittier and El-Kadi, 2009; 2014) and were based on groundwater flow models developed for the Source Water Assessment Program (Whittier et al., 2004) using hydrologic data from the 1990s. These prior models were updated for this project to incorporate the significant body of new hydrogeology information for Hawai‘i. In particular, we used updated recharge estimates from the USGS (Izuka et al., 2016) and updated groundwater models of central and west Maui from the USGS (Gingerich, 2008; Gingerich and Engott, 2012), and numerous wastewater environmental impact studies (e.g., Delavaux et al., 2018; Amato et al., 2020; Richardson et al., 2016; Glenn et al., 2012 and 2013; Babcock et al., 2019).

The modeling approach generally follows that described in the Hawai‘i OSDS studies (Whittier and El-Kadi, 2009; 2014). Two major modifications were made to the previous modeling effort. These were modifying the OSDS loading rates and quantifying the wastewater nutrient flux across short segments of shoreline. The OSDS effluent and nutrient loading rates used in the Whittier and El-Kadi 2009 and 2014 studies were updated. Previously the effluent discharge rate for each residential OSDS was based on the regulatory design requirement of 200 gallons per day (gpd) times the number of bedrooms in the residence (Hawai‘i Administrative Rules Title 11 Chapter 62 Wastewater Systems, 11-62-34(2)(A)). This regulatory based rate is the maximum rate allowable, and over-estimated actual OSDS effluent discharge rates. Here, we instead used the residential wastewater discharges rates listed in EPA (2002), that are more representative of actual values. The nitrogen N loading rates were taken from an engineering review in Babcock et al., (2020), while the phosphorus (P) loading rates were taken from Delavaux et al., (2019).

Table 1. Nutrient concentrations used to compute OSDS nitrogen and phosphorus loading

Type	**Nitrogen** (Delavaux et., 2018, Table 2; Babcock et al., 2020, Table 15) Assumes no nitrogen attenuation once the effluent leaches below the zone of treatment	**Phosphorus** (Delavaux, et al., 2018, Table 2) Assumes no phosphorus attenuation in septic or ATU
Septic or ATU with Soil Treatment	34	1.2
Septic to Pit	58	19
ATU to Pit	58	19
Cesspool	87	19
All OSDS Effluent Rate	70 gal/day/person, and 1.5 persons/bedroom (EPA, 2002)	

To assess the threat of nearshore sewage pollution impact, the groundwater flow field was discretized into flow zones with the boundary of the flow zone being delineated by the trajectory of groundwater flow lines from the mountain recharge areas to the coastal groundwater discharge zones. The groundwater flow generally remains within the confines of the individual flow zones (Freeze and Cherry, 1979; Delavaux et al., 2018) making sewage pollution flux to the coast the cumulative input of wastewater injection wells, cesspools and other OSDS within the flow zone (Figure 1).

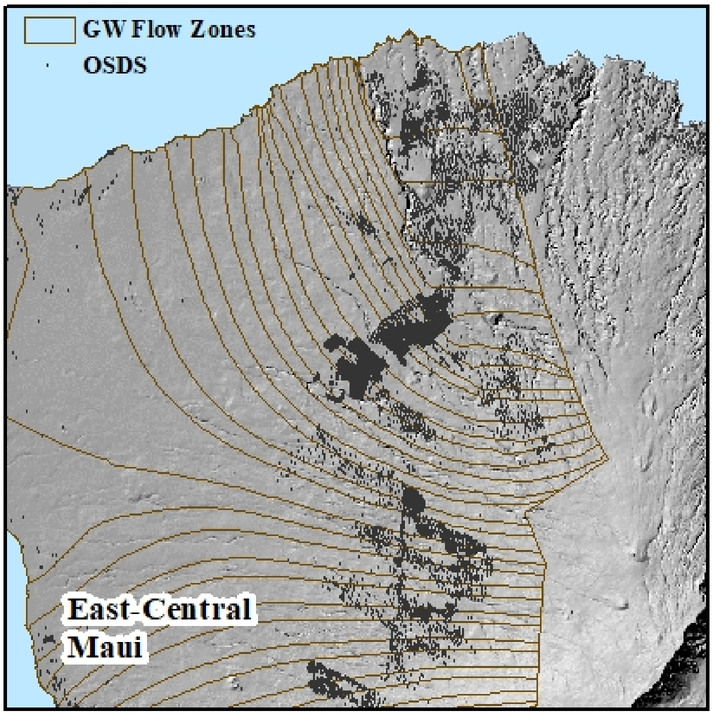


Figure 1. Central Maui groundwater flow zones and trajectories.

2.2 Nitrate transport modeling

Wastewater nitrate in the groundwater was chosen as the sewage pollution indicator with which to model the coastal impact from residential and injected wastewater. Nitrate is a principle wastewater contaminant with action limits for drinking water and for surface waters. Nitrate was modeled as a conservative species, meaning once it was introduced into the groundwater, there was no decay or attachment to the aquifer matrix. Long-term nitrate fate and transport studies have not been carried out in Hawai‘i to determine if nitrate degrades or is transformed to non-contaminant species (e.g., gaseous nitrogen) once it is introduced into the aquifer. Regardless, nitrate, a primary nutrient introduced into the marine environment, is the oxidized species of inorganic nitrogen, stable in an aerobic environment and in the oligotrophic ocean waters of Hawai‘i, a primary nutrient introduced into the marine environment.

Denitrification can convert nitrate to gaseous nitrogen, removing it from the groundwater system. This occurs in water depleted of dissolved oxygen (anaerobic) and where dissolved organic carbon is present as a nutrient source for the denitrifying bacteria. A review of Hawai‘i groundwater chemistry shows that anaerobic conditions generally do not occur in Hawai‘i groundwater (e.g., Hunt, 2004; Evans et al., 2015; Hunt and Rosa, 2009). Documented cases where denitrification does occur in the groundwater is where ample dissolved organic carbon is available, and the aerobic utilization of the organic carbon depletes the dissolved oxygen. Such a process has been demonstrated at Kaanapali, Maui where the nitrate in the injected wastewater undergoes denitrification during the transit to the coastal submarine springs (Glenn et al., 2012; Fackrel et al., 2016). In the absence of municipal scale wastewater injection, it is doubtful that conditions exist that are conducive to denitrification. For example, an investigation into the sources of nitrate at the mid-elevations of east-central Maui found that while residential disposal of wastewater was a major contributor to the groundwater nitrate, the dissolved oxygen concentrations were still near saturation (DOH, 2018). The demise of the sugar cane industry provides empirical evidence that nitrate in Hawai‘i’s groundwater behaves as a conservative species. A review of the Department of Health Drinking Water Contaminant Database (DOH, 2020a) shows that the nitrate concentrations in the groundwater slowly declined when sugarcane agriculture ended with half-lives that were on the order of years. Figure 2 shows the nitrate concentrations in three west Maui wells and one Hawai‘i Island well plotted against elapsed time since sugar cane cultivation ended. The slow decline in nitrate concentration is more indicative of the slow flushing of the aquifer rather than some decay or transformation of the groundwater nitrate.

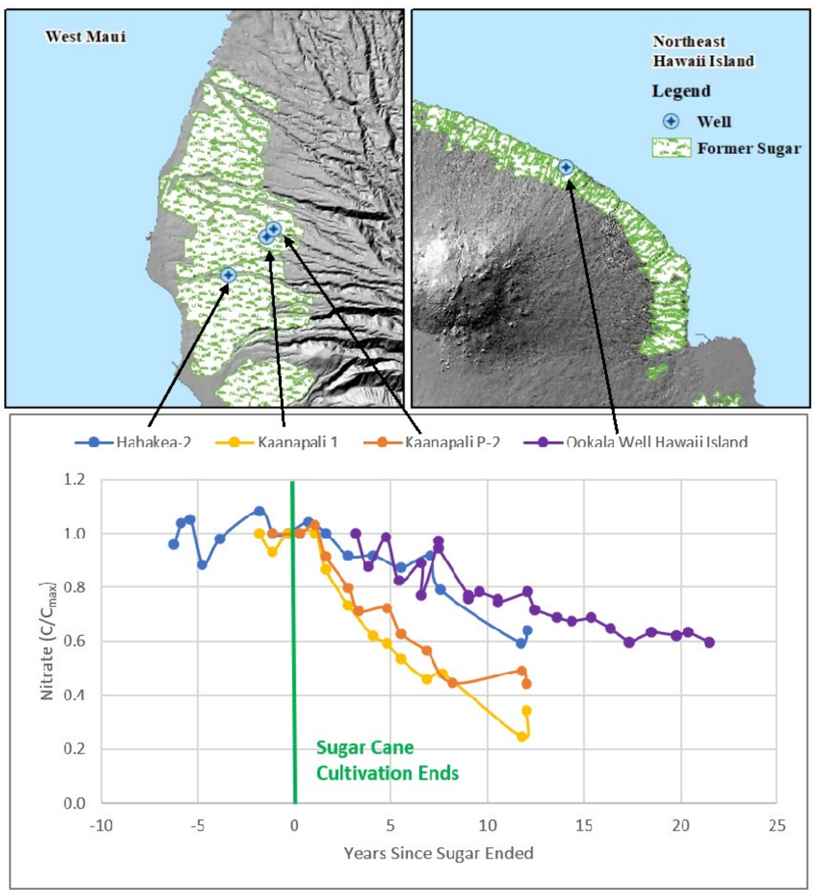


Figure 2. Groundwater nitrate concentration declines with the end of sugarcane agriculture.

2.3 OSDS modeling history

The State of Hawai‘i, Department of Health and the University of Hawai‘i have collaborated on the health and environmental concerns of residential wastewater disposal since 2009. Whittier and El-Kadi (2009) evaluated the health and environmental risk posed by OSDS for the island of O‘ahu. In that study, the OSDS health and environmental risk was a composite evaluation summing the risk factors to drinking water, streams, and coastal waters as a single metric. That study did not have a separate nearshore sewage pollution risk. Factors considered in the risk ranking were the ability of the soil to infiltrate the OSDS effluent, the proximity of the OSDS to critical receptors that included the shoreline, the modeled concentration of nitrate in groundwater from OSDS leachate, and the density of OSDS per square mile. Groundwater nitrate was modeled using the groundwater flow models of Whittier et al., (2004) and adding a contaminant transport component based on the leaching of OSDS effluent to the groundwater. The assumed loading rates were based on OSDS design regulations that assumed effluent rates of 200 gpd per bedroom. The effluent nutrient concentrations were values reported by the Water Resources Research Center and Engineering Solutions (2008).

Whittier and El-Kadi (2014) expanded the OSDS health and environmental risk assessment to the islands of Hawai‘i, Maui, and Moloka‘i. In addition to computing a composite risk value for all receptors, a risk value was computed for individual receptors including coastal zone waters. The coastal zone risk evaluation included a fixed setback of 200 ft from the shoreline, a two-year groundwater time of travel to the shoreline, and areas where the nitrogen transport modeling indicated OSDS groundwater nitrate concentrations of 1 mg/L or greater intersected the shoreline. These estimated coastal zone water risk zones overlapped making the computed risk a weighted summation of the intersections of these evaluation zones. Based on the results of Whittier and El-Kadi (2009), Amato et al. (2020) compared predicted wastewater nitrate concentration based on an O‘ahu groundwater model, that also included wastewater injection, with measured values of seaweed $\delta^{15}N$ and %N collected from the O‘ahu nearshore waters. Amato et al. (2020) found a strong correlation between estimates of coastal groundwater nitrate (from OSDS and injection wells) with measured values of nearshore seaweed $\delta^{15}N$ and %N.

The previous studies used the modeled OSDS-derived groundwater concentration of nitrate at the coast as a primary metric to evaluating the wastewater impact on the nearshore waters. However, the concentration of nitrate in the groundwater is not the same as the mass of OSDS derived nitrate discharging to the marine waters. For example, a moderate amount of OSDS leachate can significantly increase the groundwater nitrate concentration in low groundwater recharge areas such as the west side of Hawai‘i Island. By contrast, it will take a much greater amount of OSDS leachate to result in even a moderate increase in the groundwater nitrate concentration in high recharge area such as the east side of Hawai‘i Island. Delevaux et al. (2018) evaluated the wastewater impact on the nearshore environment based on mass flux rather than concentration. This was done by generating a groundwater flow field using the modeling code MODFLOW. The flow field was then spatially discretized by tracing flow lines from recharge to coastal discharge areas using the particle tracking model MODPATH. Based on the intersection of the modeled flow lines with the contributing area of submarine groundwater was partitioned into polygons with shoreline lengths of about 200 m. These “flow field” polygons represented groundwater flow in the aquifer area up-gradient of each respective shoreline segment. The mass of wastewater nutrients discharging within each polygon is the sum of that from the wastewater sources within the flow tube up-gradient from each shoreline segment. This concept was also applied studies that evaluated cost/benefit tradeoffs for various OSDS upgrade or replacement scenarios (Barnes et al., 2019; and Babcock et al., 2019).

2.4 Wastewater detection in coastal areas using seaweed

This study focused on particular areas of concern which were identified by previous modeling efforts (Whittier and El-Kadi, 2009; 2014). For wastewater influenced areas, the model's output estimated a midpoint of the wastewater plume moving from OSDS locations to the coastline. A 2-km sampling 'swath' was established with the wastewater plume's midpoint identified as the center. Seaweed collection occurred at the midpoint and at 100 m intervals on both sides of the midpoint for a total of 20 sites and 60 samples (3 samples per site) per sampling region where possible. This sampling design was selected in an attempt to detect the maximum nitrogen flux at the plume midpoint, as well as, estimate the width of the wastewater plume at the time of seaweed collection. Swaths were selected across a gradient of potential wastewater influence, from areas with little wastewater sources to areas with dense collections of OSDS units adjacent to the sampling swath. All swaths were sampled with the same procedures across all islands and in approximately the same months in 2019.

Predominantly invasive seaweeds growing in shallow coastal waters were collected in regions predicted by the OSDS model as wastewater influenced (experimental) and as low to no wastewater influence (or control areas). Dried seaweed samples were analyzed for two parameters: nitrogen stable isotope ratios ($\delta^{15}N$) which helps identify potential source(s) of nitrogen (N), and the percentage of nitrogen (%N) which provides a measure of overall flux of nitrogen loading to the area of collection (see the following references for protocols: Costanzo et al., 2005; Dailer et al., 2010; Amato et al., 2016). Seaweed samples were analyzed at the Biogeochemical Stable Isotope Facility at the School of Ocean and Earth Science and Technology at the University of Hawaiʻi at Manoa, and at the Analytical Laboratory at the University of Hawaiʻi at Hilo.

The nitrogen assimilated by the seaweed includes natural, agricultural and wastewater nitrogen. These nitrogen sources have a characteristic range of $\delta^{15}N$ values (Table 2, Kendall 1998; Owens 1987; Umezawa et al., 2002; Gartner et al., 2002; Savage and Elmgren 2004). Isotopic nitrogen ratios of ^{15}N:^{14}N are expressed as the $\delta^{15}N$ signature or value, which is a measure of the abundance of the heavy Nitrogen-15 isotope (^{15}N) in relation to the the lighter nitrogen isotope ^{14}N. Wastewater is generally enriched in ^{15}N because bacteria preferentially uptake the lighter isotope of ^{14}N leaving the wastewater enriched in the heavier isotope of ^{15}N, consequently increasing its $\delta^{15}N$ value (Heaton 1986). Chemical fertilizer, naturally occurring and atmospheric nitrogen have nearly equal amounts of ^{15}N and ^{14}N, consequently resulting in low (near 0‰) $\delta^{15}N$ signatures. Inorganic fertilizer has $\delta^{15}N$ values ranging from 0.0 to 3.0‰ (Table 2, Owens 1987). Groundwater nitrate and isotope data collected by Glenn et al. (2012) in west Maui showed that wells located in former sugarcane fields had an average $\delta^{15}N$ value of 1.8‰. A sample collected from the aeration basin of the Schofield Wastewater Treatment as a surrogate for OSDS leachate nitrogen had a $\delta^{15}N$ value of 10.9‰. Municipal wastewater $\delta^{15}N$ values are dependent upon the type of wastewater treatment and range from 13.5‰ for secondarily treated wastewater (Gartner et al., 2002) to 38.0‰ for Biological Nitrogen Removal or BNR wastewater (Savage and Elmgren, 2004, Table 2). The range of $\delta^{15}N$ values in wastewater is due to BNRs use of denitrifying bacteria to scrub the nitrogen out of the wastewater which leaves the wastewater rich in the heavier isotope of ^{15}N because the bacteria preferentially use the lighter isotope of ^{14}N (Heaton 1986).

On Hawai'i Island, the fecal indicator bacteria, *Enterococcus* spp., was also measured. *Enterococcus* spp. was not measured on the other islands because funding was not available to do so. *Enterococcus* spp. is monitored by the State of Hawai'i Department of Health in marine recreational waters as an indicator of microbial contamination, such as fecal waste in untreated or inadequately treated sewage. Sample collection followed EPA protocols (EPA 2009). Briefly, triplicate water samples were collected in sterile, acid washed, polypropylene plastic bottles select stations and analyzed for *Enterococcus* spp. Samples were taken during low tide when fresh groundwater flow is highest, and near sunrise as sunlight reduces *Enterococcus* spp. survival. *Enterococcus* spp. was analyzed using the Enterolert MPN method (IDEXX Laboratories Inc.) following manufacture's recommendations of 10 mL sample and 90 mL sterile water (Eaton et al., 2005). The upper detection limit of the Enterolert MPN method (2419 MPN/100 ml). Samples that exceeded this upper limit were diluted to not exceed the upper limit during analysis, and the reported values were corrected for sample dilution. When no wells fluoresced blue in the QuantiTray, *Enterococcus* spp. concentrations were reported as 2 MPN/100 mL, one-fifth the detection limit of the method.

2.5 Statistical analysis approach

Statistical analyses were performed to assess the change in seaweed $\delta^{15}N$ values as a function of OSDS density because these measurements provide the most direct measurements of wastewater intrusion into the coastal environment. The relationship between OSDS density and seaweed $\delta^{15}N$ values appeared non-linear at both island and state-level scales, so their relationship best-fit as a non-linear least square's response curve. Non-linear least-squares (nls) was used to determine 1) the function that best describes the shape of that relationship and 2) the best fit parameters for that function. Various nonlinear functions (arctan, hyperbolic tangent, log, Michaelis-Menten) were tested at both the within-island and statewide/combined-island scales. All models were compared to each other and to a standard linear model by comparing the coefficient of correlation (r) and the estimated corrected Akaike's Information Criterion (AICc) for each function. The function that had the best fit across both scales was then used to classify sites into wastewater dominated, wastewater influenced, and little to no wastewater intrusion categories based on the seaweed $\delta^{15}N$ values relative to the best fit parameters for the asymptotic/saturation point of the function. Final groupings for relative wastewater influence were compared against each other using linear mixed effects models with a random effect for each site within each grouping.

Table 2. Worldwide seaweed and nitrogen source $\delta^{15}N$ values

Worldwide review of seaweed and nitrogen source $\delta^{15}N$ values from natural and wastewater influenced areas. Wastewater sources include septic tank effluent (STE), percolation ponds (PP), wastewater (WW) sewage effluent (SE) wastewater treatment plant sewage effluent (WWTP SE) secondarily treated sewage effluent (2nd WWTP SE) and effluent treated with Biological Nitrogen Removal (BNR WWTP SE) (modified from Dailer et al., 2010).

Seaweed $\delta^{15}N$	Source $\delta^{15}N$	Nitrogen Source	Habitat	Location	Country	Reference
	0.0	Atmospheric Nitrogen	Natural			Owens (1987)
	0.0 - 3.0	Inorganic fertilizer	Agriculture			Owens (1987)
1.2 - 2.0		Natural	Offshore reef	Negril Marine Park	Jamaica	Lapointe and Thacker (2002)
	1.3 - 3.7	Natural	Coastal	Narragansett Bay Rhode Island	USA	Thornber et al. (2008), Chaves (2004)
0.01-1.4		Natural	Lava Flow	Keanae to Wainapanapa, Maui	USA	Dailer et al. (2010)
1.4		Natural	Estuarine	Southwestern coast Puerto Rico	USA territory	France et al. (1998)
1.9		Natural	Sandy beach	Sugar Beach, Maui	USA	Dailer et al. (2010)
1.9 - 3.9		Natural	Nearshore reef	Green Island	Taiwan	Lin et al. (2007)
< 3.0		Natural	Offshore island	Moreton Bay	Australia	Costanzo et al. (2001)
2.0		Natural	Offshore reef	Ishigaki Island	Japan	Umezawa et al. (2002)
< 3.0		Natural	Offshore reef	South of Florida Bay	USA	Lapointe et al. (2004)
2.9		Natural	Offshore island	Moreton Bay	Australia	Jones et al. (2001)
3.0 - 4.0		Natural	Estuarine	Himmerjarden Bay, Stockholm	Sweeden	Savage and Elmgren (2004)
3.0		Natural	Offshore reef	Buccoo Reef Complex,Tobago	West Indies	Lapointe et al. (2009)
3.1		Natural	Basalt	Kapalua, Maui	USA	Dailer et al. (2010)
	3.8	Natural spring water	Nearshore reef	Ishigaki Island	Japan	Umezawa et al. (2002)
3.3-3.9		Agriculture	Sandy beach	Baldwin Beach Park, Maui	USA	Dailer et al. (2010)
	> 4.6	STE	Tequesta MW #6	Southeast Florida	USA	Lapointe and Krupa (1995b)
> 5.4		WW	Estuarine	Waquoit Bay Massachusetts	USA	McClelland et al. (1997)
> 5.5		WWTP SE	Estuarine	South of Florida Bay	USA	Lapointe et al. (2004)
> 6.0		WW	Nearshore reef	Negril Marine Park	Jamaica	Lapointe and Thacker (2002)
6.0 - 12.0		SE, STE, PP	Nearshore reef	East of Central Florida	USA	Barlie (2004)
6.0		WWTP SE	Nearshore reef	Buccoo Reef Complex,Tobago	West Indies	Lapointe et al. (2009)
> 6.5		WWTP SE	Estuarine	South of Florida Bay	USA	Lapointe et al. (2004)
6.7		Sewered	Estuarine	Valley Creek Pennsylvania	USA	Steffy and Kilham (2004)
> 7.0	13.5 - 23.5	WWTP SE 2nd	Nearshore reef	Ocean Reef, Beenyup	Australia	Gartner et al. (2002)
7.3		Natural	Estuarine	Oosterschelde Estuary	The Netherlands	Riera et al. (2000)
	> 7.3	STE	Juptier Creek MW #4	Southeast Florida	USA	Lapointe and Krupa (1995a)
> 8.0		Anthropogenic	Nearshore reef	Ishigaki Island	Japan	Umezawa et al. (2002)

Table 2 continued

Seaweed $\delta^{15}N$	Source $\delta^{15}N$	Nitrogen Source	Habitat	Location	Country	Reference
8.0 - 8.6		WWTP SE	Nearshore reef	Dakwan	Taiwan	Lin et al. (2007)
8.0 - 13.0	38.0	WWTP SE 1998-2002	Estuarine	Himmerjarden Bay, Stockholm	Sweeden	Savage and Elmgren (2004)
8.0 - 10.5	24.0	WWTP SE 1994-1997	Estuarine	Himmerjarden Bay, Stockholm	Sweeden	Savage and Elmgren (2004)
8.0 - 13.6	16.1	WWTP SE	Coastal Lagoon	Southeastern Gulf of California	Mexico	Pinon-Gimate et al. (2009)
> 8.0		WWTP SE	Nearshore reef	Southeast Florida	USA	Lapointe et al. (2005)
> 8.0		Anthropogenic	Nearshore reef	Ishigaki Island	Japan	Umezawa et al. (2002)
> 8.0		WWTP SE	Estuarine	South of Florida Bay	USA	Lapointe et al. (2004)
	> 8.6	SE	N. Broward County	Southeast Florida	USA	Hoch et al. (1995)
8.8 - 12.8	13.5 - 23.5	WWTP SE 2nd	Nearshore reef	Ocean Reef, Beenyup	Australia	Gartner et al. (2002)
9.0		WWTP SE	Estuarine	Pine River Moreton Bay	Australia	Costanzo et al. (2005)
9.3	13.5 - 23.5	Algae grown in 2nd SE	Laboratory Experiment	Ocean Reef, Beenyup	Australia	Gartner et al. (2002)
9.9 - 11.9		Anthropogenic	Estuarine	Warnow System Baltic Sea	Germany	Deutsch and Voss (2006)
11.0 - 12.0		WWTP SE	Estuarine	Buccoo Bay,Tobago	West Indies	Lapointe et al. (2009)
	> 11.8	STE	Tequesta MW #10	Southeast Florida	USA	Lapointe and Krupa (1995b)
12.0 - 15.0		WWTP SE	Estuarine	Caboolture River Moreton Bay	Australia	Pitt et al. (2009)
12.1-18.4		WWTP SE & OSDS	Nearshore reef	Nanakuli, Oahu	USA	Amato et al. (2020)
12.1-18.4		WWTP SE & OSDS	Sandy beach	Waialua, Oahu	USA	Amato et al. (2020)
12.1-18.4		WWTP SE & OSDS	Nearshore reef	Kaaawa, Oahu	USA	Amato et al. (2020)
12.3		STE	Estuarine	Valley Creek Pennsylvania	USA	Steffy and Kilham (2004)
12.6 - 13.5		Anthropogenic	Estuarine	Warnow System Baltic Sea	Germany	Deutsch and Voss (2006)
13.0 - 19.3		WWTP SE	Estuarine	Brisban River Moreton Bay	Australia	Pitt et al. (2009)
13.1 - 14.9		WWTP SE	Nearshore reef	Nanwan	Taiwan	Lin et al. (2007)
13.1-17.5		WWTP SE & OSDS	Sandy beach	Waimanalo, Oahu	USA	Amato et al. (2020)
15.0		WWTP SE	Estuarine	Pine River Moreton Bay	Australia	Pitt et al. (2009)
15.0		WWTP SE	Estuarine	Narragansett Bay Rhode Island	USA	Thornber et al. (2008), Chaves (2004)
	15.3 - 18.0	WWTP SE	Effluent sample	Narragansett Bay Rhode Island	USA	Thornber et al. (2008), Chaves (2004)
16.3 - 19.6		WWTP SE 2nd	Estuarine	Moreton Bay	Australia	Jones et al. (2001)
17.0 - 19.0		WWTP SE	Estuarine	Logan River Moreton Bay	Australia	Pitt et al. (2009)
	> 19.5	STE	Juptier Creek MW #5	Southeast Florida	USA	Lapointe and Krupa (1995a)
22.3		BNR WWTP SE	Basalt	Kahului WWRF, Maui	USA	Dailer et al. (2010)
25.6		Seaweed grown in 20% BNR WWTP SE	Laboratory Experiment	Lahaina WWRF, Maui	USA	Dailer et al. (2012)
25.7		Anthropogenic	Estuarine	Scheldt River, Westerschelde Estuary	The Netherlands	Riera et al. (2000)
30.3		Seaweed grown in 20% BNR WWTP SE	Laboratory Experiment	Lahaina WWRF, Maui	USA	Dailer et al. (2012)
34.7		BNR WWTP SE	Sandy beach	Kahekili Beach Park, Maui	USA	Dailer et al. (2010)
43.3		BNR WWTP SE	Sandy beach	Kahekili Beach Park, Maui	USA	Dailer et al. (2010)
50.1		BNR WWTP SE via freshwater seep	Nearshore reef	Kahekili Beach Park, Maui	USA	Dailer et al. (2010)

SECTION 3 RESULTS: OSDS INVENTORY AND MODELING COASTAL NITROGEN LOADS

3.1 State-wide inventory of wastewater sources and nutrient loads

Table 3 provides the wastewater source nutrient fluxes per island and the state-wide total. Figure 3 shows the state-wide distribution of wastewater derived nutrients to the nearshore waters and the locations of the coastal seaweed sampling swaths. The coastline is color shaded indicating the coastal wastewater-nitrogen flux per meter of shoreline in units of kilograms per meter of shoreline per day (kg/m/d). The color coding represents the following wastewater N-fluxes, with low flux (0.000 – 0.001 kg/m/d) shown in green, moderate flux (0.0011-0.015 kg/m/d) shown in yellow, high flux (0.0151 – 0.0294 kg/m/d) shown in red. The wastewater nutrient sources considered were OSDS and wastewater injection wells (injection well locations are only shown on the specific island maps). The nutrient transport models only consider the wastewater disposal sources of the nutrient. Other significant sources of nutrients include those from agriculture, natural breakdown of organic matter, and potentially rock dissolution if phosphorus containing minerals are present.

The modeled nitrogen flux per meter of shoreline varied from 0.00 kg/m/d where there were no wastewater sources upslope from the coast to 0.29 kg/m/d at the Hilo Bay, Hawaii Island shoreline. Nitrogen flux into the nearshore waters has multiple sources. Therefore, it is informative to look at representative values for naturally occurring and agricultural derived nitrogen flux. To determine the naturally occurring nitrogen flux range, two aquifers were considered. The Pāhoa Aquifer on Hawaiʻi Island representing high recharge aquifers and the Honokōwai Aquifer on Maui representing lower recharge aquifers. Representative naturally occurring groundwater nitrogen concentrations were based on wells with little to no anthropogenic impact within their zone of contribution. The Keonopokonui Well in the Pāhoa Aquifer has a nitrate concentration of 0.2 mg/L (DOH, Drinking Water Compliance Contaminant Database), while the Honokōwai B aquifer in the Honokōwai Aquifer has a nitrate concentration of 0.3 mg/L (Glenn et al., 2012). Assuming that coastal discharge is approximately equal to recharge then specific naturally occurring nitrogen-flux is the product of concentration and recharge divided by the shoreline length of the aquifer. The naturally occurring nitrogen flux is about 0.009 kg/m/d and 0.003 kg/m/d for the Pāhoa and Honokōwai Aquifers respectively.

A wastewater nitrogen flux exceeding 0.005 kg/m/d is a reasonable threshold for beginning to consider anthropogenic contributions to the groundwater nitrate load entering the coastline. This value is indicated by the yellow to red coloring of the coastal nitrogen flux arcs in subsequent figures. Using this criterion about ~25% of the State-wide shorelines receive wastewater nitrogen fluxes that are equal to or exceed the natural nitrogen flux. Agriculture is a major source of anthropogenic nitrate. Barnes et al. (2019) estimated that the coastal nitrogen flux from past sugarcane agriculture operations varied from about 0.015 to 0.05 kg/m/d. Using the approximate average of 0.03 kg/m/d, seven percent of the state-wide coastline has a wastewater flux that is equal to or greater than this representative agricultural value. This state-wide evaluation indicates that the following areas of coastal wastewater nitrogen flux are of significant concern: the northeast coast of Hawaiʻi Island up to Hāmākua, the west side of Hawaiʻi Island from the Natural Energy Laboratory of Hawaiʻi Authority to Hōlualoa, the east portion of central Maui both north and south coastlines, several stretches of coastline on Oʻahu, and the Poʻipū, Nāwiliwili, and Kapaʻa coastlines of Kauaʻi.

Table 3. Inventory of wastewater sources and nutrient loads

	Hawaiʻi	**Maui**	**Oʻahu**	**Kauaʻi**	**State-wide Total**
Inventory					
OSDS discharging to soil treatment	11,900	3,900	2,600	3,100	**21,500**
OSDS discharging to a seepage pit	1,010	630	730	1,400	**3,700**
Cesspools	54,200	11,800	11,400	13,700	**91,100**
Total OSDS	67,100	16,400	14,800	18,100	**116,400**
Injection Wells	130	80	198	85	**493**
Wastewater Effluent Rates (mgd)					
OSDS	19	6.7	6.8	6.6	39
Injection Wells	2.6	10	1.0	1.7	16
Total	**21**	**17**	**7.8**	**8.3**	**55**
Nitrogen Discharge Rates (kg/d)					
OSDS	5,500	1,800	1,954	1,900	11,200
Injection Wells	92	320	110	13	530
Total	5,600	2,200	2,100	1,900	11,700
From Cesspools (Percent)	**89**	**76**	**83**	**86**	**85**
Phosphorus Discharge Rates (kg/d)					
OSDS	1,100	370	410	400	2,300
Injection Wells	47	59	20	2.7	130
Total	1,200	430	430	400	2,400
From Cesspools (Percent)	**93**	**80**	**88**	**89**	**89**

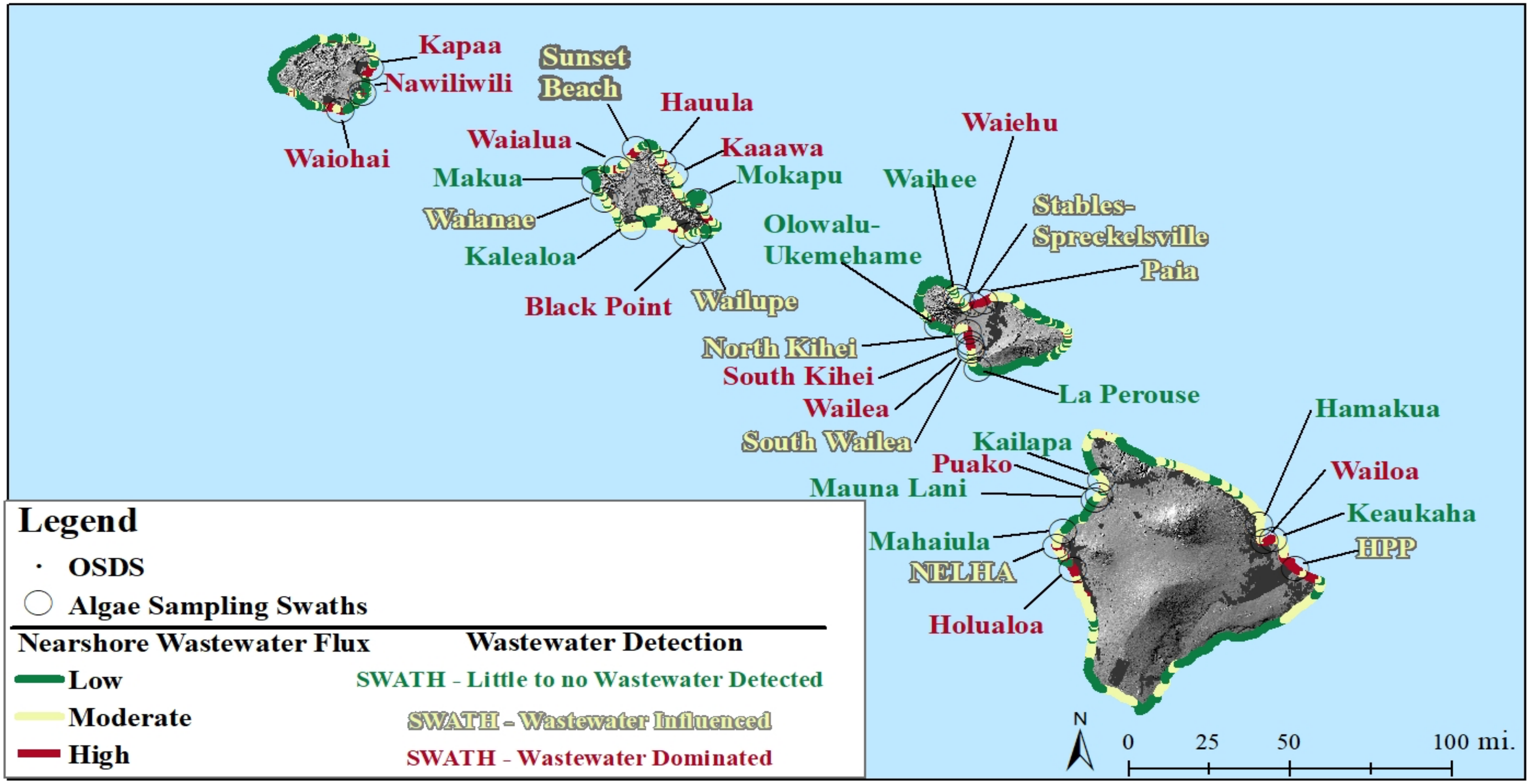


Figure 3. Summary of model results assessing wastewater influence state-wide.
The modeled wastewater N-flux is shown in three color coded ranges with low flux (0.000 – 0.001 kg/m/d) shown in green, moderate flux (0.0011-0.015 kg/m/d) shown in yellow, high flux (0.0151 – 0.0294 kg/m/d) shown in red. Seaweed sampling swaths are shown as circles and the color of their name reflects their wastewater influence category. Individual OSDS units are shown as small black dots. The swath labels are shown in three color coded categories, wastewater dominant (in red), wastewater influenced (in yellow) and little to no wastewater detected (in green). In some places, the OSDS are so numerous that their black dots coalesce to form irregularly shaped, black regions on each island.

3.2 Hawaiʻi Island OSDS inventory and coastal nitrogen loads

The modeling and source review for Hawaiʻi Island indicate over 67,000 OSDS, 138 injection wells, and a municipal seepage pit contribute to the coastal wastewater load. These sources produce a combined total of about 18.8 million gallons per day (mgd) of wastewater effluent of various qualities, for a coastal daily discharge of nearly 5,500 kilograms (kg) of nitrogen and over 1,100 kg of phosphorus to nearshore waters. Nitrogen is the primary nutrient of concern and *cesspools contribute more than 90 percent of the coastal wastewater nitrogen load (Table 3)*. The Hawaiʻi Island coastline was broken down into 220 segments. Except for long segments where there is no wastewater flux (e.g., the Volcanoes National Park coast of Hawaiʻi Island), the lengths ranged from 300 to 3,000 with an average length of 900 meters (Figure 4).

The coastlines with high wastewater nutrient loads were Hilo Bay, Pāhoa (primarily the Hawaiian Paradise Park and upslope agricultural/residential developments), and West Hawaiʻi. Hilo Bay has approximately 17,400 OSDS including about 14,400 cesspools and 18 injection wells, discharging a combined total of 5.4 mgd, 1,570 kg/d of nitrogen and 320 kg/d of phosphorus along ~ 24 miles (mi) of coastline (Figure 4). In the Pāhoa area, there are about 16,400 OSDS including 13,000 cesspools and 28 injection wells discharging a combined total of 4.5 mgd of wastewater, 1,300 kg/d of nitrogen and 263 kg/d of phosphorus along ~14 mi of coastline. In West Hawaiʻi, from the Natural Energy Laboratory of Hawaiʻi Authority (NELHA) to Kealakekua Bay there are about 12,100 OSDS including 9,700 cesspools, 31 injection wells and one municipal seepage pit, discharging a combined total of 5.6 mgd of wastewater, 1,100 kg/d of nitrogen, 260 kg/d of phosphorus along about 38 mi of coastline.

The Hilo Bay and Pāhoa are areas of high coastal groundwater discharge due to the high rainfall and groundwater recharge rates on the windward facing slopes of the island (Engott, 2011). So, while the nitrogen flux is very high, the groundwater concentrations are very low about 0.2 to 1.5 mg/L (DOH contaminant data base, HPP investigation). The Pāhoa area has the advantage of also having a high wave energy coastline that may mitigate the impact of coastal nutrient loading due to a high mixing rate with low nutrient groundwater. West Hawaiʻi on the other hand has a much lower groundwater discharge rate because West Hawaiʻi is located on the leeward, drier side of the island. This will result in higher groundwater nutrient concentrations discharging along the shoreline. The higher groundwater nutrient concentrations are further compounded by a quiet coastline because the coastal wave energy is much lower compared to that of Pāhoa, resulting in a slower dilution and mixing with low nutrient seawater. The risk for Hilo Bay is intermediate between Pāhoa and West Hawaiʻi. A large volume of groundwater recharge in east Hawaiʻi dilutes the nitrogen concentration. However, the nitrogen mass flux is still large, greater than 0.1 kg of nitrogen per meter of shoreline per day (kg/m/d). Compounding the large mass flux, is that much of the bay is sheltered from wave energy by the harbor breakwater. The lower wave energy reduces the mixing of the terrestrial derived wastewater high nutrient water with low nutrient ocean water.

While the Hilo Bay, Pāhoa, and West Hawaiʻi coastlines are regional areas of the highest wastewater input category for this island, there are several localized areas of concern. These include: Puakō, Kawaihae and south to Hāpuna Beach, Kohala, Honokaʻa, and Laupāhoʻehoʻe (Figure 4). Kohala, Honokaʻa, and Laupāhoʻehoʻe are all small communities on the northeast side of Hawaiʻi Island and are located within five miles of the shoreline. Most of the shoreline impact is moderate (0.005 to 0.015 kg/m/d) with some short segments of coastline exceeding this value.

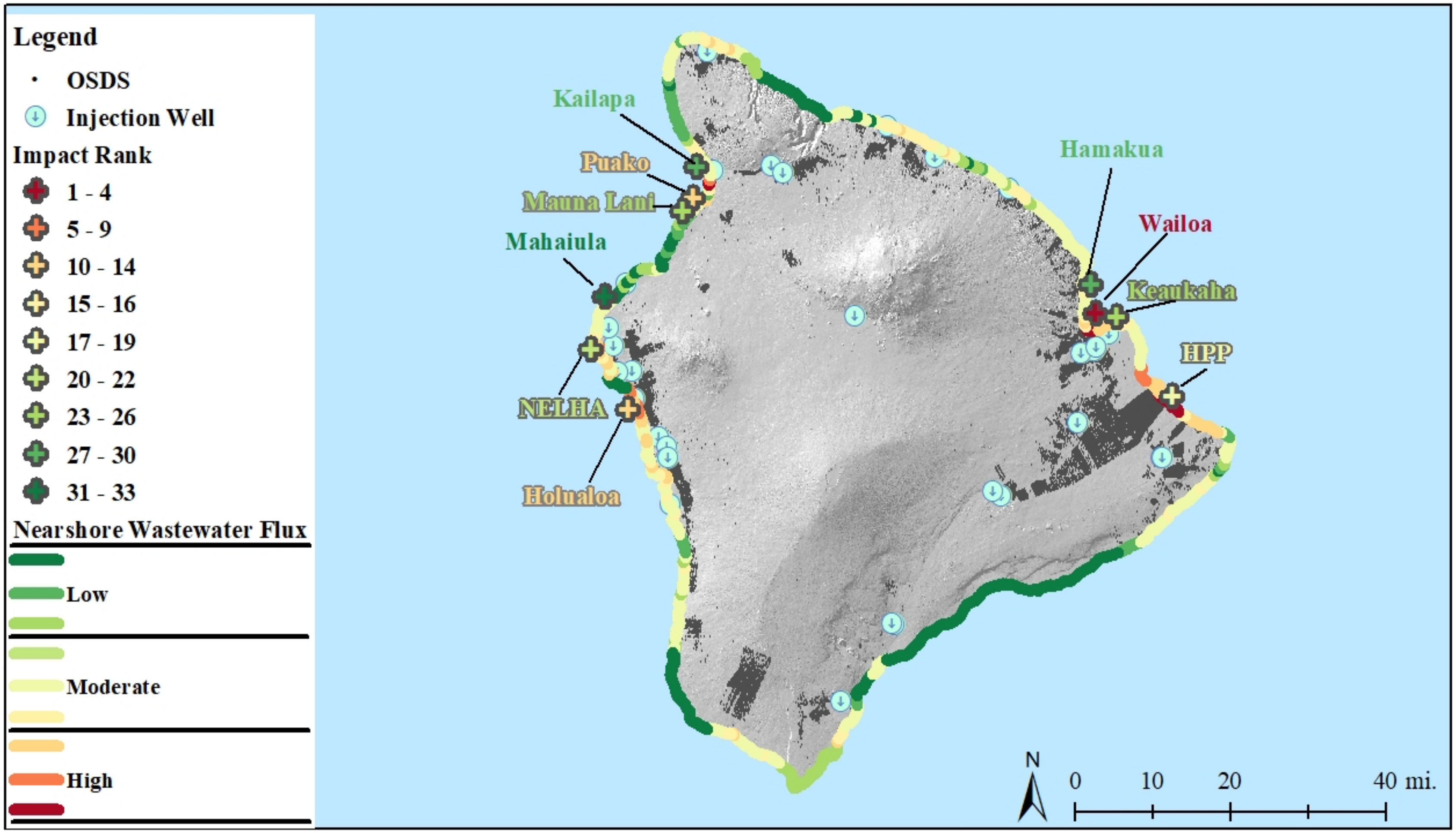


Figure 4. Hawai‘i Island map displays modeled coastal wastewater nitrogen fluxes and ranked seaweed $\delta^{15}N$ values from this state-wide assessment.

3.3 Maui OSDS inventory and coastal nitrogen loads

The modeling and wastewater source review for Maui indicate that over 16,000 OSDS, and 80 injection wells, which includes three municipal wastewater injection well fields, make up the wastewater source load for Maui. The total number of OSDS is less than previously documented (Whittier and El-Kadi, 2014). Barnes et al. (2019) identified areas previously thought to host OSDS that are served by a centralized sewage collection system. The revised estimate of wastewater discharging to Maui's nearshore waters is about 17.1 million gallons per day (mgd), with a coastal daily discharge of nearly 2,160 kilograms (kg) of nitrogen and over 427 kg of phosphorus to nearshore waters. Nitrogen is the primary nutrient of concern and on *Maui cesspools contribute about 76 percent of coastal wastewater nitrogen load (Table 3).* The Maui coastline was broken down into 262 segments. Except for long segments where there is no wastewater flux (e.g., the south coast of East Maui), segment lengths ranged from 220 to 4,000 with an average length of 1000 meters.

Shorelines of Maui with wastewater nitrogen fluxes greater than 0.05 kg/m/d include the eastern shore of the north isthmus coastline, Māʻalaea, North Kīhei, South Kīhei, and Wailea (Figure 5). The source of wastewater nitrate discharging along the eastern shore of the north isthmus is wastewater injection at the Kahului Wastewater Treatment Plant and the large number of OSDS upslope on the west flank of Haleakalā. The plume area for the Kahului Wastewater Treatment Plant injection was not assessed by this study but previous studies have shown elevated $\delta^{15}N$ values and percent nitrogen in the coastal seaweed (seaweed $\delta^{15}N$ = 22.27‰ Dailer et al., 2010; Amato et al., 2016). This study did survey the Spreckelsville area east of the municipal injectate wastewater plume.

Other coastlines of Maui where the modeling indicates elevated wastewater nitrogen flux include a short span of coastline in Kāʻanapali, downslope of the Launiupoko community in West Maui, and the Waiehu and Waiheʻe areas west north-central Maui (Figure 5). The short span of the Kāʻanapali coastline is impacted by the municipal injection of treated wastewater. The impact of nitrogen is mitigated somewhat by denitrification; however, the injected phosphorus appears to enter the coastal waters with little if any attenuation (Fackrell et al., 2016). Launiupoko is a small community that is dependent on OSDS for wastewater disposal. A previous study has documented the detection of wastewater leachate from the Launiupoko subdivision in the adjacent coastal waters through seaweed $\delta^{15}N$ values of 5.77 ‰ or wastewater influenced (Dailer et al., 2010). The Waiehu and Waiheʻe areas of west north-central Maui, also have small communities that discharge residential wastewater to OSDS. Much of the Waiehu area has sewer service, yet both the modeling and the coastal seaweed data indicated spans of coastline where there is a significant wastewater contribution to the coastal nitrogen load.

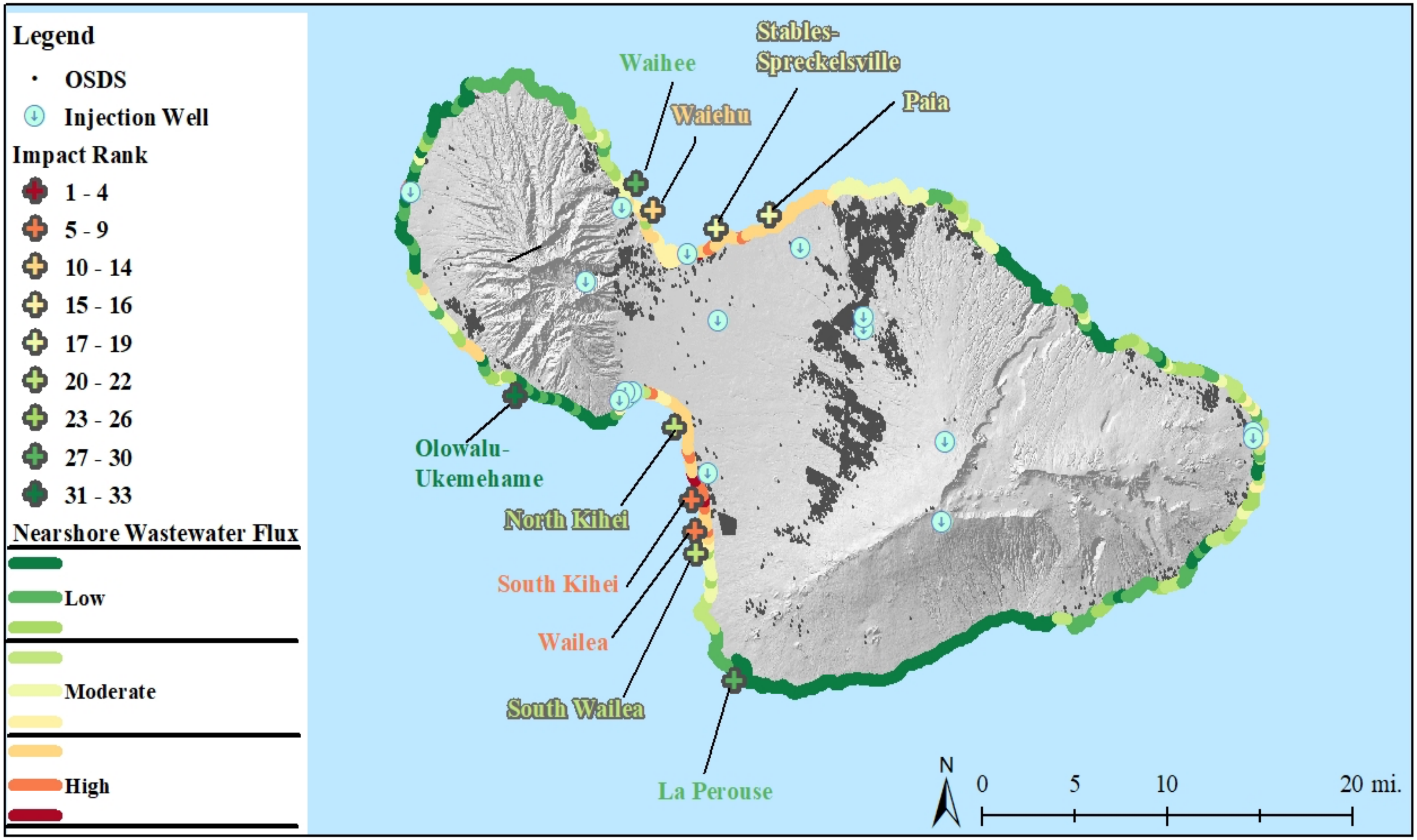


Figure 5. Maui map of the modeled coastal wastewater nitrogen fluxes and ranked seaweed $\delta^{15}N$ values from the state-wide assessment.

3.4 O‘ahu OSDS inventory and coastal nitrogen loads

The modeling and wastewater source review for O‘ahu indicate that nearly 14,800 OSDS, and 198 wastewater injection wells, which includes two municipal wastewater injection well fields, make up the wastewater source load for this island. The revised estimate of wastewater discharging to O‘ahu's nearshore waters is about 7.8 million gallons per day (mgd), with a coastal daily discharge of 2,060 kg of nitrogen and over 425 kg of phosphorus to nearshore waters. Nitrogen is the primary nutrient of concern and on *O‘ahu cesspools contribute about 83 percent of coastal wastewater nitrogen load (Table 3)*. To evaluate the spatial distribution of coastal wastewater impact, the O‘ahu coastline was broken down into 336 segments. Except for long segments along the urbanized coast of Pearl Harbor and the airport area where there is little wastewater flux, the segment lengths ranged from 232 to 4,000 with an average length of 900 meters (Figure 6).

A nitrogen flux of 0.015 kg/m/d has been previously described as a representative coastal nitrogen loading rate resulting from industrial scale agriculture. Of O‘ahu's total coastline length of 362 km, over a quarter or 97 km are subjected to a wastewater flux equal to greater than the representative value from industrial agriculture. The wastewater impacted areas include the north shore from Waialua to Sunset Beach, the windward side from Kahuku to Kahalu‘u, Waimānalo, much of the urban Honolulu coastline, and southwest O‘ahu from ‘Ewa to and including Kalaeloa (Figure 6).

Nitrogen transport modeling identified seven areas on O‘ahu where the impacted coastline length was greater than 1,000m, and the wastewater nitrogen flux is equal to or greater than 0.015 kg/d/m (Table 3). These areas are ‘Ewa, Waialua, Pūpūkea to Sunset Beach, Hau‘ula to Punalu‘u, Ka‘a‘awa, Kahalu‘u, Waimānalo, and Wai‘anae (Figure 6). Nearshore seaweed samples were collected for all of these swaths of wastewater dominated areas except for Kahalu‘u (1 site in an otherwise muddy swath with no algae) and Waimānalo (previously reported by Amato et al., 2020). Kahalu‘u has been extensively study by the University of Hawai‘i (Dores et al., 2018; Mathioudakis et al., 2018, CM Smith unpublished data) as has been Waimānalo (Amato et al., 2020).

The segment with the highest modeled shoreline nitrogen load is a community in ‘Ewa that this study confirmed is not served by sewer service has the largest modeled shoreline wastewater load (this community is denoted by the black circle in Figure 6). There are about 1,040 OSDS, of which 930 are cesspools, that elevate the wastewater nitrogen load to 0.069 kg/d/m across a 1,800m length of shoreline (Figure 6). Waialua has the second largest modeled shoreline wastewater nitrogen load with over 1,200 OSDS and 30 wastewater injection wells producing coastal nitrogen load of 0.058 kg/d/m across a 3.5 km length of shoreline. This coastline is also impacted by industrial scale agriculture, with this reflected in the elevated seaweed percent nitrogen of 2% while seaweeds from low nitrogen loading areas have %N values closer to 1%. Along a 3.6 km reach of shoreline from Hau‘ula to Punalu‘u, about 715 OSDS (of which about 480 are cesspools) and a wastewater injection well discharge about 0.024 kg/d/m of nitrogen and 0.005 kg/d/m of phosphorus to the nearshore environment. OSDS located from Pūpūkea to Sunset Beach; and at Ka‘a‘awa, Kahalu‘u, and Waimānalo also have the OSDS located on the coastal plain, which results in the wastewater contaminated groundwater being discharged near the coast.

There are three additional areas with small clusters of OSDS that result in elevated wastewater nitrogen flux to the coast. These small cluster areas are Diamond Head (Black Point), the east side of the Mōkapu Peninsula isthmus, and Nānākuli. The urban Honolulu waterfront area has segments where the modeling indicates significantly elevated wastewater nitrogen flux from OSDS serving residences upslope of the sewer coverage. The actual wastewater nitrogen discharge areas for these upslope OSDS are very uncertain due to the large number of municipal pumping wells and OSDS are generally located 3 to 6 km from the coastal discharge areas. Regardless of where the contaminated wastewater discharges at the coast, the inventory of wastewater sources discharging to the groundwater, results in problematic wastewater nitrogen fluxes to the marine environment.

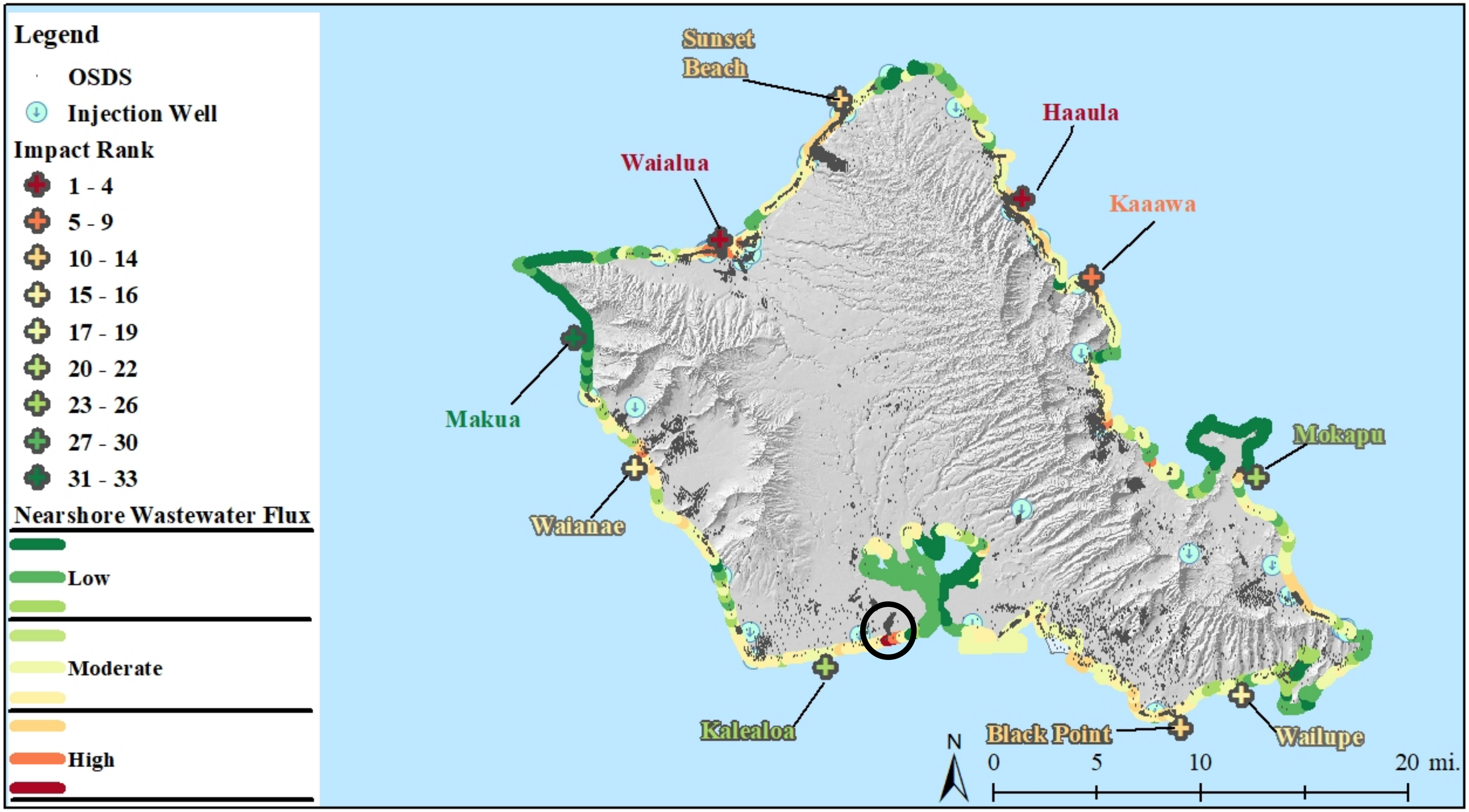


Figure 6. O‘ahu map of the modeled coastal wastewater nitrogen fluxes and ranked seaweed $\delta^{15}N$ values from the state-wide assessment.

The black circle close to Kalealoa surrounds the highest predicted wastewater nitrogen flux for O‘ahu.

3.5 Kauaʻi OSDS inventory and coastal nitrogen loads

The modeling and wastewater source review for Kauaʻi indicate that 18,000 OSDS, and 85 wastewater injection wells, make up the wastewater source load for this island. The revised estimate of wastewater discharging to Kauaʻi's nearshore waters is about 8.3 million gallons per day (mgd), with a coastal daily discharge of 1,900 kg of nitrogen and 400 kg of phosphorus to nearshore waters. Nitrogen is the primary nutrient of concern and *on Kauaʻi cesspools contribute about 86 percent of coastal wastewater nutrient load (Table 3)*. The Kauaʻi coastline was broken down into 328 segments. Except for long segments along the south and west coasts, where there is very little inland development, the lengths of the segments ranged from 200 to 2,400 with an average length of 440 meters (Figure 7).

Areas where the modeled coastal wastewater nitrogen flux exceeds 0.015 kg/d per meter of shoreline are Kāpaʻa, Kīlauea, Hanapēpē, Koloa, Poʻipū, Kekaha, Nāwiliwili, and Hanalei (Figure 7). Kāpaʻa (from Kealia to Wailua River) is the only area subjected to a wastewater nitrogen flux of 0.085 kg/d/m of shoreline over a shoreline length of 8.2 km. Kīlauea (including the eastern side of Kalihiwai Bay through Kauapea Beach and Kīlauea Point and ending at Kahili Quarry Beach) approaches the threshold of elevated wastewater with the simulated wastewater nitrogen flux of 0.048 kg/d/m over a shoreline length of 1.8 km, based on model outputs (Figure 7).

By total mass of wastewater nitrogen discharged to the nearshore environment, Kāpaʻa has the highest nitrogen load. Inland of the Kāpaʻa coastline the nearly 6,600 OSDS, including 5,300 cesspools, discharge a total of about 700 kg of nitrogen to the coastline (Figure 7). The modeling also indicates that wastewater nitrogen enrichment of the Wailuā River should be a concern. Finally, the hydrogeology of Lihuʻe Basin where Kāpaʻa is located is very complex with dense massive lavas and sediments overlying dike intruded basalts (Izuka and Gingerich, 1998; Izuka et al., 2018). Differences between the modeled and measured wastewater signal should be expected.

At Nāwiliwili and Poʻipū, the model indicated wastewater enrichment of the groundwater discharging to the marine environment. The model also predicted that smaller segments of the coastline at Waimea, Hāʻena, and Anahola would also have an elevated concentration of wastewater nitrogen in the coastal groundwater flux. However, the modeled fluxes of these smaller segments, while elevated relative to the rest of Kauaʻi, were below the 0.015 kg/d per meter of shoreline threshold that we considered as a level of concern for this study. Hāʻena is located along a segment of shoreline where the model indicated an overall low wastewater nitrogen flux (Figure 7).

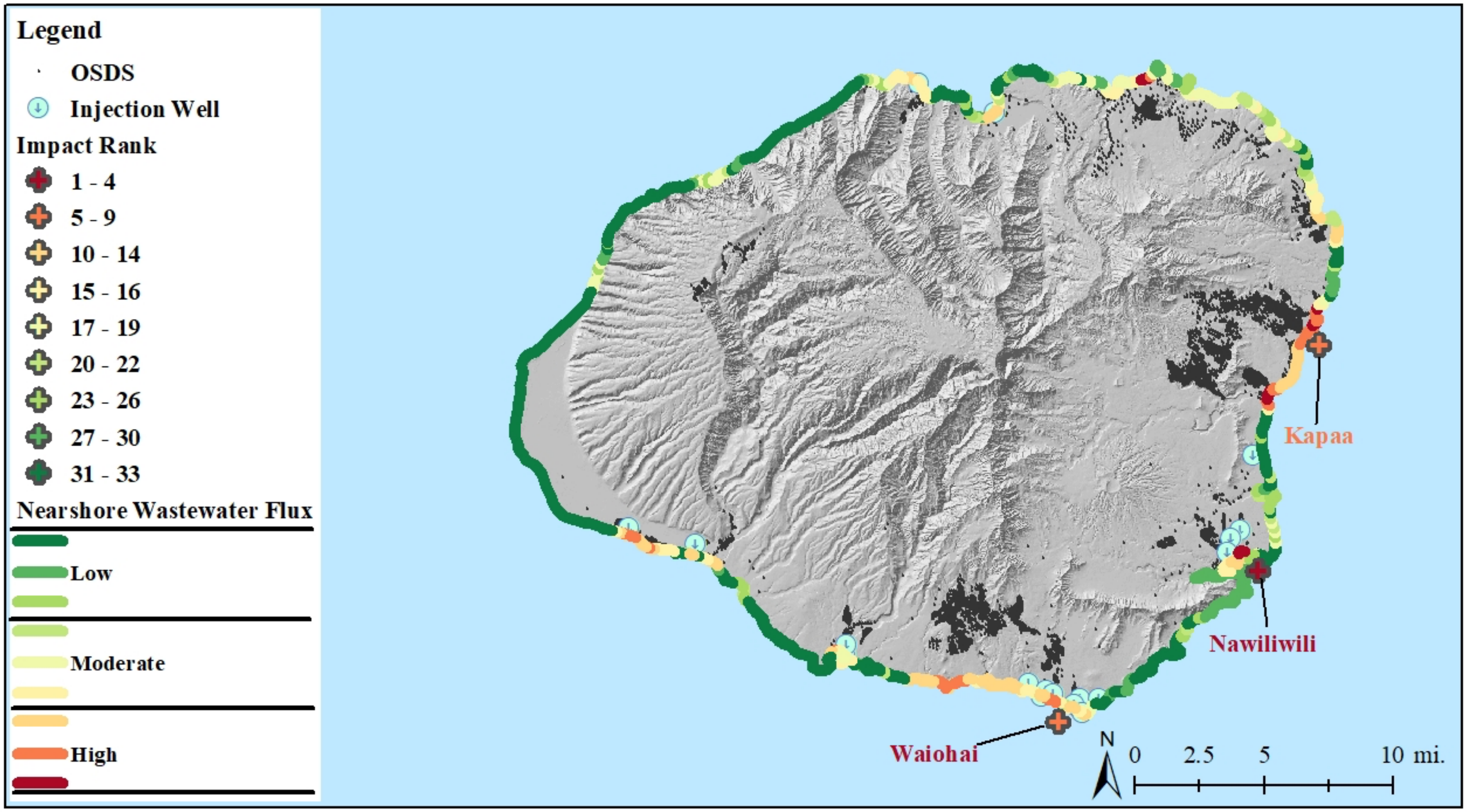
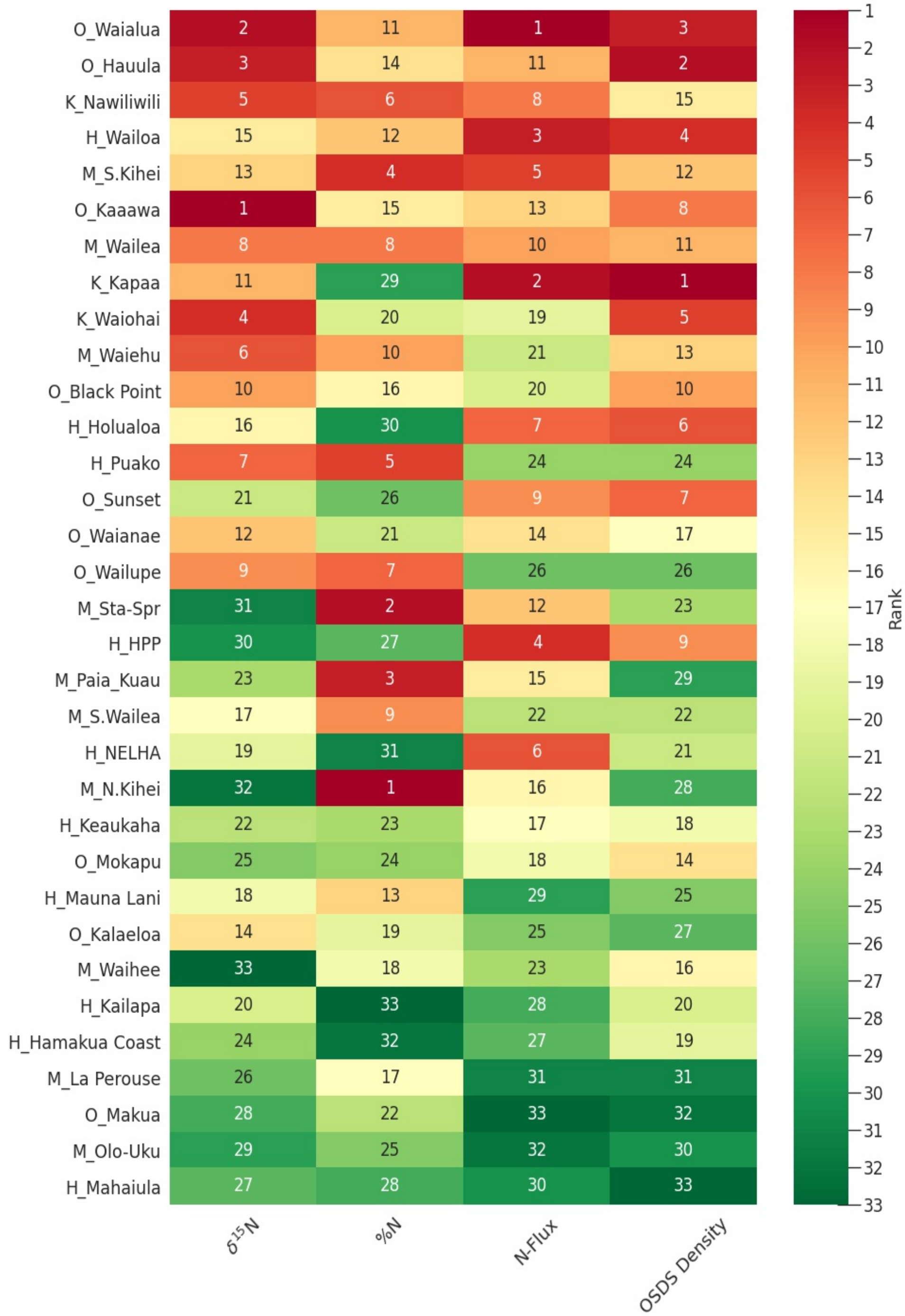


Figure 7. Kaua'i map of the modeled coastal wastewater nitrogen fluxes and ranked seaweed $\delta^{15}N$ values from the state-wide assessment.

SECTION 4 RESULTS: WASTEWATER DETECTION IN COASTAL AREAS

This state-wide ranking includes all sampled swaths under consideration for wastewater influence across four islands and four wastewater indicator paramenters. In this ranking, number 1 has the greatest extent of wastewater detection and number 33 has the lowest wastewater detection (Figure 8).



The colums include the seaweed $\delta^{15}N$ values, seaweed %N values, wastewater N-flux, and OSDS density. Swaths appear as rows, ranked in order from the most wastewater detected or modeled too little to no wastewater detected or modeled. The first letter of the swath name indicates the island where the swath was located (K=

Figure 8. State-wide ranking of wastewater indicators organized by swath.

Kaua‘i, O= O‘ahu, M= Maui, H= Hawai‘i). The state-wide wastewater rank includes all swaths (Figure 8) and allows for quick inspection of all data sets and the internal ranking for all swaths.

Two of the abovementioned wastewater indicator parameters were chosen for additional regression analyses, seaweed $\delta^{15}N$ values and OSDS density. Of the various functions that were used to fit the relationship between $\delta^{15}N$ and OSDS density, the linear model, hyperbolic tangent, and log functions all generally provided a poor fit to the data, with relatively lower coefficients of correlation or assuming a shape that did not fully describe the variance in the data. Both the arctan function and Michaelis-Menten function provided strong fits to the data, consistent with observations that the relationship between seaweed $\delta^{15}N$ values and OSDS density was both nonlinear and saturating. This is consistent with predictions of seaweed physiology, as physiological constraints likely limit nitrogen acquisition by the seaweed despite increasing environmental nitrogen due to sources like OSDS (Dailer et al., 2012). Thus, one would expect a saturating function to best describe the relationship between seaweed $\delta^{15}N$ values and OSDS density. While the arctan function (r = 0.47, AICc = 1670) described the combined-island data slightly better than the Michaelis-Menten function (r = 0.45, AICc = 1692), the Michaelis-Menten function provided the best fit for the data on Maui, Hawaii, and Kauai individually. Thus, the Michaelis-Menten function was used to describe the data overall (Figure 9).

Based on this function, areas with very low OSDS density will have low seaweed $\delta^{15}N$ values and as the OSDS density increases the seaweed $\delta^{15}N$ values will increase indicating the presence of wastewater at the coastline (Figure 9). The best-fit parameter values that describe this relationship allow for a mathematical basis for judgments on the relative impacts of wastewater on coastal regions. Sites were designated as wastewater dominated if they had an average seaweed $\delta^{15}N$ value greater than or equal to the lower 95% confidence interval of the saturation point estimated through non-linear least squares (seaweed $\delta^{15}N > 6‰$). Sites were designated as wastewater influenced if they had average seaweed $\delta^{15}N$ values between the lower 95% confidence interval of the estimated asymptotic value and 66% of the lower 95% confidence interval of the estimated asymptotic value (seaweed $\delta^{15}N$ values from 4 to 6‰). Swaths were designated as low impact if they had and average seaweed $\delta^{15}N$ values below 66% of the of the lower 95% confidence interval of the estimated asymptotic value $\delta^{15}N < 4‰$). Following this method, nine sites were designated as wastewater dominated (4 from O‘ahu, 2 from Kaua‘i, 2 from Maui, and 1 from Hawai‘i Island), 11 sites were designated as wastewater influenced (3 from O‘ahu, 1 from Kaua‘i, 2 from Maui, and 5 from Hawai;i), and 13 sites were designated as little to no wastewater detected (3 from O‘ahu, 0 from Kaua‘i, 6 from Maui, and 4 from Hawai‘i). Site designations were confirmed as statistically distinct from each other (LMME, F(2, 28.927) = 69.07, P = 9.659e-12).

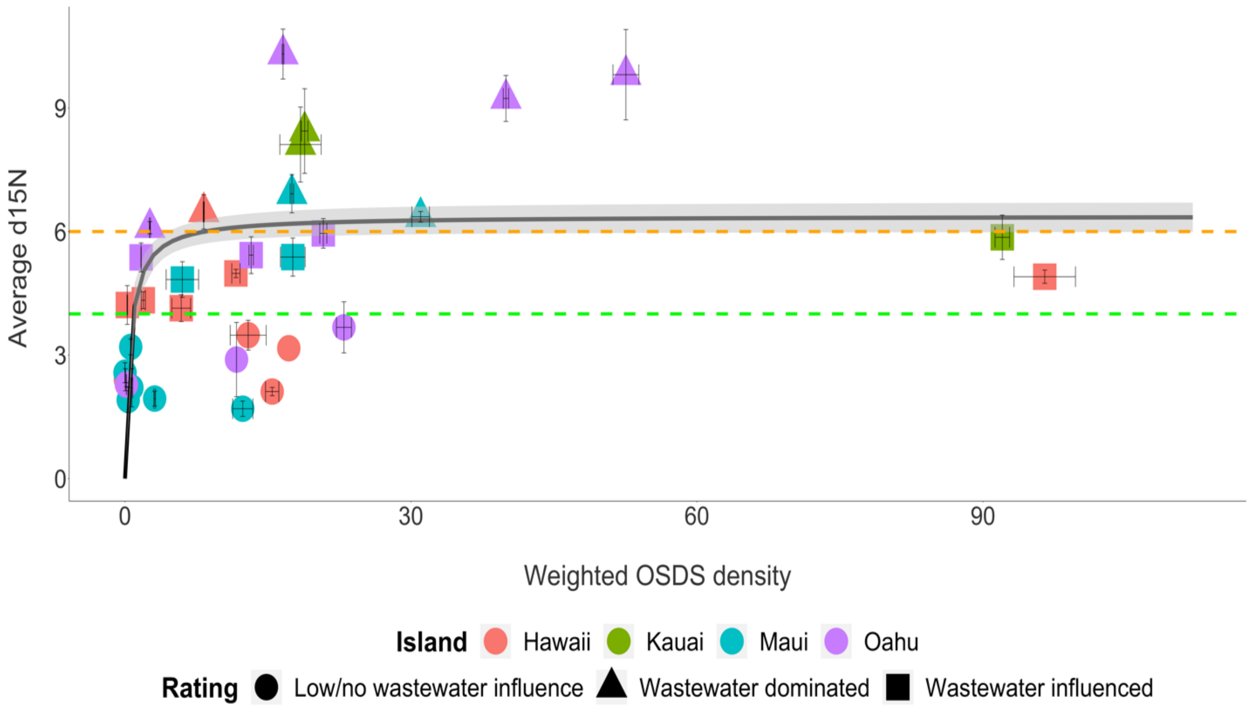


Figure 9. Mean seaweed $\delta^{15}N$ values plotted as a function of modeled OSDS density.

The relationship between OSDS density and seaweed $\delta^{15}N$ values was evaluated with the Michaelis-Menten function with best-fit parameters derived from non-linear least squares (a = 6.3761 (95% CI = (6.0009, 6.7694), p <2E-16); b = 0.5231 (95% CI = (0.2990, 0.8612), P = 1.69e-05). The shaded area was constructed from 95% Confidence Intervals (CI) of the estimated parameters. Points represent the mean seaweed $\delta^{15}N$ values for a given swath, with vertical error bars representing Standard Error (SE) of seaweed $\delta^{15}N$ values and horizontal error bars representing SE of OSDS density. Color represents island (red = Hawai‘i Island, green = Kaua‘i, blue = Maui, purple = O‘ahu) and shape represents wastewater influence designation (circle = wastewater dominant, square = wastewater influenced, triangle = little to no wastewater detected).

While our initial analysis of these data averaged all values across a swath, we also saw a benefit in highlighting other aspects of our data, including the highest single seaweed $\delta^{15}N$ and %N values among all swaths for each island. These data are highlighted because they likely indicate that significant wastewater intrusion is occurring along that coastline. Further, the highest values may represent the central region of a wastewater plume as it discharges to the coast, a useful perspective for fine scale understanding of N-input sources and loads. This approach takes us beyond the simple detection of wastewater input and has clarified a number of features we will present and highlight in the discussion.

4.1 Analysis of seaweed data from coastal regions on O‘ahu

4.1.1 O‘ahu coastal seaweed collection for $\delta^{15}N$ and %N values

On O‘ahu coastal waters, cesspools are predicted to contribute 83 percent of coastal wastewater nutrient load (Table 3, above). Thus, ten swaths on O‘ahu were sampled to detect wastewater via sampling seaweed $\delta^{15}N$ values and %N from April to August 2019, the drier months in terms of rainfall (Giambelluca et al., 2013, Rainfall Atlas of Hawai‘i). 127 sets of triplicate samples (a total of 381 seaweed samples) were collected across the south, windward, north and west facing shores of the island. Based on model predictions, swaths were initially categorized into those with little expected wastewater and those where model predicitions lead to subtantial wastewater detection.

4.1.2 O‘ahu seaweed nitrogen results

The two seaweed parameters reported here ($\delta^{15}N$ and %N) can be used to suggest the nitrogen source and amount of nitrogen loading, respectively. As shown above in Figure 9, seaweed $\delta^{15}N$ values of $\geq$ 6‰ indicate wastewater as the dominant nitrogen source and %N indicative of excessive coastal nitrogen loading (Barr et al., 2013).

Sixty-seven discrete seaweed samples had $\delta^{15}N$ values equal to or greater than 6‰. Swath averages at or above the 6.0‰ statewide cut-off designating wastewater-dominated sites were: Hau‘ula, Ka‘a‘awa, Waialua and Wailupe. Single site sampling at the Kahalu‘u boat ramp also recorded replicate values above 6.0‰. Additionally, other swaths with wastewater influence detected on O‘ahu were Black Point, Kalaeloa, Sunset, Mōkapu, and Wai‘anae. Table 4 provides an overview of data to be discussed in this section.

Table 4. O‘ahu- variations in coastal seaweed samples for swath average, maximum and ranges of $\delta^{15}N$ and %N values.

Location	Swath ave $\delta^{15}N$	$\delta^{15}N$ SD	Swath ave %N	%N SD	Swath Max $\delta^{15}N$, n=3	Swath Max %N, n=3	Swath $\delta^{15}N$ (SD) samples range, n=3: low	high	Swath %N (SD) samples range, n=3: low	high
Black Point	5.96	1.44	1.80	0.12	9.8	2.9	4.47 (0.21)	9.8 (0.10)	1.34 (0.09)	2.95 (0.38)
Hau‘ula	9.23	1.58	1.85	0.32	12.2	2.5	7.10 (0.10)	12.2 (0.61)	1.58 (0.08)	2.52 (0.09)
Ka‘a‘awa	10.3	2.71	1.84	0.29	16.2	2.6	5.77 (0.29)	16.2 (0.15)	1.35 (0.15)	2.58 (0.27)
Kahalu‘u					>6	~ 1.9				
Kalaeloa	5.37	1.11	1.52	0.32	7.6	2.1	3.80 (0.20)	7.60 (0.53)	1.16 (0.13)	2.13 (0.04)
Makua	2.29	0.13	1.44	0.12	2.5	1.6	2.10 (0.10)	2.50 (0.10)	1.25 (0.10)	1.63 (0.15)
Mokapu	2.89	2.55	1.41	0.30	8.9	1.9	1.30 (0.18)	8.93 (0.45)	0.92 (0.06)	1.90 (0.12)
Sunset	3.67	1.86	1.29	0.26	7.2	1.8	1.50 (0.15)	7.23 (0.31)	0.91 (0.05)	1.77 (0.00)
Waialua	9.81	4.39	2.04	0.50	15.7	2.7	4.30 (0.10)	15.7 (0.46)	1.30 (0.17)	2.72 (0.35)
Wailupe	6.09	0.61	2.55	0.36	7.3	3.1	4.90 (0.50)	7.30 (1.14)	2.22 (0.10)	3.14 (0.33)
Wai‘anae	5.43	1.84	1.46	0.41	8.3	2.4	2.40 (0.44)	8.27 (0.38)	0.94 (0.04)	2.43 (0.23)

4.1.3 O‘ahu average seaweed δ15N values

The variation in seaweed $\delta^{15}N$ values among swaths are presented in Figure 10 where average values for individual collection sites are shown as black dots for each swath. The highest seaweed $\delta^{15}N$ values ranging from 16.2 to 12.2‰ were found at Ka‘a‘awa, Waialua, Hau‘ula and Wailupe, sites which ultimately met the definition of wastewater dominanted. Other sites Black Point, Kahalu‘u, Wai‘anae and Kalaeloa had individual averages for seaweed $\delta^{15}N$ values well above 6.0‰ but their swath average values fell below 6.0‰, and were placed into the wastewater influenced category. Additional swaths with individual seaweed $\delta^{15}N$ values $\geq$ 6‰ included Sunset Beach with highest values over 7‰, suggesting mixed inputs did occur. For that swath average however, Sunset Beach, as well as Makua and Mokapu fell below 4‰, with limited wastewater input. Average seaweed $\delta^{15}N$ values differed significantly between sites on O‘ahu (ANOVA, $F(9,118) = 18.1$, $P < 2E-16$).

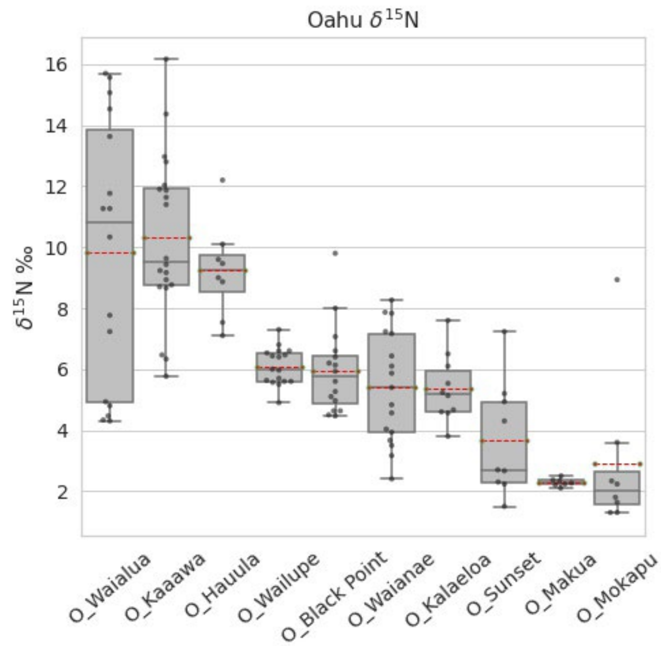


Figure 10. O‘ahu variation among swaths for average seaweed δ15N values. Red dashed lines indicate the swath-wide mean, while the black lines at the mid-point of boxes indicate median values. Boxes represent the inter-quartile range of data. Results for Kahalu‘u are in Table 4.

The highest swath average seaweed $\delta^{15}N$ values include, Ka‘a‘awa, Waialua, and Hau‘ula, which had swath average values ranging from 9.2 to 10.3‰ (Table 4) fall in the wastewater dominated category. Wailupe and Black Point sampling yielded swath averages for seaweed $\delta^{15}N$ values ranging from 6.1 to 5.9‰, indicating significant wastewater intrusion was detected. Swaths in the wastewater influenced category with seaweed $\delta^{15}N$ values greater 4 but less than 6‰ included: Wai‘anae and Kalaeloa at 5.4‰. Sites considered to have little to no wastewater are: Sunset Beach at 3.6‰, Makua at 1.44% and Mokapu at 2.9‰.

Please note: The data reported in Table 4 include Kahalu‘u and Waiahole sites are single locations with individual collection site averages, n=3 of over 6‰ at the Beach Park / boat ramp and tidal collections at Waiahole. More collections could not be made more broadly on this swath because mud covered most of the substrate resulting in a lack of seaweed to collect. Similar limited collections have been made at Waiahole and Ka‘elaea areas with elevated seaweed $\delta^{15}N$ values. Additionally, the coastal north end of Kāne‘ohe Bay has been recently studied by two Master of Science Theses under Dr. Craig Glenn in addition to two contemporary unpublished studies of the invasive seaweed in this region (CM Smith unpublished data).

4.1.4 O‘ahu geographic variability of seaweed δ^{15}N values

The variability in seaweed δ^{15}N values across a given swath illustrates the ability of this method to detect wastewater nitrogen at a fine scale and suggest that averaging across all samples may disguise sites with higher individual values. For example, the averages for seven of 15 samples in the Black Point swath ranged from 6.13 to 9.8‰, while the averages of the other eight were under 6‰ (Figure 17). The swath average was lower overall, just under 6‰ when significantly higher values were detected, mid-swath. In contrast, Wailupe had 10 sites where wastewater nitrogen was detected out of a total of 17 sites (Figure 18). The average seaweed δ^{15}N value of this swath is higher than that of Black Point, yet the single highest value for Wailupe is 7.3‰, more than 2‰ lower than the midpoint for the Black Point swath (Table 4).

Differences between maximum and minimum values were relatively large for nearly half of the swaths. Particularly high variability within a swath may be a result of physical variables or geographic boundaries that exist within the swath. For example, the Waialua swath had much lower δ ^{15}N values, which were found in the eastern region near a river that bisected the swath (Figures 13 and 14). In contrast to large differences observed between sites in a given swath, the average difference among triplicate samples from the same site was <1‰. Figures 11 through 21 show the predicted coastal wastewater N-flux, the average seaweed δ^{15}N values per site and the nearby OSDS for all of the experimental and control swaths on O‘ahu.

Figure 11**. O‘ahu- Sunset Beach experimental swath.**
The Sunset Beach experimental swath shows low seaweed δ^{15}N values (with the exception of one site), moderate predicted wastewater nitrogen flux to the coastline and dense OSDS inland from the swath.

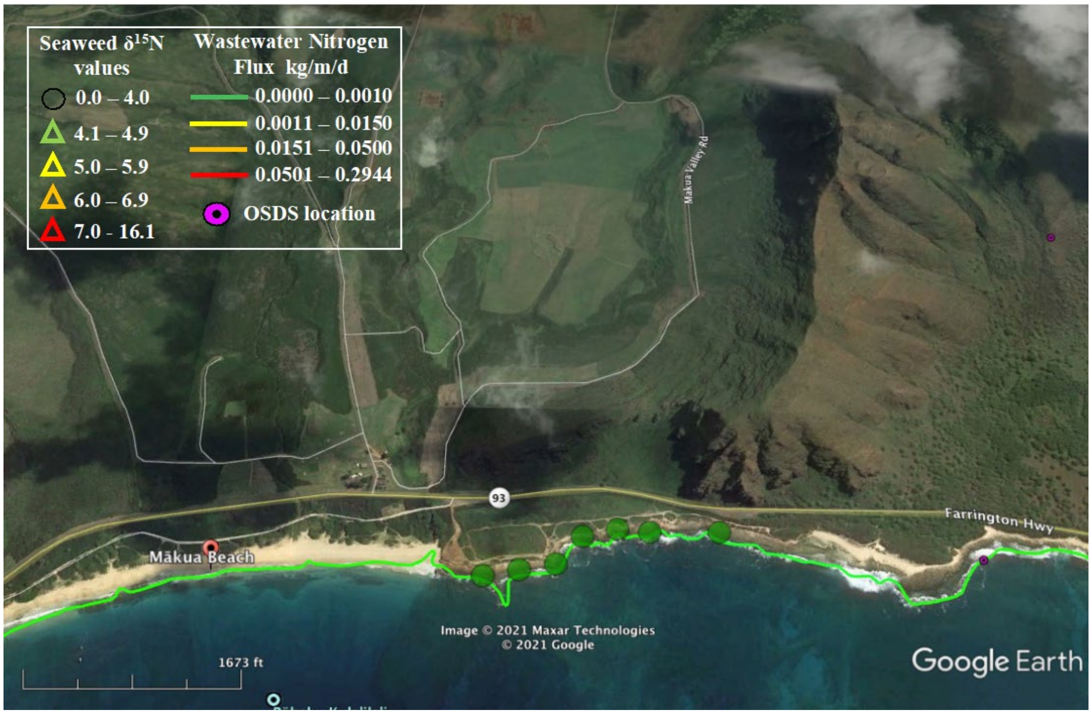


Figure 12**. O'ahu- Makua control swath.**
The Makua control swath shows low seaweed $\delta^{15}N$ values, low predicted wastewater nitrogen flux to the coastline and no OSDS inland from the swath.

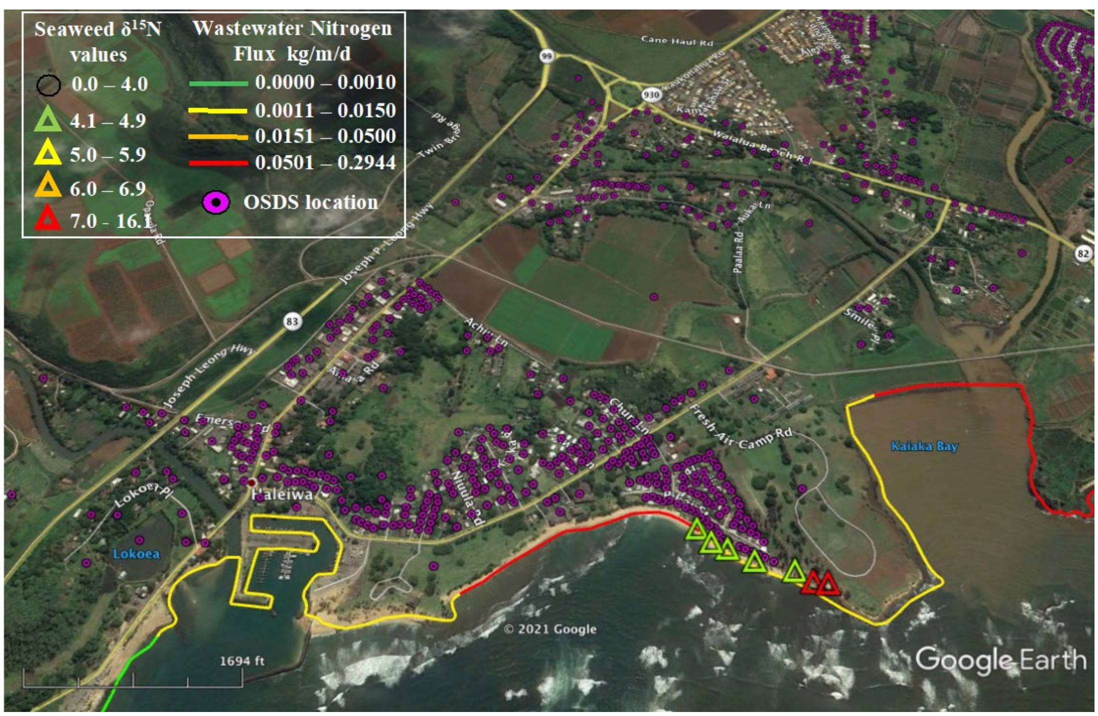


Figure 13**. O'ahu- Waialua (east) experimental swath.**
The eastern side of the Waialua experimental swath shows correspondence between high seaweed $\delta^{15}N$ values and high predicted wastewater nitrogen flux to the coastline, particularly in the region of dense OSDS near shore.

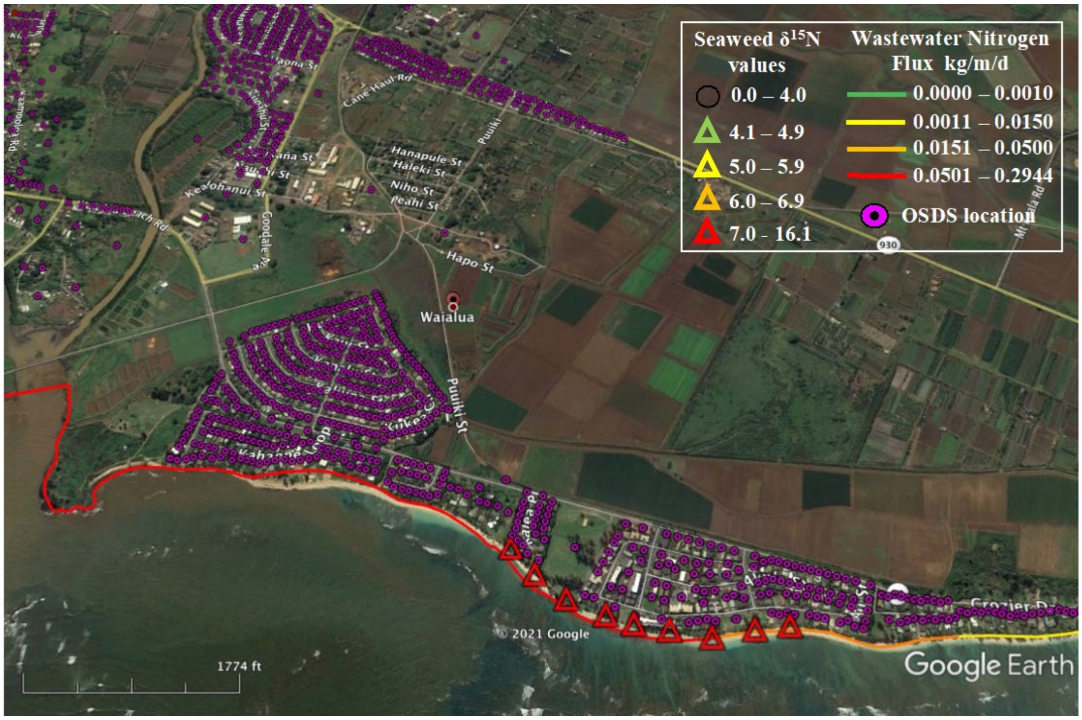


Figure 14. O'ahu- Waialua (west) experimental swath.
The western side of the Waialua experimental swath shows high seaweed $\delta^{15}N$ values, high predicted wastewater nitrogen flux to the coastline and very dense OSDS inland from the swath.

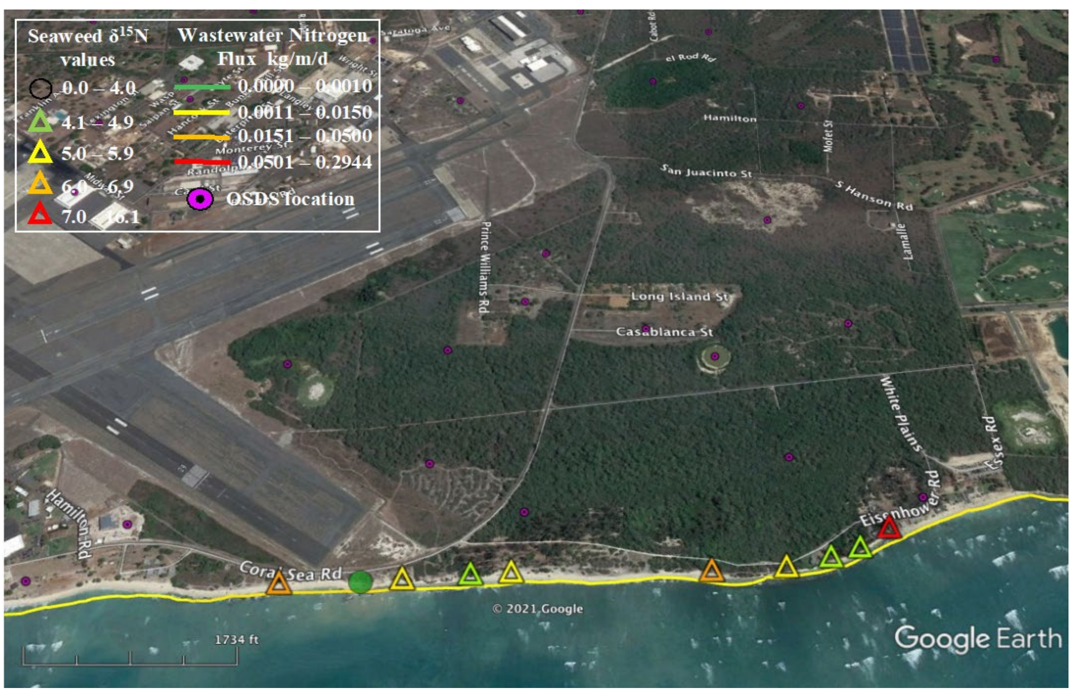


Figure 15**. O'ahu- Kalaeloa control swath.**
The Kalaeloa control swath shows a mixture of low and elevated seaweed $\delta^{15}N$ values, moderate predicted wastewater nitrogen flux to the coastline and a few OSDS inland from the swath.

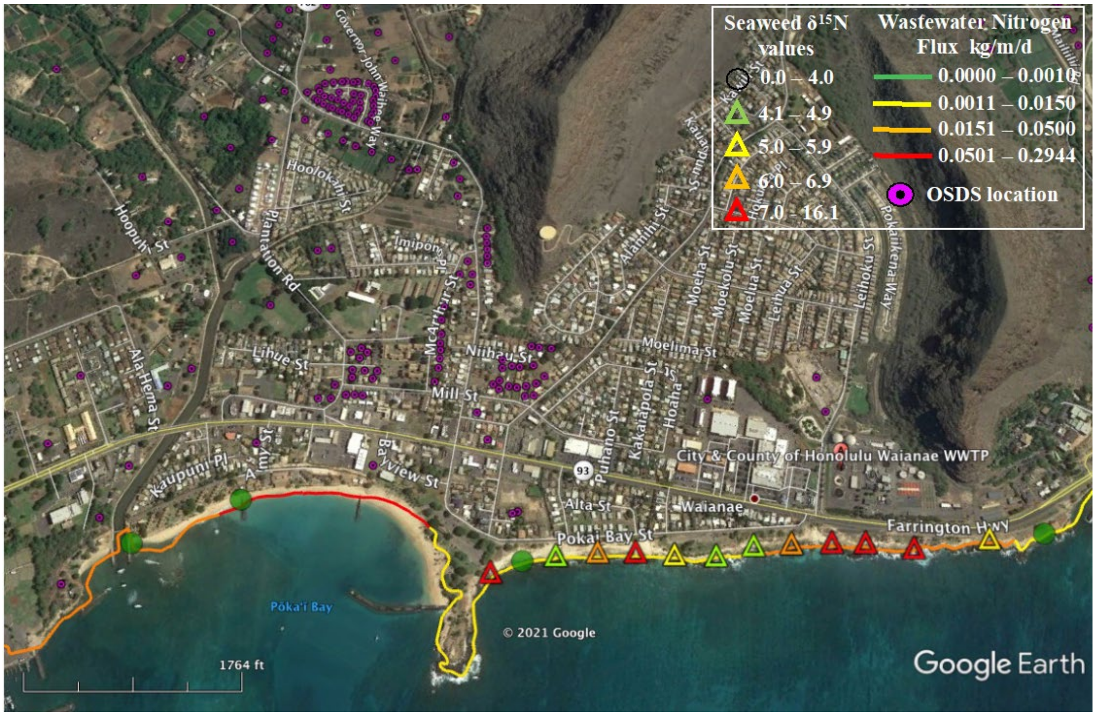


Figure 16. O'ahu- Waianae experimental swath.
The Wai'anae experimental swath shows high seaweed $\delta^{15}N$ values, high predicted wastewater nitrogen flux to the coastline, OSDS near the coast as well as the wastewater facility in this area.

Figure 17. O'ahu- Black Point experimental swath.
The Black Point swath shows high seaweed $\delta^{15}N$ values, high predicted wastewater nitrogen flux to the coastline and very dense OSDS near shore.

Figure 18**. O'ahu- Wailupe control swath.**
The Wailupe control swath shows a mixture of moderate and elevated seaweed $\delta^{15}N$ values but moderate and low predicted wastewater nitrogen flux.

Figure 19**. O'ahu- Mokapu experimental swath.**
The Mokapu experimental swath shows low seaweed $\delta^{15}N$ values (with the exception of one site), moderate predicted wastewater nitrogen flux to the coastline and dense OSDS near the swath.

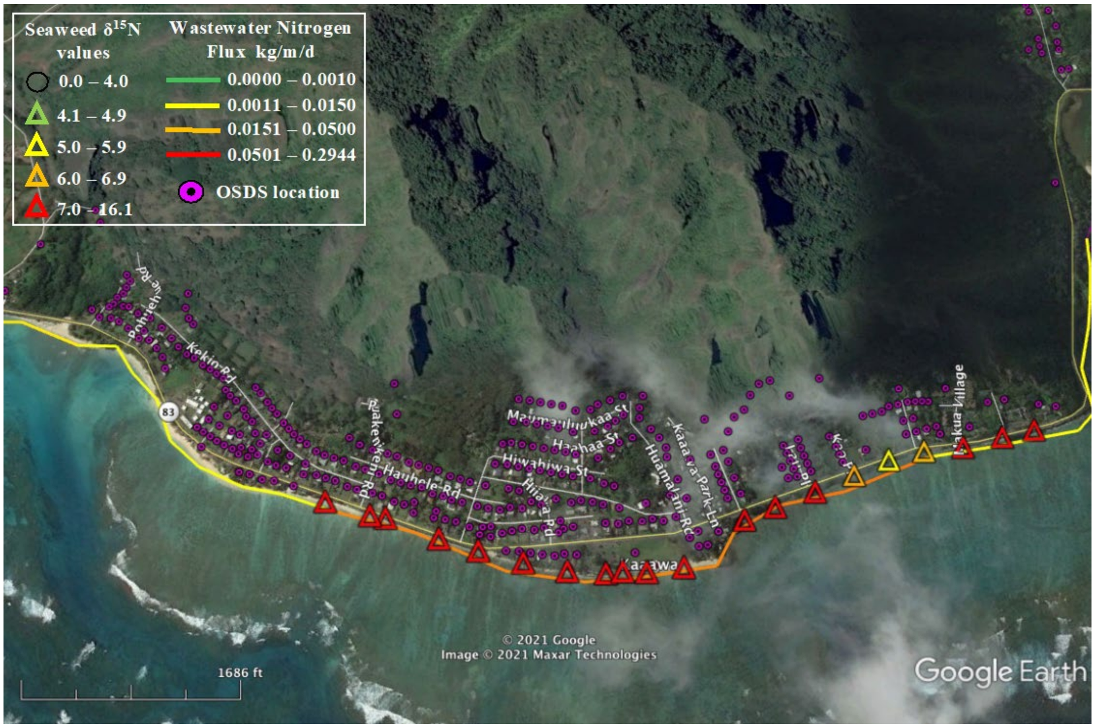


Figure 20. O'ahu- Ka'a'awa experimental swath
The Ka'a'awa experimental swath shows high seaweed $\delta^{15}N$ values, moderate to high predicted wastewater nitrogen flux to the coastline and very dense OSDS near the coast.

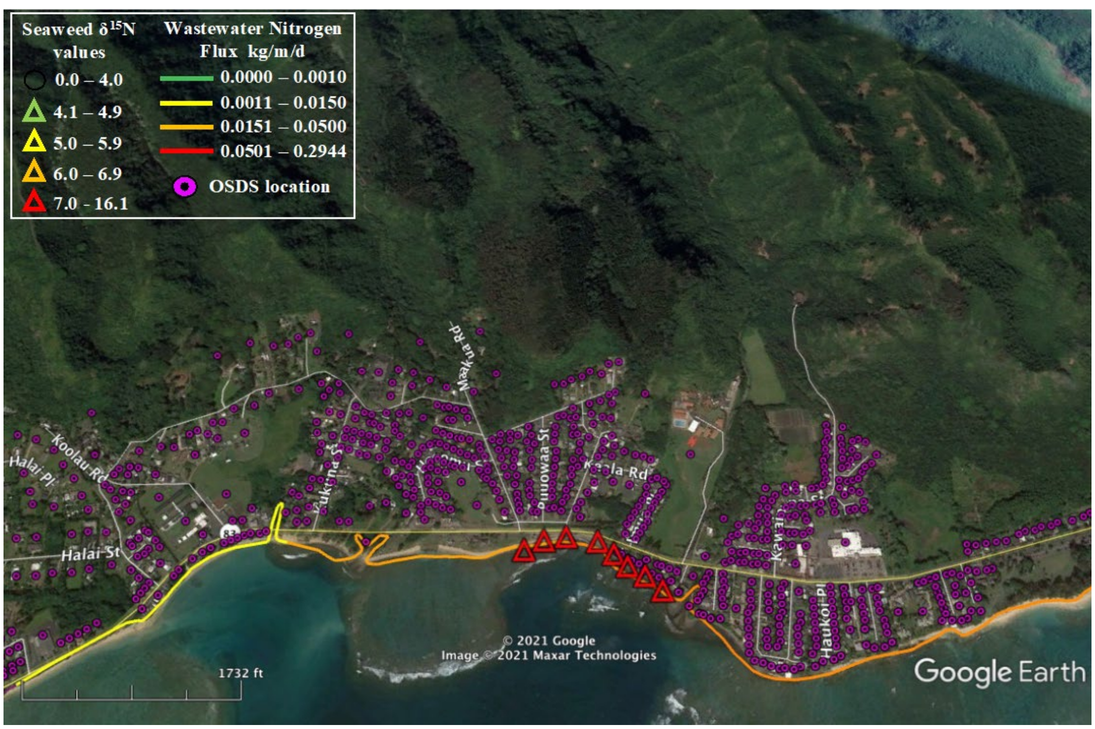


Figure 21**. O'ahu- Hau'ula experimental swath.**
The Hau'ula experimental swath shows high seaweed $\delta^{15}N$ values, moderate to high predicted wastewater nitrogen flux to the coastline and very dense OSDS inland from the swath.

4.1.5 O‘ahu maximum and average seaweed %N values

Of 127 sets of triplicate samples, or 381 independently collected seaweed samples in ten swaths across the south, windward, north and west facing shores of the island, the vast majority of samples had values of tissue N at ≥ 1 %. The data presented in Figure 22, document the distribution and values of seaweed %N sampled at each O‘ahu swath. Swaths with relatively high maximum values for %N (values over 2.0%) include Wailupe, Waialua Ka‘a‘awa, Hau‘ula and only somewhat lower for Black Point (Figure 22, Table 4).

These values are more than double % N values cited by Barr et al. (2013) for low coastal nitrogen loading. The remaining sites, Kalaeloa, Kahalu‘u, Mokapu, Wai‘anae and Sunset Beach, were identified in the lower range for % N with values between generally < 2% N (Figure 22). Few swaths, including those chosen as low wasterwater influence control swaths, had seaweed samples where the maximum N was in the range associated with low coastal N-loading (Barr et al 2013). Individual seaweed samples with ≤1% N were collected from Sunset, Mokapu and Wai‘anae.

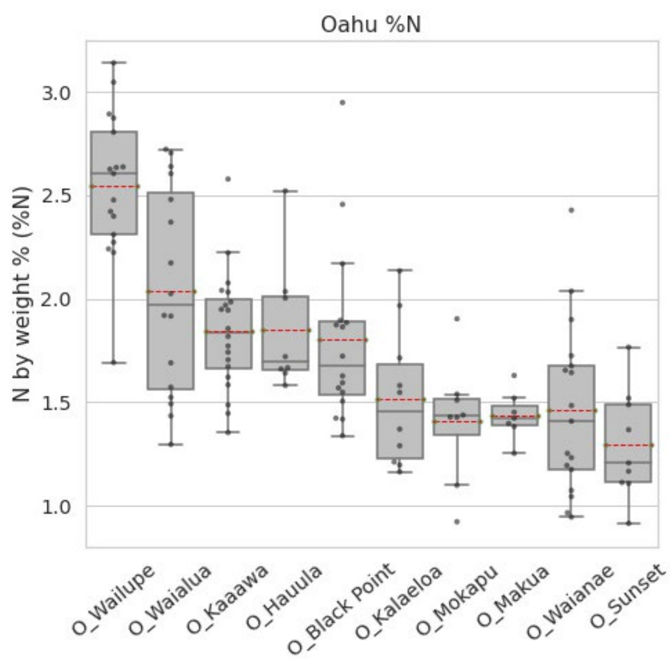


Figure 22. O‘ahu variation in seaweed %N by swath. Red dashed lines indicate the swath-wide mean, while black lines at the mid-point of boxes indicate median values. Boxes represent the inter-quartile range of data. Results for Kahalu‘u are in Table 4

Swaths with the highest swath-wide average values (1.8 to 2.5 %N) in descending order were: Wailupe, Waialua, Hau‘ula, Ka‘a‘awa Kahalu‘u single sample and Black Point.

The four swaths in the middle range for the swath average seaweed %N ranging from 1.5 to 1.3% N were: Kalaeloa, Wai‘anae, Makua, Mokapu, and Sunset Beach. No swath had swath-wide average values less than 1% N although seaweed collected at several sites - Sunset Beach, Mokapu and Wai‘anae did have a sample with values equal to or less than 1% N. Swath average seaweed %N values differed significantly between sites on O‘ahu (ANOVA, $F(9,118) = 14.7$, $P = 1 \times 10^{-14}$). These average %N values again strongly suggests that nearly all sites for all swaths were subject to substainstial nitrogen-loading from one or more sources.

4.1.6 O‘ahu geographic variability of %N values

In general, all swaths had a large amount of variability in seaweed %N. The maximum value was nearly > 1% N higher than the minimum for nearly all swaths. Similar to average seaweed $\delta^{15}N$ analyses, swath average %N values may not adequately represent sites within a swath that were exposed to excessive amounts of N. Geographic trends in %N were visible at some locations (such as Black Point, Figure 22) indicating that areas of one swath received more N loading than others. As with the $\delta^{15}N$ results, this variability highlights the fine scale nature of this approach. In contrast the average difference between triplicate samples from the same site in a given swath was <1% (Table 4).

4.2 O‘ahu wastewater indicator rank summary

The average seaweed $\delta^{15}N$ and %N values for each swath were ranked by the amount of potential wastewater detected with number one designated as the highest extent of wastewater detection to number 10 designated as the lowest wastewater detected. Similar rankings were calculated for the wastewater N-Flux and adjacent OSDS density. The end result is an unweighted wastewater indicator rank summary (Figure 23) which allows for quick inspection of all four data sets and the internal ranking for all swaths on O‘ahu.

At the top of the wastewater indicator rank summary (rank numbers 1-4 in red) are swaths with substantial adjacent OSDS and high predicted wastewater nitrogen loading which also have substantial coastal wastewater detection though elevated seaweed $\delta^{15}N > 6‰$ and %N values. These swaths include: Waialua, Hau‘ula, Ka‘a‘awa, and Wailupe. Swaths with modeled and detected mid-range wastewater inputs, such as Black Point, rank near the midpoint in this overall comparison. The Wai‘anae, Kalaeloa, and Makua swaths have low predicted wastewater intrusion combined with moderate to low detection of wastewater and are found at the bottom third of the wastewater indicator summary.

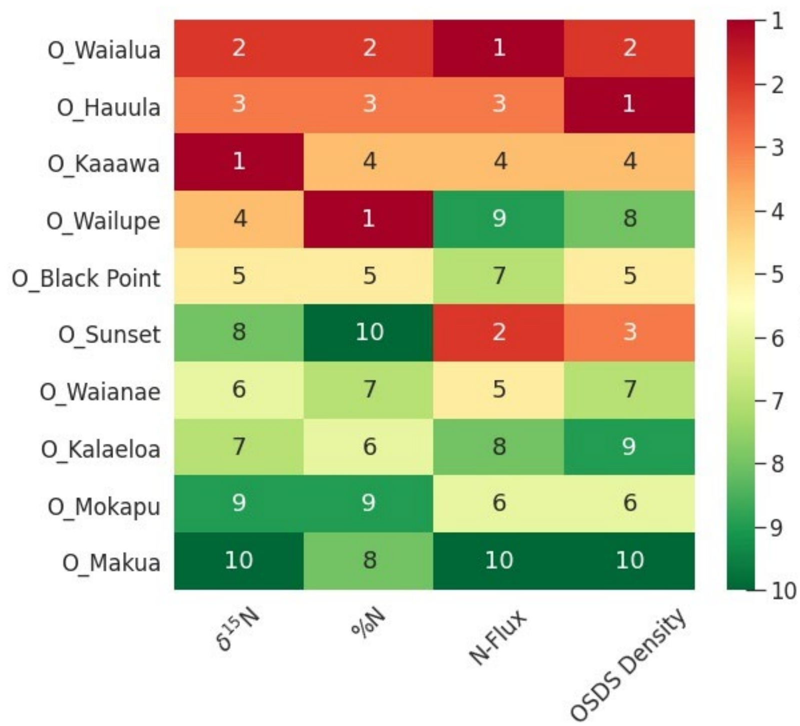


Figure 23. Summary of ranked wastewater indicators for O‘ahu

Some surprises were found where the rank orders flip among the model and seaweed data. Notably, swaths such as Sunset Beach and Mokapu were predicted to have high OSDS wastewater nitrogen loading based on modeled nitrogen-flux per meter of coastline and densities of OSDS. Yet the seaweed data show little evidence of the wastewater nitrogen loading in these areas. Several explanations for this mismatch need to be considered. Both of these swaths appear to have strong open coast currents that may be responsible for sweeping away wastewater nitrogen before a seaweed can incorporate it. Second, the path of wastewater may have a more circuitous route and not move in a manner that can be modeled as a flow zone, linearly moving downhill to the coastline. Finally, some swaths may have increased flows of naturally occurring SGD that would dilute the wastewater and hinder its detection.

Additionally, and of significant concern, Wailupe was unexpectedly found to be wastewater influenced through the seaweed data, which was opposite of the model predictions for this area (Figure 18). This site ranked #1 based on average %N for O‘ahu swaths, and yet the model calculated very low wastewater nitrogen-flux per meter of coastline and very few OSDS adjacent to the coastline. This mis-match of outputs strongly calls out for attention to the Wailupe area for remedial fixes for possible wastewater intrusion to the coastal area.

4.3 Analysis of seaweed data from coastal regions on Maui

4.3.1 Maui coastal seaweed collection for $\delta^{15}N$ and %N values

In Maui coastal waters, cesspools are predicted to contribute about 76 percent of coastal wastewater nutrient load (Table 3, above). Thus, generally, 11 coastal swaths on Maui were sampled to detect wastewater via sampling intertidal seaweed from the months of April to September, the drier months in terms of rainfall (Giambelluca et al 2013, Rainfall Atlas of Hawai‘i), maintaining consistency with the state-wide sampling efforts. A total of 507 seaweed samples were collected from those 11 coastline swaths on the west, north and south facing shores of Maui for $\delta^{15}N$ value and %N evaluations. Unfortunately, the samples from one swath in Lahaina (69 samples from 15 sites) were incorrectly processed; those samples were removed from this analysis. Of the remaining 10 swaths and 127 sites, six sites were removed from this analysis because unforseen effects of homeless encampments lead to abberant data for select sites in otherwise low wastewater nitrogen loading regions of Maui.

4.3.2 Maui seaweed nitrogen results

Of the accepted 121 sites, 26 had average $\delta^{15}N$ values equal to or greater than 6‰ (Figure 9, Tables 2, 5). The wastewater dominated areas dentified by having elevated seaweed $\delta^{15}N$ values for Maui are: Waiehu, Wailea, South Wailea and South Kīhei. Of the 121 sites only two had an average %N value less than 1%, South Wailea (0.68 ± 0.10) and Olowalu – Ukumehame (0.58 ± 0.05). Table 5 provides an overview of the data to be discussed in this section.

Table 5. Maui- variations in coastal seaweed samples of swath average, maximum and ranges of δ^{15}N and %N values.

Location	Swath ave δ^{15}N	δ^{15}N SD	Swath ave %N	%N SD	Swath Max δ^{15}N, n=3	Swath Max %N, n=3	Swath δ^{15}N (SD) samples range, n=3: low	high	Swath %N (SD) samples range, n=3: low	high
Olowalu - Ukumehame	2.21	1.64	1.33	0.55	4.30	2.69	-0.23 (0.23)	4.23 (0.12)	0.58 (0.05)	2.50 (0.16)
Stables - Spreckelsville	1.90	0.85	3.58	0.52	4.50	4.48	0.70 (0.57)	4.27 (0.21)	3.00 (0.24)	4.43 (0.04)
La Perouse	2.58	0.74	1.67	0.35	3.60	2.34	1.10 (0.30)	3.53 (0.06)	1.27 (0.02)	2.28 (0.09)
Waiheʻe	1.71	0.69	1.53	0.33	4.10	2.29	1.08 (0.25)	2.75 (0.86)	1.06 (0.24)	2.05 (0.13)
North Kīhei	1.91	0.72	3.78	0.32	3.00	4.51	0.73 (0.21)	2.80 (0.26)	3.50 (0.06)	4.21 (0.33)
South Kīhei	5.11	1.55	2.84	0.73	10.2	4.59	4.05 (0.33)	10.07 (0.06)	1.59 (0.11)	4.49 (0.10)
Waiehu	6.88	1.27	2.45	0.92	8.40	4.03	3.63 (0.12)	8.30 (0.10)	1.20 (0.16)	3.88 (0.23)
Wailea	6.36	0.65	2.49	0.83	7.40	4.50	4.87 (0.12)	7.33 (0.06)	0.90 (0.16)	4.14 (0.46)
South Wailea	4.81	1.48	2.28	1.12	8.60	4.50	3.10 (0.46)	8.50 (0.10)	0.68 (0.10)	4.38 (0.16)
Paia-Kuau	3.20	0.83	3.01	0.46	4.60	3.80	1.77 (0.20)	4.60 (0.20)	2.16 (0.09)	3.80 (0.29)

4.3.3 Maui maximum and average seaweed $\delta^{15}N$ values

The boxplots of seaweed $\delta^{15}N$ values per swath represent the distribution of average swath values with individual site values shown as black dots (Figure 24). The swaths with the highest values, Waiehu, Wailea and South Wailea, had maximum seaweed $\delta^{15}N$ values from 7.4 to 10.2‰. The lowest seaweed $\delta^{15}N$ values were from low wastewater nitrogen loading swaths, for example: Olowalu-Ukumehame (Olo-Uku; -0.23‰), Stables-Spreckelsville (Sta-Spr; 0.70‰), Kīhei North (0.73‰) (Table 5, Figure 24).

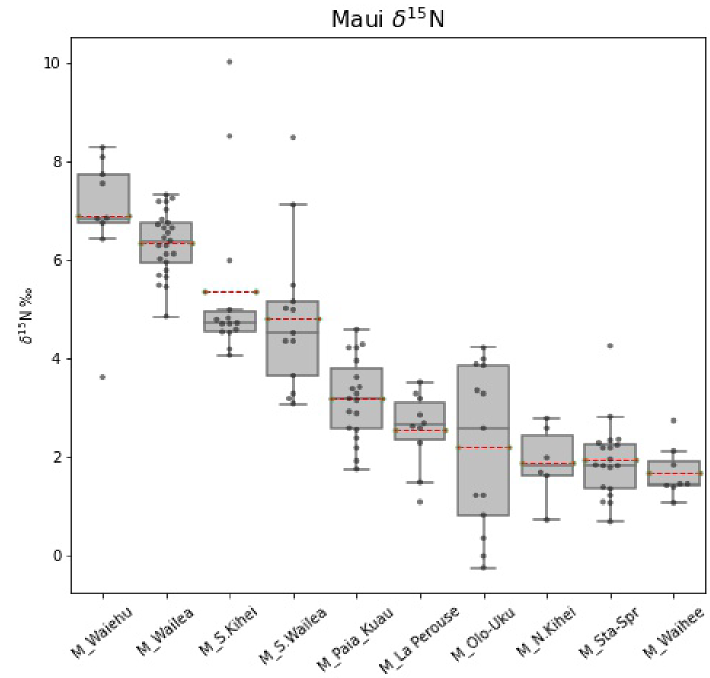


Figure 24. Maui variation among swaths for average seaweed $\delta^{15}N$ values.
Red dashed lines indicate swath-wide mean, while black lines at the mid-point of boxes indicate median values. Boxes represent the inter-quartile range of data.

The highest swath average seaweed $\delta^{15}N$ values were from Waiehu (6.88‰), Wailea (6.36‰) placing these two swaths in the wastewater dominant category while Kīhei South fell just below that 6‰ demarcation (5.11‰) (Table 5, Figure 24).

4.3.4 Maui geographic variability of seaweed $\delta^{15}N$ values

The variability in seaweed $\delta^{15}N$ values across a 2-kilometer swath illustrates the ability of this method to detect wastewater signals at a fine scale and suggest that averaging across all samples may lead to an understatement of wastewater nitrogen presence in the coastal area. For example, the South Kīhei swath average seaweed $\delta^{15}N$ value was 5.11 ± 1.55‰ but the maximum $\delta^{15}N$ value was 10.2‰ and the seaweed $\delta^{15}N$ value range was from 4.05 ± 0.33‰ to 10.07 ± 0.06‰ (Table 5, Figures 24, 27). The South Wailea swath seaweed samples had an average $\delta^{15}N$ value of 4.81 ± 1.48‰ but the maximum $\delta^{15}N$ value was 8.60‰ and the range of $\delta^{15}N$ values was from 3.10 ± 0.46‰ to 8.50 ± 0.10‰ (Table 5, Figures 24, 29). This variation can generally be attributed to natural variation in the width of a wastewater plume, in contrast to the width of a swath, because sampling clearly can include some non-plume sites in the swath.

On low wastewater nitrogen loading swaths the geographic effect is less attributable to an anticipated lack of wastewater nitrogen. The La Perouse swath seaweed samples, for example, had an average $\delta^{15}N$ value of 2.58 ± 0.74‰, maximum $\delta^{15}N$ value of 3.60‰ and the $\delta^{15}N$ value range was from 1.10 ± 0.30‰ to 3.53 ± 0.06‰ (Table 5, Figures 24, 30). The Waiheʻe control swath had a swath average $\delta^{15}N$ value of 1.71 ± 0.69‰, maximum $\delta^{15}N$ value of 4.10‰ and the $\delta^{15}N$ value range was from 1.08 ± 0.25‰ to 2.75 ± 0.86‰ (Table 5, Figures 24, 31). Average seaweed $\delta^{15}N$ values on Maui differed significantly between swaths (ANOVA, $F(8,108) = 42.0$, P = 2x10^{-16}). Figures 25 through 34 show the predicted coastal wastewater nitrogen-flux and the average seaweed δ^{15}N values per site for all of the swaths on Maui.

Figure 25**. Maui- Olowalu-Ukumehame control swath.**
The Olowalu-Ukumehame control swath shows low seaweed δ^{15}N values, low predicted wastewater nitrogen flux to the coastline and a few OSDS inland from the swath.

Figure 26. **Maui- North Kīhei experimental swath.**
The North Kīhei experimental swath shows low seaweed $\delta^{15}N$ values, high predicted wastewater nitrogen flux to the coastline and few OSDS inland from the swath. Also, due to the sandy bottom in this area, only five sites had seaweed to collect.

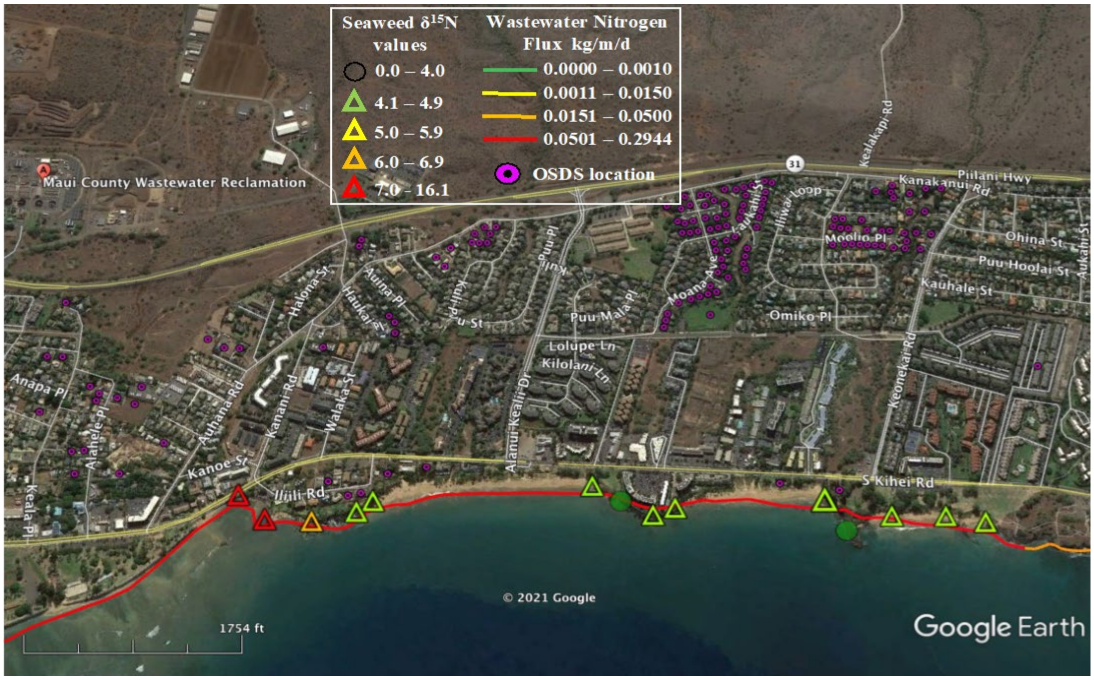


Figure 27. **Maui- South Kīhei experimental swath.**
The South Kīhei experimental swath shows elevated seaweed $\delta^{15}N$ values, high predicted wastewater nitrogen flux to the coastline, dense OSDS inland from the swath and the Maui County, Kihei Wastewater Reclamation Facility.

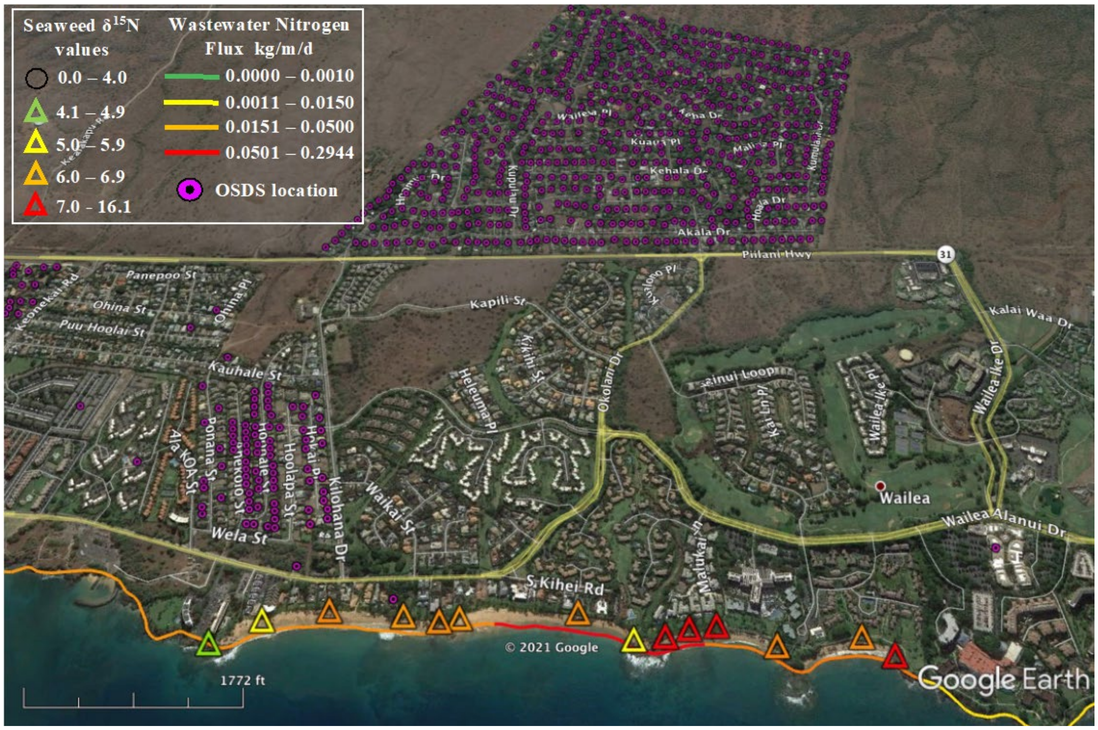


Figure 28**. Maui- Wailea experimental swath.**
The Wailea experimental swath shows high seaweed $\delta^{15}N$ values, high predicted wastewater nitrogen flux to the coastline and very dense OSDS inland from the swath.

Figure 29**. Maui- South Wailea experimental swath.**
The South Wailea experimental swath shows one site with high seaweed $\delta^{15}N$ values near the dense OSDS inland and low seaweed $\delta^{15}N$ values at the rest of the sites. The predicted wastewater nitrogen flux to the coastline was low to moderate for this area.

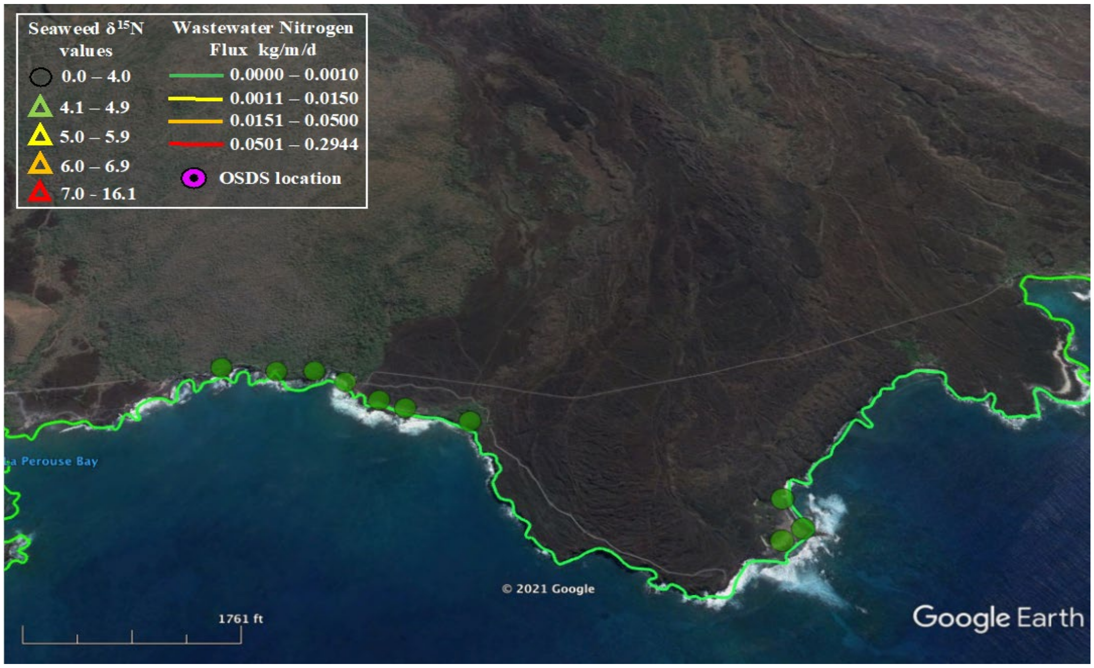


Figure 30**. Maui- La Perouse (South Maui Control) swath.**
The La Perouse control swath shows low seaweed $\delta^{15}N$ values, low predicted wastewater nitrogen flux to the coastline and no OSDS near the swath.

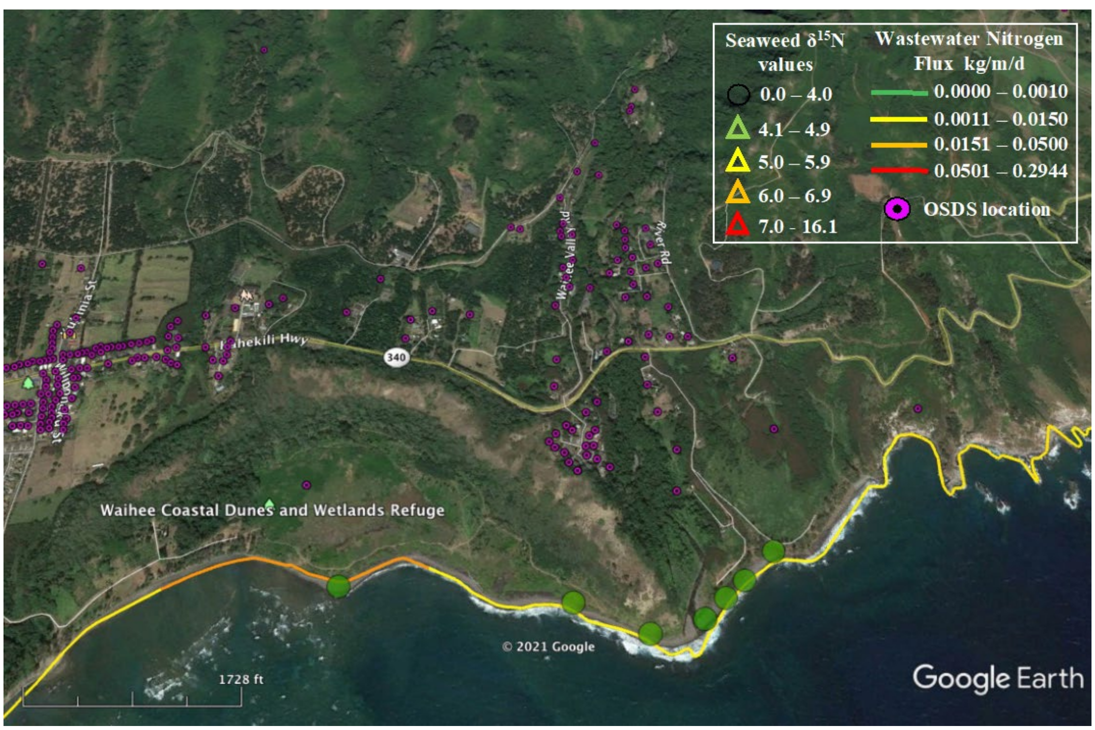


Figure 31**. Maui- Waihee control swath.**
The Waihee control swath shows low seaweed $\delta^{15}N$ values while the predicted wastewater nitrogen flux to the coastline was high to moderate for this area. Scattered OSDS are present inland from the swath.

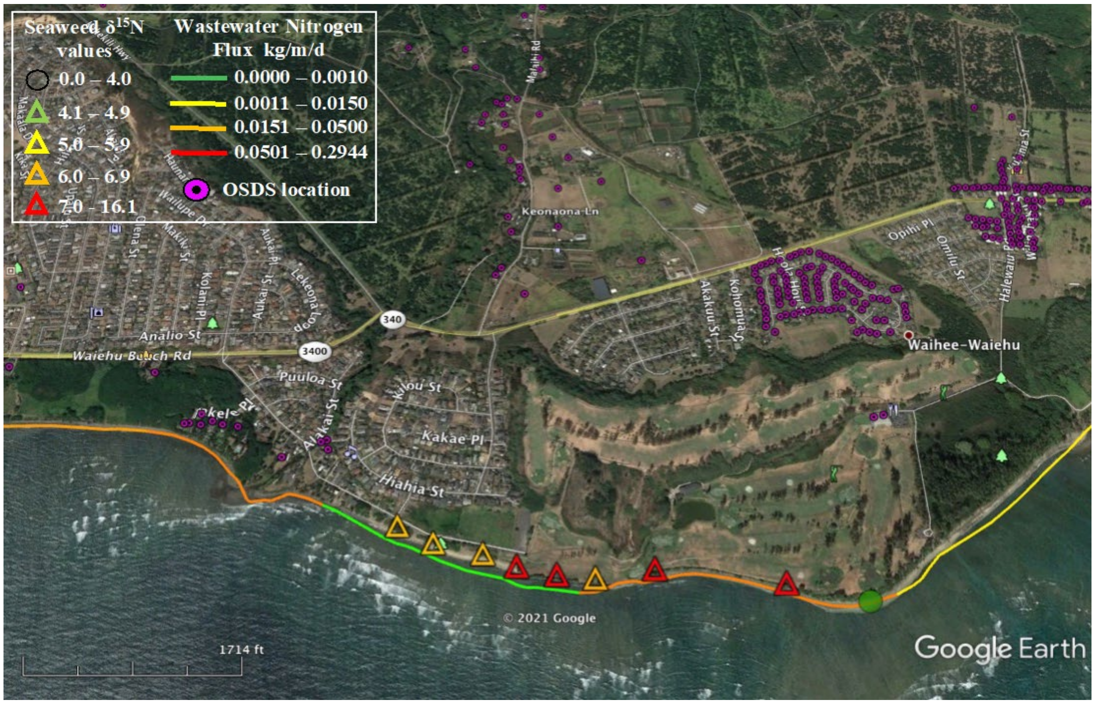


Figure 32**. Maui- Waiehu experimental swath.**
The Waiehu experimental swath shows high seaweed $\delta^{15}N$ values, mixed levels of predicted wastewater nitrogen flux to the coastline and a few clusters of dense OSDS inland from the swath.

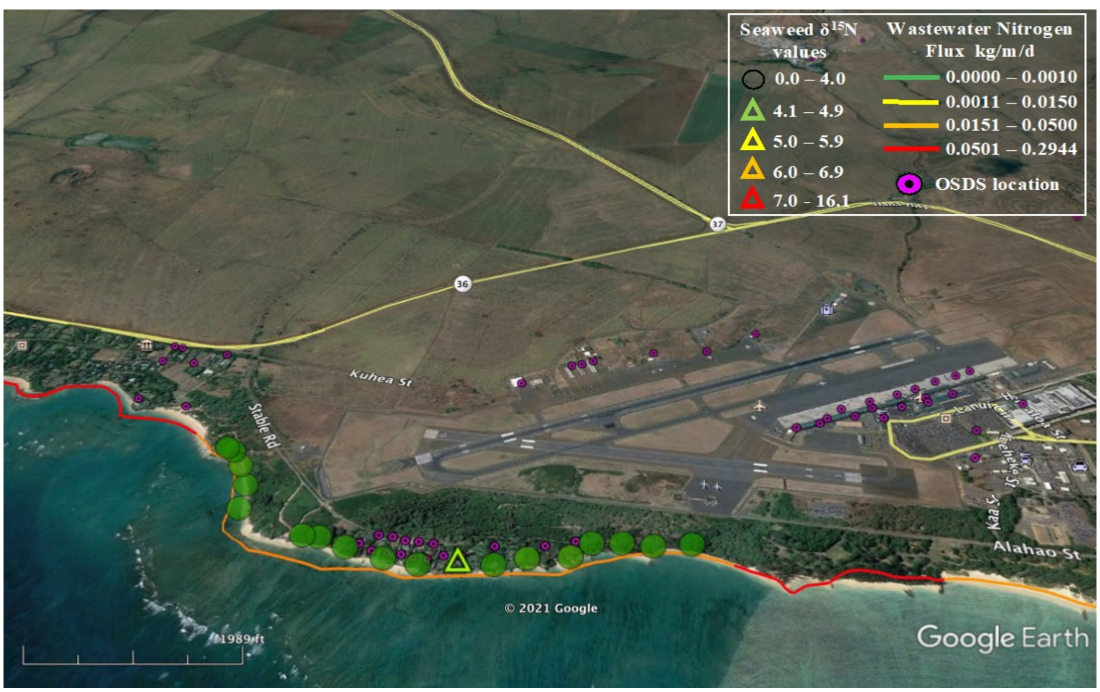


Figure 33**. Maui- Stables-Spreckelsville control swath.**
The Stables-Spreckelsville control swath shows low seaweed $\delta^{15}N$ values, high to moderate predicted wastewater nitrogen flux to the coastline and a few scattered OSDS inland from the swath.

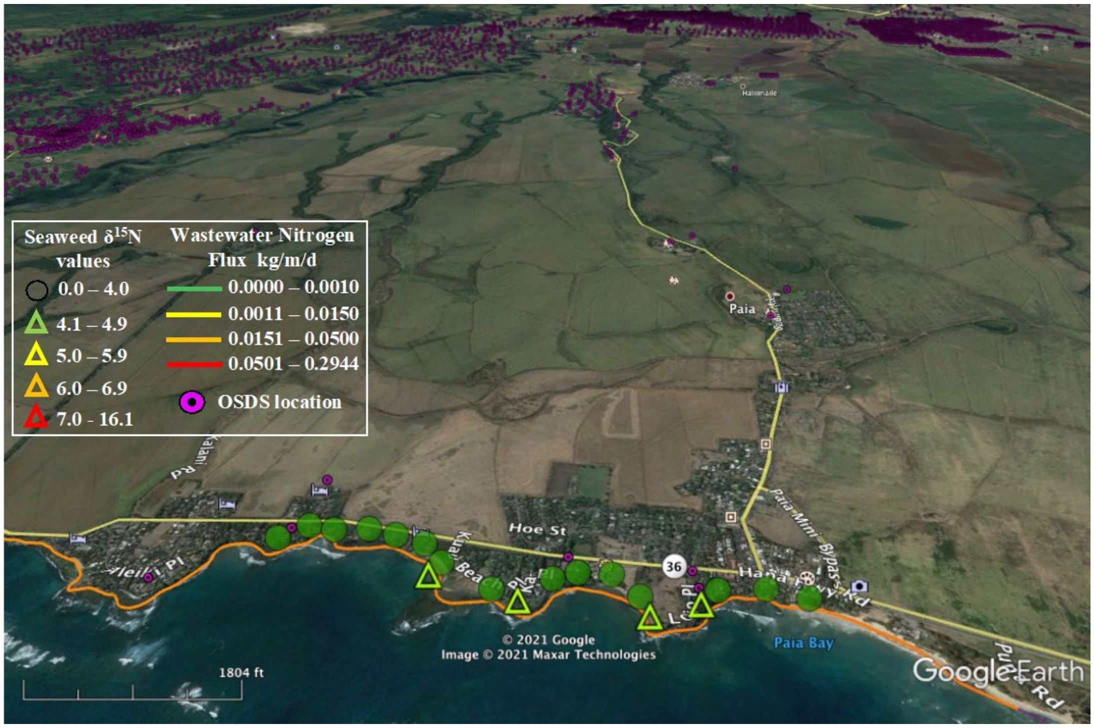


Figure 34**. Maui- Paia-Kuau experimental swath**
The Paia-Kuau experimental swath shows low seaweed $\delta^{15}N$ values, high predicted wastewater nitrogen flux to the coastline from the very dense OSDS shown high upslope from the swath.

4.3.5 Maui maximum and average seaweed %N

Figure 35 documents the distribution and individual site values (in black dots) of seaweed %N for each swath on Maui. Of 121 sites, only two had an average %N value less than 1 %N. One site was on the South Wailea swath (0.68 ± 0.10) and one site was on the Olowalu – Ukumehame swath (Olo-Uku; 0.58 ± 0.05) (Table 5, Figure 35).

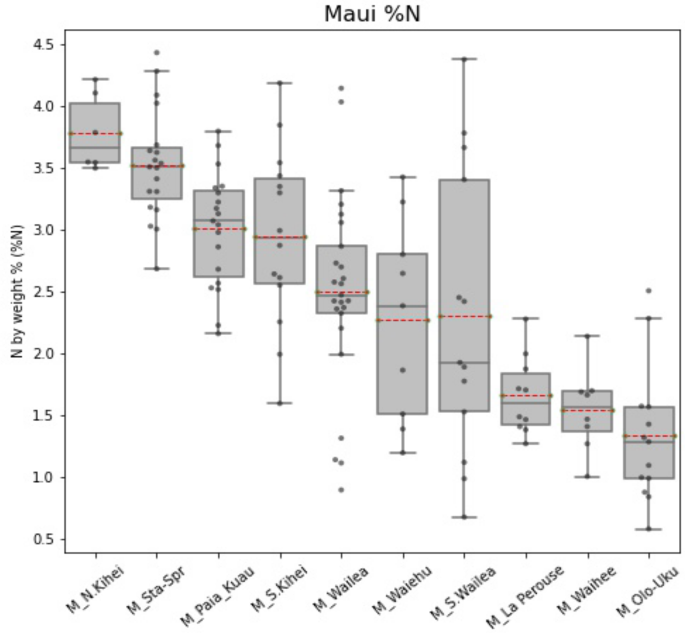


Figure 35. Maui variation among swaths for average seaweed %N. Red dashed lines indicate the swath-wide mean, while black lines at the mid-point of boxes indicate median values. Boxes represent the inter-quartile range of data

The following swaths had relatively high maximum seaweed %N values ranging from 4.03 to 4.59% N: Stables – Spreckelsville (4.48% N), North Kīhei (4.51 %N), South Kīhei (4.51% N), Waiehu (4.03% N), Wailea (4.50% N) and South Wailea (4.50% N) (Figure 35, Table 5). Similar to O'ahu, low wastewater N loading swaths on Maui had maximum seaweed %N values well above the range associated with low coastal N-loading (~ 1.5% N; Barr et al., 2013) with average seaweed %N from Olowalu-Ukumehame at 2.69% N, La Perouse at 2.34% N, and Waihee at 2.29% N (Figure 35, Table 5).

The highest average seaweed %N values were 3.58 and 3.78% N from Stables – Spreckelsville and North Kīhei, respectively (Table 5, Figure 35) and are consistent with agricultural nitrogen inputs. Average seaweed %N values ranging from 2.28 to 2.84 %N were found at the following locations: South Wailea, Wailea, Waiehu and South Kīhei (Table 5, Figure 35). The lowest average seaweed %N values were 1.33, 1.53 and 1.67% N from Olowalu-Ukumehame, Waihee and Stables-Spreckelsville, respectively (Table 5, Figure 35). These values are all more than double the typical value for the detection of elevated nutrients in the environment (Barr et al., 2013). Average seaweed %N differed significantly between sites on Maui (ANOVA, $F(8,108) = 16.6$, $P = 8.1 \times 10^{-14}$).

4.3.6 Maui geographic variability of seaweed %N

Variability in seaweed %N values was found amongst sites within swaths. This variation suggests that we sampled within and outside of nitrogen plumes. The lowest average %N value per site was often 1 to 2% lower than the highest average %N value per site for nearly all swaths (Table 5, Figure 35). South Wailea, for example, had drastic differences in seaweed %N values ranging from 0.68 ± 0.10% to 4.38 ± 0.16% (Table 5, Figure 35). Less variability in seaweed %N values was found across the Stables-Spreckelsville swath which ranged from 3.00 ± 0.24% N to 4.43 ± 0.04% N (Table 5, Figure 35). Less variability in seaweed %N values was also found across the La Perouse swath which ranged from 1.27 ± 0.02% N to 2.28 ± 0.09% N (Table 5, Figure 35).

4.4 Maui wastewater indicator rank summary

The average seaweed δ^{15}N and %N values for each swath were ranked by the amount of potential wastewater detected with number one designated as the highest extent of wastewater detection to number 10 designated as the lowest wastewater detected. Similar rankings were calculated for the wastewater N-Flux and adjacent OSDS density. The end result is an unweighted wastewater indicator rank summary (Figure 36) which allows for quick inspection of all four data sets and the internal ranking for all swaths on Maui.

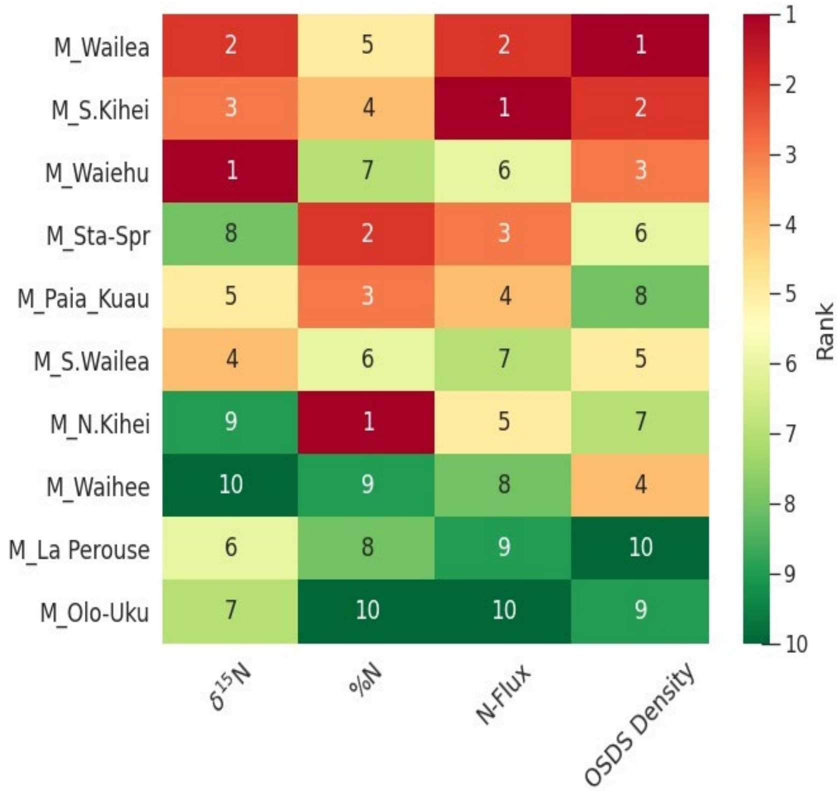


Figure 36. Summary of ranked wastewater indicators for Maui swath averages.

Each swath on Maui was ranked for seaweed δ^{15}N values and %N levels with number one rank designated as the highest extent of wastewater detection to number 10 designated as the least amount of wastewater detected.

Similar rankings were calculated using estimated nitrogen flux and adjacent OSDS density (Figure 36). The swaths with substantial wastewater nitrogen predicted via the modeling efforts and detected via elevated seaweed δ^{15}N values and high %N, end up at the top of the wastewater indicator rank summary. Wailea, South Kīhei, and Waiehu exhibited evidence of wastewater dominance. The swaths with modeled and detected mid-range wastewater inputs, such as, Wailea South and Paia-Kuau, rank as wastewater influenced in this overall comparison. Olowalu-Ukumehame, La Perouse and Waihee are swaths with little to no wastewater nitrogen inputs as well as little to no wastewater detected and round out the wastewater impact rank summary at the bottom third.

4.5 Analysis of seaweed data from coastal regions on Hawai‘i Island

4.5.1 Hawai‘i Island coastal seaweed collection for $\delta^{15}N$ and %N values

On Hawai'i Island coastal waters, cesspools are predicted to contribute about 89 percent of coastal wastewater nutrient load (Table 3, above). Thus, ten coastal swaths on Hawai‘i Island were sampled to detect wastewater via sampling seaweeds between April and June 2019, maintaining consistency with state-wide sampling efforts. These are the drier months for all coastal regions sampled except for Holualoa (Kailua-Kona), which experiences more rainfall in this period (Giambelluca et al., 2013, Rainfall Atlas of Hawai‘i). A total of 363 seaweed samples at 121 sites were collected from windward and leeward Hawai‘i Island. Along the Hamakua Coast, only one site was sampled due to the difficulty of accessing the shoreline and a lack of seaweeds in locations. Several regions with high densities of OSDS and high wastewater N-fluxes predicted by the model were not sampled because of difficulty accessing the shoreline, including Honoka‘a, N. Kohala, Kailapa and Ka’ū.

4.5.2 Hawai‘i Island seaweed nitrogen results

Based on the nitrogen loading model, the three following regions were chosen with predicted high wastewater nitrogen loads: Hilo Bay, Hawaiian Paradise Park (HPP), and West Hawai‘i (Kailua-Kona). We sampled five swaths within these three regions: Wailoa, Keaukaha (Hilo Bay), HPP (Puna), NELHA and Holualoa (N. Kona). The following swaths had maximum $\delta^{15}N$ values $\geq$6.0‰: Wailoa, Keaukaha, Puako, Mauna Lani, and NELHA (N. Kona) (Table 6). Puakō, which was identified in the modeling as an area of concern, had the highest swath average and maximum seaweed $\delta^{15}N$ values for Hawai‘i Island, while Wailoa (Hilo) and Holualoa (Kailua-Kona) swaths had the second and third highest swath average seaweed $\delta^{15}N$ values, at 4.98‰ and 4.90‰ resectively (Table 6).

The seaweed $\delta^{15}N$ values varied by an order of magnitude (0.86 – 8.6‰) among all of the samples collected on Hawai’i Island (Table 6). Of the 121 sets of triplicate samples collected on 9 swaths on Hawai’i Island, 55 discrete seaweed collections had $\delta^{15}N$ values $\geq$ 6‰. The wastewater influenced swaths identified on Hawai’i Island are: Puakō (Figure 39), NELHA (Figure 42), Mauna Lani (Figure 40), Keaukaha (Figure 46), and Wailoa (Figure 45). The %N of seaweed samples varied over a smaller range (0.66-4.15%). Table 6 provides an overview of the data to be discussed in Section 4.5.

Table 6. Hawai‘i Island-variations in coastal seaweed samples of swath average, maximum and ranges of δ^{15}N and %N values.

Location	Swath Ave δ^{15}N	δ^{15}N SD	Swath Ave %N	%N SD	Swath Max δ^{15}N, n=3	Swath Max %N, n=3	Swath δ^{15}N (SD) samples range, n=3: low	high	Swath %N (SD) samples range, n=3: low	high
Wailoa, Hilo	4.98	0.39	1.92	0.25	6.00	2.28	4.43 (0.12)	6.00 (0.61)	1.46 (0.15)	2.28 (0.41)
Keaukaha, Hilo	3.48	1.26	1.41	0.45	6.10	2.25	1.43 (0.51)	6.10 (0.10)	0.91 (0.18)	2.25 (0.15)
Hamakua Coast*	3.17		0.94		-----	----	-----	-----	-----	-----
Hawaiian Paradise Park (HPP), Puna	2.12	0.32	1.27	0.27	2.47	1.73	1.43 (0.67)	2.47 (0.15)	0.95 (0.14)	1.73 (0.03)
Kailapa, S. Kohala	4.14	0.65	0.86	0.14	4.70	0.97	3.27 (0.12)	4.70 (0.94)	0.66 (0.06)	0.97 (0.11)
Puakō, S. Kohala	6.48	1.67	2.92	1.02	8.57	4.15	3.83 (0.15)	8.57 (0.21)	1.59 (0.09)	4.15 (0.23)
Mauna Lani, S. Kohala	4.33	0.84	1.89	0.67	6.13	2.87	2.23 (0.70)	5.88 (0.87)	0.70 (0.07)	2.87 (0.93)
Mahai‘ula, N. Kona	2.40	0.89	1.26	0.62	4.10	2.70	0.87 (0.06)	4.10 (0.14)	0.79 (0.06)	2.70 (0.23)
NELHA, N. Kona	4.22	1.49	1.02	0.21	6.53	1.45	1.57 (0.32)	6.53 (0.31)	0.75 (0.05)	1.45 (0.42)
Holualoa, N. Kona	4.90	0.62	1.23	0.25	5.73	1.67	3.87 (0.42)	5.73 (0.40)	0.79 (0.11)	1.67 (0.24)

*Only one site sampled for the Hamakua Coast

4.5.3 Hawai'i Island maximum and average seaweed $\delta^{15}N$ values

The variations in seaweed $\delta^{15}N$ values among swaths are presented in Figure 37, where individual site values shown as black dots. The swaths with the highest values, Puako, Wailoa, Mauna Lani, and Keaukaha had maximum $\delta^{15}N$ values ranging from 6.00 to 8.57‰. The swaths on Hawai'i Island with the seaweed $\delta^{15}N$ values less than 2‰ were Mauna Lani (1.6‰), Hawaiian Paradise Park (HPP) (1.4‰), Keaukaha (1.4‰), and Mahai'ula (0.9‰). Seaweed $\delta^{15}N$ values differed significantly among swaths on Hawai'i Island (ANOVA, $F(9,101) = 19.3$, $P < 2\times10^{-16}$).

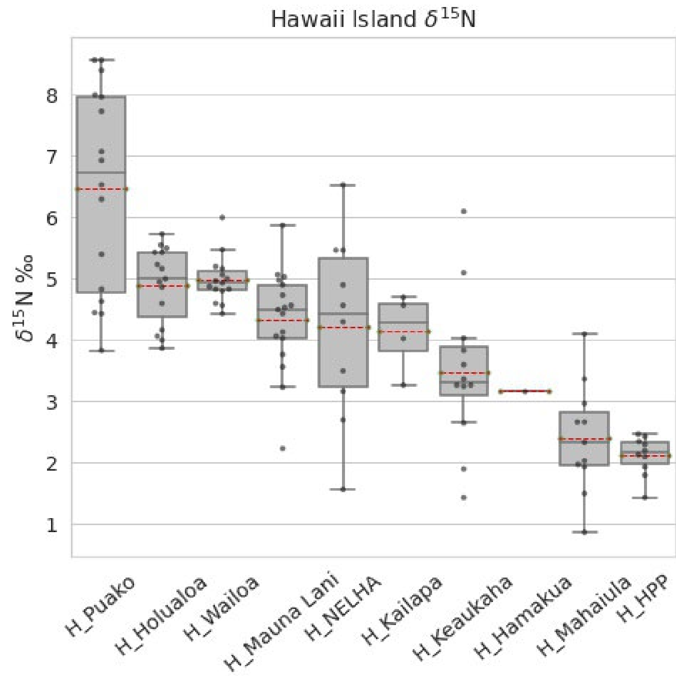


Figure 37. Hawai'i Island variation among swaths for average seaweed $\delta^{15}N$ values.
Red dashed lines indicate swath-wide mean, while black lines at the mid-point of the boxes indicate median values. Boxes represent the inter-quartile range of data.

Puakō had the highest swath average seaweed $\delta^{15}N$ (6.5‰). The next four highest swath average seaweed $\delta^{15}N$ values were Holualoa, Wailoa, Mauna Lani, and NELHA, which ranged from 5.0 to 4.2‰ and are in the wastewater influenced category. Two swaths had low maximum values (< 4.1‰) and low average values (< 2.4‰): Mahai'ula and HPP.

4.5.4 Hawai'i Island geographic varability of seaweed $\delta^{15}N$ values

The variability in seaweed $\delta^{15}N$ values across a swath illustrates the ability of this method to detect wastewater nitrogen at a fine scale and suggests that averaging across all samples may underestimate the presence of wastewater nitrogen in the coastal area. Along the Puakō swath, the seaweed $\delta^{15}N$ values increased to the south, with all of the values > 6‰ located in the south part of Puakō (Figure 39). At Mauna Lani, the average seaweed $\delta^{15}N$ values per site increased to the north (Figure 40). Along the other swaths, there were no spatial trends in seaweed $\delta^{15}N$ values. Mauna Lani, NELHA, and Keaukaha had high variability, greatest range in average seaweed $\delta^{15}N$ values ranging from 1.6 to 6.5‰ at NELHA (Figures 40, 42, and 45, respectively). Along these swaths, exposure to wastewater enriched N sources was localized, depending on the presence of groundwater springs, the magnitude of wastewater in the groundwater, and the magnitude of nearshore ocean mixing. The Wailoa and Holualoa both had relatively little variability along the swath sampled, suggesting similar availability of wastewater enriched N sources throughout these swaths (Figures 45 and 43, respectively). Figures 38 through 47 show the predicted coastal wastewater N-flux and the average seaweed $\delta^{15}N$ values per site for all of the experimental and control swaths on Hawai'i Island.

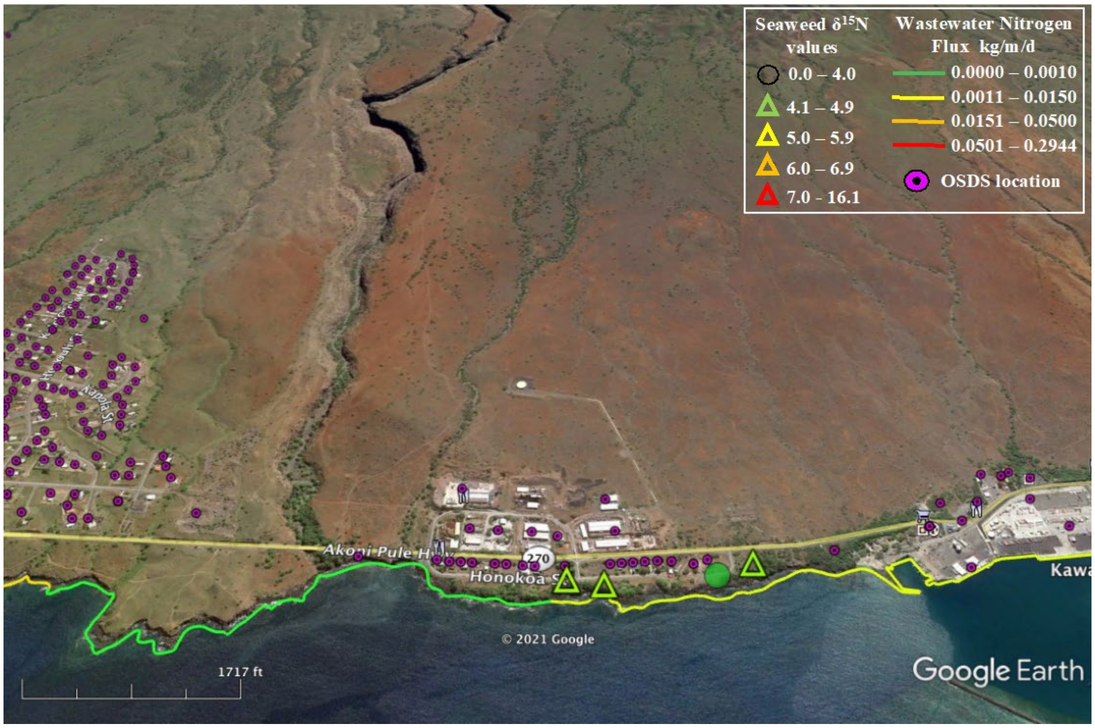


Figure 38. Hawai'i Island- Kailapa (Kawaihae) experimental swath.
The Kailapa (Kawaihae) experimental swath shows low seaweed $\delta^{15}N$ values with low to moderate predicted wastewater nitrogen flux to the coastline and a few OSDS inland from the swath.

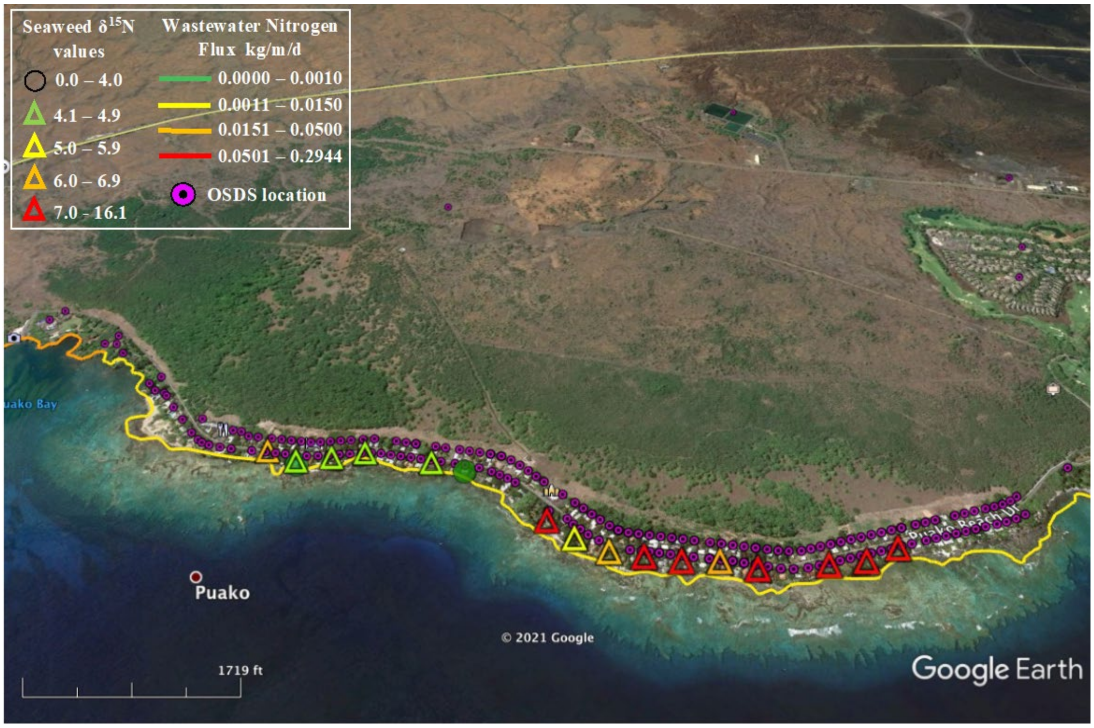


Figure 39. Hawai'i Island- Puakō experimental swath
The Puakō experimental swath shows high seaweed $\delta^{15}N$ values, moderate levels of predicted wastewater nitrogen flux to the coastline and dense OSDS along the coast next to the swath.

Figure 40. Hawai'i Island- Mauna Lani (Waikoloa) control swath.
The Waikaloa swath shows low to moderate seaweed $\delta^{15}N$ values with also low predicted wastewater nitrogen flux to the coastline and a few OSDS inland from the swath.

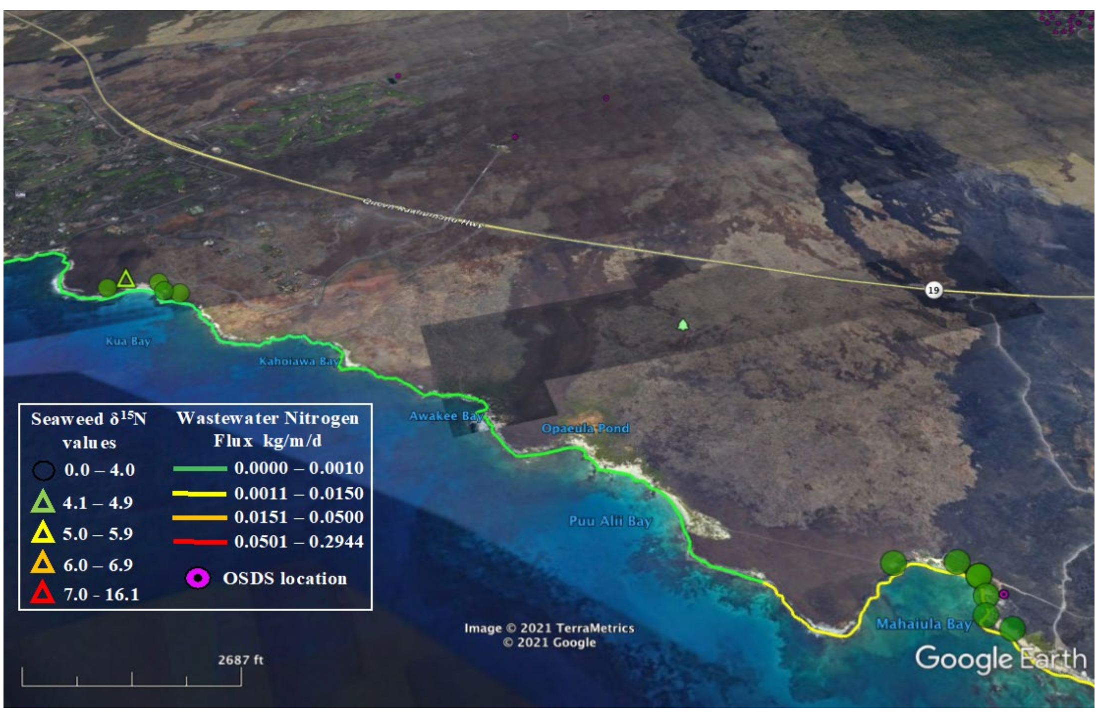


Figure 41. Hawai'i Island- Mahaiula control swath.
The Mahaiula control swath shows low seaweed $\delta^{15}N$ values with, low predicted wastewater nitrogen flux to the coastline and no OSDS inland from the swath.

Figure 42. Hawai‘i Island- Natural Energy Laboratory of Hawai‘i Authority (NELHA) experimental swath.

The Natural Energy Laboratory of Hawai‘i Authority (NELHA) experimental swath shows moderate seaweed $\delta^{15}N$ values with high predicted wastewater nitrogen flux to the coastline and very dense OSDS upslope from the swath.

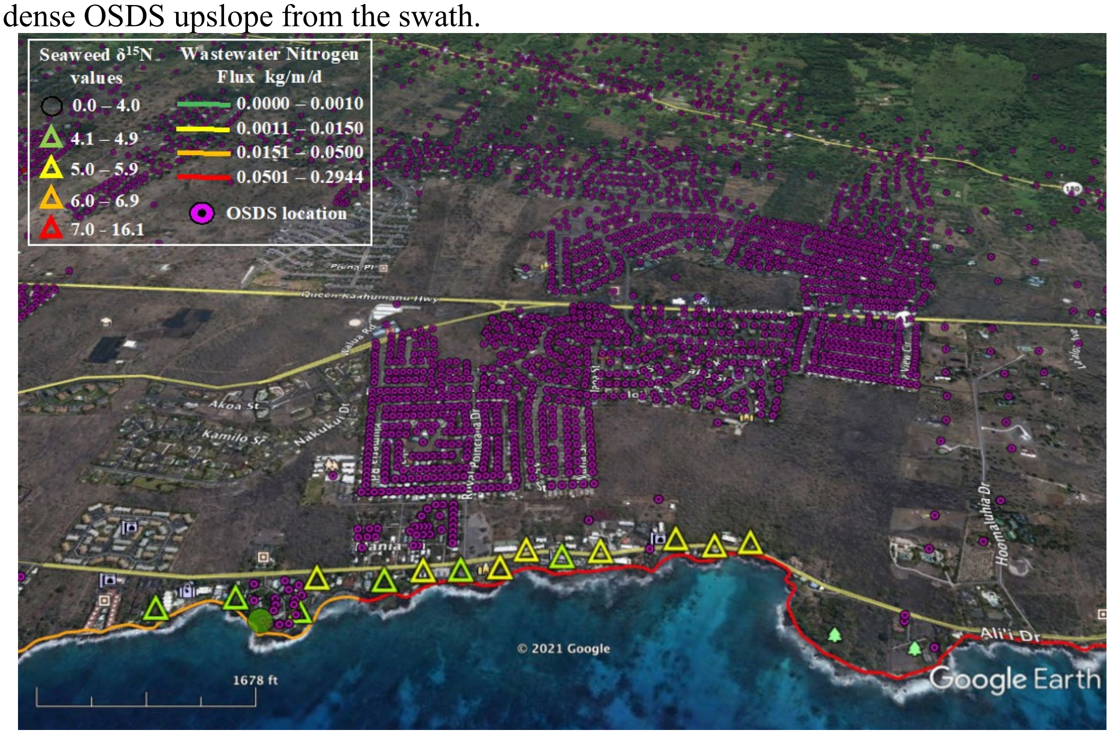


Figure 43. Hawai‘i Island- Holualoa (Kailua-Kona) experimental swath.

The Holualoa (Kailua-Kona) experimental swath shows low to moderate seaweed $\delta^{15}N$ values with high predicted wastewater nitrogen flux to the coastline and very dense OSDS inland from the swath.

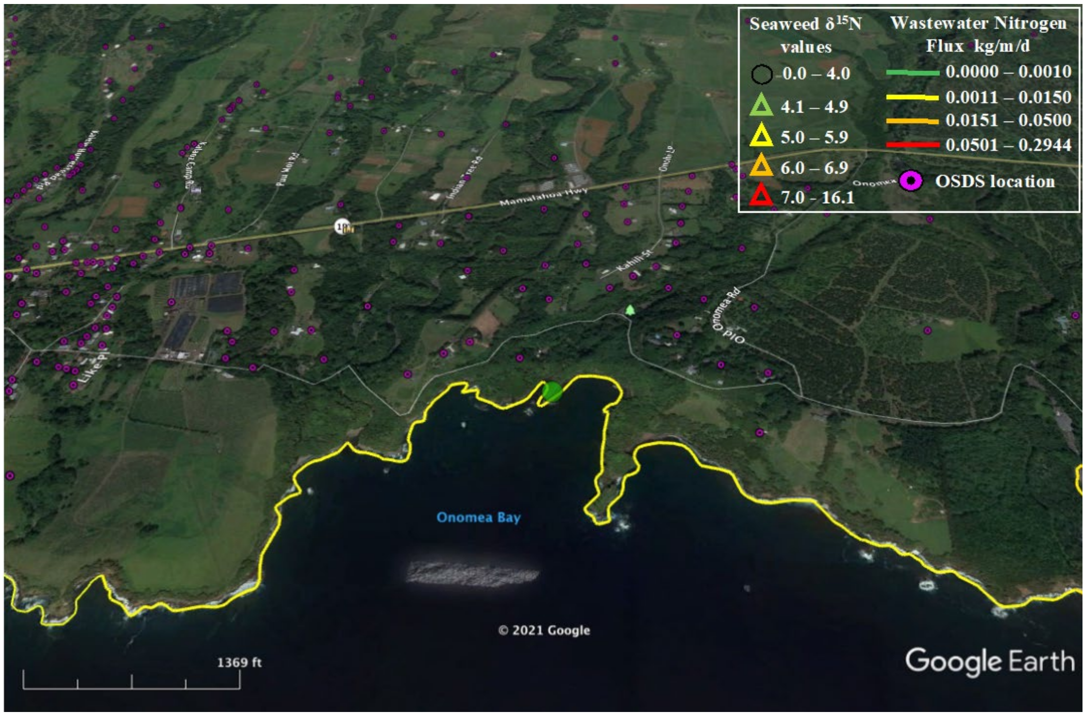


Figure 44. Hawai'i Island- Hamakua control swath.
The Hamakua control swath shows low seaweed $\delta^{15}N$ values with moderate predicted wastewater nitrogen flux to the coastline and scattered OSDS inland from the swath. Also, due to the dangerous cliffs in this area, only one site could be sampled.

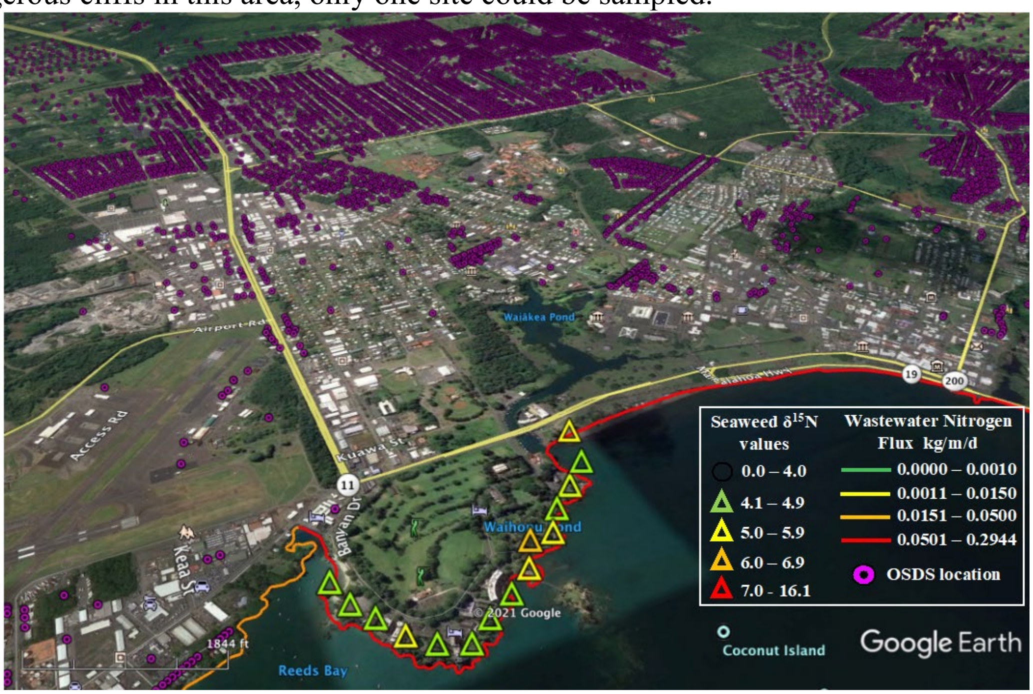


Figure 45. Hawai'i Island- Wailoa (Hilo Bay) swath.
The Wailoa (Hilo Bay) swath shows elevated seaweed $\delta^{15}N$ values with high predicted wastewater nitrogen flux to the coastline and very dense OSDS inland from the swath.

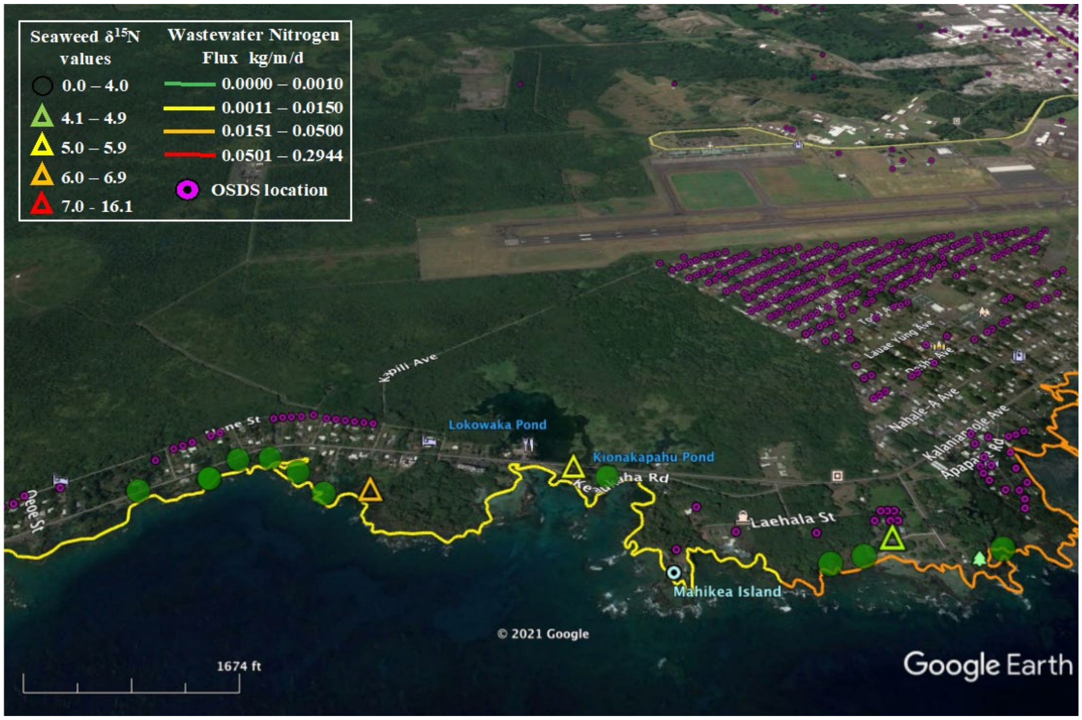


Figure 46. Hawai'i Island- Keaukaha experimental swath.
The Keaukaha experimental swath shows low seaweed $\delta^{15}N$ values with moderate predicted wastewater nitrogen flux to the coastline and a few OSDS near the coast.

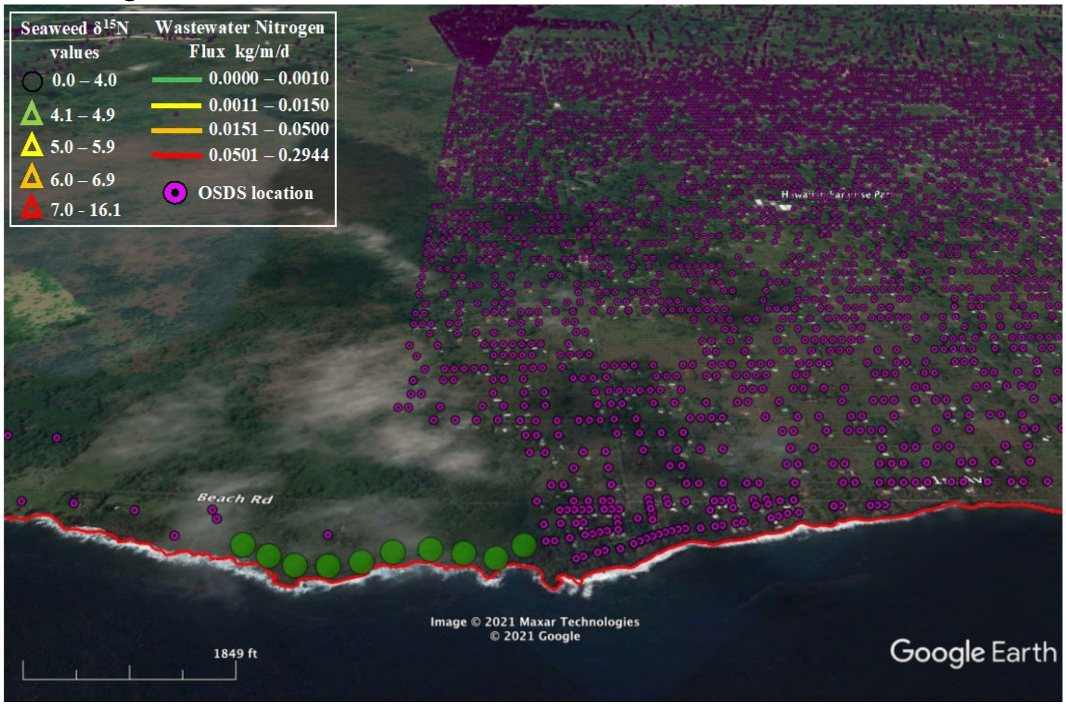


Figure 47. Hawai'i Island- Hawaiian Paradise Park (HPP) experimental swath.
The Hawaiian Paradise Park experimental swath shows low seaweed $\delta^{15}N$ values with high predicted wastewater nitrogen flux to the coastline and very dense OSDS inland and right of the swath.

4.5.5 Hawai‘i Island maximum and average seaweed %N

Of the 363 independent seaweed samples collected on the windward and leeward coasts of Hawai‘i Island, 75% were greater than 1% N (Figure 48). These values exceed the value of 1 %N cited by Barr et al. (2013) for a helathy environment threshold. Similar to the outcomes of the seaweed $\delta^{15}N$ values, Puakō eclipsed the other swaths, where the mean %N of 2.9 ± 1.0% N was greater than the maximum value measured at all the other swaths (1.0-2.9% N). The Wailoa and Mauna Lani grouped together with high maximum values (> 2.3% N) and high mean values (1.9% N). The Wailoa swath was the only swath without sites that were less than 1.0 %N. Keaukaha and Mahai'ula had multiple sites with values >2.0 %N. The remainder of the swaths had a mean %N between 0.9 – 1.3 %N. All swaths except the Wailoa had samples with < 1% N. Average seaweed %N differed significantly among swaths on Hawai‘i Island (ANOVA, $F_{(9,101)} = 14.5$, $P = 8x10^{-15}$).

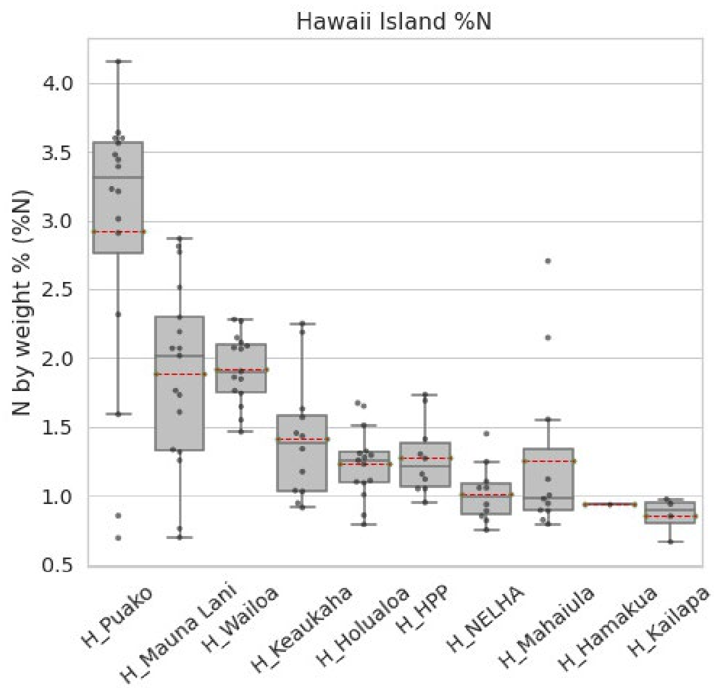


Figure 48. Hawai‘i Island variation among swaths for seaweed %N.
Dashed lines indicate swath-wide mean, while black lines at the mid-point of boxes indicate median values. Boxes represent the inter-quartile range of data.

4.5.6 Hawai‘i Island geographic variability of seaweed %N

The greatest variability in seaweed %N was found at Puako, Mauna Lani, and Mahai’ula, where the %N ranged from less than 1 to greater than 2.5%. Geographic trends in %N were visible at some locations. At Puako, the %N increased to the south, while at the Mauna Lani the %N increased to the north. This mirrored the trends in seaweed $\delta^{15}N$ values observed at these sites (Figure 39 and 40, respectively). At HPP, %N increased to the south, away from the community. The lowest variability in seaweed %N was found at Kailapa, which varied from 0.66 to 0.97%.

4.6 Hawai‘i Island wastewater rank summary

Each swath on Hawai‘i Island was ranked through seaweed $\delta^{15}N$ and %N values for the amount of wastewater detected with number one designated as the highest extent of wastewater detected to number 10 designated as the least amount of wastewater detected. Similar rankings were calculated for the predicted wastewater nitrogen flux and adjacent OSDS density. The end result is a wastewater rank summary (Figure 49) which allows for quick inspection of all four data sets and the internal ranking for all swaths on Hawai’i Island.

At the top of the summary of ranked wastewater indicators with substantial wastewater predicted from the model and detected with elevated seaweed $\delta^{15}N$ and %N values are: Wailoa (Hilo) (Figure 45) and Holualoa (Kona) (Figure 49). Also of significant concern is Puakō, which ranked first for the indication of wastewater pollution based on seaweed $\delta^{15}N$ and %N values (Figure 49). While the ranked seaweed %N at Holualoa was relatively low, the mean value was <0.05% N less than the next two higher ranks (HPP, Mahaiula), such that the ranking of these three were nearly indistinguishable. Changing those ranks would not impact the overall order presented in Figure 49.

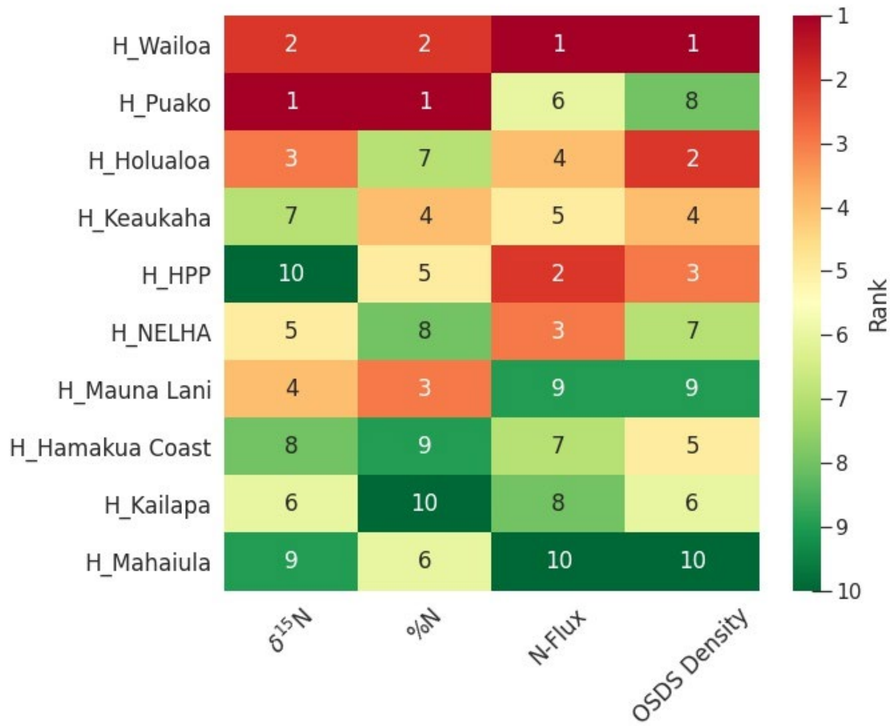


Figure 49. Summary of ranked wastewater indicators for Hawai‘i Island swath averages

In the middle of the ranking are three swaths that were predicted to be impacted by wastewater, but the detected average seaweed $\delta^{15}N$ values were not as high as the other swaths. Keaukaha (Hilo) and NELHA (N. Kona) had replicate samples indicative of wastewater presence but high variability along the swath (Figures 46, 42, and 49). Keaukaha had a site with replicate seaweed $\delta^{15}N$ values > 6.0‰, but also had seaweed samples that were less than 2‰. Based on the modeling, Hawaiian Paradise Park (Puna), was predicted to have the second-highest wastewater nitrogen flux for all of Hawai’i Island, integrating wastewater intrusion from the high density of OSDS in Upper Puna. However, HPP had the lowest seaweed $\delta^{15}N$ values and moderate seaweed %N.

Development in the Mauna Lani region is dominated by resorts and a community with sewer systems and a wastewater treatment. Based on the model, this swath had the second-lowest density of OSDS and predicted N-flux. However, Mauna Lani did have an individual seaweed sample with $\delta^{15}N$ values >6.0‰ and was the only site other than Puakō with seaweed

%N > 2.5%. At Mauna Lani, other sources than wastewater from OSDS must be contributing nitrogen and elevating the seaweed $\delta^{15}N$ signature. Swaths with moderate to low predicted wastewater inputs and moderate to low detection of wastewater included the Hamakua Coast (Figure 44), Kailapa (Figure 38), and Mahai'ula (Figure 41).

Enterococcus

Enterococcus spp. was measured at seven of the swaths on Hawai'i Island, with 146 samples processed. *Enterococcus* spp. concentrations ranged from below the detection limit (<10 MPN/100 ml) up to 3270 MPN/100 ml at Puakō (Table 7). When testing water quality, the HDOH requires that waters sampled over 30 days have a geometric mean less than 35 MPN/100ml, and a Statistical Threshold Value (STV) of 130/100 mL that shall not be exceeded by more than ten percent of samples taken within a thirty-day interval (HAR 11-54-8). Here, average and geometric means are presented, which are not directly comparable to HDOH standards because they are calculated over the entire swath instead of for individual stations. Wailoa, Keaukaha, Puako, and Holualoa all had at least one sample that exceeded the STV. All samples at Mauna Lani, Hawaiian Paradise Park, and NELHA were below the single sample maximum.

Table 7. Variations in average and maximum values for enterococcus (units = MPN/100 ml) from water samples, collected from Hawai'i Island

Locations	Sampling Date	n	% >35 MPN/100ml	Maximum	Average	+ SD	Geometric Mean
Wailoa	4/5/19	27	22%	2419	118 ±	463	11
Keaukaha	4/30/19	30	70%	1314	181 ±	268	62
Hamakua	5/14/19	2	100%	776	595 ±	256	567
HPP*	5/2/19	12	17%	100	18 ±	38	4
Puakō	5/7/19	30	70%	3270	417 ±	630	82
Mauna Lani	5/16/19	15	20%	100	22 ±	41	4
NELHA	4/18/19	15	13%	63	12 ±	20	4
Holualoa	4/16/19	15	7%	279	22 ±	71	4

* HPP = Hawaiian Paradise Park

4.7 Analysis of seaweed data in coastal regions on Kaua'i

4.7.1 Kaua'i coastal seaweed collection for $\delta^{15}N$ and %N values

On Kaua'i coastal waters, cesspools are predicted to contribute about 86 percent of the coastal wastewater nutrient load (Table 3, above). Thus, generally, eight coastal swaths on Kaua'i were sampled to detect wastewater via sampling seaweeds from the months of April to September, the drier months in terms of rainfall (Giambelluca et al., 2013, Rainfall Atlas of Hawai'i), maintaining consistency with the state-wide sampling efforts. The eight locations sampled were: Waiohai, Nāwiliwili, Kapa'a, Moloa'a, Kekaha, Nukoli'i, Kauapea, and Ha'ena. Only samples from Waiohai (4 sites), Nāwiliwili (7 sites), and Kapa'a (9 sites) met the SOP guidelines and were analyzed for results, a total of 20 sites and 60 samples across these three swaths. Further efforts to recollect were stymied by the travel restrictions that occurred at the beginning of the COVID-19 pandemic.

4.7.2 Kaua‘i seaweed nitrogen results

Out of the 20 remaining sites, 13 had average seaweed $\delta^{15}N$ values equal to or greater than 6‰. The wastewater dominated swaths identified by having elevated seaweed $\delta^{15}N$ values for Kaua‘i are: Nāwiliwili Harbor, Waiohai (in Poipu), and portions of Kapa‘a. Out of 20 sites only Kapa‘a (0.748 ± 0.08) had an average seaweed %N value less than 1%. Table 8 provides an overview of data to be discussed in this section.

Table 8. Kaua'i- variations in coastal seaweed samples of swath average, maximum and ranges of $\delta^{15}N$ and %N values.

Location	Swath ave $\delta^{15}N$	$\delta^{15}N$ SD	Swath ave %N	%N SD	Swath Max $\delta^{15}N$, n=3	Swath Max %N, n=3	Swath $\delta^{15}N$ (SD) samples range, n=3:		Swath %N (SD) samples range, n=3:	
							low	high	low	high
Kapa'a	5.86	0.47	1.25	0.10	8.93	1.66	4.25 (0.21)	8.93 (0.84)	0.75 (0.08)	1.66 (0.07)
Nāwiliwili Harbor	8.11	0.46	2.73	0.11	11.23	3.88	4.53 (0.15)	11.23 (0.70)	1.04 (0.07)	3.88 (0.15)
Waiohai (Poipu)	8.44	1.10	1.50	0.21	11.27	2.37	6.87 (1.44)	11.27 (0.57)	1.15 (0.13)	2.37 (0.51)

4.7.3 Kaua‘i maximum and average seaweed $\delta^{15}N$ values

The boxplots of seaweed $\delta^{15}N$ values per swath for Kaua‘i represent the distribution of average values with individual sites shown as black dots (Figure 50). Kapa‘a has a few sites with lower average seaweed $\delta^{15}N$ values but with some overlap with the other two swath areas.

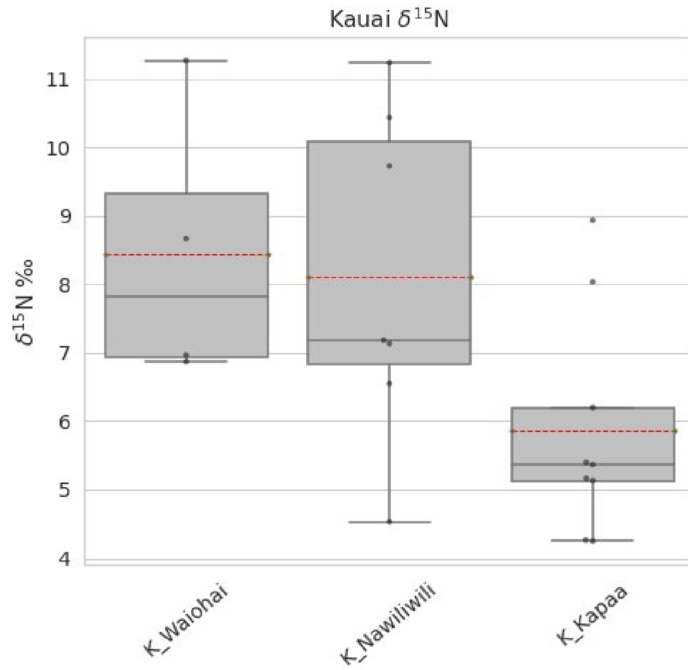


Figure 50. Kaua‘i variation among swaths for average seaweed $\delta^{15}N$ values. Red dashed lines indicate swath-wide mean, while black lines at the mid-point of the boxes indicate median values. Boxes represent the inter-quartile range of data

The two Kapa‘a sites with higher seaweed $\delta^{15}N$ values (8.93‰, 8.03‰) were in front of the Kingdom Hall of Jehovah’s Witnesses and the Kapa‘a Bypass on the Kealia side of the swath (Figure 53). Nāwiliwili had the largest range of seaweed $\delta^{15}N$ values (from 4.53 to 11.23‰, Table 8, Figure 50). The high seaweed $\delta^{15}N$ values are concentrated to the right and inside part of side of the bay, whereas the outer parts of the bay where there is more wave action have lower seaweed $\delta^{15}N$ values (Figure 51). Although Waiohai only had a four collection sites all of the seaweed $\delta^{15}N$ values were over 6‰ (Figures 50 and 52).

4.7.4 Kaua‘i geographic variability of seaweed $\delta^{15}N$ values

The geographic variability of seaweed $\delta^{15}N$ values on Kauai is presented in Figures 51, 52 and 53.

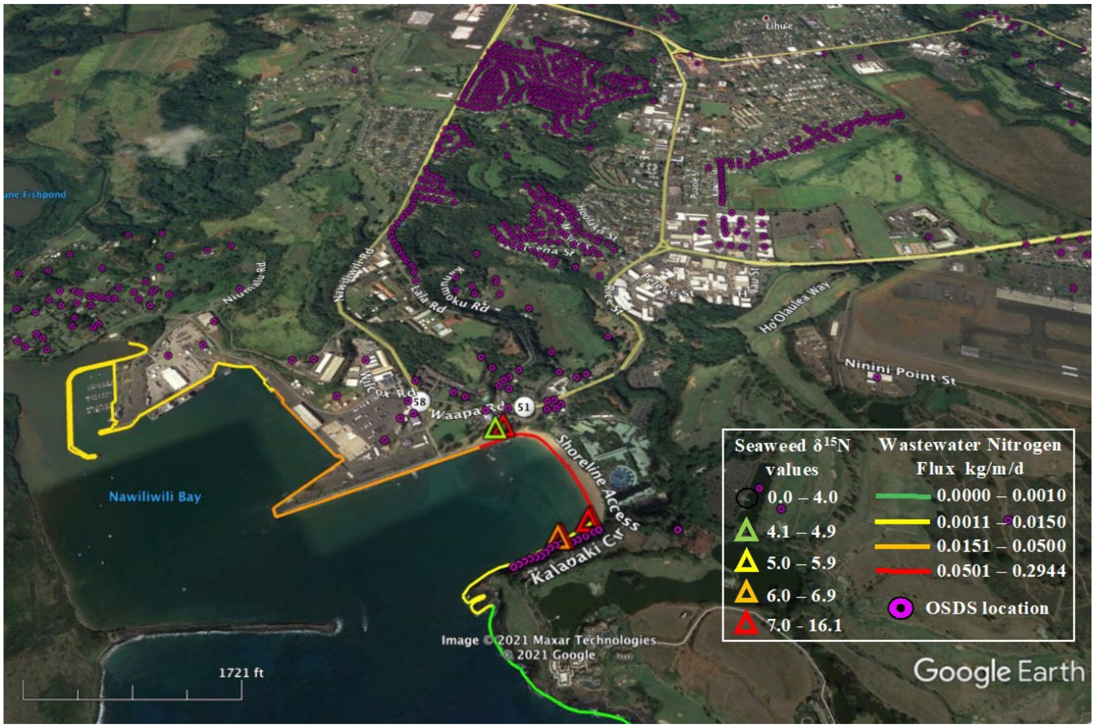


Figure 51. Kaua'i- Nāwiliwili experimental swath.

The Nāwiliwili experimental swath shows high seaweed $\delta^{15}N$ values, high predicted wastewater nitrogen flux to the coastline and very dense OSDS inland from the swath.

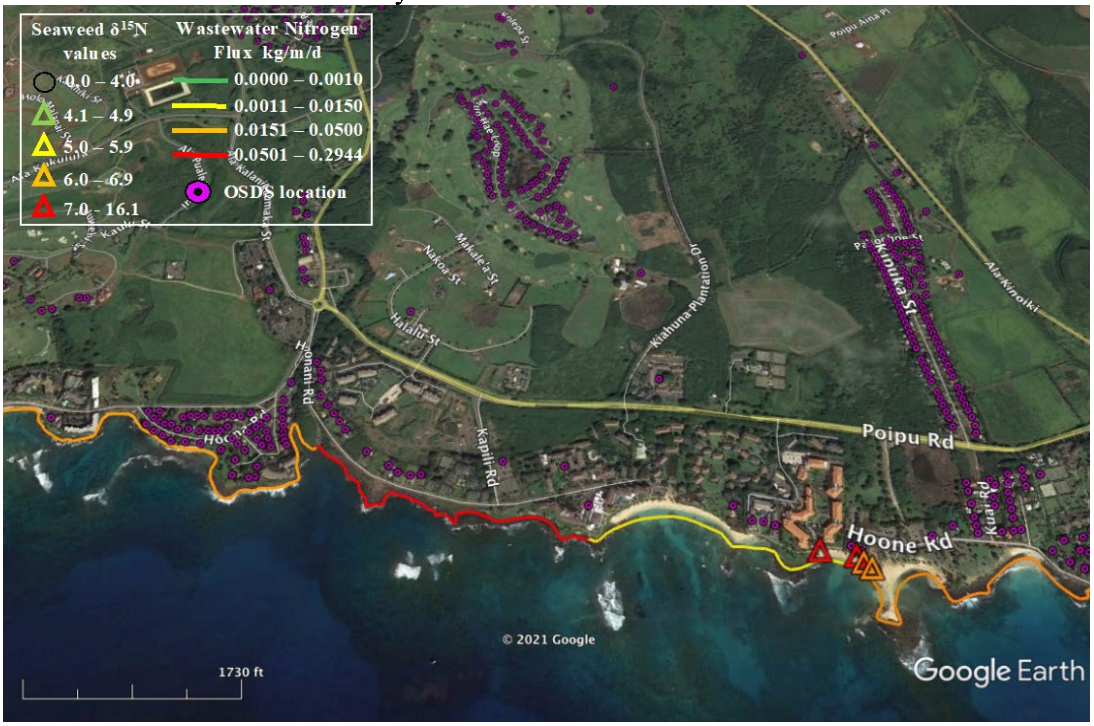


Figure 52. Kaua'i- Poipu (Waiohai) experimental swath.

The Poipu (Waiohai) experimental swath shows high seaweed $\delta^{15}N$ values, high predicted wastewater nitrogen flux to the coastline and very dense areas of OSDS inland from the swath.

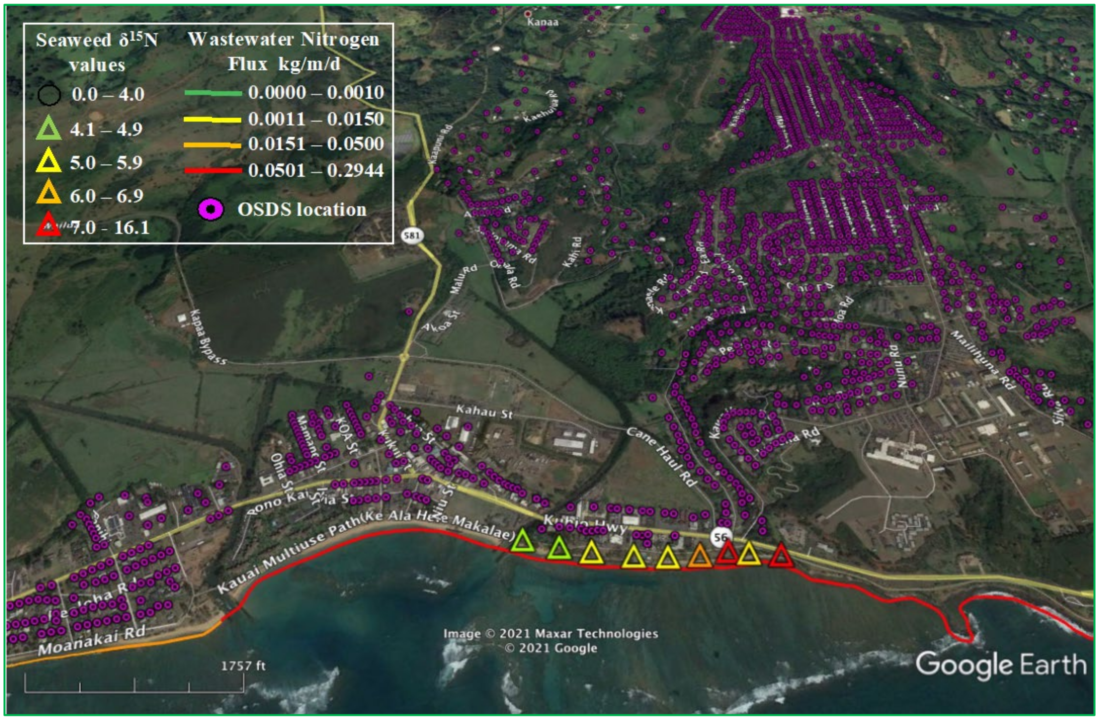


Figure 53. Kauaʻi- Kapaʻa experimental swath.
The Kapaʻa experimental swath shows elevated seaweed $\delta^{15}N$ values, high predicted wastewater nitrogen flux to the coastline and very dense OSDS inland from the swath.

4.7.5 Kauaʻi maximum and average seaweed %N

Among three swaths, only one site had an average %N value less 1% N (Table 8, Figure 54). This occurred on the Kapaʻa swath next to the Waiakaʻea canal. Maximum seaweed %N values per swath show that Nāwiliwili, has a larger range of %N values and has more sites clustered around the 2.0 – 3.5% N range (Figure 54). The Kapaʻa and Waiohai swaths have sites that are more tightly clustered around the 1.0 – 2.0% N range (Figure 54).

The swath wide averages for Kapaʻa (1.25%) and Waiohai's (1.5%) are lower than Nāwiliwili's (2.73%) (Figure 54, Table 8). However, the high %N suggests that there are elevated nutrient loads in the environment at all three of these sites (Barr et al. 2013).

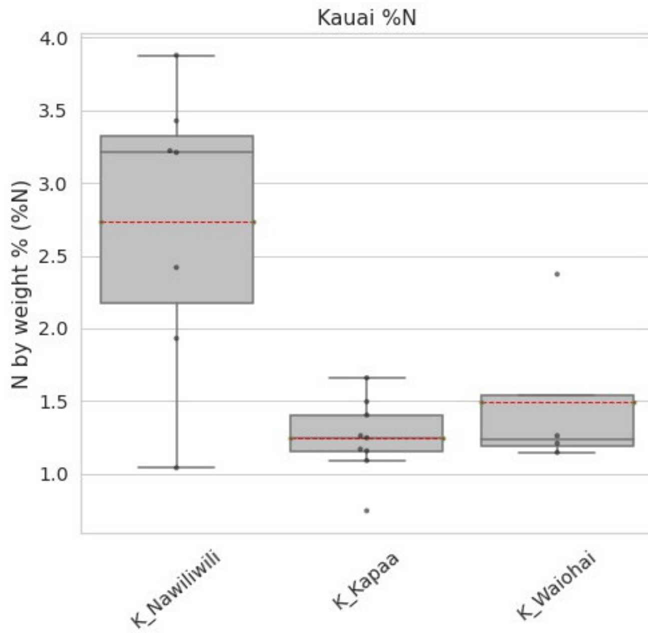


Figure 54**. Kaua‘i seaweed %N values.** Red dashed lines indicate swath-wide mean, while black lines at the mid-point of the boxes indicate median values. Boxes represent the inter-quartile range of data.

4.7.6 Kaua‘i wastewater impact rank summary

For Kaua‘i, any ranked summary is obviously limited by the few seaweed samples that were collected in the pre-COVID pandemic field work. However, this situation becomes an opportunity to use the model outputs to reassess the areas of concern for this island.

For Kaua‘i, the model predicted that Kapa‘a has the highest wastewater nitrogen load. The seaweed $\delta^{15}N$ and %N values ranked lower for Kapa‘a. Inland of the Kapa‘a coastline the nearly 6,600 OSDS, including 5,300 cesspools, discharge a total of about 700 kg of nitrogen to the marine environment. The hydrogeology of Lihu‘e Basin where Kapa‘a is located is very complex with dense massive lavas and sediments overlying dike intruded basalts (Izuka and Gingerich, 1998; Izuka et al., 2018). Because of this complex geology, differences between the modeled and detected wastewater intrusion should be expected in this area. For Waiohai, the model predicted moderate wastewater nitrogen-flux and high OSDS density. Seaweed sampling detected wastewater intrusion in the marine environment through high $\delta^{15}N$ values and a low wastewater nitrogen-flux through low %N values (Table 8, Figures 50 and 52). Nawiliwili, ranked third for OSDS density but ranked first and/or second for wastewater N-flux, seaweed $\delta^{15}N$ and seaweed %N.

SECTION 5 DISCUSSION

Seaweed sampling indicated that wastewater influence on coastal water is significant on all Hawaiian Islands included in this study. O‘ahu, Kaua‘i, Hawai‘i, and Maui all had swaths designated as wastewater dominant sites. This state-wide evaluation and comparison of surveyed swaths indicates that the modeled N-flux and mapped OSDS density results are good predictors of wastewater-derived N in coastal water as supported by the seaweed $\delta^{15}N$ and %N results. This result is further supported by strong significant statistical relationships between seaweed $\delta^{15}N$ values and OSDS density (Figure 9), consistent with results from studies around the world including Hawai‘i (Table 2; Costanzo et al., 2005; Dailer et al., 2012; Dailer et al., 2012; Amato et al., 2020).

This study documents that groundwater modeling and OSDS density can be used to estimate the wastewater impact to coastal areas of Hawai‘i. Coastal areas designated here as wastewater dominant should be given a high priority for OSDS upgrades. These regions are: Hau‘ula, Ka‘a‘awa, Waialua, Wailupe, Waiehu, Wailea, Puakō (S. Kohala), Nāwiliwili Harbor, and Waiohai. In areas designated as influenced by wastewater (Holualoa, Kailapa (S. Kohala), Mauna Lani (Kohala), NEHLA (Kailua-Kona), Wailoa River, Kapa‘a, Kihei South, Wailea South, Diamond Head, Kalaeloa, Waianae) additional information may be needed to verify that wastewater is the major source of nitrogen in these areas. Finally, regions where where average swath values for $\delta^{15}N$ were below 4.0‰ (Hamakua Coast, Keaukaha, Mahaiula, Kihei North, Olowalu-Ukumehame, Stables-Spreckelsville, Paia-Kuau, La Perouse, Waihe‘e, Makua, Mokapu, and Sunset Beach), should receive a low priority for OSDS upgrades as there appears to be little to no wastewater input.

Current efforts are underway to use the results from this study in conjunction with other data sets to assist with cesspool upgrade prioritization (Mezzacapo and Shuler, 2021). The data produced by this study are the most robust and geographically widespread assessment of wastewater influence on coastal waters and are therefore, a valuable resource to ground-truth future cesspool replacement prioritization efforts. Coastal seaweed assessments continue to be a quick, inexpensive, and effective tool to monitor changes as cesspool conversions and other wasterwater changes are underway (Barr et al., 2013; Costanzo et al., 2005; Smith et al., 2016).

The results from both the groundwater modeling and coastal seaweed sampling indicate that wastewater is detectable in coastal waters across the state of Hawai‘i. These results are in agreement with the findings of previous studies conducted in Hawai‘i that have documented the presence of wastewater in coastal areas of Hawai‘i (Hunt and Rosa, 2009; Dailer et al., 2010; Glenn et al., 2012, 2013; Amato et al., 2016, 2020; Abaya et al., 2018). While there was generally good agreement between seaweed and modeled parameters in swaths designated as wastewater dominant and little or no wastewater detected, swaths designated as wastewater influenced showed some mismatch. In addition to reasons previously discussed (agriculture, coastal mixing, etc.), it is important to understand that a location bias may exist between sampling and modeling methods in some regions. Present day understanding of Hawai‘i’s subsurface hydrogeology is very limited, which means significant assumptions had to made to create the modeled flow-paths and support the interpretation that all modeled N discharges directly to the coastline. Additional considerations are that: 1) the seaweed $\delta^{15}N$ values represent a composite of all available nitrogen sources in the groundwater discharging nearshore, 2) the percent tissue nitrogen of the seaweed is a qualitative indictor of the relative mass of nitrogen discharging nearshore and 3) the seaweed $\delta^{15}N$ values are a qualitative indicator of the dominant source of nitrogen discharging nearshore. Despite these considerations, the data presented here show strong correspondence among model results and the measured seaweed $\delta^{15}N$ and %N values.

This suggests that one could extrapolate this relationship to areas that were not surveyed for seaweed parameters in this study. For example, modeled nitrogen-flux and OSDS density values may assist with estimation of the relative impact of wastewater sources for many other areas suspected of substantial wastewater, including additional sites Kauaʻi which were not thoroughly sampled due to limitations from the COVID-19 pandemic. Thus, while cesspool nitrogen is a significant source of coastal pollution throughout the Main Hawaiian Islands, strong agreement between model results and seaweed tissue sampling for the wastewater dominated sites suggests that modeled N-flux and mapped OSDS density can be used to identify the highest priority regions for cesspool upgrades if logistical or physical conditions preclude direct field sampling.

5.1 Evaluation of the link between the OSDS and the groundwater flow field

The hypothesis of this study is that wastewater is a main driver that enriches the seaweed tissue in the nitrogen-15 isotope (reported as $\delta^{15}N$). For this study to be useful, it must be shown that a correlation exists between the magnitude of coastal discharge of OSDS wastewater N and the coastal seaweed $\delta^{15}N$ values. The seaweed $\delta^{15}N$ values reflect an integration of the nitrogen sources and processes along the groundwater flow path. The primary sources of nitrogen include atmospheric deposition, natural decay of organic matter, fertilizer leachate, and of course wastewater. This study focuses primarily on wastewater from OSDS with injected wastewater as secondary source of wastewater N source. Application of recycled water was not considered by this study, but where applied will affect the nitrogen composition of the coastal seaweed.

If the hypothesized correlation exists, the seaweed $\delta^{15}N$ values would increase as the modeled rate OSDS-N increases. To test the correlation between the measured seaweed $\delta^{15}N$ values and the modeled discharge of OSDS a spatial join in GIS was performed between the two data sets. This operation attaches the model computed OSDS-N to the center point of the seaweed sampling swath. The computed OSDS-N flux was used rather than the number of OSDS inland of the sampling swath since it is the mass of nitrogen from the various N sources that will determine the seaweed $\delta^{15}N$ values.

This test confirmed that the magnitude of the OSDS-N discharging (in kg/m/d) to the swath area shows a good correlation with measured seaweed $\delta^{15}N$ values. Figure 55 shows that this relationship is bimodal, plotting in two groups designated Group I and Group II. The sample swaths in Group I show a steep slope in the OSDS-N Flux to seaweed $\delta^{15}N$ value relationship with a coefficient of correlation of 0.64. Group II has a less steep slope but also having a very good correlation coefficient of 0.73. Two swaths failed to fall into either group. These swaths are the Hawaiian Paradise Park on the Hawaiʻi Island and the Waialua swath on Oʻahu. The results of this GIS linking are tabulated in Table 9 that lists the swath name, the swath average seaweed $\delta^{15}N$ value, the number of OSDS within the modeled flow path to the swath area, and the OSDS-N discharge per meter of shoreline. Table 9 orders the swaths by group with subordinate ordering by seaweed $\delta^{15}N$ value (from lowest to greatest value).

As Table 9 and Figure 55 show, there is a very good correlation between the measured seaweed $\delta^{15}N$ value and the modeled flux of OSDS-N the swath area. The response of the seaweed $\delta^{15}N$ value to the OSDS sourced N at the coast falls into two distinct groups with very different slopes in the N-Flux to seaweed $\delta^{15}N$ value best fit line. The Group I with the steep best fit line includes swaths where the interference from other N sources is low and the majority of the OSDS are located closer to the coast (e.g., Haʻalua, Kaʻaʻawa, and Puako). The Group II best fit line with the shallower slope includes swaths that have more interfering sources of N (e.g., Stables-Spreckelville, Paia-Kuau, North Kihei), or other factors that will influence the seaweed $\delta^{15}N$ value. Other factors include in the large infiltration of pumped seawater at NELHA and the small scale of the OSDS communities at Black Point and Mokapu.

Two swaths didn't fit into either group. The first such swath, Hawaiian Paradise Park, is located along the northeast facing coast of the Puna District on Hawaiʻi Island. This area hosts a very large number of OSDS that are primarily cesspools yet the seaweed $\delta^{15}N$ value was near the lowest measured. There are multiple factors that could be responsible for the much lower than expected seaweed $\delta^{15}N$ value. The first would be that an inspection of Figure 47 shows that the sample swath location was offset from the coastal OSDS location. However, there are many OSDS upslope that should contribute N to the sampled section of coastline. A more probable explanation is that Puna District coastline is exposed to dominant northeast trade winds with no fringing reef. This results in a large rate of water turnover, which may result in a N residence time that is too short for the seaweed to effectively assimilate the OSDS-N. A similar situation occurs on Oahu where the seaweed $\delta^{15}N$ values of the Sunset Beach are lower than expected given that there are numerous OSDS along the coast and upslope of that swath. Contrast this with Hauʻula and Kaʻaʻaʻwa where there is a fringing reef that reduces the rate of coastal water turnover, resulting in highly elevated seaweed $\delta^{15}N$ values. Delevaux et al., (2018) cites wave power of which exposure to northeast trade winds and the absence of a fringing reef are factors, as a mitigating coral reef degradation from terrestrial stresses.

The Waialua, Oʻahu swath also failed to fall into either Group I or Group II, but rather is located between the groups in Figure 55. Nitrogen from agriculture practices and the application recycled water are possibly interfering sources of N that are in the groundwater flow path to the seaweed swath area. While the interference from fertilizer leachate would tend to result in the Waialua swath falling into Group II, the wastewater contribution from recycled water would tend to reinforce the OSDS-N signal and move the resulting seaweed $\delta^{15}N$ values toward Group I. The result is that the OSDS near the coast and application of recycle water tend move this swath into alignment with Group I, but the large amount of interference from fertilizer leachate tends to move this swath into alignment with Group II. The result is that the Waialua swath plots between the two groups.

The measured seaweed $\delta^{15}N$ values integrate all sources of N and are not a direct measure of the absolute flux of OSDS-N, but rather the relative contribution of OSDS-N to the total N budget. Figure 56 shows two contrasting examples from Maui. The N contributions from natural sources and agriculture were estimated based on measured groundwater nitrate concentration in drinking water wells that are outside of the OSDS area of influence (DOH, 2020a). The concentration was converted to flux using the recharge in the aquifer discharging to coast where the swaths are located (Johnson et al., 2018). The Waiehu swath is in an area with a small amount of agriculture and some OSDS. Due to the low contribution of N from agriculture and natural sources, the coastal seaweed $\delta^{15}N$ value is 6.9‰, a value the indicates wastewater is dominating the N budget. The swath average seaweed %N is lower than that for Paia-Kuau while the swath average seaweed □ ^{15}N value is greater. The groundwater discharging at the location of the Paia-Kuau swath receives OSDS leachate from the Upcountry Maui communities but receives significant fertilizer leachate as it flows beneath the agricultural areas down slope from the communities served by OSDS. The fertilizer leachate elevates the seaweed %N while depressing the seaweed δ^{15}N value. The Paia-Kuau area has many more OSDS contributing to the N-budget than Waiehu, but the seaweed δ^{15}N values are lower than Waiehu due to the large contribution of agriculture N. The primary conclusion is that while many factors affect the seaweed δ^{15}N values and %N, a good correlation exists between the modeled OSDS-N flux and measured seaweed δ^{15}N values. This indicates that the seaweed δ^{15}N values are a reliable indicator of the relative contribution of OSDS-N to coastal N-budget.

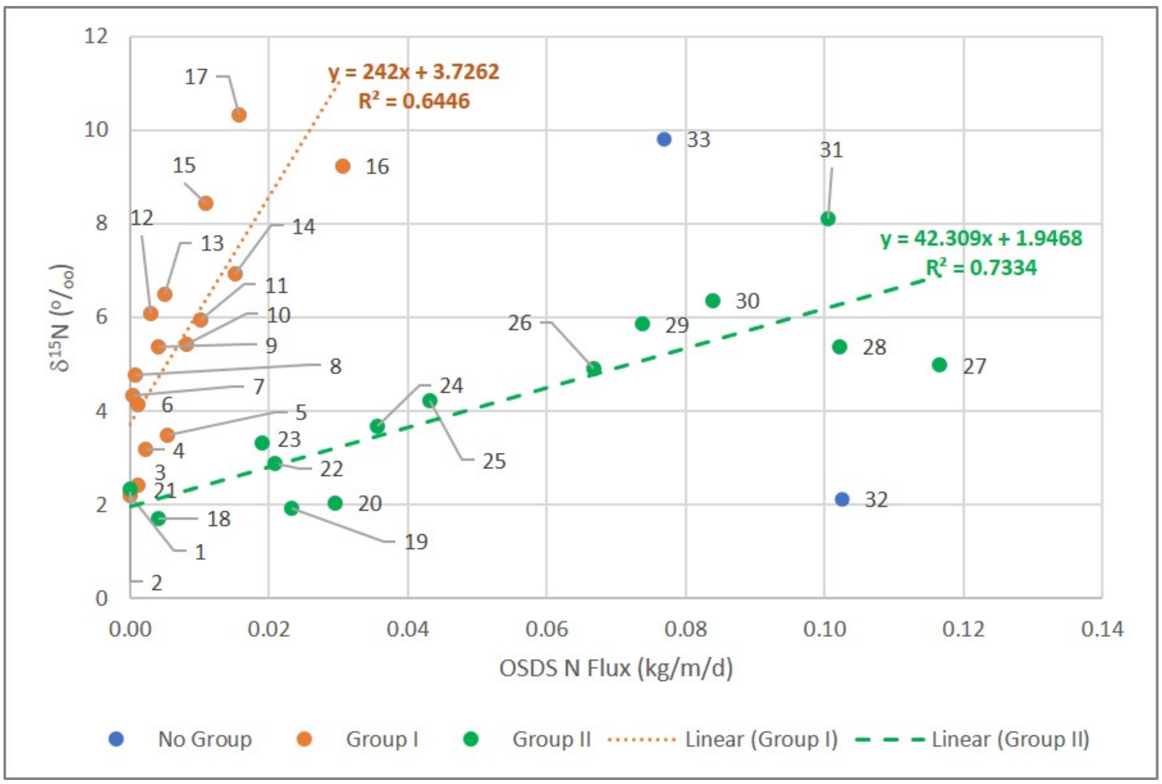


Figure 55. The relationship between modeled coastal OSDS nitrogen flux and measured seaweed δ^{15}N values.
The number labels correspond to the numbers in the "Key" column of Table 9.

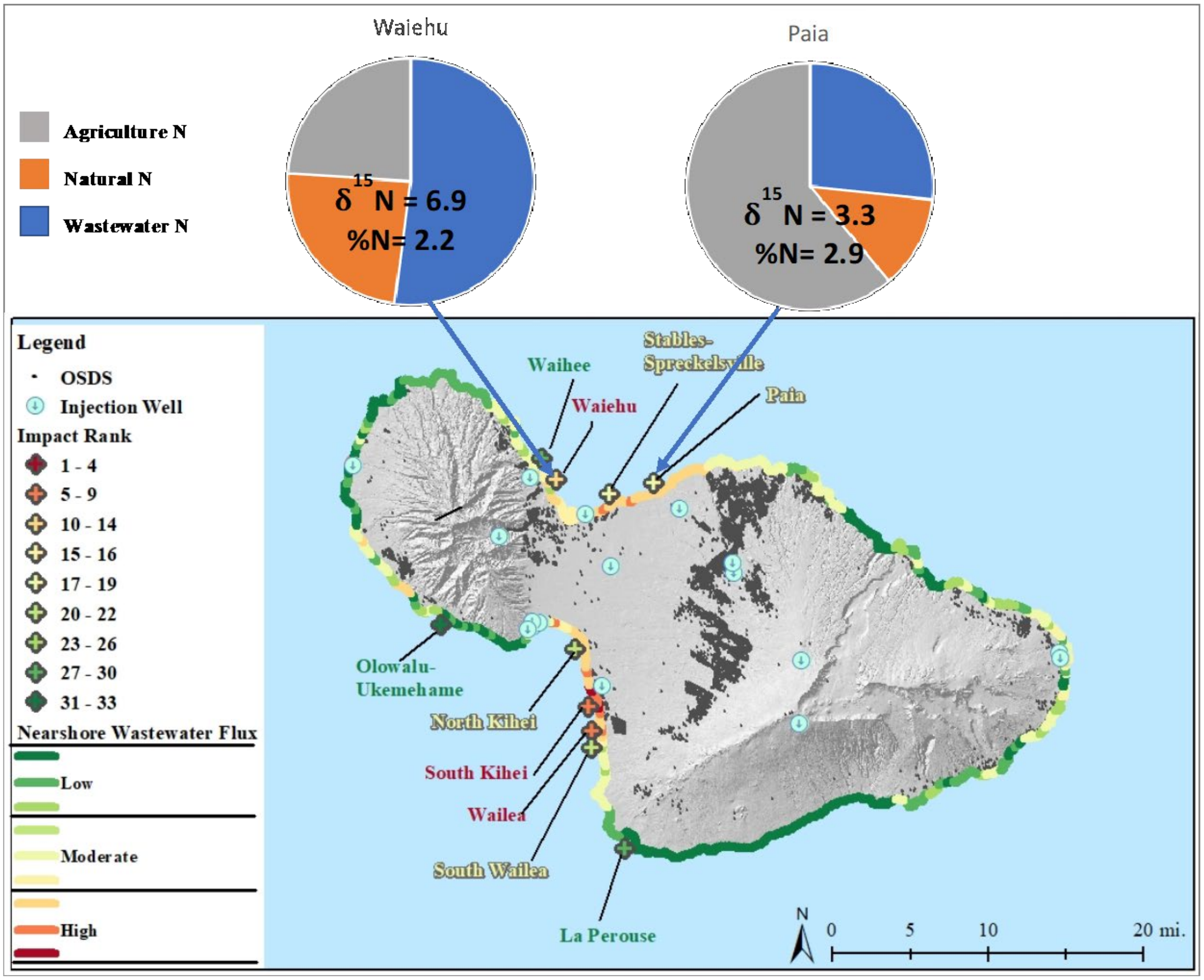


Figure 56. The distribution of the coastal OSDS-N flux, seaweed sampling swaths colored by impact rank, and pie charts of N-source contributions for two areas.
The number labels correspond to the numbers in the "Key" column of Table 9.

Table 9. Results of spatial linkage of the swath average seaweed $\delta^{15}N$ values to the modeled OSDS-N flux.

Island	Area	Swath	Group I or II or none	Key	OSDS	OSDS-N Flux (kg/m/d)	Swath Average $\delta^{15}N$ (‰)
Maui	Olowalu-Ukumehame	M_Olo-Uku	Group I	1	1	0.0001	2.2
Oahu	Makua	O_Makua	Group I	2	0	0.0000	2.3
Hawaii	Mahailula	H_mahaiula	Group I	3	65	0.0011	2.4
Hawaii	Hamakua	H_Hamakua Coast	Group I	4	113	0.0023	3.2
Hawaii	Keaukaha	H_Keaukaha	Group I	5	376	0.0054	3.5
Hawaii	Kailapa	H_Kailapa	Group I	6	37	0.0012	4.1
Hawaii	Mauna Lani	H_Mauna Lani	Group I	7	430	0.0004	4.3
Maui	South Wailea	M_S.Wailea	Group I	8	7	0.0008	4.8
Oahu	Kalaeloa	O_Kalaeloa	Group I	9	18	0.0042	5.4
Oahu	Waianae	O_Waianae	Group I	10	94	0.0082	5.4
Oahu	Diamond Head	O_Black Point	Group I	11	82	0.0102	6.0
Oahu	Wailupe	O_Wailupe	Group I	12	15	0.0031	6.1
Hawaii	Puako	H_Puako	Group I	13	108	0.0050	6.5
Maui	Waiehu	M_Waiehu	Group I	14	61	0.0152	6.9
Kauai	Waiohai	K_waiohai	Group I	15	48	0.0109	8.4
Oahu	Hauula	O_Hauula	Group I	16	210	0.0306	9.2
Oahu	Kaaawa	O_Kaaawa	Group I	17	133	0.0157	10.3
Maui	Waihee	M_Waihee	Group II	18	63	0.0041	1.7
Maui	North Kihei	M_N.Kihei	Group II	19	173	0.0233	1.9
Maui	Stables-Spreckelsville	M_Sta-Spr	Group II	20	270	0.0295	2.0
Maui	La Perouse	M_La Perouse	Group II	21	1	0.0001	2.3
Oahu	Mokapu	O_Mokapu	Group II	22	169	0.0210	2.9
Maui	Paia	M_Paia-Kuau	Group II	23	215	0.0191	3.3
Oahu	Sunset Beach	O_Sunset	Group II	24	263	0.0355	3.7
Hawaii	NELHA	H_NELHA	Group II	25	1024	0.0432	4.2
Hawaii	Holualoa	H_Holualoa	Group II	26	1060	0.0668	4.9
Hawaii	Wailoa	H_Wailoa	Group II	27	3520	0.1166	5.0
Maui	South Kihei	M_S.Kihei	Group II	28	510	0.1022	5.4
Kauai	Kapaa	K_Kapaa	Group II	29	266	0.0737	5.9
Maui	Wailea	M_Wailea	Group II	30	529	0.0839	6.4
Kauai	Nawiliwili	K_Nawiliwili	Group II	31	490	0.1006	8.1
Hawaii	Hawaiian Paradise Park	H_HPP	None	32	9168	0.1024	2.1
Oahu	Waialua	O_Waialua	None	33	537	0.0769	9.8

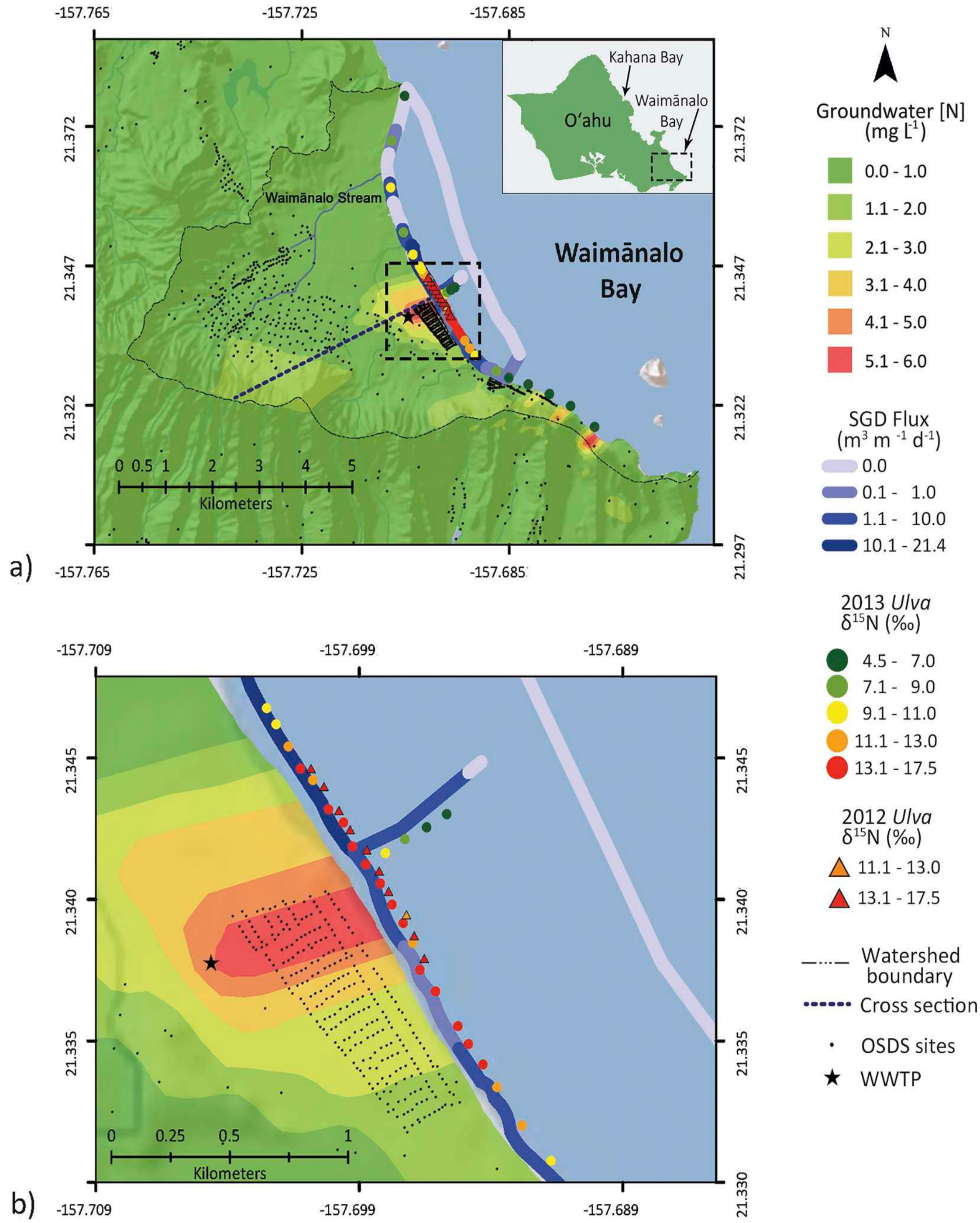
5.2 O‘ahu

On O‘ahu, cesspools contribute about 83% of the coastal wastewater nitrogen load (Table 3). The highest seaweed δ^{15}N values on O‘ahu were found at Ka‘a‘awa, Hau‘ula and Waialua and these results are indicating that wastewater is reaching the coastline in these areas in agreement with the wastewater transport modeling predictions (Figures 14, 20 and 21, Table 4). The coastal area in Waialua is also impacted by industrial scale agriculture, which is reflected the elevated percent nitrogen in the seaweed tissue of 2% (Table 4). While the model for the Wai‘anae coast indicated a significant wastewater load, the seaweed data did not reflect this across the entire swath (Table 4, Figure 16). The range of seaweed δ^{15}N values was from 2.4 to 8.27‰, which shows that there is great N source variability along this swath (Table 4, Figure 16).

Much of leeward O‘ahu occurs in the ancient caldera and the rift zone for the Wai‘anae Volcano. The dikes associated with the rift zone and caldera have a general southeast to northwest orientation (Takasaki and Mink, 1985) that will strongly influence the groundwater flow trajectory inducting uncertainty into the precise groundwater flow trajectory. Also, the OSDS in the Wai‘anae area are located more inland adding further uncertainty about where exactly along the shoreline the wastewater contaminated groundwater will discharge.

Similar to the results from Wai‘anae, the seaweed data collected at Sunset Beach are not consistent with the predicted coastal nitrogen load dominated by wastewater. At Sunset Beach, the five northeast sampling sites have few OSDS inland of them. However, the four southwest sampling sites of this area are adjacent to nearshore OSDS and should be showing an elevated δ^{15}N signature (Figure 11). Not considered by this study is effect of nearshore currents, the residence time of wastewater-N once it is discharged to the marine environment, and how rapidly the seaweed takes up the N in the submarine groundwater discharge. Sunset Beach is along a northeast/southwest trending coastline and exposed to the northeast trade winds that likely increase the turnover rate of the nearshore waters, reducing the wastewater N residence time. Also, the northwest algae samples were collected from a shoreline the fronts the University of Hawai‘i, Agricultural Experiment Station where research is done for the livestock industry. This could account for the elevated algal □^{15}N along a stretch of coastline with no OSDS.

The results from O‘ahu have good agreement with those of previous studies using similar methods in Hawai‘i (Amato et al., 2016; Amato et al., 2020). The Waimanalo area has been extensively studied because of high coastal OSDS density and municipal wastewater injection wells (Amato et al., 2020). Research conducted in Waimanalo shows that the nearshore waters are affected by both wastewater N sources through elevated seaweed δ^{15}N values and %N measured over multiple years (presented below in Fig. 3a & b, from Amato et al., 2020).



Amato et al. 2020 Fig. 3. Waimānalo case study. a) *Ulva* tissue $\delta^{15}N$ values are shown as filled triangles for 2012 deployments (n = 10) as filled circles for 2013 deployments (n =36). SGD flux estimates ($m^3\ m^{-1}\ d^{-1}$) are shown as colored blue bands. Scale for $\delta^{15}N$ and SGD flux is nonlinear. Estimated groundwater [N] ($mg\ l^{-1}$) is shown as colored polygons overlain on a shaded relief map of O'ahu. The location of OSDS sites (small back dots) and the Waimānalo WWTP (black star) are shown. The location of the geologic cross section of Waimānalo (Supp. Fig. 2) from Lum and Stearns (1970) is shown as a dashed line. b) Enlarged view of the central region of Waimānalo Bay.

Amato, D.W., Whittier, R.B., Dulai, H. and Smith, C.M. 2020. Seaweed bioassays detect modeled loading of wastewater-derived nitrogen in coastal waters of O'ahu, Hawai'i. Marine Pollution Bulletin. 150. https://doi.org/10.1016/j.marpolbul.2019.110668

5.3 Maui

On Maui, the highest seaweed $\delta^{15}N$ value was 10.2‰ from the South Kīhei swath and is likely indicating that the injection well effluent is emerging from the Kīhei Wastewater Recclaimation Facility (Table 5, Figure 27). The elevated seaweed $\delta^{15}N$ values on the South Kīhei swath are in agreement with the model results of high wastewater N-flux to this coastline (Figure 27). Previous studies have also documented the presence of wastewater emerging in this area through seaweed $\delta^{15}N$ values (Dailer et al., 2010; Hunt and Rosa 2009).

The seaweed data from the Spreckelsville and Paia-Kuau areas showed low $\delta^{15}N$ values with very elevated %N (Table 5, Figures 33 and 34). The seaweed $\delta^{15}N$ values in this area ranged from 0.7 to 4.3‰ with an average of 1.9‰ across the swath (Table 5, Figures 33 and 34). These seaweed $\delta^{15}N$ values are remarkably similar to those found previously for this coastline which ranged from 1.3 to 4.3‰ (Dailer et al., 2010), further supporting the validity of these findings. The combination of low seaweed $\delta^{15}N$ values with elevated percent tissue nitrogen (ranging from 3.00 to 4.43% and a swath average of 3.58%, Table 5) suggests that the coastal nitrogen load in this area is dominated by legacy agricultural nitrate. Sugarcane cultivation ended on the west slope of Haleakala in 2016 (Star Advertiser, 2016) but the legacy fertilizer nitrogen leaching from the soil combined with what is already in the aquifer may continue to discharge along the coastline for decades. Another factor affecting the nitrogen composition of the coastal seaweed is where the nitrogen intercepts groundwater flow path. For groundwater discharging to the eastern shore of the north isthmus, the wastewater nitrogen source is upslope of the agricultural nitrogen source. This results in the agricultural nitrogen being preferentially discharged nearshore where the seaweed samples were collected.

The seaweed data and model results for North Kīhei indicate sources of nitrogen similar to that of the north isthmus (Stables-Spreckelsville and Paia-Kuau) coastline where the modeling shows high a wastewater nitrogen flux to the coastal waters, but the seaweed $\delta^{15}N$ values indicate that the legacy agricultural fertilizer is the dominant nitrogen source (Table 5, Figure 26). Similarly, the North Kīhei swath had low seaweed $\delta^{15}N$ values ranging from 0.73 to 2.80‰ and the swath average was 1.91‰ (Table 5, Figure 26). The seaweed %N from the North Kīhei swath was very high ranging from 3.50 to 4.21% and the swath average was 3.78% (Table 5). This is consistent with the hydrology of the area since much of the groundwater that discharges along the North Kīhei coast flows beneath former sugar cane fields. In South Kīhei, the seaweed %N decreased while the $\delta^{15}N$ values increased indicating a transition from agricultural to wastewater nitrogen dominance (Figure 27). The seaweed results from Wailea show significantly elevated seaweed $\delta^{15}N$ values with a swath average of 6.36‰ and a range from 4.87 to 7.33‰ (Table 5, Figure 28) but a moderate %N (swath average of 2.49% and range from 0.90 to 4.14%, Table 5). This indicates that the total coastal nitrogen load in Wailea is less than that of North Kīhei and it is dominated by wastewater leachate. The Maui Meadows subdivision appears to the be source of the wastewater nitrogen. Although the Wailea Golf Course uses reclaimed wastewater for irrigation, the seaweed $\delta^{15}N$ values adjacent to the golf course only were not elevated (South Wailea swath, Figure 29). The seaweed $\delta^{15}N$ values were elevated across the Wailea swath adjacent to the Maui Meadows subdivision (Figure 28).

The Waiehu seaweed sampling swath overlies two coastal nitrogen model segments (Figure 32). Most of the Waiehu seaweed $\delta^{15}N$ values indicate that wastewater nitrogen is the dominant nitrogen source of the coastal nitrogen load. The seaweed $\delta^{15}N$ values for the Waiehu swath averaged 6.88‰ and ranged from 3.63 to 8.30‰ (Table 5, Figure 32). The percent tissue nitrogen for the Waiehu swath averaged 2.45% and ranged from 1.20 to 3.88% (Table 5). The model indicates a significant wastewater flux only occurs in the northwest half of the Waiehu swath. When the model results are compared to the measured seaweed %N, there is good agreement in the southeast half of the Waiehu swath. This agreement occurs because the seaweed %N values are low (1.52 to 1.86%) indicating a small wastewater flux as the model predicts. The northwest half of the Waiehu swath shows significantly elevated seaweed %N (3.43%) and seaweed $\delta^{15}N$ values (up to 8.3‰), which is consistent with the elevated wastewater nitrogen flux predicted by the model. Considering all three factors it appears that coastal nitrogen load in the Waiehu swath is dominated by wastewater, but the wastewater nutrient load is only significant in the northwest half of that swath. The Waiehu Golf Course does not use reclaimed wastewater for irrigation.

5.4 Hawai‘i Island

On the windward side of Hawai'i Island, the Hilo Bay and Hawaiian Paradise Park regions were predicted to have the highest wastewater impact based on the density of cesspools and the modeled nitrogen flux. Three swaths were sampled in these regions with different wastewater impacts. The Wailoa swath had the second-highest average seaweed $\delta^{15}N$ and %N values (Figure 45). This swath is located behind the breakwater that shelters Hilo Harbor, which limits exchange between groundwater discharge, river discharge from the Wailuku and Wailoa rivers, and the open ocean. The reduced exchange between wastewater-derrived fresh water and the open ocean likely contributed to the low variability in seaweed $\delta^{15}N$ values observed along this swath.

The Keaukaha swath was also located along Hilo Bay but outside the breakwater and away from river inputs. Along this swath, groundwater springs were abundant and seaweed $\delta^{15}N$ values varied widely, ranging from 1.4 to 6.1‰. This variability suggests that wastewater inputs are localized along this swath, depending on the magnitude of wastewater in the groundwater and the magnitude of nearshore ocean mixing (Table 6, Figure 46).

The Hawaiian Paradise Park swath had low wastewater detected, with all seaweed $\delta^{15}N$ values < 2.5‰ (Figure 47, Tables 6 & 7). The wastewater from OSDS in HPP and upland communities must reach the ocean somewhere, but it was not detected where the seaweed samples were collected despite the presence of groundwater springs. Sources of N other than OSDS, such as agriculture, may be dominating in the swath that was sampled, or the hydrology is more complicated causing the OSDS-N from upland cesspools to discharge elsewhere. Further work to determine the fate of wastewater from Puna communities is recommended. Similar to Sunset Beach, the coastline fronting HPP is exposed to the northeast trade winds that likely increase the water turnover rate, reducing the wastewater-N residence time.

On the leeward side of Hawai‘i Island, Holualoa and NELHA swaths are both located along the West Hawai'i shoreline that was predicted to have the highest wastewater nitrogen flux based on the density of cesspools. At Holualoa, only a few single seaweed samples had $\delta^{15}N$ values ≥ 6‰, but the swath maintained the third highest average seaweed $\delta^{15}N$ along the entire swath (Figure 43). The low variability of seaweed $\delta^{15}N$ and %N values suggests groundwater with similar nitrogen sources and availability along this swath.

The NELHA swath is below a large community and had the third highest modeled nitrogen flux. This swath had high variability of seaweed $\delta^{15}N$ values, similar to Keaukaha, with values > 5‰ only at stations with fresh groundwater springs present (Figure 42). Along the NELHA swath, groundwater springs were infrequent and localized at discreet points, with only two replicate samples with significant fresh groundwater inputs while sampling (salinity < 33‰).

The detected $\delta^{15}N$ was high at both of these springs ($\delta^{15}N > 5.5‰$), with one replicate sample having the highest $\delta^{15}N$ outside of Puakō ($\delta^{15}N = 6.5‰$). Away from these springs, the indicators of wastewater were absent. The adjacent Hawai'i Ocean Science and Technology Park, which disposes of saltwater into the ground through seepage pits and injection wells, may be diverting the wastewater-laden groundwater elsewhere or even mixing with the groundwater and diluting the wastewater $\delta^{15}N$ signal (Olson, personal communication, 2021).

Puakō, which was identified in the modeling as a localized area of concern, had the highest swath average and maximum seaweed $\delta^{15}N$ and %N values for Hawai'i Island (Table 6, Figure 39). Along the Puakō swath, the seaweed $\delta^{15}N$ values increased to the south, similar to previous studies (Abaya et al., 2018). The OSDS, including cesspools, at Puakō are located less than 350 feet from the shoreline, are very close to the water table (maximum surface elevation = 8 ft), and are located in fractured basalt rock with a high permeability. Combined, these factors allow wastewater to reach the shoreline within hours to days, allowing little time for treatment or dilution (Abaya et al., 2018). At Kailapa and Mahaiʻula, the model and seaweed data generally agree, as both show low wastewater influence (Figure 38, Figure 41).

Development in the Mauna Lani (Waikoloa, S. Kohala) region is dominated resorts and a community that have sewer systems and wastewater treatment. Based on the model, this swath had the second-lowest density of OSDS and predicted wastewater N-flux. However, the Mauna Lani swath did have a maximum $\delta^{15}N$ values > 6.0‰ and was the only swath other than Puakō with %N > 2.5% (Figure 40). Mauna Lani likely has N sources that are contributing nutrients and enriched ^{15}N nitrogen to the coastline that are not from OSDS. The resort at Mauna Lani has a permit to irrigate their green areas with recycled water (DOH, 2020b). This application of recycled water was not considered in the N-transport model but will certainly affect the nitrogen chemistry of submarine groundwater discharge.

Enterococcus spp. was also measured on Hawai'i Island. *Enterococcus* spp. is recommended by the EPA as a fecal indicator bacteria because it lives in the intestinal tracks of warm-blooded animals. *Enterococcus* spp. is found in fecal matter from humans as well as other sources, including warm-blooded wildlife, beach sediments and aquatic vegetation (Byappanahalli et al. 2012; Boehm and Sassoubre 2014). Research has identified that the highest risk in bathers contracting gastrointestinal illness is when the source of FIB, such as *Enterococcus* spp., is wastewater, because it includes fecal discharge from human intestinal tract, which is the site of multiplication for FIB and all human enteric pathogens (Fujioka et al. 2015).

Puako, with a swath average seaweed $\delta^{15}N$ value of 6.5‰, was identified as a wastewater dominated area and had the highest *Enterococcus* spp. concentrations (Table 7). Similar to the seaweed $\delta^{15}N$ and %N values, high *Enterococcus* was primarily observed in the southern part of the swath. The northern part was characterized by low *Enterococcus* spp. concentrations, with 8/12 samples below the detection limit. The HDOH "Puako Middle Lots" station, which generally reports values < 35 MPN/100 ml, is within this northern part, just north of the lowest measured seaweed $\delta^{15}N$ values (Figure 40).

The second-highest single sample *Enterococcus* spp. sample was at the Wailoa, adjacent to the HDOH "Wailoa River Mouth" station. While the HDOH has only sampled here since 2021, 2/3 of the samples collected exceeded 35 MPN/100 mL, and 1/3 exceeded the Statistical Threshold Value of 130 MPN/100 mL. At the other end of our swath, we measured an average of 8 MPN/100 mL close to the DOH "Exit of Ice Pond" station, which has an average *Enterococcus* spp. concentration of 36 MPN/100 mL based on 9 samples collected since sampling restarted there in August 2020.

5.5 Kaua‘i

In Kapa‘a, the coastal seaweed samples indicate wastewater influence from the upslope OSDS (Figure 53). The northeast half of the sampling swath is directly down gradient from a cluster of OSDS that extend well inland, and the seaweed data show elevated $\delta^{15}N$ values of 8.9‰ (Table 8, Figure 53). The OSDS are adjacent to the coast and the seaweed $\delta^{15}N$ values decrease to near background at 4.3‰ (Figure 53). The seaweed %N at the southwest end of the sampling swath was very low at 0.8% indicating that the area is not likely influenced by agricultural fertilizers.

At Nāwiliwili and Poipu, the modelled wastewater nitrogen-flux and OSDS densities and the seaweed $\delta^{15}N$ and %N indicated wastewater intrusion to the marine environment (Figures 51 and 52). Two seaweed samples were collected at Ha‘ena along a segment of shoreline the model indicated would have a low wastewater nitrogen flux. Consistent with the model, the seaweed $\delta^{15}N$ and %N values were low (1.4‰ and 1.1%, respectively).

For Waiohai, the model predicted low wastewater nitrogen-flux. Seaweed sampling detected wastewater intrusion in the marine environment through high $\delta^{15}N$ values (Table 8, Figures 50 and 52). Nawilwili, ranked low for OSDS but ranked high for wastewater N-flux, seaweed $\delta^{15}N$ and seaweed %N. The difference in rankings may arise in part from the small coastal segment sampled for seaweed versus the large scale of the modelled segment. For instance, the Nāwiliwili seaweed sampling swath length was about 0.7 km of coastline where the wastewater influence was predicted to be the highest. The Nāwiliwili modelled estimated wastewater influence segment spanned 14-km of coastline. The land-use across the 14-km consisted of areas with high OSDS density and areas of low OSDS density which were being used for agriculture.

5.6 Continuing applications and next steps

The data collected through this study represent an early effort in the international push to assess ecosystem health by using marine plant assays across large landscapes that are too costly and time-consumtive to consider deployment of arrays of sensors or probes. Specifically, the seaweed $\delta^{15}N$ and %N values collected through this project are currently being used in a follow-on study funded by the State of Hawai‘i, Department of Health targeted at developing a state-wide prioritization scheme for every cesspool in the state. To date, this seaweed parameter dataset is the most complete and spatially robust that has been collected across the state of Hawai‘i, which makes it uniquely valuable for validation of prioritization methods applied across multiple diverse islands. Additionally, ecosystem modeling efforts funded by NOAA's West Hawai‘i Integrated Ecosystem Assessment, are currently using this data to validate models designed to determine the primary drivers of coral and fish health and recovery potential. Many ecosystem assessments suffer from a lack of cohesive and comparable observation datasets that are representative of differences in human impacts. Therefore, the scope and quality of the data collected for this study make this dataset ideal for validating and calibrating these types of models. While an assessment of the ecological and health impact of OSDS exceeded the scope of this study, sewage waste has well-documented negative impacts on both coral reef and human health (Maragos 1972; Smith et al., 1981; Kinsey, 1985; Lapointe et al., 2005; Dailer et al., 2012; Prouty et al., 2017). Further assessment on how OSDS affects disease prevalence and the spread of invasive/pest species of algae will be necessary to fully understand the scope of the impact of OSDS on coastal waters. These examples are only the first in what is likely to be a robust set of studies that will benefit from the application of the seaweed data collected in this study.

In addition, the work performed during this project serves to validate the representativeness of the state-wide conceptual model of groundwater flow applied in construction of the numerical groundwater models developed by the Department of Health, Safe Drinking Water Branch, Source Water Assessment Program and described in depth in this report. This work also verifies, as they are currently parameterized, that the quantitative results from the numerical models also appear to be robust in their ability to satisfactorily allow for predictions of OSDS based impacts to coastal waters within a reasonable range of uncertainty. Coastal seaweed $\delta^{15}N$ values are expected to be elevated in areas predicted by the model to have high wastewater N-flux to the coastline from concentrated OSDS even if those areas were not directly sampled in this study. This contribution not only benefits our understanding of coastal flow-paths and groundwater quality, but also allows these models along with components of their conceptual and numerical frameworks to be applied in other studies such as the aforementioned OSDS prioritization project.

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