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Letter from the Editors

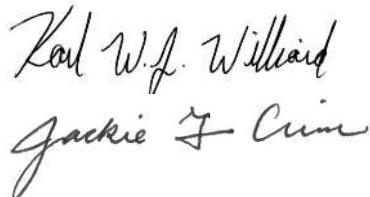
The *Journal of Contemporary Water Research and Education* is evolving to better serve our authors and readership. We are pleased to introduce new article categories published in the *Journal of Contemporary Water Research and Education*. *JCWRE* now accepts submissions to five distinct categories: 1) Original Research, 2) Case Study, 3) Review, 4) Research Note, and 5) Perspective Piece.

The majority of articles published in *JCWRE* have been Original Research articles. Case Studies differ from an Original Research article in that Case Studies are “example” applications of concepts, tools, and models. The purpose of this category is to allow professionals to share new ideas, projects, or new applications of previously published research. Similar to an Original Research article, authors must identify how the research is novel and how it contributes to the existing literature. Authors must demonstrate an original contribution and cannot simply replicate previous studies. Review articles are comprehensive reviews of applied research, policy, education, or outreach/extension in water and watershed science and management. A Review article titled “Hawai‘i’s Cesspool Problem: Review and Recommendations for Water Resources and Human Health” is published in this journal issue. Research Notes provide brief research communications, shorter than an Original Research article, and limited in scope. Examples of a Research Note would be to introduce a new method and/or compare existing methods, to report on preliminary data that may have a significant impact in the author’s field, or to provide an update to previously published data. Perspective Pieces are commentaries on current water issues from experts in the field.

All submitted manuscripts should be of interest to the wide variety of water-related disciplines that encompass *JCWRE* readership. Each category has specific author guidelines that are found on www.ucowr.org. All categories, except Perspective Pieces, are peer-reviewed and subject to standard publication fees. Perspective Pieces are reviewed internally by our Editors and are not charged a publication fee. We look forward to receiving your manuscript submissions.

The *JCWRE* Editorial Staff is continually striving to enhance the journal and increase visibility. We want to thank past authors, reviewers, and Associate Editors for their contributions to *JCWRE*.

Sincerely,

The image shows two handwritten signatures. The top signature is "Karl W.J. Williard" and the bottom signature is "Jackie F. Crim". Both signatures are written in cursive ink.

Karl W.J. Williard and Jackie F. Crim
Co-Editors, *Journal of Contemporary Water Research and Education*

Assessing the Vulnerability of an Aquifer to Climate Variability through Community Participation in Arivaca, Arizona

Kristine Uhlman¹, *Chris Eastoe², Zack Guido³, Michael A. Crimmins⁴, Anne Purkey-Deller⁵, and Susanna Eden⁶

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Abstract: In Arivaca, Arizona, groundwater isotope measurements (stable O and H, tritium, and carbon-14) were made in conjunction with water level measurements and climate data. Recharge is predominantly young (post-1950) and is mainly from summer monsoon precipitation. Following a five-month period of unusually low $\delta^{18}\text{O}$ and $\delta^2\text{H}$ in precipitation in 2014-2015, corresponding shift in groundwater $\delta^{18}\text{O}$ and $\delta^2\text{H}$ was observed only at a site with recently built gabions. Water levels near the basin outlet increase in summer following periods of high storm frequency. Water levels also rebound in winter, possibly because of cessation of transpiration. The young groundwater is vulnerable to climate change, e.g., to protracted periods with summers that are drier or hotter than normal. Rapid assessment of groundwater and its connection to climate can provide valuable information to local water managers and citizens for whom more expensive studies are not feasible. Such assessments, based on relatively inexpensive isotope analyses and groundwater level data collected by volunteers, engage the community in management of its water resources. In Arivaca, the community responded to the results of the assessment with heightened interest in managing their water for sustainability and the construction of gabions to increase recharge from stormwater.

Keywords: *Arizona, groundwater, recharge, O and H isotopes, tritium, carbon-14, climate, water levels*

Drought is a common feature in the arid western U.S. (Ni et al. 2002; Hirschboeck and Meko 2005; Weiss et al. 2009; Griffin et al. 2013), and has been exacerbated in recent years by the effect of warming temperatures on evapotranspiration demand. Between 2012 and 2014, California experienced large precipitation deficits that were not uncommon in the historical record but when combined with temperature produced the most severe three-year drought in the last 1200 years (Griffin and Anchukaitis 2014). Like California, other states in the western U.S. have also recently experienced severe multiyear warm droughts (Cook et al. 2004; MacDonald 2010). By

some estimates, Arizona has been in a prolonged drought since 2000 (Arizona Department of Water Resources 2019a, 2019b; Westwide Drought Tracker 2019). The severity of summer drought has been increasing in recent decades (Goodrich et al 2004; Morino 2008), while winter precipitation has shown a general decrease since the late 1990s (e.g., Eastoe and Dettman 2016). With projections of continued warming (United States Global Climate Research Program 2017), the higher temperatures and periodic rainfall deficits will be a main challenge to the management of water resources (Milly et al. 2008; Udall and Overpeck 2017).

The impacts of climate on surface water are well documented. Research has demonstrated the effects of evaporation of water stored in reservoirs (Friedrich et al. 2018), the widespread declines in streamflows (Udall and Overpeck 2017), and shifting streamflow seasonality caused by changes in snowpack conditions (Stewart et al. 2005). Equivalent studies on the impact of climate on groundwater have lagged behind (Earman and Dettinger 2011; Green et al. 2011) despite direct influence of seasonal precipitation and evapotranspiration on groundwater recharge. Understanding the complex interplay between climate and recharge is important to assessing the vulnerability of an aquifer to climate variability.

Across portions of the southwest U.S. there are two main modes of rainfall: 1) frontal systems during winter months, and 2) convective storms during the summer monsoon, largely between July and September (Sheppard et al. 2002). Monsoon rains generate most streamflow in the Sonoran Desert of Arizona (Constantz et al. 2007), while groundwater recharge can occur from both summer and winter precipitation, although proportions can vary between basins (Eastoe and Towne 2018). Precipitation is often less than evapotranspirative demand, preventing infiltration beyond the root zone (Hogan et al. 2004). Large areas of basin floors provide little to no recharge to underlying aquifers; in such basins, most recharge is likely to be focused in ephemeral channels where flow may occur only several hours per year (Uhlman 2005; Stonestrom et al. 2007; Glenn et al. 2015). Basin-floor recharge could, however, be significant during extended periods of high precipitation and low evapotranspiration in the fall and winter seasons (Coes and Pool 2007).

Arizona is strongly dependent on groundwater for water supply. Moreover, carbon-14 (^{14}C) age dates of groundwater in major aquifers in Arizona have revealed a wide range of residence times (e.g., Smalley 1983; Eastoe et al. 2004; Baillie et al. 2007; Hopkins et al. 2014). Ages of more than 10,000 years before present can be explained either as indicating older water left after younger water has been over-pumped or as recording the last significant recharge in aquifers that were filled in the late Pleistocene, when climate was

colder and wetter (Phillips et al. 1986; Artiola and Uhlman 2009).

Younger aquifer systems (recharged since 1950) are more vulnerable to drought than aquifers holding mainly fossil water, but this vulnerability could be partially offset by a change in water management strategy, such as construction of gabions to detain and infiltrate stormwater. Detailed, expensive research studies of local groundwater are mostly unavailable to small, rural communities. Rapid assessments of groundwater character and its connection to climate can provide valuable information to local water managers and citizens' groups. These assessments, built on relatively inexpensive isotope analyses and groundwater level data collected by volunteers, have the advantage of encouraging citizens to participate in water management.

The rural community of Arivaca is dependent on groundwater in a small alluvial basin (Figure 1). This report presents the results of an initial, rapid assessment of the Arivaca Basin in 2009, augmented by a second round of sampling in 2015. The first phase of assessment was envisioned as a low-cost investigation of the basin aquifer, encompassing: 1) planning with community members, including initiation of water level and climate monitoring, and 2) field sampling over a period of one to two months, followed immediately by laboratory work. The second assessment phase was an unanticipated addition to original plans following a fortuitous observation. Long-term measurement of oxygen and hydrogen isotopes in Tucson rain indicated a five-month period of rain, late August 2014 to early February 2015, of extreme isotope composition (Eastoe 2016) providing an unusual opportunity for the identification of recent recharge. Results of these campaigns are combined with overlapping observations of climate and water levels collected in other contexts over different time frames. The principal aims of the study were 1) establishing recent trends in local climate and groundwater levels through measurements undertaken by Arivaca residents; 2) determining aquifer vulnerability and recharge seasonality by application of isotope measurements; and 3) augmenting local knowledge of water resources in a low-cost study, with a view to enabling community participation in sustainable water management.

Study Area

Geography

The rural community of Arivaca, with a population of around 1,000, is located approximately 80 kilometers southwest of Tucson, Arizona (Figure 1). Arivaca lies within the Tucson Active Management Area (AMA), one of five AMAs established by the State of Arizona under the 1980 Groundwater Management Act (Arizona Department of Water Resources 2019c). The Tucson AMA covers 10,013 square kilometers in southern Arizona and encompasses extensive basin-fill aquifers in the Santa Cruz River Basin. The Tucson AMA has a statutory goal of achieving ‘Safe-yield’ by 2025 and maintaining it thereafter (Arizona State Legislature 2019). ‘Safe-yield’ requires that average annual pumping not exceed natural or artificial recharge in the AMA as a whole. The Arivaca Basin lies within the boundaries of the AMA but is not in direct hydraulic connection with the larger basins (Pima Association of Governments 2006).

Climate

The climate in Arivaca is characterized by mild winters and hot summers. July is the hottest month.

The region has a bimodal annual distribution of precipitation. More than half falls during the monsoon season between June and September, and most of the remaining precipitation occurs in the winter between November and March (Figure 2). The two to three months prior to the monsoon are the driest season.

The monsoon rains tap moisture from the tropical Pacific Ocean and the Gulf of Mexico (Michaud et al. 1995; Adams and Comrie 1997; Diem and Brown 2006). Monsoon storms commonly yield short, intense rain events of limited spatial extent. Arivaca is located on the western fringe of the core area of the monsoon and receives slightly more precipitation than areas to its north and less than Nogales to the southeast (Figure 3). Winter rains are the product of regional frontal storms, generally lower in intensity and more widespread than monsoon storms. In some years, tropical cyclonic storms from the Pacific Ocean bring precipitation between September and November; a single such event can account for a high percentage of annual precipitation.

Hydrogeology

The following description of the groundwater basin at Arivaca is based on a report of Pima

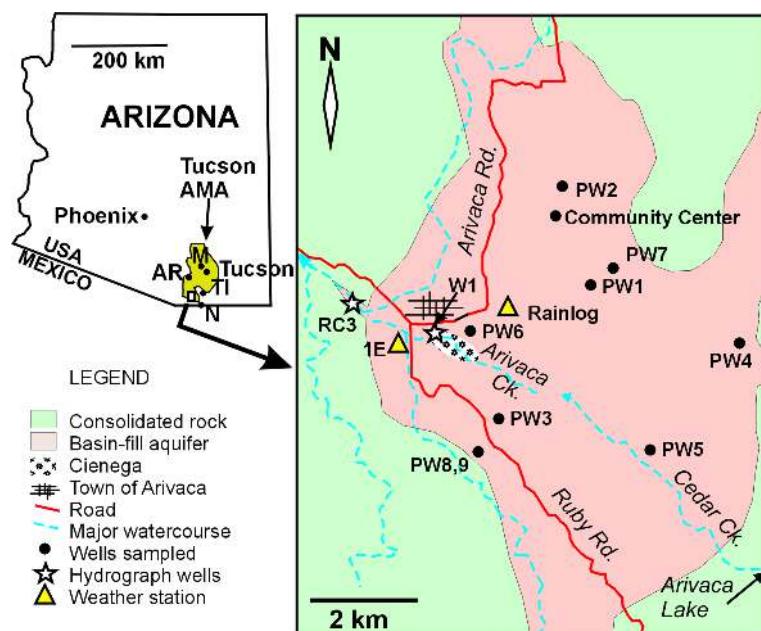


Figure 1. Location map, showing locations of wells sampled for this study, hydrograph wells, and weather stations. Inset map shows locations of Tucson Active Management Area (AMA) and five observation stations: Tucson, Anvil Ranch (AR), Marana (M), Tumacacori (TI), and Nogales (N).

Association of Governments (2006). The isolated aquifer system of the Arivaca groundwater basin extends over 39 km² and supports more than 200 wells in addition to perennial streamflow, lush riparian habitat, and a ciénega (wetland) with diverse terrestrial and aquatic ecosystems. The basin is a graben within Mesozoic and Cenozoic crystalline rocks that compose a horst of the Basin-and-Range province. Unconsolidated Holocene alluvium beneath the larger washes (streambeds that are usually dry) overlies Tertiary to Quaternary semi-consolidated conglomerate and sandstone up to 200 m thick in the southeast part of the basin. These sediments form the unconfined regional

aquifer of the Arivaca Basin. Groundwater flow is generally from the basin edges towards a discharge area in the ciénega located where Arivaca Creek crosses a sill of shale. From the ciénega, groundwater leaves the basin to the west, along Arivaca Creek (Figure 1).

Watercourses are ephemeral except for Arivaca Creek within the ciénega. Arivaca Lake, an artificial impoundment built on Cedar Creek to the southeast of the study area in the 1970s, discharges water infrequently when the reservoir overflows. Modeling combined with water level data shows a general decline of about 1 m in groundwater levels since the 1970s, the largest declines being north of

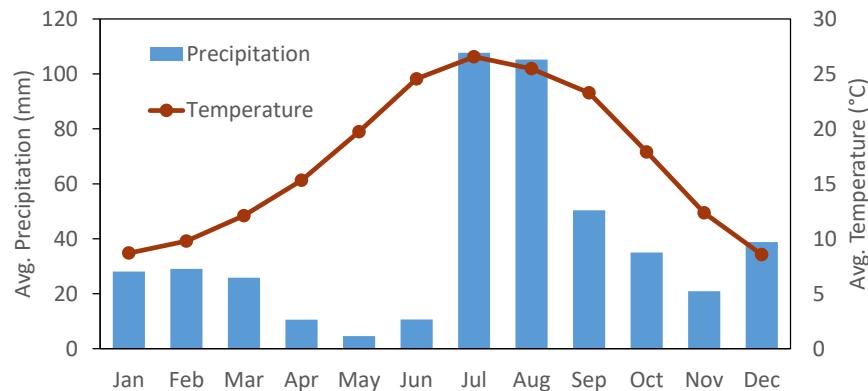


Figure 2. Average monthly precipitation in Arivaca, 1956-2018 (Western Regional Climate Center 2019).

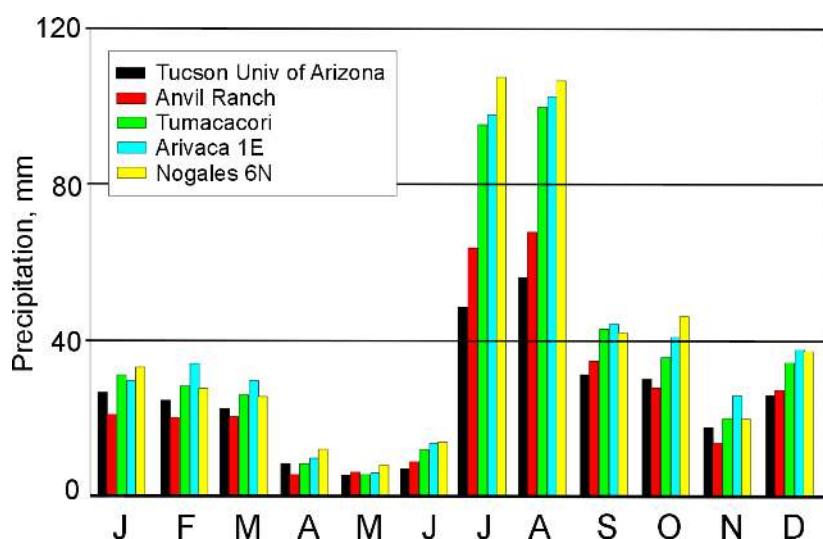


Figure 3. Comparison of average monthly precipitation in Arivaca with that of surrounding stations at Tucson, Anvil Ranch, Tumacacori, and Nogales. Month names are abbreviated JFMAMJJASOND, January to December.

the ciénega. The decline has occurred concurrently with a decrease in base flow in Arivaca Creek, putting the riparian ecosystem of the ciénega at risk (Pima Association of Governments 2006).

Usefulness of Isotope Data

Research using multiple isotope parameters has contributed to the understanding of groundwater origins, flow paths, and residence times in the alluvial basins of southern Arizona (Eastoe et al. 2004; Baillie et al. 2007; Hopkins et al. 2014; Gungle et al. 2016; Eastoe and Towne 2018). These studies have used stable isotopes of hydrogen (H), oxygen (O), and sulfur (S), along with tritium and ^{14}C in determining groundwater origins and residence times.

In Tucson, Eastoe et al. (2011) showed that the average level of cosmogenic tritium in rainwater is about 5.3 tritium units (TU; 1 TU = 1 atom of tritium per 10^{18} atoms of hydrogen). Similar levels have been observed in short-term datasets from other stations in southern Arizona (Eastoe et al. 2011). The half-life of tritium is 12.32 years (Lucas and Unterweger 2000); thus, pre-bomb tritium has now decayed to less than the level of detection in the University of Arizona laboratory, 0.6 - 0.7 TU. Bomb tritium peaked in 1963-1964 at about 1,000 TU (annual average) and is still present in aquifers recharged with rainwater since about 1955.

The half-life of ^{14}C is 5,730 years (Godwin 1962), so that ^{14}C measurements enable estimation of water ages up to about 20,000 years. Pre-bomb levels of ^{14}C were near 100 percent modern carbon (pMC), and at the culmination of the atmospheric testing bomb peak (1963-1964), levels near 180 pMC were reached (Burchuladze et al. 1989). ^{14}C can be measured in dissolved inorganic carbon (DIC) species in groundwater. The carbon comes from two sources: carbon dioxide (CO_2) gas in soil or near-surface sediment through which the recharging water passes, and rock calcite. Soil gas has ^{14}C content near that of plant matter in equilibrium with the atmosphere. In southern Arizona, plant matter ^{14}C content had fallen to about 102 pMC by 2002 (Eastoe unpublished data). Accurate age dating using ^{14}C commonly requires correction for the addition of rock carbon containing no ^{14}C (see Methods).

Data Sources and Methods

Water Sample Sites

After reviewing well-log data (Arizona Department of Water Resources 2019d), a list of priority wells, mainly private domestic wells, was identified and access to the wells was requested from community members. Selection criteria included representative spatial distribution and depth, along with feasibility of access. Well depths ranged between 36 and 87 m below land surface. Seven wells were sampled during our initial assessment in 2009 and nine were sampled in late 2015. A surface-water sample was collected from Arivaca Lake in 2015. Sampling sites are shown in Figure 1. Measurements of stable isotopes (O, H, and C) and radioactive isotopes (tritium and ^{14}C) were carried out.

The 2015 sampling provided a unique opportunity to identify recent recharge. Isotope data for Tucson rain during the period August 25, 2014 to January 31, 2015 contained unusually low amount-weighted mean values of $\delta^{18}\text{O}$ and $\delta^2\text{H}$ (Eastoe 2016). During this period, 311 mm of rain fell at Arivaca Post Office. The unusual precipitation was, in part, associated with hurricanes Marie, Norbert, Odile, and Simon. Groundwater reflecting this isotope signature would indicate recharge from these cyclonic storms.

Field Hydrological Data

Monthly water use, depth to groundwater, and volunteer metering data have been collected and maintained by Pima County and the community for several years (Fonseca 2008), but pumping data from across the study area were insufficient to address the effect of pumping on water levels.

Daily depth-to-groundwater data were obtained from Arivaca volunteers using an automated Level Troll data logger to monitor five groundwater wells made available by local residents; results from two wells (sites shown in Figure 1) are given here. Volunteer citizen scientist measurements began in March 2007 and terminated in late 2014. Wells RC-3 and W1 were chosen to analyze connections between climate and groundwater because they are farthest from known high-production wells.

Precipitation data were obtained from two sites in Arivaca (Figure 1): the National

Weather Service (NWS) Cooperative Observer Program (Coop) station 1E (National Ocean and Atmosphere Administration 2019) for the period August 1, 2005 to February 28, 2010, and a Rainlog observation site for 2014-2015 (Rainlog 2019). Monthly precipitation data were obtained from Western Regional Climate Center (2019) for the Arivaca 1E station and four Coop stations near Arivaca: The University of Arizona in Tucson, Anvil Ranch, Tumacocori National Monument, and Nogales.

While these records represent the best available high-resolution precipitation data for the Arivaca area, they are not without blemishes. The Arivaca Coop station did not record temperature measurements, and weekend precipitation was recorded on the following Monday. To compensate, average monthly temperatures for Arivaca were obtained from interpolated data generated by the Parameter-elevation Regressions on Independent Slopes Model (PRISM) from nearby monitoring stations. PRISM generates climate data for a 4 x 4 km grid covering the continental United States (Westmap 2019).

Evapotranspiration (ET) data — which are used to measure changes in ET— were obtained from the closest station (AZMET 2019) in Marana, Arizona, 96 km northwest of Arivaca.

Isotope Analytical Methods

Isotope measurements were undertaken at the Environmental Isotope Laboratory, University of Arizona. Stable O, H, and C isotopes were measured by isotope ratio mass spectrometry. The results are expressed using δ -notation, e.g.:

$$\delta H = \left(\frac{R(\text{sample})}{R(\text{standard})} - 1 \right) * 1000 \text{ ‰}$$

where $R = {}^2\text{H}/{}^1\text{H}$ and the standard is Vienna Standard Mean Ocean Water (VSMOW). The definitions of $\delta^{18}\text{O}$ and $\delta^{13}\text{C}$ are analogous, with standards VSMOW for O, and VPDB for C. Tritium and ${}^{14}\text{C}$ were measured by liquid scintillation counting. Results are expressed as TU and pMC, respectively. Details of preparation techniques, instrumentation, analytical precision, and calibration may be found at University of Arizona Geosciences (2019).

Correction of Carbon-14 Data

The raw data were corrected using $\delta^{13}\text{C}$ measurements of DIC, as outlined by Clark and Fritz (1997). Additional information required for the correction calculation included 1) an average value of $\delta^{13}\text{C}$ in rock calcite, assumed to be -1‰ as in Tucson Basin sediments (Eastoe unpublished data), and 2) an average $\delta^{13}\text{C}$ value for soil CO_2 , assumed to be -19.9‰, representing decay of organic matter of which 25% originated as C_4 and 75% as C_3 plant material.

Statistics

Linear regressions of time-series data were calculated using Excel software.

Results

Climatology

Arivaca received an average of 467 mm of precipitation per year between 1956 and 2018. July and August experience the most precipitation, averaging 105-107 mm per month (Figure 2).

Seasonal precipitation has exhibited large interannual variability since 1955, particularly during the June - September period (Figure 4). Over this period, the data suggest increasing precipitation for the months July through September, but neither of the trends in Figure 4 is significant at >95% confidence level ($p \leq 0.05$). Seasonal temperatures show slight warming trends between 1955 and 2018. Winter temperatures have increased about 0.14°C per decade and summer (monsoon season) temperatures increased about 0.13°C per decade. The changes over time, although small, are statistically significant (Figure 5).

Evapotranspiration is greatest between May and September and least between December and February. Evapotranspiration measured between 2007 and 2010 at Marana exceeded average Arivaca precipitation (1955-2018) in all but three months (Figure 6).

Climate Change

Over coming decades, temperatures are projected to increase across the southwest U.S., while precipitation is expected to decrease. Rainfall predictions have large uncertainties, but most

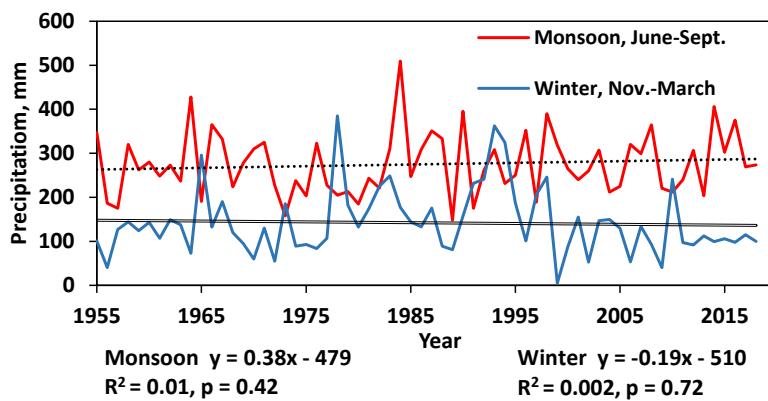


Figure 4. Seasonal variation in precipitation since 1955, presented as totals for the summer monsoon (June-September) and winter (November-March).

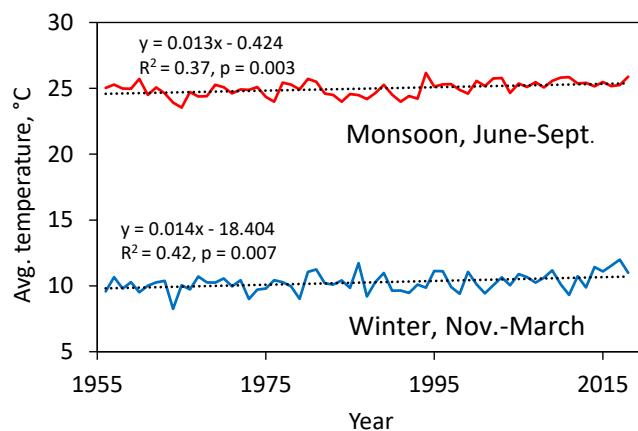


Figure 5. Seasonal temperature variation since 1955, presented as averages for the summer monsoon (June-September) and winter (November-March).

down-scaling from global models has converged with relatively high confidence on a drying trend over Arizona during winter and spring (Seager et al. 2007; United States Global Change Research Program 2009, 2017) as the winter jet stream retreats northward (Lu et al. 2007). Precipitation projections for summer and fall are less clear because the North American monsoon and tropical cyclonic weather systems have not yet been sufficiently characterized (United States Global Climate Research Program 2017). The current drought had not led to perceptible long-term decline in summer (June-September) precipitation by 2018 (Figure 4).

Temperature increases are predicted during all seasons and are expected to be greatest during the

summer season. Summer increases may exceed 2 to 3 °C by 2050, driving higher evapotranspiration rates and lower recharge rates, especially in areas like Arivaca where most recharge appears to occur during the summer monsoon season (see below).

Groundwater Hydrographs

Groundwater, as measured by citizen scientist volunteers, fluctuated from 1.5 to 10 m below land surface during the period of study (Conway, pers. comm. 2019). Results presented here are for site RC3 (in streambed alluvium at the basin outlet; Figure 1), where groundwater levels increased during two of three monsoon seasons and all three winter seasons over the original study period (Figure 7A). In the summer of 2007, for example,

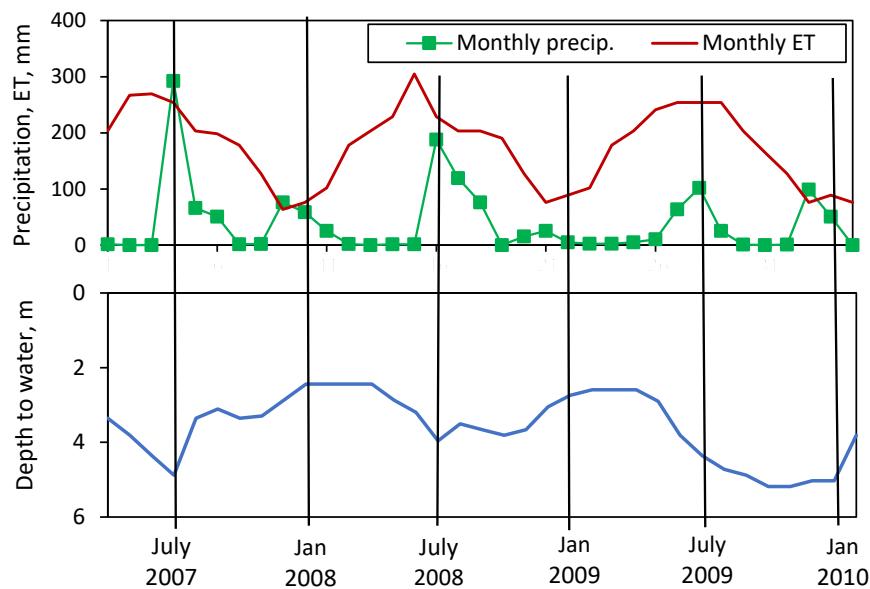


Figure 6. Relationship of water levels at site RC3 to summer and winter rains (measured in Arivaca) and evapotranspiration (measured at Marana, Figure 1) over three years.

several storms in July caused groundwater to rise about 1.5 m. The general pattern during the study period was groundwater rebound during both rainy seasons and decline during the drier spring and fall. A detailed comparison of groundwater levels in 2007 and 2008 at RC3 with individual monsoon rain events (Figure 7A) showed that groundwater levels rose only after at least 75 to 100 mm of rain had fallen within a 15-day period (an arbitrary choice of period, but one that appears to encompass groups of heavy rains in the examples given). In 2009, the monsoon was delayed and no comparable change in groundwater level was observed.

For the 2014 monsoon and subsequent tropical cyclonic rain, the hydrograph is from well W1 in the cienega, close to the basin outlet (Conway, pers. comm. 2019), where groundwater levels rose sharply early in the monsoon, fell during a period of tropical cyclonic rain, and rebounded once again in the winter (Figure 7B). Rainfall data in Figure 7 are from Rainlog (2019).

Stable O and H Isotopes

Isotope data are listed in Table 1 and plotted in Figure 8 alongside amount-weighted means for seasonal precipitation based on data for the Tucson Basin (Eastoe and Dettman 2016). The means are adjusted to 1,150 masl, the average elevation of

Arivaca Basin, using isotope altitude gradients from Wright (2001). Following Eastoe and Dettman (2016), summer in this context is considered to be June to October, and winter, November to May. The precipitation data are represented in three ways: 1) long-term (1982-2012) seasonal means defining a local meteoric water line (LMWL) (Eastoe and Dettman 2016); 2) long-term means for summer and winter including only the wettest 30% of months in each season - this choice reflecting the patterns of isotope data in neighboring alluvial basins in which most groundwater isotope data fall on a modified LMWL (Eastoe and Towne 2018), shown as LMWL (wettest 30%) in Figure 8; and 3) amount-weighted means for individual seasons as labeled on Figure 8, with summer 2014 divided into monsoonal (July to mid-August) and tropical cyclonic (mid-August to October) sub-seasons. The means for the tropical cyclonic sub-season and the following winter are identical. Mean values of $\delta^{18}\text{O}$ and $\delta^2\text{H}$ from mid-August 2014 to February 2015 were about -11.8 and -88‰, respectively, significantly lower than the long-term winter means (Figure 8).

The 2009 groundwater data plot in a single group near the summer mean for either the LMWL or LMWL (wettest 30%) (Figure 8). In 2015, most groundwater data plotted in a field to the right of

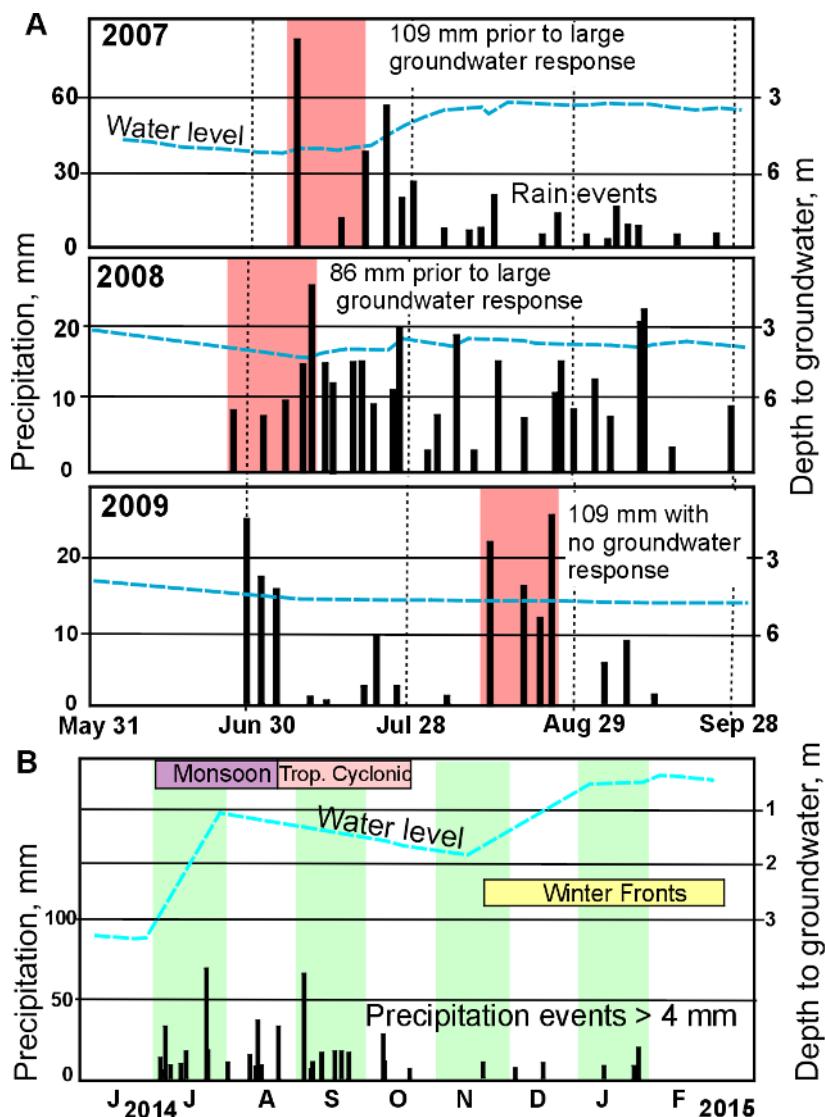


Figure 7. A) Response of water levels at site RC3 to monsoon rain events, 2007 to 2009; black bars represent individual precipitation events, and orange rectangles highlight intervals of heavy precipitation, as labeled. B) Response of water levels at site W1 to monsoon, tropical cyclonic, and winter-frontal rain events in 2014-2015. Black bars represent individual precipitation events >4 mm. Green and white shading indicates months.

the 2009 data; four of the well samples in 2009 had changed measurably in $\delta^{18}\text{O}$ and $\delta^2\text{H}$ (Table 1). Groundwater sampled in 2015 plots near the monsoon-2014 mean. The shift in values of $\delta^{18}\text{O}$ and $\delta^2\text{H}$ between 2009 and 2015 corresponds to the difference in seasonal means for the monsoon in 2008 and 2014. The data for PW9 plot apart from the main data group of 2015, in the direction of the winter (2014-2015) and tropical cyclonic (2014) means. The sample taken from Arivaca Lake in 2015 has $\delta^{18}\text{O}$ and $\delta^2\text{H}$ values of -4.0 and -46‰,

respectively, and is highly evaporated. Assuming an evaporation trend of slope 4, typical for southern Arizona (Eastoe and Towne 2018), this water originated as precipitation with a bulk $\delta^{18}\text{O}$ value near -10‰.

Tritium

Most of the samples contained 0.8 to 1.2 TU (5.3 TU was measured at PW5 and < 0.5 TU at PW3). The measurements can be compared with the long-term weighted mean tritium content, 5.3 TU, in

Table 1. Isotope Data.

Site	Type	$\delta^{18}\text{O}$	δD	$\delta^{18}\text{O}$	δD	$\delta^{13}\text{C}$	Tritium	C-14	C-14	Age
		(‰)	(‰)	(‰)	(‰)	(‰)	(TU)	(pMC)	(pMC) corrected ^b)	(years)
		2009	2009	2015	2015	2009	2009	2009	2009	
CC	GW	-7.1	-52	-7.0	-52	-8.6	1.2	66.3	115	post-bomb
PW1 ^a	GW	-7.3	-49	-6.9	-50	-7.1	1.1	51.2	111	post-bomb
PW2 ^a	GW	-7.5	-50	-7.1	-52	-9.4	1	57.0	90	850
PW3 ^a	GW	-6.9	-50	-6.9	-53	-4.7	<0.5	74.1	264 ^c	invalid
PW4 ^a	GW	-6.9	-50	-6.6	-52	-7.3	0.9	53.5	112	post-bomb
PW5	GW	-7.5	-51			-8.6	5.3	99.6	173	post-bomb
PW6	GW	-7.2	-50	-7.1	-52	-7.1	0.8	49.4	107	post-bomb
PW7	GW			-6.7	-51					
PW8	GW			-6.5	-45					
PW9	GW			-8.4	-60					
Arivaca Lake	SW			-4.0	-46					

Note: PW = private well; GW = groundwater; SW = surface water

^aWells that changed in isotope composition from 2009 to 2015.

^bCorrected using a carbon ratio of C₃:C₄ = 3:1 in soil gas; and $\delta^{13}\text{C} = -1\text{‰}$ in sedimentary carbonate.

^cInvalid result; higher than peak bomb pulse in atmosphere.

Tucson rain. Tritium in Tucson precipitation since 1992 had decayed to 1.8 TU or higher by 2009, and Tucson precipitation that fell between 1970 and 1992 had decayed to about 1.8 TU by 2009 (Eastoe et al. 2011). The Arivaca samples, therefore, are most likely mixtures of post-1955 recharge with pre-1955 recharge, except at PW3, where pre-1955 recharge predominated, and at PW5, which is adjacent to Cedar Creek and appears to have received recharge of meteoric water that underwent little radioactive decay since infiltration; if bulk infiltration in this case contained 5.3 TU, the precipitation in question fell since about 2007.

Carbon-14

The ^{14}C content in groundwater ranges from 49 to 100 pMC (Table 1). Corresponding corrected values range from 90 to 173 pMC. The corrected ^{14}C content at PW3, 264 pMC, is invalid, indicating incorrect assumptions in the correction method in that case. The corrected ^{14}C data are approximate but suggest groundwater only a few decades old.

The corrected ^{14}C ages are broadly similar to the tritium ages; both are consistent with mixtures of pre-bomb (TU below detection at sampling, 95 to 100 pMC) with post-bomb (TU > 1.8 at sampling, pMC > 100) recharge.

Discussion

Hydrographs

In addition to total precipitation, the season, magnitude, frequency, and duration of precipitation events all seem to influence the character of the groundwater response. In southern Arizona, such factors are reflected in the isotope composition of groundwater, which results from recharge during wetter months (Eastoe and Towne 2018).

The 2007 and 2008 monsoon seasons produced water level rises at site RC3, while well water levels declined in the 2009 monsoon (Figure 7A). In 2007, groundwater rose after 109 mm of rain had fallen in a 15-day period; in 2008, groundwater began rising after 86 mm had fallen in a 15-day

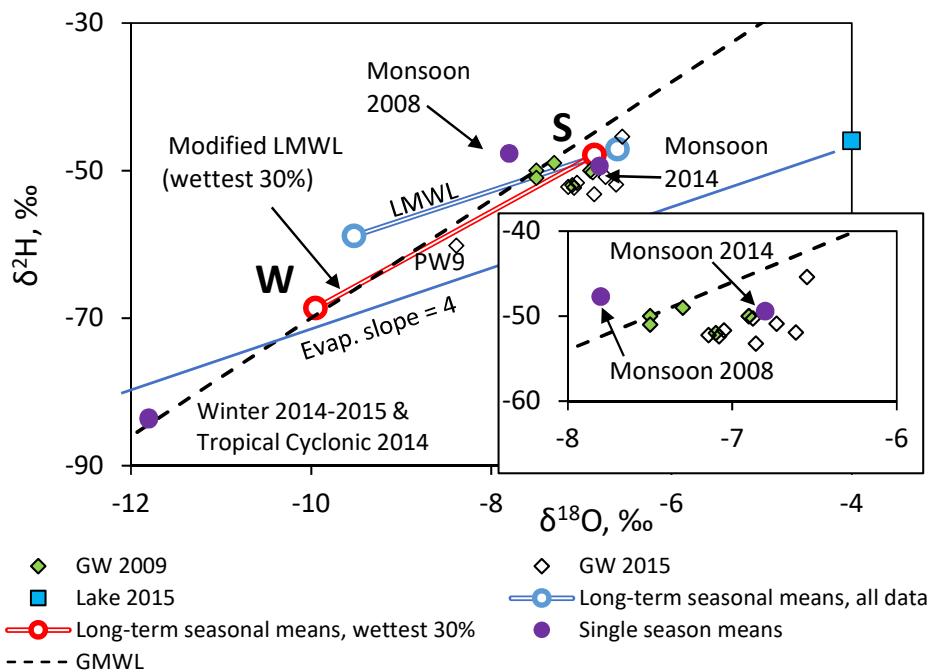


Figure 8. Plot of $\delta^2\text{H}$ vs. $\delta^{18}\text{O}$, showing: 1) data for Arivaca groundwater (GW) sampled in 2009 and 2015 - detail in the inset; 2) long-term seasonal amount-weighted averages for rain at 1150 masl, based on all data from Tucson Basin, 1981-2012 (Eastoe and Dettman 2016) with altitude correction (Eastoe et al. 2004) - linked by a local meteoric water line (LMWL); 3) long-term seasonal amount-weighted averages for rain at 1150 masl, based on data for the wettest 30% of months from Tucson Basin, 1981-2012 (Eastoe and Dettman 2016; Eastoe and Towne 2018) with altitude correction (Eastoe et al. 2004) - linked by a modified local meteoric water line, (Modified LMWL wettest 30%); 4) single-season amount-weighted means for the monsoon (July-Aug.) 2014, tropical cyclonic rain (Aug.-Oct. 2014) and winter (Nov. 2014-Feb. 2015) - note that tropical cyclonic and winter points are identical; and 5) surface water from Arivaca Lake sampled in 2015, with a proposed evaporation trend of slope 4. GMWL = global meteoric water line. W = winter; S = summer.

period. These observations suggest that storm intensity and frequency are important factors, and under favorable conditions create a saturated soil or streambed horizon that can effectively transmit water from the surface to the water table. Because rainfall frequency was higher in 2008 than in 2007, less total rainfall was needed in 2008 before recharge occurred (Figure 7A). After protracted dry weather, as when precipitation was delayed during the 2009 monsoon season, initial rainwater is unable to infiltrate to the aquifer through dry soil or through ephemeral streambeds in which evapotranspiration may intercept recharge. The 2014 monsoon produced a water level rise at W1, but a comparable amount and frequency of rain from tropical cyclonic systems did not, perhaps because the saturated soils allowed for runoff (Figure 7B).

Isotope Data

The $\delta^{18}\text{O}$ and $\delta^2\text{H}$ data suggest that summer precipitation strongly dominates recharge in Arivaca Basin. June through October precipitation accounts for about 66% of annual precipitation (Figure 2). The isotope data indicate a summer contribution of 75% or more to recharge, relative to the LMWL for all precipitation data, or the modified LMWL for the wettest 30% months, or individual seasonal mean data (Figure 8). The difference between the main groups of $\delta^{18}\text{O}$ and $\delta^2\text{H}$ groundwater data for 2009 and 2015 suggests a rapid response to changes in monsoon precipitation isotopes, but not to tropical cyclone or winter rain. Only one site, PW9, a well 46 m deep situated in a small wash in which the owner had installed several gabions, showed a large shift towards the more negative $\delta^{18}\text{O}$ and $\delta^2\text{H}$ values of tropical cyclone isotope precipitation.

The isotope data indicate very young groundwater in Arivaca Basin. The ^{14}C and tritium data are consistent with bulk groundwater ages of decades rather than years as suggested by the rapid shift in $\delta^{18}\text{O}$ and $\delta^2\text{H}$ data between 2009 and 2015. The apparent inconsistency may reflect the combination of waters of different age in our samples or a strong recharge event just prior to the 2015 sampling but not prior to the 2009 sampling.

Relationship of Isotope and Hydrograph Data

The hydrograph observations, indicating both summer and winter rebound of groundwater, appear to differ from the stable isotope data, which indicate mainly summer recharge. The hydrograph wells are located at the basin outlet or near the basin axis (Figure 1) where riparian vegetation is well-developed along Arivaca and Cedar Creeks. In these areas, summer recharge may predominate, as indicated by isotope data. Transpiration also potentially controls water levels, however, when transpiration ceases in winter months, water levels may rebound with or without winter recharge, in response to the removal of vegetation demand for water. Isotope data, not available in this study for any of the hydrograph wells, might elucidate winter rebound of water levels.

Community Involvement

While detailed studies of water budgets are beyond the funding capability of small communities like Arivaca, rapid assessment of groundwater character and connection to climate has the potential to offer valuable information to local residents. In the present case, a relatively small isotope study (constrained by limited funding) coupled with climate data and volunteer measurements of water levels has produced a significant increase in local understanding of water resources. A major advantage of this strategy is that it engages local participants in the research from the beginning. Making use of community volunteers can facilitate data collection and augment the limited research resources and, perhaps most important, can catalyze community action. Anecdotal evidence suggests that those community members who participated in the research through volunteering their well, collecting well data, and attending information meetings became better informed

about their water resources and the management of water in general. They also appear to have developed positive attitudes toward managing for sustainability and a greater sense of their capacity to manage their water.

Notably, at least one landowner (well PW9) installed gabions across his property following a workshop on surface water harvesting in the early 2000s. The owner built the gabions in order to slow surface water flow and enhance groundwater recharge. Well PW9 was not sampled in 2009. The 2015 resampling detected the isotope signature of August 2014 to February 2015 rain at this site, indicating enhanced recharge that had not occurred in areas without gabions, and demonstrating the potential for enhancing recharge elsewhere in the basin.

Access to private wells was critical to this study. Such access is commonly difficult to obtain in small, rural communities. This study demonstrates the benefits to well-owners of making groundwater samples available for analysis.

Regional Implications

The findings of this study suggest that low-cost assessments can produce useful results in small communities that rely on groundwater in semiarid to arid regions. A similar exercise in Cascabel, Arizona, 120 km northeast of Arivaca, led to an improved comprehension of groundwater ages and recognition of the warning signs of groundwater depletion in response to drought (Eastoe and Clark 2018). A global synthesis of the findings from 140 recharge study areas in semiarid and arid regions found that recharge may be enhanced through management of land use activities (Scanlon et al. 2006). Land use practices, such as the installation of gabions for storm-water management will enhance groundwater recharge. In addition, recognition that local aquifers are replenished annually in normal years can lead to management strategies that enable individuals to balance withdrawals with deposits.

Recommendations

Monitoring data (i.e., well level and precipitation data) collected by citizens of Arivaca were critical in assessing local conditions, as well as filling in gaps in state and federal monitoring networks.

Maintenance of the volunteer monitoring system will further the understanding of the vulnerability of the Arivaca aquifer system to climate variability. Other rural communities in Arizona would profit equally from similar citizen involvement. Researchers and communities undertaking future aquifer assessments of this kind may learn from the present example. The data presented here are from a variety of sources, and do not in all cases match in time. Similar studies would profit from better coordination of data collection, for instance in measuring time-series of isotope data from hydrograph wells.

Conclusions

Groundwater in the Arivaca aquifer is young, with residence times of decades or less. Summer recharge predominates. Recharge is controlled not only by season, but also by the frequency and size of rain events. Winter rebound of groundwater appears to be linked to seasonal decrease in evapotranspiration. The aquifer system is vulnerable to extended drought and delays in the onset of summer rains, or to a warming climate that leads to increased summer evapotranspiration. Implementation of storm-water management options to capture water for groundwater recharge has been shown to be an effective management option.

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Training Early Career Great Lakes Scientists for Effective Engagement and Impact

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Abstract: Freshwater systems worldwide are increasingly facing complex environmental issues. In the Laurentian Great Lakes region, harmful algal blooms are one example spanning agriculture, municipal drinking water, science and monitoring, water quality, and human health. Addressing these challenges and working across stakeholder interests requires sound science and additional skills that are not necessarily taught to graduate students in the apprentice research model. Effective stakeholder engagement and science communication are two areas consistent with emphases on broader impacts from the National Science Foundation, information and dissemination of the National Institutes of Health, and community engagement of the National Institutes of Health's Institute of Environmental Health Sciences. The lack of training in these areas creates a gap for outreach, engagement, and science communication training to help enable researchers to translate important science to influential stakeholders, policy makers, and members of the public. To address this gap, we held a Community-Engaged Scholarship Workshop for graduate students and early career faculty. The workshop used an established community-engagement framework and was tailored to address the complex environmental issue of harmful algal blooms. It addressed four community-engagement competencies, including community-engaged partnerships, community-engaged teaching and learning, community-engaged research, and science communications. Here, we report evaluation results on changes in these four competencies and participant satisfaction. We conclude with a discussion of potential improvements and next steps for those seeking to host similar community-engaged trainings.

Keywords: *harmful algal blooms, professional development, science communication, science to policy, complex environmental problems*

Since the early 2000s, there have been calls for Great Lakes scientists to bridge science and policy communities as communication between scientists and policy makers can be an effective way to address any disconnect, especially for complex environmental problems (Rittell and Webber 1973; Innvaer et al. 2002; Krantzberg 2004; Dreelin and Rose 2008). In Michigan, nearly half of a statewide water policy fellows group, composed of representatives from academia, local governments, state agencies, environmental groups, industry, agriculture, and business, identified that not enough science is currently being used in water policy decisions (Dreelin and

Rose 2008). Regionally, community engagement within policy implementation arenas is identified as critical to achieving a prosperous Great Lakes-St. Lawrence River basin (Krantzberg et al. 2015).

Graduate students play an important role in cutting edge research; however, the graduate education in science, technology, engineering, and math (STEM) fields generally follows an apprenticeship model where graduate students learn from an established researcher (Vergara et al. 2014). Even though students are prepared to conduct independent research, the challenge is in developing skills and facilitating experiences that will help graduate students see how their research addresses

complex environmental problems, while working across multiple disciplines and with stakeholders, especially if they pursue a nonacademic career (Muir and Schwartz 2009; Vergara et al. 2014; Matthews et al. 2015). To complement student learning in their disciplinary training and graduate research, professional development programs can be effective at helping students develop other useful skills and learn new perspectives (Leshner 2007; Matthews et al. 2015). In the context of complex environmental problems, community-engagement and science communications training are necessary to narrow the skills gap for scientists, so that they may collaborate across a variety of disciplines, government agencies, community partners, and sector stakeholders effectively (Latimore et al. 2014). The Great Lakes Center for Fresh Waters and Human Health recently hosted a community-engaged scholarship professional development workshop, primarily geared toward graduate students and post-doctoral students associated with the Center.

In this manuscript, we (1) describe the professional development workshop, (2) present evaluation results, and (3) discuss implications of this type of program for preparing scientists to work in partnership on complex environmental problems affecting the Great Lakes. The conceptual model for the workshop, impacts, and discussion of implications of this program may provide valuable information for similar institutions working in other regions in order to build the capacity necessary for effective community engagement and science communication.

Program Description

To facilitate in-depth learning, the Community-Engaged Scholarship Workshop was held on four consecutive days from May 20-23, 2019 at the Maumee Bay Lodge and Conference Center in Oregon, OH, USA. This workshop model is considered to be a mid-level training program because there are more contact hours than a single workshop, but fewer than a year-long fellows program (Prevost et al. 2017). Participants were recruited from the recently established Great Lakes Center for Fresh Waters and Human Health (hereafter Great Lakes Center) faculty,

staff, students, and partners via email invitation and meeting announcements. Great Lakes Center leaders were encouraged to share the training program opportunity with their labs and networks. This training is a key component of the community-engagement core of the Great Lakes Center, created in 2018 and led by faculty from Bowling Green State University (BGSU). The Great Lakes Center is a collaborative effort with nine other universities and research institutions and is one of four centers funded through the National Science Foundation (NSF) and the National Institute of Environmental Health Sciences (NIEHS) – a unit within the National Institutes of Health. Additional recruitment occurred at the other NSF/NIEHS-funded centers, the Great Lakes Sea Grant Programs, Michigan State University (MSU) Extension/Michigan Sea Grant Extension fellows, MSU Environmental Science and Policy Program, and other professional networks within the Great Lakes region.

Michigan State University is a national leader with its Graduate Certification in Community Engagement that has evolved since its inception in 2008. The certification consists of 20 competency areas aligned to the following eight dimensions (Doberneck et al. 2017, 128):

1. foundations in community-engaged scholarship;
2. community partnerships;
3. criticality in community engagement;
4. community-engaged scholarship and practice;
5. approaches and perspectives;
6. evaluation and assessment;
7. communication and scholarly skills; and
8. successful community-engagement careers.

The program reported herein was based on the community-engagement competency framework described above, and was refined through an informal needs assessment to better meet the learning interests of the participants with focused interests on fresh water, Great Lakes, and water quality, including challenges caused by harmful algal blooms (HABs). The workshop content utilized a variety of teaching methods, including traditional lecture-style presentations, case studies that highlighted community-based HABs response, expert panel discussions, “speed networking”

round-tables featuring community-engagement programs, and a field trip where participants were able to get a first-hand look at water treatment plant infrastructure and HABs response protocols. The overall workshop sessions, descriptions, format, and contacts are listed in Table 1.

A planning committee consisted of representatives from the Michigan Department of Natural Resources, MSU Extension, Michigan Sea Grant, Michigan Department of Agriculture and Rural Development, Ohio State University Stone Lab and Ohio Sea Grant, the Great Lakes Center, BGSU, University of Windsor, and community partners. The committee completed the pre-workshop informal needs assessment, and through it, reduced the above eight competency areas to four and increased the emphasis on science communication, consistent with the competencies of community-engagement and Extension professionals (Blickley et al. 2013; Suvedi and Kaplowitz 2016; Atiles 2019). Our learning goals were to:

1. Increase knowledge of approaches to community-engaged partnerships;
2. Increase knowledge of community-engaged teaching and learning;
3. Increase knowledge of community-engaged research; and
4. Increase knowledge of science communications tools, resources, and perspectives of professionals in the field.

Methods

The purpose of this evaluation was to determine efficacy of this mid-level professional development workshop at achieving the above stated learning goals. An evaluation survey included retrospective pretest-posttest questions (Nimon et al. 2011) related to community-engagement competencies, Likert-type questions focused on the workshop's organization, and open-ended qualitative questions. Participants were asked to rank their self-assessed proficiency in 19 competency areas on a 4-point Likert scale from none to proficient, where none = 0, basic = 1, intermediate = 2, and proficient = 3. These competency areas addressed participant knowledge in partnership principles, community-engagement tactics, and science communication

strategies. In addition, the Community-Engaged Scholarship Workshop sought to evaluate participants' perception of the water treatment industry's response to HABs. This was addressed in part through a field trip where participants heard from the Administrator of the Toledo Water Treatment Plant and given a tour of a low pumping station, part of the City of Toledo water treatment infrastructure. This tour allowed participants to see the facilities and hear directly from staff who were involved in the City of Toledo's microcystin water contamination event in 2014 and response afterwards.

In order to assess program structure and organization, workshop participants were asked to rank statements pertaining to individual sessions as well as the workshop as a whole. Program statements were ranked from strongly disagree to strongly agree, with strongly disagree = 1 and strongly agree = 4. Eight statements were about program sessions; examples include: sessions built together well as a whole, the learning activities helped reinforce the main points of the sessions, and there was enough time for questions and answers during sessions. Additionally, participants were asked to rank statements pertaining to how they felt about the workshop overall from strongly disagree to strongly agree, with strongly disagree = 1 and strongly agree = 4. Ten program statements were utilized to gauge participants' perceptions on how the workshop content helped them to better understand stakeholder perspectives, how well it provided beneficial resources and tools, and whether attending this workshop strengthened their professional network or career.

Workshop participants were also asked what, if any, resources from this program they planned to take back and share in their workplaces. This question reflects the value of the resources provided by the program speakers and how participants saw resources fitting into their work. Resources presented during the workshop were designed to introduce participants to a range of tools, networks, and techniques that may assist in sharing their work and/or engaging their community partners. These resources were also designed to provide inspiration and novel brainstorming for participants' current research as well as for future projects. Resources included target audience and stakeholder

Table 1. Great Lakes Center for Fresh Waters and Human Health, Community-Engaged Scholarship Workshop, Ohio, 2019.

Session	Description - Objectives
Principles of partnerships	Session 1: Workshop welcome and introduction
	Session 2: Stakeholder identification and engagement
	Session 3: Collaborative partnerships with landowners
	Session 4: Principles of community partnerships
	Session 5: Collaboration with landowners/farmers
Communication and public health	Session 6: Community engagement for public health
	Session 7: Toledo Water Treatment tour
Community-engaged teaching and learning	Session 8: Partnerships for community-engaged teaching/learning
	Session 9: Community-engaged research/science
Community-engaged research	Session 10: Citizen science partnerships
	Session 11: Multi-stakeholder coalitions for transnational community-engaged research
Science communication	Session 12: Developing a science communication plan
	Session 13: Communicating with policy makers
	Session 14: Communicating with journalists
Session 15: Social media and video strategies	Practice: Social media and video strategies. Speaker: David Ruck, Great Lakes Outreach Media

identification strategies, communication strategies for different audiences, digital engagement tools and techniques (e.g., social media, videography, photography), and community-engagement opportunities (i.e., programs and networks with which to become involved or to share with partners and stakeholders). Additionally, a series of open-ended evaluation questions assessed what program aspects participants found the most impactful, both positively and negatively, and guided recommendations for program revisions.

Survey questions relied on participant self-reports to assess changes in knowledge of the community-engagement topics covered, the perceived value of the training to their careers, and their satisfaction with the training overall. A complete copy of the survey questions can be found in Appendix A. MSU Institutional Review Board approved this study STUDY00000920. The survey was distributed at the conclusion of the workshop in May 2019.

Results

Socio-demographics

Twenty-one participants attended. Of these, 20 provided feedback through the evaluation distributed at the workshop, for a 95% evaluation return rate. Of the 20 completed evaluations, there were 11 females, 8 males, and 1 transgender individual; 8 participants were Master's students, 8 participants were Doctoral students, and 4 identified as Other (respondents included 2 Post-Doctoral researchers, 1 educator, and 1 outreach professional). There was no significant racial diversity. The participant group was largely White (15 responses), though it included 3 Asians and 1 White/Hispanic individual. One survey was

returned without a response to this question.

The majority of the respondents were 20-29 years of age (12 responses). The remaining respondents in descending order were: 40-49 years (4 responses), 30-39 years (3 responses), and 50-59 years (1 response). If participants were graduate students or fellows, they were also asked to indicate how likely they were to pursue careers from a list of eight options provided, ranking each option from extremely unlikely to extremely likely, where extremely unlikely = 1 and extremely likely = 5. Eighteen out of twenty surveys returned responded to this question. Nine responses indicated that the participant was extremely likely to pursue a career in research ($M = 4.28$, $SD = 0.87$), the highest response mean of careers provided. The remaining career fields were: a university Extension program; outreach; communication; education; policy; management; and engagement. Participants were also given the option to provide their own response, of which four did so, describing fields including: mathematics, laboratory technician, consultant, and one individual considering all given options. Participant responses to their likelihood to pursue fields outside of research were distributed on the Likert scale between neutral and likely (mean range was 2.89 to 3.50).

Community-Engagement Competencies

Prior to participating in the workshop, the self-assessed proficiency mean across all 19 topic areas was 1.26, representing a basic level of proficiency for the group as a whole (Table 2). At the completion of the workshop, the overall mean increased to 2.11, indicating an intermediate level of proficiency. Therefore, the content of this event increased participants' self-assessed competency overall and by one rating level on average.

Table 2. Great Lakes Center for Fresh Waters and Human Health, Community-Engaged Scholarship Workshop, Ohio, 2019, evaluation of overall proficiency (n=19).

	Number of Items	Mean ^a	Standard Deviation	df	p
Before participation	19	1.26	0.29	18	0.000
After participation	19	2.11	0.22	18	0.000

^aMean responses on a 4-point scale with "none" coded as a 0 and "proficient" coded as a 3.

The self-assessed knowledge of the Community-Engaged Scholarship Workshop participants significantly increased across all program areas (Table 3). Notably, “Water treatment plant response to HABs” was the topic with the highest variability in knowledge ($M = 1.05$, $SD = 1.10$, $v = 1.21$) prior to the workshop, with the mean score commensurate with a basic level of knowledge. Individual responses showed that 40% of respondents (8 responses) had no knowledge of water treatment plant’s response to HABs, 30% had basic knowledge (6 responses), 15% had intermediate knowledge (3 responses), and 15% considered themselves proficient (3 responses). At the conclusion of the workshop, the participants’ self-assessed knowledge increased overall to an intermediate level of knowledge ($M = 2.15$, $SD = 0.67$, $v = 0.45$). Zero respondents indicated they had no knowledge of the topic following the completion of the workshop, 15% indicated basic knowledge (3 responses), 55% indicated intermediate knowledge (11 responses), and 30% indicated they were proficient (6 responses). “Engaging vulnerable populations for public health” was the topic with the lowest overall knowledge base before the workshop ($M = 0.60$, $SD = 0.60$, $v = 0.36$) (Table 3). Prior to completing the workshop, 45% of respondents had no knowledge of this area (9 responses), 50% had basic knowledge (10 responses), 5% had intermediate knowledge (1 response), and none responded as being proficient. Following the workshop these numbers reversed, with none responding as not having any knowledge, 45% having basic knowledge, 40% having intermediate knowledge, and 15% stating they were proficient.

The participants’ pre-workshop level of knowledge was variable, with as much as one level of competency difference between the highest and lowest topic knowledge. “Engaging vulnerable populations for public health” was ranked the lowest with a mean of 0.60. “General principles of partnerships” was ranked highest with a mean of 1.70. This relative difference in the highest and lowest ranked topic knowledge category was similar post-workshop, though the highest ranked topic changed. “Engaging vulnerable populations for public health” remained the lowest competency topic area, though with an increased mean of 1.70

($SD = 0.73$), while “translating science for public audiences” became the highest ranked topic area with a mean of 2.50 ($SD = 0.61$).

Following participation in and completion of the workshop, one participant indicated they had no knowledge in a single workshop topic called the “Spectrum of Participation” – a figure that compares promise to the public, public participation goal, along the axis of inform, consult, involve, collaborate, and empower categories along an axis of increasing impact of the decision (IAP2 2020).

Program Organization

Workshop participants’ responses to rank questions pertaining to individual sessions as well as the workshop as a whole provided data from which to assess program structure and organization. None of the evaluation respondents stated they strongly disagreed with any of the statements provided. Eight disagree responses were stated in the evaluation; these were distributed among the following statements: the individual sessions built on each other without being repetitive (1 response); the sessions fit together well as a whole (1 response); the main points of sessions were clearly presented and easily understood (1 response); the handouts/materials provided clear explanations of the ideas (1 response); the case studies provided good examples of engagement work in the Great Lakes region (1 response); there was enough time for questions and answers during the sessions (1 response); and there was enough time throughout the Institute for me to think about how to implement new ideas in my work (2 responses). The majority of respondents selected agree or strongly agree across all program statements (Figure 1).

Participants also provided responses to rank statements pertaining to how they felt about the workshop overall, from strongly disagree to strongly agree. Overall, participants agreed or strongly agreed with all provided statements (Figure 2). There was one disagree response in six of ten program statements including: this Institute provided useful tools for me to intentionally include a wider range of partners in my community-engaged work (1 response); this Institute helped me to better understand the public health dimensions of HABs (1 response); this Institute provided me with strategies to use in my community-engaged

Table 3. Great Lakes Center for Fresh Waters and Human Health, Community-Engaged Scholarship Workshop, Ohio, 2019, respondents' (n = 20) self-ratings of pre-program and post-program community-engagement topic competencies.

Community-engagement Topic Area	Pre-workshop		Post-workshop		Diff.	Z	p ^b
	Mean ^a	SD	Mean ^a	SD			
Partnerships							
Community outreach and engagement approaches	1.40	0.75	2.25	0.55	0.85	-3.900	0.000
Stakeholder and community partner identification	1.35	0.93	2.30	0.66	0.95	-3.578	0.000
Spectrum of participation	1.26	0.93	2.10	0.85	0.84	-3.557	0.000
Multi-institutional coalition building	1.15	0.75	1.80	0.62	0.65	-3.357	0.001
General principles of partnerships	1.70	0.80	2.21	0.71	0.51	-3.051	0.002
Engaging vulnerable populations for public health	0.60	0.60	1.70	0.73	1.10	-3.640	0.000
Water treatment plant responses to HABs	1.05	1.10	2.15	0.67	1.10	-3.470	0.001
Community-engaged teaching and learning							
Partnerships for advancing teaching and learning	1.25	0.72	1.95	0.61	0.70	-3.500	0.000
Multiple practices for engaged teaching and learning	1.45	0.76	2.10	0.64	0.65	-2.968	0.003
Community-engaged research							
Partnerships for advancing science and research	1.55	0.76	2.30	0.57	0.75	-3.638	0.000
Multiple practices for engaged science and research	1.45	0.83	2.30	0.66	0.85	-3.494	0.000
Science communication							
Developing a science communication plan	1.20	0.77	2.15	0.67	0.95	-3.819	0.000
Identifying multiple public audiences for your work	1.65	0.88	2.35	0.59	0.70	-3.500	0.000
Translating science for specific public audiences	1.60	0.88	2.50	0.61	0.90	-3.626	0.000
Multiple practices for engaging with policy makers	0.95	0.83	1.75	0.72	0.80	-3.771	0.000
Multiple practices for engaging with journalists	0.80	0.89	1.85	0.75	1.05	-3.666	0.000
Social media strategies for science communication	1.20	0.77	2.05	0.69	0.85	-3.494	0.000
Capacity to engage stakeholders and partners in the sustainability of the Great Lakes region	1.10	0.79	2.05	0.69	0.95	-3.578	0.000
Strategies for strengthening communication, outreach, and engagement activities related to your own work	1.20	0.70	2.15	0.59	0.95	-3.578	0.000

^aMean responses on a 4-point scale with "strongly disagree" coded as a 0 and "strongly agree" coded as a 3.^bStatistical significance between post- and pre-program determined using Wilcoxon signed rank tests ($p \leq 0.05$).

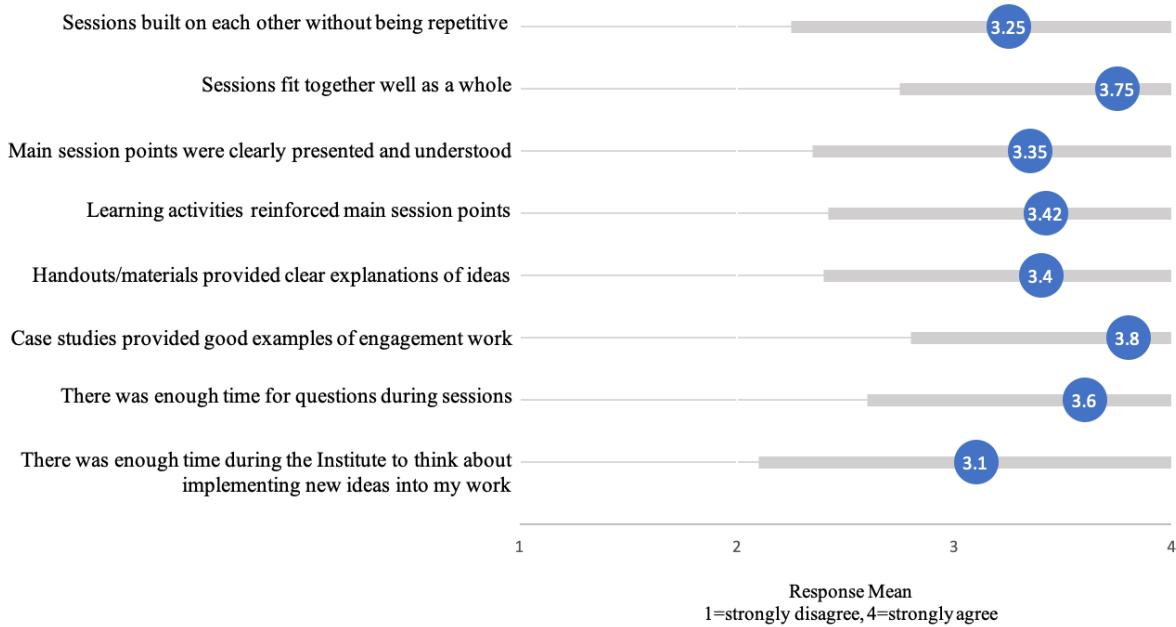


Figure 1. Great Lakes Center for Fresh Waters and Human Health, Community-Engaged Scholarship Workshop, Ohio, 2019, participants' (n=20) agreement or disagreement with session statements.

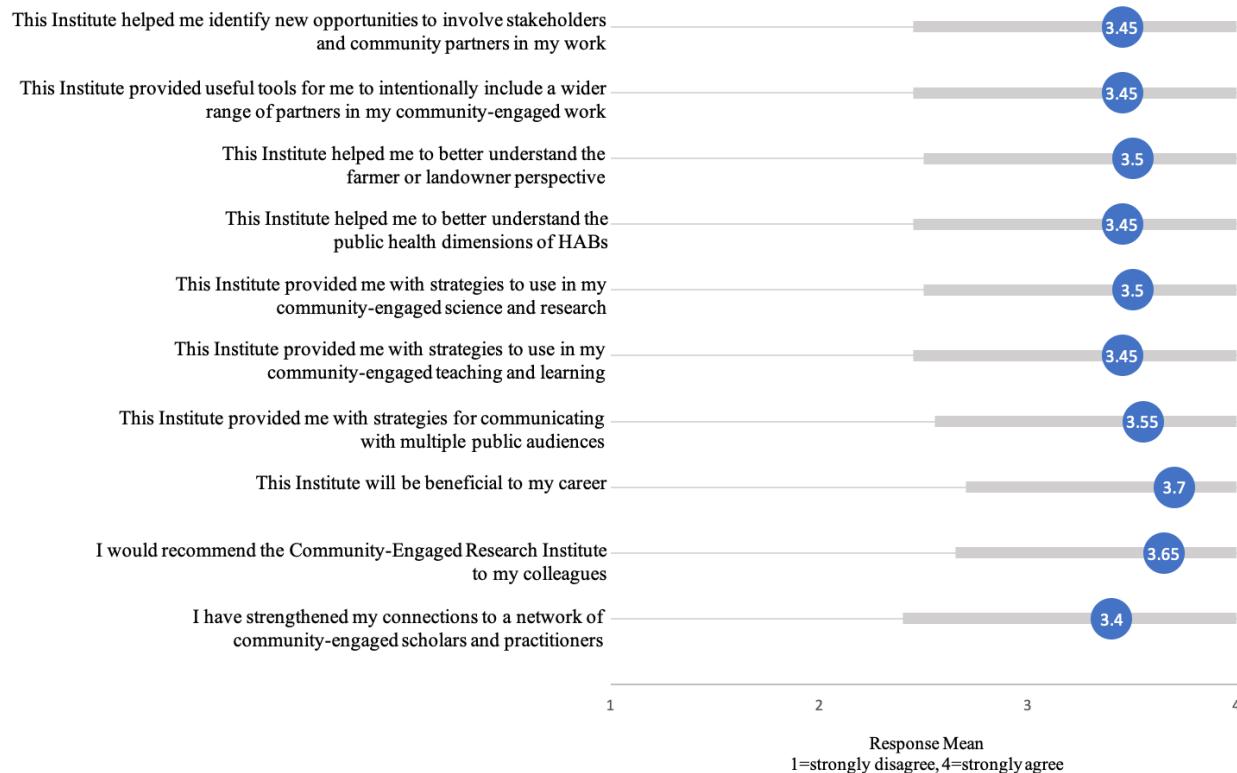


Figure 2. Great Lakes Center for Fresh Waters and Human Health, Community-Engaged Scholarship Workshop, Ohio, 2019, participants' (n=20) agreement or disagreement with overall program statements.

teaching and learning (1 response); this Institute will be beneficial to my career (1 response); I would recommend the Community-Engaged Research Institute to my colleagues (1 response); and I have strengthened my connections to a network of community-engaged scholars and practitioners (1 response).

The evaluation survey also addressed workshop areas that could be added or expanded as well as those that participants were dissatisfied with and could be re-evaluated in future program planning (Table 4). Responses to open-ended questions were summarized for interpretation of program impact. There were 18 responses to workshop areas that could be added or expanded and 15 responses to workshop areas that needed improvement or adjustment. Four responses to the question “What session topics should we consider dropping?” stated that they had no recommendations and were not listed in Table 4. Overall, participants had more positive written comments regarding session topics and case studies than negative comments and had few recommendations on how to improve the workshop. Those recommendations that were listed included revising session duration, more inclusion of real world application of presented concepts, more focus to the speed networking round-table discussions, and increased variety of teaching methods (less lecture). Responses from open-ended questions also informed as to which parts of the program participants enjoyed the most or least. Again, there were more positive responses than negative (Table 5), and many responses for least favorite aspects were suggestions of improvements for future workshops rather than statements of dissatisfaction. In all questions regarding workshop content preferences, participant opinion was variable, with some of the same topics listed as both an area to expand upon as well as one to consider dropping.

Lastly, the evaluation asked participants which of the provided workshop resources they planned to take back to share with their workplace, research team, or home campus. Seventeen participants provided responses to this question. The open-ended format allowed participants to list multiple resources in the same response. The program elements participants planned to take back and share in their workspaces were:

- Community partnerships and stakeholder engagement strategies – including identifying partners outside of academia in order to broaden community discussion and impact of projects/programs (9 responses);
- Science communication’s *Message Box* (Compass 2020) activity (7 responses);
- Science communication strategies (3 responses);
- Video/social media strategies (3 responses);
- Citizen science programs (3 responses); and
- Networking/contact information (1 response).

In addition, two responses indicated that they found all program information and resources useful and planned to share them with their workspaces. Two responses mentioned the skills and information learned during the workshop in general terms, stating that they would use it in their future work.

Discussion

The Community-Engaged Scholarship Workshop achieved its overall learning goals. These included assisting graduate students and early career scientists in gaining a better understanding of community partnerships, especially related to the public health aspects of HABs and related challenges facing water treatment facilities, and in gaining science communication skills broadly defined. This works toward building capacity for scientists to communicate with policy makers thereby decreasing the current gap in science-informed water policy decisions (Krantzberg 2004; Dreelin and Rose 2008). These community-engagement and science communication skills can enable scientists to engage with the public and teach about their science effectively and to address the need for well-educated, engaged, and influential stakeholder communities on Great Lakes topics (Krantzberg et al. 2015). Such science-to-society translational skills will become increasingly important as complex environmental problems, such as toxin-producing HABs, become more prevalent and severe (Creed and Laurent 2015). Without broader impacts training (Heath et al. 2014), Sandford (2015, 195) warns that “ineffective engagement is the kiss of death” during a time when a coherently coordinated Great Lakes basin governance is needed even more now than in the past.

Table 4. Great Lakes Center for Fresh Waters and Human Health, Community-Engaged Scholarship Workshop, Ohio, 2019, respondents' session preferences.

Topics to Expand or Add (n=18)	Topics to Adjust or Eliminate (n=15)
<p>Content</p> <ul style="list-style-type: none"> • Speed networking • Partnerships (both with specific stakeholders like policy makers/public health officials as well as in general) • Increased practice time – science communication's <i>Message Box</i> activity (Compass 2020) • Increased time with journalist panel • Specific examples of successful/unsuccessful community engagement (more "how to" and lessons learned) • Link research and community-engagement outreach – translating abstracts into science stories, applying <i>Message Box</i> (Compass 2020) into research • Public health and engaging the public (more applied level) <p>Organization</p> <ul style="list-style-type: none"> • Goal setting to be more developed at beginning of training • Opportunity for participant networking 	<p>Content</p> <ul style="list-style-type: none"> • <i>Message Box</i> (Compass 2020) activity – needed clarification • Ohio Sea Grant/Stone Laboratory field trip for policy makers • Shorten sessions – "Collaborative partnerships with landowners" & "Who are stakeholders and why should we engage them?" <p>Organization</p> <ul style="list-style-type: none"> • More focus/variety to speed networking • More case study/real world application, fewer lectures

Table 5. Great Lakes Center for Fresh Waters and Human Health, Community-Engaged Scholarship Workshop, Ohio, 2019, participants' (n=20) most and least favorite program aspects.

Most Favorite	Least Favorite
<p>Content</p> <ul style="list-style-type: none"> • Field trip • Speed networking • Panel discussions • Science communication's <i>Message Box</i> (Compass 2020) activity • Networking opportunities • Science to Solutions presentation • Case study examples <p>Organization</p> <ul style="list-style-type: none"> • All-inclusive, wide range of topics covered • Appreciation for schedule and time management 	<p>Content</p> <ul style="list-style-type: none"> • Introduction to/synthesis of speed networking • Communicating with policy makers <p>Organization</p> <ul style="list-style-type: none"> • Balance of activities vs. lecture • Breaks too short • Desire more networking opportunities with speakers/participants (possible social hour following sessions?) • Too little time outside • Not enough session clarity – need to outline key skills per session; what are participants supposed to learn?

The Community-Engaged Scholarship Workshop self-assessed evaluation showed a substantial improvement of knowledge of presented topics, particularly those focused on communication, vulnerable populations and HABs, water treatment facility response to HABs, and engaging audiences. The high means of program competencies post-workshop demonstrate that the program was effective in conveying this information, particularly in community-engagement areas in which participants were not previously familiar. No competency area mean increased by less than 0.5 and 6 of 19 (32%) increased by less than 0.8, which indicates a moderate self-assessed knowledge gain by participants based on the Likert scale provided, ranking self-assessed competency from zero to four, where zero indicated no proficiency and four indicated high proficiency. The areas of moderate knowledge gain were those regarding creating partnerships and advancing scientific research. This result may be due to the audience's research background and affiliation with the Great Lakes Center. However, since both overall competency and individual competency area means increased post-workshop, this would indicate that workshop content proved useful to participants in improving their self-assessed knowledge. Due to the fact that there was only one individual who indicated they had gained no knowledge post-workshop, this is likely a reflection of one individual's feelings on the program, rather than the knowledge gained by the participants as a group, which is consistent with the fact that all other program topics eliminated the "no knowledge" responses post-workshop. This supports the assessment of workshop informational content being beneficial to reducing the knowledge gap of participants.

The workshop was rated highly by participants for program satisfaction, indicating participants agreed that session structure, session content, and workshop organization were carried out effectively. Specifically noted was the use of case studies featuring community-engagement work in the Great Lakes region. We believe this method of teaching enabled participants to gain enhanced knowledge of engagement work as well as identified points of contact related to those projects, which may be useful in pursuing similar projects themselves in the future. The workshop was also

rated as being successful at helping participants with strategies for communicating with multiple public audiences.

Respondents strongly agreed that the professional development will be beneficial to their careers and professional networks and would recommend it to their colleagues. The number of survey responses indicating a career path in research may be reflective of the audience's affiliation with the Great Lakes Center rather than any impact of the workshop content. This choice may be indicative of other factors such as personal interest of study, preferred career pathway or goals, or a participant's area of expertise.

Given the preliminary evaluation of this workshop, other academic institutions, departments, or organizations may be interested in drawing upon this model and tailoring it to meet their desired learner needs in order to achieve the necessary skills in effective engagement and science communication. One way may be through graduate student professional development, such as the Michigan Sea Grant/MSU Extension Graduate Fellows Program (Triezenberg et al. 2020) that was modeled after MSU Graduate School's Future Academic Scholars in Teaching Fellowship Program (Prevost et al. 2017). Another option may be to offer or require courses on outreach, engagement, and science communication in graduate degree programs (Heath et al. 2014; Latimore et al. 2014). This is increasingly important as federal granting agencies in the United States often require proposals be reviewed according to the science and the broader impacts (Heath et al. 2014). These are built upon the assumption that the science is better as a result of ongoing feedback between the researchers and the public (Heath et al. 2014) and the community use of information developed in these approaches is enhanced (Doberneck et al. 2017).

If academic units adopt professional development programs or offer coursework in outreach and engagement, we recommend utilizing the eight community-engagement competency areas for graduate and professional students or Extension professionals (Suvedi and Kaplowitz 2016; Doberneck et al. 2017; Atiles 2019). As with any initiative, tailoring program goals to their specific audience or desired topics (e.g.,

HABs, microplastics, invasive species) based on a community needs assessment and input from an advisory council responsible for oversight of workshop goals and objectives is necessary. Similar future workshops at other institutions may also consider improving teaching and learning strategies for how to effectively address the importance of strong community partnerships. If an institution's workshop audience is more diverse than that which was presented in this study, these concepts may be even more necessary in order to address background knowledge gaps in these areas.

Based on the results of the Community-Engaged Scholarship Workshop evaluations, considerations for future workshops would include the incorporation of experiential learning such as field trips and the inclusion of community partners and practitioners as guest speakers. We also recommend the involvement of state and local officials, public health officials, researchers, journalists, other media leaders, and non-governmental leaders, in order to strive for diversity in perspectives and backgrounds that would facilitate community discussion and understanding. Further research is also needed in order to identify additional existing relevant case studies or to develop new relevant case studies for inclusion into future workshops. The addition of active learning activities such as lightning talks, interactive polls, mind-mapping, reflection worksheets, social learning discussions, practice, etc., can help participants bridge theory and practice and develop their own community-engaged scholarship approaches. Active learning is an effective technique helping learners to advance understanding and application in STEM concepts (Freeman et al. 2014). Evaluation is necessary to assess outcomes, make workshop improvements, and inform future professional development practice. This community-engaged approach could prepare scientists to work together and with communities to address the grand challenges of the Laurentian Great Lakes region.

While we had limited racial and ethnic diversity among our survey respondents of program participants, we had greater variation in gender identity with approximately half identifying as female. The lack of racial and ethnic diversity may be mostly attributed to the population of graduate students and early career professionals affiliated

with the Great Lakes Center and other NSF-NIEHS funded centers. However, women, Black, Indigenous, and people of color are more likely to be community-engaged scholars (Post et al. 2016; Flaherty 2017). Therefore, to some extent, our training reached White male participants who are traditionally underrepresented in community-engaged scholarship trainings, even though these demographics are contrary to diversification goals of STEM fields.

Future research could explore the longer-term impact of the concepts learned in the workshop because nearly half of the respondents indicated that they would utilize the concepts of community partnerships and stakeholder engagement strategies in their work. Additionally, if we combine general science communication with the *Message Box* activity (Compass 2020), nearly half of respondents indicated they would bring these topics and activities back to their program.

Conclusion

Graduate school is a time of socialization for future careers that includes internalizing norms and expectations of given society (Austin et al. 2009). Employing best practices for community-engaged scholarship, bridging the science to policy gap, and communicating with public audiences (Krantzberg 2004; Dreelin and Rose 2008) requires commitment of experienced scientists, as well as commitment of graduate students and early career scientists toward improving Great Lakes governance needs (Sandford 2015).

Scientists will be able to more effectively work together and partner with agencies, communities, and other stakeholders in addressing complex environmental issues if they have a solid foundation in community-engaged scholarship and science communication. Here, we presented the program model and evaluation results for a Community-Engaged Scholarship Workshop for graduate students and early career scientists within the context of the Great Lakes Center. Overall, we achieved learning goals of increased knowledge of community-engaged partnerships, community-engaged teaching and learning, community-engaged research, and science communication. Our program was based on the literature on professional

development for community engagement and then refined through the informal needs assessment. The result was four main areas to concentrate on conceptually: partnerships, teaching/learning, research, and science communications. These points of emphases are consistent with scholarship on graduate student professional development for broader impacts and conservation careers.

This community-engagement workshop model can be used by academic programs to build capacity in order to achieve broader societal impacts, and to inform and disseminate critical information to stakeholders – outcomes desired by funding agencies such as the NSF, the National Institutes of Health, and the National Institute of Environmental Health. Effective utilization of community-engaged scholarship approaches can result in better science due to the feedback from communities (Heath et al. 2014). At the same time, communities are more likely to utilize the information needed because they were involved in the process and it yields results important for them to consider.

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Appendix A

Great Lakes and Human Health Community-Engaged Research Institute Scholarship, May 20-23, 2019, Evaluation Survey.

1. BEFORE you participated in this program, what was your level of competency in each of the following areas? (None, Basic, Intermediate, or Proficient?)
 - a. Stakeholder and community partner identification
 - b. Spectrum of participation
 - c. Multi-institutional coalition building
 - d. General principles of partnerships
 - e. Engaging vulnerable populations for public health
 - f. Water treatment plant response to HABs
 - g. Partnerships for advancing teaching and learning
 - h. Multiple practices for engaged science and research
 - i. Developing a science communication plan
 - j. Identifying multiple public audiences for your work
 - k. Translating science for specific public audiences
 - l. Multiple practices for engaging with policy makers
 - m. Multiple practices for engaging with journalists
 - n. Social media strategies for science communication
 - o. Capacity to engage stakeholders and partners in the sustainability of the Great Lakes region
 - p. Strategies for strengthening communication, outreach, and engagement activities related to your own work
2. NOW what is your level of competency in each of the following areas? (statements provided were the same as question 1)
3. Please indicate how much you agree or disagree with each of the following statements about the sessions:
 - a. The individual sessions build on each other without being repetitive.
 - b. The sessions fit together well as a whole.
 - c. The main points of sessions were clearly presented and easily understood.
 - d. The learning activities helped reinforce the main points of the sessions.
 - e. The handouts/materials provided clear explanations of the ideas.
 - f. The case studies provided good examples of engagement work in the Great Lakes region.
 - g. There was enough time for questions and answers during the sessions.
 - h. There was enough time throughout the Institute for me to think about how to implement new ideas in my work.
4. What session topics should we consider expanding or adding?
5. What session topics should we consider dropping?
6. Please indicate how much you agree or disagree with the following about the program overall:
 - a. This Institute helped me identify new opportunities to involve stakeholders and community partners in my work.
 - b. This Institute provided useful tools for me to intentionally include a wider range of partners in my community-engaged work.
 - c. This Institute helped me to better understand the farmer or landowner perspective.
 - d. This Institute helped me to better understand the public health dimensions of HABs.
 - e. This Institute provided me with strategies to use in my community-engaged science and research.
 - f. This Institute provided me with strategies to use in my community-engaged teaching and learning.
 - g. This Institute provided me with strategies for communicating with multiple public audiences.
 - h. This Institute will be beneficial to my career.

- i. I would recommend the Community-Engaged Research Institute to my colleagues.
- j. I have strengthened my connections to a network of community-engaged scholars and practitioners.
- 7. What was the best part of the program?
- 8. What aspects of the program could be improved?
- 9. Are there resources you plan to take back and share with your research team, lab, or home campus? If so, what do you plan to share?
- 10. Any additional comments about the program?
- 11. I am a: (please select one)
 - a. Master's student
 - b. Doctoral student
 - c. Other (please specify)
- 12. I identify myself as: (please select one)
 - a. Female
 - b. Male
 - c. Transgender
 - d. Other
- 13. What is your race? (please select one)
 - a. American Indian or Alaska Native
 - b. Asian
 - c. Black or African American
 - d. Native Hawaiian and other Pacific Islander
 - e. White
 - f. Other, please specify:
- 14. What is your ethnicity? (please select one)
 - a. Hispanic, Latino or Spanish origin
 - b. Not of Hispanic, Latino or Spanish origin
 - c. Other, please specify:
- 15. I am in this age range: (please select one)
 - a. 20-29 years
 - b. 30-39 years
 - c. 40-49 years
 - d. 50-59 years
 - e. 60 years and above
- 16. If you are a graduate student or fellow, how likely is it that you will pursue a career in... (please select one per row)
 - a. Extension
 - b. Outreach
 - c. Communication
 - d. Education
 - e. Policy
 - f. Management
 - g. Engagement
 - h. Research
 - i. Other, please describe:

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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,

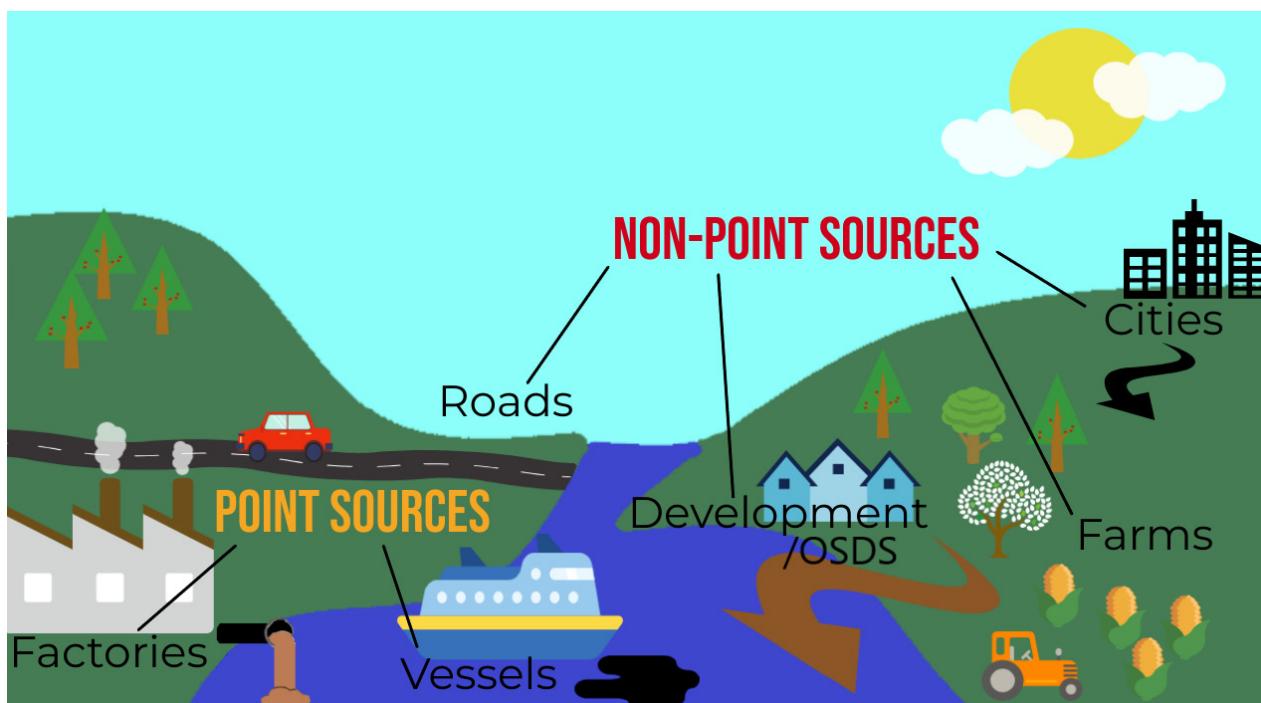


Figure 1. Illustration of various origins of point and nonpoint source pollution. Point sources can include factories and vessels. Cities, roads, farms, developments, and onsite sewage disposal systems (OSDS) are examples of nonpoint sources of pollution.

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,

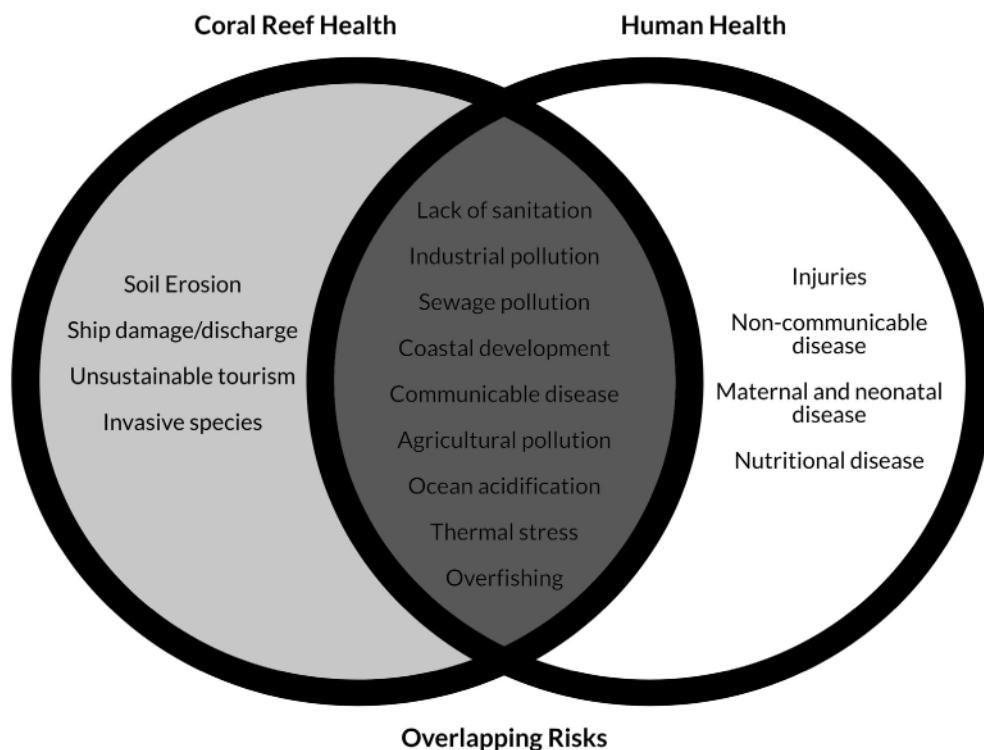


Figure 2. Venn diagram illustrating selected threats to coral reef and human health and the intersection identifying common threats. Wear (2019) conducted a literature review and supplemented the review with the Global Burden of Disease Compare Data Visualization tool from the Institute for Health Metrics 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 (Charoenca 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 (Dakhllala 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

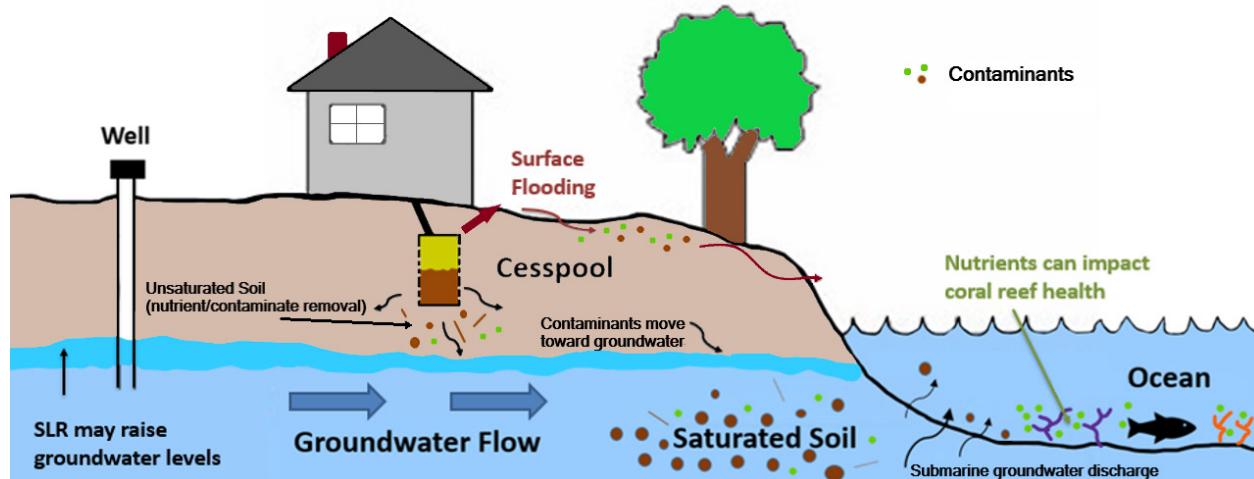


Figure 3. An illustration of the multiple pathways by which cesspool wastewater and associated contaminants can enter nearby water resources. Adapted from the State of Hawai‘i Department of Health (2017).

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

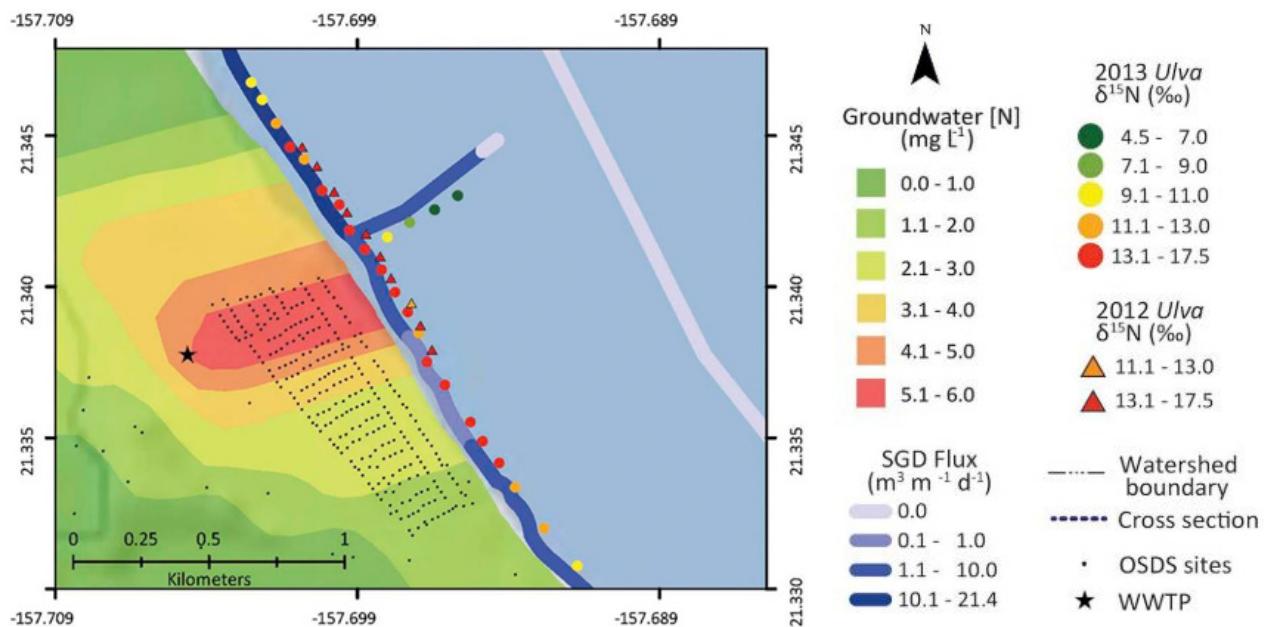


Figure 4. Map showing locations and values of *Ulva lactuca* tissue $\delta^{15}\text{N}$ in 2012 (triangles) and 2013 (circles), estimated groundwater nitrogen (polygons), submarine groundwater (SGD) flux estimates (blue band), onsite sewage disposal systems (black dots), and the Waimanalo Wastewater Treatment Plant (WWTP; black star) along a portion of the Waimanalo, 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 Hawaii'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; Erfemeijer 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.

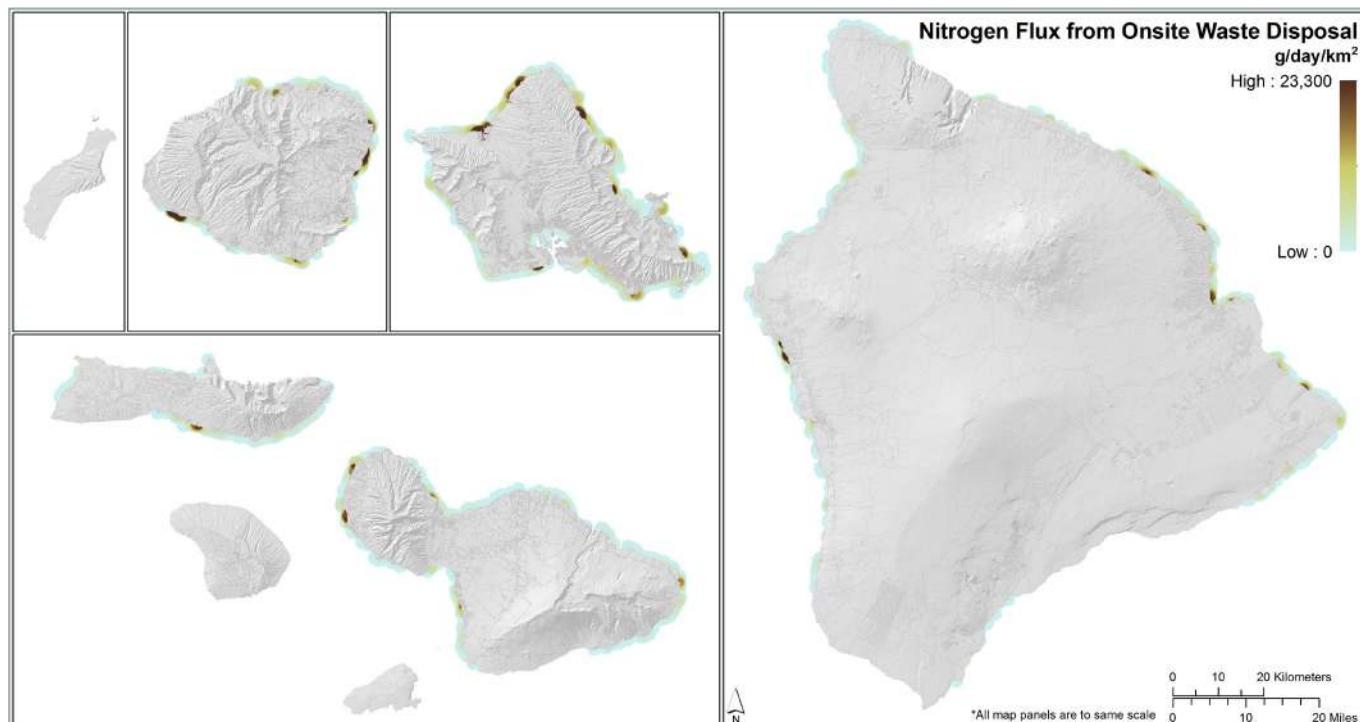


Figure 5. Map of the main Hawaiian Islands illustrating the nitrogen flux (gallons/day/km²) from onsite waste disposal systems (cesspools and septic tanks) located within 1.5 km of the coastline. Darker areas indicate more nutrients from sewage entering nearshore waters as evidenced by greater nitrogen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

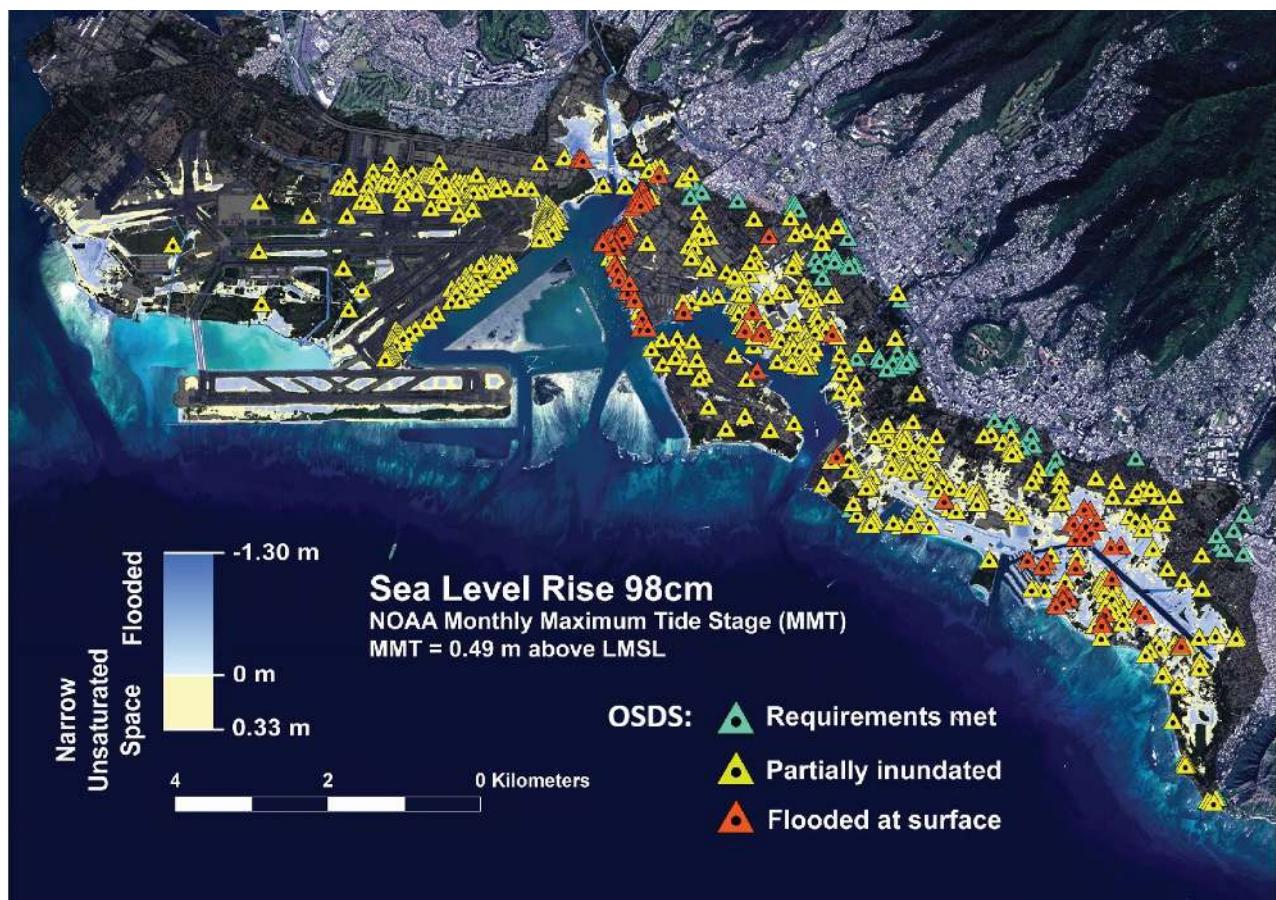


Figure 6. A simulation of groundwater inundation (blue) and narrow unsaturated space (pale yellow) for the greater Honolulu, Hawai‘i area representing 0.98 m of sea-level rise for a tide height representing the average monthly maximum tide measured at the Honolulu tide gauge. The known onsite sewage 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.

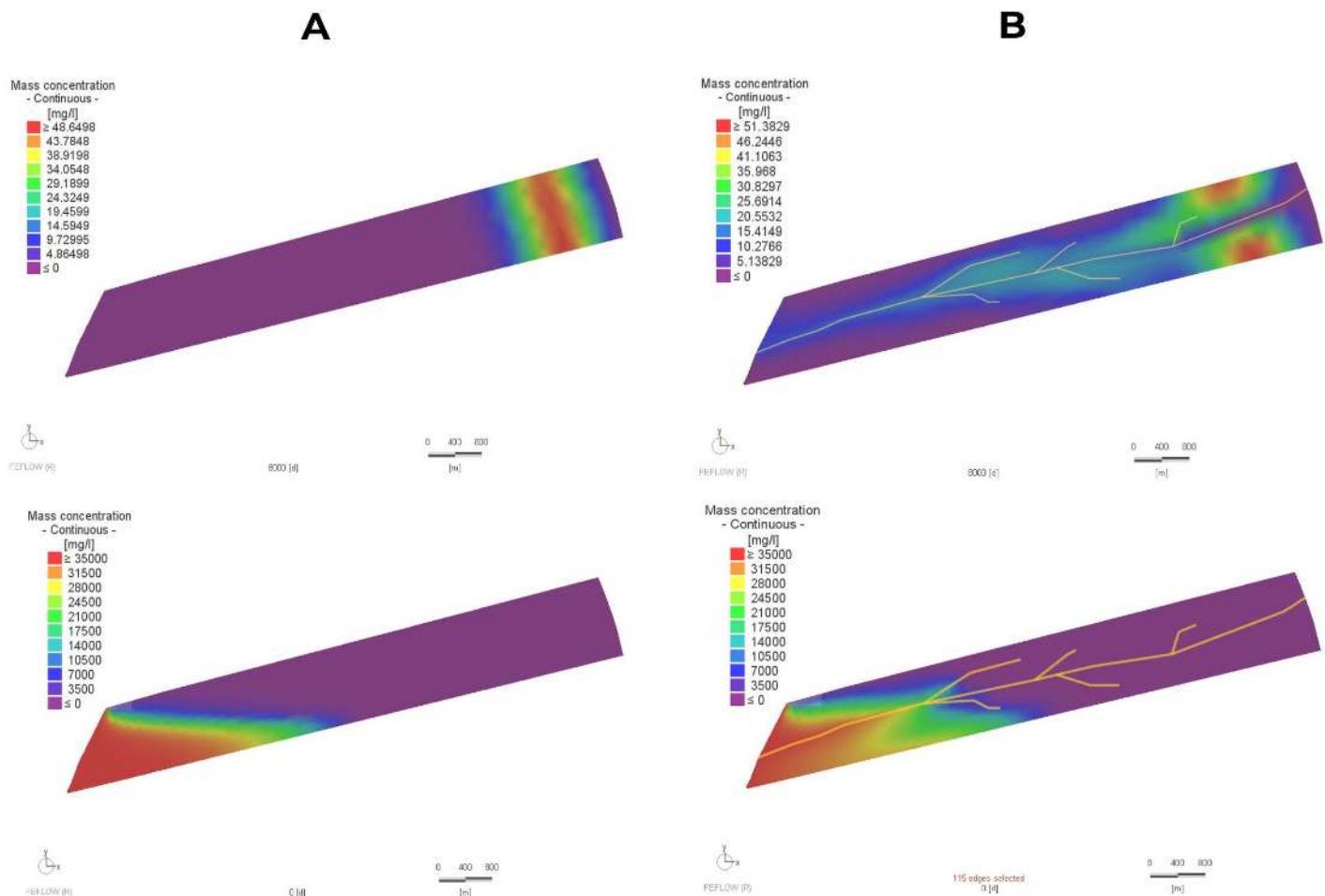


Figure 7. Simulated effect of the absence (A) and presence (B) of a subsurface lava tube (white line) on the transport of a limited-time pollutant injection in a hillslope (upper panels) and salinity distribution (lower panels). The presence of the lava tube in (B) results in an atypical transport plume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

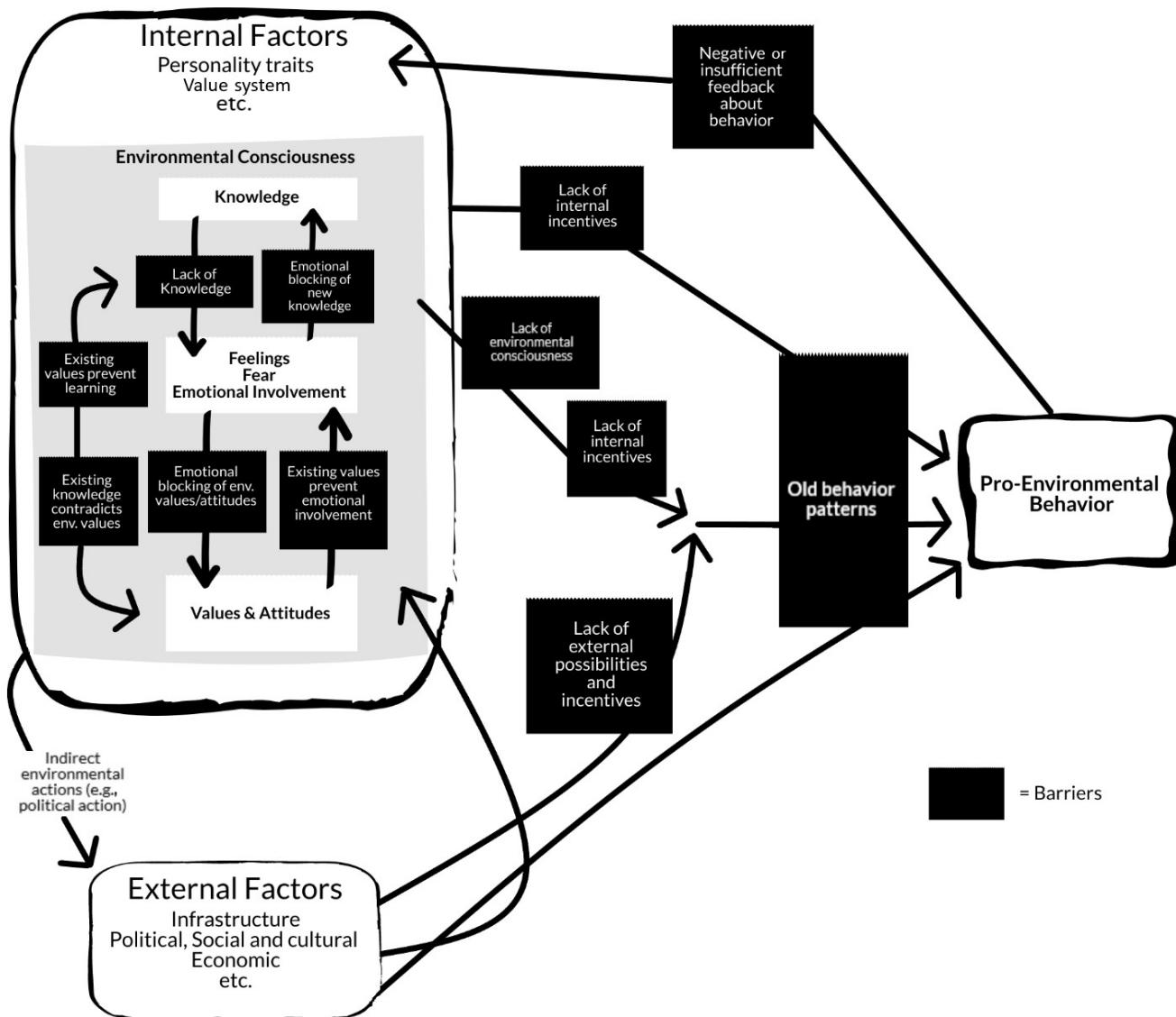


Figure 8. Model of pro-environmental behavior. Source: Adapted from Kollmuss and Agyeman (2002).

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

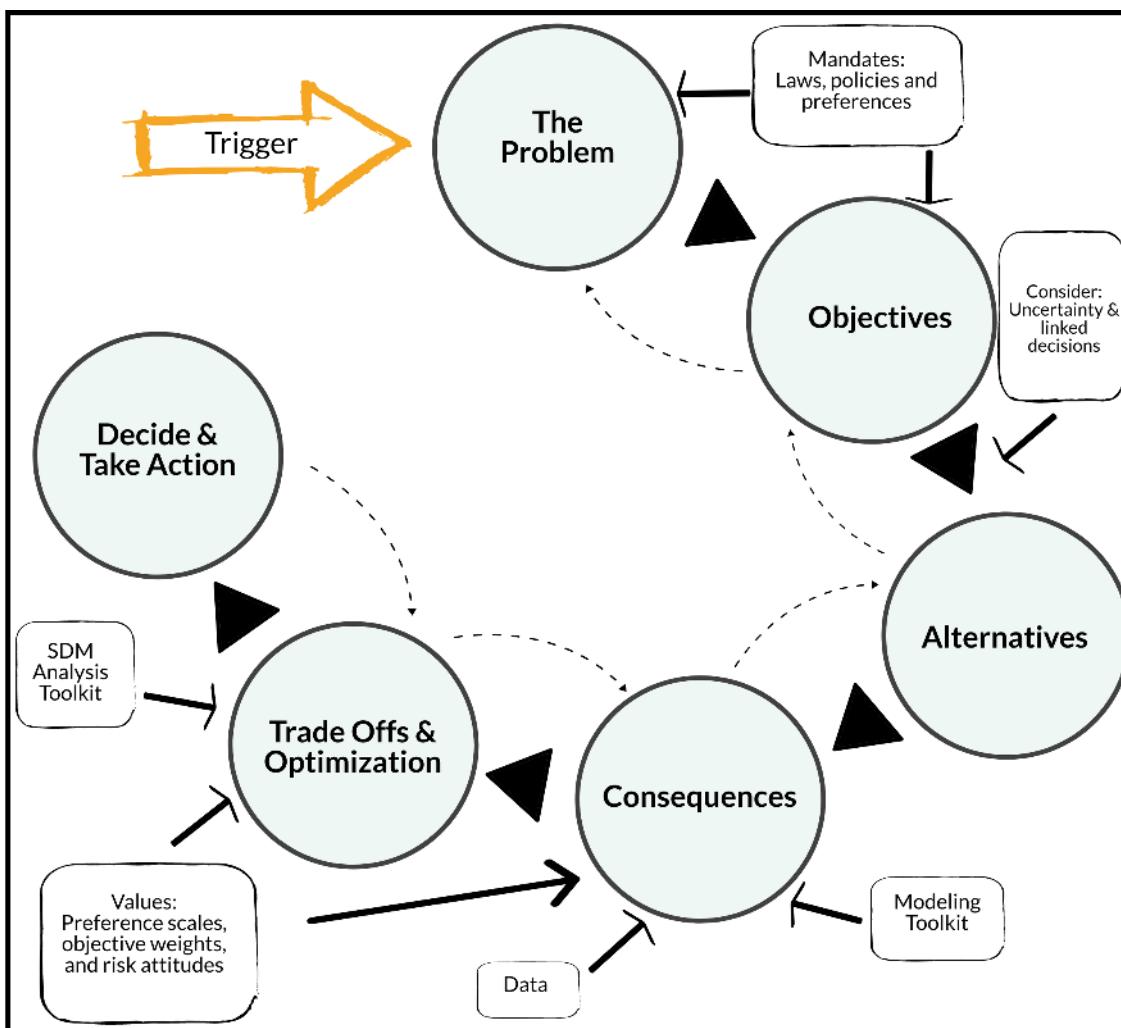


Figure 9. Structured decision analysis method diagram (SDM). A decision analysis process that “triggers” priority areas impacted by wastewater pollution from onsite sewage disposal systems (OSDS) may also be relevant and advantageous for the state of Hawai‘i to identify pollution mitigation strategies 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 δ¹⁵N, 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>

2021 UCOWR/NIWR
Annual Water Resources Conference
June 8-10, 2021
Hyatt Regency, Greenville, SC



The conference planning committee is busy planning the 2021 conference to be held June 8-10. Please note, the planning committee is aware of and carefully considering the potential pandemic impacts through June 2021. There will be a conference in June 2021!

Join us as we head to the Southeast in 2021. Nestled up against the foothills of the Blue Ridge Mountains in the heart of South Carolina's Upcountry, Greenville is a social distancing dreamland. The region's rich history, state parks, national forests, and wilderness areas provide endless opportunities for outdoor exploration. UCOWR is a family-friendly organization and we invite you to extend your conference participation and enjoy the abundance of opportunities a trip to Greenville offers.

Attendees will delve into current perspectives on a range of contemporary water resources challenges and solutions (at community, watershed, regional, national, and/or global scales). In addition to the vast range of water-related topics and disciplines that are typical of a UCOWR conference, a special focus will be on Water and Social-Environmental Justice. The Call for Abstracts will be sent out in January. Online abstract submission will open in January.

For more information on the conference, please visit
<https://ucowr.org/conference/>.

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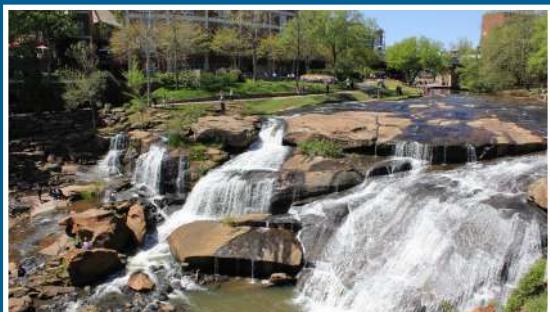
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