Title: Decision analysis to support wastewater management in coral reef priority area

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Abstract (max **150** words, currently **158**)
A cocktail of land-based sources of pollution threatens coral reef ecosystems, and addressing these has become a key management and policy challenge in Hawai‘i, US and territories, and globally. In West Maui, Hawai‘i, nearly one quarter of all living corals were lost between 1995-2008. Onsite disposal systems (OSDS) for sewage are common contaminants for 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 in coastal systems worldwide which are struggling with identifying pollution mitigation actions on limited budgets.

Keywords: conservation, decision science, cost efficiency, effective management, ecosystem services, spatial planning

Highlights

- There is a direct trade-off between cost and pollution reduction.
- Low-benefit alternatives poorly support critical ecosystem services in West Maui.
- Highly cost-effective solutions also have limited feasibility, so a mix of options are required.
- Open, accessible and current data can improve public policy decisions.
- Decision Science is a transparent, powerful tool for managing coastal systems.

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 (Carpenter et al. 2003). Tropical island tourism economies are particularly at risk. While 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 threatens coral reef ecosystems (Grigg, 1994; Pastorok and Bilyard, 1985; Reopanichkul et al., 2009; Yoshioka et al., 2016). Addressing these threats has become a key management and policy challenge worldwide, particularly to increase reef resilience in the face of climate change (Carpenter et al., 2008).

In rich and poor countries alike, inadequate sewage management causes declines in water quality (Burke et al., 2011; NOAA Coral Reef Conservation Program, 2009). 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., Hawaiʻi, 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.

In Hawaiʻi, 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 Hawaiʻi. A cesspool is a belowground well into which raw sewage enters and then percolates through an open bottom and porous sides. Because of Hawaiʻi's volcanic geology, untreated sewage can easily contaminate groundwater, streams, and the ocean with disease-causing pathogens and harmful chemicals. In addition to these contaminants, up to 10,000 kg of nitrogen and 2,800 kg of phosphorus are discharged from cesspools each day across the State of Hawaiʻi (Based on 2007 baseline; Whittier and El-Kadi, 2014). As the nitrogen in the cesspool discharge oxidizes to nitrate, which is stable in groundwater, the majority of this nutrient migrates to the ocean in submarine groundwater discharge (Paytan et al., 2006), where it enters highly oligotrophic coastal water, disrupting ecological processes.

In 2015, the Hawaiʻi State Legislature banned installation of new cesspools in the State (HB1140; §11-62), making Hawaiʻi 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 feet 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 HI DOH to evaluate residential cesspools and develop a prioritization method for upgrades. The subsequent report to the legislature (DOH, 2018) 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.

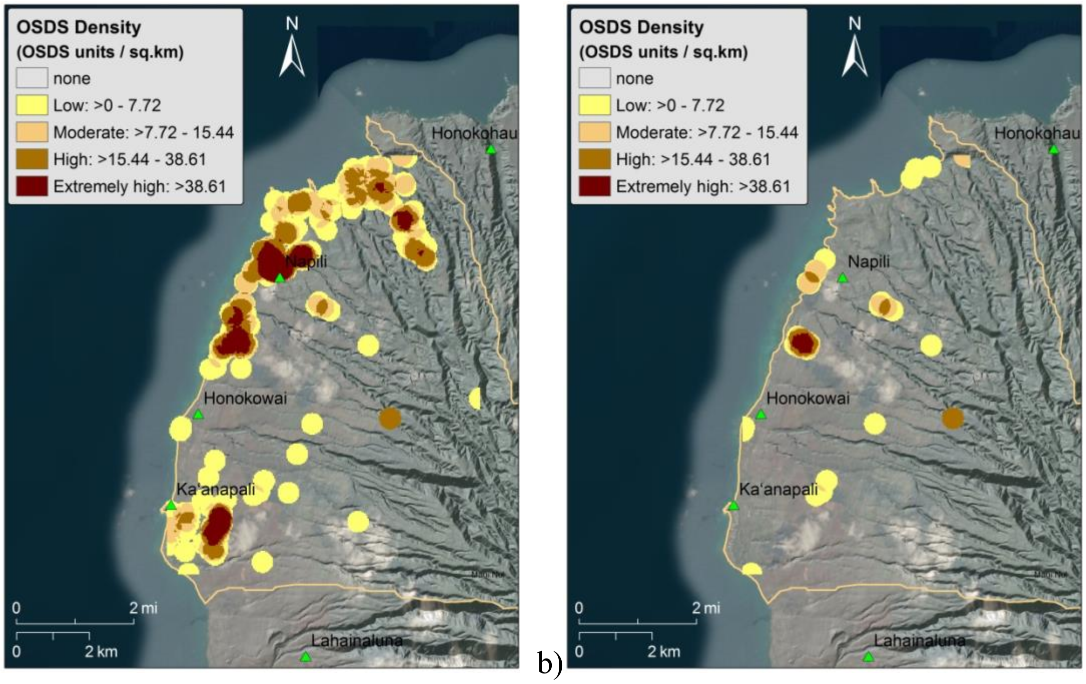
We integrated spatially explicit biophysical modelling, economic analysis, and an ecosystem service value function to identify the most cost-effective onsite solutions (i.e., greatest level of pollution mitigation benefit per dollar spent). We evaluated alternatives using a spatially distributed model 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 Hawaiʻi, focusing on the national coral reef priority area of West Maui, 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 Hawaiʻi, and the approach is adaptable to jurisdictions across the Pacific.

Methods

Study area

5 watersheds in The West Maui, Hawaiʻi, USA includes five spanning ~90 km^2 that have been prioritized by the state and the U.S. Coral Reef Task Force, to protect some of the most vulnerable and economically valuable coral reefs in the United States (NOAA Coral Reef Conservation Program, 2009) In 2007, the site had hundreds of cesspools (Figure 1a). In 2017, only dozens remain after significant county investment in sewer connections (Figure 1b).



a) b)

Figure 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.

<u>Decision analysis</u>

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 Hawai‘i Department of Health (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 analysis was conducted in R Version 3.5.0 (R Core Team, 2018) and ArcGIS 10.2.2 (ESRI 2017) unless otherwise specified.

1. Problem

Cesspools in West Maui are likely contaminating valuable nearshore areas, harming reef, and degrading people’s recreational experience. It 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”

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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 Hawai'i's 2050 policy goal to eliminate cesspools are to minimise degradation of sensitive waters including nearshore coastal waters with coral reefs and drinking water sources, and minimize risk of human impacts (DOH, 2018). 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: minimise 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.

4. Options and Costs

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 as (in order of decreasing suitability): not limited, slightly limited, moderately limited, or severely limited. We used this index to determine what upgrade options were appropriate for individual OSDS within our study site (Figure 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.

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 1,000 gallons 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%) (OMB 2016). In both cases, we applied an annual inflation rate of 1.8% (based on Real GDP for Hawai'i's economy, March 2017; dbedt.hawaii.gov).

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 **$5,083**	Septic **$14,933**	ATU NSF 40 **$126,730**	Advanced Treatment NSF 40/245 **$50,864**
None	**$0**	$5,083			
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 **$3,780**	Septic **$13,630**	ATU NSF 40 **$103,217**	Advanced Treatment NSF 40/245 **$42,440**

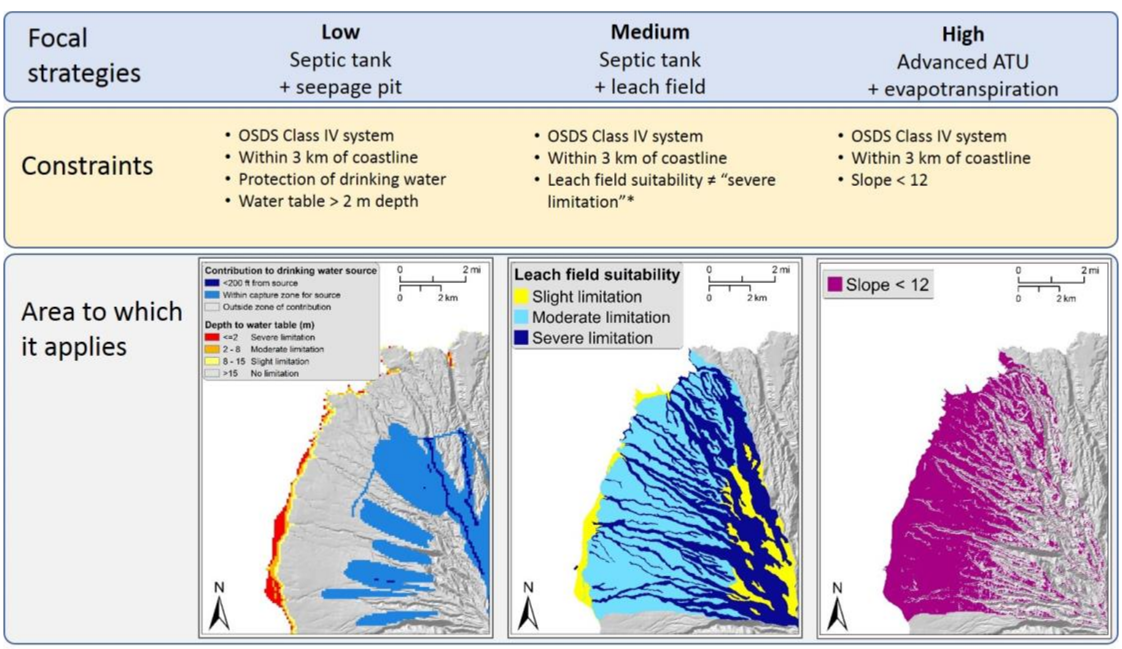
None	**$0**	$3,780			
Seepage Pits	**$10,471**		$24,101	$113,687	$52,911
Leach Field	**$33,094**		$46,725	$136,311	$75,534
Infiltration Chambers	**$17,000**		$30,630	$120,217	$59,440
Drip Irrigation + Standard	**$22,000**			$125,217	$64,440
Evapotranspiration	**$20,378**			$123,595	$62,818

5. Alternatives

Alternatives represent different ways of attacking the problem. We developed four alternatives which represent a range of costs and nitrogen 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 (Figure 2; Table S2; Table S3). Only Class IV (cesspool) systems that can feasibly be upgraded and that are within 3km of the coast, approximating a two to four-year travel time for nutrients, are considered for upgrading.



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

Figure 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.

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 nitrogen 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 (Delevaux et al., 2018) by using USGS groundwater flow code MODFLOW (Harbaugh, 2005) and contaminant transport code MT3D-MS (Zheng and Wang, 1999; Supplementary Methods) to estimate the magnitude and spatial distribution of nutrient flux delivered to the nearshore environment. The watersheds are divided into a flow net, made up of discrete flow tubes that trace from the coast upland to 420m above mean sea level based on the Hawai‘i State 10m 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).

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 (nitrogen reduction) values by distance to reef using benthic habitat maps of the West Maui focal area from the NOAA Pacific Island Fishery Science Center (Pacific Islands Fisheries Science Center, 2017) (Figure 3). To weight the utility function for recreation, we mapped recreational value using InVEST’s photo user day model (Wood et al., 2013b; Figure 3; Supplementary Information).

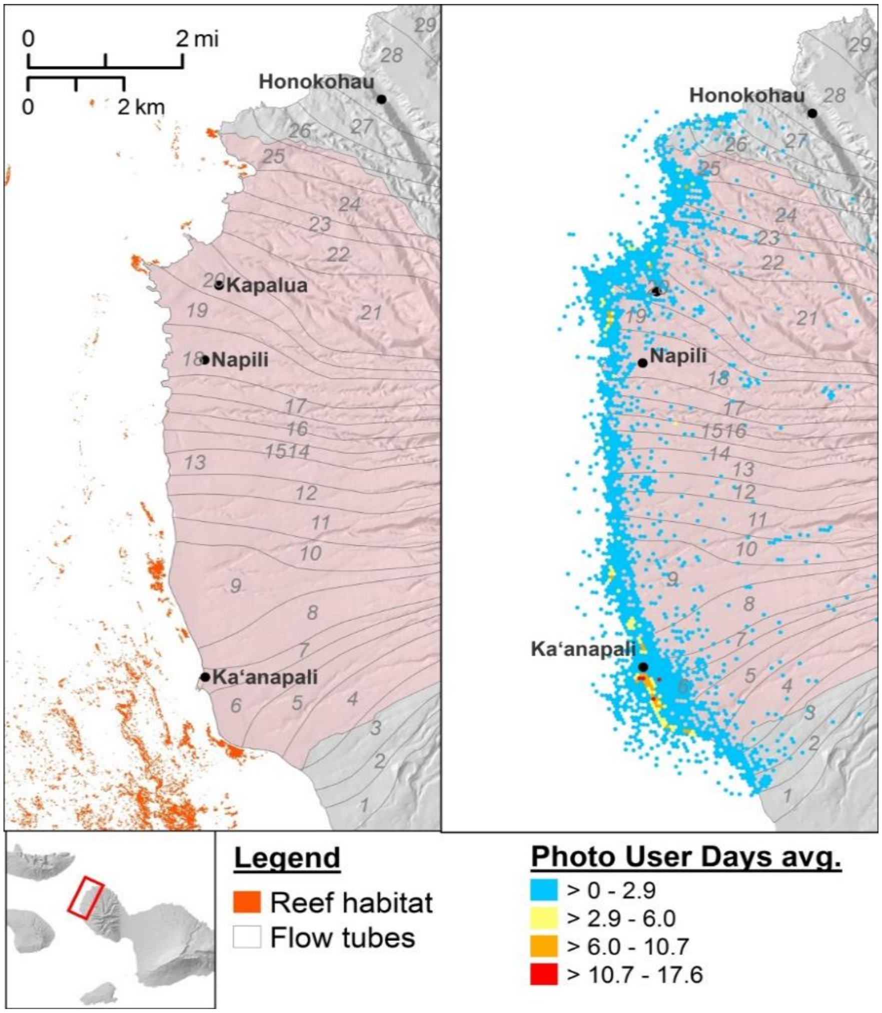


Figure 3. Two different weightings to reflect stakeholder preferences: a) illustrates coral reef habitat data (Pacific Islands Fisheries Science Center, 2017) used to calculate distance to nearest reef for each flow tube, and b) illustrates the average Photo User Days, a proxy for human visitation and recreational value, within coastal segments, estimated by the Flickr model; higher values represent higher visitation.

Cost Efficiency

We calculated the cost efficiency (CE) as the achieved change in nitrogen 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.

Results

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 (Figure 3, SI "Groundwater Modeling"). The highest groundwater nitrate concentrations and the greatest nitrate flux were in the southern part of the study area (Figure 3). The largest cumulative load was legacy nitrogen 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 nitrogen 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).

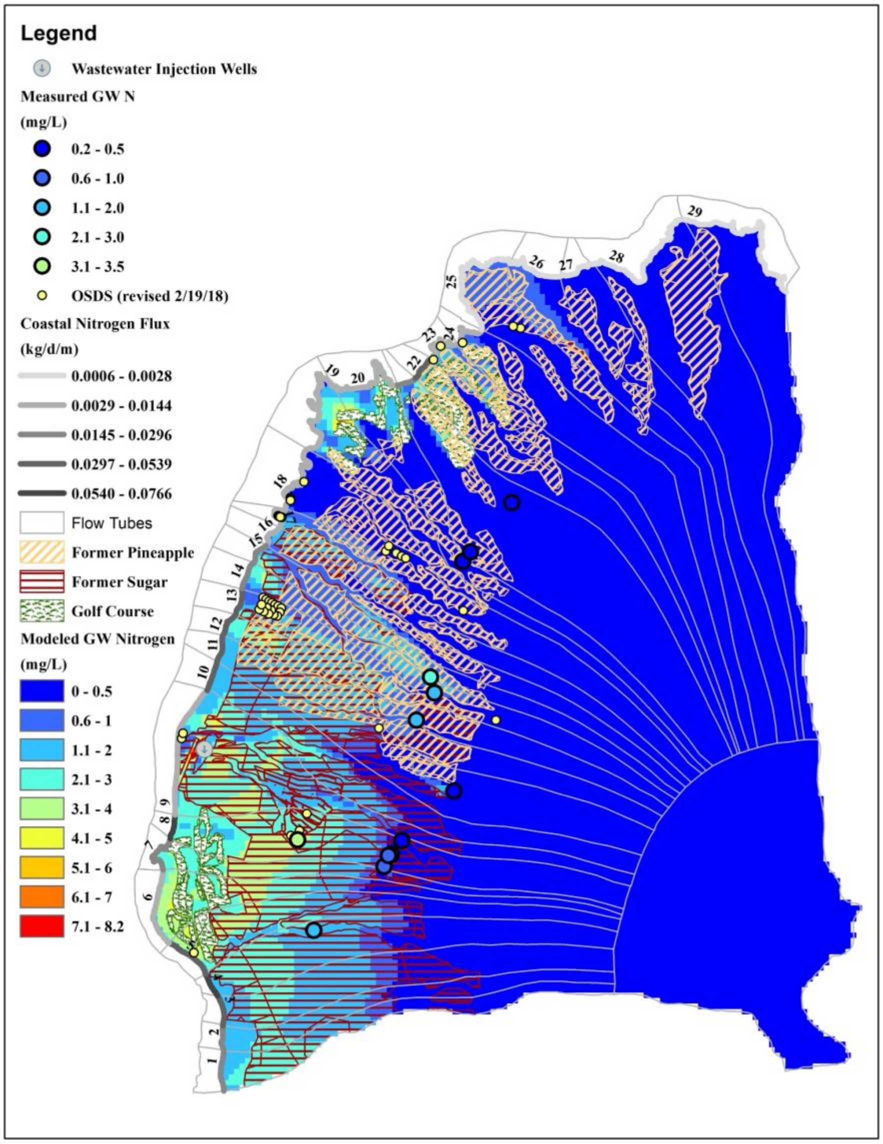


Figure 4. Flow tubes overlaid on the mapped distribution of land uses that add nitrate to the groundwater, illustrating simulated coastal nitrate flux in units of kg per day per meter of shoreline per day (kg/d/m). See "SI Groundwater Modelling Calibration" for base data

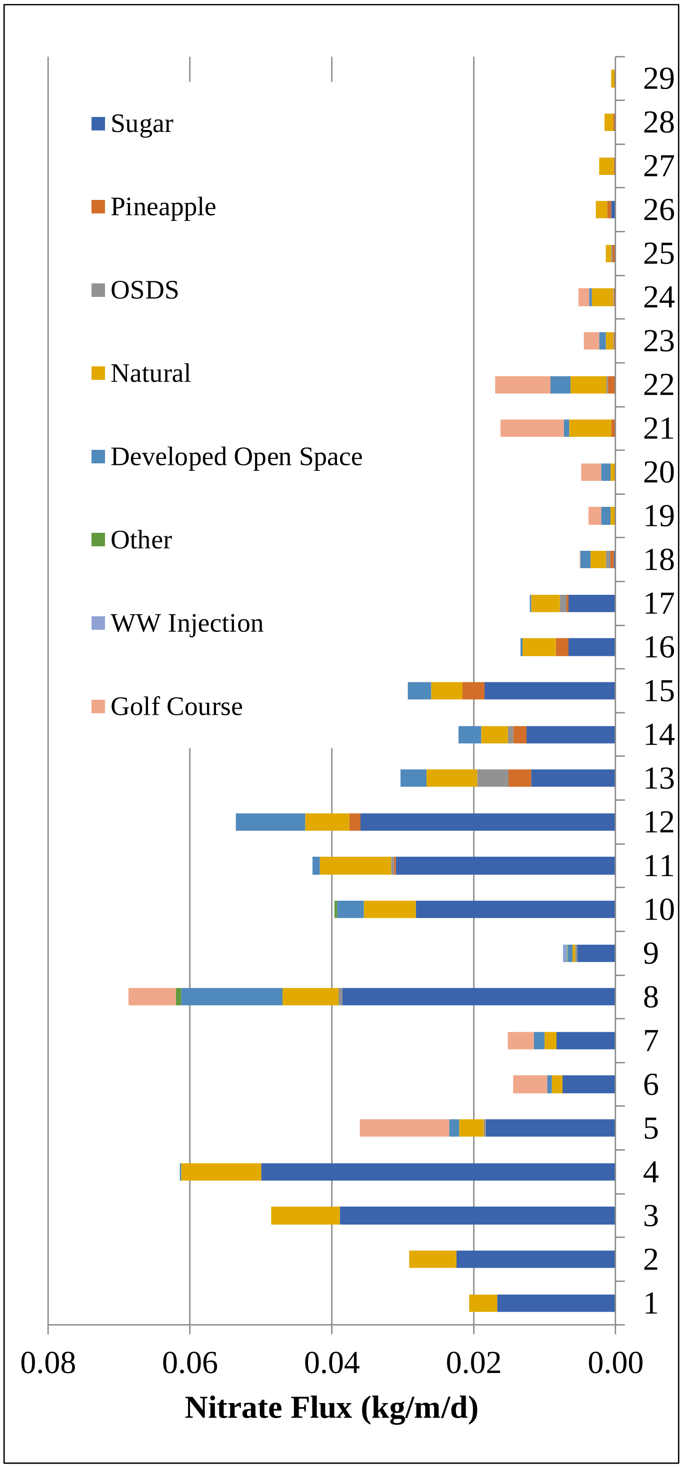


Figure 5. Bar graph with numbers corresponding to flow tubes showing the magnitude of nitrate sources for each flow tube in kg/m/day.

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 Figure 6).

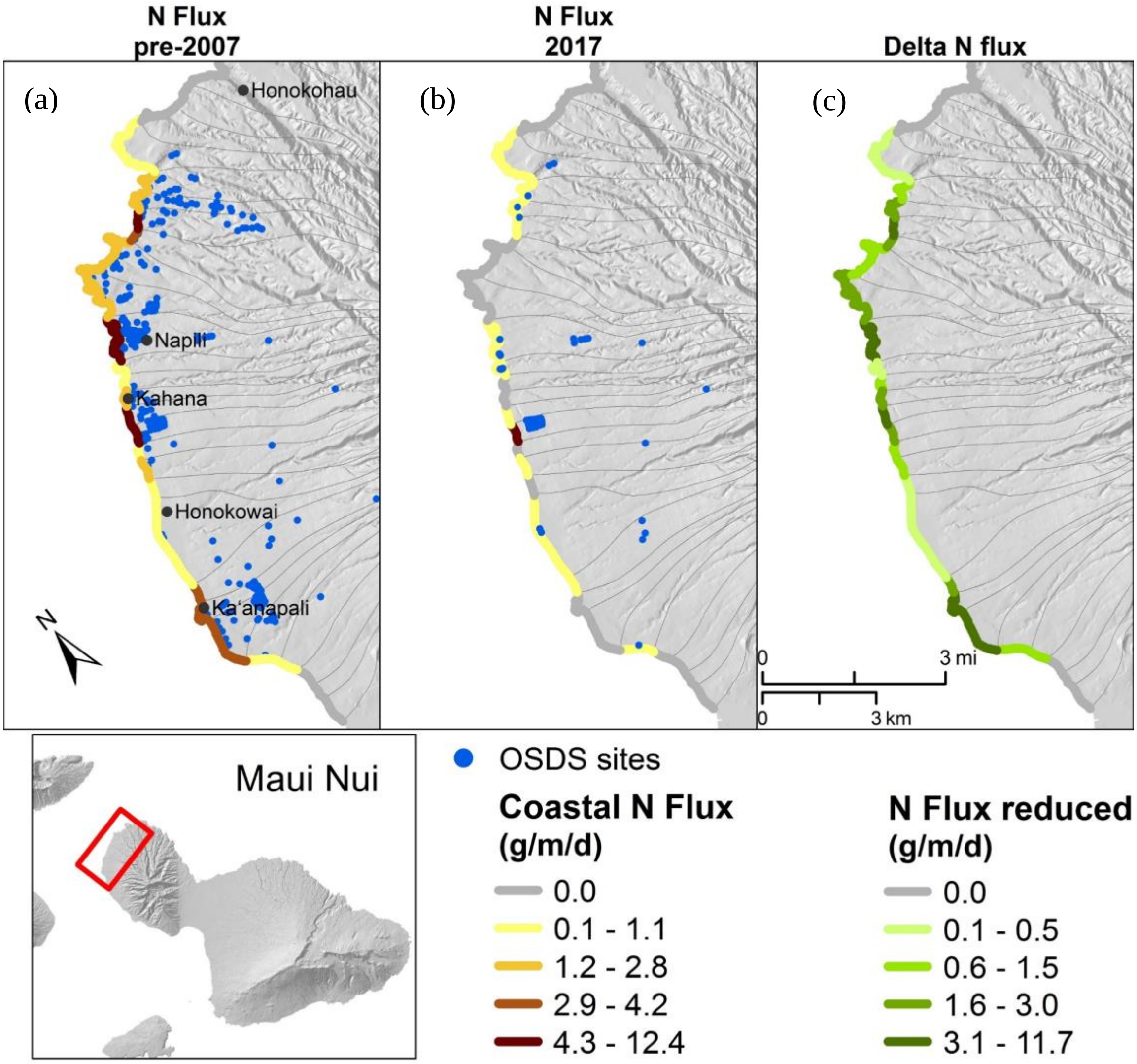


Figure 6. Coastal nitrate (N) flux, in grams per meter per day, by segment (per flow tube), in (a) pre-2007, and (b) 2017, and (c) Benefit, or amount of coastal N reduced from 2007 to 2017. Grey coastal segments have no N flux or change.

We next evaluated the the various upgrade alternatives for OSDS remaining in 2017 (currently contributing to 6.5 kg/d of N flux based on our model; Figure 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). Figure 7 illustrates net nitrate flux reductions in each coastal segment for each alternative, Figure S1 costs, and Figure 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 (Figure 6, Figure 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 (Figure 1; Figure 6).

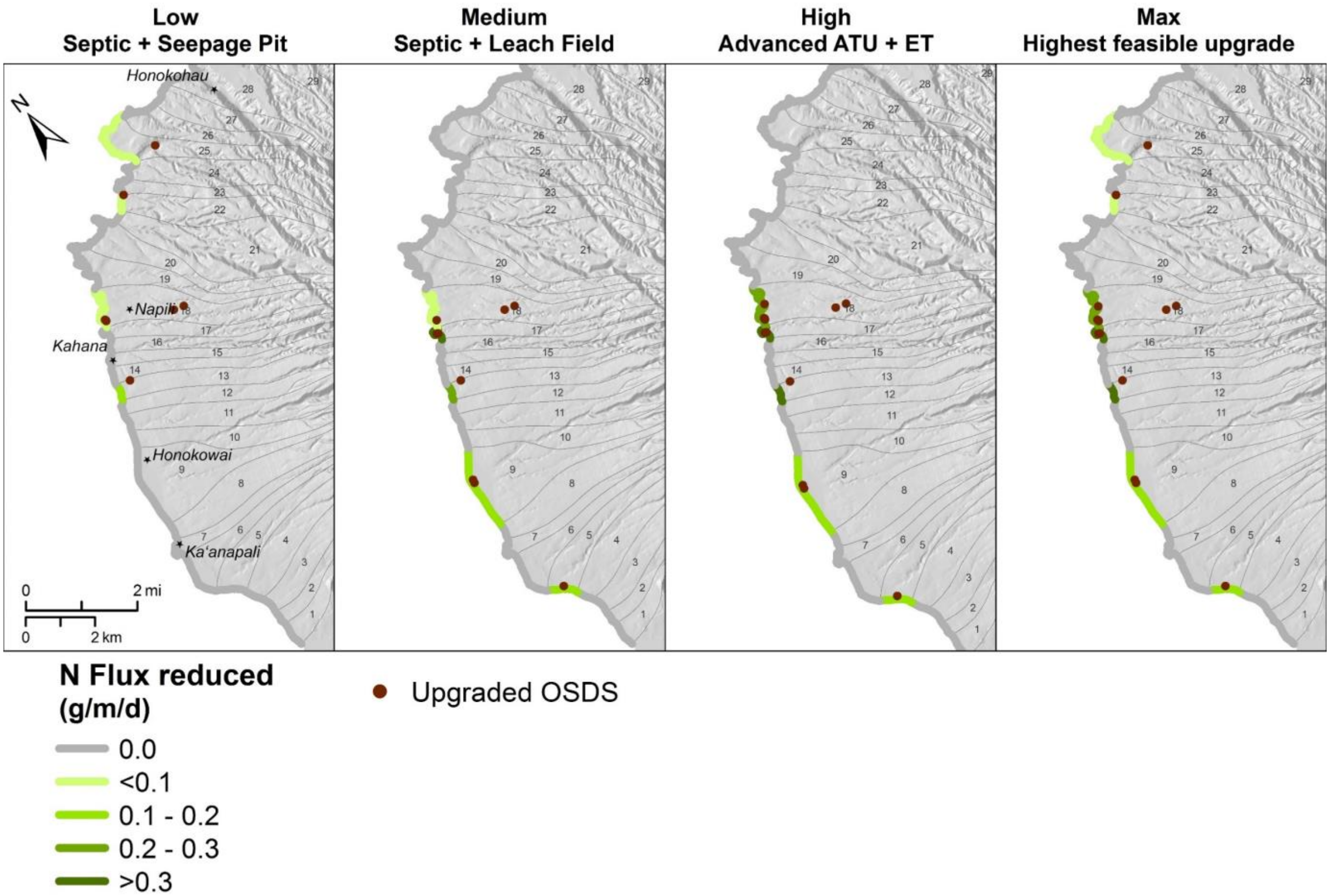


Figure 7. Benefit: Coastal nitrate (N) flux reduced, in grams per meter per day, by segment (flow tube), for each of the alternatives considered for upgrading existing (2017) cesspools. Grey coastal segments indicate where no OSDS upgrades occurred.

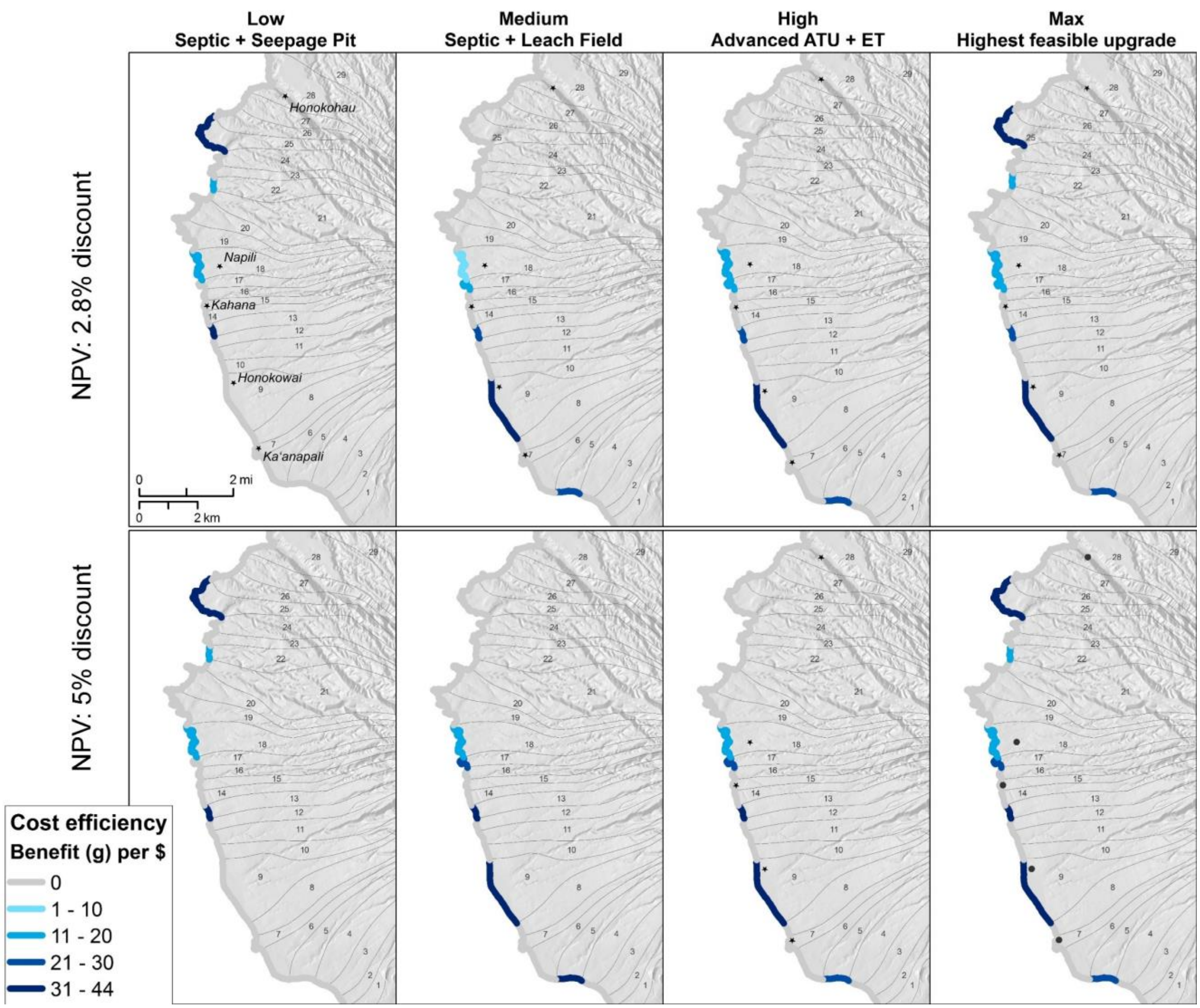


Figure 8. Cost efficiency by coastal zone for each alternative; total benefit (grams of nitrogen reduction over a 30-year period) per dollar. Grey coastal segments have no change, which indicate coastal segments where no upgrades were selected under that scenario.

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 6). 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 (Figure 3; Table 4), Nitrogen 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 (Figure 1). When values are weighted to reflect recreational use, then benefits are higher in high population density areas (Figure 1; Table 4). When reefs are weighted, solutions that reduce pollution near highly valuable reefs have higher benefits (Table 4).

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 (N reduced, [kg/30yrs]	NPV Discount: 2.8%			NPV Discount: 5%		
2007	484	61.86							
2017	57	6.5	55	NPV [$]	CE (B/C) [kg/$]	Cost per B [$/kg]	Cost	CE (B/C)	Cost per B
Low	8	6.12	4,127	204,784	0.0202	49.62	192,808	0.0214	46.72
Med	10	5.43	11,750	564,930	0.0208	48.08	467,250	0.0251	39.77
High	13	4.96	16,859	927,849	0.0182	55.04	816,634	0.0206	48.44
Max	15	4.83	18,316	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 colour gradient from yellow (worst), to blue (best). QTY denotes the number of OSDS systems upgraded in each alternative.

	QTY [#]	Total N 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 colour gradient from yellow (worst), to blue (best). QTY denotes the number of OSDS systems upgraded in each alternative.

	QTY [#]	Total N flux [kg/d]	Weighted Benefit (PUD)	NPV Discount: 2.8%			NPV Discount: 5%		
2007	484	61.86							
2017	57	6.5	379.29	NPV [$]	CE (B/C) [kg/$]	Cost per B	Cost	CE (B/C)	Cost per B
Low	8	6.12	22.13	204,784	0.0001081	9252	192,808	0.0001148	8711.16
Med	10	5.43	87.67	564,930	0.0001552	6444	467,250	0.0001876	5329.62

High	13	4.96	132.73	927,849	0.000143	6991	816,634	0.0001625	6152.78
Max	15	4.83	136.76	979,045	0.0001397	7159	864,836	0.0001581	6323.69

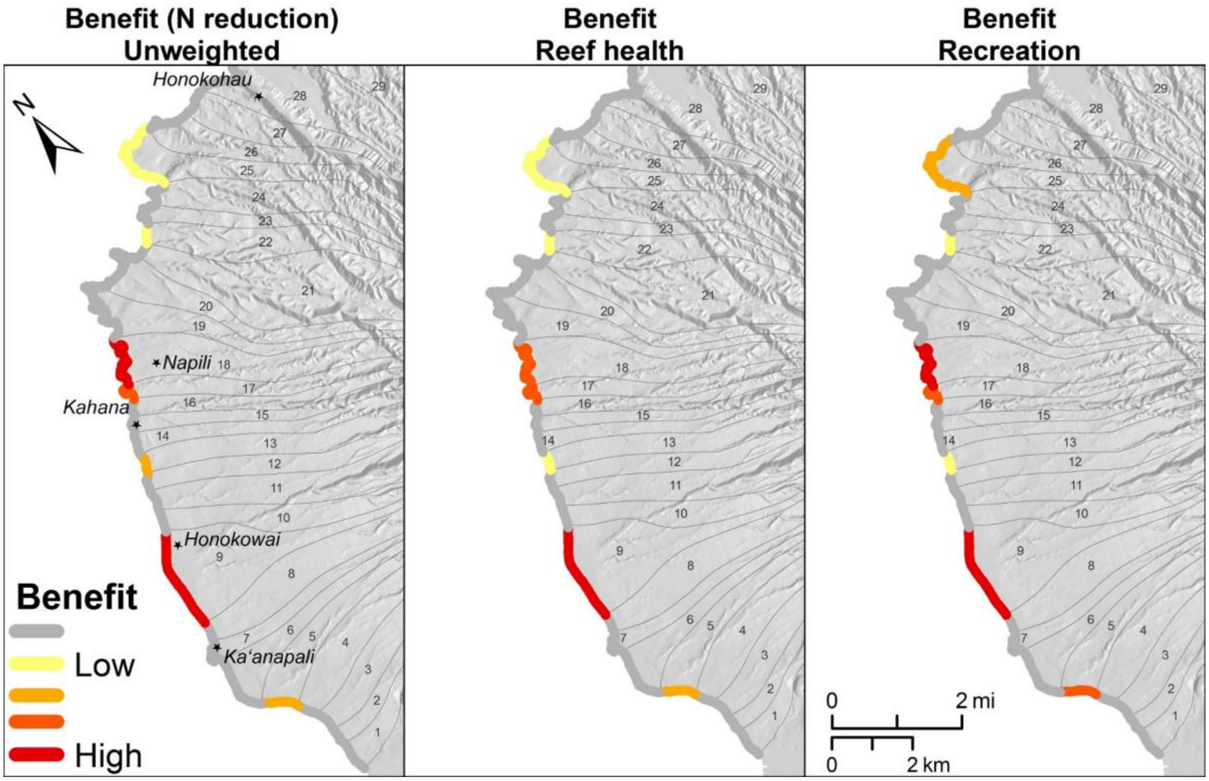


Figure 9. Coastal benefit (Nitrogen reduction) resulting from the Max upgrade scenario; benefit values unweighted, weighted for reef health (by distance to nearest reef), and weighted for public recreation (by Photo User Days).

Discussion

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 Hawai‘i to protect 30% of coastal areas by 2030 (State of Hawaii, 2018) offered a unique opportunity for landscape management in 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 (Allen and Bartram, 2008). 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.

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 nitrogen 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 nitrogen budget coming from OSDS is a prudent strategy when resources for OSDS upgrades are limited.

Tradeoffs

There are differences in Cost, Benefit, and CE across the watersheds (Figures 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 Lowalternative 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. Honokōwai to Kaʻanapali 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 or segment 9, Moderate upgrades) are available because of site constraints (Figure 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; Figure 3, Table 3) and the risk to areas with high tourism and recreation potential (PUD user days; Figure 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).

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 (Figure 4), home to one of the best condition reefs in the area (Vargas-Angel et al., 2017). When the subterranean estuary is operating correctly, there is a high degree of nitrate removal by denitrifying bacteria (Glenn et al., 2013b), but if not operating correctly (Dailer et al., 2010; Glenn et al., 2013a), this high-value reef may be exposed to high risk. 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 is 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 nitrogen contribution of OSDS is lower than some other sources (Figure 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 Hawaiʻi can be in 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.

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 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; 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.

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Supplementary Figures and Tables

OSDS Validation
The existence of OSDS in West Maui 2017 was validated by identifying the current status according to Maui County Wastewater Infrastructure Records (Table S3), and confirmed by a field team in West Maui, who identified sewer mains, and contacted local residents, property managers, and county representatives.

Options
We initially considered incorporating connection to sewer as an additional option, but it was screened out as beyond the scope at this stage for three reasons: 1) although county actions do focus on connection to sewer, current state policy is focused on supporting upgrades, 2) benefits were entirely dependent on treatment efficacy, 3) costs were deemed too variable to contribute to a meaningful cost-benefit analysis without much further consultation with additional parties.

OSDS in Hawaiʻi are classified by a) the type of wastewater *treatment* system, which treats wastewater by mechanical or biological means to reduce harmful contaminants, and b) the type of wastewater *disposal* system, which discharges the treated wastewater into the environment (Table 1; Whittier and El-Kadi, 2014). The most common OSDS in West Maui are cesspools, which have no wastewater treatment. The next most common are septic systems that discharge to a leach field. Waste collects in a tank, where solid material passively separates and settles, and lengths of perforated pipe distribute liquid effluent across the surrounding soil where natural filtering and bacterial action remediates some of the wastewater contaminants before entering the groundwater. OSDS types vary in their capacity to remove nitrogen from wastewater (Table 4), and installation, operation and maintenance costs (Table S4). They are also subject to different constraints to their utilisation (Table S3, Figure S2).

Table S1. OSDS Classes

OSDS Class	Individual Wastewater System and Disposal Type
Class I	Any system receiving soil treatment. This includes disposal types listed as bed, trench, and infiltration/chambers.
Class II	Septic systems discharging to a seepage pit. The effluent receives primary treatment only.
Class III	Aerobic units discharging to a seepage pit. The effluent receives primary and secondary treatment.
Class IV	All cesspools where the effluent receives no treatment.

Note: Seepage pits are dry wells that disperses effluent from septic tanks. The effluent receives no treatment other than settling of solids that occurs in the septic tank.

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Table S2. Matrix of system nitrogen reduction rates by each treatment-disposal combination. Numbers represent: % of influent nitrogen remaining in system effluent after treatment (Whittier & El Kadi 2009, WRRC 2008, WRRC Report 2015-01). In all cases, nitrogen reduction rates are dependent upon good system maintenance.

		Cesspool **100**	Septic **66**	ATU NSF 40 **57**	Advanced Treatment NSF 40/245 **47**
None	**100**	0			53
Seepage Pits	**100**		34	43	53
Leach Field	**59**		61	66	72
=Infiltration Chambers	**59**		61	66	72
Drip Irrigation + Standard	**59**			66	72
Evapotranspiration	**59**			66	72

Constraints

Table S3. Matrix of site condition recommendations, adapted from WRRC (2008); NR = Not Recommended, P = Possible, R = Recommended. ATU = Aerobic Treatment Unit.

	Treatment			Disposal			
Site conditions influencing selection of treatment and disposal system	Septic	ATU NSF 40	Advanced Treatment NSF 40/245	Seepage pit / injection	Leach Field / Infiltration chamber / beds / trenches	Drip Irrigation	Evapotran-spiration
High water table	P	R	R	NR	NR	R	P
Impermeable soil or rock formation	P	R	R	P	NR	R	R
Steep terrain	P	R	R	R	NR	R	NR
Flood zones	NR	NR	NR	NR	NR	NR	NR
Close to inland surface water (both streams and other bodies of water)	NR	R	R	NR	P	R	P
Close to coastal waters	P	R	R	P	P	R	P
High density of cesspools	P	R	R	NR	P	R	P
Protection of groundwater resources	P	R	R	P	P	R	R
Protection of drinking water	P	R	R	NR	NR	R	R
Hydrogeology	P	R	R	P	P	R	P

Our analysis doesn't take into consideration fine-scale site restrictions such as minimum distance to large trees, property lines, etc. (OSDS spatial data is TMK centroid, not exact location of system). But as these restrictions apply generally, to all types of systems, and our analysis involves upgrades (rather than entirely new systems), we assumed that these criteria were previously met.

Costs

Table S4. Cost Assumptions

*Operation & maintenance (O&M) costs are estimated as annual averages
** All costs are general estimates; can vary with specific site conditions

TREATMENT SYSTEMS		Cost ($)	Notes	Reference
Cesspool:				
Initial	Installation	**15,000**	*not included in cost calculations; analysis does not consider new cesspools (illegal)	WRRC (2008)
O&M	Pumping	**200**	$150-550 per visit, every 2-3 yrs	WRRC (2008)
Septic:				
Initial	Installation and material	**9,850**	Mid-value of $7,000-12,700 range; includes material, equipment, labor	WRRC (2008)
O&M	Pumping	**200**	$150-550 per visit, every 2-3 yrs	WRRC (2008)
ATU - International Wastewater Tech				
Initial	*Tanks*	*10,000*		(AQUA Engineering and Coral Reef Alliance, 2015)
	Installation	*22,000*		(AQUA Engineering and Coral Reef Alliance, 2015)
	Electrical install	*3,000*		(AQUA Engineering and Coral Reef Alliance, 2015)
	Total initial costs	**35,000**		
O&M	*Inspections & Service*	*750*		(AQUA Engineering and Coral Reef Alliance, 2015)
	Septage pumping	*550*		(AQUA Engineering and Coral Reef Alliance, 2015)
	Pump/blowers	*2,309*	15 kWhr/day, with power rates @ $0.4217, based on 2013 residential power estimates given from Hawai‘i Electric Light Company	(AQUA Engineering and Coral Reef Alliance, 2015)
	Total Operating Costs/Annum	**3,609**		

ATU WaiPono Pure				
Initial	Tank(s), installation, and materials	**18,000**		(WaipoonoPure, 2017, April)
O&M	*Inspections & Service*	*900*	Quarterly inspections for first two years; bi-annual thereafter	(WaipoonoPure, 2017, October)
	Power Consumption	*180*	$15/month; air compressor 71W continuous; effluent pump 1/2 HP, 115V, 60Hz, 10.0A, 12 mins/hour	(WaipoonoPure, 2017, October)
	Spare & Replacement Parts	*112.50*	Air compressor $180 every 3 years; effluent pump $315 every 6 years	(WaipoonoPure, 2017, October)
	*Other**	*100*	Contingency for service adjustments & parts	(WaipoonoPure, 2017, October)
	Total Operating Costs/Annum	**1292.50**		
DISPOSAL SYSTEMS				
Seepage pit				
Initial	Installation	**10,000**		WRRC (2008)
O&M	Pumping	**200**	$150-550 per visit, every 2-3 yrs	WRRC (2008)
Leach field				
Initial	Installation	**12,500**	Mid-value of $7,000 – 18,000 range	WRRC (2008)
O&M	Replacement costs for septic system leach fields	**8,750**	Leach fields of septic systems typically fail within 7 years due to contaminant loading in soil; replacements costs estimated as 70% of installation cost. Note: this would not be required as frequently with advanced treatment systems.	Dennis Poma, Nguyen Le pers. comm.
Drip irrigation				
Initial	Installation	**22,000**	The costs associated with the specific systems for recycling water are quite specific; can vary drastically	Dennis Poma, Nguyen Le pers. comm.; WRRC (2008)
O&M		**0**	Without a definitive concept of a proposed system, O&M costs cannot be generalized	WRRC (2008)
Evapotranspiration				
Initial	Installation	**20,000**	Mid-value of $15,000 – 25,000 range	WRRC (2008)
O&M	Inspection	**20**	Simple inspection of observation wells; plus electrical costs for pumping when needed	WRRC (2008)

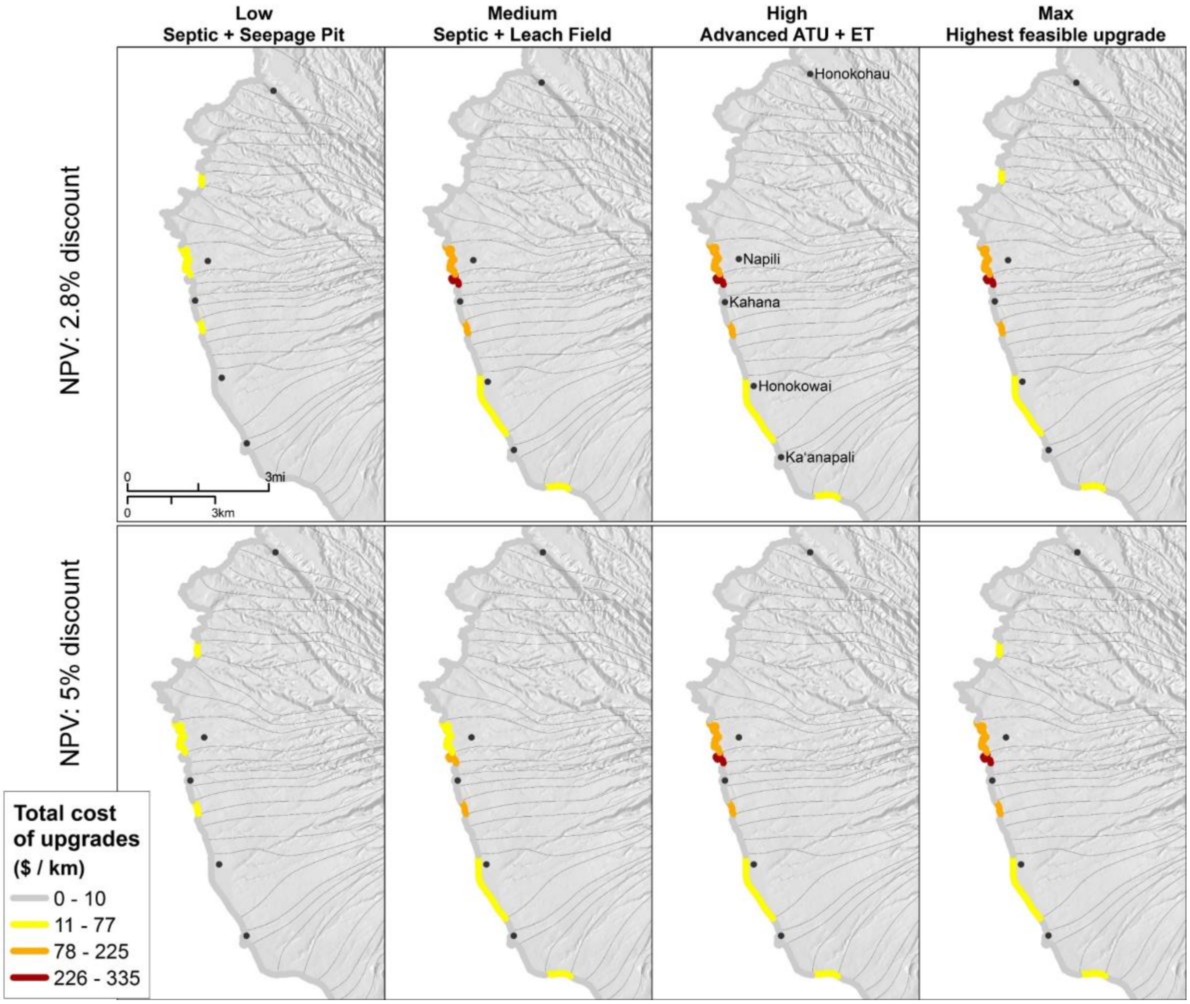

Figure S1. Lifetime (30-yr) cost of upgrades, in USD (2017) (Calculated based on Supplementary Table S2) in $/km within each flow tube of each alternative.

Groundwater and Transport Modeling

The numerical groundwater flow and transport modeling sought to achieve three goals:

1. Replicate the groundwater flow patterns in northwest Maui and more specifically the distribution of coastal fresh groundwater discharge;

2. Replicate the distribution of nutrients (primarily nitrate) in the groundwater of northwest Maui; and

3. Estimate the distribution and magnitude of the coastal nutrient load and identify the source of the nutrients to the extent practical.

Replicating the distribution of nutrients in the aquifer and the estimating the coastal nutrient load requires modeling codes that simulate groundwater flow, plot groundwater flow paths, and simulate contaminant transport. The USGS code MODFLOW 2005 simulates the movement of groundwater by solving the groundwater flow equations for a grid of cells (Harbaugh, 2005). MODPATH (Pollock, 2016) uses the MODFLOW solution to track the path of virtual particles either with the flow of groundwater (forward tracking) or the exact opposite direction of groundwater flow (reverse tracking). MODPATH was used to develop groundwater flow tubes to sub-divide the model for computation of coastal nutrient flux. Nutrient transport was simulated using the modeling code MT3DMS (Zheng and

Wang, 1999). This transport modeling code uses the MODFLOW solution to simulate the movement of contaminants in the groundwater. MT3DMS can simulates contaminant processes of advection (movement with the flow of groundwater due to differences in hydraulic head potential), dispersion (spreading of the plume due to heterogeneities in the aquifer), and molecular diffusion (movement due to a concentration gradient). MT3DMS also simulates sorption (the attachment of the contaminant to the aquifer matrix) and degradation. MT3DMS is ideal for this study since it can simulate the transport of multiple contaminants species simultaneously.

The groundwater model combined USGS calculated recharge for Maui (Johnson et al., 2014), with land use coverages from the State of Hawaiʻi Office of Planning Statewide GIS program (http://planning.Hawaiʻi.gov/gis/) to identify and simulate nutrient sources for current and future conditions.

All of the modeling codes described above perform calculations in algebraic array based on a rectangular grid of cells. The Groundwater Modeling System (GMS) (Aquaveo, Provo, Utah) graphical user interface was used to convert a conceptual model that is in the form geographical information system elements consisting of shapes with data parameter values attached to the numerical modeling grid using ArcGIS 10.1 (ESRI, 2012).

Model Description

A groundwater flow and transport model simulated nutrient leachate delivery from on-land recharge zones to points of coastal discharge using USGS groundwater flow code MODFLOW (Harbaugh, 2005) and contaminant transport code MT3D-MS (Zheng and Wang, 1999; Supplementary Methods). Both codes used the Groundwater Modelling System (Aquaveo, Provo, UT, USA) user interface to populate models. The modelling uses the concept of a flow net to divide the model domain into 25 flow tubes. The flow net's flow lines represent an impermeable boundary (Freeze and Cherry, 1979, pg 168-170) that trace from the coast up to the 420 m msl groundwater contour, where they converge. An assumption of flow nets is that there is no groundwater exchange between flow tubes, thus the nutrient mass applied to each flow tube, either as recharge or wastewater injection, remains in that flow tube. (Koh et al., 2007). Coastal nutrient mass discharge flux is the sum of the mass from the individual sources into each flow tube. This is based on an assumption that much of the applied nutrients nitrify to nitrate, a conservative and mobile species in groundwater, and do not sorb onto the aquifer matrix (Koh et al., 2007).

The groundwater model simulated groundwater flow nutrient transport in the Honokowai, Honolua, and Honokohau Aquifer Systems of northwest Maui (Mink and Lau, 1990). This selection of aquifers completely covered the study watersheds. Figure S2 shows the model domain relative to the study watershed boundaries. The aquifer boundaries were chosen since they boundaries between aquifers are more consistent with the groundwater flow regime that watersheds are.

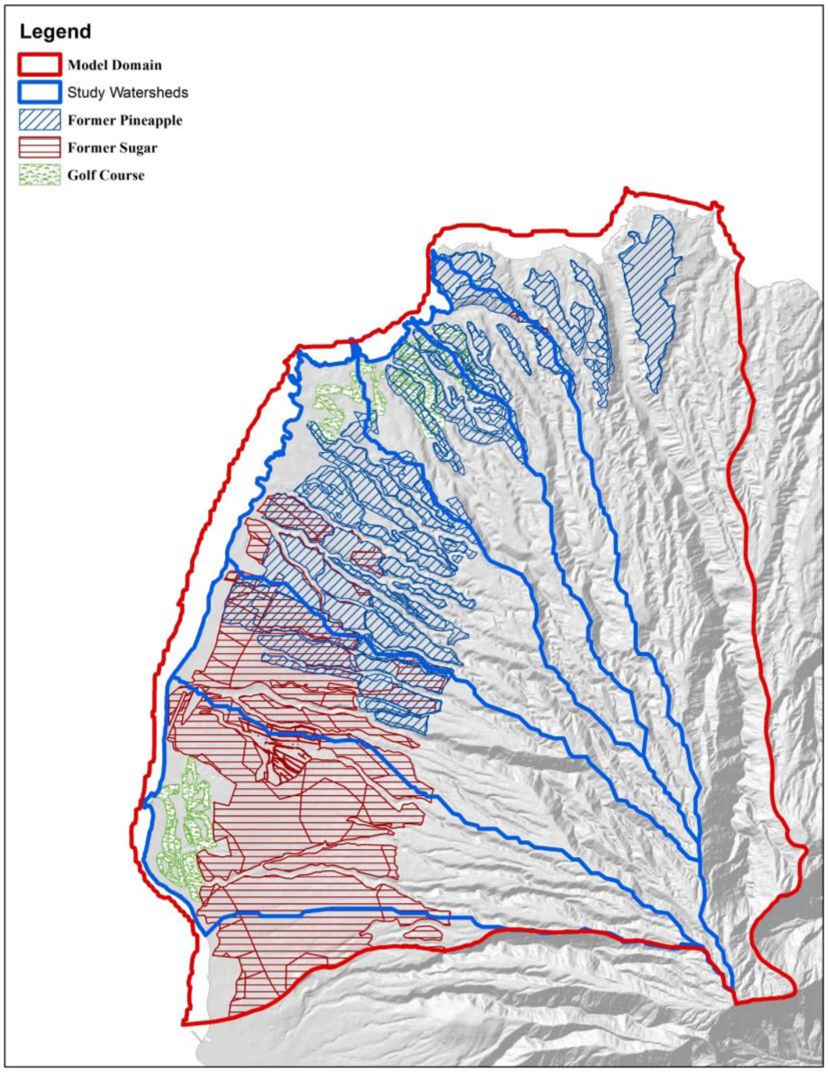

Figure S2. Groundwater model domain relative to the study watershed boundaries

The model domain was mapped to a three-dimensional grid for MODFLOW to perform the groundwater flow calculations. The model grid consisted of 527,360 cells arrange in 4 layers, 320 columns and 412 rows. Of these cells only 291,840 were active as the others fell outside of the boundary of the conceptual model. In plan view the cell size was uniform at 50 m on a side. Vertically the cell size varied with the thickness of the simulated aquifer.

This study adapted the USGS model of (Gingerich and Engott, 2012) that used the density dependent modeling code SUTRA (Voss and Provost, 2002) to simulate groundwater flow in west Maui. MODFLOW assumes a uniform groundwater density and cannot dynamically simulate the interaction between the freshwater lens and the underlying saltwater that buoyantly supports the freshwater lens. MODFLOW does have the advantage of the direct linkage with the modeling code MT3DMS for simulation of contaminant transport. To simulate the freshwater discharge to the nearshore environment, we assigned and equivalent freshwater head to all submarine boundary cells. The equivalent freshwater head is the depth of the mid-point of the submarine boundary cell times 0.025 to account for the difference in density between freshwater and saltwater. Motz and Sedighi (2009) compared the outputs of the density dependent flow modeling code SEAWATs (Langevin et al., 2008) with MODFLOW to compare the simulation of freshwater discharge to the coastal marine zone between the two model types. They found that when the coastal and submarine fresh groundwater discharge was simulated using equivalent freshwater head based on water depth, that MODFLOW adequately simulated the water table elevation and the coastal freshwater flux. Thus the combination of MODFLOW and MT3DMS meets the needs of modeling goals and significantly stream lines the modeling process.

There are many unknown geomorphic processes such as similar to the paleo stream channel identified by Hunt and Rosa (2009) that will influence entry points of nutrients into the nearshore environment. While known geology such as the aforementioned stream is included, there is likely to also be unmapped geology that may influence flowpaths.

Boundary Conditions

The model boundary conditions assign parameter values as the model boundaries while the numerical grid calculates the values of hydraulic head and inter-cell flow within the model grid. The upper boundary of the model is the top of the water table where an assigned flux based on the groundwater recharge estimated by the USGS Maui (Johnson et al., 2014). The lateral boundaries of the model were delineated along the designated aquifer boundaries (Mink and Lau, 1990) and were assigned a no-flow condition. This is consistent the generally accepted conceptual model that there is very limited exchange of groundwater between aquifers (Wilson Okamoto Corporation, 2008). The bottom boundary was a no flow boundary based on the elevation of the midpoint of the freshwater/seawater transition zone as simulated by Gingerich (2012).

Geologic zones and associated hydraulic conductivities were taken from Gingerich (2012). Since the groundwater model grid is rectangular and the lava bedding is more radial in geometry the no horizontal anisotropy was simulated. The hydraulic conductivities assigned were the longitudinal values from Gingerich (2012). Well pumping rates, groundwater discharge to streams, and target groundwater elevations were also taken from Gingerich (2012). Streams were simulated as drains with the conductance of the stream arcs adjusted so that the simulated discharge of groundwater to the streams approximated that modeled by Gingerich (2012).

NUTRIENT TRANSPORT MODELING

As described above the distribution of nutrients in the groundwater was simulated using the transport modeling code MT3DMS (Zheng & Wang, 1999; and Zheng, 2010). Both nitrate and phosphate were modeled. However, phosphate has a rate of sorption to the soil (Canter, 1985; Froelich, 1988), resulting in low groundwater concentrations except where the injected municipal wastewater discharged at the coast in submarine springs (Glenn et al., 2012). The primary sources of nitrate modeled were:

- Golf course fertilizer,
- Landscaping fertilizer from developed open spaces,
- Legacy fertilizer leached from former sugar cane and pineapple cultivation,
- Onsite sewage disposal leachate,
- Application of recycled wastewater, and
- Subsurface injection of treated wastewater.

Table S5 lists the concentrations or leaching rates used for the model and the basis for the values selected. The assumption is that the dominant form of nitrogen is nitrate and it is a conservative and mobile species in the groundwater. Nitrate is the stable form of nitrate under oxidizing conditions and dominant aquifer material is basalt where there is very little opportunity for sorption to the aquifer matrix (Koh et al., 2007).

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Table S5. Nitrate Sources and Basis for modeled concentration (mg/L) and $\delta^{15}N$

Nitrate Source	Species	Simulation Method	Modeled Concentration (mg/L)	$\delta^{15}N$
Natural[1]	Natural	Recharge	0.3	2
Former Sugar Cane Ag.[2]	Sugar	Recharge	11.7	2
Former Pineapple Ag.[2]	Pineapple	Recharge	0.5	2.1
Coffee[3]	Other	Recharge	1.8	2.1
Golf Course[4]	Golf Course	Recharge	6.3 to 13.8*	2.1
Developed Open Space[5]	Developed Open Space	Recharge	0.3 to 5.9*	2.1
Recycled Water Application[6]	Reuse	Recharge	13.8	28
Wastewater Injection[7]	Injection	Well injection	5	90
Cesspools[8]	OSDS	Well injection	87	16
Septic System with Soil Treatment[8]	OSDS	Well injection	51	16

[1]Average from west Maui wells not affected by ag. (DOH, 2016), [2]Adjusted recharge concentration so modeled concentration equaled that in wells located in former sugar cane and pineapple areas (Glenn et al., 2012; DOH, 2016), [3]Adjusted recharge concentration to match leaching rate of (Fenilli et al., 2008), [4]Adjusted concentration in recharge to get a leaching rate of 49 kg/ha/yr (Throssell et al., 2009) based on USGS reported recharge rates for 1978 through 2007 (Johnson et al., 2014), [5]Assumed same fertilizer practices as golf courses adjusted for the fraction of the recharge polygon that was DOS. [6]Adjusted recharge concentration to equal that measured in a spring at Black Rock Lagoon by Hunt and Rosa, 2009, [7]Data from DOH (2016) and Glenn et al (2012), [8]Based on raw wastewater values and nitrate removal rates reported by Tasato and Dugan (1980), Lowe (2009); McCray (2009).

Nitrate Transport Model validation

The simulated groundwater nitrate was compared with data from DOH compliance sampling (DOH, 2016a), and with the studies of Glenn et al (2012) and Hunt and Rosa (2009) that measured groundwater nitrate concentrations in West Maui (Supplementary Data).

Data used for calibration was from years between 2008 and 2016 and gathered from a review of available samples at DoH, and published and grey literature (Supplementary Data).

There was very good agreement between the measured and modeled groundwater nitrate with the exception of two outliers. The two outliers are located at the upper edge of the former sugar cane fields and in close proximity to wells where there was good agreement between the model results and the measured data (see circled area). There is variability in this area that was not captured by the model. Figure S3 shows the measured versus simulated values. The average error was -0.11 mg/L while the RMS error was 0.5 mg/L. The model used recharge from detailed analysis of the USGS (Johnson et al., 2014), which means that the water input to the model is peer reviewed and valid.

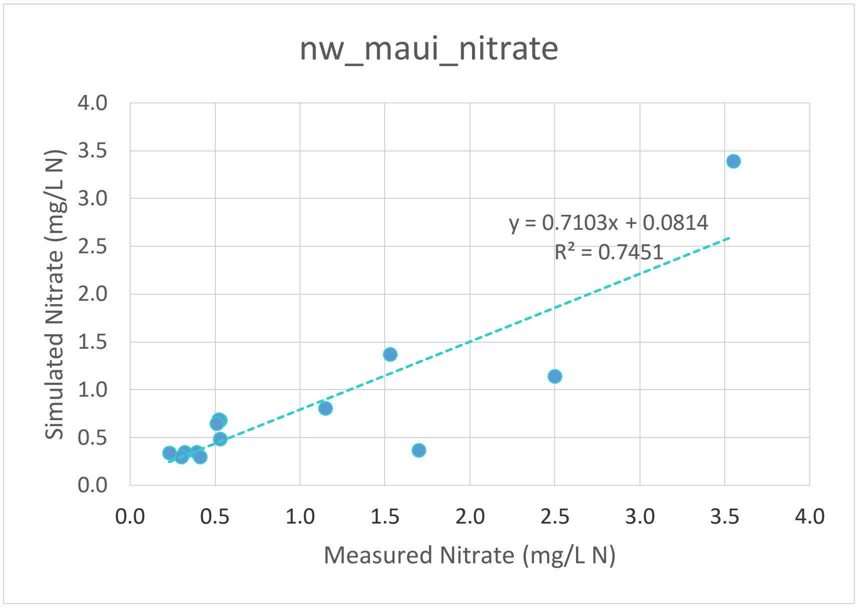

Figure S3.Validation of groundwater model showing predicted (x) against observed values (y)

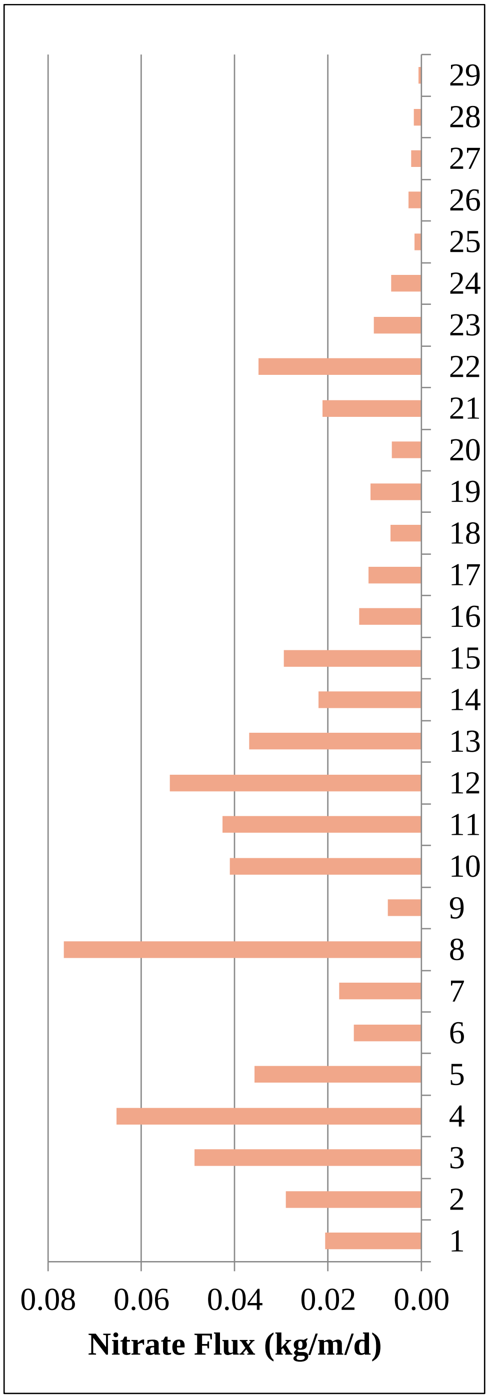

Figure S4. Bar Chart of total N flux (kg/m/d) for each of the 31 flow tube segments in the study area.

INTERFACE BETWEEN GW MODEL AND DECISION MAKING MODEL

The primary purpose of the groundwater flow and transport modeling was to provide the coastal nitrate flux distribution for the cost/benefit analysis. This analysis was best done using GIS and a method was needed to calculate the coastal nitrate over discrete segments of coastline. This study used the concept of a flow net to divide the model domain into 25 flow tubes. In a flow net, a flow line represents an impermeable boundary (Freeze & Cherry, 1979; pg 168-170). The flowlines are delineated using the particle tracking model MODPATH in the reverse tracking mode to trace flow lines from the coast up to the interior recharge zones of the model. Polygons were created from the intersections of the flow path arcs with coastal and 420 m msl groundwater contour. Above the 420 m msl groundwater elevation contour the flow lines converged resulting in widths that were only a few cells wide. Since in flow nets, there is no groundwater exchange between flow tubes, the nutrient mass applied to each flow either as recharge or wastewater injection, remains in that flow tube until captured by a well, discharged to a stream, or discharged to the ocean. The quantity of water captured by wells or discharged to steams is negligible so the coastal nutrient mass discharge flux becomes the sum of the mass from the individual sources into each flow tube. This analysis is done in ArcGIS 10.1 using the spatial union tool that combined the geometry and attributes of the flow tube, recharge, OSDS, and injection well coverages.

GROUNDWATER MODEL FINDINGS

Table S6. Summary of Groundwater Model Findings

Source	(kg/d)	(% Flux)
Sugar	214.3	46.8
Pineapple	11.7	2.6
OSDS	64.1	14.0
Natural	79.8	17.4
Dev. Open Space	37.3	8.2
Coffee	0.7	0.2
Wastewater Injection	1.4	0.3
Golf Courses	48.3	10.6
Total Flux	458	100

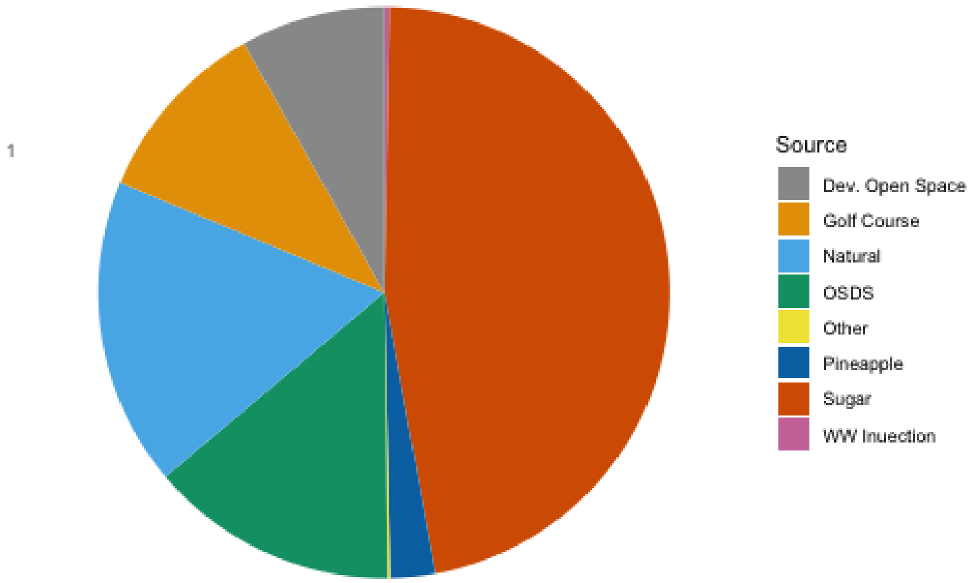

Figure S5. Pie Chart showing a summary of the contribution of each potential N source across the entire area of study

The greatest volume of coastal Nitrate contribution by source nitrate appears to be legacy nitrate from past sugar cane agriculture (90%; Figure 3, Table 8). OSDS is the next largest source by type overall (5%) followed closely by Golf Courses and Developed Open Space (4% each). Denitrification of the injected wastewater results in low nitrate flux at flow tube 8 (Figure 3). The high rate of injection (about 11,000 m3/d) displaces the higher nitrate groundwater from upgradient around the coastal discharge zone for the injectate.

Spatial Processing
Data sources for all spatial processing are described in Table S7.

Alternatives
Spatial data layers for these conditions were used to attribute OSDS point data with associated values in ArcMap 10.1 (ESRI, 2012). Slope values were extracted from a raster layer generated from Digital Elevation Model data using the Slope tool in the Spatial Analyst toolbox, and attributed to overlaid OSDS points. OSDS points that intersected with a flood zone polygon layer were selected and categorized as such.

Values
Reef distances were generated using the Near tool in the ArcMap Spatial Analyst toolbox. They were calculated from each of the shoreline segments, representing coastal interfaces of the groundwater flow tube polygons, to the nearest edge of reef structure class polygon from the NOAA Benthic Habitat Map (Pacific Islands Fisheries Science Center, 2017). Distances were then attributed to each of the OSDS units within the associated flow tube polygon. Values for recreational value of coastal segments were generated from Flickr InVEST model outputs, which predicts the spread of person-days of recreation in space based on number of geotagged photo uploads to the Flickr website (Wood et al., 2013a). The InVEST model was run on the study area for all available years (2010-2014), for an output of 100-m2 hexagons. Visitation values are represented as Photo User Days (PUD), and weightings are the sum of the visitation raster cells for each coastal segment, standardized by length of coastal interface. Coastal segment areas were defined by a 100m flat-end buffer for each of the coastal interface segments from the groundwater flow tubes. The segment-specific PUD values were then attributed to the associated OSDS, consistent with the manner in which reef distance weightings were applied.

Table S7. Data sources

Spatial dataset	Source
Hawai‘i State 10 DEM	Hawai‘i State GIS Website, tab 010 Image and Base Maps http://planning.hawaii.gov/gis/download-gis-data/
OSDS point shapefile 2007	On-site sewage disposal systems (OSDS) for the island of Maui as of 2010. State of Hawai‘i Department of Health. Accessed from Hawai‘i Statewide GIS Program. https://www.arcgis.com/home/item.html?id=108b8d29611a4a5e8bed2f7c658ddf68
OSDS point shapefile 2017	(DOH (OSDS point shapefile 2007; adjusted based on field validation conducted by Tova Callender). Available here: https://www.dropbox.com/sh/563akg2qlwuzx8n/AAD1a-0CJywZFqQ3yJjZVZrta?dl=0

Slope, generated from 5 m resolution DEM	NOAA-CSC. (2014). Interferometric Synthetic Aperture Radar based Digital Elevation Model. Retrieved from: https://coast.noaa.gov/dataregistry/search/dataset/info/coastalifsar
Flood zone	Flood Hazard Areas – State of Hawai'i, Federal Emergency Management Agency (FEMA). March 2012. Accessed from Hawai'i Statewide GIS Program. http://planning.hawaii.gov/gis/
Leach field suitability	Whittier, R.B., El-Kadi, A., 2014. Human health and environmental risk ranking of on-site sewage disposal systems for the Hawaiian Islands of Kauai, Molokai, Maui, and Hawai'i. Final report prepared for State of Hawai'i Department of Health. Safe Drinking Water Branch.
Coastal recreation (Flickr Photo User Days)	Sharp, R., Tallis, H.T., Ricketts, T., Guerry, A.D., Wood, S.A., Chaplin-Kramer, R., Nelson, E., Ennaanay, D., Wolny, S., Olwero, N., Vigerstol, K., Pennington, D., Mendoza, G., Aukema, J., Foster, J., Forrest, J., Cameron, D., Arkema, K., Lonsdorf, E., Kennedy, C., Verutes, G., Kim, C.K., Guannel, G., Papenfus, M., Toft, J., Marsik, M., Bernhardt, J., Griffin, R., Glowinski, K., Chaumont, N., Perelman, A., Lacayo, M. Mandle, L., Hamel, P., Vogl, A.L., Rogers, L., Bierbower, W., Denu, D., and Douglass, J. 2016. InVEST +VERSION+ User's Guide. The Natural Capital Project, Stanford University, University of Minnesota, The Nature Conservancy, and World Wildlife Fund. http://data.naturalcapitalproject.org/nightly-build/invest-users-guide/html/recreation.html
Complex reef habitat: NOAA West Maui Dominant Benthic Structure habitat map	Pacific Islands Fisheries Science Center, 2017: Dominant Benthic Structure and Biological Cover Habitat Maps for West Maui and West Hawai'i from 2010-06-15 to 2010-08-15. NOAA National Centers for Environmental Information, https://inport.nmfs.noaa.gov/inport/item/32811
West Maui County Infratructure Database	https://mauicounty.maps.arcgis.com/apps/View/index.html?appid=2adf24d194f7473ab71c7e4cc7b3061a

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