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Decision analysis to support wastewater management in coral reef priority area

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Abstract

A cocktail of land-based sources of pollution threatens coral reef ecosystems, and addressing these has become a key management and policy challenge in the State of Hawai'i, other US territories, and globally. In West Maui, Hawai'i, nearly one quarter of all living corals were lost between 1995 and 2008. Onsite disposal systems (OSDS) for sewage leak contaminants into drinking water sources and nearshore waters. In recognition of this risk, the Hawai'i State Department of Health (DOH) is prioritizing areas for cesspool upgrades. Independently, we applied a decision analysis process to identify priority areas to address sewage pollution from OSDS in West Maui, with the objective of reducing nearshore coral reef exposure to pollution. The decision science approach is relevant to a broader context of coastal areas both statewide and worldwide which are struggling with identifying pollution mitigation actions on limited budgets.

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Appendix A. Supplementary data

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Keywords

Conservation; Decision science; Cost efficiency; Effective management; Ecosystem services; Spatial planning

1. Introduction

Proper sewage management is critical to the health of nearby reefs (Wear and Vega Thurber, 2015). Coral reefs are declining across the world, with major implications for the livelihoods and sustainability of coastal communities and threatened coral species (Anthony et al., 2015; Ateweberhan et al., 2013; Weijerman et al., 2018; Wolff et al., 2018). Tropical island tourism economies are particularly at risk. The interacting threats of overfishing (Jackson, 2001; Williams et al., 2016), increasing ocean temperatures and acidity due to climate change (Fabricius et al., 2011; Hughes et al., 2003; Hughes et al., 2007), and poor water quality resulting from the combined impacts of sedimentation from land based runoff elevated nutrient concentrations, increased freshwater flux, and harmful household chemicals and harmful household chemicals (Fabricius, 2005; Prouty et al., 2017; Syvitski et al., 2005), place coral reefs at imminent risk (Burke et al., 2011; D'Angelo and Wiedenmann, 2014; Staley et al., 2017). Complex ecology obscures the direct causal links between reef declines and deleterious inputs, events, or actions, it is clear that a cocktail of local, land-based pollution seriously threaten coral reef ecosystems through impacts on water quality (Grigg, 1994; Pastorok and Bilyard, 1985; Reopanichkul et al., 2009; Yoshioka et al., 2016).

In rich and poor countries alike, inadequate sewage management causes declines in water quality (Burke et al., 2011; National Oceanic and Atmospheric Administration (NOAA) Coral Reef Conservation Program, 2009), and has major implications for coral reef health alongside other impacts (Prouty et al., 2017). In many coastal developing countries, poorly treated or raw sewage directly enters the coastal waters (Shahidul Islam and Tanaka, 2004; Wear and Vega Thurber, 2015). Even in economically developed nations (e.g., the State of Hawai'i, USA and the Caribbean), sewage management commonly fails to meet technical standards (Babcock et al., 2014). With a projected two billion more people on earth by 2050 (Gerland et al., 2014) – many of whom will live in tropical coastal regions (Neumann et al., 2015) - the amount of sewage entering nearshore waters will increase in the absence of significant intervention. Unlike climate change, point-source pollution is a threat that can be addressed locally, with potentially large benefits to coral reef health. Consequently, addressing the challenge of sewage pollution has become a key management and policy challenge worldwide, particularly to increase reef resilience in the face of the unmanageable onset of near term climate change impacts (Anthony et al., 2015; Ateweberhan et al., 2013; Weijerman et al., 2018; Wolff et al., 2018), and the rapid projected growth of both resident and tourist populations in vulnerable island and coastal nations (County of Maui, 2010; World Bank Group, 2018).

The focus of this paper is using the wastewater management decision making process to reduce the impact of this stressor on the coral reefs. Elevated nutrient concentrations are the

dominant nearshore pollutant from wastewater disposal. Nitrate is the wastewater derived nutrient of concern since it is the major nitrogen species in Hawaii groundwater that discharges to reefs (Glenn et al., 2012; Hunt, 2007; Hunt and Rosa, 2009). The mass of wastewater phosphorus, the other major wastewater nutrient, is effectively reduced by sorption on the soil matrix (Manahan, 2004). Elevated nitrate in Hawai'i's nearshore ecosystems have resulted in algae out competing corals leading to significant coral reef declines (Smith et al., 2005; Smith et al., 1981). When excess nutrients enter the nearshore ecosystem it can result in reefs dominated by algae (Hughes et al., 2007; Lapointe et al., 2005; Prouty et al., 2017; Smith et al., 2016), and increased bio-erosions of the reef skeletal structure (Carreiro-Silva et al., 2009; DeCarlo et al., 2015; Prouty et al., 2017). Increased nutrient levels can also reduce heat stress tolerance in some corals (DeCarlo et al., 2015; Smith et al., 2016).

In the State of Hawai'i, onsite disposal systems (OSDS) for sewage are common and contaminate drinking water sources and nearshore waters in some areas (Dollar et al., 1999; Laws et al., 2004; Swarzenski et al., 2016). OSDSs are decentralized systems which collect, treat, and/or dispose of domestic wastewater from a single or multiple dwellings or buildings, relying on physical, mechanical, and/or biological processes. Cesspools are one form of OSDS and number approximately 88,000 in the State of Hawai'i. A cesspool is a belowground well into which raw sewage enters and then percolates through an open bottom and porous sides. Because of the volcanic geology in the State of Hawai'i, untreated sewage can easily contaminate groundwater, streams, and the ocean. In particular, up to 10,000 kg of nitrogen and 2800 kg of phosphorus are discharged from cesspools each day across the State of Hawai'i (Based on 2007 baseline; Whittier and El-Kadi, 2014), as well as harmful chemicals, and pathogens (although these do not normally survive subsurface transport – see Supplementary Materials, Groundwater Modelling and Transport – Background). Since it receives no treatment, cesspool effluent is analogous to raw wastewater where the nitrogen is present mainly as dissolved organic nitrogen (DON), with the majority of DON being transformed to inorganic ammonium (Lowe, 2009). When the infiltrating cesspool effluent encounters aerobic conditions the ammonium is oxidized to nitrate (McCray et al., 2009). Hawaii's basal groundwater is predominantly oxic (Glenn et al., 2012; Hunt, 2004; Hunt and Rosa, 2009) making nitrate in the groundwater a mobile and stable pollutant (Manahan, 2004). Submarine groundwater discharge is the primary delivery mechanism of nitrate and other nutrients to oligotrophic coastal waters (Bienfang, 1980; Paytan et al., 2006) where they are disruptive to ecological processes.

In 2015, the Hawai'i State Legislature banned installation of new cesspools in the State (HB1140; §11–62), making Hawai'i the last US state to prohibit their construction. Signed into law as Act 120, incentives were established to convert cesspools to more environmentally friendly alternatives. To date, few homeowners have taken advantage of the tax credit. To accelerate conversions, HB1244/Act 125 was enacted in mid-2017 to broaden the eligibility criteria for the tax credit. Now, cesspools within 500 ft of the shoreline, perennial streams, or wetland are eligible, as are cesspools shown to impact recreational waters or drinking water supply, as well as those certified by a sewer company to be appropriate for sewer connection. Act 125 also required the conversion, upgrade, or sewer connection of all existing cesspools by 2050.

Act 125 directed the Hawai'i Department of Health (DOH) to evaluate residential cesspools and develop a prioritization method for upgrades. The subsequent report to the legislature (DOH, 2018a) identified large priority areas on each island according to their level of risk to humans, drinking water sources, and sensitive waters (e.g., impaired waterways, reefs). In some areas of the state, cesspools can be connected to nearby sewer systems, but in other areas, sewerage is not an option due to cost or feasibility constraints. Focusing on the latter, we used a decision theoretic approach to facilitate prioritization of which cesspools to upgrade.

We integrated spatially explicit biophysical modelling, economic analysis, and an ecosystem service value function to identify the most cost-effective onsite solutions (i.e., greatest level of pollution mitigation benefit per dollar spent). We evaluated alternatives using a spatially distributed model of nutrient flux to nearshore waters due to submarine groundwater discharge. The value to society of pollution reduction in a given place was also evaluated based on that place's ecological significance and recreational use.

We conducted a decision analysis to support state policy and management in the State of Hawai'i, USA, focusing on the national coral reef priority area on the western region of the Island of Maui (West Maui), in the State of Hawai'i. West Maui is a designated state and national priority area due to its economic importance and declining coral reefs; coral cover has declined 31–76% over the past three decades (Sparks et al., 2016). Recent evidence shows that groundwater emerges in the nearshore (Swarzenski et al., 2017). The county recently connected many communities in the area to sewer, but dozens of cesspools remain along a coastline that hosts rich coral habitat, and supports a booming tourism economy. We ask: How can we best act to cost-effectively address remaining OSDS pollution to minimize nearshore exposure to the risks associated with sewage? We then evaluate alternative prioritization strategies to highlight the relative gains in efficiency from each. The model and decision process are relevant throughout the State of Hawai'i, and the approach is adaptable to jurisdictions across the Pacific.

2. Methods

2.1. Study area

The study area is comprised of five watersheds in West Maui, on the island of Maui, in the State of Hawai'i, USA. These watersheds span ~90 km², and have been prioritized by the State of Hawai'i and the U.S. Coral Reef Task Force, to protect some of the most vulnerable and economically valuable coral reefs in the United States (National Oceanic and Atmospheric Administration (NOAA) Coral Reef Conservation Program, 2009). In 2007, the site had hundreds of cesspools (Fig. 1a). In 2017, only dozens remain after significant county investment in sewer connections (Fig. 1b).

2.2. Decision analysis

Collaborating with the West Maui Ridge to Reef (West Maui R2R) working group and the West Maui R2R funding and agency and support team (FAST) comprised of state and federal agency representatives, a DOH cesspool working group, and the County of Maui

Planning Department, we embarked on a decision analysis process to evaluate the utility (in terms of estimated conservation benefits) of interventions to date, and the potential utility of additional actions to address remaining sewage pollution from OSDS in West Maui. Our process involved seven steps, consistent with a decision-theoretic process:

1. Define problem
2. Define objectives
3. Select metrics
4. Identify, cost and map feasible options (and constraints)
5. Develop strategies and alternatives
6. Estimate consequences (accounting for local preferences and values)
7. Evaluate trade-offs.

All analyses were conducted in R Version 3.5.0 (R Core Team, 2018) and ArcGIS 10.2.2 (ESRI, 2012) unless otherwise specified.

1. Problem—Cesspools in West Maui are likely contaminating valuable nearshore areas, harming reef, and degrading people's recreational experience through their influence on the reef and fish, water clarity, and pollution (Ateweberhan et al., 2013; Beharry-Borg and Scarpa, 2010; Brander et al., 2007; Cooper et al., 2009; Inglis et al., 1999; Principe et al., 2012). The decision is a classic resource allocation problem and DOH and county/community partners seek to identify which cesspools to prioritize for action, and what the “best” options are for upgrading. Physical site characteristics and regulations restrict technical upgrade options, while threat varies spatially according to proximity to nearshore habitats and recreation zones.

2. Objectives—The *fundamental objectives* (aka end goals) of the State of Hawai'i's 2050 policy goal to eliminate cesspools are to minimize degradation of sensitive waters including nearshore coastal waters with coral reefs and drinking water sources, and minimize risk of human impacts (DOH, 2018a). Since the science is still equivocal about the specific magnitude, mechanisms, processes, and dose-responses underpinning coral reef responses to wastewater effluent, we collaboratively re-defined the objective of this research as: minimize pollutants reaching nearshore ecosystems, particularly in high value areas (i.e., near coral reefs, tourism use zones) resulting from OSDS systems. This re-definition assumes a linear relationship between pollution reduction and reduced risk of coral reef degradation. Absent an adequate model of effluent-exposure-reef response, this simple assumption is easy for policy makers to interpret, and directly linked to a range of potential management actions.

3. Metrics—To evaluate the utility of a range of upgrade options, we estimated the change in groundwater nitrate flux at the coastline as a measure of nearshore pollution (See SI – ‘Groundwater modelling’). We use levels of nitrate as a proxy for other pollutants present in wastewater, such as hormones and pathogens, although their decay and transport behavior differ,

We focus on nitrogen to estimate the benefits derived from upgrades to domestic wastewater systems since in Hawai'i, phosphorus from domestic wastewater disposal poses a much lower risk to nearshore marine ecosystems than nitrogen, as domestic wastewater is discharged into the soil where the phosphorus sorbs strongly to the soils (Manahan, 2004; Supplementary Material Groundwater Transport Model). Nitrate is the primary contaminant of concern for domestic wastewater disposal as it dominates biologically available nitrogen at the point of groundwater discharge into the nearshore marine ecosystem Supplementary Material Groundwater Transport Model). In the face of multiple stressors, sewage in particular is known to have detrimental impacts on coral reefs and affect resilience to bleaching (Wear and Vega Thurber, 2015). Monitoring of the reefs in West Maui point to overfishing and pollution as causes of a decline in coral cover (Sparks et al., 2016), and a recent study showed that effluent from cesspools plays a key role in determining reef state in Hawai'i (Jouffray et al., 2019);

4. Options and costs

2.3. Options

Several types of OSDS are feasible for cesspool upgrades, each consisting of a treatment and a disposal system. Each has different nitrogen reduction rates (Table S2), capital/O&M costs (Table S4), and physical constraints (SI 'Constraints'). The characteristics and conditions of a site (slope, soil type, etc.) determine the appropriateness of disposal systems in a given location, while treatment system selection is effectively independent of site conditions (WRRC, 2008). Individual characteristics are listed in Table S3. Reflecting these limitations, Whittier and El-Kadi (2014) developed an index, which classifies a given site's suitability for a leach field or infiltration chamber. This index was a cumulative score of septic siting limitation factors developed by National Resources Conservation Service soils database (NRCS, 2011). Each factor was assigned a score varying from 0.0 to 1.0. A score of 0.0 indicated no limitation while a score of 1.0 indicated a severe limitation. These factors considered include:

- Depth to groundwater;
- Depth to bedrock or cemented pan;
- Degree to which the soil is subject to flooding or ponding;
- Filter characteristics of the soil;
- Rate of water infiltration through the soil;
- Rate of seepage out of the bottom layer of the soil;
- Topographic slope;
- Susceptibility to flooding or ponding;
- Amount of subsidence the soil likely to undergo after leach field installation; and
- Fraction of rock fragments in the soil.

A review of the Whittier and El-Kadi's (2014) soil site limitation coverage for west Maui shows the primary limiting characteristics were; depth to groundwater, depth to bedrock or

cemented pan, degree to which the soil is subject to flooding or ponding, and topographic slope.

We used this index to determine what upgrade options were appropriate for individual OSDS within our study site (Fig. 2; Table S2; Table S3). Options outside of upgrading, such as installing cluster systems that treat wastewater from multiple dwellings might also be possible, but since it is unclear at present what characteristics of those systems would determine installation feasibility and cost, we were unable to include them.

2.4. Costs

Budget guidelines were used to compare system costs, and are documented in detail in Table S4. Costs were based on the assumption that the treatment system treats 1000 gal per day of domestic wastewater. Estimated costs include: labor, materials, equipment, mobilization, installation, contractor's overhead and profit, construction contingencies, operations, and maintenance considered for a 30-year lifetime of the system (WRRC, 2008). Variations in cost may occur due to site conditions such as soil type (e.g., excavation in rock), site isolation or accessibility, or slope. We calculated the net present cost (NPV) of installation and maintenance of OSDS upgrades for a 30-year period (Table 1, \$ 2017, Table S4), using two discount factors reflecting the private cost of capital (5% home equity loan rate) and a rate reflective of public sector investment (2.8%) (US Department of State, 2016). In both cases, we applied an annual inflation rate of 1.8% (based on Real GDP for the State of Hawai'i's economy, March 2017; dbedt.hawaii.gov).

5. Alternatives—Alternatives represent different ways of attacking the problem. We developed four alternatives which represent a range of costs and nitrate reduction levels:

1. Low treatment: All feasible systems upgraded to a septic system with seepage pit disposal.
2. Medium treatment: All feasible systems upgraded to a septic system with leach field disposal.
3. High treatment: All feasible systems upgraded to an advanced Aerobic Treatment Unit (ATU) with evapotranspiration (ET) disposal system.
4. Maximum Feasible Reduction: Each unit is upgraded to the unit with the best nutrient reduction that is feasible.

For each alternative, the feasibility of upgrade was based on the constraints of the selected system combination, and the characteristics and conditions of a site (Fig. 2; Table S2; Table S3). Only Class IV (cesspool) systems that can feasibly be upgraded and that are within 3 km of the coast, approximating a two to four-year travel time for nutrients, are considered for upgrading.

6. Consequences—To estimate the consequences (i.e. the change in each objective) due to implementing each alternative, we reclassified OSDS to the upgraded systems specified by the alternative and estimated nitrate flux based on the nitrogen reduction rates (Table S2) of the proposed upgrades to treatment and disposal systems. We then implemented a linked

land-sea model (Deleaux et al., 2018) by using USGS groundwater flow code MODFLOW (Harbaugh, 2005) and contaminant transport code MT3DMS (Zheng and Wang, 1999; Supplementary Methods) to estimate the magnitude and spatial distribution of nutrient flux delivered to the nearshore environment. We estimate the proportion of N flux due to each source in the base model, and then estimate reductions as a result of modified flux due to cesspools upgrades, therefore the entire estimated benefit is attributable to cesspools, but there may be an undocumented additional benefit due to decreases in inputs from legacy fertilizer. The watersheds are divided into a flow net, made up of discrete flow tubes that trace from the coast upland to 420 m above mean sea level based on the Hawai'i State 10 m DEM (Table S7. Data sources). Well data, coastal nitrates, and nitrogen application rates from multiple datasets were used to validate the groundwater model (from years 2009–15; see SI 'Groundwater model' for details).

2.5. Valuation

To account for variation in how beneficial pollution reductions were spatially, we applied weightings to the baseline estimates of nutrient reduction to reflect stakeholder preferences. Stakeholders identified pollution that 'reached the reef' (i.e. risk that the reef will be exposed to damaging nutrient levels), and that 'influences recreation' (i.e. risk that cesspool effluent will contaminate nearshore water used for a range of recreational activities) as more important for conservation and tourism-based recreation, respectively. Thus, we also estimated the utility of each alternative when these ecosystem services were reflected. First to account for influence on reefs, we multiplied the estimated benefit (nitrate reduction) values using Eq. (1), such that closer reefs received a higher weight,

$$\frac{(D - d) + 0.01}{d} \quad (1)$$

2.5.1. Weighting function—where D indicates the maximum distance of any reef from the OSDS in m, d indicates the closest reef to the OSDS in m, and 0.01 is an arbitrary very small number (1 mm). Reef location was derived based on benthic habitat maps of the West Maui focal area from the NOAA Pacific Island Fishery Science Center (Pacific Islands Fisheries Science Center, 2017) (Fig. 3). To weight the utility function for recreation, we mapped recreational value using InVEST's photo user day model (Wood et al., 2013; Fig. 3; Supplementary Information).

2.5.2. Cost efficiency—We calculated the cost efficiency (CE) as the achieved change in nitrate flux (Benefit, B, in kg nitrate) divided by cost of the upgrades (C, NP in \$2017) i.e. a modified Cost-Benefit Analysis, then ranked the options.

3. Results

3.1. Nutrient flux model

The numerical model produced outputs that mapped the distribution of nitrate in the groundwater and mass flux of nitrate to the coastal zone (Fig. 3, SI 'Groundwater Modelling'). The highest groundwater nitrate concentrations and the greatest nitrate flux

were in the southern part of the study area (Fig. 4). The largest cumulative load was legacy nitrate from past sugar and pineapple production, while golf courses (Flow Tube 5–8, and 18–24, pink color) and a sewage treatment plant injection well (Flow Tube 9, pale blue) had concentrated effects in certain areas. Cumulatively across the entire study area, OSDS was the second largest source of nitrate based on the pre-2007 dataset, contributing 14% of total load (64.1 kg/d) (Table S6). OSDS nitrate primarily contributed to the coastal nitrate load in flow tubes 13 to 18 (around Napili).

Our investigation evaluated the benefit of upgrades and sewer connections conducted since 2007 by comparing estimates for baseline DOH OSDS data from pre-2007 (published in 2014) and current county data complemented by field validation Table S7, Data Sources). We estimate that these improvements have resulted in an 89% reduction in nitrate (N) flux (corresponding to a load reduction of 55.36 kg/d) across the study area (illustrated spatially in Fig. 6).

We next evaluated the various upgrade alternatives for OSDS remaining in 2017 (currently contributing to 6.5 kg/d of N flux based on our model; Fig. 6). The Low alternative reduces N flux (from 2017 levels) by 7% (0.37 kg/d), Medium by 22% 1.07 kg/d), High by 24% (1.54 kg/d) and Max by 27% (1.67 kg/d). Fig. 7 illustrates net nitrate flux reductions in each coastal segment for each alternative, Fig. S1 costs, and Fig. 8, cost efficiency.

Depending on where in the watershed upgrades occur, in some segments the Low upgrade option could support *greater* overall N reduction than the ‘High’ option (Fig. 6, Fig. 7), since the High option is not always feasible (coastal stretch of flow tube 25). In 2017, one major hotspot remains, and the greatest benefit can be derived by addressing nitrate pollution in flow tube 18 near Napili, due to the remaining high OSDS density in that area (Fig. 1; Fig. 6).

To examine the utility of each focal strategy, we produced strategy evaluation tables to illustrate outcomes for a) unweighted, b) weighted for reef exposure, and c) weighted for human visitation. Unsurprisingly, there is a direct trade-off between upgrade cost and pollution reduction, i.e. spending more gets you more benefit. There is also a trade-off between CE and benefit, i.e. more cost efficient individual solutions do not deliver maximal nutrient reduction. Given a budget, implementing the most cost-efficient options will deliver the most benefit per dollar spent, but the interaction with feasibility creates a trade-off. A solution that incorporates additional, more costly measures is necessary to maximize reductions across the study watersheds. Interestingly, for unweighted and reef weighted benefits, the upgrade alternative with the highest CE varies depending on the NPV discount rate used (Table 2–3). The Low alternative (Septic + Seepage pit) is the most cost-effective at a 2.8% public discount rate, and the Medium (Septic + leach field) at a 5% private discount rate. There is a direct trade-off between cost and pollution reduction, and cost-effectiveness also trade-offs of benefits to coral reefs. The Max alternative is 80% as cost effective as the Low alternative, but delivers over four times the benefit. Upgrading to seepage is cheapest in both cases, but results in highly limited benefits for too high a cost (performs worst on cost-efficiency). The Medium alternative is the most cost-efficient for

private citizens, and the Low alternative for public benefit, but both trade absolute benefits for cost efficiency.

When benefit is adjusted to reflect the utility of reducing exposure of coral reefs to pollution using proximity (Fig. 3; Table 4), nitrate reduction benefit and cost still increase stepwise from Low to Max strategies, as for unweighted values (Table 3). When benefit is adjusted to reflect utility for recreational use the Max alternative (Highest feasible upgrade) is clearly superior for benefit. While the most costly, it delivers six times the (now weighted) benefit (i.e. utility) and is more cost effective than all other alternatives. The recreation focused weighting also results in the Medium alternative being selected as the most cost-effective (Table 3). There are clear trade-offs between absolute cost and benefit regardless of what services are emphasised. The spatial distribution of benefits is also affected (Fig. 1). When values are weighted to reflect recreational use, then benefits are higher in high population density areas (Fig. 1; Table 4). When reefs are weighted, solutions that reduce pollution near highly valuable reefs have higher benefits (Table 4).

4. Discussion

4.1. Decision analysis

Decision analysis applied to wastewater management can guide transparent, cost-effective decisions. We illustrate the process of evaluating wastewater management options in decision analytic framework. This process is scalable and broadly applicable to the widespread challenge of mitigating wastewater pollution for at-risk ecosystems in island economies worldwide. Locally, the calibrated groundwater model, broadly applicable cost data, and excellent partnerships between scientists, local NGOs and the relevant State Department of Health (DOH) facilitate rapid scaling up to assess the Statewide contribution of cesspools and other nutrient sources to nearshore pollution, and quantify the impacts of a full suite of management options. The recent commitment by the governor of the State of Hawai'i to protect 30% of coastal areas across the State by 2030 (State of Hawaii, 2018) offered a unique opportunity for landscape management in the State of Hawai'i that can benefit from the structure, rigor, and engaged nature of a structured decision making approach. Similarly, this structure can be applied regionally, as aquifers, streams, and coasts Pacific-wide are threatened by cesspool wastewater contamination. For instance, over a quarter (26%) of homes in Guam used OSDS (primarily cesspools) in 2000. Our framework could be modified with location-appropriate cost estimates to provide much needed cost-efficiency estimates to help policy makers select high-impact and cost-efficient wastewater management strategies to meet environmental and social goals (Fig. 9).

Cesspools are not the only source of nutrients to coral reef ecosystems, but upgrading them is a tangible, manageable option to reduce the total amount of nitrate getting to the coast in many places (Yoshioka et al., 2016). Unlike many sources of LBSP, OSDS are, in effect, point sources. OSDS are clearly identifiable, with feasible short-term solution that can be enacted by local communities (unlike international issues such as climate change). Addressing OSDS may also be less controversial than reducing other stressors to coral reefs, such as overfishing in Pacific communities. Determining which reefs show both high

nutrient concentrations and have a significant portion of their nitrate budget coming from OSDS is a prudent strategy when resources for OSDS upgrades are limited.

4.2. Tradeoffs

There are differences in Cost, Benefit, and CE across the watersheds (Figs. 3–6; Table 2). The High alternative is sensitive to whether a public or private discount rate is applied, so which solution is most cost-efficient is dependent on whether funds come from public or private sources. Upgrading to a seepage pit (Low alternative) is cheapest in both cases, but results in limited benefits for a high cost (performs worst on cost-efficiency). The Medium alternative (Septic + leach field) is the most cost-effective for private citizens (5% discount rate), and the Low alternative for public benefit (2.8% discount rate). In both cases, *absolute benefits are traded off for cost efficiency*, i.e. more cost-efficient alternatives (least expense per unit benefit) have lower absolute benefits. The higher discount rate (i.e. lower long-term cost because future costs are diminished) also switches the most cost-efficient option from Low (in 2.8% scenario) to Med, selecting an alternative with higher overall cost, but greater long term gain. Honok wai to Ka'anapali and around Kahana (segments 9, 13 and 25) are the most cost-efficient Segments of coast to focus on, but essentially represent where cheaper upgrades (either in the Low or in the case of segment 9, Moderate upgrades) are available because of site constraints (Fig. 8), and don't achieve the greatest total benefits. In these areas, it may be worth evaluating the costs and benefits of sewer connection, given the constraints to benefits from OSDS systems. Given the trade-off among these objectives, stakeholder preferences for each objective should be considered before a decision is taken.

We also examined how alternative selection varied depending on stakeholder ecosystem service (ES) preferences, incorporating risk to coral reef assets (reef distance; Fig. 3, Table 3) and the risk to areas with high tourism and recreation potential (PUD user days; Fig. 3; Table 4). The optimal alternative changes depending on what values (i.e. ecosystem services) are considered, but there are clear trade-offs between absolute cost and benefit regardless of what services are emphasised. When utility is adjusted to reflect reef distance the pattern of selections is similar to the unweighted solution (Table 3). But when utility is adjusted to reflect recreational use, the “High” and “Max” alternatives are clearly superior, delivering six times more utility than the Low (Seepage pit) alternative, and illustrating how poorly low-benefit solutions support critical ecosystem services for local people in West Maui (Table 3).

4.3. Beyond OSDS

Our findings indicate that sewer connections and OSDS upgrades made since 2007 have reduced total OSDS nitrate flux to the nearshore by 84.6% (of the ~14% of total N input generated by OSDS), highlighting the impact of improved wastewater management in coastal areas. However, sewage wastewater in West Maui is treated, then injected to groundwater, which flows to nearshore reef communities. Wastewater injectate enters near Kahekili (Fig. 4), home to one of the best condition reefs in the area (Vargas-Angel et al., 2017). When the injectate is not disinfected with chlorine as has been done in the past, there is a high degree of nitrate removal by denitrifying bacteria (Glenn et al., 2013b) (Dailer et al., 2010; Glenn et al., 2013a). Disinfecting the injectate using chlorine disrupts the

population of denitrifying bacteria and may expose this high-value reef to a significantly elevated nitrate load. Regardless of the degree of denitrification, the injected wastewater enters the nearshore as non-saline water, with elevated temperature and phosphorus all of which have the potential to degrade the coastal environment (Glenn et al., 2012).

So we are faced with the question – is sewer in West Maui simply a spatial relocation of wastewater impacts, or perhaps a shift in influence among contaminants? Consequently, understanding stakeholder risk tolerance (Hammond et al., 2015) and thresholds of concern, as well as examining the full scope of contaminants are important for determining an acceptable wastewater management strategy in this and other coral reef dependent communities.

Whether or not the cesspool upgrades have had a positive ecological impact on reef condition remains a standing question. Since 2006, an array of changes that may have affected local coral reef systems have occurred: coral reef bleaching in 2014/15 (Rosinski et al., 2017), increasing water temperatures due to climate change, cessation of active pineapple cultivation (reducing upland fertilizer loads) in 2009, increasing coastal development, the establishment of an herbivore fishery management area (Kahekili Herbivore Fisheries Management Area), which prohibits the take of herbivorous fish, and the wastewater management upgrades (e.g., cesspool to sewer connection) we documented, among others. In West Maui, while the overall nitrate contribution of OSDS is lower than some other sources (Fig. 3), nutrients from past sugarcane and pineapple fields remain significant threats, and it remains unclear how long it will take for the legacy of these monocultures to subside. Algal growth in the waters of the State of Hawai'i can be triggered by relatively low levels of nitrate, which could be triggered by levels commensurate with legacy nitrates (Fackrell et al., 2016), and bio-erosion presents a significant risk in the presence of high nitrate (Prouty et al., 2017). The specific relationship between wastewater management and coral reef health is thus difficult to ascertain, and is complicated by mixing complexity and temporal variability, biogeochemical interactions, and nitrogen pulses as a result of rainfall events (Swarzenski et al., 2012).

Open government data can help improve public policy decisions. Maui County maintains a database describing the status of properties connected to sewer in West Maui (Table S3), but we found that the State, local researchers, some county staff, and the Watershed coordinator were unaware of and unable to access this resource prior to this process. The state Department of Health's map of OSDS in West Maui was not based on current data held by the county, leading state officials to overestimate the quantity of OSDSs by an order of magnitude (400 vs. 50). This substantially influences selection of priority areas using all selected metrics, and such an oversight might misdirect public investment. Given the looming deadline to upgrade over 80,000 cesspools statewide by 2050 statewide, a refined inventory of the location and type of OSDS along with additional system characteristics is critical for diagnosing threats and directing meaningful management actions. Regardless of the OSDS management option selected, the path to effective statewide management of wastewater pollution has just begun.

4.4. Current efforts

Current state efforts to incentivize upgrades through tax credits are insufficient, even regressive. No specific financing approaches have yet been developed to meet the 2050 cesspool ban. Homeowners with cesspools/OSDS are required to pay nothing while those connected to sewerage pay around 1000 USD per annum. Yet upgrade costs, especially for high-benefit units that meet National Sanitation Foundation wastewater treatment standards (Table S4), substantially exceed the \$10,000 tax credit adopted by the State legislature (HB1125/Act 115), and ultimately, the out-of-pocket upgrade costs are a high burden for many homeowners. Moreover, tax credits are a reimbursement approach, making the incentive inaccessible to those who cannot afford large capital outlays, and excluding homeowners who do not earn enough to pay income tax, making it unlikely to motivate a transition. Alternative financing solutions such as revolving loan funds or publicly funded infrastructure upgrades would likely meet goals for managing wastewater both more rapidly, and more equitably. More innovative approaches to income generation may create funds necessary to increase the viability for both the basic and innovative solutions to cesspool pollution. For instance one option (that also increases equitability for other homeowners who pay for sewerage) would be to charge a ‘fee’ (e.g. by county) to homes not connected to sewer. Although we did not cost installation of small-scale wastewater treatment plants for particular communities with high density of OSDS, this might also be a more cost-effective option, or have more support at the County and State level for financing, simultaneously reducing the spatial relocation to some of the highest value reefs in West Maui.

Potential alternative management options to wastewater injection identified in stakeholder discussions include use of reclaimed or recycled water for irrigation or drinking, artificial treatment ponds and wetlands. The use of a wastewater injection system at a site with lower risk for coral reefs was also identified as a potential option. Reclaimed water re-use for irrigation holds promise, but similarly risks spatially relocating threats if instigated without consideration of the implications for coral reef ecosystems. Fortunately, the structured decision making approach used for this work provides a foundation to evaluate such risks, and bring stakeholders to the table to consider multiple costs and benefits. Combined with a consultative approach to identify potential sites and determine costs, high risk locales can easily be screened out (Vymazal, 2011). The use of reclaimed or recycled water as drinking water (‘toilet to tap’) could solve multiple challenges, since the State of Hawai‘i’s freshwater is scarcer as its population grows (County of Maui, 2010; Engott et al., 2015), but is costly, and would require a shift in the perception that such water is ‘dirty’ through targeted outreach and better trust with homeowners (Coxon, n.d.; Ormerod and Scott, 2013).

A more holistic, data-driven approach to wastewater management policy in West Maui and statewide that accounts for multiple objectives and stakeholder values is needed, and can be supported by structured decision making. This and other decision science approaches are relevant to the often conflict laden management of coastal systems worldwide.

Supplementary Material

Refer to Web version on PubMed Central for supplementary material.

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Fig. 1.

Density of OSDS in the study area in West Maui, Hawai'i, from a) 2007, and b) 2017, after sewer connections. Green triangles represent the locations of communities labelled in black text. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

**constraint by leach field suitability limitation, defined by Whittier & El-Kadi 2014*

Fig. 2. Four alternatives were considered for upgrades for on-site disposal systems in West Maui: Low, Medium, and High levels of treatment, plus a fourth Max alternative, which considers the highest upgrade level possible for each given system. System upgrade feasibility was constrained by the recommendations or limitations of the given disposal system option.

Fig. 3.

Two different weightings to reflect stakeholder preferences: a) illustrates mapped coral reef habitat data based on benthic habitat maps of the West Maui focal area (Pacific Islands Fisheries Science Center, 2017) used to calculate distance to nearest reef for each flow tube, and b) illustrates the average Photo User Days, a proxy for human visitation and recreational value, within coastal segments, estimated by the Flickr model; higher values represent higher visitation.

Fig. 4.

Flow tubes overlaid on the mapped distribution of land uses that add nitrate to the groundwater, illustrating simulated coastal nitrate flux in units of kg per day per meter of shoreline per day (kg/d/m). See “SI Groundwater Modelling Calibration” for base data.

Fig. 5.
Bar graph with numbers corresponding to flow tubes showing the magnitude of nitrate sources for each flow tube in kg/m/day.

Fig. 6. Coastal nitrate (N) flux, in grams per meter per day, by segment (per flow tube), in (a) pre-2007, and (b) 2017, and (c) Benefit, or amount of coastal N reduced from 2007 to 2017. Grey coastal segments have no N flux or change.

Fig. 7. Benefit: Coastal nitrate (N) flux reduced, in grams per meter per day, by segment (flow tube), for each of the alternatives considered for upgrading existing (2017) cesspools. Grey coastal segments indicate where no OSDS upgrades occurred.

Fig. 8.

Cost efficiency by coastal zone for each alternative; total benefit (grams of nitrate reduction over a 30-year period) per dollar. Grey coastal segments have no change, which indicate coastal segments where no upgrades were selected under that scenario.

Fig. 9.

Coastal benefit (nitrate reduction) resulting from the Max upgrade scenario; benefit values unweighted, weighted for reef health (by distance to nearest reef), and weighted for public recreation (by Photo User Days).

Table 1

Matrix of System Costs for feasible combinations of treatment and disposal systems, for NPV discount rates of (a) 2.8% and (b) 5%; greyed boxes indicate unviable system combination. Values represent typical initial installation and maintenance costs, adjusted to net present value of a 30-year period (sources: WRRC (2008); Dennis Poma, pers. comm). Bottom left corner.

(a) NPV discount: 2.8%						
		Cesspool	Septic	ATU NSF 40	Advanced treatment NSF 40/245	
		\$5083	\$14,933	\$126,730		\$50,864
None	\$0	\$5083				
Seepage pits	\$10,664		\$25,598	\$137,394		\$61,528
Leach field	\$41,560		\$56,493	\$168,290		\$92,424
Infiltration chambers	\$17,000		\$31,933	\$143,730		\$67,864
Drip irrigation + standard	\$22,000			\$148,730		\$72,864
Evapotranspiration	\$20,508			\$147,238		\$71,373
(b) NPV discount: 5%						
		Cesspool	Septic	ATU NSF 40	Advanced treatment NSF 40/245	
		\$3780	\$13,630	\$103,217		\$42,440
None	\$0	\$3780				
Seepage pits	\$10,471		\$24,101	\$113,687		\$52,911
Leach field	\$33,094		\$46,725	\$136,311		\$75,534
Infiltration chambers	\$17,000		\$30,630	\$120,217		\$59,440
Drip irrigation + standard	\$22,000			\$125,217		\$64,440
Evapotranspiration	\$20,378			\$123,595		\$62,818

Table 2

Strategy evaluation table, with 2.8 and 5% discount rates, unweighted. Each row represents an alternative, while each column is an objective. Each objective is color-coded with a 4 -point color gradient from yellow (worst), to blue (best). QTY denotes the number of OSDS systems upgraded in each alternative.

	QTY [#]	Total N flux [kg/d]	Benefit (nitrate reduced, [kg/30 years])	NPV discount: 2.8%			NPV discount: 5%		
				NPV [\$]	CE (B/C) [kg/\$]	Cost per B [\$ /kg]	Cost	CE (B/C)	Cost per B
2007	484	61.86							
2017	57	6.5							
Low	8	6.12		204,784	0.0202	49.62	192,808	0.0214	46.72
Med	10	5.43		564,930	0.0208	48.08	467,250	0.0251	39.77
High	13	4.96		927,849	0.0182	55.04	816,634	0.0206	48.44
Max	15	4.83		979,045	0.0187	53.45	864,836	0.0212	47.22

Table 3

Strategy evaluation table, with 2.8 and 5% discount rates, showing objectives after weighting to represent coral reef proximity. Each row represents an alternative, while each column is an objective. Each objective is color-coded with a 4-point color gradient from yellow (worst), to blue (best). QTY denotes the number of OSDS systems upgraded in each alternative.

	QTY [#]	Total nitrate flux [kg/d]	Weighted benefit (REEF)	NPV discount: 2.8%			NPV discount: 5%		
2007	484	61.86							
2017	57	6.5	3.72	NPV [\$]	CE (B/C) [kg/\$]	Cost per B	Cost	CE (B/C)	Cost per B
Low	8	6.12	0.2667	204,784	0.0000013	767814	192,808	0.00000138	722911.56
Med	10	5.43	0.8942	564,930	0.00000158	631752	467,250	0.00000191	522517.83
High	13	4.96	1.2218	927,849	0.00000132	759429	816,634	0.0000015	668401.53
Max	15	4.83	1.3416	979,045	0.00000137	729784	864,836	0.00000155	644652.29

Table 4

Strategy evaluation table showing objectives after weighting to represent recreation utility using a 5% discount rate Each row represents an alternative, while each column is an objective. Each objective is color-coded with a 4 -point color gradient from yellow (worst), to blue (best). QTY denotes the number of OSDS systems upgraded in each alternative.

	QTY [#]	Total nitrate flux [kg/d]	Weighted benefit (PUD)	NPV Discount: 2.8%			NPV discount: 5%		
				NPV [\$]	CE (B/C) [kg/\$]	Cost per B	Cost	CE (B/C)	Cost per B
2007	484	61.86							
2017	57	6.5	379.29	204,784	0.0001081	9252	192,808	0.0001148	8711.16
Low	8	6.12	22.13	564,930	0.0001552	6444	467,250	0.0001876	5329.62
Med	10	5.43	87.67	927,849	0.000143	6991	816,634	0.0001625	6152.78
High	13	4.96	136.76	979,045	0.0001397	7159	864,836	0.0001581	6323.69
Max	15	4.83							