

Review Article

Hawai'i's Cesspool Problem: Review and Recommendations for Water Resources and Human Health

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Abstract: Cesspools as onsite sewage disposal systems (OSDS) are widespread in the Hawaiian Islands and of concern due to their lack of primary treatment and direct discharge of pathogens and nutrients into groundwater. Approximately 88,000 cesspools in Hawai'i release nearly 55 million gallons per day (mgd) of sewage into the ground. Here, we review the status of wastewater pollution, with an emphasis on cesspools, and associated impacts to water resources, nearshore ecosystems, and human health. We present evidence supporting the creation of a cesspool conversion plan, highlighting the need to upgrade cesspools. Knowledge gaps in areas such as hydraulic/hydrologic modeling and technological limitations in identifying specific wastewater sources present barriers to addressing cesspool challenges. We show many of these constraints can be diminished. For example, limitations in identifying specific sources from wastewater indicators using %N and $\delta^{15}\text{N}$ can be reduced with available land-use information and potential pollution sources to clarify concentration and isotopic data. Resource management presents many challenges, including recognition of diverse societal views and values. To overcome discrepancies in available data, and varying societal values, the use of transparent, adaptable framework methods such as "structured decision-making" offers approaches for problem solving. Such frameworks are consistent with a holistic management approach to OSDS that couple the natural and social sciences in identifying and addressing barriers to reduce negative impacts. Maintaining momentum through adoption of clearly articulated short-, medium-, and long-term achievement benchmarks associated with such a management approach is recommended.

Keywords: *onsite sewage disposal system, coral reef, nonpoint source pollution, submarine groundwater discharge, nitrogen pollution, water quality indicators, wastewater policy*

Anthropogenic activities are the main source of groundwater pollution (U.S. EPA 2015). Wastewater pollution is one facet of pollution which enters groundwater and nearshore environments via multiple pathways, including point and nonpoint sources (Figure 1). Establishing connections of specific nonpoint pollution sources with ecosystem degradation is extremely difficult. Consequently, nonpoint source pollution remains the greatest source of water quality declines across the United States (U.S.) (Lewis 1999). The Clean

Water Act of 1972 addresses point source and nonpoint source pollution; however, mandatory federal regulations exist only for point source pollution (Brown and Froemke 2012).

Onsite sewage disposal systems (OSDS) are a type of nonpoint source pollution and can include cesspools, as well as systems that provide some level of treatment such as septic systems. Cesspools are empty pits in the ground with perforated brick or concrete walls. Wastewater and solids entering the cesspool "percolate" into the surrounding

soil and groundwater causing environmental and human health issues. Unlike cesspools, a septic system (with regular maintenance) provides anaerobic treatment of waste within a sealed tank of concrete or fiberglass and an engineered leach field further removes most pathogens and some level of nutrients.

Cesspool concerns in Hawai'i have been raised by 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. The results indicated that incomplete degradation of wastewater effluent in test soil lysimeters (a container used to determine soil-water drainage or chemical movement within soil) in two basic soil types on O'ahu Island, Hawai'i, make wastewater a definite hazard to groundwater (Koizumi et al. 1966).

There are estimated to be 88,000 cesspools in the state of Hawai'i, with most on Hawai'i Island (~50,000), though significant numbers are on Kaua'i (~14,000), Maui (>12,000), O'ahu (>11,000), and Moloka'i (>1,400) (State of

Hawai'i Department of Health 2017). Hawai'i's cesspools release nearly fifty-five million gallons of human waste into the ground each day (State of Hawai'i Department of Health 2017). Installation of new cesspools was permitted in the state of Hawai'i until 2016 and in 2017, Act 125 (State of Hawai'i Department of Health 2017) required all cesspools to be upgraded, converted to an approved disposal onsite system, or connected to a sewer system by January 1, 2050. Upgrading cesspools in Hawai'i is recognized as a tangible action to reduce nutrients reaching coastal waters from human development (Yoshioka et al. 2016). However, numerous multidisciplinary challenges exist that require attention to address this issue.

Signs of wastewater influx into coastal and ocean environments include excess nutrient levels, usually nitrogen and phosphorus (U.S. EPA 2019c). Eutrophication in Hawaiian waters, however, may not be obvious if dilution, coastal currents, or nutrient uptake are significant. Other areas in the U.S. facing significant nutrient pollution from OSDS, such as Suffolk County in the State of New York and coastal areas of the state of Rhode Island,

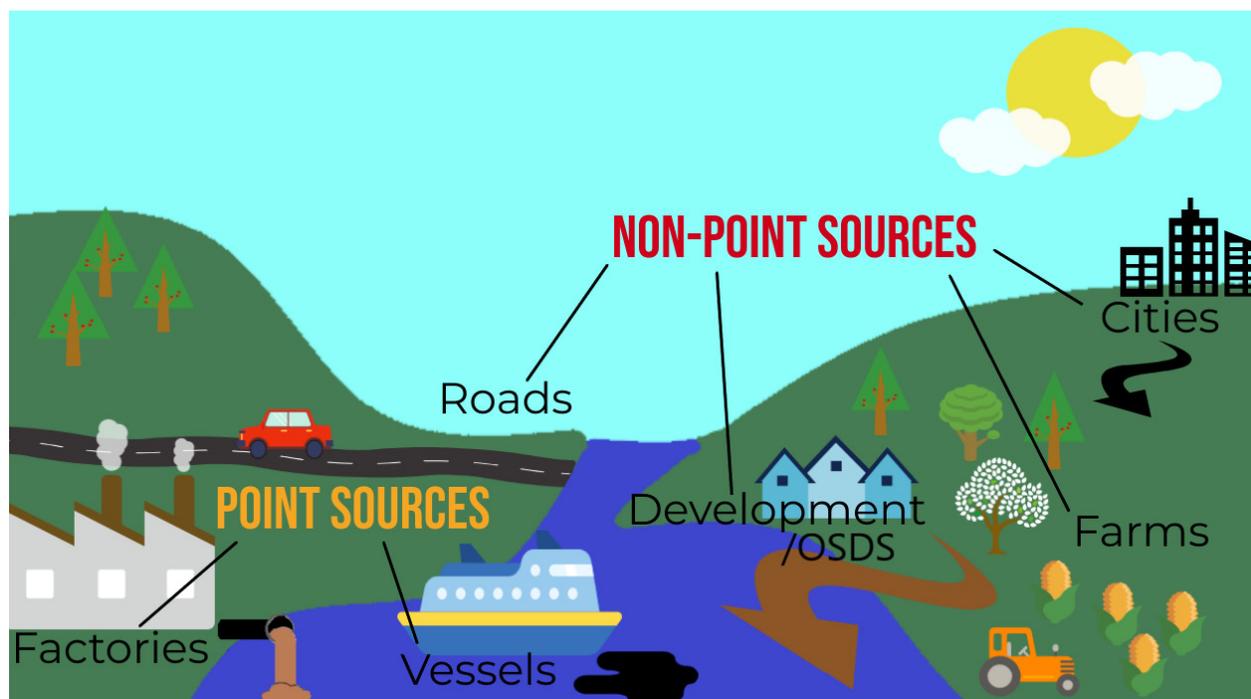


Figure 1. Illustration of various origins of point and nonpoint source pollution. Point sources can include factories and vessels. Cities, roads, farms, developments, and onsite sewage disposal systems (OSDS) are examples of nonpoint sources of pollution.

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; University of Rhode Island Cooperative Extension 2015).

This review paper was inspired in part by a request of the State of Hawai'i Cesspool Conversion Working Group (CCWG) under the authorization of Act 132, passed by the Twenty-Ninth Hawai'i State Legislature. Section two, objective three, of Act 132 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" (Hawai'i Senate Bill 2567 2018, 1). The primary goal of this review is to synthesize and evaluate knowledge gaps of relevant research regarding wastewater pollution science and policy in the state of Hawai'i. A secondary goal is to explore and identify data driven solutions and recommendations to assist the state of Hawai'i in meeting its mandate of converting all cesspools by 2050. Supporting objectives include developing specific recommendations for consideration by the state and other stakeholders in each of the four categories: *Ocean/coastal/groundwater impairment and human health*; *Wastewater pollution indicators*; *Water resource modeling/monitoring/risk analysis*; and *Policy and community engagement*. Central pillars of the review include wastewater impacts to water resources, associated natural communities, and human health.

Methods

Online searches were performed using Google Scholar, PubMed, Science Direct, Web of Science, and Google. Results included academic studies, other scholarly publications, general journal articles, theses, websites, and reports. We obtained search results using the keywords of: cesspool; Hawai'i; wastewater; nutrient pollution; bacterial pollution; water quality; septic pollution; algae; pathogens; micropollutants; tracer injections; contaminants of emerging concern (CEC); and wastewater management. One hundred and twenty-

four primary documents were discovered from which summaries and syntheses were developed. Information presented here was also informed by consultation with subject experts, including researchers, in relevant disciplines. We specifically explored four topics to better understand the status of the impacts of cesspools on nearshore Hawaiian waters, groundwater, and associated ramifications for human health. The four topics were 1) ocean/coastal/groundwater impairment and human health, 2) wastewater pollution indicators, 3) water resource modeling/monitoring/risk analysis, and 4) policy and community engagement. For each topic, we identified both key concepts and knowledge gaps.

A full examination and comparison of all onsite wastewater treatment systems, including septic systems and novel systems, is beyond the scope of the present review, though we recognize such technologies have a role in enhancing nearshore water quality through potential upgrading of legacy cesspools. Here, we focus on cesspools and use the term onsite sewage disposal systems or OSDS to conform to the nomenclature used in state of Hawai'i laws and regulations.

Results and Discussion

Ocean/Coastal/Groundwater Impairment and Human Health

Ecosystem Impacts in Hawai'i. As no point of land in the state of Hawai'i is beyond 50 km from shore, all of the state is considered to be in the "coastal zone" designation, with terrestrial activities impacting inland, coastal, and ocean water quality (State of Hawai'i Office of Planning-Coastal Zone Management Program 2020). Numerous studies have evaluated impacts to water resources and ecosystems across the Hawaiian islands, including coral reef communities, which are vitally important to Hawai'i's environment, economy, and culture. Land-use practices directly impact surface and groundwater quality as well as adjacent reef communities (Amato et al. 2016). Groundwater adjacent to these areas enters the ocean through submarine groundwater discharge (SGD) and surface waters, which transport nutrients and harmful pathogens (McKenzie et al. 2019). Our understanding of the relationships among

groundwater pollution, connected hydrologic systems, and ecological impacts is extensive but incomplete (Amato et al. 2016). Additional field data to inform models and frameworks currently in use will improve our understanding of these processes.

Eutrophication from OSDS pollution or other terrestrial sources (e.g., stormwater runoff or agricultural fertilizer) is associated with the presence of invasive algae, high macroalgal cover, and low benthic biodiversity (Amato et al. 2016). Such negative impacts to nearshore coral reef ecosystems extend to associated local economies, fisheries, and cultural practices. The most common impact to coral reefs from eutrophication is algal overgrowth (Dailer et al. 2010; Abaya et al. 2018a). Corals can become stressed under high nutrient loads with coral reef mortality correlated to eutrophication (Smith et al. 2001; Parsons et al. 2008; please see Abaya 2018 for summary). Couch et al. (2014) have also presented high nitrate concentrations as a potential contributor to coral growth anomalies.

Direct and indirect losses to both coral reef ecosystems and human communities can be attributed to wastewater pollution. Maui Island residents in the North Kihei area have experienced severe algae overgrowth problems, likely from nutrient pollution due to a high number of cesspools and other OSDS in the area (Smith and Smith 2006). Cesar and van Beukering (2004) measured annual impacts to condominium property values from excessive algal biomass accumulating on Maui beaches and estimated annual losses in property values were greater than \$9 million U.S. dollars in 2004. Combining losses of property values and rental income, and accounting for expenditures for algae removal, estimated losses exceeded \$20 million U.S. dollars per year.

Damage to and loss of coral reefs can have widespread consequences, while intact and healthy reefs can increase food security, promote tourism, provide infrastructure protection, and improve community resiliency from major storms (Gutierrez 2019; Storlazzi et al. 2019). Coral reefs provide an estimated \$835.4 million dollars in physical protection from storms and erosion to buildings on the islands of Maui, O'ahu, Kaua'i, and Hawai'i (Gutierrez 2019; Storlazzi et al.

2019). Cesar and van Beukering (2004) estimated net benefits provided by coral reefs to Hawai'i's economy in 2004 at \$360 million U.S. dollars per annum. The value provided by the state's 1660 km² of potential reef area in the main Hawaiian islands was estimated at nearly \$10 billion U.S. dollars in 2004 (Cesar and van Beukering 2004).

Several areas in Hawai'i experienced decreases in coral cover adjacent to areas with high cesspool densities and high dissolved nitrogen levels. Minton et al. (2012) found coral coverage decreased nearly 50 % at various sites around Puakō, Hawai'i Island, in an area with elevated nitrogen, short groundwater travel time, and elevated *Enterococcus* bacteria. 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; Bahr et al. 2015). Delevaux et al. (2018) developed a unique land-sea modeling framework to connect the many factors that impact corals. The framework uses local data and fine scale groundwater and coral reef models. Delevaux et al. (2018) incorporated impacts from groundwater and nutrients, human activities, and marine variables such as waves, geography, and habitat in a "reef-to-ridge" system to evaluate vulnerable areas and potentially inform place-based ridge-to-reef management.

Future studies exploring alternative metrics to link wastewater pollution and ecosystem impacts, such as microbial source tracking (MST) and developing enhanced data or models to understand water movement, especially in embayments where reefs may be particularly affected by decreased water quality, are recommended (Yoshioka et al. 2016). The potential for the diverse impacts discussed above indicate many more studies must be undertaken to fully understand future risks to Hawaiian ecosystems, especially from wastewater pollution. The lack of complete data, however, should not hamper or delay adoption of an adaptive management framework to address OSDS impacts, for which actionable data exist.

To overcome some difficulties of studying the sources of 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, Hawai'i Island. The study used fecal indicator bacteria (FIB) as a wastewater indicator, measurements of ocean bottom cover, macroalgal bioassays, and a unique pollution scoring tool. Coral cover was negatively correlated with FIB, macroalgal $\delta^{15}\text{N}$ levels, and overall nutrient concentrations (Abaya et al. 2018a). Although wastewater concentrations were most detectable nearer the shoreline, results demonstrated tidal pulses might be delivering pollution to offshore reefs (Abaya et al. 2018a). Understanding flow patterns in water bodies may be vital to understanding which areas may be susceptible to the greatest impacts from pollution sources. Other studies, such as Delevaux et al. (2018), also used a multi-technique approach through development of a linked land-sea modeling framework. Delevaux et al. (2018) investigated the Hā'ena area on the windward side of Kaua'i Island and Ka'ūpūlehu on the leeward side of Hawai'i Island. Using local data and coupled groundwater and coral reef models, Delevaux et al. (2018) sought to determine the impacts of land-based processes, influenced by human activities and marine drivers. Results indicated land-based and marine drivers varied at studied locations due to natural systems and island age (Delevaux et al. 2018). The Hā'ena study site was primarily influenced by large-scale drivers, such as rainfall and wave action, while the Ka'ūpūlehu site was influenced by local drivers, including habitat and nutrients (Delevaux et al. 2018). Understanding the types of drivers and sources of wastewater pollution will be essential to maintain environmental and human health standards.

The authors believe that frameworks to track, monitor, and evaluate wastewater pollution and mitigation are vitally important. One such framework 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 (U.S. EPA 2019a). An AOC is a designation that 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 (U.S. EPA 2019a).

Examples of impairments are eutrophication, loss of fish habitat, or drinking water quality reductions (U.S. EPA 2019a). Remedial action plans (RAPs) are then developed to mitigate BUIs and remove an AOC designation. A RAP includes: identifying which BUIs exist and their causes; criteria for restoring listed BUIs; remedial methods and actions to be taken; and a method to track progress toward delisting (U.S. EPA 2019a). Development of an AOC approach for marine environments is warranted for Hawai'i.

Scientists studying the complex dynamics of marine ecosystems have highlighted the potential for rapid, dramatic changes in ocean conditions, called tipping points, triggered by seemingly small anthropogenic pressures, including wastewater pollution (Ocean Tipping Points 2019). The Ocean Tipping Points Project (<http://oceantippingpoints.org/>) seeks to understand these inflection points and develop management tools to avoid ecosystem damages, monitor indicators, prioritize management actions, and evaluate progress toward ecosystem objectives (Ocean Tipping Points 2019). The state of Hawai'i's "30 by 30" initiative to manage 30 % of its nearshore waters by 2030 acknowledges the need to manage local stressors, including sediment and nutrient runoff, to achieve and maintain resilient coastal ecosystems. Monitoring information and management tools generated by the Ocean Tipping Points (2019) project or the "30 by 30" project may inform cesspool management in Hawai'i. Nonetheless, it may be difficult to establish direct correlations to cesspool and other OSDS pollution and declines in ecosystem health as variables are multifactorial and may include global climate change and local land-use changes. Regardless, lack of a definitive correlation between specific OSDS and environmental degradation has not restricted other states' efforts to upgrade outdated or failing OSDS to improve human communities and ecosystems (Mezzacapo 2019).

Human Health and Ecosystem Health are Inextricably Linked. Human health and coral reef health share common threats, highlighting the importance and commonality of a healthy reef and a healthy public (Figure 2). However, limited studies evaluating the toxicity and persistence of various environmental contaminants in

wastewater on marine biota have been conducted (Hunter et al. 1995). Further, we are unaware of any studies in Hawai'i that have tested septic tank or cesspool sludge and effluent for various types of contaminants, compounds, bacteria, and viruses. It may be valuable to understand different compounds or substances that exist in various populations to more accurately test groundwater or coastal environments (M. Kirs, personal communication). Additionally, little is understood on how many types of CEC or organic wastewater contaminants (OWCs) are transported and interact with other chemicals or treatment system characteristics and subsurface variables, and how or what impacts to local water resources may result (Conn et al. 2006). Additional testing of human waste for specific chemicals, genetic markers, or expanded pathogens might yield future wastewater pollution indicators and generate studies to evaluate their impacts to human health and ecosystems.

Protecting human health and the environment is an important role for governments and other institutions (U.S. EPA N.D.), though the proper processing and disposing of human waste presents many challenges (Andrzejewski 2019). Understanding Hawai'i's human health risk from sewage contamination is essential to prioritize cesspool upgrades. Epidemiologic studies have associated human health risks with point source pollution (Fleisher et al. 2010). However, little information is known regarding risks to recreational bathers in subtropical climates absent a known source of sewage pollution, i.e., nonpoint pollution sources (Fleisher et al. 2010). Additional studies to explore and confirm correlations of risk and wastewater indicator organisms in tropical and subtropical climates are necessary (Fleisher et al. 2010). It is, however, evident that malfunctioning cesspools and other OSDS can provide a reservoir for pathogenic bacteria, which can enter nearshore environments through groundwater, surface water,

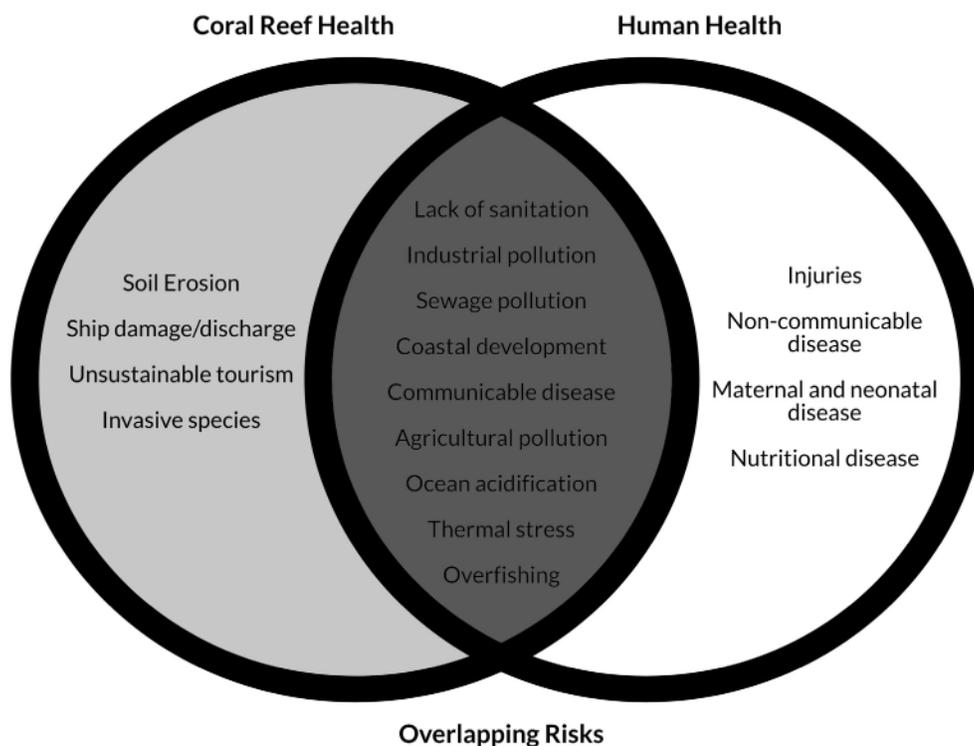


Figure 2. Venn diagram illustrating selected threats to coral reef and human health and the intersection identifying common threats. Wear (2019) conducted a literature review and supplemented the review with the Global Burden of Disease Compare Data Visualization tool from the Institute for Health Metrics and Evaluation to identify common threats to human health. The Reefs at Risk Revisited report by Burke et al. (2011), was also incorporated to identify common threats to coral reef and human health. Adapted from Wear (2019).

and SGD, potentially causing water quality hazards (Figure 3; Ground Water Protection Council 2016).

Recreational water quality is important to residents and visitors who use Hawai'i's ocean resources (Kirs 2018). However, little is known about baseline bacteria levels and transport dynamics of bacteria and viruses in wet tropical and subtropical regions where recreational water use occurs year-round (Strauch et al. 2014; Rochelle-Newall et al. 2015; Strauch 2017; Economy et al. 2019). Pathogens such as *Staphylococcus aureus* are recognized as a potential environmental human health threat, though *S. aureus* is naturally found in the environment and on the skin and nasal passages of most healthy humans (Zetola et al. 2005; and see Economy et al. 2019). Nonetheless, recreational bathers in Hawai'i are four times more likely to develop *S. aureus* infections (Charoenc and Fujioka 1995; Economy et al. 2019; Taylor and Unakal 2019) and these infections on the skin can cause boils, impetigo, styes, folliculitis, and furuncles (Minnesota Department of Health 2010). Economy et al. (2019) identified *S. aureus* and Methicillin-resistant *S. aureus* (MRSA) in wastewater effluent in Hawai'i and showed relationships with other FIB in nearshore waters of Hilo, Hawai'i.

Hawai'i's rate of MRSA infections is double the national average (Chaiwongkarjohn et al. 2011; and see Economy et al. 2019). This bacterium is responsible for several difficult-to-treat infections

in humans (CDC 2019). *Staphylococcus aureus* is found in many parts of watersheds, even areas where humans typically are not recreating, as well as in wastewater (Economy et al. 2019). Economy et al. (2019) show *S. aureus* and other FIB were common in Hawaiian estuarine waters, rivers, and watershed sources, though their origin remains unclear, as do what risks, if any, they pose to humans. Rainfall amounts and changing climate patterns (higher water amounts, higher bacterial counts) may influence the transport of bacteria, including pathogens, from watersheds to nearshore waters (Dakhlalla and Parajuli 2019). The authors believe improved identification of specific bacterial sources posing threats to human health will assist appropriate government institutions or local organizations in creating localized watershed management strategies as preventative measures, with the aim of reducing pathogen loads from multiple sources (stormwater, OSDS, agriculture). Models developed for wet tropical regions, such as that by Economy et al. (2019), use hydrologic and water quality metrics to predict pathogen loading to nearshore waters. Such models could inform water resource managers regarding health risks to recreational water users in Hawai'i and other insular tropical and subtropical environments.

Decreasing Wastewater Inputs Can Improve Water Quality. Following Smith et al. (1981), who investigated ecosystem changes in Kāne'ohe Bay, O'ahu, Hunter and Evans (1995) subsequently

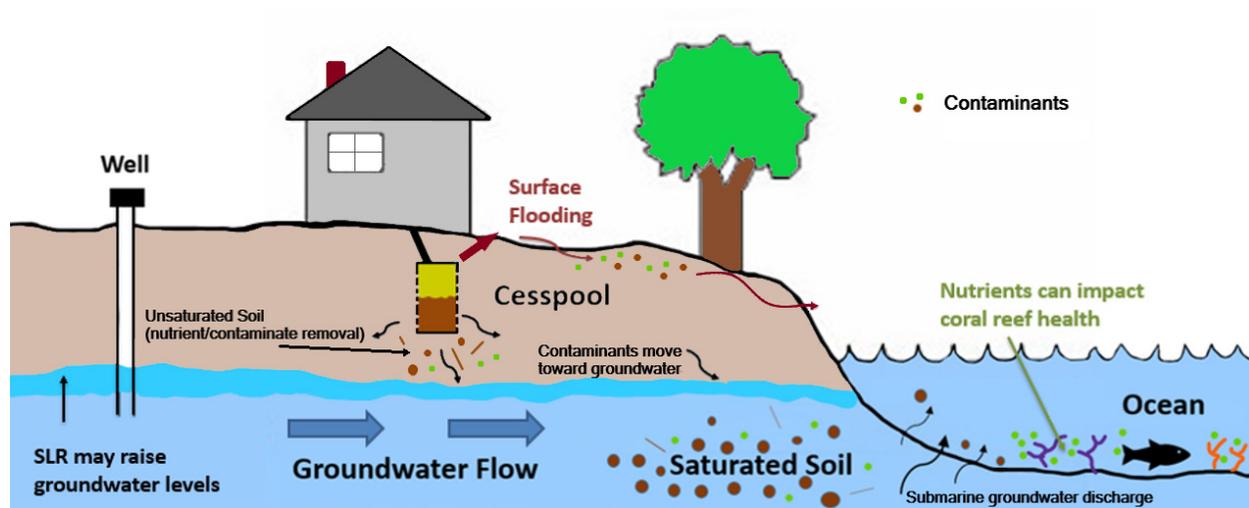


Figure 3. An illustration of the multiple pathways by which cesspool wastewater and associated contaminants can enter nearby water resources. Adapted from the State of Hawai'i Department of Health (2017).

detailed one of the best-documented transitions in ecosystem composition in the bay. Historically, Kāne'ohe Bay suffered from poor water quality and high nutrient levels from various pollution sources including wastewater and sediments from terrestrial runoff. The relative percentages of nutrient inputs from specific sources were unknown; however, large amounts of pollution resulted from leaky sewer lines, cesspool 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 decrease in nutrients, turbidity, and phytoplankton abundance in areas surrounding the outfalls. Changes in the environment occurred rapidly, from areas dominated by algae and filter and deposit feeders, to “coral gardens,” more representative of healthy Hawaiian reefs. Changes were observed in less than ten years, with the alga *Dictyosphaeria cavernosa* decreasing to just 25 % of its 1970 era abundance and coral cover more than doubling (Hunter and Evans 1995). In recent years, algal blooms have returned, puzzling scientists. One hypothesis, developed by the authors, is that legacy nutrients, from years of historical wastewater input, flow into shallow and slow-moving areas of the bay attaching to sediment. When storms, currents, or other disturbances resuspend these nutrients, bloom cycles may reoccur, however, additional research to explore this hypothesis is recommended.

Wastewater Pollution Indicators

The origins of nonpoint source pollution are diffuse and understanding how to best measure where this pollution originates, both from human and environmental sources, remains challenging. Various indicators to track pollution sources have been developed and tested, though many have limitations. To obtain accurate representations of pollution sources, employing a suite of indicators has proven useful. Abaya et al. (2018b) used a combination of dye tracer studies, sewage indicator bacteria measurements, nitrogen isotopes in macroalgae, and a unique pollution scoring tool. However, quantifying many subsurface processes

such as biological and chemical degradation rates, mixing of putative sources (e.g., cesspools and wastewater effluent injection), dispersion, and even groundwater flow lines can be difficult and introduces uncertainty in identifying the location and magnitude of sources. Yet, use of the best available science and recognized indicators is useful for decision-making and resource management.

Chemical Wastewater Indicators. The use of the $\delta^{15}\text{N}$ as a wastewater tracer to understand nutrient sources is well established (Valiela et al. 1997; Cole et al. 2004; Kendal et al. 2015; Wiegner et al. 2016), and $\delta^{15}\text{N}$ has been used since the 1970's to identify nitrate sources (Zhang et al. 2019). The $\delta^{15}\text{N}$ in coastal water has been used as a wastewater indicator in numerous studies in Hawai'i and provided evidence of wastewater pollution (Dailer et al. 2010, 2012; Wiegner et al. 2016; Abaya et al. 2018a). Many studies were carefully timed to capture the strongest SGD signature, which is understood to deliver nutrients from land-based sources (Richardson 2016; Wiegner et al. 2016; H. Dulai, personal communication). Nonetheless, because SGD varies in many parts of Hawai'i with tidal cycles and daily and seasonal time scales (Waters 2015), we propose performing an integrated nitrate isotope signature via sampling of certain coastal organisms (such as macroalgae), which may more accurately assess wastewater pollution presence.

The $\delta^{15}\text{N}$ values of invasive algal tissue have been used to map locations and potential sources of nutrients. Dailer et al. (2010) identified certain macroalgae in Hawai'i as suitable indicators of human sources of nitrogen due to the algae's ability to acquire high nutrient concentrations. Sessile macroalgae acquire and integrate all sources of water column nutrients over short and long periods of time, are easily collected, and can be analyzed for relatively minimal cost (Dailer et al. 2010). Such algae may be a representation of nutrients deposited through SGD, especially if the algae grow near a seep (Dailer et al. 2010). Limitations with regard to this method included the inability to identify a single nutrient source when multiple nitrogen sources were present (e.g., cesspools, fertilizers, wastewater effluent injection); though some limitations can be overcome by using multi-tracer methods and land-based data to analyze

sources. Identification of specific sources of nitrogen pollution in Hawai'i through use of $\delta^{15}\text{N}$ values coupled with %N data is realistic with the assistance of available land-use information and putative pollution sources to clarify the isotopic data.

Indeed, $\delta^{15}\text{N}$ values are used globally to detect human sources of nitrogen, proving useful in tracing sewage under appropriate conditions (Gartner et al. 2002; Dailer et al. 2010). 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. (2017), C. Smith and colleagues at the University of Hawai'i are analyzing $\delta^{15}\text{N}$ and %N (with additional water quality parameters such as pH, salinity, and temperature) in algal and water samples from a sewage contamination event in Hawai'i. Algal species under evaluation are *Acanthophora spicifera* and *Ulva lactuca*; restricting algae analyzed to these two species reduces experimental variables for more direct measurements of nitrogen concentrations versus averaging values community-wide (LaPointe 1987; Derse et al. 2007). Other recent work (Amato et al. 2020) supports previous modeling efforts connecting onsite sewage disposal sites and marine ecosystems on O'ahu Island. Amato et al. (2020) compared algal tissue data ($\delta^{15}\text{N}$ and %N) and nitrogen transport from wastewater models demonstrating a correlation between modeled estimates of coastal groundwater nitrogen and measured *Ulva* spp. $\delta^{15}\text{N}$ values and concluded, "These results indicate that both algal bioassays and groundwater N models are effective indicators of wastewater in the nearshore environment" (Figure 4). These results demonstrate the value of this approach, including application at moderate geographic scales, in identifying locations in need of OSDS upgrades to improve water quality and ecosystem health.

As nitrogen undergoes biochemical reactions moving from pollution sources to water bodies and is influenced by land-use, climate, and hydrogeological conditions, there is a need for additional data to categorically identify specific pollution sources and pathways. Such research may focus on factors influencing identification of pollution sources and tracing the migration and transformation of nitrogen (Zhang et al. 2019).

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

A study in Tutuila, American Samoa by Shuler et al. (2019), which could be reproduced in Hawai'i because of similar climate and hydrology, used a water quality analysis to show a link between elevated levels of dissolved total nitrogen in the groundwater and areas on land with a significant number of OSDS. A model framework was created that includes land-use information, hydrological data, and water quality analyses of nitrogen. This study, along with previous research, has indicated that OSDS contributed significantly more nitrogen to Tutuila's aquifers than any other source (Shuler et al. 2017, 2019).

Phosphorus is also an essential element in plant growth and nutrient in wastewater pollution, though a lack of phosphorus isotope signatures (phosphorus is mono-isotopic and only the oxygen isotopes in phosphate can be used as tracers) limit utility as a wastewater tracer (Paytan and McLaughlin 2011). Nonetheless, one study documented increased community diversity of cyanobacteria, which bloom in the presence of excess phosphorus (Brown 2019), in wastewater plumes offshore of western Maui Island. Coupling phosphate with other wastewater indicators may prove useful in nearshore systems to detect wastewater pollution and cyanobacterial blooms.

Biological Wastewater Indicators. Measuring the type and quantity of certain bacteria in water is commonly used as a proxy for the presence of wastewater pollution, though present technology does not permit source identification via a single test. Known as FIB, these bacteria are normal inhabitants of the gastrointestinal tract of many mammals including humans (Byappanahalli et al. 2012a). Typical FIB are *Enterococcus* spp. or *Escherichia coli* (Byappanahalli et al. 2012b). The presence of FIB is used to estimate the potential for pathogenic bacteria or viruses to cause human

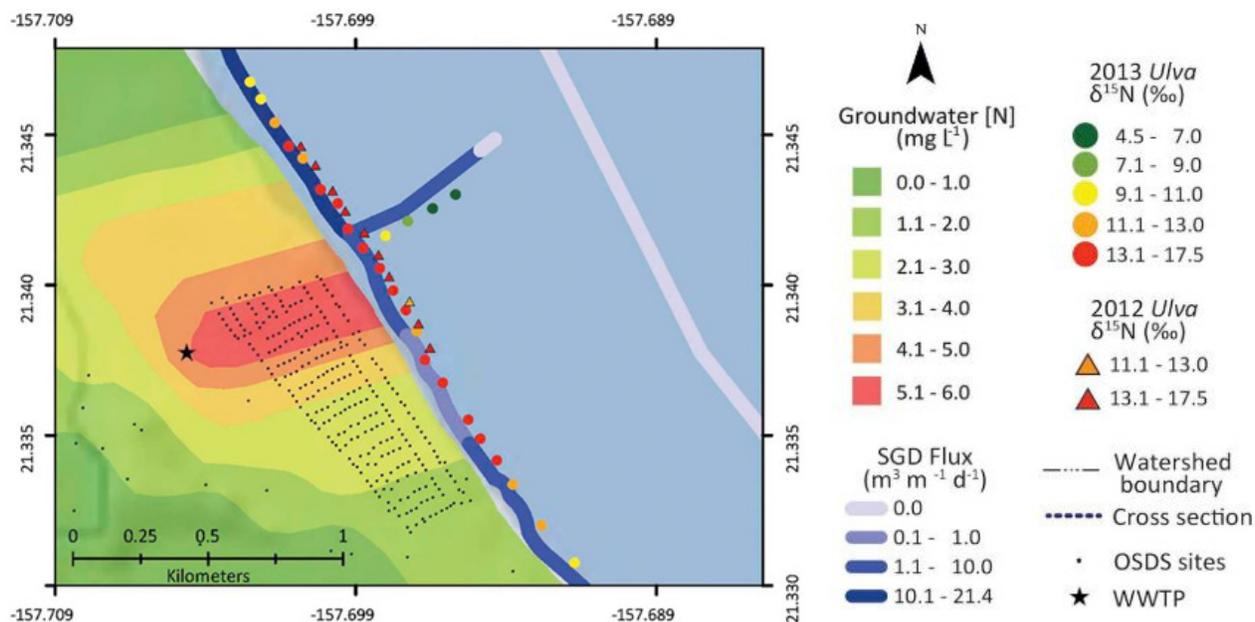


Figure 4. Map showing locations and values of *Ulva lactuca* tissue $\delta^{15}\text{N}$ in 2012 (triangles) and 2013 (circles), estimated groundwater nitrogen (polygons), submarine groundwater (SGD) flux estimates (blue band), onsite sewage disposal systems (black dots), and the Waimanālo Wastewater Treatment Plant (WWTP; black star) along a portion of the Waimanālo, O'ahu Island shoreline. Scales for $\delta^{15}\text{N}$ and SGD flux are nonlinear. These data support the use of both algal bioassays and groundwater nitrogen models as indicators of wastewater in the nearshore environment. With permission from Amato et al. (2020).

illness. However, many epidemiological studies have failed to find strong correlations between human health outcomes and FIB levels in subtropical waters (Fleming et al. 2006; Harwood et al. 2014).

Using typical and alternative FIB combined with molecular marker tests (which examine molecules within a sample to reveal specific source characteristics) may assist in more accurately identifying the presence of wastewater pollution (Kirs et al. 2016). Because enterococci are commonly found in the guts of mammals and birds and shed in feces, they have historically been used to estimate human health risks (Byappanahalli et al. 2012b). However, these bacteria are often found in high natural concentrations in Hawaiian soils, making it difficult to discern appropriate bacterial reference levels (Byappanahalli et al. 2012a). During heavy rainfall events, large amounts of sediment and other materials are suspended in water, rendering concentrations of *Enterococcus* in nearshore waters less indicative of exclusively 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. 2016, 2017). Fujioka (2001) suggests that *Clostridium perfringens* may be more appropriate to identify fecal contamination in Hawai'i's coastal marine waters. Furthermore, FIB presence does not always correlate with pathogen presence, i.e., FIB associated microbes may or may not cause or be associated with illness (Lund 1996; Bonadonna et al. 2002; Lemarchand and Lebaron 2003; Anderson et al. 2005; Harwood et al. 2005, 2014).

Alternative bacterial indicators can include *C. perfringens* and F⁺-specific coliphage and both have been suggested for use as water quality indicators in Hawai'i (Fujioka 2001; Fujioka and Byappanahalli 2003; Luther and Fujioka 2004; Viau et al. 2011; Kirs et al. 2017). Further research on the use of alternative wastewater pollution indicators to accurately predict human health risks is warranted. As bacteria are readily found in the environment, distinguishing among different sources (soils or animals) at an

appropriate location can be difficult (M. Kirs, personal communication). A newer method to trace microbes and identify specific pollution sources is 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 specific sources, such as leaching cesspools or farming activities, is critical to 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 Hawai'i 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 on MST should be continually monitored and evaluated for applicability, efficacy, and accuracy in identifying wastewater pollution sources in Hawai'i.

Certain types of *Bacteroides* can also be used as microbial markers to identify the presence of wastewater pollution (Betancourt and Fujioka 2006; Boehm et al. 2010). *Bacteroides* is a genus of 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. Boehm et al. (2010) found traces of human-associated *Bacteroides* in Hanalei Bay, Kauai, with putative sources nearby cesspools. Certain *Bacteroides* have also been documented in the Wai' Ōpae Tide Pools on Hawai'i Island following Tropical Storm Iselle and in Hilo Bay, Hawai'i (Wiegner and Mead 2009; Wiegner et al. 2017). However, human-associated *Bacteroides* and human viruses are imperfect indicators and can be difficult to detect, even in waters with known wastewater pollution (T. Wiegner and M. Kirs, personal communication). Sensitivity (only a certain percentage of humans may carry certain markers) and specificity (sources can be 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 identify sources (M. Kirs, personal communication).

An example of combining biologic methods for detecting and tracing wastewater pollution in Hawai'i was conducted 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 on O'ahu Island. Kirs et al. (2017) concluded using both enterococci and *C. perfringens* (typical and alternative indicator bacteria, respectively) simultaneously is well suited for Hawai'i 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. Additionally, Kirs et al. (2017) showed 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 (e.g., climate, land-use, etc.) and environmental degradation.

Emerging Wastewater Indicators. An indicator of anthropogenic pollution is the presence of synthetic chemicals or compounds such as those in personal care products (PCP), artificial sweeteners (AS) such as sucralose, and pharmaceuticals (including synthetic hormones) in water bodies. Research on these chemicals of emerging concern (CECs) found that pharmaceuticals, PCPs, and AS might be promising markers for detecting and identifying wastewater sources (Tran et al. 2014; Lim et al. 2017). These markers are persistent, not naturally produced in the environment, not entirely removed by wastewater treatment plants or OSDs, and tend to be relatively stable during transport (Lim et al. 2017). It remains highly challenging to accurately predict the extent of wastewater contamination using the methods developed for these chemical markers; no single chemical serves as a definitive marker for wastewater contamination for all sites accurately, due to lifespan, environmental interactions, and other factors. Enhanced understanding of land-use patterns, types and levels of contaminants in wastewater, and the fate and transport of CECs is needed to assist in the use

of suitable contaminate markers (Lim et al. 2017).

Several studies have investigated emerging indicators for wastewater pollution in Hawai'i. Knee et al. (2010) investigated caffeine as a wastewater tracer in SGD on the island of Kaua'i. Hunt (2014) identified multiple pharmaceuticals and other wastewater tracers, such as fabric brighteners, in groundwater discharge to Honokohau Harbor, Hawai'i Island, possibly linked to nearby wastewater effluent wells or pits. Recent advancements in analytical detection of CECs allows broader, more effective screening. These advancements prompted multiple studies in Hawai'i investigating anthropogenic indicators of wastewater pollution in streams and coastal springs (Dulai et al. in prep; McKenzie et al. 2017; H. Dulai, personal communication) and colleagues at the University of Hawai'i at Mānoa have targeted high-density cesspool areas and confirmed the presence and analyzed trends of compounds such as carbamazepine (anticonvulsant), caffeine (stimulant), ibuprofen (nonsteroidal anti-inflammatory), sulphamethoxazole (antibiotic), fluoroquinolones (antibiotic), and ethinylestradiol (estrogen medication) in streams and coastal springs of O'ahu Island and Hawai'i Island. These substances have been shown to have potential negative effects on ecosystems (Jobling et al. 1998; Lange et al. 2001; Shved et al. 2008; Pollack et al. 2009; Qiang et al. 2016). Anthropogenic compounds as pollution indicators appear promising and future studies will further inform with regard to potential applications in Hawai'i.

Distinguishing the origin of a wastewater indicator is critical for management and mitigation and remains an imperfect process. In some cases, there are tests which can provide insight to the human or animal origin of microorganisms or chemicals within wastewater (Sinton et al. 1998). For example, fecal steroids and caffeine have been used as accurate environmental tracers (Aufdenkampe et al. 2006). Combinations of indicators integrated with information such as land-use patterns and hydrologic and hydraulic modeling may be the most appropriate process to distinguish among various sources. Sinton et al. (1998) recommend a multivariate statistical approach, using the most appropriate chemical or microbial options for the site under evaluation. Emerging

DNA-based methods, such as environmental DNA (eDNA) and more information regarding baseline concentrations of microorganisms in varied environments will advance our confidence in identifying robust wastewater indicators.

Tracing Wastewater Pollution Pathways to Nearshore Waters.

Wastewater pollution has multiple pathways to enter the ocean, including point sources like discharge pipes and nonpoint sources such as surface water. Groundwater has the ability to deliver significant quantities of new and recycled terrestrial nutrients to various sources. Along with other natural or human sources, nutrient and chemical pollution can enter surface waters through groundwater connections (Dulai et al. 2016). Enhanced information regarding SGD is key to understanding water quality and coastal nutrient balance and fluxes. Studies by Richardson (2016), Amato et al. (2016), and Bishop et al. (2017) measured parameters of SGD, marine and groundwater quality, and compared land-use characteristics to better understand SGD nutrient transport. Critically, Bishop et al. (2017) were able to distinguish between agricultural and OSDS pollution sources on Maui Island and identified rates of nitrogen flux into the coastal zone. Isotope type testing and water age data can also support such investigations. By understanding nutrient levels and $\delta^{15}\text{N}$ within SGD fluxes, land-use patterns, and recharge data, research can examine the potential for nutrient loading within local aquifers; this in turn can inform risk evaluation and prioritization of practices to reduce pollution.

An established method to track and trace groundwater flow into coastal waters from SGD is the use of dye tracer tests, such as that performed by Abaya et al. (2018b) and Glenn et al. (2013). To track and estimate SGD parameters more comprehensively, multi-tracer approaches measuring salinity, temperature, silica, radon, radium isotopes, and temperature have also been employed (Dulai et al. 2016; Kelly et al. 2019; Taniguchi et al. 2019). Using anthropogenic indicators and methods such as those of Dulai et al. (2016) may provide the ability to track nutrient pathways to understand how and which water resources are impacted by pollution. Other SGD tracking methods include tracking fluorescent dissolved organic matter (fDOM) solutes (Nelson

et al. 2015). These fDOM 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. Critically, 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).

The connectivity between wastewater and adjacent waters in Hawai'i has also been investigated through examination of hydraulic and geochemical processes. Groundwater flow into coastal zones on Hawai'i Island has been measured using aerial infrared imaging (Johnson et al. 2008; Kelly et al. 2013). Such studies contribute to understanding how contaminants and nutrients move from OSDS to nearshore waters. Models incorporating datasets discussed above will enable watershed management and policy to be based on site-specific parameters. There are clear hydraulic connections among groundwater, SGD, and streams which signal the need for comprehensive watershed management practices including stricter control and inventory of nonpoint source pollution sources (Mathioudakis 2017). The authors believe a number of wastewater indicators and hydrologic tracers have a meaningful role to play in calibrating and validating wastewater modeling. Calibrated and validated models can be used to forecast aquifer and oceanic conditions and contamination to inform management decisions.

Water Resource Modeling/Monitoring/Risk Analysis

What Can Different Types of Models Tell Us? In general, models are simplifications of real-world systems and can provide generalized information about such systems under multiple scenarios as parameters are varied. Without site-specific data and the ability to track and trace pollution from a specific source, such as a cesspool, model results are only as robust 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. Because models can compare different scenarios (e.g.,

nutrient quantities and wastewater transit times from varying OSDS upgrade schemes), they are useful for natural resource managers and policy makers to compare management plans.

Various models, including empirical and physically-based models, can either be deterministic or statistical in nature. Deterministic models predict the contaminant levels at a particular time and location. Statistical models use parameter statistics to predict expected values or the probability of the occurrence of an outcome. For example, a statistical model would predict *how likely* the concentration of a contaminant would exceed a certain value at a particular time and location. Empirical models, 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), originally developed by Mink (1981) for the determination of sustainable yield of Hawai'i 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 analysis of a problem (e.g., controlling for water flow and chemical transport). The area of interest is divided into individual cells and the variable of interest (e.g., 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. Because 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 instances, higher resolutions approaching tens of meters are needed. These include density dependent problems or areas, including nearshore sites where saltwater and freshwater interact. Although the models permit variations of parameters on the cell scale, the authors recognize that limited data presently

restrict use to lower resolution regional or aquifer-size values.

Using the Appropriate Model Can Assist Policy Makers. Regional or large-scale models can provide useful information to track OSDS pollution versus other pollution sources. Models that evaluate annual rates of sediment load, which can impact offshore environments, particularly coral reefs, may be useful in determining pollution sources and impacts (Ogston and Field 2010; Erftemeijer et al. 2012). Regional results can guide future data collection and stimulate needed research or analyses in localized areas, but may not be optimal for statewide policy creation. Models to better assist in crafting a comprehensive statewide cesspool conversion plan include a 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 (2019). The model used input data consisting of estimated nitrogen flux from each state Tax Map Key parcel with an OSDS. Total nutrient export to the ocean was then calculated. This model is particularly

useful as it encompassed the entire state of Hawai'i and modeled broad inputs/impacts to the coastal zone across all watersheds (Figure 5).

On a smaller geographic 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, OSDS, and other human-development, using a delivery ratio-based empirical model that was calibrated and customized specifically for Hawai'i. Results were then estimated for coastal waters of Maui Nui, Maui Island and West Hawai'i, Hawai'i Island following Lecky (2016). Although input data were similar to Lecky (2016), InVEST NDR was unique as it included all potential nutrient sources to the coastal zone, critical for determining priority mitigation actions. Estimated percentages of nutrients originating from OSDS, wastewater treatment plants, agriculture, and golf courses were calculated; this allows managers to better understand the proportion of nitrogen input specifically due to OSDS and cesspools versus other sources.

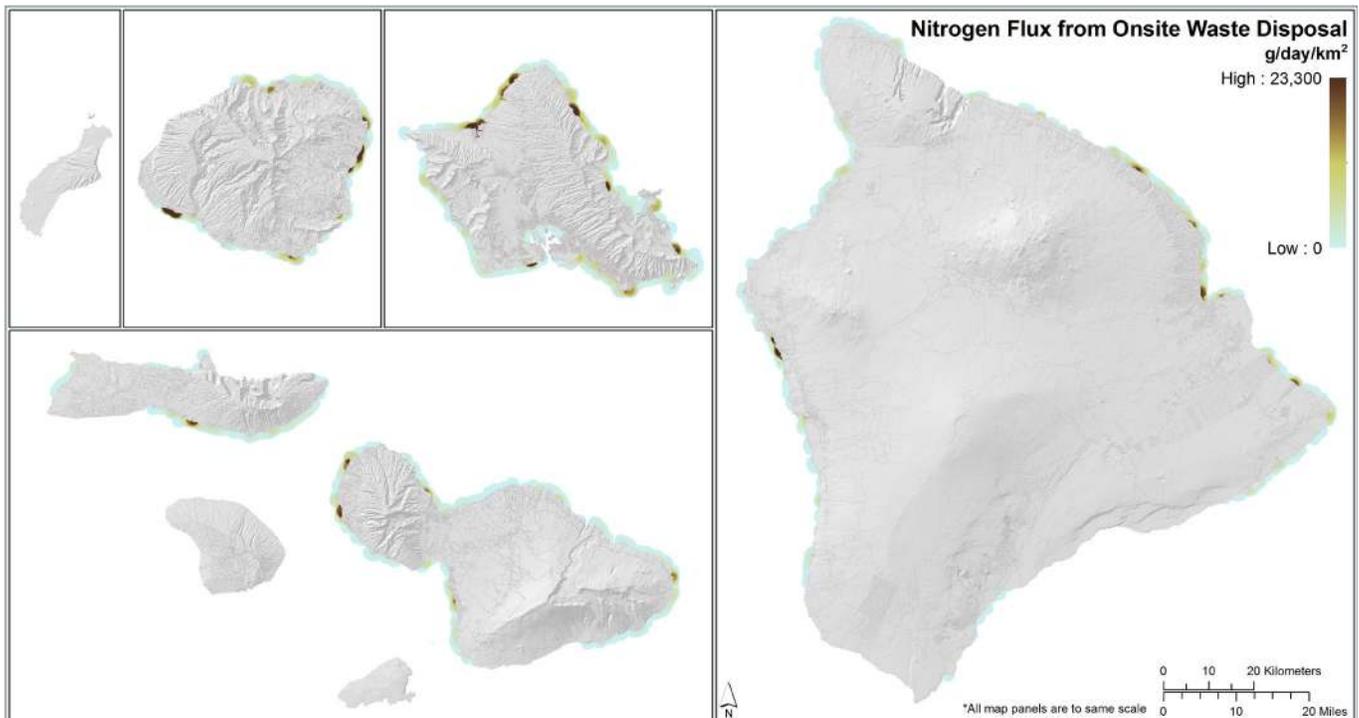


Figure 5. Map of the main Hawaiian Islands illustrating the nitrogen flux (gallons/day/km²) from onsite waste disposal systems (cesspools and septic tanks) located within 1.5 km of the coastline. Darker areas indicate more nutrients from sewage entering nearshore waters as evidenced by greater nitrogen flux. With permission from Lecky (2016).

The U.S. Geological Survey suite of models are commonly 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.

The U.S. Geological Survey 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 (Whittier et al. 2010; Pollock 2016). The package also includes MT3DMS, which was combined with MODPATH to assess potential OSDS contamination in Hawai'i (Whittier and El-Kadi 2009, 2014). MT3DMS differs from MODPATH by including transport dynamics caused by the dispersion phenomenon (Zheng 2010); thus, MT3DMS can better represent the dispersion of a chemical in pores or fractures of an aquifer due to variations in available pathways and velocities which is important for Hawai'i's unique geology. MODFLOW used alone has limitations in addressing density dependent flows by only simulating freshwater movement, which is less buoyant than saltwater. Other limitations, as perceived by the authors, of MODFLOW relevant to OSDS pollution are:

1. estimating dynamics and circulation of water and chemicals in the saltwater-freshwater zone;
2. 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;
3. estimating groundwater sustainability due to saltwater influxes;
4. properly calculating salinity measurements and water flow to provide accurate parameters for assessing chemical transport;
5. incorporating the ability to predict the effect

of sea level rise and expected increase saltwater intrusion to aquifers, and;

6. 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 freshwater and saltwater mixing zones. Model outputs include water levels, chemical concentrations, and most importantly, salinity distributions. An application of SEAWAT in Hawai'i was introduced by El-Kadi et al. (2014) in a study that dealt with sustainability of groundwater resources. Management scenarios assessed sustainability of aquifer use, establishing limits for declines in water levels and spring flows and increases in salinity. More precise and accurate management of nearshore aquifers can be expected when including variables such as salinity impacts, particularly when moving towards an integrated "one water" approach for water management.

Once groundwater or surface water enters nearshore waters, different types of models are used to predict its fate. Due to the complexity of systems, predictive and empirical models are not often used for these scenarios. Numerical models are more suited to estimate particle pathways and mixing dynamics of substances. Groundwater and oceanographic models are typically run as separate systems because of the uncertainties in both systems. In Hawai'i, a combination of modeling and monitoring efforts has been used including a biophysical model in Maunaloa Bay on O'ahu Island to connect ocean dynamics with coral reef health (Wolanski et al. 2009). Tomlinson et al. (2011) and Ostrander et al. (2007) focused on using ocean observing data from buoys in Kane'ohe Bay, O'ahu Island and water quality sampling to map runoff plumes; they determined storm events can lead to plumes persisting in the bay for up to 48 hours. Connolly et al. (1999) created mathematical models to understand contributions of wastewater outfalls and shoreline sources of organisms in Mamala Bay, O'ahu Island. 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 with high cesspool densities and sensitive resources that can be negatively impacted by wastewater pollution, such as coral reefs.

An additional example of the effective use of a model is the nutrient transport/loading model created by Shuler and Comeros-Raynal (2019) for the island of Tutuila, American Samoa. This model classified coastal areas for pollution management using levels of dissolved inorganic nitrogen (DIN) loads from surface and groundwater discharge. The model determined DIN loading rates for every watershed on the island (Shuler and Comeros-Raynal 2019). Further data refinement allowed the ranking of impacts to each watershed. Hawai'i could benefit from the development of a prioritization model similar to that of Shuler and Comeros-Raynal (2019).

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 OSDS in Hawai'i. One study estimated nearly 10 mgd of sewage is released into the environment, with much reaching groundwater (Whittier and El-Kadi 2009). Cesspools comprised about 77 % of the total estimated release of untreated effluent and 96 % of potential nitrogen release. Groundwater models in certain areas estimated nitrate concentrations could reach a maximum level of 11 mg/L above background, exceeding the U.S. EPA maximum contaminant levels of 10 mg/L (U.S. EPA 2019b). Because soil is the primary treatment mechanism for OSDS, soil conditions and slope may be a limiting factor determining levels of effluent treatment, even in areas with a low density of OSDS. Whitter and El-Kadi (2009) recommend a vertical distance between ground surface and groundwater of at least 25 feet (7.62 m) for proper treatment of effluent by the soil; *however, many areas in Hawai'i fail to meet this condition.*

Using source-water protection assessments (e.g., Whittier et al. 2010) can provide the state with data on source-water susceptibility to contamination and inform a decision-making model to develop 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 available (Whittier et al. 2010). However, the model did not include flow in the unsaturated zone, chemical reactions, or chemical dispersion data (Whittier et al. 2010). Additional studies yielding such data are needed to improve modeling due to Hawai'i's unique geology and hydrology.

Achieving 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 the value of a dependent variable. The model was applied to the Pearl Harbor and Honolulu aquifers on O'ahu Island. 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). Such models can assist in areas with limited 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 multiple 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).

Models can also assist in identifying infrastructure vulnerabilities and informing long-term planning efforts. A model by Habel et al. (2017) simulates sea-level rise induced narrowing of the unsaturated space (treatment zone) between OSDS and groundwater. Results revealed 86 % of 259 active OSDS in the study area on O'ahu Island are likely inundated by groundwater at present. Simulations considering nearly one meter of sea-

level rise show the percentage of likely inundated OSDS increased to 91 %, 39 of which are flooded to the ground surface. Locations of OSDS and whether they meet minimum requirements under 98 cm of sea-level rise are shown in Figure 6. 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 OSDS or predict potential failures.

Addressing Difficulties of Modeling Hawaiian Islands Aquifers. As noted previously, surface water transport of contaminants can be a significant contributor to ocean contamination. For example,

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 59 % of pollution came from surface sources while 41 % were subsurface contributions (Welch et al. 2019). The authors believe that an integrated surface-subsurface modeling approach might be necessary in Hawai‘i. However, such efforts are complicated due to the synergy of processes in the two systems and disparity of water travel times; as such, a simplified approach is usually adopted. Such an approach typically involves simplifying parameters of a single system. For example, groundwater modelers can treat streams as drains receiving water from the aquifer without details regarding surface water

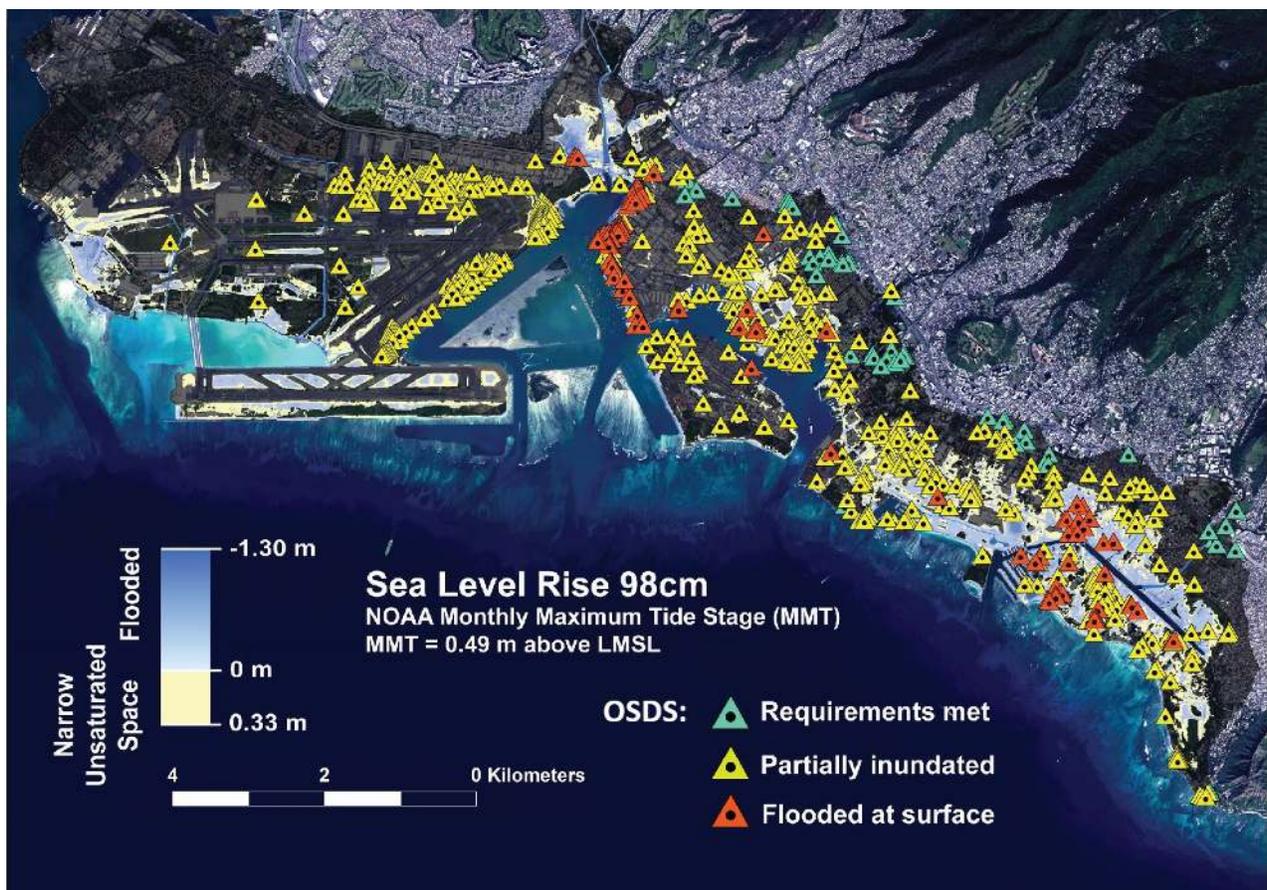


Figure 6. A simulation of groundwater inundation (blue) and narrow unsaturated space (pale yellow) for the greater Honolulu, Hawai‘i area representing 0.98 m of sea-level rise for a tide height representing the average monthly maximum tide measured at the Honolulu tide gauge. The known onsite sewage disposal systems (OSDS) in the area are represented by triangles. The color of the OSDS triangles indicate the potential vulnerabilities of the infrastructure. With permission from S. Habel (2017).

flow or transport processes. Another approach would be utilization of 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 U.S. Geological Survey GSFLOW model (Markstrom et al. 2008), which integrates the U.S. Geological Survey 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 Hawai'i, concern exists regarding a lack of efforts to integrate surface and subsurface modeling. There is a material 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 (Gassman et al. 2007; Food and Agriculture Organization 2019). However, SWAT does not include a detailed subsurface water flow component; to overcome this limitation, SWAT can be coupled with MODFLOW (Bailey et al. 2016).

Models currently exist for larger, statewide scales to assist in the prioritization of cesspool upgrades, including those in Lecky (2016) and Falinski (2016), and may be sufficient to assist in the creation of a cesspool prioritization plan. Nonetheless, such modeling will continue to benefit from additional data to better understand these complex systems. Possible sources of future data may include citizen science efforts, traditional and indigenous knowledge, and other sources. Njue et al. (2019) and Falinski et al. (2019) show 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 Hawai'i, groups such as *Hui O Ka Wai Ola* on Maui Island are demonstrating the usefulness and potential of citizen scientists. This organization established strict sampling

protocols and data quality control measures prior to delivery of collected data to the state of Hawai'i Department of Health. Other citizen science groups include the *Surfrider Blue Water Task Force* with greater than 70 water quality sampling sites statewide. The above notwithstanding, citizen scientists may not have access to groundwater wells or other locations where data collection is needed. Citizen scientists may also struggle to identify which data are important for models and why. Therefore, we suggest that researchers may wish to incorporate the use of evolving technology, such as smartphones, which can potentially decrease sampling complexity and costs, or partner with experts and students to train citizen scientist volunteers.

Hawai'i Modeling Data Gaps. Limited data have hindered efforts to model OSDS hydrology and pollution in Hawai'i. For example, a model developed by Whittier and El-Kadi (2009; 2014) used available OSDS data from the University of Hawai'i and State of Hawai'i Department of Health; however, data on OSDS location, capacity, and leaching rates were limited. Additionally, hydrogeological parameters, such as hydraulic conductivity and porosity were estimated based on available water-level data, which were scarce. Due to these limitations, the model's results require critical evaluation and conservative interpretation (Whittier and El-Kadi 2009; Barnes et al. 2019). In fact, Barnes et al. (2019) found nearly 90 % of cesspools in West Maui were converted to sewer or septic between 2007 and 2017, an important distinction when estimating pollution from these specific sources. Any long-term cesspool conversion plans for other areas in the state would benefit from an updated OSDS inventory coupled with wastewater modeling efforts using field data such as algal bioassays and hydrogeophysical methods (Amato et al. 2020). The most comprehensive OSDS inventory review in Hawai'i was conducted in 2009 for O'ahu Island and in 2014 for the remaining main Hawaiian Islands (Whittier and El-Kadi 2009, 2014).

Obtaining additional parameters of each OSDS, such as leach field size, installation location, depth to groundwater, soil parameters, and tank size may be useful to modelers, other researchers, and

government and resource managers. Coupling OSDS information with updated census data or a “person to bedroom” ratio may also yield more information on how OSDS are being used in real-world conditions (i.e., within or outside of permit and design specifications) and potential risks to nearby water resources (Amato et al. 2020).

Detailed hydrogeologic information, such as hydraulic conductivity, recharge rates, and soil type are critical for accurate site assessment and model prediction accuracy. For example, hydraulic conductivity, which is a measure of the ease with which water flows through sediments or rocks, is an important parameter 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 Hawai‘i 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 under development by the University of Hawai‘i Water Resources Research Center. These efforts aim to provide three-dimensional images of the subsurface over large areas to better understand the distribution, properties, and flow of subsurface fluids. Such information allows data-driven interpolation between wells and provides more robust data for model input.

The authors recognize that aquifer parameters and surface/subsurface soil properties are key factors that control water movement and chemical leaching to the underlying aquifer which are useful to modelers. Currently, soil maps and soil type information are maintained by the U.S. Department of Agriculture Natural Resource Conservation Service. Most maps in Hawai‘i have not been updated since the 1960s and 1970s. The filtering characteristics of soil are relevant for OSDS design, function, water movement (that controls recharge), and nutrient and pathogen transport.

Model reliability can also be compromised by the failure to accurately represent Hawaiian volcanic geology, including subsurface distinguishing irregularities (such as lava tubes). Simulated effects of a lava tube on the transport of

a time-limited injection in a synthetic hillslope is shown in Figure 7. Rather than a typical transport plume, a highly variable and fast-spreading plume results from the presence of the lava tube (A. El-Kadi, unpublished data). Such features can transport or disperse pollution in alternate patterns, creating difficulties in tracking. Modeling that allows for the consideration of discrete fractures within porous material is needed; the existence of large fractures or openings may invalidate current approaches.

While improved assessments of contaminant distribution and transport times are critical for supporting decision-making processes or management of water resources near cesspools, data 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 might include the use of geophysical techniques such as active and ambient noise seismics, electrical resistivity tomography, self-potential, gravity, and magnetotellurics (N. Grobbe, personal communication).

Lastly, the authors recognize an important, but sometimes overlooked, input to both hydrologic and oceanographic models is weather data. Hawai‘i has varying topography and a narrow coastal plain, which can aid in quickly flushing water from the mountains to the ocean. Because of this topography and geography, rainfall amounts vary widely across individual islands and the archipelago. Researchers at the University of Hawai‘i at Mānoa are actively improving the state’s rain gauge network, aiming to provide long-term hourly precipitation datasets in multiple locations within watersheds. These data can improve model accuracy and predictions, as well as monitor long-term climate trends. Similarly, wind and tidal data are important for oceanographic models, though tide stations are not always located near sites being modeled. Instruments and monitoring stations can be deployed in areas of interest, though collection of robust datasets takes time as well as the financial and human resources to monitor and maintain data collection sites.

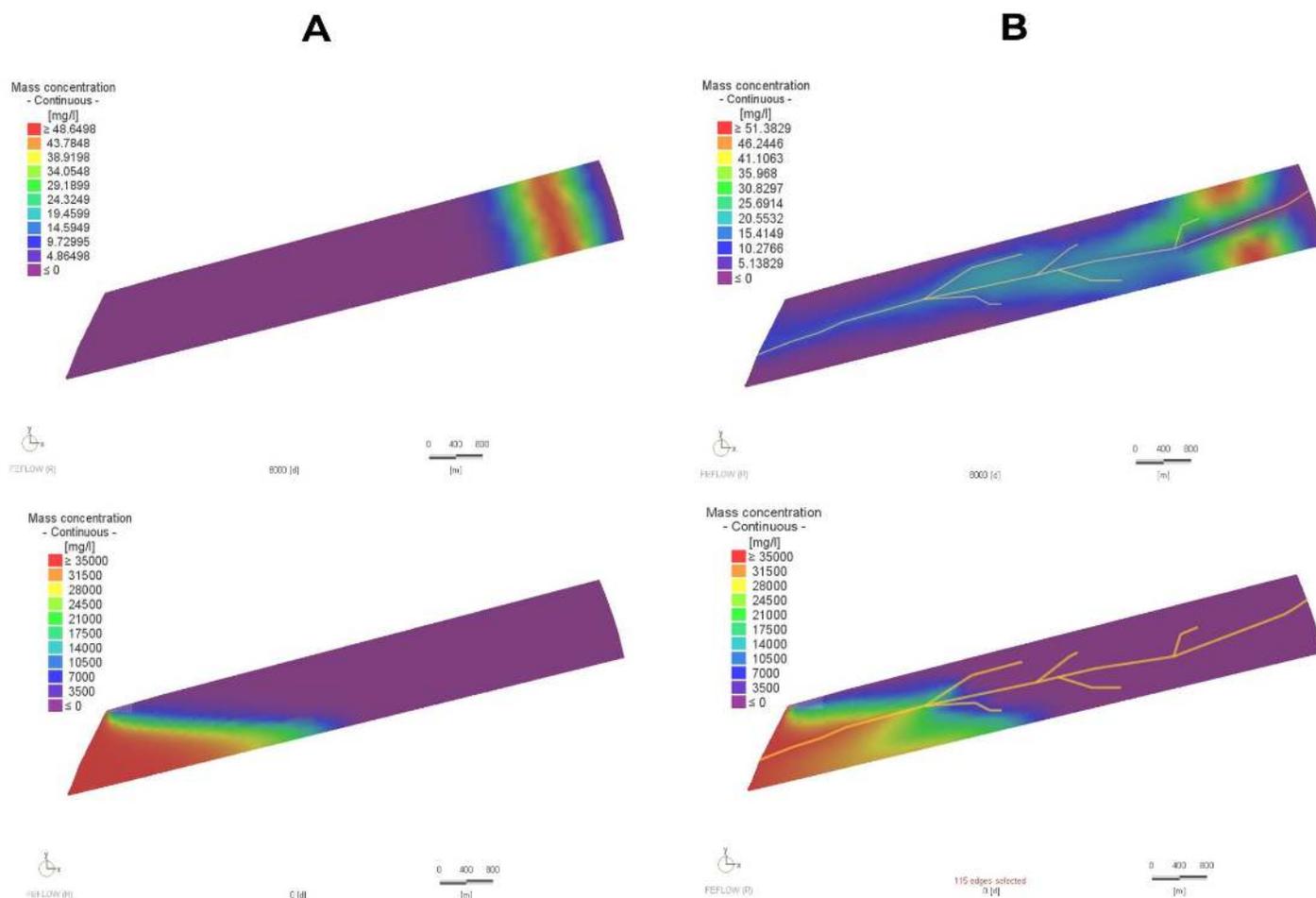


Figure 7. Simulated effect of the absence (A) and presence (B) of a subsurface lava tube (white line) on the transport of a limited-time pollutant injection in a hillslope (upper panels) and salinity distribution (lower panels). The presence of the lava tube in (B) results in an atypical transport plume in the upper right panel and atypical salinity distribution in lower right panel. Source: A. El-Kadi (unpublished data).

In summary, the authors believe that an understanding and assessment of the transport and fate of contaminants in groundwater and ocean waters are critical to achieving state of Hawai'i water quality goals. Models at different spatial scales—including statewide or aquifer only—may be useful to inform the prioritization of management actions or create science-based OSDS conversion timelines. Models can be limited by a weak understanding of certain processes, such as groundwater and surface water interactions, preferential flows, and contaminant interactions between bedrock, soil, and other compounds (Cornell University N.D.). Critically, the quality of all model results is determined by the veracity and volume and data available for model input.

Policy and Community Engagement

What is Our Capacity to Monitor and Maintain Onsite Sewage Disposal Systems (OSDS)?

Failing OSDS may pose a significant threat to the environment and ensuring the state's capacity—financial, personnel, and regulatory—to monitor OSDS operation and installation will be essential to protecting human health and water resources. In Hawai'i, nearly one of every three OSDS were classified as deficient and in need of immediate repairs or maintenance to address problems (Babcock et al. 2014). Despite caveats of the Babcock et al. (2014) study, such as small sample size, their results suggest Hawai'i's wastewater challenges are widespread. Failing OSDS are not

unique to Hawai‘i. The U.S. EPA (2005) estimates at least 10 % of the nation’s OSDS are not functioning properly due to such factors as poor maintenance, lack of knowledge, or financial challenges. Addressing poor maintenance schedules and modeling system failure risk are possible. Recent model results from Kohler et al. (2016) suggest mandatory inspections through renewable permits can reduce life cycle repair, failure frequency, and severity of failure, ultimately reducing OSDS costs

to owners and potentially reducing environmental impacts.

A recent policy gap analysis by Spirandelli et al. (2019) reinforces conclusions by Kohler et al. (2016) by detailing several deficiencies when analyzing the state of Hawai‘i’s ability to implement recommendations in various U.S. EPA models (Table 1). Hawai‘i’s current policies and procedures were deficient in the following areas: alignment between land-use and watershed-

Table 1. United States Environmental Protection Agency onsite wastewater treatment systems (OWTS) management models. Adapted from U.S. EPA (2003).

Model	Description
1. Homeowner Awareness Model	Specifies appropriate program elements and activities where treatment systems are owned and operated by individual property owners in areas of low environmental sensitivity. This program is adequate where treatment technologies are limited to conventional systems that require little owner attention. To help ensure that timely maintenance is performed, the regulatory authority mails maintenance reminders to owners at appropriate intervals.
2. Maintenance Contract Model	Specifies program elements and activities where more complex designs are employed to enhance the capacity of conventional systems to accept and treat wastewater. Because of treatment complexity, contracts with qualified technicians are needed to ensure proper and timely maintenance.
3. Operating Permit Model	Specifies program elements and activities where sustained performance of treatment systems is critical to protect public health and water quality. Limited-term operating permits are issued to the owner and are renewable for another term if the owner demonstrates that the system is in compliance with the terms and conditions of the permit. Performance-based designs may be incorporated into programs with management controls at this level.
4. Responsible Management Entity (RME) Operations and Maintenance Model	Specifies program elements and activities where frequent and highly reliable operation and maintenance of decentralized systems is required to ensure water resource protection in sensitive environments. Under this model, the operating permit is issued to an RME instead of the property owner to provide the needed assurance that the appropriate maintenance is performed.
5. Responsible Management Entity (RME) Ownership Model	Specifies that program elements and activities for treatment systems are owned, operated, and maintained by the RME, which absolves the property owner from system responsibility. This program is analogous to central sewerage and provides the greatest assurance of system performance in the most sensitive of environments.

based planning; performance goals; inventory of systems; public outreach; homeowner education; and mechanisms that ensure regular upkeep and maintenance of OSDS (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 OSDS, as well as reactions by the public and government offices of various management options at either the state or local level. OSDS upgrade programs and their success or failure may hinge on addressing the policy gaps identified by Spirandelli et al. (2019).

Hawai'i may also benefit by evaluating programs and outreach methods conducted by the Cape Cod Commission in its most recent 208 Plan Update to address nutrient pollution (Cape Cod Commission 2017). The project used a watershed-based focus on both stakeholder engagement and technical evaluation. This focus sought to maximize the benefits of local planning, traditional and nontraditional strategies, and allowed local stakeholders to decide which range of options to pursue rather than mandating a single solution (Cape Cod Commission 2017). By creating an outreach plan which utilizes facilitated discussion of values, needs, and solutions with stakeholders on a watershed basis, a greater understanding of community knowledge, attitudes, and behaviors can be achieved.

To proceed in addressing the gaps identified by Spirandelli et al. (2019), further research, as well as legislative updates are needed. The state may wish to evaluate actions that can be undertaken now, such as legislation or streamlining internal processes that permit technologies used in other states (i.e., composting toilets, drip irrigation leach fields, or gray water recycling in homes) (Babcock et al. 2019; Mezzacapo 2019). Furthermore, the creation of groundwater quality/threshold criteria by the state of Hawai'i Department of Health is needed to evaluate and measure pollution, guide decision-makers, and engage and inform residents (Babcock et al. 2019).

Understanding Community Behaviors and Engaging Stakeholders to Achieve Success. Increasing knowledge of OSDS issues among homeowners, regulators, and the public will likely

lead to better maintenance and awareness of the wastewater disposal problems in Hawai'i. Babcock et al. (2014) highlight that homeowners were generally interested in how their OSDS function, how to maintain them, and what indicators might lead to future problems or failures. A foundational step in addressing concerns regarding OSDS operations, however, is the development of a georeferenced database inventory of all OSDS within the state (Spirandelli et al. 2019). Such a database should include details about installation date, maintenance schedules, engineering documents, and other key attributes. Additionally, Babcock et al. (2014) recommend a statewide OSDS management program to address OSDS failures and the likely future increase in failures of the remaining neglected systems. The U.S. EPA Operating Permit Model option in Table 1 would create a framework to improve the current conditions highlighted by Babcock et al. (2014).

A survey, such as that in Lamichhane and Babcock (2013), may inform the state and associated regulators regarding which technologies are accepted by certain consumers and how to improve consumer attitudes. Some citizens in Hawai'i had positive attitudes towards urine diverting toilets and human waste recycling (Lamichhane and Babcock 2013). Therefore, conducting additional surveys and data collection could assist in customizing professional outreach to targeted groups, with the aim of ultimately changing behavior toward OSDS, mitigating environmental impacts, and achieving greater compliance of OSDS best practices. Updating data regarding existing OSDS type, location, and critical system characteristics such as maintenance and permitting will be crucial for diagnosing pollution threats and directing meaningful management actions (Barnes et al. 2019). The sharing and leveraging of appropriate data, planning documents, capital, and human resources by state and county governments and departments will support achievement of the overarching goal of Act 125, to protect the state of Hawai'i's water resources and human and ecosystem health.

Due to limited human and capital resources, large and diverse geographic areas, and diverse stakeholder viewpoints in Hawai'i, it may be worthwhile to explore the creation of a watershed

management framework, similar to an approach taken by the state of Minnesota to comprehensively assist with land-based pollution reduction (State of Minnesota 2014). Such “one water” programs efficiently manage all aspects of nutrient reduction to water resources and clearly articulate roles and responsibilities of stakeholders and other entities.

Furthermore, we propose 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 OSDS challenges. It would likely be advantageous for the state to explore partnering with such organizations in conducting professional outreach when establishing and implementing a long-range OSDS management plan.

Behavioral Change is Difficult. Creating behavior change is difficult. For this example, a 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, 240). Many factors shape our individual perceptions, decisions, and ultimately actions. Previous linear progression models of understanding pro-environmental behavior failed to capture the complexity in humans and societies (Kollmuss and Agyeman 2002). 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; Kollmuss and Agyeman 2002), though many organizations and governments still use this approach. Historically, ideas and hypotheses 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; Kollmuss and Agyeman 2002, 247). Additionally, the power to drive environmental change and achieve action on an issue is often unevenly distributed amongst society. Individuals’ values are “negotiated, transitory, and sometimes contradictory” (Redclift and Benton 1994; Blake 1999, 7; Kollmuss and Agyeman 2002).

One model available to better understand the status of, or solicit, pro-environmental behavior is by Kollmuss and Agyeman (2002) and shown in Figure 8. Kollmuss and Agyeman (2002) recognize the model is incomplete 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, 256). Such innovative models that establish and capture non-traditional parameters may prove critical in successful outreach on OSDS and other pressing environmental issues.

The state of Hawai‘i and others that may organize and execute an outreach plan may employ such models and integrate social science research and behavioral economics to optimize the efficacy of outreach and education efforts. Social and psychological scientists can assist with the formation of effective community-based messaging, “marketing,” and outreach strategies to drive sustainable behavioral change (McKenzie-Mohr 2011). Such behavior change will be required to achieve successful widespread cesspool conversions and resulting improvements in water quality and human health.

What Frameworks Can Assist in Outreach, Decision-making, and Solutions? Future monitoring and research will help evaluate if cesspool upgrades will have the positive ecological impact desired. Water quality and coral reef health hinge on several overlapping issues, some global and some local, of which wastewater pollution is one. We believe the relationships among wastewater management, human health, and coral reef health are complicated, indirect, and difficult to research. For example, 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. 2017; Barnes et al. 2019). However, simply focusing on one variable in a system misses the

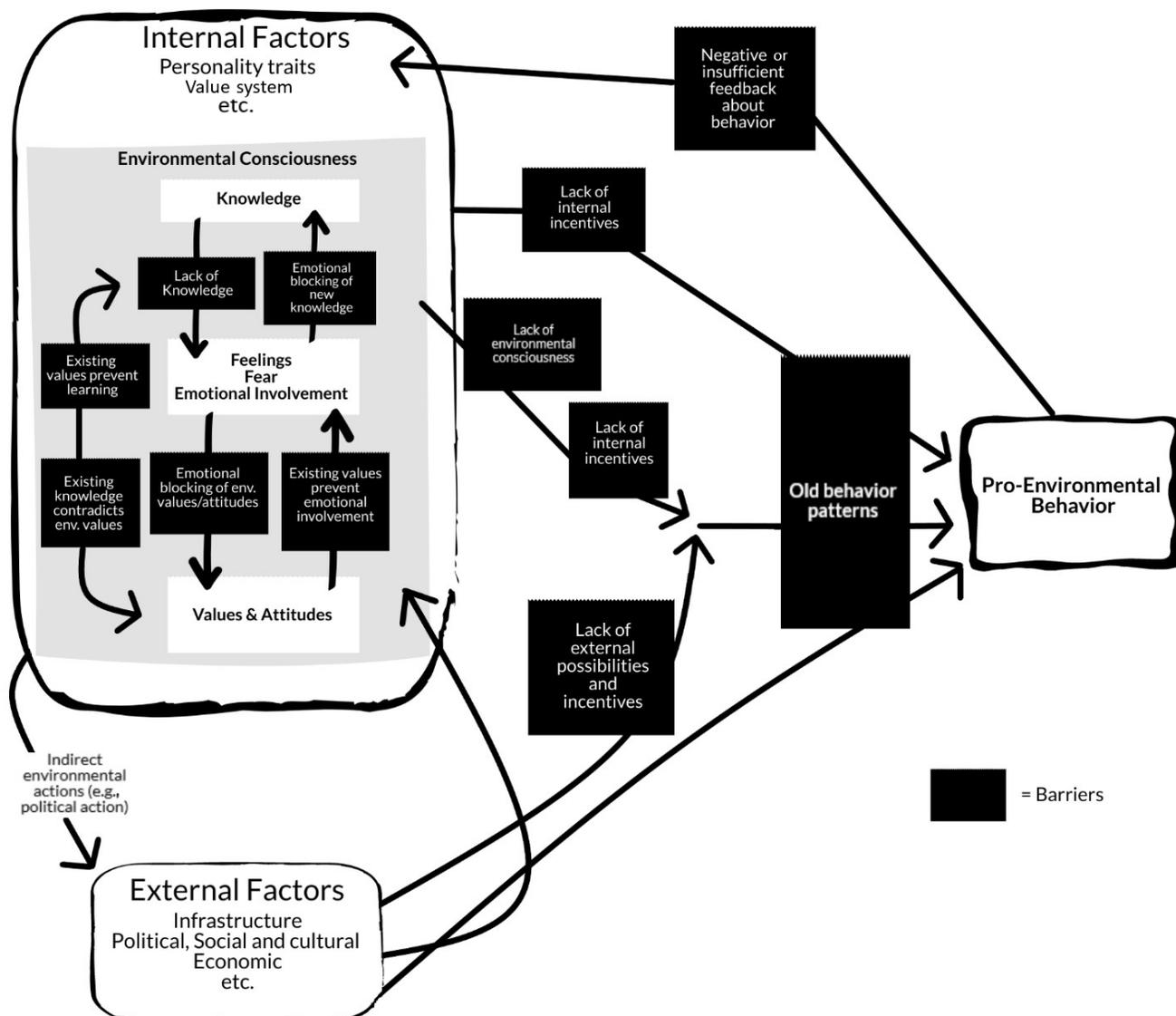


Figure 8. Model of pro-environmental behavior. Source: Adapted from Kollmuss and Agyeman (2002).

interconnected nature of systems as well as 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 and engagement about the linkage between health (ecosystem and human) and cesspools may be important to gain compliance to upgrade requirements in Act 125. Employing methods such as those in the West Hawai'i Integrated Ecosystem Assessment, which provides a framework to help track changes in key social-ecological processes, can better inform

policy makers, and direct tailored outreach and education activities. Such frameworks may include ecological, climate, ocean, and social indicators (Gove et al. 2019).

Policy makers 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 cesspool replacement while balancing multiple stakeholder objectives. 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 decision-making process, ultimately enhancing the effectiveness, efficiency, and equity within ecosystem-based management.

Other potential frameworks include a structured decision-making (SDM) process which was evaluated by Babcock et al. (2019) on upcountry Maui Island. The SDM process, highlighted in Figure 9, 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, 4). This process uses a set of concepts and steps rather than a rigid prescriptive approach (USGS N.D). Babcock et al. (2019) used this type of approach to determine how alternative management practices may influence groundwater nutrients, costs, and where the most benefits would be realized to satisfy

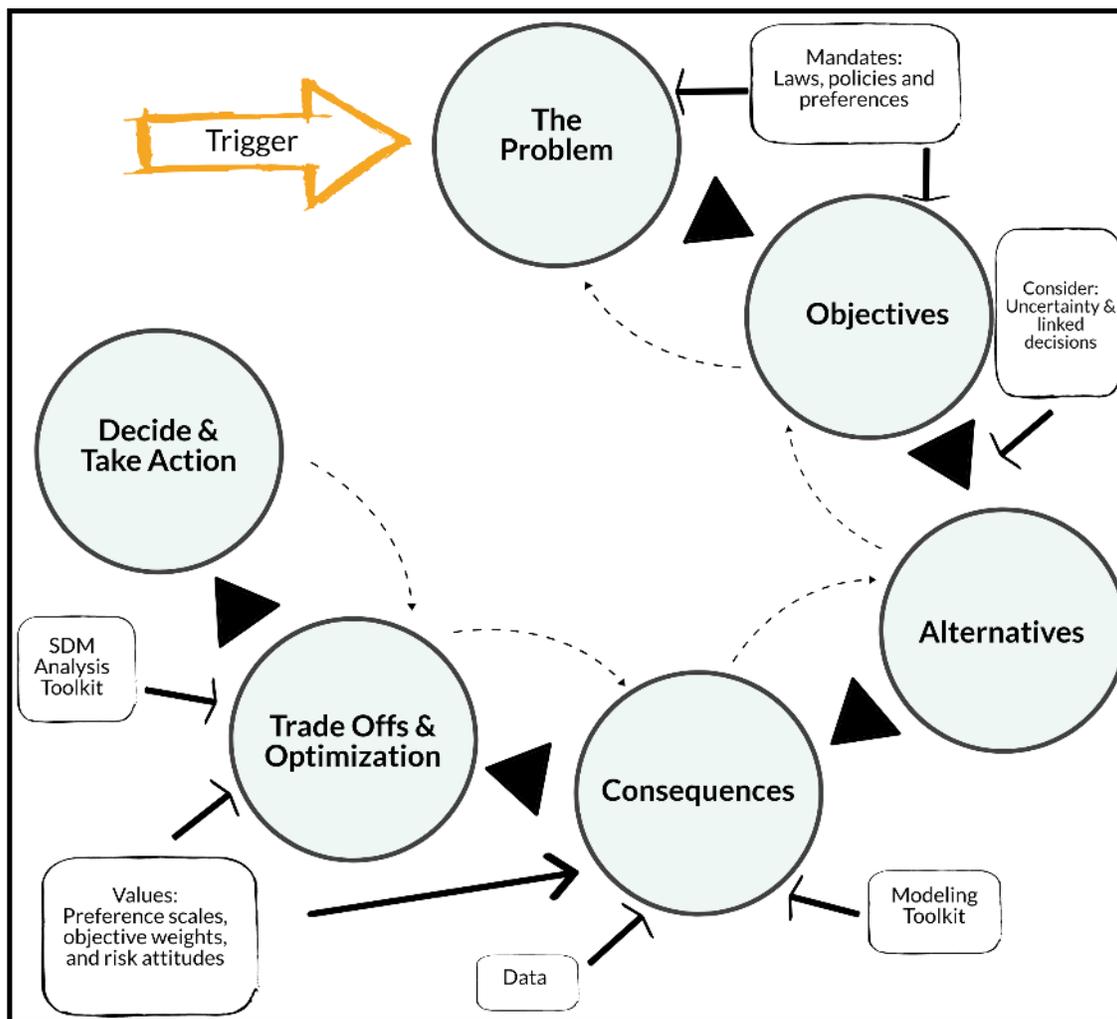


Figure 9. Structured decision analysis method diagram (SDM). A decision analysis process that “triggers” priority areas impacted by wastewater pollution from onsite sewage disposal systems (OSDS) may also be relevant and advantageous for the state of Hawai‘i to identify pollution mitigation strategies in a cost-effective manner. The tools of the SDM toolkit descend from the decision science field. Examples of SDM tools include: Influence Diagrams (graphical representation of relationships); Value Trees (highlight how objectives are linked to sub-objectives and performance metrics); and Value Models (a scale that weights and combines different impacts into a single score). Modeling Toolkits may include computer applications to model consequences linked to actions. Adapted from: 4th Joint Government Water Conference, Babcock et al. (2019).

regulations/objectives and social goals (Babcock et al. 2019). Babcock et al. (2019) report the process achieved the following: identified a suite of cesspool replacement options; developed a range of management alternatives to upgrade cesspools that incorporate feasibility; analyzed the environmental benefit of each alternative; enumerated costs of the alternatives; and provided recommendations on the alternatives relative to cost, environmental benefit, and stakeholder-identified objectives. It then recommends a participatory and SDM process to find solutions to challenging environmental problems; problems that are difficult or impossible to solve because of incomplete, contradictory, or changing requirements (Babcock et al. 2019). Such an approach could be applied to other areas in the Hawaiian Islands or other insular communities (geographic or socioeconomic) facing similar wastewater challenges.

A decision analysis process that targets priority areas impacted by wastewater pollution from OSDS may also be relevant and advantageous for the state of Hawai'i to identify pollution mitigation strategies in a cost-effective manner (Figure 9; Barnes et al. 2019). Key points 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 (lesser benefit) and high cost (greater benefit) strategies; and decision science, when used appropriately, can be a transparent, accessible, and useful tool to manage ecosystem health and pollution drivers. Proper decision analysis structure parallels well with the state of Hawai'i's "30 by 30" initiative to protect coastal areas and ecosystems 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).

Previous work by Whittier and El-Kadi (2014) also provides a useful framework to calculate risk by categorizing the threats a cesspool or OSDS may pose to an ecosystem and human health. The risk score was then displayed spatially on global

information system (GIS) rectified maps and considered such factors as the proximity of OSDS to an area that may be harmed by wastewater pollution; the ability of the soil to transmit or treat OSDS effluent; the 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 for a more comprehensive and practical approach to OSDS. Although Whittier and El-Kadi (2014) stressed that a field study is necessary to confirm model results and determine the degree to which groundwater is being degraded by OSDS, the utility of the expansion and update of such a scoring mechanism is inarguable.

Conclusions

- Cesspools, and other OSDS, especially those that are poorly maintained or malfunctioning, have been shown to negatively impact water resource quality and coral reef and human health.
- The continuation of large-scale, state-wide sampling of multiple sewage pollution indicators may help inform a decision-making framework and improve existing water resource model accuracy; future studies should include long-term sampling to capture temporal patterns of sewage pollution as well as diminishing patterns of nutrient loading predicted in regions with high rates of cesspool conversions.
- Although not required by state or federal regulations, widespread testing of private drinking water wells in areas where large numbers of cesspools are in use could provide the state with vital data on groundwater quality, improve human health risk assessments, and inform permitting requirements.
- Development of an approach similar to the Great Lakes AOC program for marine environments is recommended to assist with cesspool upgrade programs and track and monitor progress towards identified goals (ecosystem or human health) and replacement benchmarks.

- A georeferenced database of all onsite wastewater systems in Hawai'i is critically needed for diagnosing pollution threats, developing community outreach/education efforts, watershed planning, and ensuring proper system maintenance. Updating this information is also crucial to meaningful management actions and to inform pollution models.
- Fast-tracking legislation or streamlining internal government processes that permit approved residential onsite wastewater technologies such as composting toilets, drip irrigation leach fields, or greywater recycling is recommended.

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Appendix A

Cesspool, and Other Onsite Sewage Disposal System, Impacts on Water Resources and Human Health in Hawai'i		
Topic	Category	Key Concept or Knowledge Gap
A. Ocean/coastal/ groundwater impairment and human health concerns.	A.1. Key Concepts	<p>A.1.a. Many studies have connected sewage effluent discharge with decreased species diversity, increased eutrophication, and substantially altered ecosystem structure.</p> <p>A.1.b. Eutrophication is associated with elevated nitrogen in algal tissues, the presence of invasive algae, high invasive macroalgal cover, and low biodiversity on coastal reefs.</p> <p>A.1.c. Coral cover was negatively correlated with the presence of FIB, elevated macroalgal $\delta^{15}\text{N}$ levels, and overall nutrient concentrations; tidal pulses are likely to be delivering wastewater pollution to reefs offshore.</p> <p>A.1.d. Several areas in Hawai'i have experienced decreases in coral cover adjacent to high cesspool densities and dissolved nitrogen concentrations.</p> <p>A.1.e. In Hawai'i, recreational bathers are four times more likely to develop <i>Staphylococcus aureus</i> infections and Hawai'i has two times more MRSA infections than the national average.</p>
	A.2. Knowledge Gaps	<p>A.2.a. More field data are needed to enhance understanding of the relationships between groundwater pollution, connected hydrologic systems, and ecological impacts to inform models and elucidate pollution sources.</p> <p>A.2.b. Improved understanding of coastal water flow regimes is vital to discern locations most vulnerable to impacts from land-based pollution sources.</p> <p>A.2.c. Studies are required to evaluate impacts resulting from interactions of multiple pollution compounds and the environment.</p> <p>A.2.d. Although not required by state or federal regulations, testing private drinking water wells in locations where large numbers of cesspools are in use may provide the state with vital data on groundwater quality and improve human health risk assessments.</p> <p>A.2.e. Though examples in Hawai'i show 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 (i.e., nonpoint source pollution).</p> <p>A.2.f. Research is needed to evaluate if legacy nutrients will negatively impact the magnitude and speed of ecosystem recovery after replacing cesspools and other outdated onsite sewage disposal systems.</p>

Appendix A, Continued

Cesspool, and Other Onsite Sewage Disposal System, Impacts on Water Resources and Human Health in Hawai'i		
Topic	Category	Key Concept or Knowledge Gap
B. Wastewater Pollution Indicators	B.1. Key Concepts	<p>B.1.a. Many identified wastewater indicators have limitations and are best combined with a suite of other indicators to evaluate pollution sources; scoring tools have been developed that combine evidence from multiple pollution tracers.</p> <p>B.1.b. Nitrogen isotope values ($\delta^{15}\text{N}$) and %N algal tissue analysis are robust, initial screening indicators to map locations and sources of nutrients, such as cesspools, however, they may represent an aggregate of nitrogen sources pending the features of each site.</p> <p>B.1.c. Wastewater derived contaminants have multiple pathways to enter the ocean, including surface water and submarine groundwater discharge (SGD), which can be tracked by researchers.</p> <p>B.1.d. 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.</p> <p>B.1.e. Anthropogenic contaminants of emerging concern (CEC) detected in Hawaiian streams are likely entering these waters via cesspools; an advantage of CECs is their uniqueness to wastewater, however, a definitive attribution to municipal injection well or cesspool origin is not yet possible.</p> <p>B.1.f. Though ecosystem-level impacts of wastewater pollution are difficult to quantify and predict, especially given global threats such as rising temperatures and ocean acidification, benthic algal and sessile invertebrates have already shown changes.</p>
	B.2. Knowledge Gaps	<p>B.2.a. Epidemiological studies are needed to determine where certain pathogens, such as <i>Staphylococcus aureus</i> are entering water resources from wastewater and if they are causing health issues to recreational water users or drinking water.</p> <p>B.2.b. Large-scale, statewide sampling of multiple wastewater indicators is needed to inform a decision-making framework process and improve hydrologic model accuracy.</p> <p>B.2.c. Future studies should include long-term wastewater indicator sampling to capture temporal patterns of sewage pollution as well as diminishing N-loading predicted in regions of cesspool conversions.</p> <p>B.2.d. More data on relationships between water-borne nutrients and %N in algal tissues are needed as well as the use of mixing models to examine specific contributions of different nitrogen sources to coastal waters.</p> <p>B.2.e. Additional human health risk assessment studies are critically needed to understand if there is appreciable risk to human health from potential pharmaceutical and other CEC exposure and assess long-term effects of consuming low-levels of certain anthropogenic compounds.</p> <p>B.2.f. Methods that investigate the applicability of $\delta^{15}\text{N}$ 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 Hawai'i as wastewater indicators.</p> <p>B.2.g. More information is needed on background bacteria levels such as <i>Enterococcus</i> in tropical soils and waters, and their transport dynamics in wet tropical regions where recreational water use occurs year-round.</p>

Appendix A, Continued

Cesspool, and Other Onsite Sewage Disposal System, Impacts on Water Resources and Human Health in Hawai'i		
Topic	Category	Key Concept or Knowledge Gap
C. Water resource monitoring/ modeling/risk assessment	C.1. Key Concepts	<p>C.1.a. Statewide coastal models have been created detailing cesspool impacts.</p> <p>C.1.b. Monitoring data collected, including radon²²² and $\delta^{15}\text{N}$, are significant resources for understanding nutrient loading from sources to the coastal environment.</p> <p>C.1.c. Models can be used to evaluate potential impacts to infrastructure and assist with long-term planning efforts.</p> <p>C.1.d. Cesspools comprise about 77% of the total estimated release of untreated effluent and 96% of the potential nitrogen release on O'ahu Island, where nearly 10 mgd of sewage enters the environment posing risks to human and environmental health.</p> <p>C.1.e. The use of source-water protection assessments can provide the state with data on source-water susceptibility to contamination, which can be inputted into a decision-making model for determining system upgrade requirements or timetables.</p> <p>C.1.f. There are available contaminant-specific models in Hawai'i that identify groups of drinking water wells with the lowest/highest reported contaminate detections and the lowest/highest nitrate concentrations.</p> <p>C.1.g. A vertical distance between ground surface and groundwater of 25 feet was recommended for proper onsite sewage disposal system effluent treatment; many areas in Hawai'i cannot meet this condition.</p> <p>C.1.h. Recent studies have validated wastewater modeling approaches with algal bioassays, including similar models by Whittier and El-Kadi in 2009 and 2014.</p> <p>C.1.i. Decreasing wastewater inputs can improve ecosystem and human health.</p>
	C.2. Knowledge Gaps	<p>C.2.a. Further field studies are necessary to obtain data to calibrate and validate models to determine the degree to which groundwater is being degraded by onsite sewage disposal systems.</p> <p>C.2.b. Site-specific data are necessary to improve current models regarding density effects and preferential groundwater flow.</p> <p>C.2.c. Three-dimensional hydrologic models simulating chemical fate, transport processes, and mixing dynamics are needed for various contaminants in coastal areas with high concentrations of cesspools and sensitive resources.</p> <p>C.2.d. Studies or models that evaluate variations in site-specific conditions are needed to assist in the onsite sewage disposal system permitting process; through enhanced understanding of different soils, and other site conditions, more tailored regulations can be created for system installations.</p> <p>C.2.e. An enhanced understanding of aquifer vulnerability is critical for risk analysis and planning, models that include sea-level rise impacts on wastewater plumes must be made available or developed.</p>

Appendix A, Continued

Cesspool, and Other Onsite Sewage Disposal System, Impacts on Water Resources and Human Health in Hawai'i		
Topic	Category	Key Concept or Knowledge Gap
D. Policy and Community Engagement	D.1. Key Concepts	<p>D.1.a. According to one study, 1/3 of onsite sewage disposal systems in Hawai'i are deficient and require immediate repairs or maintenance to address problems.</p> <p>D.1.b. Homeowner engagement through education, outreach, and other participation can lead to better onsite sewage disposal system maintenance and a reduction in nutrient pollution and associated health risks.</p> <p>D.1.c. Survey results show positive attitudes towards human waste recycling in Hawai'i.</p> <p>D.1.d. A decision analysis process to identify priority areas impacted by wastewater pollution from onsite sewage disposal systems may be relevant and advantageous to identify pollution mitigation strategies in a cost-effective manner.</p> <p>D.1.e. A participatory and structured decision-making process is recommended to help solve "wicked" environmental problems, characterized by a high level of complexity, uncertainty, and multiple points of stakeholder involvement.</p>
	D.2. Knowledge Gaps	<p>D.2.a. There is a lack of understanding of community knowledge, values, attitudes, and behaviors in relation to onsite sewage disposal system use, pollution, management, and replacement strategies.</p> <p>D.2.b. There is a need to match census data, permit requirements, onsite sewage disposal system use, and environmental health risk.</p> <p>D.2.c. The state lacks critical information on onsite sewage disposal system inventory - specifically a georeferenced database of all systems in Hawai'i - to support: targeted management actions, community outreach/education efforts, and pollution model development.</p> <p>D.2.d. 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 leach fields, or gray water recycling in homes.</p> <p>D.2.e. The creation of groundwater quality criteria by the state of Hawai'i Department of Health is needed to evaluate, measure, and track pollution; guide decision-makers; and inform residents.</p>