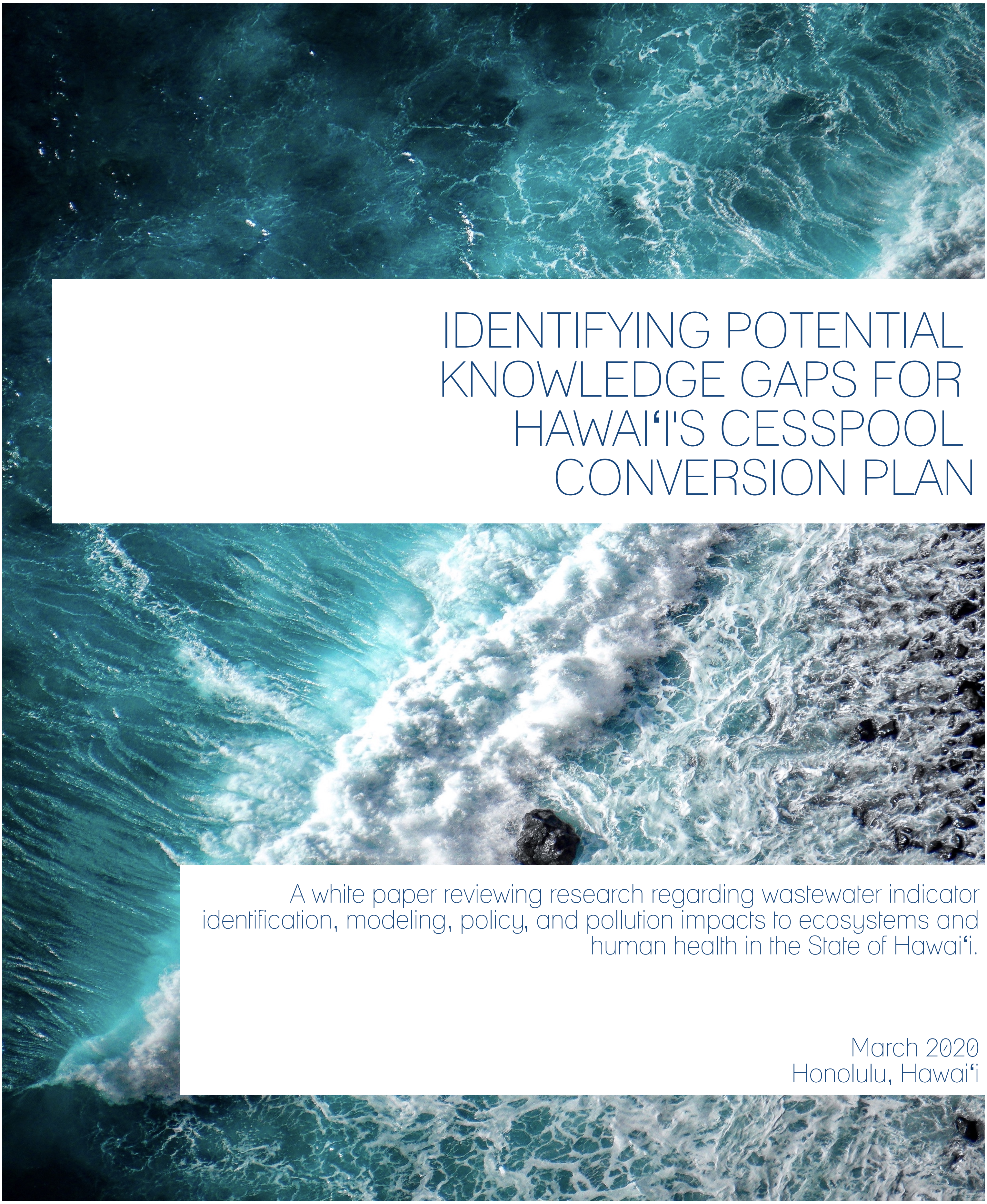

IDENTIFYING POTENTIAL KNOWLEDGE GAPS FOR HAWAIʻI'S CESSPOOL CONVERSION PLAN

A white paper reviewing research regarding wastewater indicator identification, modeling, policy, and pollution impacts to ecosystems and human health in the State of Hawaiʻi.

March 2020
Honolulu, Hawaiʻi

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Michael Mezzacapo

March 2020

SPECIAL REPORT WRRC-SR-2020-03
UNIHI-SEAGRANT- TT-19-03

PREPARED FOR
Cesspool Conversion Working Group (Authorized under Act 132)
Wastewater Branch, Hawai‘i State Department of Health
PROJECT REPORT FOR
“Water Resources Research Center Sewage Contamination Study”
Project No: 1200560
Project Period: 07/01/2019-01/14/2023
Principal Investigator: Darren T. Lerner, Ph.D.

WATER RESOURCES RESEARCH CENTER
HAWAI‘I SEA GRANT COLLEGE PROGRAM
The University of Hawai‘i at Mānoa
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Acronyms/Abbreviations

AOC	Area of Concern
ARB	Antibiotic-resistant bacteria
ARG	Antibiotic-resistant genes
AS	Artificial sweetener
BUI	Beneficial Use Impairment
CCWG	Cesspool Conversion Working Group
CEC	Contaminants of emerging concern
DON	Dissolved organic nitrogen
DIN	Dissolved inorganic nitrogen
fDOM	Fluorescent dissolved organic matter
FIB	Fecal indicator bacteria
INVEST	Integrated Valuation of Ecosystem Services and Tradeoffs
MCL	Maximum contaminate levels
MRSA	Methicillin-resistant *Staphylococcus aureus*
NRCS	United States Department of Agriculture, Natural Resources Conservation Service
OWTS	Onsite wastewater treatment systems
PCP	Personal care products
N	Nitrogen
NDR	Nutrient Delivery Ratio
NOAA	National Oceanic and Atmospheric Administration
P	Phosphorus
RAM	Robust Analytical Model
RAP	Remedial Action Plan
SDM	Structured decision-making
SGD	Submarine groundwater discharge
SWAT	Soil and Water Assessment Tool
UH	University of Hawai‘i
USEPA	United States Environmental Protection Agency

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Introduction

Authorization and goals

This white paper was requested by the Cesspool Conversion Working Group (CCWG) under the authorization of Act 132, passed by the Twenty-Ninth Hawaiʻi State Legislature. Section two, objective three, of Act 132 which tasks the CCWG with identifying areas “where data is insufficient to determine a priority classification of cesspools for conversion and determine methods and resources needed to collect that data and conduct analysis of those areas” (Hawaiʻi Senate Bill 2567, p.2). The goal of this white paper is to provide the CCWG with a resource to evaluate current and past research, evidence, and information relating to the impacts of cesspool and wastewater pollution, as well as highlight any knowledge gaps for future study. It is beyond the scope of the white paper and proposal for the author to recommend specific actions for prioritization, rather the information is provided to inform members about available data to construct a prioritization and upgrade scheme. The author has surveyed, summarized, and analyzed academic research, theses, and relevant published works relating to wastewater indicator identification, policy, modeling, human health, and potential impacts to ecosystems in Hawaiʻi. In addition to reviewing research, many scientists and experts were consulted and interviewed to provide technical feedback on their subject matter and assist with distillation of scientific concepts. The scope of the white paper is limited to the main Hawaiian Islands and will not address research or case studies from other islands in the Pacific region.

Analysis and scope

The analysis and science translation portion of this report is divided into four topics: *Wastewater Pollution Indicators; Ocean/Coastal/Groundwater Impairment and Human Health Concerns; Water Resource Modeling/Monitoring/Risk Analysis; and Policy and Community Engagement*. Before each section are key concepts and identified knowledge gaps on the preceding topic. Onsite wastewater technology is not evaluated in this white paper. Carollo Engineers was awarded a contract by the Hawaiʻi Department of Health (DOH) to investigate onsite wastewater treatment system (OWTS) technology options for upgrading cesspools. The evaluation will create a technology matrix to describe the benefits and challenges of implementing various OWTS technology, including operations and maintenance considerations, life-cycle, installation cost, availability, and level of treatment provided. The Carollo report will also consider site constraints and Hawaiʻi’s unique geology and topography, such as the occurrence of a high-water table, variations in soil permeability, slope of terrain, and proximity to flood zones and other water resources.

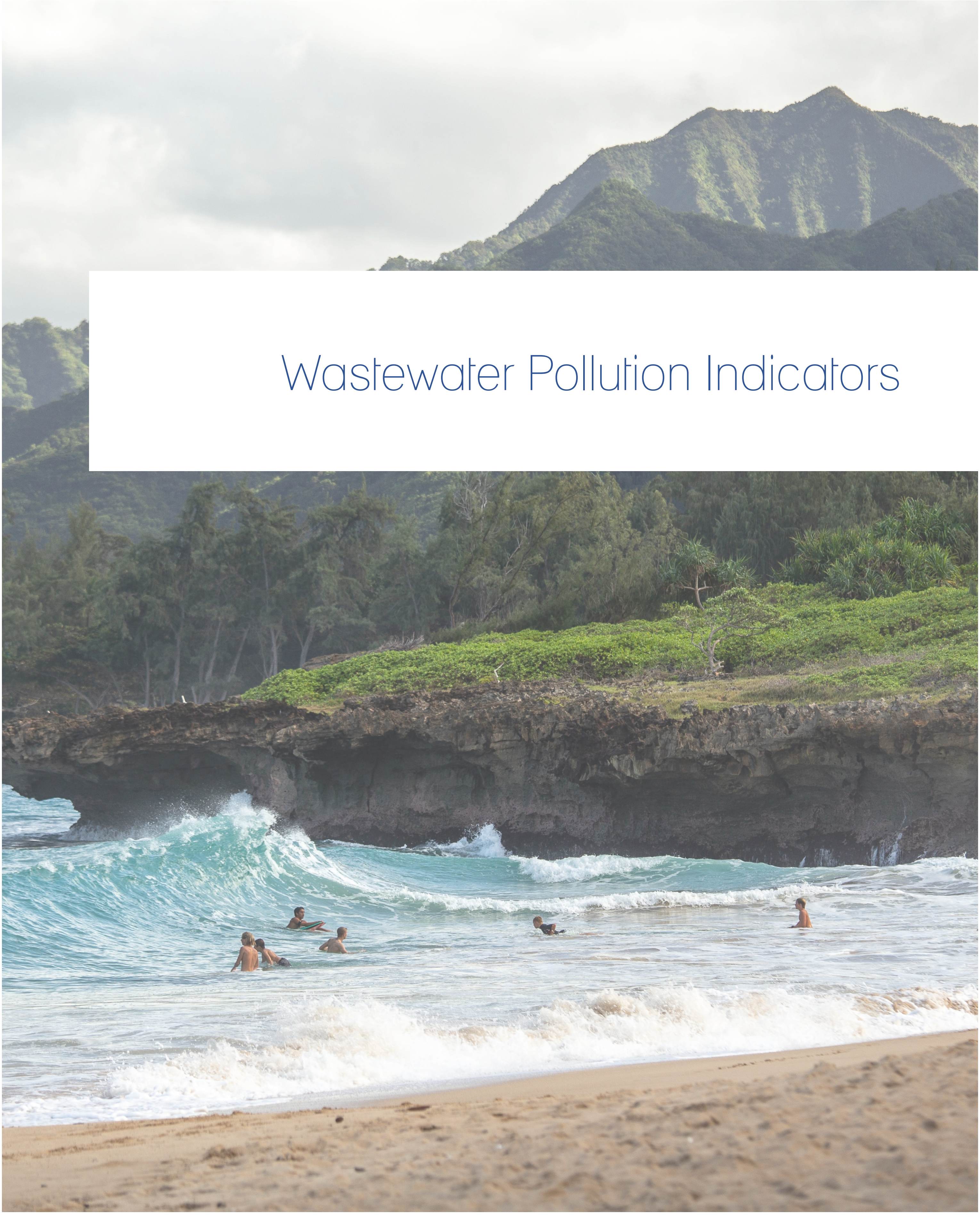
Methods

Searches were performed using Google Scholar, PubMed, Science Direct, Web of Science and Google. Results included academic studies, scholarly publications, general journal articles, theses, websites, and reports using the keywords such as: cesspool; Hawaiʻi; wastewater; nutrient pollution; bacterial pollution; water quality; septic pollution; algae; pathogens; micropollutants; tracer injections; contaminants of emerging concern and wastewater management. One hundred and twenty-four primary documents were discovered. The conclusion section in this report summarizes strategies the CCWG may wish to pursue and challenges that surfaced within the topics researched. Every attempt has been made to accurately summarize and represent the materials reviewed. Chapters have been reviewed by subject experts where appropriate. Finally, a reference list is provided in in Appendix I to inform the reader of available sources relating to wastewater pollution research in Hawai‘i.

Summary

Assembling a comprehensive list of research studies regarding wastewater pollution and associated impacts has identified a significant body of work and data within Hawai‘i. Many of the studies within this white paper provide valid scientific evidence to support the creation of a long-range cesspool conversion plan. There are gaps that exist in certain topics, including hydraulic and hydrologic modeling, and methods with limitations, including identifying specific wastewater sources. However, many of these limitations can be overcome. For example, limitations in identifying specific sources from wastewater indicators using % N and $\delta^{15}N$ can be overcome with the assistance of available land-use information and potential pollution sources to clarify the isotopic data. Resource management presents many challenges, especially in areas that include competing views and values. To overcome discrepancies in available data, and varying societal values, the use of a transparent and adaptable frameworks can be a key approach for problem solving. A holistic OWTS management approach that addresses scientific and social needs is the ideal solution to overcoming any identified hurdles.

Wastewater Pollution Indicators



How can we measure if wastewater pollution is entering the environment, and where is it coming from?

5 Key Concepts

Regarding Water Pollution Indicators

Many of the wastewater indicators identified have limitations and are best combined with a suite of other indicators to evaluate pollution sources. Pollution scoring tools have been developed that combine evidence from multiple pollution tracers.

Several studies used nitrogen isotope values ($\delta^{15}N$) and % N algal tissue analysis to map locations and potential sources of nutrients, such as cesspools. $\delta^{15}N$ values and % N in algal tissues are a good, initial screening method, for source pollution investigation. However, isotope values and % N values may possibly result from a combination of multiple nitrogen sources, depending on the features of each field site.

Wastewater derived pollution has multiple pathways to enter the ocean, including surface water and submarine groundwater discharge (SGD). Researchers can track the pathways and discharge points of wastewater derived contaminants into the ocean.

Bacterial community studies can complement microbial source tracking studies, assist with tracking environmental impacts, and may be useful for long-term monitoring programs concerned with the change (climate, land-use, etc.) and degradation of our environment.

Preliminary studies have discovered compounds such as carbamazepine, caffeine, ibuprofen, sulfamethoxazole, and ethynylestradiol in streams and coastal waters of Hawai‘i, which are likely entering the waters from cesspools. The advantage of using these tracers is their uniqueness to wastewater. To date, there are no publications showing their application or ability to distinguish between municipal injection well or cesspool sources, however, research is underway.

7 Knowledge Gaps

Regarding Water Pollution Indicators

Epidemiological studies are needed to determine where certain pathogens, such as *Staphylococcus aureus* are entering the water from wastewater sources and if they are causing health issues to recreational water users or drinking water.

Large scale state-wide sampling of multiple indicators may help inform a decision-making framework process and improve existing model accuracy. Future studies should include long-term sampling to capture temporal patterns of sewage pollution as well as capture patterns as N-loading diminishes in regions where cesspool conversions have taken place.

Ecosystem level impacts of wastewater pollution are difficult to quantify and predict, especially in the face of global threats like rising temperatures and ocean acidification, but benthic communities of plants and sessile invertebrates have already shown change.

More studies are needed to elaborate on relationships between water-borne nutrients and % N in algal tissues. There is abundant information on the measurements of stable isotopes of nitrate in water. However, the use of mixing models may be helpful to examine specific contributions of different nitrogen sources to coastal waters and works well at large scales

More human health risk assessment studies are critically needed to understand if there is appreciable risk to human health from potential pharmaceutical exposure and the long-term effects of consuming low-levels of certain anthropogenic compounds

Methods that investigate the applicability of $\delta^{15}N$ in other forms of nitrogen, such as ammonium and dissolved organic nitrogen, along with isotopes of other biogeochemically important elements should be tested for use in Hawaiʻi as wastewater indicators. These could be done in water and dissolved or on particulate organic matter, rather than marine plants which may not acquire these isotopes without fractionation.

Little is known about natural background bacteria levels such as *Enterococcus* in tropical soils and waters, or their transport dynamics in wet tropical regions where recreational water use occurs year-round.

Non-point pollution is difficult to trace

Drawing a linear connection to explicit non-point pollution sources and ecosystem degradation is extremely difficult. Non-point pollution remains the greatest source of water quality declines across the United States (Lewis, 1999). The Clean Water Act of 1972 addresses point source and non-point source pollution, however, mandatory federal regulations only exist for point-source pollution (Brown and Froemke, 2012). Hawai‘i’s cesspools (generally regarded as a non-point pollution source), on average, release an estimated fifty-five million gallons of human waste into the ground each day (Hawai‘i Department of Health, 2016). Upgrading cesspools are a tangible first step to reduce the many sources of nutrients getting to the coast from human development (Yoshioka et al., 2016). Understanding how to best measure where non-point pollution originates, both human and environmental, is difficult. Researchers have developed and tested various indicators that can be used to track pollution sources. Many of the indicators identified in the next several sections have some limitations. To have the most accurate representation of pollution sources, it is best to combine a suite of pollution indicators. Such an effort was made by Abaya et al. (2018b), using dye tracer studies, sewage indicator bacteria measurements, nitrogen isotopes in macroalgae, and a unique pollution scoring tool. However, it can be difficult to quantify many of the processes occurring in the subsurface such as biological and chemical degradation rates, mixing of various sources (e.g., cesspools and wastewater effluent injection), dispersion, and groundwater flow lines, making it challenging to have complete certainty when identifying the exact location and magnitude of pollution sources. Yet, this does not mean that the current science and identified indicators should not be used for decision-making or resource management. By properly analyzing the merits of the research and its limitations, a comprehensive process can be developed by combining the best site-specific or regional indicators, alongside other data, to thoroughly examine and measure the presence of pollution and its impacts on humans and the ecosystem.

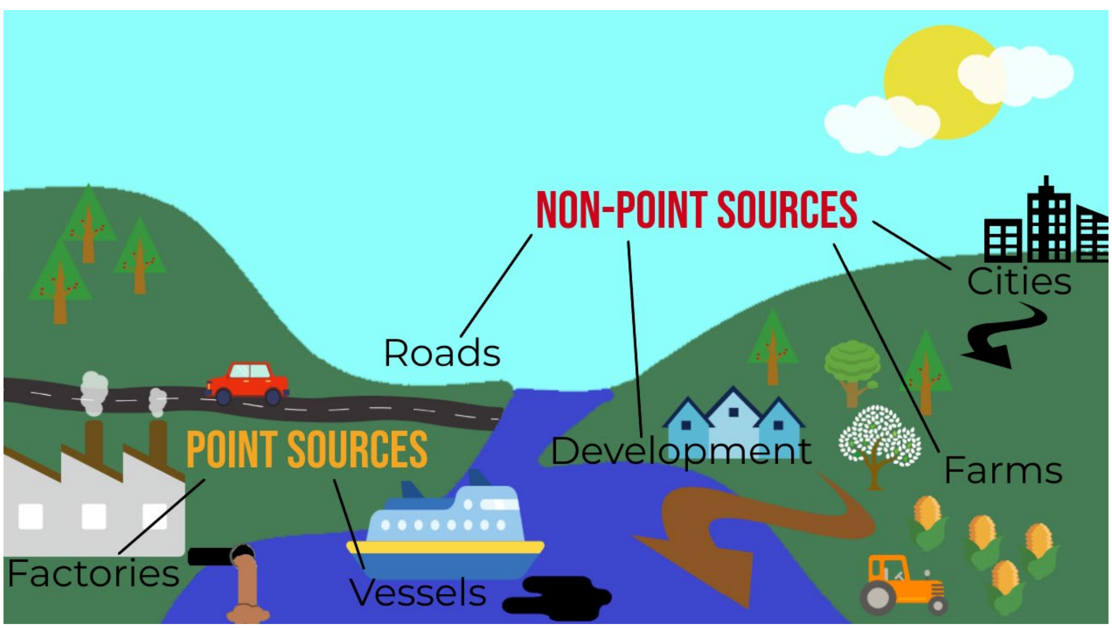


Figure 1. Examples of various origins of point and non-point pollution. Source: Michael Mezzacapo.

What are some recognized indicators available to detect wastewater pollution?

Chemical Indicators

The primary signs of wastewater influx into the coastal ocean are excess nutrient levels, usually nitrogen and phosphorus. The signs of eutrophication (excess nutrients) in these waters, however, may not be obvious if dilution, coastal currents, or nutrient uptake are significant, such as in the waters around Hawaiʻi (C. Smith, personal communication, December 20, 2019). Other areas in the continental United States facing significant nutrient pollution from OWTS, such as Suffolk County in the State of New York, have already experienced aquatic ecosystem impacts from eutrophication, including harmful algal blooms and the reduction of native seagrasses (government of Suffolk County, New York, 2015). Many of these impacts have negative consequences to ecosystems, economies, infrastructure, or human health, which have spurred regulatory actions.

Humans have different ways of responding to environmental changes (National Research Council, 1992). Changes that a direct, visual, or highly impactful to our behaviors are often the most noticed. With the advancement of scientific knowledge and our understanding of our influence on the environment, there is now a rational basis for acting to prevent such degradation (National Research Council, 1992). In the case of Hawaiʻi's OWTS challenges, policymakers and stakeholders face two options. The first option is one that involves anticipatory action, which addresses the nutrient loading problem before severe consequences are noticed, such as algal blooms or coral die-off. The second is delayed action, which depends on resource users awaiting the experience of environmental change or degradation in order to justify actions taken. The latter methodology may carry higher risks to ecosystems and economies reliant on such resources.

In an effort to understand sources of nutrient pollution, the use of nitrate stable isotopes ($\delta^{15}N$) was developed as a wastewater tracer and is well established within the scientific community (Valiela et al., 1997; Kendal et al., 2015; Cole et al., 2004; Wiegner, 2016). Isotopes are variants of chemical elements with the same number of protons and electrons, but different number of neutrons, which vary its mass. Nitrate stable isotopes have been used since the 1970's to identify nitrate sources (Yang et al., 2019). The $\delta^{15}N$ of nitrate in coastal water has been used as a wastewater indicator in numerous studies in Hawaiʻi and provides evidence of wastewater pollution. Many of these studies were carefully timed to capture the strongest submarine groundwater discharge (SGD) signature, which is understood to deliver nutrients from land-based sources (Richardson et al., 2016; H. Dulai, personal communication, November 18, 2019; Wiegner et al., 2016). However, because SGD varies over tidal cycles and daily and seasonal time scales, it is often more useful to get an integrated nitrate isotope signature via sampling of certain coastal organisms (such as algae), which efficiently capture nitrogen, to more accurately assess wastewater pollution.

Although phosphorus is an essential factor in plant growth and another nutrient in wastewater pollution, there are no phosphorus isotope signatures (phosphorus is mono-isotopic and only the oxygen isotopes in phosphate can be used as tracers) available for use as a wastewater tracer (Paytan and McLaughlin, 2011). However, Brown (2019) documented increased community diversity of the types of cyanobacteria, which bloom when there is excess phosphorus, in wastewater plumes off the western shores of Maui.

Using phosphate in combination with other wastewater indicators may prove to be a useful linkage in a system to detect wastewater pollution and cyanobacterial blooms (C. Smith, personal communication, January 24, 2020).

Several studies identified for this white paper focused on using $\delta^{15}N$ values in algal tissue to map locations and potential sources of nutrients. Dailer et al. (2010), identified certain macroalgae in Hawaiʻi to be suitable as an indicator of human sources of nitrogen due to the algae's ability to acquire high nutrient amounts. The macroalgae also acquire and integrate all sources of water column nutrients over short to long periods and are present in the coastal benthic (ocean bottom) community. The algae may represent nutrients deposited through SGD (especially if the algae grow on top of the seep) and are easily collected and analyzed for a relatively minimal cost (Dailer et al., 2010). Some limitations do exist, including the ability to identify a single nutrient source when multiple nitrogen sources are present (cesspools, fertilizers, wastewater effluent injection). Some of these limitations can be overcome by using multi-tracer methods and land-based data to analyze sources. Overall, the possibility of identifying the specific sources of nitrogen pollution by using $\delta^{15}N$ values coupled with %N data is realistic in Hawaiʻi with the assistance of available land-use information and potential pollution sources to clarify the isotopic data (C. Smith, personal communication, November 25, 2019). Because nitrogen undergoes biochemical reactions moving from the pollution source to water body, and is influenced by land-use, climate, and hydrogeological conditions, there is a need for additional data to categorically identify specific sources of pollution. More research may wish to focus on the influencing factors for identifying the pollution sources and tracing the migration and transformation of nitrogen (Yang et al., 2019).

Despite any potential limitations, such as an overlap of various nitrogen sources (natural denitrification, wastewater effluent, cesspool leachate), $\delta^{15}N$ values are used globally to detect human sources of nitrogen (Kendall, 1998; Gartner et al., 2002, cited in Dailer et al., 2010). The $\delta^{15}N$ values can, and have, provided a useful means of tracing sewage under the right conditions. Professor Celia Smith and the students and staff in her laboratory are analyzing data of $\delta^{15}N$ and %N values (along with other water quality parameters such as pH, salinity, and temperature) in algal and water samples from the 2019 Water Resources Research Center sewage contamination study across the main islands of Hawaiʻi, building on contributions by Smith and Smith (2006); Dailer et al. (2010; 2012); Cox et al. (2013); Amato, et al. (2016; 2020); and Shuler et al. (2018). Only a couple of taxa are considered for $\delta^{15}N$ tissue analysis in the most recent Water Resources Research Center sewage contamination study. The two algae species under evaluation are *Acanthophora spicifera* and *Ulva lactuca.* By limiting the number and type of algae analyzed, scientists have more control for variables, and more direct measurements of nitrogen concentrations versus averaging values community-wide (Derse et al. 2007; LaPointe, 1987). Research performed between 2012-2014 has confirmed previous modeling efforts to connect OWTS pollution and marine ecosystems on the island of Oʻahu, as shown in Fig. 2. Amato et al. (2020) compared algal tissue data ($\delta^{15}N$ and %N) and nitrogen transport from wastewater models, concluding that a strong relationship exists between modeled estimates of coastal groundwater nitrogen and measured *Ulva* $\delta^{15}N$ values. "These results indicate that both algal bioassays and groundwater N models are effective indicators of wastewater in the nearshore environment" (Amato et al., 2020, p. 9). The results also signal the value of this approach and its use at a moderate scale to identify areas in need of OWTS upgrades to improve water quality and ecosystem health.

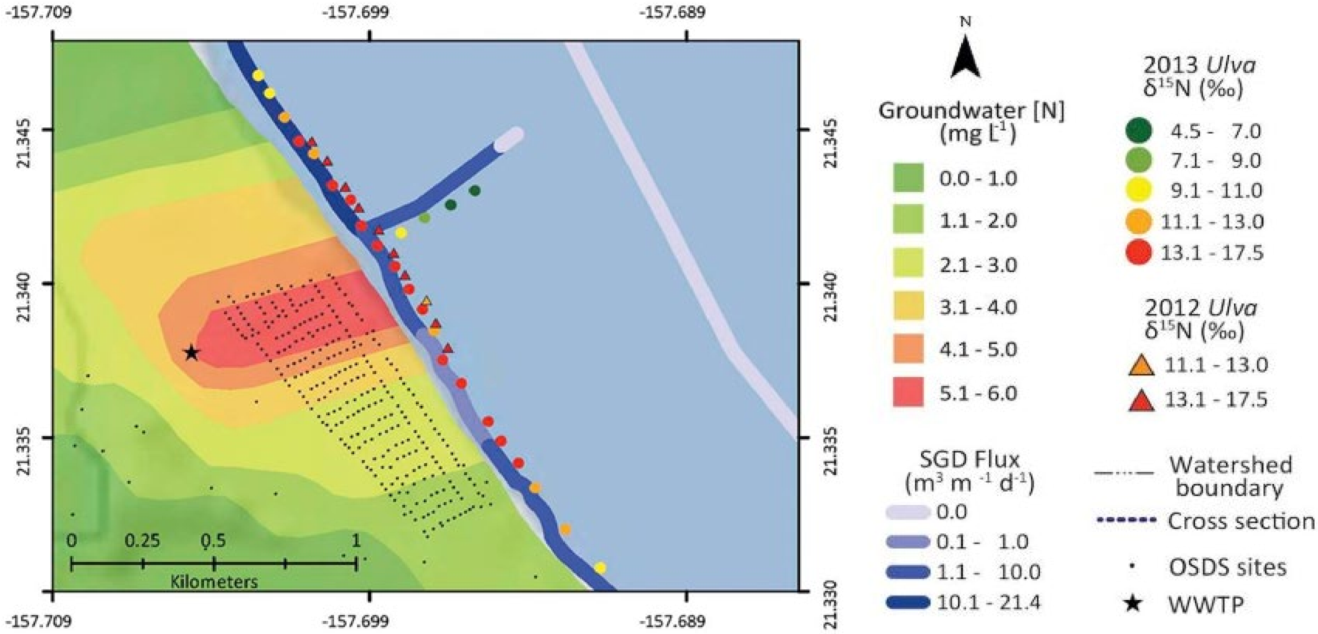


Figure 2. Zoomed view of Waimānalo study area. *Ulva lactuca* tissue $\delta^{15}N$ values are shown as triangles for the 2012 sampling and as circles for the 2013 sampling. SGD flux estimates are shown as blue bands. Scale for $\delta^{15}N$ and SGD flux is nonlinear. Estimated groundwater nitrogen is shown as colored polygons. The location of OSDS sites are noted as small back dots and the Waimānalo WWTP is represented by a black star. Source: Amato et al., 2020; *Marine Pollution Bulletin*. Used with permission.

Methods that investigate the applicability of $\delta^{15}N$ in other forms of nitrogen, such as ammonium and dissolved organic nitrogen, along with isotopes of other biogeochemically important elements (S,C,D,O, B (Boron)) may be promising for use as indicators and should be considered for testing in Hawai‘i to measure and track wastewater pollution sources (Aravena and Robertson, 1998; H. Dulai, personal communication, November 19, 2019; Young et al., 2009; Victoria et al., 2008).

Biological Indicators

Measuring a specific type and quantity of bacteria in water is a common method that can be used to identify if wastewater pollution may be present, however, current technology does not accurately permit the ability to identify the source through a single test. These bacteria are known as fecal indicator bacteria (FIB). Fecal indicator bacteria are normal inhabitants of the gastrointestinal tract of humans and many mammals. The presence of FIB is used to estimate the potential for pathogenic bacteria to cause human health illness. However, many epidemiological studies have failed to find correlation between human health outcomes and FIB levels in subtropical waters (Harwood et al., 2014; Fleming et al., 2006). Typical FIB are *Enterococcus* or *Escherichia coli*.

Using typical and alternative FIB, along with molecular marker tests (tests to examine molecules contained within a sample to reveal specific characteristics about the source) may assist in more accurately identifying the presence of wastewater pollution (Kirs et al., 2017). Enterococci are commonly found in the guts of mammals and birds, shed in the feces, and historically were used to estimate human health risks (Byappanahalli et al., 2012a). However, these bacteria are often found in high natural concentrations in Hawaiian soils, making it difficult to discern the appropriate reference levels of the bacteria (Byappanahalli et al., 2012b). During heavy rainfall events, large amounts of sediment and other materials are suspended in the water, rendering concentrations of *Enterococcus* in nearshore waters less indicative of only wastewater pollution (Fujioka et al., 2015). State water quality monitoring programs and related water management decisions should not rely solely on enterococci levels (Kirs et. al., 2017). Furthermore, FIB presence does not correlate with pathogen presence, meaning that the pathogens associated with FIB may or may not be present to cause illness (Lund, 1996; Bonadonna et al., 2002; Lemarchand and Lebaron, 2003; Anderson et al., 2005; Harwood et al., 2005, cited in Harwood et al., 2014).

Alternative bacterial indicators can include *Clostridium perfringens* and F+-specific coliphage, which have both been suggested for use as water quality indicators in Hawaiʻi (Fujioka and Byappanahalli, 2003; Kirs et al., 2017; Luther and Fujioka, 2004; Viau et al., 2011). However, more research needs to be done in this area of alternative wastewater pollution indicators to accurately predict human health risks. Because bacteria are readily found in the environment, distinguishing between the origination of different sources (soils or animals) at an appropriate location can be difficult (M. Kirs, personal communication, November 19, 2019). Additionally, relying on certain indicator bacteria to detect and identify pollution sources in Hawaiian marine environments is not recommended due to naturally low concentration levels (Kirs, 2015).

A newer method that may be able to trace microbes and identify specific sources of pollution is microbial source tracking (MST). Microbial source tracking is a complex method with analytical protocols and a decision-making process that can be used to identify specific fecal contamination sources (Stoeckel, 2005). Identification of contamination sources such as leaching cesspools or farming activities is important, as it enables the establishment of meaningful management practices and remediation strategies. Several molecular tools targeting source-specific microorganisms have been developed to discriminate between contamination sources and are summarized by Boehm et al. (2013). Some of the most promising source-specific markers identified were evaluated for use in Hawaiʻi based upon their sensitivity and specificity as well as die-off characteristics. Research is ongoing, but MST may provide scientists, public health experts, and land managers with better tools to identify and track pollution sources; further research should be continually monitored and evaluated for applicability and accuracy.

Certain types of *Bacteroides* can also be used as microbial markers to identify the presence of wastewater pollution (Betancourt and Fujioka, 2006; Boehm, 2010). *Bacteroides* are gram-negative, non-spore forming, anaerobic bacteria found in the gut of warm-blooded mammals (Wexler, 2007). Host specific identification is possible and can help track specific pollution sources such as cesspools or natural sources of animal waste. A 2010 study by Boehm et al. found traces of human-associated *Bacteroides* in Hanalei Bay with the likely sources being pollution from nearby cesspools. Other studies have also found certain *Bacteroides* in the Waiʻ Ōpae Tide Pools following Tropical Storm Iselle and in Hilo Bay (Wiegner, 2017; Wiegner, 2009; T. Wiegner, personal communication, November 19, 2019). However, human-associated *Bacteroides* and human viruses are not perfect indicators and can be difficult to detect, even in waters with known wastewater pollution (T. Wiegner, personal communication, November 19, 2019). Sensitivity (only a certain percentage of humans carry certain markers) and specificity (source can come from different types of animals) are significant limitations to this type of molecular marker being readily used to identify wastewater pollution sources. Therefore, it may be helpful to combine these types of indicators with other indicators to more accurately detect wastewater pollution and attempt to identify sources (M. Kirs, personal communication, December 2, 2019).

An example of combining biologic methods for detecting and tracing wastewater pollution in Hawaiʻi was performed by Kirs et al. (2017). The study used human-associated *Bacteroides*, human polyomaviruses, and bacterial community analyses to identify wastewater-related impairment in the Mānoa watershed. The conclusions from the study are as follows. 1) Using both enterococci and *Clostridium perfringens* (typical and alternative indicator bacteria) simultaneously is well suited for Hawaiʻi as an initial, cost-effective method to screen for the presence of wastewater pollution. However, molecular tests for source-specific markers are needed to confirm wastewater sources. 2) Bacterial community studies improve MST evaluations (by adding to databases of marker identification) and may be useful for long-term monitoring programs concerned with change (climate, land-use, etc.) and degradation of the environment.

What are some emerging wastewater pollution indicators?

One clear indicator of anthropogenic pollution is non-natural chemicals or compounds like personal care products (PCP), artificial sweeteners (AS), such as sucralose, and pharmaceuticals or hormones. Research by Tran et al. (2014), cited in Lim et al. (2016) found that pharmaceuticals, PCPs, and AS might be promising markers for detecting and identifying wastewater sources. These markers are persistent, not naturally produced in the environment, not entirely removed by wastewater treatment plants or OWTS, and tend to be relatively stable during transport (Lim et al., 2016).

> It remains highly challenging to accurately predict the extent of wastewater contamination using the methods developed using these chemical markers. Currently, there is no single chemical that could serve as a marker for wastewater contamination for all sites accurately. Understanding of land-use patterns, types and levels of contaminants in wastewater, and fate and transport of chemicals are needed in order to select suitable markers (Lim et al., 2016, p. 2).

Knee et al. (2009) were able to study caffeine as a wastewater tracer in SGD on the island of Kauaʻi. Hunt (2014) has also identified multiple pharmaceuticals and other wastewater tracers such as fabric brighteners in groundwater discharge to Honokohau Harbor, which may possibly be linked to nearby wastewater effluent wells or pits. Recent advancements in the testing of chemicals of emerging concern (CEC) allows broader, more effective screening for various CECs in the environment. This advancement has prompted multiple studies underway in Hawaiʻi focused on streams and coastal springs along the shoreline to study human-made indicators of wastewater pollution (Dulai et al., in prep; McKenzie et al., 2017).

Preliminary studies by Professor Henrietta Dulai and her laboratory at UH Mānoa targeted high-density cesspool areas and confirmed the presence of, and analyzed trends of compounds such as carbamazepine, caffeine, ibuprofen, sulphamethoxazole, fluoroquinolones, and ethynylestradiol in streams and coastal springs of Oʻahu and the Kona coast of Hawaiʻi Island. These substances have been shown to have potential negative effects on ecosystems and the organisms that inhabit them (Qiang, 2016; Lange, 2001; Shved, 2008; Jobling, 1998; Pollack, 2009).

Although not specifically studied in Hawaiʻi, recent studies have attempted to determine if there is significant evidence linking antibiotic resistance to human pathogens when humans are exposed to antibiotic-resistant bacteria (ARB) and antibiotic resistant genes (ARGs) in drinking water. Economy et al. (2019) identified *Staphylococcus aureus* and Methicillin-resistant *S. aureus* (MRSA) in wastewater effluent and showed relationships with other FIB in nearshore waters of Hilo, Hawaiʻi. There is limited information on how OWTS process certain ARBs or ARGs, though antibiotics undergo some natural degradation in the environment through photo, chemical, and biological processes. However, these processes are dependent on temperature, moisture, and chemical composition of the effluent treatment mechanisms (Helt, 2012). Sanganyado and Gwenzi (2019) conclude that human health risks from low-dose exposure to PCPs and pharmaceuticals remain weak, however, consuming drinking water contaminated with ARBs and ARGs may contribute to the development of antibiotic resistance in humans. In order to have an accurate risk assessment of ARBs or ARGS in groundwater, scientists and healthcare providers need to integrate disease outbreak analysis, human exposure modeling, and clinical data to estimate the dose-response relationships of pathogenic ARB in drinking water (Sanganyado and Gwenzi, 2019). However, using human made chemicals as a pollution indicator looks promising and future studies will reveal more about its application and use in Hawaiʻi.

Distinguishing between the origin sources of a sewage indicator is important, however, it still an incomplete process. To date, there are no single test methods to identify if a microorganism or chemical marker is from human or animal waste (Sinton et al., 1998). Combinations of indicators, along with proper additional information such as land-use patterns and uses, along with hydrologic and hydraulic modeling, may be the most appropriate method to help distinguish between sources. Sinton et al. (1998) recommend a multivariate statistical approach, using the most appropriate chemical or microbial options for the site. Newer DNA-based methods and more information regarding natural concentrations of microorganisms in different environments will help advance our ability to be more confident when studying fecal contamination in the future.

How are wastewater pollution indicators reaching water resources?

Wastewater pollution has multiple pathways to enter the ocean, including non-point sources such as surface water, SGD, and point sources like pipes. One method of tracking and tracing groundwater flow into coastal waters from SGD is to use dye tracer tests, such as that performed in Abaya et al. (2018b) and shown in Fig. 3.

Figure 3. Dye tracer test used to measure travel time of wastewater to ocean environments. Source: University of Hawaiʻi, N.D.

In an effort to track and estimate SGD parameters more comprehensively, researchers have used multi-tracer approaches by measuring salinity, silica, radon, radium isotopes, and temperature (Dulai et al., 2016; Taniguchi et al., 2019; Kelly et al., 2019). Using anthropogenic indicators and methods such as those researched by Dulai et al. (2016) may provide the ability to track the pathway of nutrients to understand how and what waters are being impacted by pollution. Other SGD tracking methods include tracking fluorescent dissolved organic matter (fDOM) solutes. The solutes may provide a cost-effective and efficient monitoring tool to measure and map groundwater dispersal along coastal environments and coral reefs. The fDOM solutes of SGD can be analyzed and visualized with geospatial software to create maps of potential areas of SGD, as shown in Fig. 4. According to recent research, fDOM has the potential to differentiate groundwater sources according to land-use, hydrology, or other factors, in combination with other biogeochemical parameters (Nelson et al., 2015).

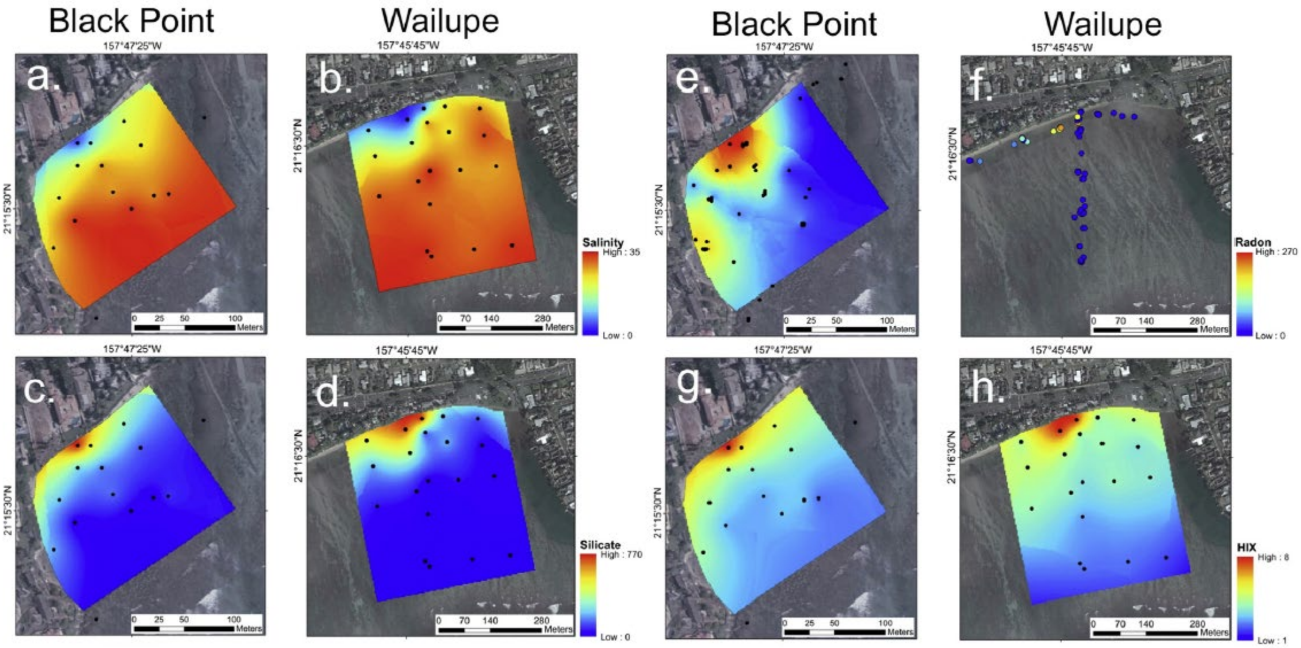


Figure 4. Fluorescent dissolved organic matter (fDOM) in the spatial context of submarine groundwater discharge (SGD) in Maunalua Bay. Contour plots of conservative solutes and fDOM solutes at Black Point (a, c, e, g) and Wailupe (b, d, f, h) 28–29 May 2014, including salinity (a, b), silicate concentrations (c, d) (log10 μmol L−1), radon concentrations (e, f) (dpm L−1) and the fDOM humification index (g, h) (HIX). Source: Nelson et al., 2015; *Marine Chemistry*. Used with permission.

Having better information around elements of and within SGD is important when attempting to understand water quality and coastal nutrient balance and fluxes. Studies by Richardson et al. (2015), Bishop et al. (2017), and Amato et al. (2016) measured parameters of SGD, marine and groundwater quality, and compared land-use characteristics to understand how nutrients can be moved by SGD. By understanding nutrient levels and nitrate isotopes within fluxes of SGD, land-use patterns, and recharge data, researchers can examine the potential for nutrient loading within the local aquifers, which may be useful for risk evaluation and prioritization of practices to reduce pollution.

Groundwater has the ability to deliver significant quantities of new and recycled terrestrial nutrients from various sources. Via natural or human sources, nutrient and chemical pollution can enter surface waters through groundwater connections (Dulai et al., 2016). Several studies investigated wastewater indicators and connectivity between pollution sources and adjacent waters in Hawaiʻi. Professor Craig Glenn and his team at UH Mānoa are currently investigating hydraulic, geochemical, and stable isotopic connections between wastewater and other land-uses to ocean waters. Groundwater flow into coastal zones on the islands of Oʻahu, Maui and Hawaiʻi Island have been mapped and measured by Glenn's group using aerial infrared imaging from both aircraft and drones, such as shown in Fig. 5 (Johnson, et al., 2008; Glenn et al. 2012, 2013; Kennedy, 2011, 2016; Kelly et al., 2013, 2019; Mathioudakis, 2017, 2018). This type of combined information can inform models or resource managers. The overall goal is to understand how contaminants and nutrient loading can move from OWTS (by using remote sensing techniques like thermal imaging combined with field and laboratory studies of SGD to surface waters. By measuring nitrogen stable isotopes within algal tissues, measuring SGD discharge, and using microbial genomic fingerprinting, this data can be incorporated into advanced watershed and groundwater transport models, enabling watershed management and policy to be based on field-tested parameters for specific sites. There are clear hydraulic connections between groundwater, SGD, and streams, which signal the need for broad watershed management practices, including stricter control and inventory of non-point source pollution sources (Bishop et al. 2017; Dores, 2017; Mathioudakis, 2018).

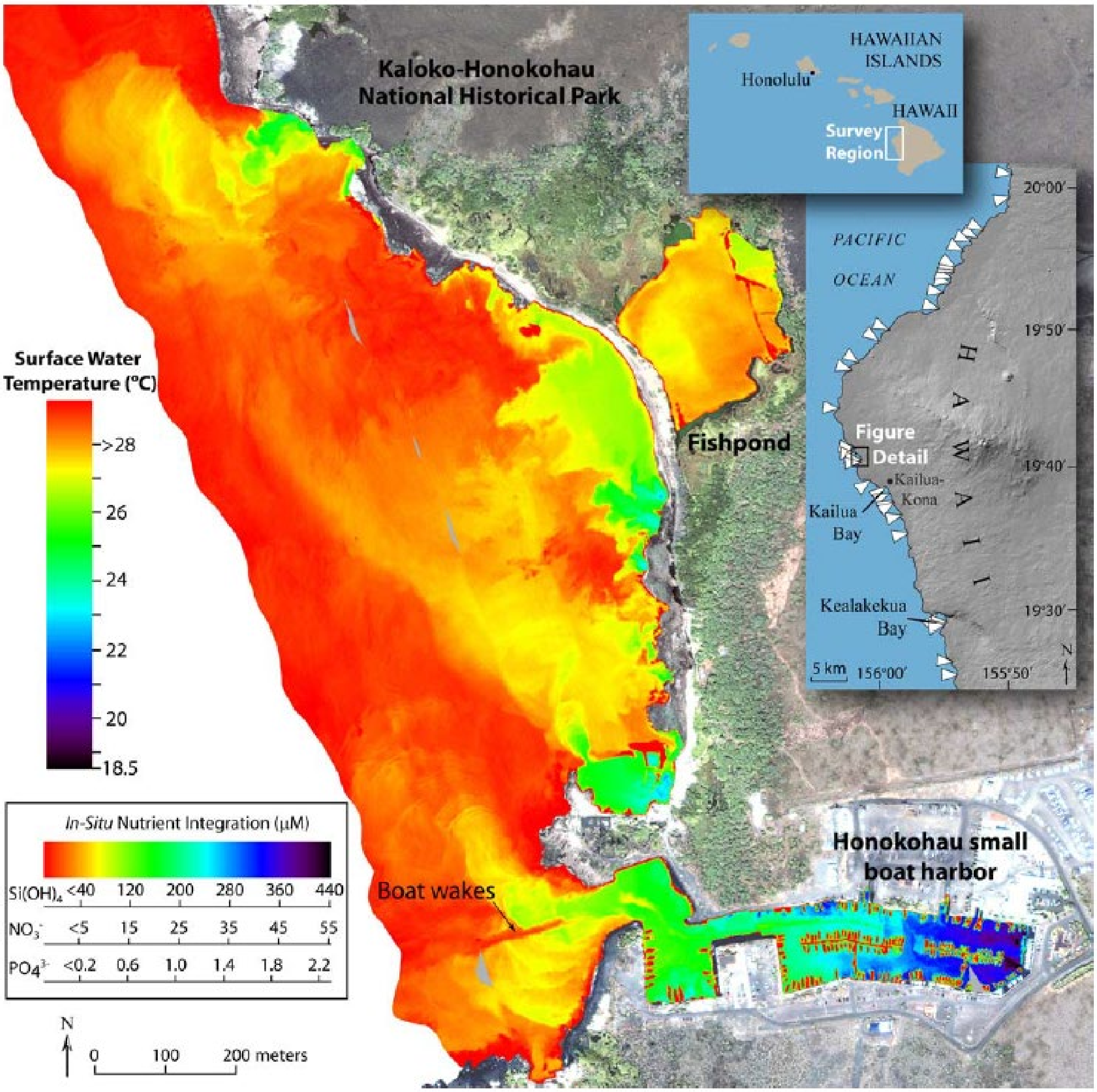
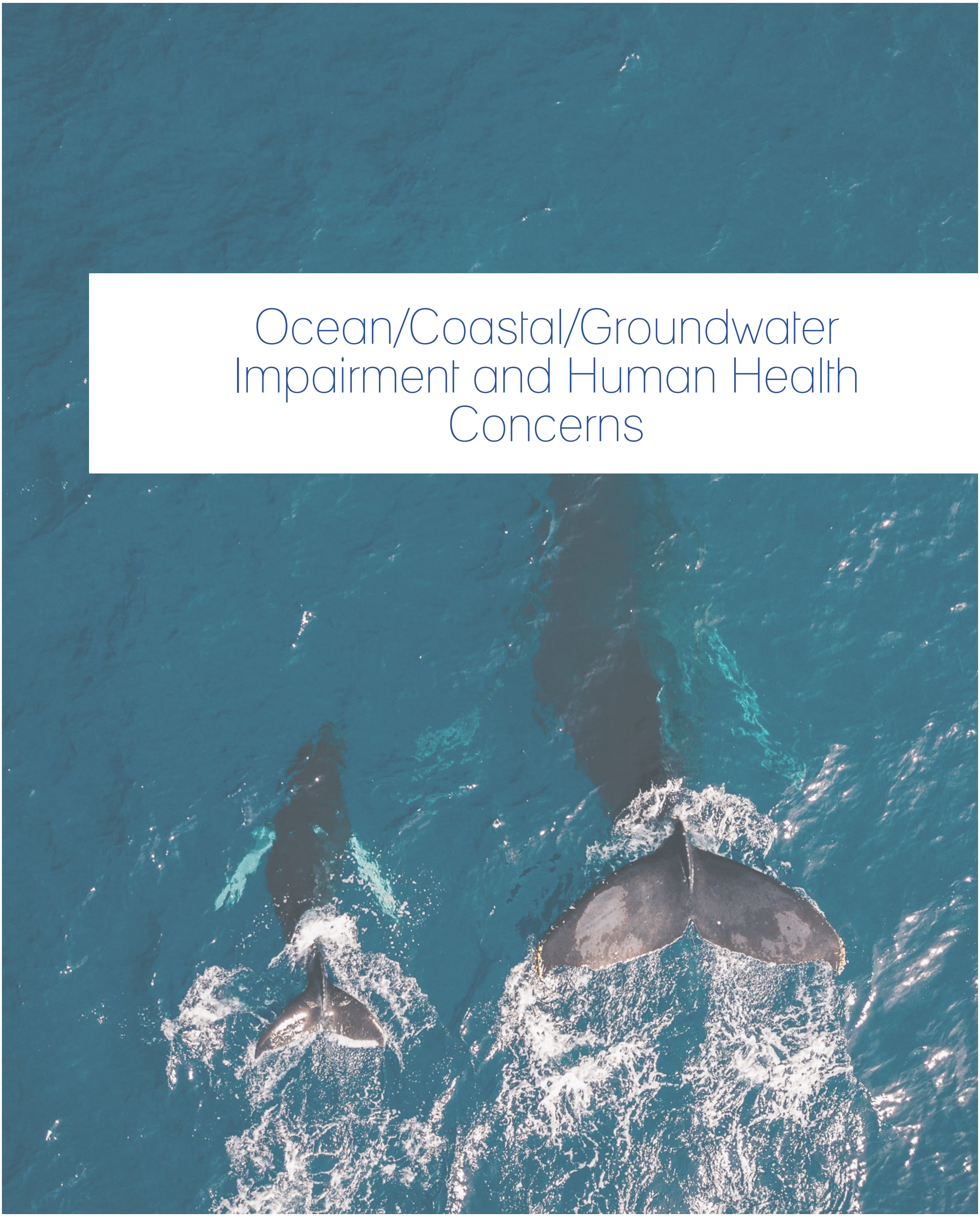


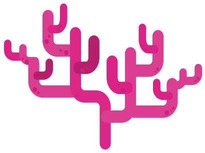
Figure 5. 2005 sea surface temperature map using low altitude thermal infrared aerial imaging over waters near the Kaloko-Honokohau National Historical Park, western Island of Hawaiʻi. Red indicated sea water temperature while other colors indicate SGD. White triangles in the inset indicate the positions of thirty-one major point-sourced SGD plumes identified by the imagery. Source: Johnson et al., 2008. Used with permission.

Ocean/Coastal/Groundwater Impairment and Human Health Concerns

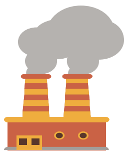


What are some of the impacts to water resources and human health from wastewater pollution?

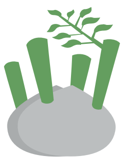
5 Key Concepts



Regarding Ocean/Coastal/Groundwater Impairment and Human Health Concerns



Excessive nutrient pollution is associated with high nitrogen levels in algae tissues, the presence of invasive algae, high invasive macroalgal cover and low biodiversity on coastal reefs.



Many studies have connected sewage effluent discharge with decreased species diversity, increased eutrophication, and substantially altered ecosystem structure.

Coral cover was negatively correlated with the presence of FIB, high macroalgal $\delta^{15}N$ levels, and overall nutrient concentrations. Tidal pulses are likely to be delivering wastewater pollution to reefs offshore.

There are several examples of areas in Hawai‘i that have seen decreases in coral cover adjacent to areas with high cesspool densities and dissolved nitrogen levels.

In Hawai‘i, recreational bathers are four times more likely to develop *S. aureus* infections. Hawai‘i has two times more MRSA infections than the national average.

6 Knowledge Gaps

Regarding Ocean/Coastal/Groundwater Impairment and Human Health Concerns

Gathering more field data to enhance our understanding of the relationships between groundwater pollution, connected hydrologic systems and the ecological impacts can inform models to improve our understanding of these processes and pollution sources.

Understanding coastal water flow regimes may be vital to understanding which areas may receive the greatest impacts from land-based pollution sources.

More studies need to be performed to evaluate any impacts from the interactions of multiple pollution compounds and the environment.

Although not required by state or federal regulations, testing private drinking water wells where large numbers of cesspools are in use may provide the state with vital data on groundwater quality and improve human health risk assessments.

Though there are examples in Hawai‘i of improvements to water quality and ecosystem health after point source wastewater pollution discharges were eliminated, more research is needed to evaluate the impacts to ecosystems after the replacement of cesspools.

Research needs to be performed to evaluate if legacy nutrients will negatively impact the amount and speed of the recovery of ecosystems after replacing cesspools and outdated OWTS.

What are the types of impacts to various ecosystems in Hawai‘i?

Because no point of land is beyond thirty miles from the shore, all of the State of Hawai‘i is considered part of the “coastal zone”, meaning activities on land have an impact on inland water quality and coastal water quality (Department of Health, 2015). There are numerous research studies listed in the primary reference list that evaluate the impacts to water resources and various ecosystems across the Hawaiian islands. Several of these studies focused on the impacts to coral reef communities, which are vitally important to Hawai‘i and beyond. The following section will attempt to answer questions about potential impacts to water resources, associated natural communities and human health concerns from OWTS pollution. One conclusion, however, that isn’t in question is that land-use practices can and do directly impact surface and groundwater quality as well as adjacent reef communities (Amato et al., 2016; C. Smith, personal communication, December 3, 2019). Figure 6 below demonstrates that extensive human land-use practices have impacts to offshore environments, one being increased nutrient amounts in algal tissues. Groundwater adjacent to these areas enters the ocean through SGD and surface waters, which can carry nutrients and harmful pathogens (McKenzie et al., 2019). Our understanding of the relationships between groundwater pollution, connected hydrologic systems, and ecological impacts is extensive but not complete (Amato et al., 2016). By gathering more field data and using it to inform models and frameworks currently in use, we can improve our understanding of these processes.

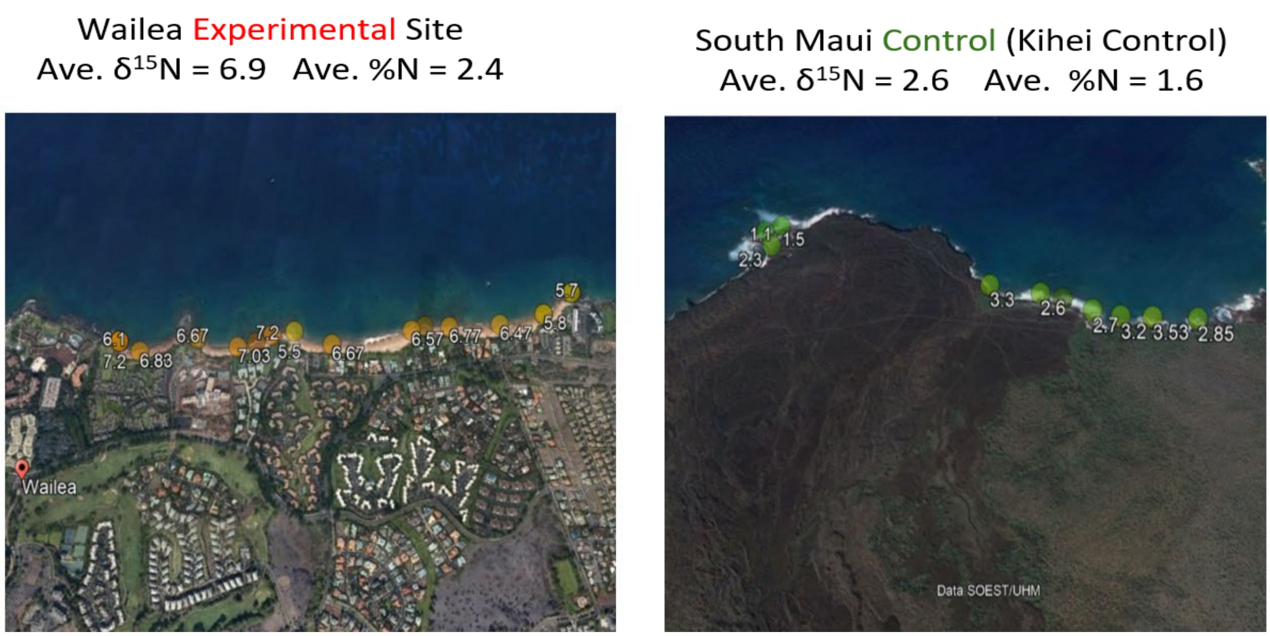


Figure 6. Maui algal tissue $\delta^{15}N$ values comparing a highly developed area to a non-developed area. Source: 2019 Water Resources Research Center Sewage Contamination Study, (unpublished). Used with permission.

Excessive amount of nutrients from OWTS pollution or other land sources such as stormwater runoff or agricultural fertilizer are associated with high nitrogen levels in algae tissues, the presence of invasive algae, and high macroalgal cover and low benthic biodiversity (Amato et al., 2016). These impacts can be damaging to coral reefs and the various supported local economies, landscape, fisheries, and cultural practices. The most common impact to coral reefs from nutrient pollution is algal overgrowth (Dailer et al., 2010; Abaya et al., 2018a). Corals can become stressed under high nutrient loadings with coral reef mortality being linked to excessive nutrient concentrations (Abaya, 2018). Couch et al. (2014) has also linked high nitrate concentrations to coral growth anomalies.

Damage to and loss of coral reefs can have widespread consequences, including severe economic losses. It is estimated that intact coral reefs provide $835.4 million dollars in protection to buildings on the islands of Maui, Oʻahu, Kauaʻi and Hawaiʻi (Gutierrez, 2019; Storlazzi et al., 2019). Intact and healthy reefs can increase food security, promote tourism, provide protection to infrastructure and improve community resiliency from major storms (Gutierrez, 2019; Storlazzi et al., 2019). According to Cesar and van Beukering (2004), the net benefits provided by coral reefs to Hawaiʻi's economy are estimated to be $360 million a year. The value provided by the State's 1660 km^2 (410,000 acres) of potential reef area in the main Hawaiian islands is estimated at nearly $10 billion (Cesar and van Beukering, 2004).

Direct and indirect losses to corals and human communities can be attributed to wastewater pollution. Maui residents in the North Kihei area have experienced severe algae growth problems, likely from nutrient pollution, due to a high number of cesspools and OWTS in the area (Smith and Smith, 2006). Cesar et al. (2002) measured annual impacts to condominium property values from excessive algal biomass piling on beaches and estimate annual losses in property values were over $9 million dollars. By combining losses of property values, loss in rental income, and money spent for algae cleanup costs, the total estimated losses jump to over $20 million dollars per year. The CCWG may wish to identify certain communities where holistic research studies could be performed to evaluate wastewater management schemes, recovery mechanisms, bacterial counts, $\delta^{15}N$ values, and economic assessments to evaluate the successes of post cesspool conversion program outcomes.

Frameworks to track, monitor and evaluate progress are important. One such framework used to track and evaluate environmental degradation and restoration efforts are Areas of Concern (AOC), used by the U.S. and Canada in the Great Lakes Water Quality Agreement. An AOC identifies an area that has experienced environmental degradation through beneficial use impairments (BUI). A BUI is defined as a change in the chemical, physical, or biological integrity of an ecological system that causes significant environmental degradation (USEPA, 2019a). Remedial action plans (RAPs) are then developed to restore BUIs and remove an AOC designation. A RAP is a plan that includes: identifying which BUIs exist and their causes; criteria for restoring the listed BUIs; remedial methods and actions to be taken; and a method to track progress toward delisting (USEPA, 2019a). More information on the AOC framework can be found at https://www.epa.gov/great-lakes-aocs.

Amato et al. (2016) highlighted that coastal and reef areas adjacent to less anthropogenic disturbance typically have lower nitrogen concentrations in SGD and algae cover than areas adjacent to more disturbance. Researchers observed low nutrient levels in coastal surface waters, high species richness, an abundance of corals, and little benthic macroalgae compared to locations adjacent to higher human disturbance. Scientists studying the complex dynamics of marine ecosystems have highlighted the potential for rapid, dramatic changes in ocean conditions, called tipping points (Ocean Tipping Points, 2019).

Even seemingly small pressures from human influence can cause rapid and large-scale changes in a system. Projects such as the Ocean Tipping Points Project (http://oceantippingpoints.org/) seek to understand these tipping points in our region and develop management tools to avoid ecosystem damages, monitor indicators, prioritize management actions, and evaluate progress toward ecosystem objectives (Ocean Tipping Points, 2019). Hawaiʻi's 30 by 30 initiative to manage thirty-percent of its nearshore waters acknowledges the need to manage local stressors, including sediment and nutrient runoff, to have sustainable and resilient coastal ecosystems. The CCWG may wish to incorporate management tools or monitoring information provided by the Ocean Tipping Points project or the 30 by 30 project into its long-range plan. As noted previously, it may be difficult to draw a direct correlation to OWTS pollution as declines in ecosystem health have many factors involved, such as globally influenced climate change, or local land-use changes. Concretely identifying correlation between specific OWTS and environmental degradation has not restricted other states' efforts to upgrade outdated or failing OWTS as part of plans to improve ecosystems an create healthier communities (Mezzacapo, 2019).

In an effort to overcome some the difficulties of studying reef impacts, Abaya et al. (2018b) attempted to use a multi-technique approach to document reef impacts and indicators from various sources of nutrients associated with water column mixing and SGD in Hilo Bay. The study used FIB as a wastewater indicator, measurements of ocean bottom cover, macroalgal bioassays (bioassays are analytical measures of a concentration or potency of a substance and its effect on living cells or tissues), and a pollution scoring tool. Coral cover was negatively correlated with FIB, macroalgal $\delta^{15}N$ levels, and overall nutrient concentrations (Abaya et al., 2018a). Although wastewater concentrations were most detectable close to the shoreline, results did show that tidal pulses might be delivering pollution to the reef offshore. Therefore, understanding flow patterns in waterbodies may be vital to understanding which areas may receive the greatest impacts from pollution sources. Other studies, including one by Delevaux et. al. (2018) sought to also use a multi-technique approach by developing a linked land-sea modeling framework. The study researched Hāʻena on the windward side of Kauaʻi and Kaʻūpūlehu on the leeward side of Hawaiʻi Island. By using by using local data, coupled groundwater and coral reef models, researchers sought to determine the impacts of land-based processes influenced by human activities and marine drivers on coral reefs.

Hawaiian ecosystems are already experiencing impacts

There are several examples of areas in Hawaiʻi that have seen decreases in coral cover adjacent to areas with high cesspool densities and high dissolved nitrogen levels. Minton et al. (2012), cited in Abaya (2018), found coral coverage decreased nearly fifty percent at various sites around Puakō, an area with high levels of nitrogen, short groundwater travel time, and high levels of *Enterococcus* in nearby waters. Many other studies have connected wastewater effluent discharge with decreased species diversity, increased eutrophication, and substantially altered ecosystem structure (Pastorok and Bilyard, 1985; Jokiel, 1991; Stimson et al., 2001, cited in Bahr et al., 2015). Figure 7 highlights common threats to coral and human health from a literature review and a data visualization comparing tool. The figure illustrates the overlap between nine common threats to coral and humans. Connecting the various factors that impact coral and human health is important because of overlapping interdependency on resources.

Delevaux et al. (2018) developed a unique land-sea modeling framework to connect many factors that play a role in impacting coral. The framework uses local data and fine scale groundwater and coral reef models. They incorporate impacts from groundwater and nutrients, human activities, and marine variables like waves, geography, and habitat in a reef to ridge system to evaluate vulnerable areas and potentially inform place-based ridge-to-reef management.

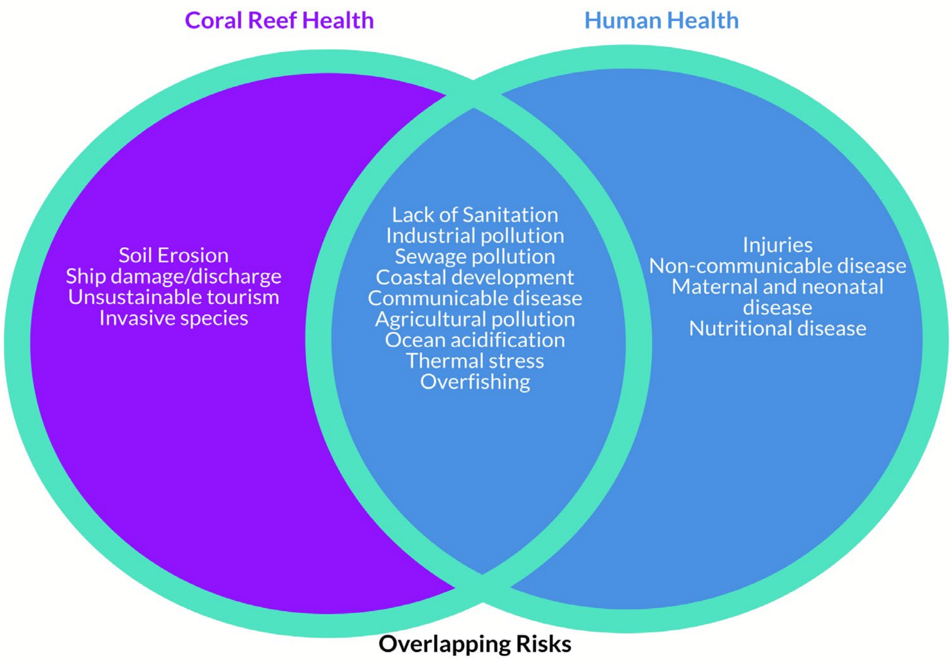


Figure 7. Diagram used to visualize the evidence of common threats overlapping for coral reefs and human health. Wear (2019) surveyed literature and used the GBD Compare Data Visualization tool from the Institute for Health Metrics and Evaluation to identify common threats to human health and Reefs at Risk Revisited (Burke et al. 2011, cited in Wear, 2019) to identify common threats to coral reef health. Adapted from Wear, 2019.

There have been limited studies around Hawaiʻi evaluating the toxicity and persistence of various environmental contaminants in wastewater on marine biota from certain sources of pollution (Hunter et al., 1995). Human health concerns in seafood are typically focused on heavy metals, pesticides, and organics, which tend to concentrate in sediment and fish, and are often attributed to industrial activity. Examination of research for this white paper did not discover any studies in Hawaiʻi that tested septic tank or cesspool sludge and effluent for different types of contaminates, compounds, or bacteria and viruses. Additionally, little is understood how many types of CECs or organic wastewater contaminates (OWCs) move and interact with other chemicals or treatment system characteristics and subsurface variables, and how or what impacts to local water resources may occur (Conn et al., 2006). More testing of human waste for specific chemicals, genetic markers, or expanded pathogens might yield future wastewater pollution indicators and generate studies to evaluate their associated impacts, human, or ecosystem based.

Wastewater pollution is thought to impact physical ocean characteristics as well, which can indirectly and directly impact ocean organisms and systems. According to studies by Richardson et al. (2018); Prouty et al. (2017); Silbiger and Sorte (2018) wastewater discharge has been associated with effects on coastal water pH through increased dissolved inorganic carbon flux. Decreased pH can impact coral growth and overall resiliency (Bennett, J., Ocean Portal Team, and NOAA, 2019). Coastal ocean acidification is happening at a faster rate than acidification in the open ocean, which can more directly impact human settlements (Strong et al., 2014). Other studies outside Hawaiʻi demonstrate that corals exposed to caffeine are less resistant to coral bleaching (Pollack et al., 2009). Pharmaceuticals have also been linked to lower male to female ratios in stream fish exposed to ethynylestradiol (Nash et al., 2004). These various impacts indicate that many more studies need to be undertaken to completely understand future risks to ecosystems, especially from wastewater pollution. As these studies demonstrate, impacts are already happening and may have serious and costly repercussions.

In the Florida Keys, high human density and associated wastewater loadings were linked to elevated $\delta^{15}N$ values and harmful algal blooms, which can impact recreational water activities and drinking water supplies (USEPA, 2018). According to Lapointe et al. (2005), cited in Dailer et al. (2010) freshwater effluent from SGD, originating from injection wells, are likely impacting Florida coral reefs by providing excess amounts of nutrients. It is important to note that effects from reducing pollution through the elimination of diffuse sources such as OWTS, may still impact the environment through redistribution via point sources, such as injection wells. A similar example is evident in Hawaiʻi through the Lahaina wastewater treatment plant case (Fackrell et al., 2016; Glenn et al., 2013; Hunt and Rosa, 2009). And may also be applicable for injection wells at Keehi, Kahului, and the Waimanālo wastewater treatment plan (Amato et al., 2016; Amato et al., 2020).

Finally, a 2016 study by Yoshioka et al. investigated the potential of increased rates of disease on coral reefs from wastewater pollution. The 2016 paper examined whether enterococci concentrations along the shoreline waters and $\delta^{15}N$ values had any relation to coral reef disease offshore. The study had limitations, however, and could not conclusively draw causation as many variables existed and data was limited. The authors did highlight the importance and need for long-term sampling to capture temporal patterns of wastewater pollution (Yoshioka et al., 2016). Future studies may also wish to continue to explore alternative metrics to link wastewater pollution and ecosystem impacts, such as MST, and develop better data or models to understand water movement, especially in embayments where reefs may be particularly affected by decreased water quality (Yoshioka et al., 2016).

What are the effects of wastewater pollution to human health?

Protecting human health and the environment is an important role for governments and other institutions (USEPA, N.D). Ensuring the proper processing and disposing of human waste presents many challenges to achieving the goal of a healthy environment (Andrzejewski, 2019). Waste disposal challenges aren't unique to Hawaiʻi. Other locations in the United States also have a significant amount of antiquated waste disposal systems such as cesspools (Suffolk County Health Department, 2019). Dangerous pathogens such as *Vibrio cholerae* were once widespread across the United States in the 1800's, but because of upgrades in water treatment technology, many dangerous pathogens aren't of major concern anymore (WebMD, 2019). Understanding Hawai'i's human health risk from sewage contamination is essential to properly prioritize cesspool upgrades. There are epidemiological studies associating risks with point source pollution, however, limited information regarding risks of non-point pollution in subtropical climates. Cesspools and OWTS that are malfunctioning can provide a reservoir for pathogenic bacteria, which can enter nearshore environments through groundwater, surface water and SGD, potentially causing water quality hazards, illustrated in Fig. 8 (Ground Water Protection Council, 2016).

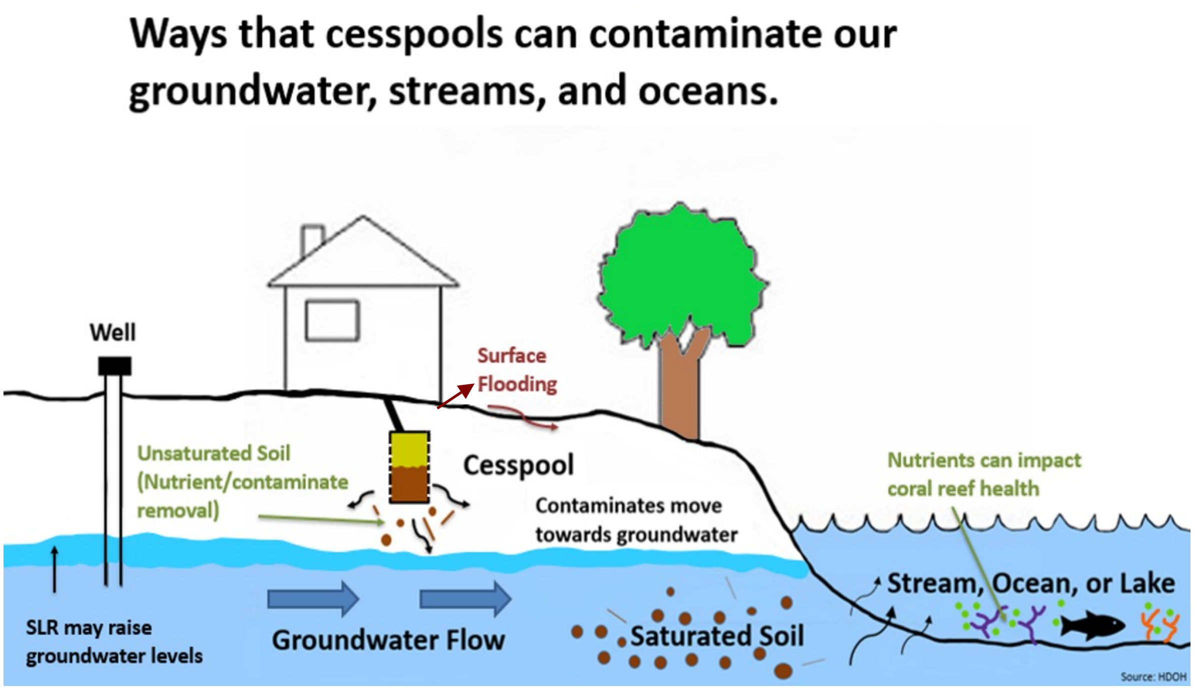


Figure 8. Multiple pathways that cesspool pollution can enter water resources. Source: Adapted from Hawai'i Department of Health (N.D.).

Recreational water quality is important to locals and tourists who use Hawai'i's ocean resources (Kirs, 2018). However, little is known about background bacteria levels and transport dynamics of bacteria and viruses in wet tropical regions where recreational water use occurs year-round (Strauch et al., 2014; Rochelle-Newall et al., 2015; Strauch, 2017, cited in Economy et al., 2019). Pathogens such as *Staphylococcus aureus* are recognized as a potential environmental human health threat, even though *S. aureus* is naturally found in the environment and on the skin and nasal passages of most healthy humans (Zetola et al., 2005, cited in Economy et al., 2019). Recreational bathers in Hawai'i are four times more likely to develop *S. aureus* infections (Charoenca and Fujioka, 1995, cited in Economy et al., 2019; Taylor and Unakal, 2019). And infections of *S. aureus* on the skin can cause boils, impetigo, styes, folliculitis, and furnacles (Minnesota Department of Health, 2010).

More concerning is Hawai'i's rate of methicillin-resistant *S. aureus* (MRSA) infections, which is two-times the national average (Chaiwongkarjohn et al., 2011, cited in Economy et al., 2019). This bacterium is responsible for several difficult-to-treat infections in humans. *Staphylococcus aureus* is being found in many parts of watersheds, even areas where humans typically aren't recreating, and often found in wastewater (Economy et al., 2019). Results from an evaluation and modeling done by Economy et al. (2019) show *S. aureus* and other FIB were common in Hawaiian estuarine waters, rivers, and watershed sources, although it still isn't clear if these are from natural or human sources and what risks, if any, they may pose to humans. Rainfall amounts and changing climate patterns (higher water amounts, higher bacterial counts) may influence the transport of bacteria and pathogens from the watershed to nearshore waters.

By better identifying specific bacterial sources that are threats to human health, appropriate government institutions or local organizations can create more localized watershed management strategies as preventative measures, in an effort to reduce pathogen loads from multiple sources (stormwater, OWTS, agriculture). Models designed for wet tropical regions, like that in Economy et al. (2019), used hydrologic and water quality metrics to predict pathogen loading to nearshore waters and could be used to inform recreational water users or water resource managers of health risks to recreational water users.

Although many human health risk assessment studies have yet to show appreciable risk to human health from potential environmental exposure to pharmaceuticals and personal care products, the problem needs to be viewed in a larger context (Cunningham et al., 2009). The long-term effects to humans or organisms through the consumption of low-levels of certain anthropogenic compounds are still unknown, which does not mean the risk is zero. Pharmaceuticals, for example, are a known and added stressor to aquatic ecosystems. Many aquatic ecosystems have other stressors that include flow regime changes, temperature fluctuations, habitat destruction, overfishing, eutrophication, invasive species, and diseases (Johnson and Sumpter, 2014). Ultimately, adding stressors may reduce the resilience of certain ecosystems and their ability to respond to changing climates or further human development.

Decreasing wastewater inputs can improve water quality

Starting with Smith et al. (1983), who studied changes in Kāneʻohe Bay, Hunter and Evans (1995) followed and detailed one of the best-documented transitions in ecosystem composition within Kāneʻohe Bay. In the past, Kāneʻohe Bay suffered from poor water quality and high nutrient levels from various sources of pollution, including wastewater and sediment from terrestrial runoff. It's unclear the exact percentage of nutrient inputs from each source, however, large amounts of pollution were derived from leaky sewer lines, cesspools and septic tank discharges, commercial tour and recreational boat waste discharges, and periodic sewage diversions from municipal wastewater treatment plants (Hunter and Evans, 1995). In 1977–1978, two municipal wastewater outfalls were diverted from the bay. What followed was a dramatic decrease in nutrients, turbidity, and phytoplankton abundance in areas surrounding the outfalls. Changes in the environment occurred rapidly, from areas dominated by certain algae and filter and deposit feeders, to "coral gardens" which more closely matched the natural evolution of Hawaiian reefs. In less than ten years, the algae *D. cavernosa* had decreased to a quarter of its 1970 era abundance and coral cover more than doubled, as detailed in Fig. 9 (Hunter and Evans, 1995). In recent years, algal blooms have returned, puzzling scientists.

One theory is that legacy nutrients from years of wastewater sources flow into the shallow and slow-moving portions of the bay are attaching to sediment. When storms, currents, or disturbance re-suspend these nutrients, bloom cycles may reoccur (C. Smith, personal communication, December 20, 2019). However, more research needs to be performed to validate this possibility.

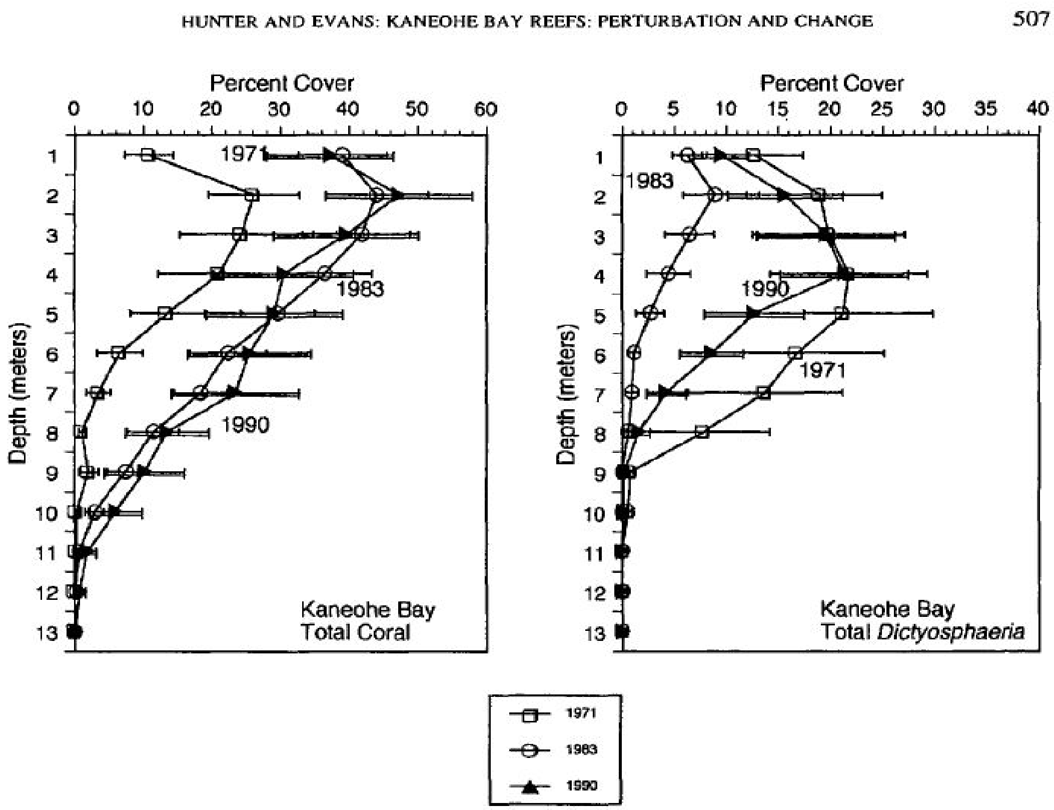
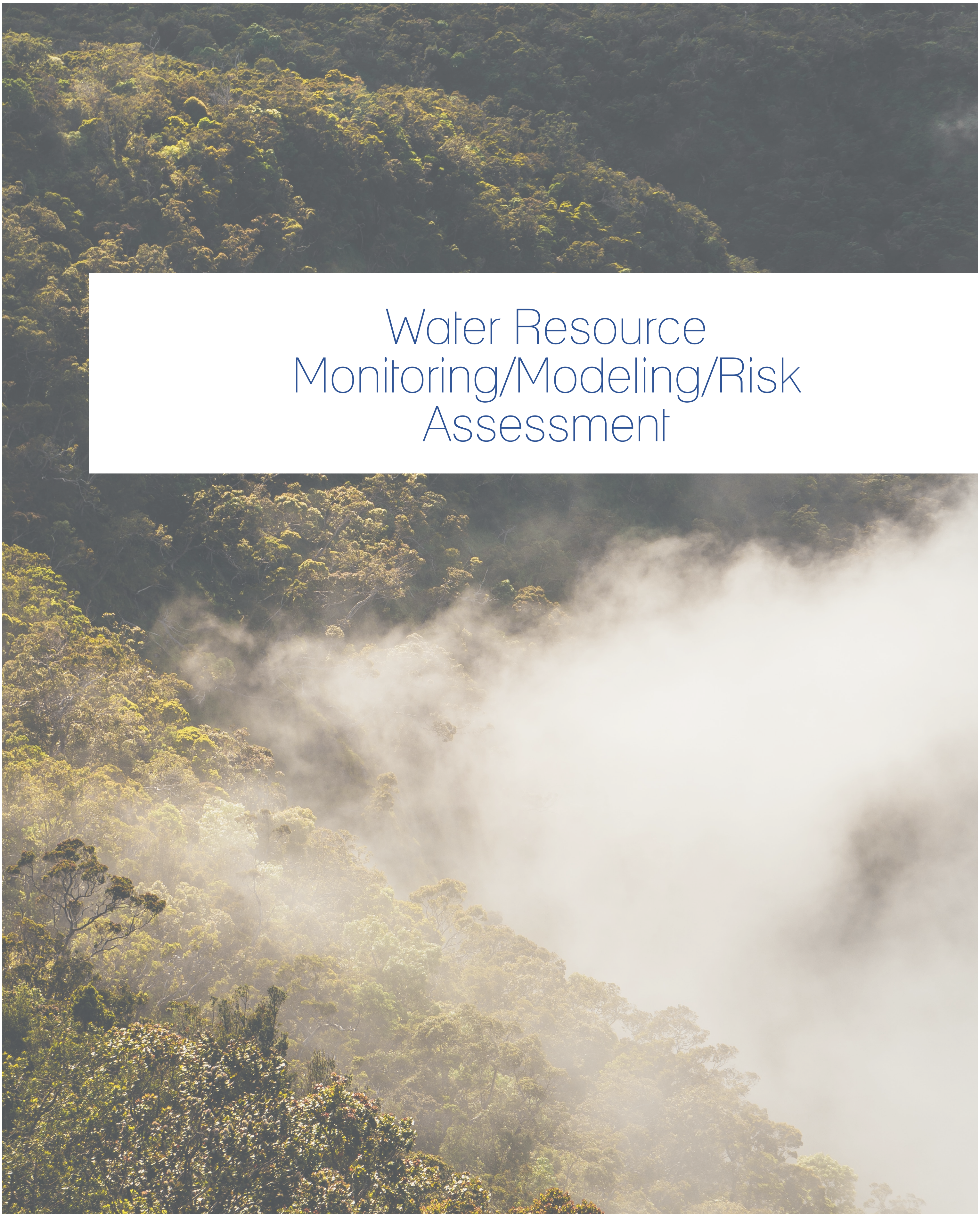


Figure 9. Depth profiles of mean percent cover of a) total coral and b) *Dictyosphaeria cavernosa* averaged over fifteen survey sites in Kāne‘ohe Bay censused in 1971, 1983, and 1990. Source: Hunter and Evans, 1995; *Bulletin of Marine Science*. Used with permission.

Other research has been performed to assess impacts of repairing failing OWTS and associated microbial water quality. One study based in North Carolina from Conn et al. (2012) determined that repairing failing OWTS can improve microbial groundwater quality. However, because of land-use patterns and the continued presence of bacteria in surface waters, researchers suggest a multi-tiered monitoring approach, using simple cost-effective methods and microbial tracers, including FIB and phage to track whether upgrades were successful. According to the authors, “The findings are a first step of developing a systematic approach towards selecting the type, number, and locations for pre/post monitoring of OWTS and in the selection of specific microbial tracers to be monitored” (Conn et al., 2012, p.223). Challenges still remain to develop a comprehensive understanding of the connection between human activities (which contribute pollution), marine and freshwater environments, and human health. Increasing levels and distribution of anthropogenic substances into the environment have the potential to significantly impact human health. These risks should not be underestimated and must continue to be studied (Fleming et al., 2006).

Water Resource Monitoring/Modeling/Risk Assessment



What tools do we have to attempt to understand complicated environmental processes?

9 Key Concepts

Regarding Water Resource Monitoring/Modeling/Risk Assessment

Statewide coastal models have been created detailing cesspool impacts.

Monitoring data collected, including radon^{222} and δ^{15}N, are significant resources for understanding nutrient loading from sources to the coastal environment. These and other hydrological data are critically needed for model applications.

Models can be used to evaluate potential impacts to infrastructure and assist with long-term planning efforts.

A study evaluating the human health and environmental risk posed by OWTS on O'ahu estimated that nearly 10 mgd of sewage is released to the environment, much of it reaching the groundwater. Cesspools made up about 77 percent of the total estimated release of untreated effluent and 96 percent of the potential nitrogen release.

Using source-water protection assessments can provide the CCWG with data on source-water susceptibility to contamination, which can be inputted into a decision-making model for determining system upgrade requirements or timetables.

There are available contaminant-specific models that identified groups of drinking-water wells with the lowest/highest reported contaminate detections and the lowest/highest nitrate concentrations.

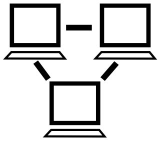
A vertical distance between ground surface and groundwater of 25 feet was recommended for proper OWTS effluent treatment, many areas in Hawaiʻi cannot meet this condition.

Decreasing wastewater inputs can improve ecosystem and human health.

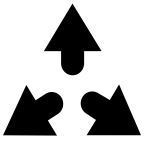
Recent studies have validated wastewater modeling approaches with algal bioassays, including similar ones by Whittier and El-Kadi in 2009 and 2014.

5 Knowledge Gaps

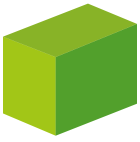
Regarding Water Resource Monitoring/Modeling/Risk Assessment



Further field studies are necessary to collect data used to calibrate and validate models in order to determine the degree groundwater is being degraded by OWTS.

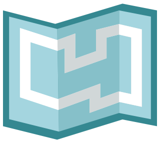


Site specific data are necessary to improve current models regarding density effects and preferential groundwater flow.



Three-dimensional hydrologic models simulating chemical fate, transport processes, and mixing dynamics are needed for various contaminants in coastal areas that have high concentrations of cesspools and sensitive resources.

More studies or models that evaluate variations in site specific conditions may be needed to assist in the OWTS permitting process. By better understanding the capabilities of different soils, and other site conditions, more tailored regulations can be created for OWTS installations.



Having a better understanding of aquifer vulnerability is important for risk analysis and planning. It is unknown if anyone has extended models to include sea-level rise impacts on wastewater plumes.

What can different types of models tell us?

One of the main questions often asked is: can models tell us which cesspools are causing pollution and impacts to water resources? The answer is, unfortunately, probably not. In general, models are simplifications of real-world systems and are good at providing generalized information about that system. Without site-specific data and the ability to track and trace pollution from a specific source, like a cesspool, model results are only as good as their input data. Despite such limitations, models are still very useful tools that can simulate and assess important and often complex processes within a system. Additionally, models can compare different scenarios, for example, nutrient quantities and travel times from different OWTS upgrade schemes.

The first step in the modeling process is to develop a site conceptual model, as shown in Fig. 10, which includes all available hydrogeological information about the site and a list of variables to simulate. An appropriate numerical model is then chosen, simulating the processes controlling water flow and contaminant transport. Example models, often used across Hawai‘i, include several from the USGS, including MODLOW, GSFLOW, and PSLoadEsT. More information about each model is available at https://www.usgs.gov/mission-areas/water-resources/software.

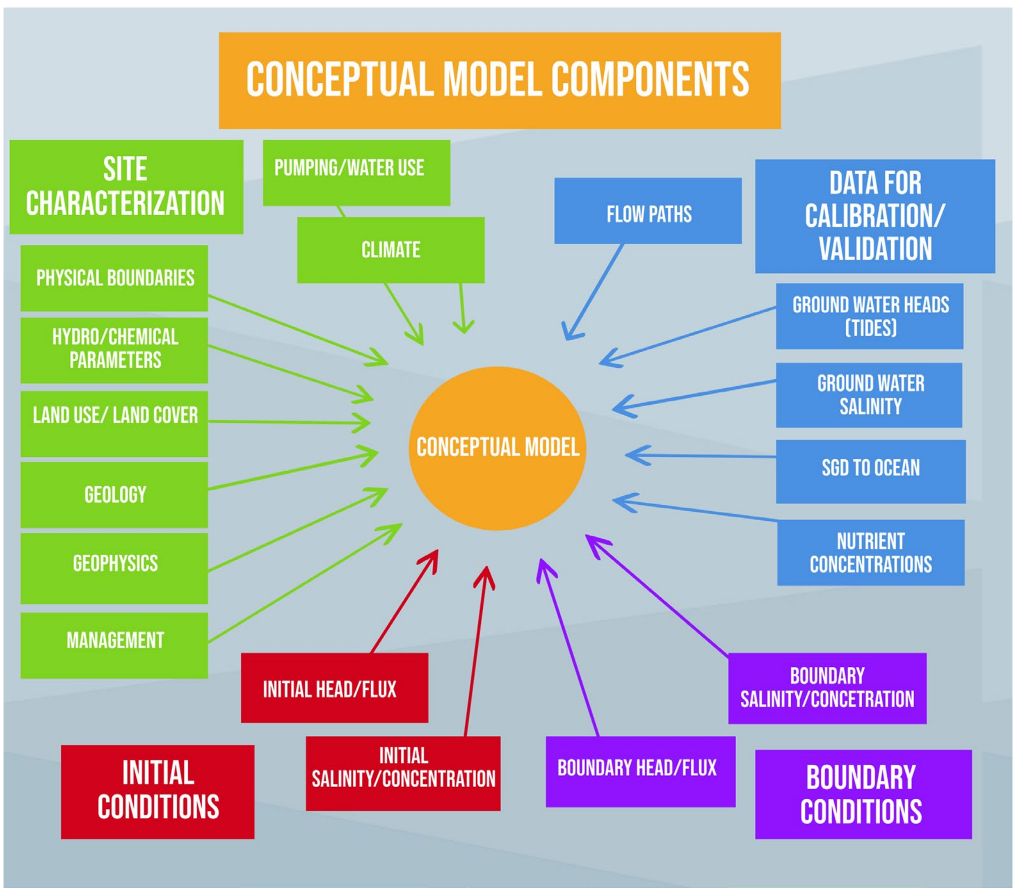


Figure 10. Elements of a groundwater conceptual model. Adapted from El-Kadi, personal communication, December 20, 2019.

Various models, including empirical and physically-based models, can either be deterministic or statistical in nature. The latter models differ by using parameter statistics to predict expected values or the probability of the occurrence of an outcome. For example, a deterministic model would predict a contaminant level at a certain time and location. A statistical model would predict how likely the concentration of a contaminant would exceed a certain value at the same time and location.

Empirical models, which are based on verifiable observations or experiences, rely mainly on calibrations to forecast an outcome. An example of an empirical model is the robust analytical model (RAM), which was originally developed by Mink (1981) for the determination of sustainable yield for Hawaiʻi aquifers by calculating variations of an aquifer head (water level) in response to water pumping.

Physically-based models, such as those developed by Whittier et al. (2010) and El-Kadi et al. (2014), predict outcomes utilizing measured or calibrated parameters. A numerical model is usually used in the analyses, controlling for water flow and chemical transport. The area of interest is divided into individual cells and the variable of interest, for example, water level or a contaminant concentration, is calculated by the numerical model at the center of each cell. Depending on the characteristics of the site, numerical models can be either two or three-dimensional. Three-dimensional models are more appropriate in characterizing the variable nature of complex natural systems.

Input data determines the quality of the model results

Understanding and assessing the transport and fate of contaminates in groundwater and the ocean are critical to assisting the State's water quality goals. Models at different spatial scales—including statewide or aquifer only—may be useful to inform where to prioritize management actions or create science-based OWTS conversion timelines.

Some models can use limited amounts of data, although more data will generally improve model accuracy. Models can be limited by a weak understanding of certain processes, such as groundwater and surface water interaction, preferential flow (uneven and often rapid movement of water and solutes through pores, fractures, and other hydrogeological structures causing significant anomalies in hydraulic conductivity), and contaminant interactions between bedrock, soil, and other compounds (Cornell University, N.D.) For example, hydraulic conductivity, which is a measure of the ease of which water flows through sediments or rocks, is an example of an important parameter needed for subsurface groundwater modeling (Rotzoll and El Kadi, 2008). One way to measure hydraulic conductivity is by performing well pumping tests or using measured water levels. However, many areas in Hawaiʻi have limited wells or are remote and inaccessible to researchers. Many of these limitations are difficult to overcome because of logistical, financial, and time constraints. Newer, less expensive, hydrogeophysical methods are being tested by Professor Niels Grobbe to provide 3D images of the subsurface over large areas, to better understand the distribution, properties, and flow of subsurface fluids. Such information allows for data-driven interpolation between wells, and provides better data for models.

Most models lacking parameterization data can generally be calibrated with other data (Whittier et al., 2010). Limited data can negatively affect the calibration process resulting in non-unique sets of parameters, however, when combined can provide acceptable results. In other words, different combinations of parameters can provide the same answer to overcome limited data in another (A. El-Kadi, personal communication, December 27, 2019). Using field data to constrain or limit parameters in a model based on field measurements can also reduce calibration uncertainties and narrow down the list of non-unique data sets.

More data is needed in Hawai‘i for certain modeling activities

As stated previously, hydrologic models depend on accurate and thorough data. Limited data has hindered efforts to model OWTS pollution and hydrology in Hawai‘i. For example, a model developed by Whittier and El-Kadi (2009, 2014) used available OWTS data from the University of Hawai‘i and Hawai‘i Department of Health. However, there were limited amounts of data on OWTS location, capacity, and leaching rates. Additionally, hydrogeological parameters, such as hydraulic conductivity and porosity were estimated based on available water-level data, which were scarce, although newer methods of data acquisition are being explored. Due to these limitations, the model's results may need to be carefully interpreted and reevaluated (Barnes et al., 2019; El-Kadi and Whittier, 2009). In fact, Barnes et al. (2019) found that nearly ninety-percent of cesspools in West Maui were converted to sewer or septic between 2007 and 2017. When proceeding with long-term cesspool conversion plans for other areas in the state, it may be beneficial to perform an updated inventory review and confirm wastewater modeling efforts with field data such as algal bioassays and hydrogeophysical methods (Amato et al., 2020). The most comprehensive OWTS inventory review was last performed in 2009 for O‘ahu and 2014 for the remaining main Hawaiian Islands by Whittier and El-Kadi.

Obtaining additional parameters of each of the OTWS, such as leach field size, installation location, depth to groundwater, soil parameters, and tank size may be useful to researchers, modelers, or government and resource managers. Coupling OWTS information with updated census data or a person to bedroom ratio may also yield more information on how OWTS are being used in real world situations (within or outside of permit and design specifications) and potential risks to nearby water resources (Amato et al., 2020; D. Amato, personal communication, December 3, 2019).

Detailed hydrogeologic information, such as hydraulic conductivity, recharge rates, and soil type are critical for accurate site assessment and model prediction accuracy. Numerical models assign surface and subsurface spatial data to area cells, variations in information or data gaps can cause problems, which may become evident in data resolution discrepancies. Typical resolution of area cells is displayed on the scale of hundreds of meters. In some cases, higher resolutions, closer to tens of meters are needed. These include density dependent problems or areas, including nearshore sites where saltwater and freshwater interact. Although the models can allow variations of parameters on the cell scale, limited data only permits the use of the lower resolution regional or aquifer-size values.

Aquifer parameters and surface/subsurface soil properties are other important factors that control water movement and chemical leaching to the underlying aquifer and are useful to modelers. Currently, soil maps and soil type information are maintained by the United States Department of Agriculture Natural Resource Conservation Service. Most maps in Hawaiʻi have not been updated since the 1960s and 1970s. The filtering characteristics of the soil are important for OWTS design, function, and estimating water movement (that controls recharge) and the transport of nutrients and pathogens. Model reliability can be reduced by the failure to accurately represent Hawaiian volcanic geology, including distinguishing irregularities (such as lava tubes) under the surface. Figure 11 illustrates simulated results showing the effects of a lava tube on the transport of a time-limited injection in a synthetic hillslope. Rather than the typical transport plume pattern seen in the left figure, a highly variable and fast spreading plume can result as noted in distributed colors of the right figure. These features can carry or disperse pollution in different patterns making it difficult to track.

Improved assessment of contaminant distribution and travel times are also critical for supporting decision-making processes or management of water resources. However, data for characterizing lava tubes and similar subsurface features that cause preferential flow and transport can be difficult and costly to obtain. Alternative approaches to collect data, obtain detailed spatio-temporal images of the subsurface rock formations and pore-fluid distribution and properties, and identify hydrologically relevant geological structures can include the use of geophysical techniques such as active and ambient noise seismics, electrical resistivity tomography, self-potential, gravity, and magnetotellurics. Many of these techniques are currently being investigated at the UH Water Resources Research center by Professor Niels Grobbe.

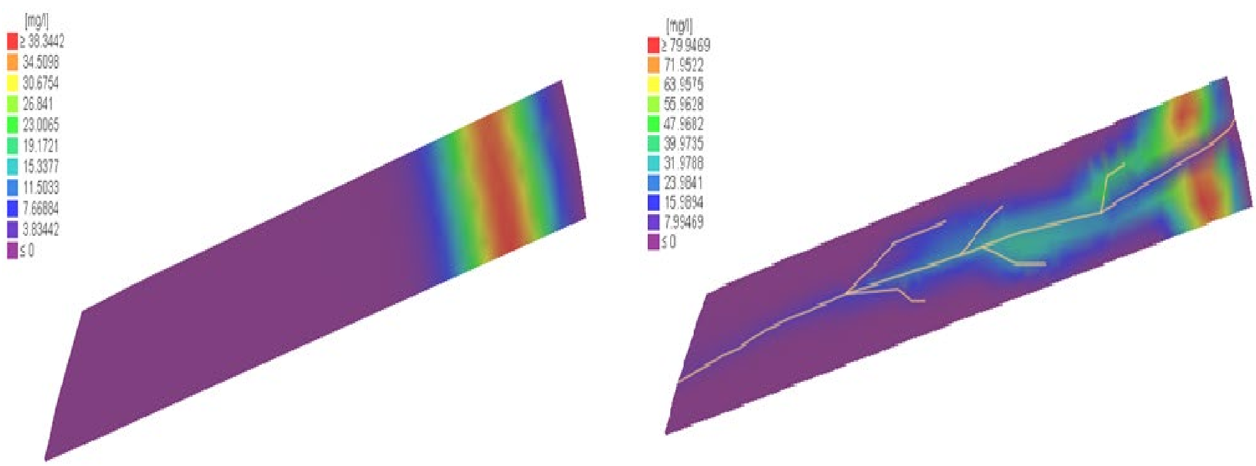


Figure 11: Effect of a lava tube on the transport of a limited time pollutant injection in the right side of a hillslope followed by “clean” injection. (left) Area with no lava tube and (right) with a lava tube. Source: El-Kadi, (unpublished data). Used with permission.

Finally, another important, but sometimes overlooked, input to both hydrologic and oceanographic models is weather data. Hawaiʻi has varying topography and a narrow coastal plain, which can aid in quickly flushing water from the mountains to the ocean. Because of topography and geography, rainfall amounts vary widely across the islands. Professor Thomas Giambelluca of the UH Water Resources Research Center and his laboratory are actively improving Hawai‘i’s rain gauge network, aiming to provide long-term hourly precipitation datasets in multiple locations of a watershed. This type of data can be used to improve model accuracy and predictions, along with monitoring long-term climate trends. Similarly, wind and tidal data are important for oceanographic models, but tide stations are not always located close to where the modeling is being implemented. Instruments and monitoring stations can be deployed in the areas of interest, but it takes a long time to build robust datasets as well as financial resources to monitor and maintain data collection sites (K. Falinski, personal communication, November 25, 2019).

Tracking pollutants and pathogens using models

In general, subsurface OWTS contamination and pollution movement can be simulated through groundwater models. Nutrients and pathogens, which can directly leach into the subsurface through the unsaturated zone (dry soil), can be traced as they continue to undergo various transformation processes in the saturated zone (wet soil). However, significant contamination can occur through surface water via groundwater that reaches streams, also known as base flow. Base flow can infiltrate back to the subsurface at other locations or end up in the ocean. Therefore, ocean contamination can be traced back to both surface water and groundwater origins, with both having the potential to take up or deposit pollutants along the way.

Regional or large-scale models can provide useful information to track OWTS pollution, such as annual rates of sediment load to the ocean, which is important because sediment holds nutrients. Regional results can guide future data collection and possibly prompt more research or analyses in localized areas. Examples of such models include the conceptual statewide model of nutrient inputs to the coastal zone, created in 2016 by Lecky, and published as part of the Ocean Tipping Points Project. The model used input data consisting of estimated nitrogen flux from each Tax Map Key parcel with an OWTS. Total nutrient export to the ocean was then calculated. This model was particularly useful because it covers the entire state of Hawai‘i and can show broad inputs/impacts to the coastal zone across all watersheds, as highlighted in Fig. 12 (K. Falinski, personal communication, January 8, 2020). Similarly, on a smaller scale, Falinski (2016) used the Integrated Valuation of Ecosystem Services and Tradeoffs (InVEST) and Nutrient Delivery Ratio (NDR) model to calculate nutrient flux, including nutrients from agriculture, OWTS, and human-development, using a delivery ratio-based empirical model that was calibrated and customized specifically for Hawai‘i. The results were then estimated off the coastal waters of Maui Nui and West Hawai‘i, using the same methods as Lecky (2016). Although the input data was similar to Lecky (2016), InVEST NDR was unique because it included all potential sources of nutrients to the coastal zone. The results estimated percentages of nutrients coming from OWTS, wastewater treatment plants, agriculture, and golf courses, which can help managers better understand the proportion of nitrogen input specifically due to OWTS versus other sources (K. Falinski, personal communication, January 8, 2020).

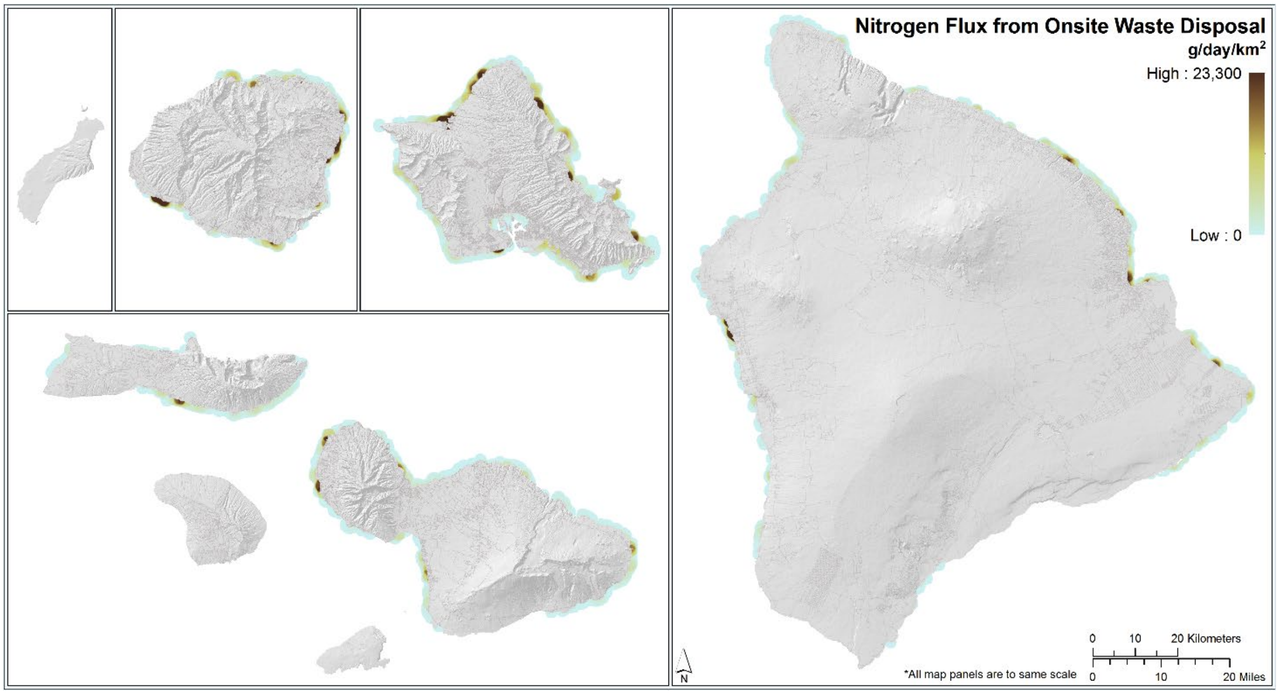


Figure 12: Nutrients from sewage. This map shows the nitrogen flux from onsite waste disposal systems (cesspools and septic tanks) located within 1.5 km inland from the coast. Source: Lecky, 2016. Used with permission.

The USGS suite of models is typically applied when investigating water flow and pollution contamination in Hawai‘i (El-Kadi and Moncur, 2006). With an understanding of water flow, levels, and flow velocities, a solute or chemical transport model can be used to assess chemical pathways and concentrations at various locations and times. The models can also estimate various water and contaminant fluxes reaching drinking water wells or surface water bodies, such as the ocean. A few of these models are discussed below.

The MODFLOW model is widely used to simulate groundwater flow (Harbaugh et al., 2000). The MODFLOW family of models includes MODPATH, which is a particle tracing software that has been applied in Hawai‘i for source water assessment delineations (Pollock, 2016; Whittier et al., 2010). The package also includes MT3DMS, which was combined with MODPATH to assess potential OWTS contamination in studies done in Hawai‘i (Whittier and El-Kadi, 2009, 2014). MT3DMS differs from MODPATH by including transport dynamics caused by the dispersion phenomenon (Zheng, 2010). Meaning MT3DMS can better represent the dispersion of a chemical in the pores or fractures of an aquifer caused by variations in available pathways and velocities, which is important for Hawai‘i’s unique geology. A contaminant will spread, forming a plume as it moves in the direction of the flowing water, and covering a larger area over time. MODFLOW alone has limitations in dealing with density dependent flows by only simulating freshwater, which is less buoyant than saltwater.

Limitations of MODFLOW relevant to OWTS pollution include (A. El-Kadi, personal communication, December 29, 2019):

a. Estimating dynamics and circulation of water and chemicals in the saltwater-freshwater zone.

b. Realistically incorporating dynamic brackish zones of a freshwater aquifer, which can change based upon aquifer condition, from pumping and/or recharge. Future models should incorporate parameters for dynamic aquifer bottoms versus a fixed aquifer bottom.

c. Estimating groundwater sustainability due to saltwater influxes.

d. Properly calculating salinity measurements and water flow to provide accurate parameters for assessing chemical transport.

e. Incorporating the ability to predict the effect of sea level rise and expected increase saltwater intrusion to aquifers.

f. Considering salinity in modeling scenarios where there is a concern about the potential effects of high salinity in leaching wastewater that can affect water quality in the aquifer.

To overcome MODFLOW's limitations, SEAWAT was developed to address water flow and contaminant transport in nearshore environments where saltwater and freshwater interact (Langevin, 2009). The model predicts dynamic zones where freshwater and saltwater mix. Model outputs include water levels, chemical concentrations, and most importantly, salinity distributions. An example application of SEAWAT was introduced by El-Kadi et al. (2014) in a study that dealt with the sustainability of groundwater resources. Management scenarios assessed sustainability of aquifer use, setting limits for decline in water levels and spring flows and an increase in salinity values. More precise and accurate management of nearshore aquifers can be expected when including variables like salinity impacts, especially when moving towards an integrated "one water" approach for water management.

Difficulties of modeling aquifers in the Hawaiian Islands

As stated earlier, surface water transport of contaminants can be a significant contributor to ocean contamination. For example, a recent study by Welch et al. (2019) utilized field measurements and modeling for a watershed in American Samoa to assess the relative contributions of surface and subsurface sources of ocean contamination. An estimated fifty-nine percent of pollution contributions came from surface sources while forty-one percent were from subsurface contributions. An integrated surface-subsurface modeling approach might be necessary in Hawai'i. However, the effort can be complicated due to the interactive nature of processes in the two systems and disparity of water travel times (A. El-Kadi, personal communication, December 27, 2019). To overcome such hurdles, a simplified approach is usually adopted. This typically involves simplifying parameters of one of the systems. For example, groundwater modelers can treat streams as drains receiving water from the aquifer without any details regarding surface water flow or transport processes. Another approach would be to utilize a "soft coupling" method, where the two detailed systems are run in sequence utilizing the output from one as an input to the other. A more accurate “fully coupled” approach is utilized in the USGS GSFLOW model (Markstorm et al., 2008), which integrates the USGS Precipitation-Runoff Modeling System (PRMS-V) and MODFLOW. The GSFLOW model, however, can only simulate water flow and is not equipped to assess water quality.

Across Hawaiʻi, there is concern that there is a lack of efforts to integrate surface and subsurface modeling. There is a real need to initiate a comprehensive plan to compile the required and available data, specifically in low-lying coastal areas where interaction between surface water and groundwater is significant. Examples of models that emphasize a surface water assessment approach include the Soil Water Assessment Tool (SWAT), a watershed-model that can quantify the impact of land management practices in large, complex watersheds (Food and Agriculture Organization, 2019; Gassman, Reyes, Green and Arnold, 2007). However, SWAT does not include a detailed subsurface water flow component, to overcome this limitation, the model can be coupled with MODFLOW (Bailey et al., 2016).

For some parameters and scales, there is a lack of data available for more accurate model calibration and validation. However, models currently exist for a larger, state-wide scale to assist in the prioritization of cesspool upgrades, including those in Lecky (2016) and Falinski (2016). Large-scale models may be all that is needed to prioritize cesspool upgrade zones (K. Falinski, personal communication, January 8, 2020). However, more data is always beneficial to understand complex systems. Possible sources of future data may include local citizen-science organizations and non-traditional initiatives. Recent research by Njue et al. (2019) and Falinski et al. (2019) showed it is possible to successfully engage the public in hydrological monitoring and obtain extensive datasets with broad spatial and temporal coverage. Data collected by citizen scientists have been found to be comparable to professional data (Njue et al., 2019). In Hawaiʻi, groups like Hui O Ka Wai Ola (https://www.huiokawaiola.com/) on Maui are demonstrating the usefulness of citizen scientists and illustrating the potential of these groups. The group established strict sampling protocols and QA/QC of data, which is provided to DOH. Other citizen science groups include the Surfrider Blue Water Task Force with seventy-plus water quality sampling sites statewide. However, citizen scientists may not have access to groundwater wells or other locations where data collection is needed. They may also struggle to identify which data is important for models and why. Therefore, researchers may wish to incorporate the use of technology, such as smart phones, which can potentially decrease sampling complexity and costs, or partner with students and experts to train volunteers and share resources.

It is important to note that OTWS modeling efforts so far have overlooked salinity effects by only modeling freshwater flow and transport (Whittier and El-Kadi, 2009, 2014). This can be a serious limitation due to the lack of accurate representation of the nearshore conditions, where the majority of OTWS are located. Additionally, none of the evaluated modeling studies in Hawaiʻi address the issue of preferential flow caused by major fractures, including lava tubes (A. El-Kadi, personal communication, December 27, 2019). Modeling technology that allows for the consideration of discrete fractures within porous material is needed. For example, Fig. 13 illustrates saltwater intrusion in a synthetic hillslope aquifer with and without a lava tube. It is clear that the lava tube causes a significant increase in saltwater intrusion, including additional spread of the brackish zone. A major research effort is needed to build accurate geological models accounting for volcanic formations. The existence of large fractures or openings may invalidate the current approaches usually adopted for fractured rocks. Field reconnaissance, including geophysical investigations, guided by modeling, can help in such an effort. Leaking stormwater/drain pipes and future flooding events from tidal inundation might also need to be studied with respect to preferential flow paths (D. Amato, personal communication, March 9, 2020).

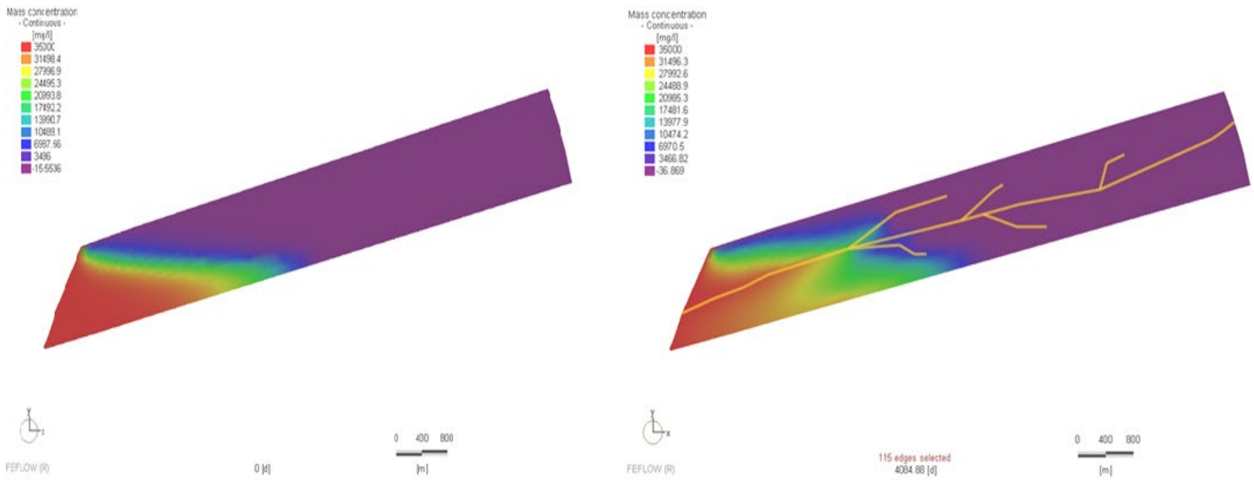


Figure 13: Effect of a lava tube on salinity distribution on a simulated hillslope. (left) Area with no lava tube and (right) with lava tube. Source: El-Kadi (unpublished data). Used with permission.

Understanding how pollution reaches ocean/coastal/groundwater environments

Anthropogenic activities are the main source of groundwater pollution (EPA, 2015). Tracer tests are effective means to understand various physical, chemical, and biological processes to secure valuable data for model calibration and validation. They also can be used to test hypotheses and answer critical questions, such as identifying sources of pollution and assessing expected contaminant levels and travel times. Various information from the land and ocean uses, combined with hydrological, chemical, biological, and weather data, can be used in such an endeavor. Bishop et. al (2017) used water isotopes to track recharge locations and rainwater flow paths to the ocean through land-use types and cesspool areas on Maui. Isotope type testing and water age data can also support these investigations (A. El Kadi, personal communication, December 29, 2019).

The use of multi-tracer tests can provide information and data to more comprehensively understand aquifer characteristics. The ideal groundwater tracer does not react with its environment and is easily detected, non-toxic, and moves with the same velocity as water particles. Example studies include those by Glenn et al. (2013), which used fluorescein dye and sulpho-rhodamine-B dye to assess potential ocean contamination from deep well wastewater injection in Lahaina, Maui. In addition to synthetic tracers, natural tracers such as dissolved radon gas have been successfully used (Dulai et al., 2010). Calibrated and validated models, which are based on data from tracer tests, can be used in a predictive mode to assess future aquifer and ocean conditions or contamination and inform management decisions. However, the accuracy of model predictions depends on the quantity and quality of data, although sensitivity and statistical analyses can address some of the uncertainty in these issues. Examples of successful use of models and tracer data include Amato et al. (2020), which was able to couple Rn with modeling to determine the flux of wastewater N to the coast off Waimanālo.

In addition to the tracer types listed above, agricultural chemicals and nutrients can be analyzed as tracers (see the first section of this report) and used in models. For example, on the island of Maui, Bishop et al. (2017) used modeling as part of a study that included chemical and land-use data to identify potential sources of nutrients. Using a suite of techniques, his team was able to distinguish between agricultural and OWTS pollution sources and identified rates of nitrogen flux into the coastal zone. Another model was developed by Dailer et al. (2012) and used field data from algal bioassays of the nearshore region on Maui to track and document a wastewater plume near the Lahaina Wastewater Reclamation Facility. The algal bioassays used $\delta^{15}N$ values to document movement of wastewater effluent to the surface waters through SGD. From the data, the authors simulated a three-dimensional wastewater plume and observed spatial variability in $\delta^{15}N$ values over time (Dailer et al., 2012). Combining this type of data with other physical studies or models (e.g., Storlazzi and Field, 2008) can inform managers where pollution is traveling or have the most impact on humans or natural resources.

A study in Tutuila, American Samoa, which can be reproduced in Hawaiʻi by Shuler et al. (2017), used a water quality analyses to show a link between elevated levels of dissolved total nitrogen in the groundwater and areas on land with a significant number of OWTS. A model framework was created that includes land-use information, hydrological data, and water quality analyses of nitrogen. Results indicated that OWTS contributed significantly more nitrogen to Tutuila’s aquifers than any other source. The above framework demonstrated a way to identify specific sources of non-point pollution across many areas to assist with best management practices. Another study by Welch et al. (2019) used a similar framework and examined SGD and connections between land use and nutrient loading in Faga'alu Bay, American Samoa. Coastal $radon^{222}$ measurements, dissolved nutrient concentrations, and $\delta^{15}N$ values in water and algae can be used to investigate SGD, base flow of nutrients, and determine probable nutrient sources (Shuler et al. 2019). Nutrient loading correlated well with human impact, although differences in location hydrogeology, impact distribution, and wastewater infrastructure also play a role (Shuler et al., 2017). The SGD nutrient fluxes were found to be more prominent than base flow nutrient fluxes (Shuler et al., 2019).

Models for prioritization and upgrade schemes

Environmental models representing various physical processes (e.g., groundwater flow and nutrient transport models) as well as models that incorporate social and economic drivers (e.g., cost-benefit analyses) need to be combined in order to develop a comprehensive prioritization framework and upgrade scheme for the State’s cesspools. An example of one possible component in this framework is the existing nutrient transport/loading model by Shuler and Comeros-Raynal (2019). This model was created for the island of Tutuila, American Samoa to classify coastal areas below each of the island’s watersheds for pollution management. The model is based on levels of dissolved inorganic nitrogen (DIN) loads from surface and groundwater discharge, as shown in Fig. 14. The model was calibrated using measurements of DIN loading rates from all hydrologic pathways in watersheds where samples were available. Three hydrologic pathways were used, including stream base flow from shallow aquifers, surface runoff from rainfall events, and SGD (Shuler and Comeros-Raynal, 2019). Sources of human-derived DIN included OWTS, pigs, and synthetic agricultural fertilizer. Both historical and current stream flow observations were used in the model.

The model then determined DIN loading rates for every watershed on the island via individual nitrogen release rates based on the number of modeled nutrient sources in each watershed (Shuler and Comeros-Raynal, 2019). Further data refinement allowed the ranking and prioritization of impact to each watershed. The CCWG may wish to consider working with researchers to develop a prioritization model that builds upon components similar to the Shuler and Comeros-Raynal (2019) model. Other methods, including those by Barnes et al. (2019) and Babcock et al. (2019) also evaluate multiple objectives, nutrient loading, costs, risks, benefits and tradeoffs of cesspool upgrades, and are discussed in the Policy and Community Engagement section.

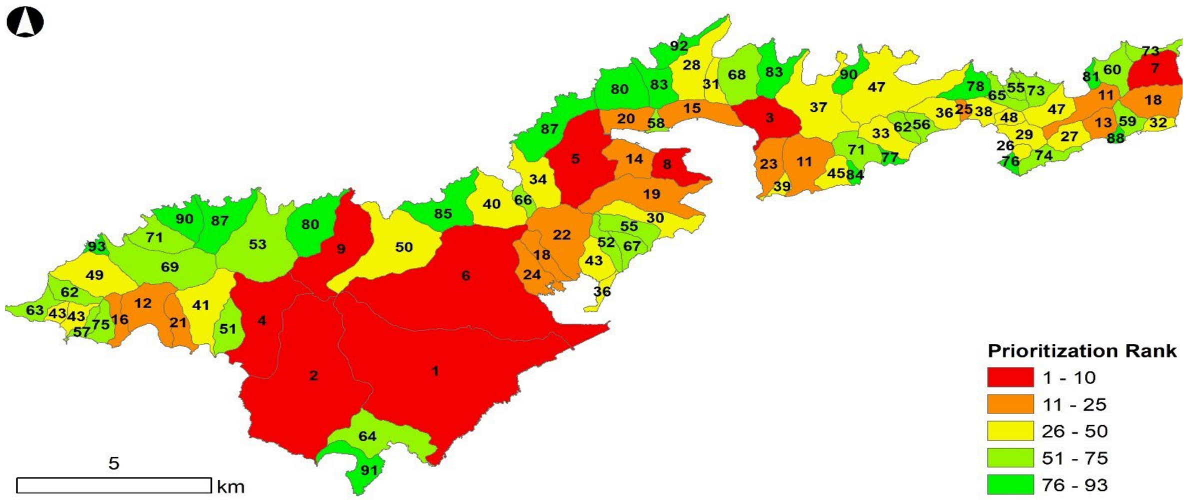


Figure 14. Map highlighting the prioritization ranking of each watershed on Tutuila, American Samoa. The red areas are the most impacted, while the green areas are the least impacted. The study used coastal loading of dissolved inorganic nitrogen (DIN) and indexed the impact in each watershed based on 1) the amount of DIN released by all known human sources in each watershed; 2) the area of each watershed; and 3) the coastline length of each watershed. Source: Shuler, 2019. Used with permission.

Estimating where pollution will end up in ocean environments

Once the groundwater or surface water enters the ocean, different types of models are used to predict where it may end up. Because of the complexity of systems, predictive and empirical models are not often used for these scenarios. Rather, numerical models are more suited to estimate possible pathways for particles and mixing dynamics of substances. Groundwater and oceanographic models are typically run as separate systems and not commonly combined because of the uncertainties in both systems. For example, ocean plume dynamics are poorly understood, and concrete connections between human sources of nutrients and ecosystem health in the ocean need more research. In Hawaiʻi, a combination of modeling and monitoring efforts have been used including Wolanski et al. (2009), who created a biophysical model in Maunalua Bay on Oʻahu to connect ocean dynamics with coral reef health. Tomlinson et al. (2011) and Ostrander et al. (2007) focused on using ocean observing data from buoys in Kāne'ohe Bay and water quality sampling to map out plumes. The researchers determined that storm events can lead to plumes of runoff remaining in the bay for up to forty-eight hours.

Finally, Connolly et al. (1999), created mathematical models to understand contributions of wastewater outfalls and shoreline sources of organisms in Mamala Bay. The results were then used by a pathogen fate model to predict the distributions of wastewater contamination indicator organisms and specific pathogens in the Bay (Connolly et al., 1999). Future models, similar to those previously described, may be developed for other coastal areas that have high concentrations of cesspools and sensitive resources that can be negatively impacted by wastewater pollution, such as coral reefs.

Using models to reduce risk

Risk analyses, such as those performed by Whitter and El-Kadi (2009, 2014), evaluated the human health and environmental risk posed by OWTS. One study estimated that nearly 10 mgd of sewage is released into the environment, with much reaching groundwater (Whittier and El-Kadi, 2009). Cesspools made up about seventy-seven percent of the total estimated release of untreated effluent and ninety-six percent of the potential nitrogen release. Groundwater models in certain areas estimated that nitrate concentrations could reach a maximum level of 11 mg/L above background values, which is higher than USEPA maximum contaminate levels of 10 mg/L (USEPA, 2019b). Because soil is the primary treatment mechanism for OWTS, even in areas with low density of OWTS, soil conditions and slope may be a limiting factor determining levels of effluent treatment. Whitter and El-Kadi (2009) recommend a vertical distance between ground surface and groundwater of twenty-five feet for proper treatment of effluent by the soil, however, many areas fail to meet this condition.

Using source-water protection assessments (e.g., Whittier et al., 2010) can provide the CCWG with data on source-water susceptibility to contamination, which can be inputted into a decision-making model to determine system upgrade requirements or timetables. The approach by Whittier et al. (2010) uses groundwater models, aquifer locations, and geographic information system data. A groundwater-flow model used site-specific data, where possible, to provide a numerical score that quantifies susceptibility to contamination. This approach is adaptable and can be updated with new data as it becomes available (Whittier et al., 2010). This assessment, however, isn’t without its caveats. The model did not include flow in the unsaturated zone, chemical reactions, or chemical dispersion data (Whittier et al., 2010). More studies yielding data are needed to improve modeling due to Hawai‘i’s unique geology and hydrology. Many stakeholders can benefit from increased collaboration and the sharing of resources and data by multiple agencies to protect water resources.

Having a greater understanding of groundwater vulnerability is important for risk analysis and planning. Mair and El-Kadi (2013) developed a model that combined well capture zones with multiple-variable logistic regression modeling, where two or more independent variables are used simultaneously to predict a value of a dependent variable. The model was applied to the Pearl Harbor and Honolulu aquifers. The results produced contaminant-specific models that identified groups of wells with the lowest and highest reported detections and the lowest and highest nitrate concentrations (Mair and El-Kadi, 2013). Models like these can help in areas with limited amounts of data and can complement efforts to further develop drinking water protection zones. Reducing risk to natural systems such as coral reefs requires synthesis and processing of data from different disciplines.

A methodology to integrate spatial data on environmental and anthropogenic drivers of coral reefs was developed by Wedding et al. (2018). Their research sought to quantify and analyze spatial drivers of change on coral reefs to understand how reef resilience and diversity might be impacted by human causes (Wedding et al., 2018).

Groundwater models can assist with evaluating infrastructure vulnerabilities

Models can be used to identify infrastructure vulnerabilities and inform long-term planning efforts. One such model by Habel et al. (2019), simulates sea-level rise induced narrowing of the unsaturated space (treatment zone) between OWTS and groundwater. Results of the study revealed that eighty-six percent of the 259 active OWTS in the study area are likely inundated by groundwater at present. Simulations considering nearly one meter of sea-level rise show an increase in the percentage of likely inundated OWTS to ninety-one percent, of which thirty-nine are identified as flooded to the ground surface. Figure 15 details the locations of OWTS and whether they meet minimum requirements under 98 cm of sea-level rise. These results highlight the potential for increasing prevalence of public contact with contaminated waters. Results of this model and similar models may help strengthen infrastructure permitting processes and regulatory requirements when attempting to install OWTS or predict potential failures.

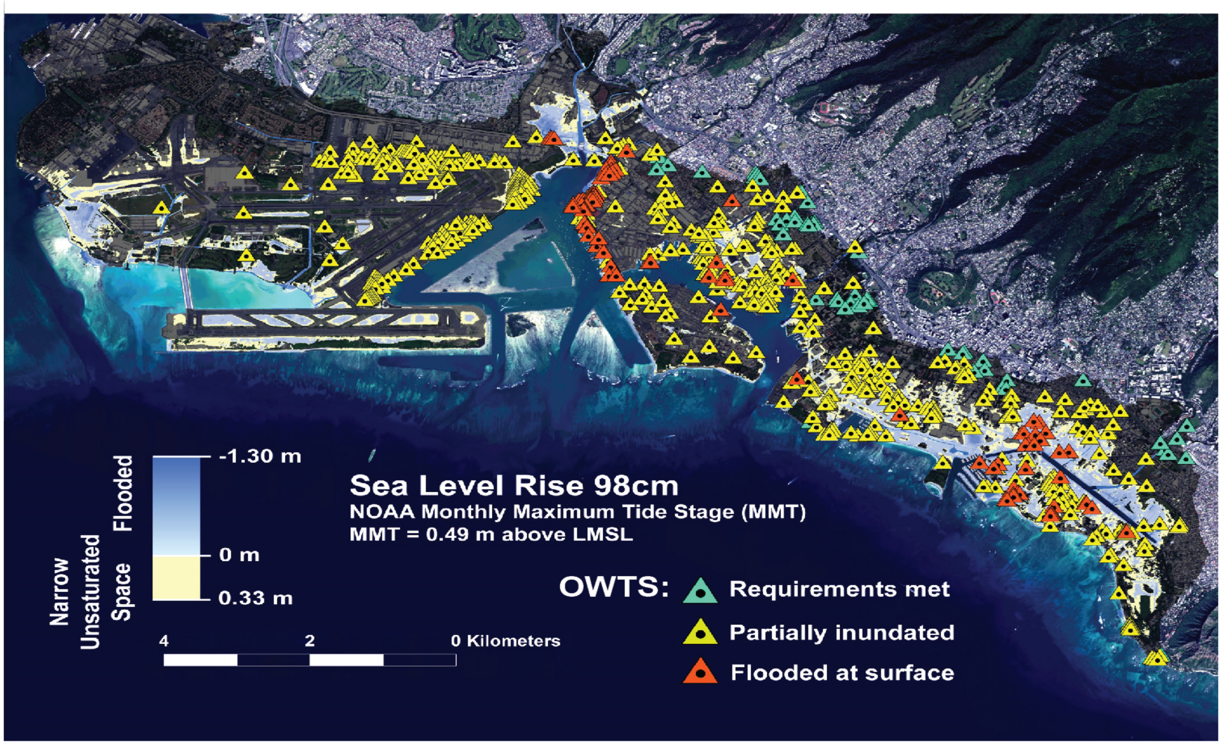


Figure 15: Simulation of groundwater inundation (blue) and narrow unsaturated space (yellow) representing 0.98 m of sea-level rise for a tide height representing the average monthly maximum tide measured at the Honolulu tide gauge. The OWTS data are superimposed upon simulations to identify potential vulnerabilities of the infrastructure. Source: Shellie Habel, 2019. Used with permission.

Improving OWTS nutrient reduction capacity using models and simulations

Some states have a developed university research center regarding OWTS technology and workforce development related to that region (Mezzacapo, 2019). Although no official center exists at the University of Hawaiʻi at Mānoa, there are past and ongoing projects regarding this topic. The CCWG may wish to explore the creation of such a center in Hawaiʻi to develop tailored technologies, test and certify OWTS units, and train a growing wastewater workforce.

It's clear that cesspools have been on the mind of researchers for a number of years, as evidenced by a laboratory experiment performed by Koizumi et al. (1966) to test conditions contributing to cesspool failure and the degree of treatment by cesspools. The results indicated that incomplete degradation of wastewater effluent in test soil lysimeters, which is a container used to determine soil-water drainage or chemical movement within soil, in two basic soil types on Oʻahu make wastewater a definite hazard to groundwater (Koizumi et al., 1966). More studies such as this, which evaluate site specific conditions, may assist the permitting process by understanding the capabilities of different soils or materials, and develop more tailored regulations for OWTS.

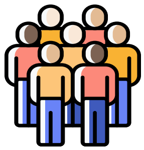
Recent research by Professor Roger Babcock and his laboratory at UH Mānoa examines the nutrient removal potential for passive absorption beds for use with a conventional septic tank. The process uses a set of fourteen laboratory columns designed to mimic typical absorption beds. The columns contain various types of locally-available media and layers of sawdust. The different media also included ¾-in gravel, coral sand, basalt sand, and recycled glass to mimic materials used in the construction of absorption beds. The sawdust layer (with fifty percent sand mix) was either four inches or eight inches deep and arranged to allow adequate flow through or saturation to affect anoxic conditions. Different simulated daily loading rates with raw wastewater were evaluated. Researchers are currently measuring parameters including COD, TSS, total-N, ammonia, nitrate, nitrite, total-P and phosphate (R. Babcock, personal communication, January 10, 2020).

The preliminary results show excellent nitrification/denitrification of wastewater effluent (up to eighty or ninety percent) can be achieved in these passive systems. Passive systems may have an advantage over aerobic treatment units due to their less frequent maintenance schedule, lack of required electricity, and minimal additional cost compared to a conventional septic tank and absorption system. Researchers are comparing the different media and the configuration of depth and saturation of the denitrification (sawdust) layer to find an optimal cost benefit scheme. The two main concerns to be investigated in the future are the lifespan of the sawdust layer and how to control clogging in the sawdust layer. Research is ongoing to develop cost effective methods for cesspool replacements in Hawaiʻi (R. Babcock, personal communication, January 10, 2020).

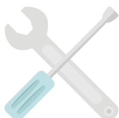
Policy and Community Engagement

How can well crafted policies and community engagement contribute to successful outcomes?

5 Key Concepts



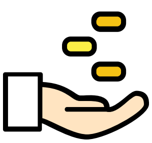
Regarding Policy and Community Engagement



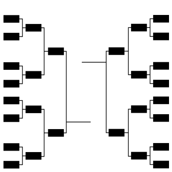
According to one study, one-third of the OWTS in Hawai‘i are deficient and in need of immediate repairs or maintenance to address problems.

Homeowner engagement through education, outreach and participation can lead to better OWTS maintenance and reduction in health risks and nutrient pollution.

Survey results show positive attitudes towards human waste recycling in Hawai‘i.



A decision analysis process to identify priority areas impacted by wastewater pollution from OWTS may be relevant and advantageous to identify pollution mitigation strategies in a cost-effective manner.



A participatory and structured decision-making process is recommended to help solve “wicked” environmental problems. A “wicked” problem is one with a high level of complexity, uncertainty, and multiple points of stakeholder involvement.

5

Knowledge Gaps

Regarding Policy and Community Engagement

There is a lack of understanding of the community knowledge, values, attitudes, and behaviors in relation to OWTS use, pollution, management, and replacement strategies.

There is a need to match census data, permit requirements, OWTS use and environmental health risk. Understanding the number of residents using systems in relation to permitted bedrooms may help the state ensure systems are functioning properly and protecting environmental health.

The State lacks critical information on OWTS inventory, specifically a georeferenced database of all systems in Hawaiʻi – this is needed for diagnosing pollution threats, community outreach/education, watershed planning support, and ensuring proper OWTS maintenance. Updating this information will be crucial to direct meaningful management actions and to inform pollution models.

The state may wish to evaluate actions that can be taken now, such as recommending legislation or streamlining internal processes that permit onsite wastewater technologies such as composting toilets, drip irrigation leachfields, or gray water recycling in homes.

The creation of groundwater quality criteria by the DOH is needed to evaluate, measure, and track pollution, guide decision-makers and inform residents.

What is our capacity to monitor and maintain OWTS?

Failing OWTS may pose a significant threat to the environment. Ensuring the State's capacity—financial, personnel, and regulatory—to monitor OWTS operation will be essential to protecting human health, ground and surface waters. In Hawai'i, nearly one out of every three OWTS were classified as deficient and in need of immediate repairs or maintenance to address problems, according to a study by Babcock, et al. (2014). Although there were limitations to the previous study, including a small sample size and the survey approaches used, the information provided may represent larger systemic problems, discussed below, regarding Hawai'i's wastewater challenges. Failing OWTS are not unique to Hawai'i. The USEPA (2005) estimates at least ten percent of OWTS are not functioning properly across the country due to many factors including poor maintenance and lack of education or financial resources. There may be ways to overcome poor maintenance schedules and perhaps ways to model when failure is likely. Recent model results from Kohler et al. (2015) suggest that mandatory inspections through renewable permits can reduce the life cycle repair, failure frequency, and severity of failure, ultimately lowering OWTS total costs to owners and potentially reducing environmental impacts. The USEPA has identified five OWTS management models (Table 1) and the CCWG may wish to choose one most applicable to implement in Hawai'i.

A recent policy gap analysis by Spirandelli et al. (2019) reinforces conclusions by Kohler et al. (2015) by detailing several deficiencies when analyzing the State's ability to implement recommendations in the various USEPA models (Table 1). Hawai'i's current policies and procedures were deficient in the following areas: alignment between land-use and watershed-based planning; performance goals; inventory of systems; public outreach; homeowner education; and mechanisms that ensure regular upkeep and maintenance of OWTS (Spirandelli et al., 2019). Another specific knowledge gap outlined in Spirandelli et al. (2019) is the lack of understanding of community knowledge, attitudes, and behaviors in relation to OWTS, as well as reactions by the public and government offices of various management options at either the state or local level. The OWTS upgrade programs and their success may hinge on addressing the policy gaps identified by Spirandelli et al. (2019). Hawai'i may benefit by evaluating programs and outreach methods performed by the Cape Cod Commission in its most recent 208 Plan Update to address nutrient pollution. The project used a watershed-based focus on both stakeholder engagement and technical evaluation, seeking to maximize the benefits of local planning, traditional and nontraditional strategies, and allowing local stakeholders to decide which range of options to pursue, instead of mandating a single solution (Cape Cod Commission, 2017). The CCWG may wish to set the parameters for facilitated discussion of solutions with stakeholders on a watershed basis, allowing for a better understanding of community knowledge, attitudes, and behaviors.

To move forward with addressing some of the gaps identified by Spriandelli and others, further research along with legislative updates are needed. It is anticipated that Carollo Engineers will recommend specific technologies for Hawai'i upon completion of its technology analysis report in 2021. However, the CCWG may wish to evaluate actions that can be taken now, such as recommending legislation or streamlining internal processes that permit technologies used in other states such as composting toilets, drip irrigation leachfields, or gray water recycling in homes (Babcock et al., 2019; Mezzacapo, 2019). Updating plumbing codes may also be useful prior to implementation of the State's long-range cesspool upgrade plan. Furthermore, the creation of groundwater quality/ threshold criteria by the State DOH is needed to evaluate and measure pollution, guide decision-makers, and inform residents (Babcock et al., 2019).

Understanding community behaviors and engaging homeowners

Increasing knowledge of OWTS issues among homeowners, regulators, and the public may lead to better maintenance and awareness of the wastewater disposal problems in Hawaiʻi. Babcock et al. (2014) highlights that homeowners were generally interested in how their OWTS function, how to maintain them, and what indicators might lead to future problems or failures. The very first step to addressing concerns regarding OWTS operations, however, is to develop a georeferenced database inventory of all OWTS within the state (Spirandelli et al., 2019). Additionally, Babcock et al. (2014) recommends a statewide OWTS management program to address OWTS failures and the likely future increase in failures of the remaining systems that are being neglected. The USEPA Operating Permit Model in Table 1 would create a framework to improve the current conditions highlighted by Babcock et al. (2014). States like Oregon track OWTS information through an online permitting system simplifying the permitting and tracking process (from creation to maintenance); the CCWG may wish to study other state efforts regarding database creation.

Table 1. USEPA OWTS Management Models Table. Source: Halvorsen and Gorman (2006).

Model	Description
1. Homeowner Awareness Model	Represents minimal level of management; appropriate for areas where most sites without sewer access are suitable for conventional septic systems; relies on construction permits and public awareness
2. Maintenance Contract Model	Represents the level of management desirable where alternative OSS technologies are common; appropriate for areas of moderate environmental sensitivity
3. Operating Permit Model	Represents the level of management necessary to protect areas that are environmentally sensitive, such as wellhead protection zones, shellfish waters, and water contact recreational areas; includes performance monitoring
4. Responsible Management Entity Operations and Maintenance Model	Represents a level of management appropriate for areas where onsite and clustered systems are the main form of sewage treatment; establishes an authority to manage the maintenance of all systems
5. Responsible Management Entity Ownership Model	Represents a level of management appropriate for areas where onsite and clustered systems are the main form of sewage treatment; establishes an authority that owns and manages all systems

Surveys like the one used in Lamichhane and Babcock (2013) may be able inform the State and associated regulators which technologies are accepted by certain consumers and how to improve attitudes. Some citizens in Hawaiʻi had positive attitudes towards urine diverting toilets and human waste recycling. Therefore, additional surveys and obtaining more data may help the State target informational and educational campaigns to those who were or were not favorable to new technologies, with the hopes of ultimately improving environmental behaviors. Updating the inventory of OWTS type, location, and critical system characteristics like maintenance and permitting data will be crucial for diagnosing pollution threats and directing meaningful management actions (Barnes et al., 2019). State and county governments and departments need to share appropriate data, planning documents, capital, and human resources to work together to achieve the overarching goal of Act 125, which is to protect the State's water resources and human and ecosystem health.

Due to limited human and capital resources, large and diverse geographic areas, and diverse stakeholder viewpoints, it may be worthwhile for the CCWG to explore the creation of a watershed management framework, similar to the approach taken by the state of Minnesota to comprehensively assist with land-based pollution reduction, as noted in Fig. 16 (State of Minnesota, 2014). These programs efficiently manage all aspects of nutrient reduction to water resources and clearly spell out roles and responsibilities of stakeholders and other entities.

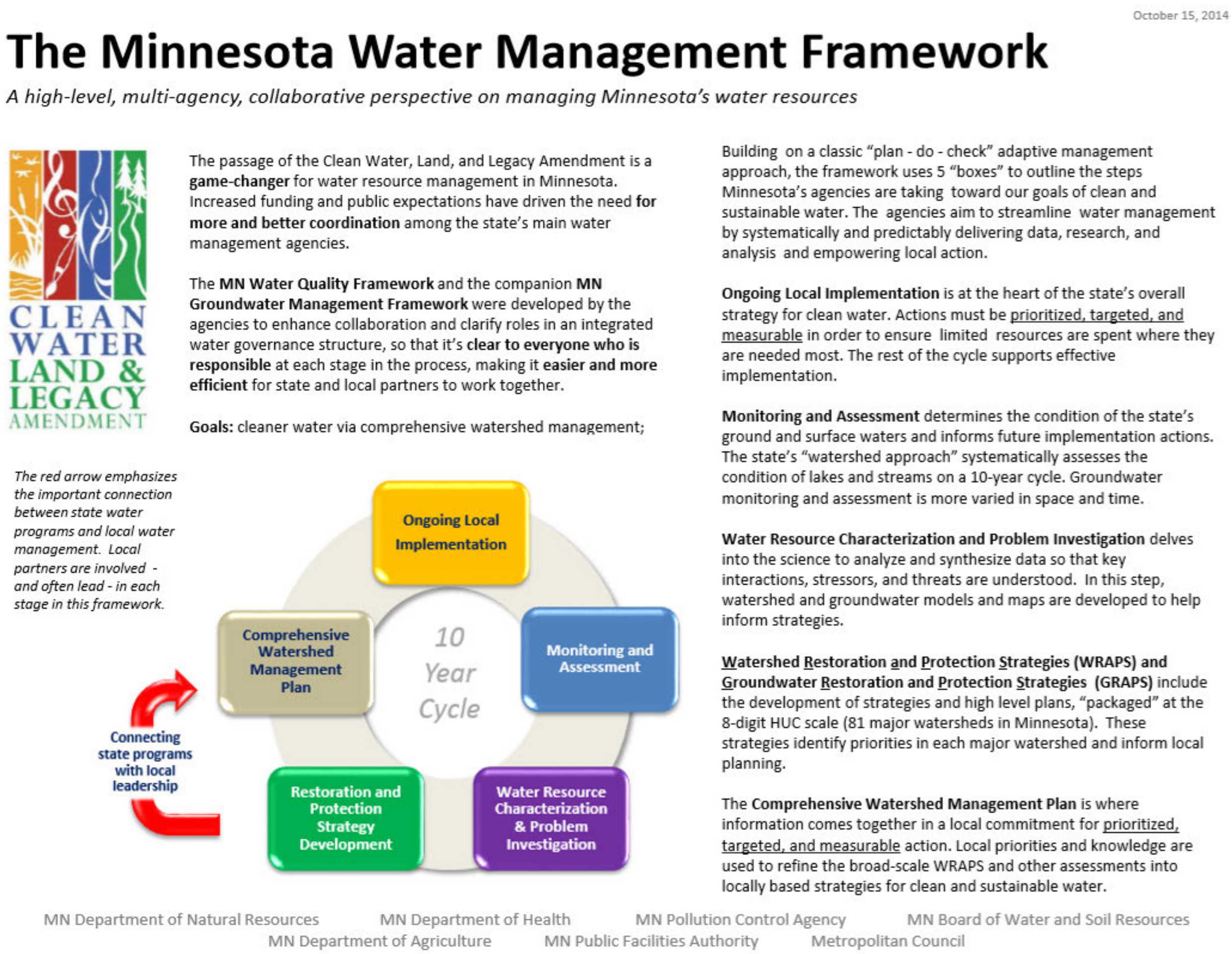


Figure 16. The Minnesota Water Management Framework. Source: State of Minnesota, 2014.

Furthermore, including local organizations in such management programs may benefit the State where there is a lack of understanding of attitudes and behaviors in specific regions and populations. Local organization objectives may also align with needed actions at the state or watershed level such as managing land-based pollution and increasing awareness among citizens about pollution and OWTS challenges. It may be advantageous for the group to explore partnering with such organizations when administering parts of the CCWG long-range plan and conducting outreach activities.

Behavioral change is difficult

Creating pro-environmental behavior is difficult. For this example, pro-environmental behavior is defined as one “that consciously seeks to minimize the negative impact of one’s actions on the natural and built world” (Kollmuss and Agyeman, 2002, p.240). Many factors shape our perceptions, decisions, and ultimately our actions. Previous linear progression models of understanding pro-environmental behavior (Fig. 17) failed to capture the complexity in humans and societies. Older, rationalist models assumed that education of an issue would lead to pro-environmental behavior, however, ultimately these theories proved false (Burgess et al., 1998, cited in Kollmuss and Agyeman, 2002). Many organizations and governments still use this approach, and science has shown there is often a disconnect between attitude and behavior or actions. Research has attempted to explain this disconnect through causes listed below:

- ***Direct versus indirect experience:*** learning about a problem isn’t as effective as seeing it for yourself.
- ***Normative influences:*** social norms and cultural traditions can widen the gap between pro-environmental attitude and behaviors.
- ***Temporal discrepancy:*** actions and people’s attitudes can change overtime.
- ***Attitude-behavior measurement:*** measured attitudes are often broader and do not always correlate with a specific measurable action.

Figure 17. Early pro-environmental behavior models. Adapted from Kollmuss and Agyeman, 2002.

Historically, the ideas and theories regarding environmental behavior often discounted “individual, social, and institutional constraints, and assumed that humans are rational and make systematic use of the information available to them” (Blake, 1999, cited in Kollmuss and Agyeman, 2002, p.247). The power to drive environmental change and make a difference on an issue is often unevenly distributed amongst society. People’s values are “negotiated, transitory, and sometimes contradictory” (Redclift and Benton, 1994, p.7–8, quoted in Blake, 1999, cited in Kollmuss and Agyeman, 2002).

One possible model that can be used to understand or solicit pro-environmental behavior is by Kollmuss and Agyeman (2002) (Fig. 18). The authors understand that the model is not complete and that there is no direct connection between receiving knowledge and performing an action. However, by combining environmental knowledge, values, and attitudes with emotional involvement on a subject, it may contribute to a type of environmental consciousness. Within the model, this consciousness is “embedded in broader personal values and shaped by personality traits and other internal as well as external factors” (Kollmuss and Agyeman, 2002, p. 256).

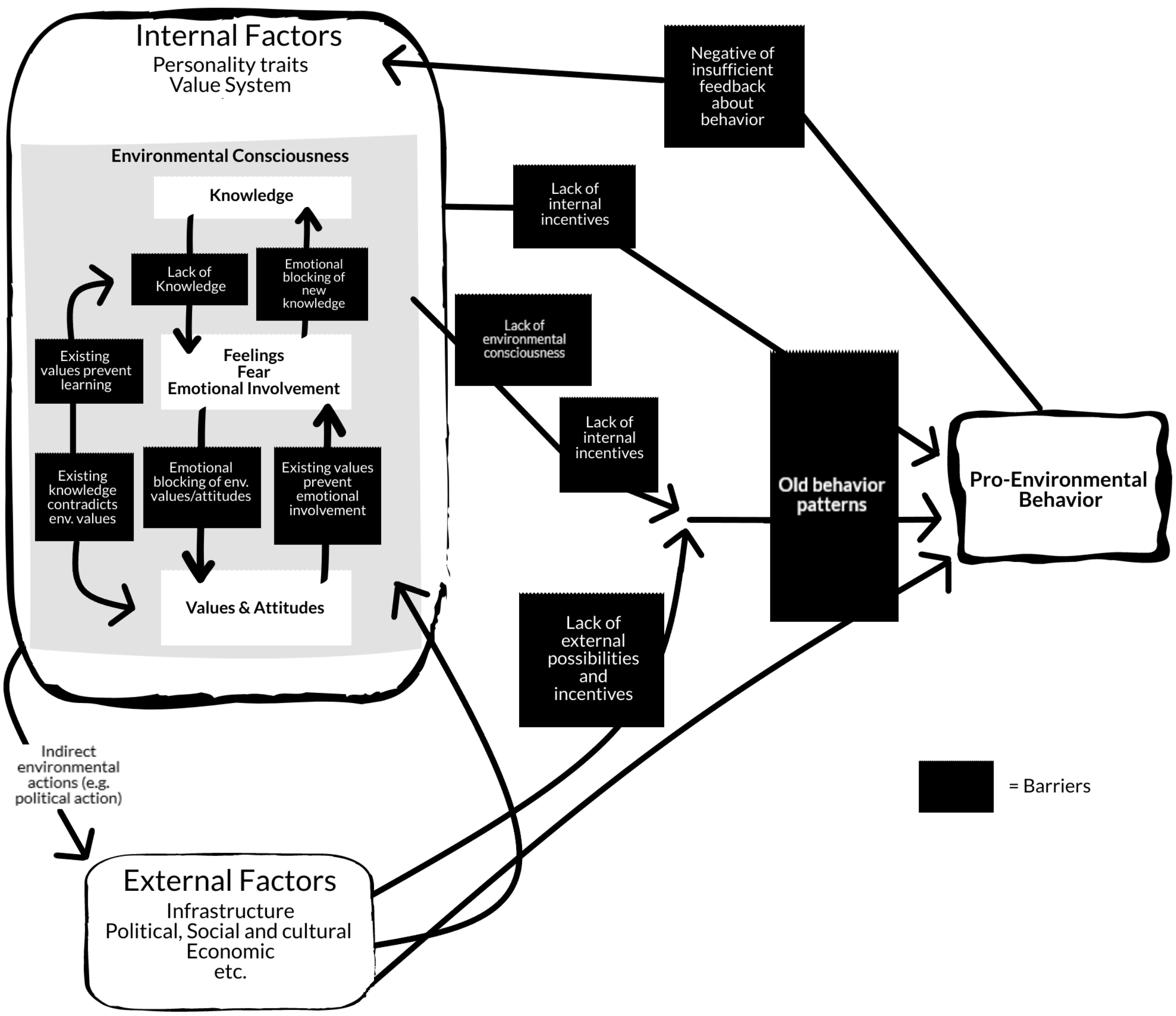


Figure 18. Model of pro-environmental behavior. Source: Adapted from Kollmuss and Agyeman, 2002.

The CCWG outreach subcommittee may wish to use these models and integrate social science research and behavioral economics to potentially improve outreach and education efforts. It is recommended that social and psychological scientists study the cesspool conversion issue and assist the CCWG to form effective messaging and outreach strategies. The hope is to have a better chance of driving behavioral change, which is necessary for cesspool conversions and the improvement of water quality and human health.

What frameworks can assist in the decision-making processes and solutions?

It remains to be seen if cesspool upgrades will have the positive ecological impact desired. Coral reef health hinges on several overlapping issues, some global and some local, and wastewater pollution is just one of them. Understanding the relationship between wastewater management, human health, and coral reef health can be complicated, indirect, and often costly. Studying ecosystem impacts can include many variables including how coastal water currents vary over time and locations, biogeochemical interactions, and nitrogen pulses from rainfall events (Swarzenski et al., 2012 as cited in Barnes et al., 2019). However, simply focusing on ecosystem impacts misses the larger context and the human connection and reliance on the environment. Pollution can negatively impact human behavior and health. Furthermore, personal beliefs about negative health effects are an important predictor of compliance to advisories (Evans et al., 1988). Improving citizen knowledge about the linkage between health and cesspools may be important to gain compliance to Act 125. By using methods like that of the West Hawaiʻi Integrated Ecosystem Assessment, it can provide a framework to help track changes in key social-ecological processes, better informing policy makers, and ultimately linking tailored outreach and education activities. Such indicators may include ecological, climate, ocean, and social indicators (Gove et al., 2019).

"Ecosystems are fundamentally intertwined with human well-being and ignoring this important connection can undermine the sustainability of an ecosystem and related resource management goals" (Millennium Ecosystem Assessment 2005, quoted in Gove et al., 2019, p.40). The CCWG may wish to consider using the most reproducible and applicable available science, combined with place-based management and other policy or integrated solution-based frameworks to develop a holistic strategy to determine and define wastewater impacts, priority upgrade areas, social needs and mechanisms for replacement while balancing multiple stakeholder objectives and its own overarching goal. Using ecosystem service evaluation tools (e.g., Oleson et al., 2014) that link water models and integrate ecological indicators and stakeholder values can better inform the difficult decision-making processes. The tool stresses stakeholders' values and can help improve the effectiveness, efficiency, and equity within ecosystem-based management.

The CCWG may wish to review the formal structured decision-making (SDM) process evaluated by Babcock et al. (2019) in upcountry Maui. The SDM process is based in decision theory and risk analysis and defined as a "collaborative process for decision-making that combines analytical methods from ecology and decision science with facilitation/negotiation and social psychology to develop rigorous, inclusive, and transparent solutions" (Babcock et al., 2019, p. 4). It uses a set of concepts and steps rather than a rigid prescriptive approach (USGS, N.D). The authors of this research used this type of approach to determine how alternative management practices may influence: groundwater nutrients; cost; and where the most benefits would be realized to satisfy regulations/objectives and social goals (Babcock et al., 2019). According to the authors, the process achieved the following: 1) identified a suite of cesspool replacement options; 2) developed a range of management alternatives to upgrade cesspools that incorporate feasibility; 3) analyzed environmental benefit of each alternative; 4) enumerated costs of the alternatives; and 5) provided recommendations on the alternatives relative to cost, environmental benefit, and stakeholder-identified objectives. It then recommends a participatory and structured decision-making process to help solve wicked environmental problems, which are problems that are difficult or impossible to solve because of incomplete, contradictory, or changing requirements (Babcock et al., 2019).

A decision analysis process to identify “trigger” or priority areas impacted by wastewater pollution from OWTS may also be relevant and advantageous for the State of Hawai‘i to identify pollution mitigation strategies in a cost-effective manner (Fig. 19; Barnes et al., 2019). Key takeaways from Barnes et al. (2019) include: there is a direct trade-off between cost and pollution reduction; low-benefit solutions do not always support ecosystem protection; solutions for pollution mitigation should be balanced with a mix of low cost (low benefit) and high cost (more benefit) strategies; and decision science, when used appropriately, can be a transparent, accessible, and a useful tool to manage ecosystem health and pollution drivers. Decision analysis parallels well with the State’s 30 by 30 initiative to protect coastal areas and ecosystems by 2030 and uses SDM methods (State of Hawai‘i Division of Aquatic Resources, 2019). A structured, rigorous and engaged decision-making approach can be applied regionally to aquifers, streams, and coasts threatened by cesspool wastewater contamination (Barnes et al., 2019).

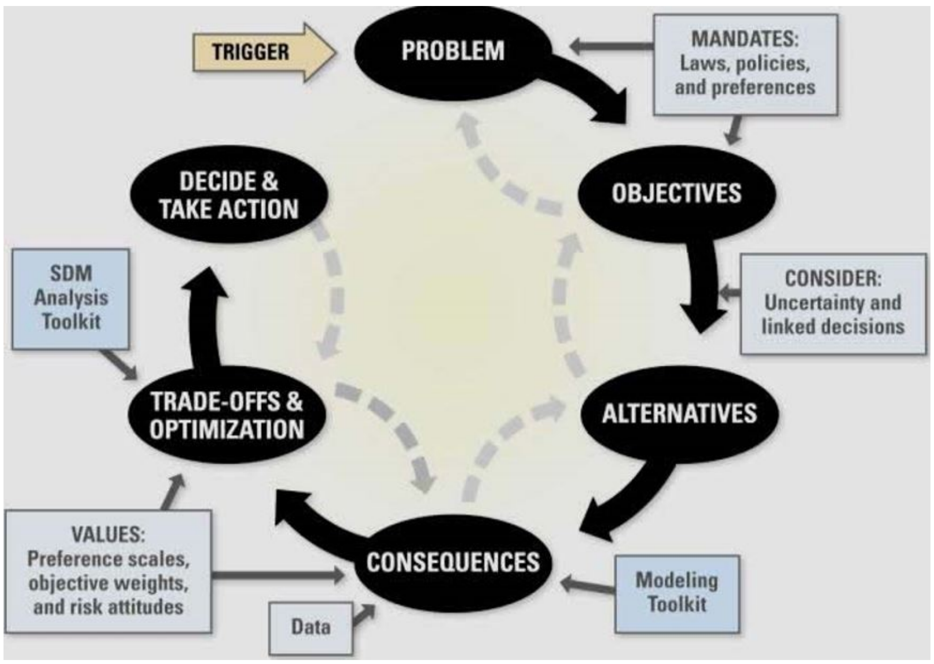
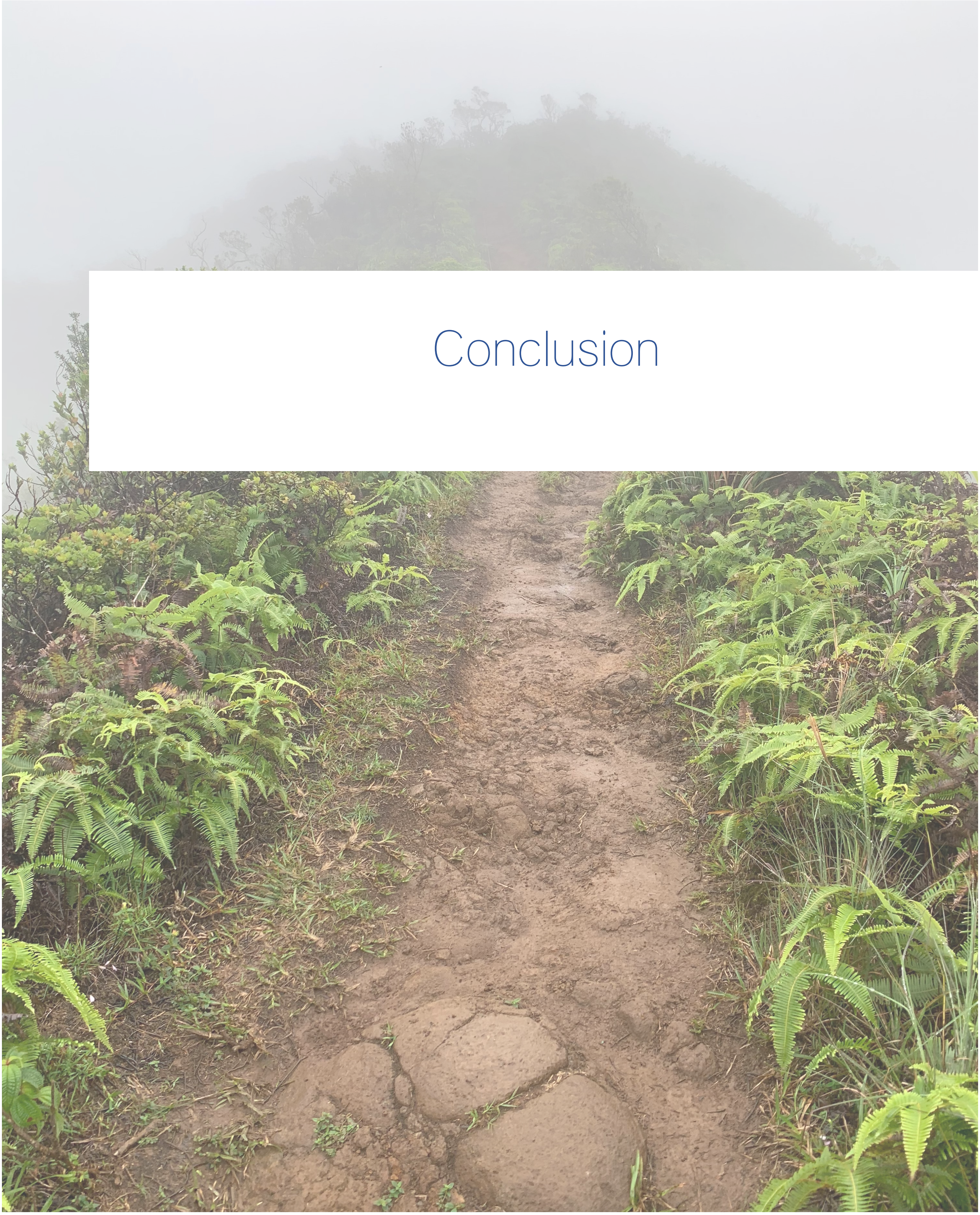


Figure 19. Decision analysis method diagram. Source: 4th Joint Government Water Conference, Kirsten L.L. Oleson; Babcock et al., 2019.

Previous work by Whittier and El-Kadi (2014) also provided a useful mechanism to calculate risk by categorizing the threats an OWTS may pose to an ecosystem and human health. The risk score was then displayed spatially on GIS maps. The risk score included factors such as the proximity of OWTS to an area that may be harmed by wastewater pollution, ability of the soil to transmit or treat OWTS effluent, amount of dilution the effluent is subjected to in the saturated zone, and other hydrologic factors (Whittier and El-Kadi, 2014). This type of scoring tool can be combined with other decision-making mechanisms to assist the CCWG with its long-range plan. Although the authors stressed that a field study is necessary to confirm model results and determine the degree groundwater is being degraded by OWTS, the expansion and update of such a scoring mechanism could be advantageous (Whittier and El-Kadi, 2014).

Conclusion



Enough valid scientific information exists to to develop a long-range comprehensive upgrade plan.

The evolving nature of research, data, and new methods to evaluate the source and severity of wastewater pollution make it difficult to create a single set of conclusive and prescriptive recommendations for prioritization. One thing that is apparent when reviewing the literature is that the current research and data can, and has supported, an informed and comprehensive decision analysis methodology and anticipatory action framework. This has been made evident by research from Barnes et al. (2019) and Babcock et al. (2019) among others. Scaling up this process and retrieving the needed information for various locations, specifically on hydraulic modeling, will take time, monetary resources, and personnel. These tools can help guide the CCWG to select high-impact and cost-efficient wastewater management strategies to meet local and state environmental and social goals (Barnes et al., 2019).

Combining the decision-making analysis framework with place-based management of ocean, land, and surface water resources could reduce human impacts and improve the resiliency and sustainability of human and natural systems, which continually face external threats such as climate change or excessive resource extraction (Delevaux et al., 2018). Coral reefs impacted by wastewater pollution cannot provide the millions, if not billions, of dollars in benefits that healthy reefs can. The cesspool conversion issue can be combined with other statewide efforts and watershed plans to resolve pressing coastal problems and issues not comprehensively addressed by a single agency or mandate. One such example is the State of Hawaiʻi Ocean Resources Management Plan (ORMP). The ORMP, currently being updating from the 2013 plan, uses a place-based approach to manage connected ocean and terrestrial resources, emphasizing demonstration projects leading to potential policy changes (State of Hawaiʻi Office of Planning, 2019).

There is an existential threat that exists by waiting too long to obtain large amounts of data on water quality, geology, ecosystem, or human health impacts, versus obtaining and using the right type of available data to make an informed decision or create an adaptable management strategy. Many of the studies reviewed in this analysis clearly point to wastewater pollution as a contributor, if not a significant one, to human health risks and ecosystem impacts. Coupled with the fact that Hawaiʻi's water resources are often sole source and limited in nature, this presses the need for the state to act in tandem with those performing further research or obtaining pertinent water quality information. A very useful tool to identify wastewater pollution is the use of nitrate stable isotopes ($\delta^{15}N$), which have been developed as a wastewater tracer and is well established within the scientific community. The possibility of identifying the specific source of nitrogen pollution with $\delta^{15}N$ values is realistic in Hawaiʻi' with the assistance of sophisticated and available land-use information and potential pollution sources to clarify the isotopic data. By using available scientific tools with adaptive management strategies, coupled with a structured iterative process, new information can be easily incorporated into plans, and strategies can be adjusted to meet the original stated goals. Understanding where programs have failures or gaps can also ensure that past OWTS management mistakes are not repeated if new challenges are faced.

Wastewater and water management issues, in general, can best be described as a wicked problem. Wicked problems have a high level of complexity, uncertainty, and multiple points of stakeholder involvement (Patterson et al., 2013; Cook et al., 2013 cited in Mguni, 2015). Multi-stakeholder approaches can have high degrees of complexity where stakeholder interests are entrenched or conflicting (Mguni, 2015). The CCWG may wish to evaluate how the State manages risk in terms of pollution sources and amounts, or survey and establish an acceptable risk level among multiple stakeholders impacted by OWTS pollution. The OWTS management will always have some level of risk because OWTS do not produce nutrient and chemical free effluent. In order to help address key issues of the OWTS problem, a new strategy on handling risk may be warranted. One developed by NASA (2013) and cited in Mguni (2015), manages risk through the integration of both top-down and bottom-up approaches. Policy and regulatory responsibility can be handled by those in the State and County government (or leadership positions) and coordinated with local groups who utilize affected resources at site-specific areas.

Because science evolves to provide new information, there is a need to build in site-specific adaptation to management frameworks (Mguni, 2015). According to Mguni (2015, p.28), both NASA (2013) and Beller-Simms et al. (2014) offer methods to encourage "flexible adaptation pathways" to provide "a continuous and dynamic consideration of risk tolerances and corresponding policies". Flexible adaptation pathways are established within the bounds of "acceptable risk levels" and detailed in Fig. 20. Groups are not locked into a single strategy from imperfect information but, rather, adapt as better information becomes available, dovetailing into frameworks like SDM.

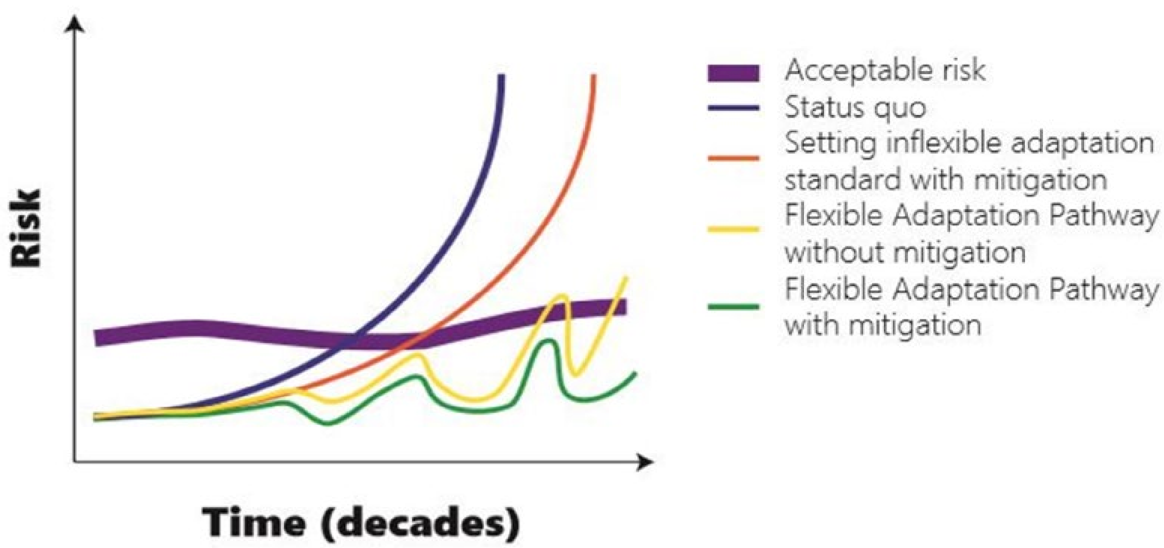


Figure 20. Adaption pathways chart. Source: Mguni, 2015.

Site specific information, such as research on nutrient pollution or ecosystem changes, can be provided by research institutions, traditional practitioners, citizen scientists, or government departments. Public policy and transparency could be improved by incorporating the best available information with flexible adaption pathways and sharing information with local stakeholders and other partners (Mguni, 2015). Additionally, community values can change through local and global contextual drivers (Ferguson et al., 2013, cited in Mguni, 2015). Resource limitations, environmental impacts, and changing socio-economic conditions create the need for an underlying and integrated structure, which is flexible and adaptable to accommodate any unforeseen changes.

Efforts to continue to bring together County and State departments involved directly or indirectly in wastewater management will be crucial to meeting the State’s goals by 2050. By creating a multi-tiered strategy similar to California, Hawaiʻi may be able to improve efficiency and communication between state and local agencies dealing with wastewater issues. Examples of actions may include: streamlining or improving permit processes; updating inventory of systems; integrating financial incentives; integrating water quality sampling into databases; training requirements; and public messaging (Borer, 2018; Spirandelli et al., 2019). Studying behavioral change models and integrating social science research and behavioral economics into conversion plan strategies may guide more strategic policy recommendations that encourage pro-environmental behavior. It is recommended that planners and social and psychological scientists join the outreach subcommittee to study the cesspool conversion issue and assist the CCWG to form effective messaging and outreach strategies, perhaps using professional facilitation with stakeholders to identify unique objectives and values. The CCWG may also wish to research opportunities and barriers to integrating OWTS into a one-water framework, including social research on the effectiveness of public education, outreach, and other factors that could change behavior or increase compliance with OWTS regulations (Spirandelli et al., 2019).

Finally, the CCWG may wish to invite counterparts from other states, such as New York or Rhode Island who are, or have, developed a robust OWTS management strategy and frameworks, to partner with Hawaiʻi’s efforts. Because of the interdisciplinary nature of water resource protection and infrastructure involved, the issues and associated mandates do not fall neatly into one agency within the state or county governments. The CCWG should review options such as the creation of a new department/utility or partnering with watershed organizations or a third party, similar to Washington State, which utilized a non-profit organization to assist with financial aspects of OWTS management and upgrades. Success or failure of a program will not be easily measured by a single variable, such as the number of systems replaced. Rather, a program should be holistic, transparent, and able to easily adapt to needed management requirements (natural or human), state, federal and local laws, financial needs, and public support and perception.

Acknowledgements

This document was developed, in part, through Grant No: 1200560, from the Hawaiʻi State Department of Health, authorized under Act 132. This paper is also funded, in part, by a grant/cooperative agreement from the National Oceanic and Atmospheric Administration, Project A/AS-1, which is sponsored by the University of Hawaiʻi Sea Grant College Program, SOEST, under Institutional Grant No. NA18OAR4170076 from NOAA Office of Sea Grant, Department of Commerce. UNIHI-TT-19-03. The views expressed herein are those of the author(s) and do not necessarily reflect the views of NOAA or any of its sub-agencies. This informational resource was written with the assistance of multiple individuals in several fields. I am very grateful for the level of cooperation and assistance by every person I consulted and requested data from. Significant contributions from these individuals listed below, along with countless others were essential to the development of the document.

- Celia Smith Ph.D.—University of Hawaiʻi at Mānoa
- Tracy Wiegner Ph.D.—University of Hawaiʻi at Hilo
- Henrietta Dulai Ph.D.—University of Hawaiʻi at Mānoa
- Kim Falinski Ph.D.—The Nature Conservancy
- Aly El-Kadi Ph.D.—University of Hawaiʻi at Mānoa
- Marek Kirs Ph.D.—University of Hawaiʻi at Mānoa
- Daniele Spirandelli Ph.D.—University of Hawaiʻi at Mānoa
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