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A spatial framework for improved sanitation to support coral reef conservation☆

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ABSTRACT

Coral reefs are one of the most valuable yet threatened ecosystems in the world. Improving human wastewater treatment could reduce land-based impacts on coral reefs. However, information on the quantity and spatial distribution of human wastewater pollution is lacking. Here, we develop a spatial model linking residential human wastewater pollution (nitrogen and phosphorus/year) and conservation sectors [coral reefs] to better understand the relative differences in the distribution and efficacy of different sanitation services and their potential implications for conservation monitoring and management. We apply our model to Fiji, where ongoing initiatives and investments in wastewater treatment for human health could be leveraged to cost-effectively improve coral reef condition. We estimate that wastewater treatment plants account for nearly 80% of human wastewater nutrients released into surface waters. Wasterwater nutrient pollution is widespread, affecting 95% of reefs, but is concentrated across a few watersheds. Our spatially explicit approach can be used to better understand potential benefits and trade-offs between sanitation service improvements and coral reef health, helping to bridge the sanitation and conservation sectors as well as inform and prioritize on the ground action.

1. Introduction

Coral reef systems across the world's oceans are experiencing unprecedented losses due to multiple anthropogenic impacts. Reef systems have seen declines of up to 50% in recent decades (Hoegh-Guldberg et al., 2019) primarily due to climate change (e.g., bleaching events) and poor water quality (Andrello et al., 2022; Burke et al., 2011). It is estimated that coral reefs are worth nearly US$30 billion a year from fisheries, coastal protection, tourism, and biodiversity value, which could be lost with reef degradation (Samonte-Tan, 2008). In addition, the potential loss of climate risk reduction benefits, such as wave energy reduction, is estimated to affect 100–197 million people (Ferrario et al., 2014).

Coastal run-off can degrade coastal water quality, which can reduce coral reef productivity, increase coral mortality and decrease marine ecosystem services (e.g., coastal protection, food provision from fisheries) (Burke et al., 2011; Carlson et al., 2019; Fabricius, 2005; Wenger et al., 2020). Excess nutrients, specifically, can facilitate macroalgal growth and algal blooms that reduce the area for corals to grow and have been shown to be a driver of coral disease and bleaching (D'Angelo and Wiedenmann, 2014; Lapointe et al., 2019; Wear and Vega Thurber, 2015). Untreated wastewater is a major contributor to excess nutrient loads. An estimated 6.2 Tg of wastewater nitrogen is released into coastal environments each year (Tuholske et al., 2021), and over 45% of people on the planet lack access to safe sanitation (UNESCO, 2023). Wastewater can also contain pathogens, endocrine disruptors, heavy metals, and toxins that can be detrimental to both marine life and human health (Wear, 2019; Wear and Vega Thurber, 2015; WHO, 2018).

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Improving wastewater management is a global priority (e.g., Sustainable Development Goal 6), and essential for achieving both conservation and human health goals (Wakwella et al., 2023; Wear, 2019; WHO, 2018). However, there is limited information and data about the sources and distribution of nutrient pollution from human wastewater, which hinders the ability to strategically prioritize where and how to best improve sanitation services. Here, we use a spatial model to estimate the amount of nutrient pollution (nitrogen [N] and phosphorus [P], tonnes/year) produced from residential human wastewater sources connected to wastewater treatment plants (WWTP), septic tanks, and other treatment strategies (e.g., pit latrines and tanks). We then determine how much of this nutrient pollution may be reaching coral reefs, using Fiji as a case study. We use this information to identify relative differences between treatment types and watersheds and key data gaps for improving wastewater monitoring and management to provide the greatest benefits to coral reefs, particularly in data limited areas.

2. Methods

2.1. Case study area: Fiji

Improving sanitation services is a national priority in Fiji (Ministry of Economy, 2017). Nutrients have been identified as a major risk to reef condition, particularly from agriculture (Andrello et al., 2022), but also in highly populated areas (Mangubhai et al., 2019) and tourism hotspots such as the Coral Coast (Mosley and Aalbersberg, 2003; SPREP, 2007; Tamata and Morrison, 2012). Ninety-five percent of Fiji's population is estimated to have access to basic sanitation services, which generally consist of improved latrine front-ends (washable floor) that are not shared (WHO and UNICEF, 2021). However, the proportion of safely managed sanitation systems (i.e., adequate containment or treatment of human excreta) is not formally reported (WHO and UNICEF, 2019), and recent research in Fiji indicates that safe sanitation coverage is low; ranging from 11 to 21 % of households (Nasim et al., 2023).

In rural areas this is a particular problem as the majority of systems are pit-latrines or poorly constructed tanks that offer limited containment of fecal sludge and present a high risk for sub-surface leaching into environmental water bodies (Nasim et al., 2023). Further, the efficacy of sanitation services may be inadequate due to large demand and/or shortfalls in management, maintenance and regulation (SPREP, 2007). Understanding the distribution, efficacy, and potential implications of different sanitation services is essential to inform decision making for meeting goals across sanitation, conservation, and human health sectors.

Fiji is committed to addressing sanitation and water issues locally, with innovative pilot projects underway to reduce human health risks and improve environmental benefits through development of hybrid septic tank and constructed wetlands in urban areas (e.g., RISE study (Leder et al., 2021),) and systems approaches to watershed management (e.g., WISH Fiji project (Jupiter et al., 2023; McFarlane et al., 2019)). We develop a spatial model of nutrient pollution from three sanitation service types across the two largest islands in Fiji – Viti Levu and Vanua Levu - to estimate coral reef nutrient exposure and potential implications for strategic sanitation improvements to benefit coral reef health.

2.2. Populations by wastewater system type

We consider three types of sanitation systems: populations connected to municipal sewer systems ("connected"), populations that use on-site septic tanks ("septic", impermeable/water-tight) and populations that use on-site sub-surface pits or permeable tanks ("other"). Pit latrines and permeable tanks are the common sanitation system used by the majority of rural Fijian households (Nasim et al., 2023), while open defecation is minimal (WHO and UNICEF, 2021). In this analysis, we classify pit latrines and tanks within the "other" system type because they are constructed at similar depths, are not contained, rarely emptied and subject to flooding events (Jenkins et al., 2019; Nasim et al., 2023). In addition to these sanitation systems, we also calculated nutrients from visitor arrivals (i.e., tourism). Due to uncertainties on the final treatment and discharge locations, however, we were unable to spatially resolve tourism estimates to a level that permitted inclusion in further analyses. We present methods and results for our tourism estimates in the Supplemental Materials.

To estimate nutrient pollution (N and P) from wastewater, we first determined the number of people that used different sanitation systems (connected, septic and other). Population percentages for each treatment type and urban classification were based on Fiji statistics (WHO and UNICEF, 2021) that report 58.9% of urban and 68.1% of rural populations use septic systems and 5.4% of urban and 27.2% of rural populations use other systems (Table 1). Population density was estimated from Pacific Data Hub Fiji population grid data at 100 m resolution (Pacific Data Hub, 2020). These data combine 2007 household listing locations with the CIESIN Fiji High Resolution population grid data (CIESIN, 2016). Population sizes were then allocated using Fiji 2017 census population counts at enumeration level, assuming a 0.38% yearly growth rate to reach 2020 population values.

In Fiji, there are eleven WWTPs operated by the Water Authority Fiji (WAF); Kinoya, Deuba [Pacific Harbor], Nadali, Namara, Lautoka Natabua, Navakai, Olosara, Votua, Wailada, ACS and Naboro. These WWTPs all provide secondary wastewater treatment to residential sewage with light industrial inputs. There are two types of treatment systems used: primary settlers and trickling filters in parallel (e.g., Kinoya WWTP servicing Suva) or waste stabilization ponds (e.g., Natabua WWTP servicing Lautoka). Final treated effluent discharges to rivers or oceans. To determine connected populations, we summed the population within the area serviced by each WWTP based on data from WAF. The small populations (reported as ~4,000 people or <0.5% of the population) within areas serviced by the Wailada, Naboro correction facility and ACS treatment plants were not considered because the focus of our study was on residential wastewater and these primarily serve industrial and institutional purposes (WAF, *personal communication*) (Fig. 1).

Sanitation services can vary significantly between urban and rural populations (SPREP, 2007), with higher levels of sewered wastewater treatment in urban compared to on-site systems for rural populations. We classified the remaining population that was not connected to a WWTP into urban and rural based on town boundaries. Town names and area estimates (hectares) were sourced from the Ministry of Lands and Mineral Resources (2018). The geographic coordinates (latitude/longitude) of each town were found through an internet search. Circular buffers were then created around each town location equal to the reported area, with an additional 0.05% circular buffer added to account for potential urban sprawl and peri-urban areas and to ensure urban population estimates matched reported values. Next, we ranked the population grid cells within these urban areas based on population density and "urban" land use classification (Jung et al., 2020). Populations were classified into urban and rural groups as described above until the reported population thresholds were reached (Table 1).

Table 1
The reported percent of the population within each treatment category (WHO and UNICEF, 2021) compared to model estimates.

Population	Treatment type	Reported (%)	Model estimate (%)
Urban	Connected	35.4	29.1
	Septic	58.9	59
	Other	5.4	5.4
Rural	Connected	1.4	0
	Septic	68.1	68.1
	Other	27.3	27.2
National total	Connected	20.7	17.3
	Septic	62.8	62.8
	Other	14.8	14.4

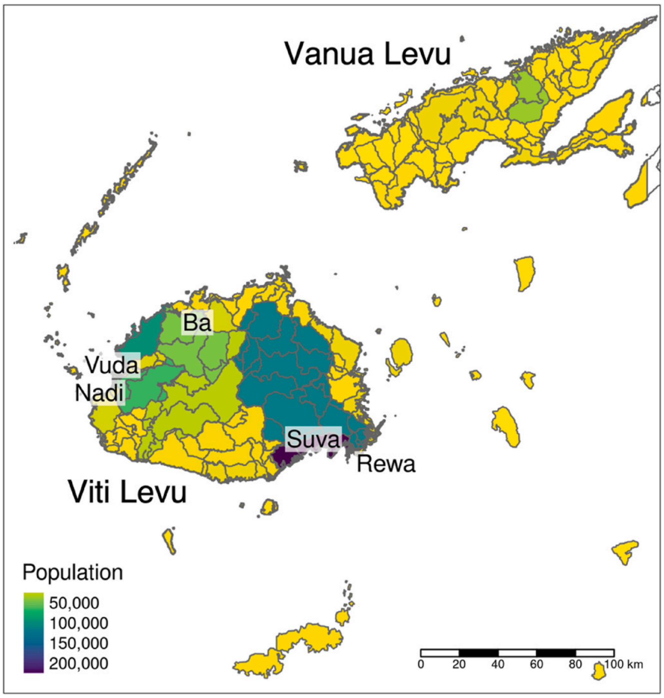

Fig. 1. Population within each watershed of the two main islands of Fiji: Viti Levu and Vanua Levu. Tikina borders (geographic subdivision in Fiji between the village and province level) are shown within each watershed. Tikinas most relevant to results are labeled for geographic context in white boxes. (Print in color). (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

2.3. Nutrient pollution

We combined the population data (described above) with protein intake data to estimate the total N and P emissions from human wastewater in each grid cell and by each treatment type. Protein intake values (I_N for nitrogen and I_P for phosphorus) were sourced from protein supply data (71.14 g/capita/day total vegetal and non-vegetal (P) and 42.72 g/capita/day vegetal only (P_v)) (FAOStat, 2018). To estimate protein N intake, it was assumed that 13% (Jonsson et al., 2004; Wang et al., 2019) of protein intake (g/capita/day) is N. We assumed protein P intake was 1.1% of protein intake, and vegetable protein was accounted for twice as it is generally considered to have twice as much P per gram as animal protein (Jonsson et al., 2004; Wang et al., 2019). Values were then converted to kg/capita/year by multiplying by 0.365.

$$I_N = P * 0.13 * 0.365$$

$$I_P = 0.011 * (P + P_v) * 0.365,$$

Finally, N and P estimates were multiplied by the population density in each grid cell to estimate total human nutrient emissions per cell.

Different sanitation systems result in varying levels of nutrient removal before wastewater enters the environment. To determine nutrient removal rates from WWTPs in Fiji, we used municipality data on wastewater sample analyses of total N and P concentrations of raw sewage and final effluent for each WWTP obtained from WAF, as well as yearly water flow rate data. In some cases, final nutrient load values were greater than raw values. It is relatively common for WWTP to occasionally work sub-optimally or overload (e.g., due to rainfall). We retained these values as they can occur when there is increased turbulent flow that releases nutrients from accumulated sludge and/or due to reduced hydraulic retention times. We calculated total effluent nutrient loads by multiplying the average yearly effluent concentrations (mg/L, based on approximately monthly monitoring) by the yearly flow rate (L). The efficiency of nutrient removal of each WWTP was then determined using the average raw and final effluent values between 2017 and 2019. Nutrient removal efficiency, $B_{n,i}$, for each nutrient (N or P) was then calculated as:

$$B_{n,i} = \frac{R_{n,i} - F_{n,i}}{R_{n,i}}$$

Where $R_{n,i}$ is the average raw sewage estimate for nutrient n (i.e., N or P), and $F_{n,i}$ is the average final nutrient effluent estimate for nutrient n at WWTP i.

For on-site sanitation systems (as opposed to sewered systems connected to WWTP) nutrients are removed either via treatment by septic tanks and degradation in situ or adsorption via surrounding soil after leaching from pit-latrines, permeable tanks, and septic tank drainage fields (based on soil types and distances from water bodies). There is an absence of data on the exact nutrient removal rates and back-end structural characteristics from different on-site latrine backend types in Fiji (Nasim et al., 2022). Hence, removal rates were based on a review of literature with similar sanitation back-end types to what is present in Fiji (Tables S1 and S2). From the literature a range of removal values were identified for septic tanks ranging from 20% for N and 30% for P for poorly functioning and overloaded systems to 80% for N and 100% for P for optimally treating septic systems (Beal et al., 2005; Montangero and Belevi, 2007; Spuhler et al., 2021; Withers et al., 2014). For pit latrines and permeable tank type back-ends from the limited literature the range for removal was 80% up to maximum removal rates of 98% for N and 99% for P (Graham and Polizzotto, 2013; Montangero and Belevi, 2007; Nyenje et al., 2013). There was no lower limit for P removal identified in the literature as P is highly degradable in most soil types (Beal et al., 2005). While we assess a range of removal rates, we use lower bounds of nutrient removal for the coral reef exposure analysis because they are likely to be most realistic as they account for common shortfalls of these systems, such as limited emptying of faecal sludge (<3% of rural households empty) (Nasim et al., 2023) and direct piping from backends into rivers, drains, and along coasts (Nasim et al., 2023, WISH Fiji *personal communication*). For pit latrines and permeable tanks, similarly the lower limits were also used because full pits/tanks are rarely emptied in Fiji.

For septic tanks and other on-site systems (pit latrines and permeable tanks), the probability of nutrients reaching rivers, streams, coasts, and subsequently coastal water bodies is limited by distance from these water bodies, as well as other factors such as soil types, topography, and precipitation. We consider a lateral nutrient travel distance for latrines from water bodies (rivers and coasts) of 35 m based on guidelines for safe distances for on-site sanitation which states that at 30 m there is little risk of contamination, especially from nutrients (Tilley et al., 2014). Hence, if a grid cell fell within 35 m of a river or a coast, it was considered that the latrine nutrients would make it into surface and/or groundwaters and subsequently coastal waters. We did not consider vertical leaching because pits are generally shallow (<2 m) relative to the water table (>10 m) which is considerably greater than the 2 m vertical distance recommended for safety (Hussain et al., 2017; Mrimi et al., 2020; Tilley et al., 2014).

We acknowledge that removal rates are likely to be highly variable in different locations in Fiji depending on back-end conditions (Nasim et al., 2022); soil types (Beal et al., 2005); water table height (which we have not assessed); precipitation (e.g. flooding), and maintenance (e.g., infrequent or no emptying) (Jenkins et al., 2019; Nasim et al., 2022; SPREP, 2007). Notably, we do not consider the contamination impacts on coastal waters from the illegal disposal of faecal sludge from emptying septic tanks, other tanks, or pit-latrines. The values used in our model for nutrients from on-site sanitation systems are based on limited available data but represent an important starting point for these types of coastal impact estimations.

2.4. Nutrient exports reaching coral reefs

For on-site sanitation systems (e.g., septic and other types) any contamination enters the environment near the latrine (<35 m), whereas treated effluent from WWTPs is often piped to discharge points. WWTP pourpoints (i.e., outfalls) were located using Google Earth based on information from the national liquid waste management strategy and action plan (SPREP, 2007). For the two WWTP that discharge in the ocean, the outfall was located at the specified distance from the WWTP (SPREP, 2007). For WWTP that have outfalls in rivers, and septic and other wastewater treatment types, we located the pourpoint of each river into the ocean by finding the most downstream point in RiverAtlas (Linke et al., 2019) within each watershed, based on level 12 main basins from the HydroBASINS database (Lehner and Grill, 2013). For watersheds with more than one pourpoint, total nutrient export from septic and other treatment types in the watershed were allocated based on the mean annual discharge of each river in the watershed (m^3/year), under the assumption that rivers with higher levels of discharge are more likely to transport a greater proportion of nutrients from a watershed (Suárez-Castro et al., 2021). We assumed nutrients entered coastal waters from the nearest coastal grid cell for septic and other waste disposal within 35 m of the coast.

We used a diffusion plume model to estimate the relative amount of nitrogen effluent from all sanitation types discharged from river pourpoints that reach coral reefs. The discharge point of the watershed (i.e., pourpoint) was considered as the source location for nutrient dispersion, which was then modeled as a 2D diffusion process using a cost-path surface, where a decay function evenly distributes 0.5% of the initial potential nutrient value to all adjacent cells (Suárez-Castro et al., 2021). We applied the plume model to all treatment types combined, as well as connected (WWTP) and unconnected (septic and other) treatment types separately because nutrient reduction recommendations between these treatment types vary substantially. Finally, we applied the plume model to nutrients from each watershed individually to better track the risk that nutrients from each watershed pose to coral reefs. We used this information to assess relative differences between treatment types and locations. Reef locations were based on the Allen Coral Atlas database, which uses remote sensing techniques to classify coral reefs up to 15 m depth (Allen Coral Atlas, 2022). Next, we quantified the coral reef nitrogen exposure per square kilometer of coral reef by converting the coral reef layer to a 1 km × 1 km grid and summing total nitrogen plumes within each pixel where coral reefs were present. Notably, we focus on N for this analysis, but as N and P are correlated, we would expect similar patterns for reef exposure to P.

3. Results

3.1. Population by treatment type

We estimate Fiji's population to be 887,648, with 153,302 people (17.3%) connected to a WWTP (Table 1). Our estimate of Fiji's population is 0.25% less than recent population estimates (894,389 in 2019) (FBS, 2020), and our estimate of the connected population is ~3.4% less than values reported by the Joint Monitoring Programme (JMP) (WHO and UNICEF, 2021). Connected population estimates were lower at all WWTP than 2007 reported values, except Lautoka Natabua WWTP (9.5% higher). However, our estimates are highly correlated to reported values ($R^2 = 0.99$, p=<0.0001, (SPREP, 2007), Fig. S1) giving us confidence in relative results. Modeled septic and other system types accounted for 82.3% of the population and these values were also consistent with reported JMP values (Table 1).

3.2. Nutrient pollution

We estimate that the Fijian residential population excretes a total of 2,828.7 tonnes of N and 383.1 tonnes of P annually. Of this, 365.7 tonnes N and 55.8 tonnes P enter surface waters considering a 35 m later travel distance and lower nutrient level bounds (20% N and 30% P) for septic and other treatment types.

Most nutrients entering surface waters were from WWTPs, with nutrient removal rates ranging from ~24% to ~70%. WWTPs accounted for 79.5% of N and 85% of P released to the environment (i.e., after treatment) (Fig. 2 and Fig. S2). We estimate 517.5 tonnes of N and 70.1 tonnes of P enter Fiji's WWTPs each year. Based on WWTP nutrient removal rates, ~56.6% (293 tonnes) of human excreted N and 68.9% (48.3 tonnes) of P that enter WWTPs are subsequently released into the environment (Fig. 2). Our estimates of sewage effluent are positively correlated with reported final effluent values by WAF ($R^2 = 0.98$, p = 0.00002 for N and $R^2 = 0.98$, p = 0.00001 for P, Fig. S3). Kinoya WWTP, which services the largest number of people, has the greatest level of annual nutrient discharge making up 63% of all effluent from WWTPs, followed by Lautoka and Navakai WWTP (Fig. 2). Nutrient discharge was lowest at Deuba (Pacific Harbor), Nadali and Olosara (Fig. 2).

For other wastewater disposal systems, surface water N loads range from <2.4 (98% N removal) to 4.8 tonnes (80% N removal) and P loads are likely <0.3 tonnes (99% removal rate) considering a 35 m lateral travel distance (Fig. 3A). Wastewater input from coastal populations accounted for 31% of septic and 35.1% of other wastewater effluent. We estimate septic systems treat ~1,880.2 tonnes of N and ~254.6 tonnes of P per year in Fiji (Fig. 1), accounting for 66.5% of human N excretion. Surface water N loads (35 m lateral travel distance) range from 0 to 70 tonnes (80% or 20% nutrient removal rate), while P loads range from 0 to 8.3 tonnes (100% or 30% removal rate) (Fig. 3B).

3.3. Residential nitrogen exports reaching coral reefs

We estimate that over 8.4% (30.6 tonnes) of nutrients that enter surface and coastal waters reach coral reefs (Figs. 4 and 5). Nearly 95% of reef areas in Fiji are estimated to have some level of N exposure from human wastewater, covering over 1,250 km^2. However, just 1.5% of reef units with N exposure account for 90% of total estimated N loading.

We found a strong positive correlation between estimates of watershed N discharge and coral reef exposure ($R^2 = 0.99$, $p < 2.2e\text{-}16$) (Fig. 4A). Coral reefs with the highest N loading were also those near watersheds containing WWTPs: Suva (Kinoya WWTP), followed by Vuda (Lautoka WWTP) and Rewa (Nadali WWTP) (Fig. 4). Suva was a hotspot for nutrients reaching reefs from both connected and unconnected (septic and other) sources (Figs. 4 and 5A) relative to other areas. Across nearly 75% of reefs, the source of most nutrient pollution (>50%) is from unconnected wastewater treatment (septic and other) (Figs. 4 and 5A). Coastal nitrogen loads from human wastewater on Vanua Levu were generally lower, with some higher levels near the Namara WWTP on the northern side of the island. We also estimate that most coral reefs (83%) are exposed to nutrients originating from multiple watersheds, nearly four on average (maximum of 9; Fig. 5B).

4. Discussion

The role of human wastewater pollution in ecosystem and human health has gained attention over recent years (Nasim et al., 2022; Wakwella et al., 2023; Wear, 2019). Several global goals (SDG 6) and initiatives (e.g., Ocean Sewage Alliance, WASH in Watersheds) aim to reduce nutrient pollution from human wastewater for ecosystem and human health but lack spatial data to inform monitoring and management decisions. Our spatial model estimated nutrient pollution from residential human wastewater reaching coral reefs and provides information on where potential environmental and health impacts may be highest, and which management strategies could result in the greatest nutrient reductions. Our case study in Fiji revealed that WWTPs account for the vast majority (80%) of residential nitrogen pollution entering the environment, followed by septic systems (20%) and other treatment systems. We estimate that 95% of coral reefs (1,250 km^2) are exposed to

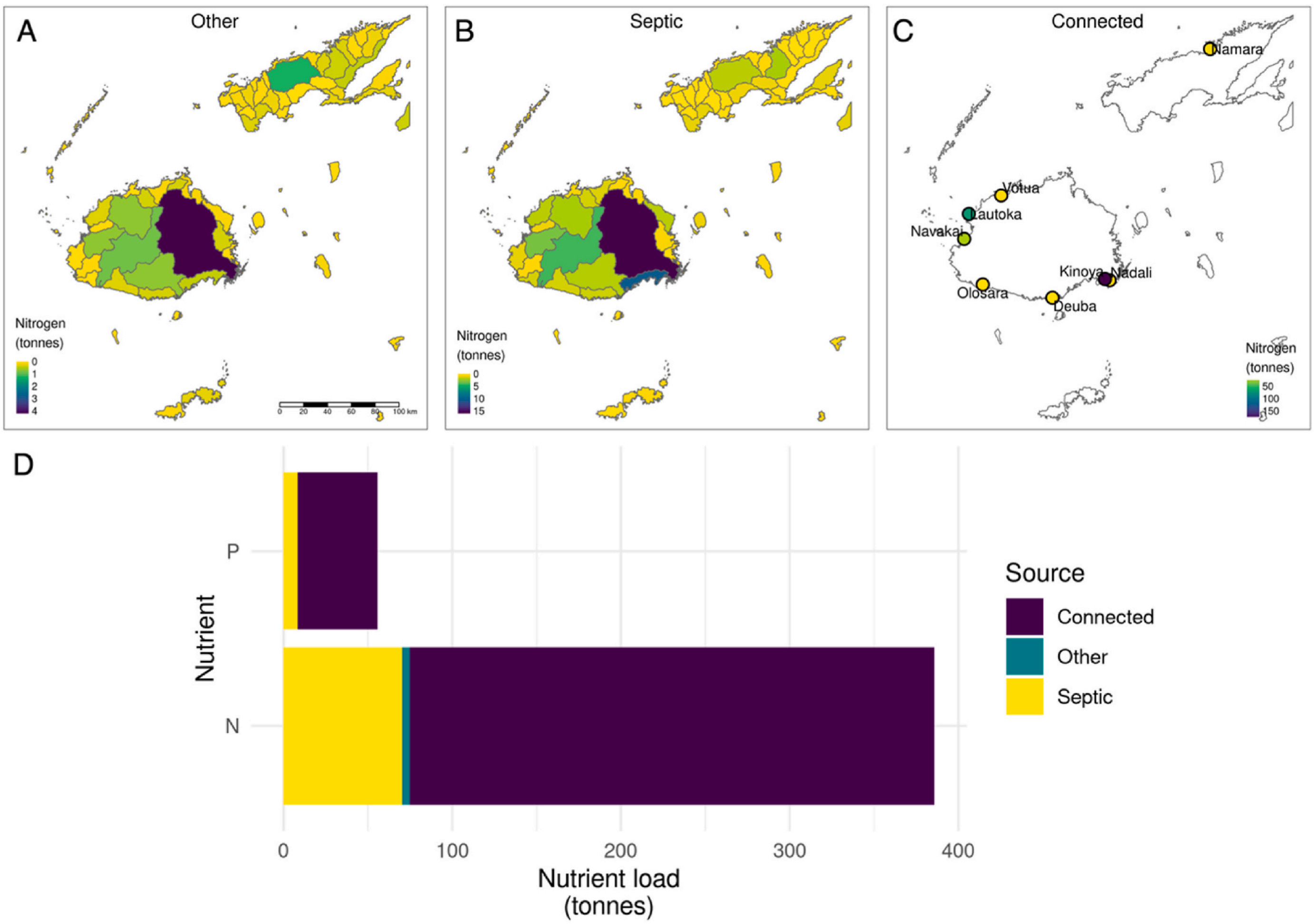

Fig. 2. Nutrients by watershed and treatment type in Fiji. Nitrogen released into surface waters from each residential treatment type: A) other (sub-surface pits or permeable tanks (non-standard septics), B) septic, and C) connected (municipal sewer systems). D) The total tonnes of nitrogen for each treatment type across the entire study area. Note differences in scales. Maps of phosphorus results show similar patterns and can be found in Fig. S2. (Print in color). (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

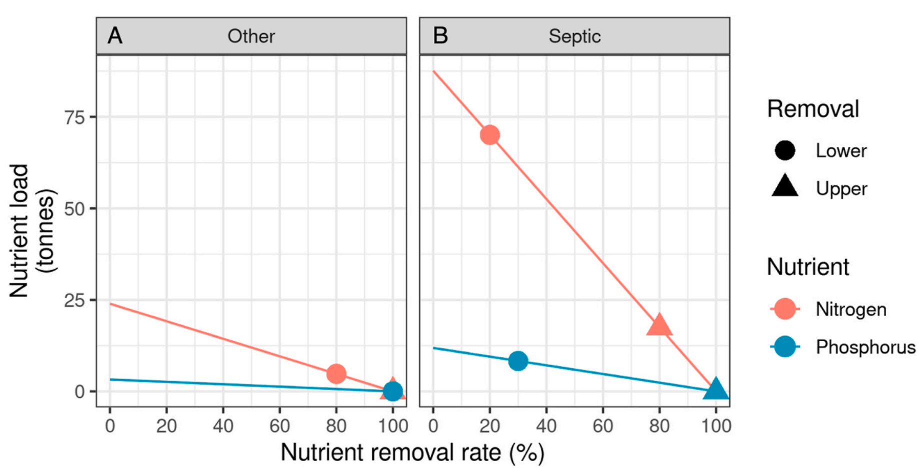

Fig. 3. Effects of nutrient removal rate (0–100%) on nutrient pollution estimates (tonnes/year). Changes in nitrogen and phosphorus estimates for varying nutrient removal rates for (A) other (i.e., sub-surface or permeable tanks) and (B) septic systems considering a 35 m surface water buffer. Points represent values lower bounds of nutrient removal rates that were used in the main text (20% nitrogen and 30% phosphorus nutrient removal for septic, 80% nitrogen and 98% phosphorus removal rate for other). Triangles represent likely "best case" estimates for upper bounds of nutrient removal (80% nitrogen and 100% phosphorus for septic, 98% nitrogen and 99% phosphorus for other).

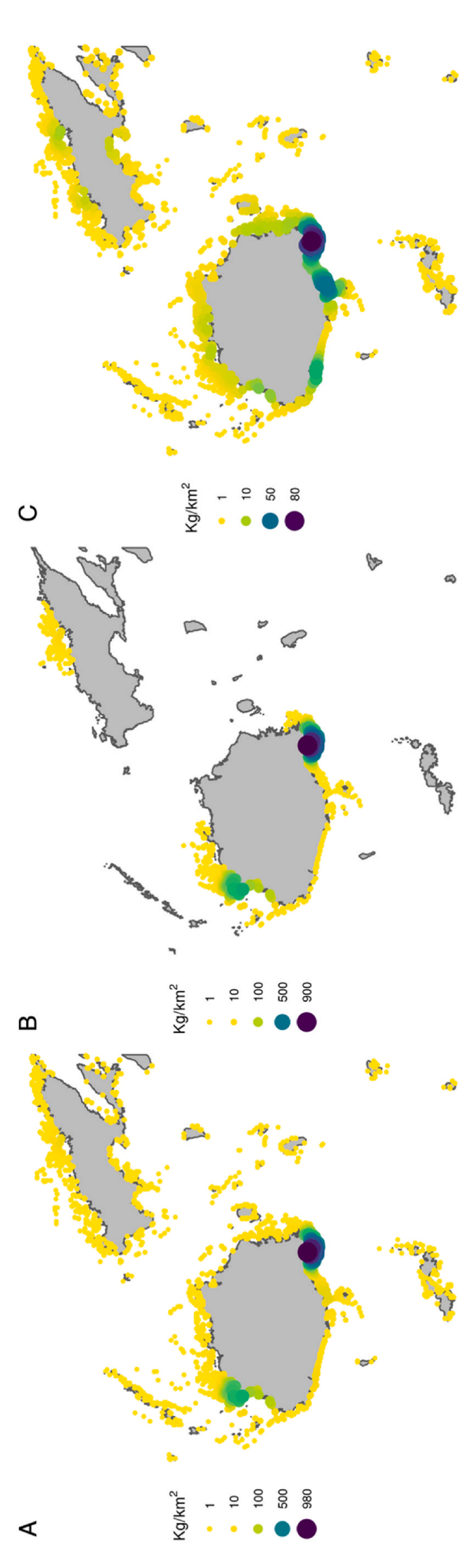

Fig. 4. Residential wastewater nitrogen reaching coral reef areas (kg/km^2). A) Total estimated nitrogen from all treatment types reaching coral reef areas (kg/km^2), B) estimated nitrogen from connected (i.e., Wastewater Treatment Plants) reaching coral reef areas (kg/km^2), and C) estimated nitrogen from unconnected (septic and other) treatment types reaching coral reef areas (kg/km^2). Note differences in scale. (Print in color). (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

residential nutrient pollution, and although septic systems only account for 20% of nitrogen pollution, they had the largest impact in terms of coral reef area affected. This information, along with consideration of human health factors,fills significant gaps in the data-poor region of Fiji and can be applied to other locations to better understand how bridging sanitation and conservation sectors can achieve multiple UN Sustainable Development Goals (e.g., SDG 3, 6, 14, 15).

WWTPs were the largest contributors of residential human wastewater effluent, with the largest WWTP, Kinoya, accounting for 50% of all N entering the environment. While WWTPs are often the gold standard in wastewater nutrient removal (Van Drecht et al., 2009; Wang et al., 2019), they can concentrate large amounts of waste (Ehalt Macedo et al., 2022) that are discharged directly into rivers or coastal environments, particularly when service is overloaded or interrupted. For example, power disruptions (planned and unplanned) are common throughout Fiji (Energy Fiji Limited, https://efl.com.fj), which can impact pumps and reduce the effectiveness of WWTPs. Coral reefs with the greatest nitrogen exposure were those in areas of high population density and WWTP facilities, such as Suva and Nadi. Indeed, coral reefs and coastal habitats in these areas have documented degradation due to anthropogenic activity and land-based run-off (CRISP, 2009).

Improving treatment levels at WWTP is one way to reduce nutrients entering coastal waters but this process is costly and takes significant time to implement. The Asian Development Bank's Green Climate Fund project is already working to update and strengthen the capacity of the Kinoya WWTP, with a project expected to be completed in 2026 and financing of >USD$405 million (GCF, 2015). Their plans include upgrading the sewage network and expanding capacity, but the level of treatment to be achieved is unclear (ADB, 2022). While improving Kinoya WWTP treatment levels could result in substantial reductions in nutrients released into the environment, additional factors causing disruptions should be identified and minimized to improve the efficacy of existing infrastructure. Appropriate planning is needed to ensure any methods used to increase treatment are sustainable into the future as populations, and thus strain on facilities, continue to grow. Further, recovering material from wastewater that can be reused (i.e., resource recovery) could help to offset upgrade costs and reduce the overall nutrient load entering the environment (Thomas and Gold, 2021).

We estimate that >80% of excreted N is treated using septic and other systems signifying their widespread use across Fiji. Although these systems only accounted for ~20% of N entering surface waters, their widespread spatial distribution resulted in larger coral reef area exposure (75% of reefs). Septic tank treatment levels could be improved by ensuring they are built to standard (Nasim et al., 2023) or located further from surface water. Even areas dominated by WWTP effluent had high levels of other and septic treatment nutrient loads highlighting the need for multiple sanitation intervention strategies to reduce nutrient pollution in this region. Further, while risks to reefs are highest near urban areas, urban populations are generally less reliant on adjacent reefs for food and income than in more rural places. Management decisions should incorporate aspects of marine resource dependence, particularly fisheries, to consider nutrition and food safety outcomes for the country. We also expect coastal septic systems and other treatment types to be more vulnerable to the impacts of flooding, sea level rise, and extreme weather, which may lead to pulse events of high nutrient loads from overflowing backends (Nasim et al., 2023). In fact, elevated nutrient samples collected in Fiji at Laucala Bay (near Suva) have been attributed to overflowing and untreated sewage during wet weather (Singh et al., 2009). Additionally, the inclusion of flooding induced sewer overflow and WWTP bypass events is another high pollutant loading that needs to be considered (Vermeulen and Hofstra, 2014). Examining the potential vulnerability and exposure of coastal septic systems and pit latrines to climate change and seasonal weather patterns, and the resulting impacts on people and coastal habitats, should be a priority for future research.

In this work we consider transport of nutrients from latrines via

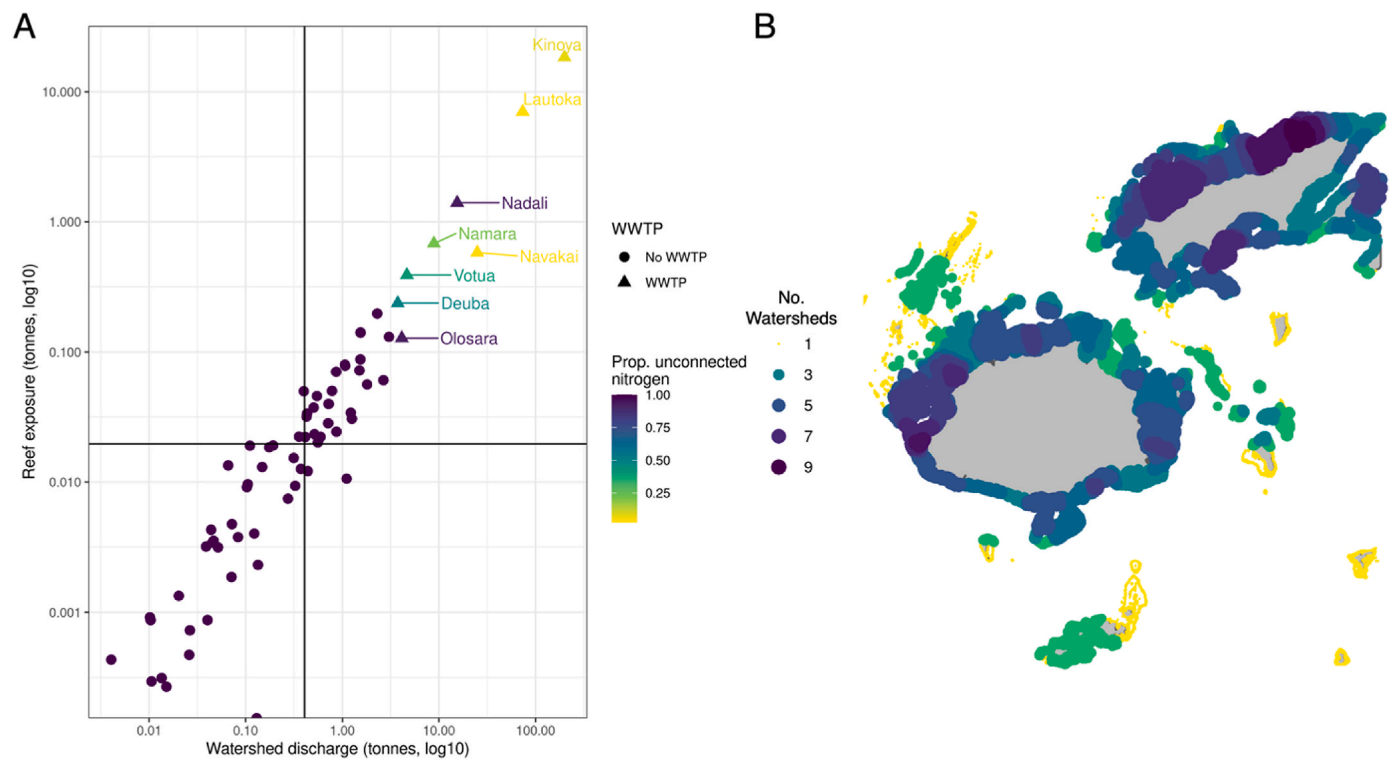

Fig. 5. Watershed nutrient discharge compared to nutrient reef exposure. (A) Nutrient export (tonnes) from each main watershed compared to the coral reef nutrient exposure (tonnes) from each watershed. (B) The number of watersheds contributing to nutrients reaching each coral reef areas. Colors in A represent the proportion of nutrients discharged from each watershed that are from an unconnected treatment type (septic or other, 1 indicates nutrients entirely from unconnected treatment types whereas values < 1 indicate some nutrients originated from Wastewater Treatment Plants (WWTP)). The shape of points indicates whether the watershed contains a WWTP, which are labelled near points. The vertical line indicates the median nitrogen discharge, and the horizontal line indicates the median nitrogen exposure on reefs from each watershed. (Print in color). (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

saturated soils but have not included transport via deeper aquifers. This is due to the common latrine depth being shallow (<2 m) (Nyenje et al., 2013) and the hydrogeology of Fiji having volcanic perched aquifers accessed via springs in elevated areas and the basal aquifers being quite deep and difficult to access (Singh et al., 2001). Our model's nutrient transport distances of 35 m from on-site systems is also likely an over estimate of contamination risk, as recent field studies in Fiji have shown nutrient plumes are undetectable from the latrine source in common clay-silt soils at 10 m and higher permeability sandy coastal soils at 15 m (Nasim *personal communication*). Notably, we did not consider transport of nutrients from latrines via smaller tributaries (e.g., creeks or drains) that lead to the larger river systems. However, if included we would anticipate that the nutrient loads would increase. Additionally, a recent study of 1,500 rural Fijian households found that 51–64% of households over reported septic tank use when they actually had a permeable tank (Nasim et al., 2023), of which some directly pipe into creeks and drains and could raise the nutrient transfer loads described here. Illegal dumping by vacuum tankers of emptied septic tanks, tanks or pits in rivers and oceans is another source of high pollution loading that is common in other developing country contexts (Okaali et al., 2021), but little is known about the prevalence of these activities in Fiji.

Our preliminary analysis of tourism (Supplemental Materials) showed that it may be an important factor for reducing nutrients on reefs, making up 15% of all N pollution after accounting for treatment. However, we excluded tourism due to the coarse resolution of our estimates and uncertainties on the final treatment and discharge locations. For example, many resorts and hotels in Fiji either pump waste to neighboring WWTPs, have on-site treatment plants, or recycle wastewater for garden and golf course irrigation, making it difficult to track. While all strategies still must dispose of fecal sludge, which attributes to some level of nutrient pollution, recycling wastewater may decrease nitrogen entering coastal waterways due to natural filtering. Reef tourism plays a large role in Fiji's economy, with over 870,000 tourists in 2018 (pre-COVID-19), nearly equal to Fiji's entire population. Targeting sanitation interventions to areas with high wastewater (from all sources) and high tourism may provide additional economic value. Nadi, the Coral Coast, and Mamanuca Islands accounted for >80% of tourism nitrogen potentially released into the environment (Supplemental Materials, Fig. S4). Notably, Nadi Bay and Suva Harbor are major cruise ship ports, which may result in large influxes of tourist wastewater during day visits as seen in similar studies in the Mesoamerican reef (Berger et al., 2022). As tourism begins to re-open following a long period of COVID-19 lockdowns, there is opportunity to better assess the influence of tourism on coastal water quality and take actions to mitigate impacts.

Local scale parameterization of our model is an improvement on estimates of Fiji wastewater pollution from best available globally parameterized models (Ehalt Macedo et al., 2022; Tuholske et al., 2021). However, there are some important caveats to consider. First, there are large data gaps in Fiji - particularly related to water quality monitoring. Monitoring is often done sporadically, and the data are not made publicly available. This makes it difficult to test whether our model estimates of nutrients reaching reefs and coastal waters reflect in situ conditions. Long-term in situ nutrient monitoring coupled with long-term monitoring of coral condition would help improve our model and allow for model performance evaluation. However, we ensured that population estimates and treatment statistics for all sources followed expected trends based on reported data making relative comparisons feasible. Second, we estimate coral reef nutrient exposure, but the impacts of coral reefs to nutrients is highly context dependent. Our model of nutrient dispersion is relatively simple and future work could incorporate more complex models of nutrient transport dynamics and pathways. For example, our dispersion model likely overestimates nutrients in areas with strong hydrodynamic processes (e.g., currents, waves) that play an important role in nutrient flushing in the region. Impacts from coral reef nutrient exposure are likely to be higher in relatively sheltered areas with minimal flushing (e.g., Nadi Bay, Laucala Bay) (Fredston-Hermann et al., 2016), as opposed to more exposed and well-flushed areas. Further, it is difficult to disentangle impacts of human wastewater nutrients on coral reefs from other sources of pollution (agriculture, coastal development, sedimentation), and further field and laboratory work is necessary to determine nutrient enrichment effects, potential thresholds, and biological responses of corals to nutrient exposure. Future work should aim to incorporate model performance evaluation and increased temporal and spatial resolution if data become available. This would allow for further confidence in the model, as well as evaluation of seasonal changes and better accounting of coastal and river-adjacent nutrient sources with higher resolution data. Our framework could also be modified to incorporate coral reef health, recovery potential, and feasibility considerations to prioritize watershed management actions to maximize return on investment (Bottrill et al., 2008), as well as assess differences between human health and coral reef health objectives to determine the potential for achieving win-win solutions.

5. Conclusions

Improving wastewater treatment has the potential to achieve multiple benefits, including for coastal conservation. Sanitation and marine conservation practitioners have often remained siloed due to capacity shortfalls, data limitations and a lack of understanding of potential co-benefits. Fiji provides an excellent case study where ongoing action to improve wastewater could also improve coastal habitat conditions if planned appropriately. Our study provides a spatial framework for assessing human wastewater exposure risk to coral reefs, which can be used to better understand knowledge gaps and potential benefits and trade-offs of sanitation improvements for nutrient pollution and coral reef health, even in data limited areas such as Fiji.

Author contributions

Conceptualization - all authors contributed to the conceptualization of the project; *Methodology* - CDK, JT, AW, SDJ, AFC, NN; *Software* - CDK, AFC; *Validation* - CDK, JT, NN; *Formal analysis* - CDK; *Data curation* - CDK; *Writing - Original draft* - CDK; *Writing - Review and Editing* - all authors*Visualization* - CDK; *Supervision* - OHG, SDJ, AW*Project administration* - CDK; Funding *acquisition* - OHG.

Statement of inclusion

Several authors on the paper are part of the WISH Fiji Project, which is working directly with government and local landowners in Fiji to improve water quality through a combination of nature-based solutions and improvements to water and sanitation infrastructure within targeted watersheds. Our team received guidance and data from Fiji government authorities and locally based NGOs to parameterize the model to best represent real-world conditions in Fiji (Acknowledgements).

SDJ is a Fijian dual-national, resides in Fiji, and is regional director of an NGO specializing in providing evidence-based recommendations to decision-makers for better natural resource management practices. SDJ and her team will be integrating outcomes from this study into national dialogue to improve wastewater management to achieve Fiji's national sustainable development targets.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

All code and data to reproduce the analysis are avaialble at github.com/cdkuempel/Fiji_sewage.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.envpol.2023.123003.

References

ADB, 2022. Urban water supply and wastewater management investment program. Tranche 1 4.

Allen Coral Atlas, 2022. Imagery, Maps and Monitoring of the World's Tropical Coral Reefs.

Andrello, M., Darling, E.S., Wenger, A., Suárez-Castro, A.F., Gelfand, S., Ahmadia, G.N., 2022. A global map of human pressures on tropical coral reefs. CONSERVATION LETTERS 15. https://doi.org/10.1111/conl.12858.

Beal, C.D., Gardner, E.A., Menzies, N.W., 2005. Process, performance, and pollution potential: a review of septic tank-soil absorption systems. Aust. J. Soil Res. 43, 781–802.

Berger, M., Canty, S.W.J., Tuholske, C., Halpern, B.S., 2022. Sources and discharge of nitrogen pollution from agriculture and wastewater in the Mesoamerican Reef region. Ocean Coast Manag. 227, 106269 https://doi.org/10.1016/j.ocecoaman.2022.106269.

Bottrill, M.C., Joseph, L.N., Carwardine, J., Bode, M., Cook, C., Game, E.T., Grantham, H., Kark, S., Linke, S., McDonald-Madden, E., Pressey, R.L., Walker, S., Wilson, K.A., Possingham, H.P., 2008. Is conservation triage just smart decision making? Trends Ecol. Evol. 23, 649–654. https://doi.org/10.1016/j.tree.2008.07.007.

Burke, L., Reytar, K., Spalding, M., Perry, A., 2011. Reefs at Risk Revisited.

Carlson, R.R., Foo, S.A., Asner, G.P., 2019. Land use impacts on coral reef health: a ridge-to-reef perspective. Front. Mar. Sci. 6, 562. https://doi.org/10.3389/fmars.2019.00562.

CIESIN, 2016. Facebook Connectivity Lab and Centre for International Earth. Science Information Network - CIESIN- Columbia University. High resolution settlement layer (HRSL).

CRISP, 2009. South-West Pacific Status of Coral Reefs Report 2007.

D'Angelo, C., Wiedenmann, J., 2014. Impacts of nutrient enrichment on coral reefs: new perspectives and implications for coastal management and reef survival. Curr. Opin. Environ. Sustain. 7, 82–93. https://doi.org/10.1016/j.cosust.2013.11.029.

Ehalt Macedo, H., Lehner, B., Nicell, J., Grill, G., Li, J., Limtong, A., Shakya, R., 2022. Distribution and characteristics of wastewater treatment plants within the global river network. Earth Syst. Sci. Data 14, 559–577. https://doi.org/10.5194/essd-14-559-2022.

Fabricius, K.E., 2005. Effects of terrestrial runoff on the ecology of corals and coral reefs: review and synthesis. Mar. Pollut. Bull. 50, 125–146. https://doi.org/10.1016/j.marpolbul.2004.11.028.

FAOStat, 2018. Food Balances Sheets Protein Supply Quantity.

FBS, 2020. Visitor Arrival Statistics.

Ferrario, F., Beck, M.W., Storlazzi, C.D., Micheli, F., Shepard, C.C., Airoldi, L., 2014. The effectiveness of coral reefs for coastal hazard risk reduction and adaptation. Nat. Commun. 5, 3794. https://doi.org/10.1038/ncomms4794.

Fredston-Hermann, A., Brown, C.J., Albert, S., Klein, C.J., Mangubhai, S., Nelson, J.L., Teneva, L., Wenger, A., Gaines, S.D., Halpern, B.S., 2016. Where does river runoff matter for coastal marine conservation. Front. Mar. Sci. 3.

GCF, 2015. Fiji Urban Water Supply and Wastewater Management Project.

Graham, J.P., Polizzotto, M.L., 2013. Pit latrines and their impacts on groundwater quality: a systematic review. Environ. Health Perspect. 121, 521–530. https://doi.org/10.1289/ehp.1206028.

Hoegh-Guldberg, O., Jacob, D., Taylor, M., Guillén Bolaños, T., Bindi, M., Brown, S., Camilloni, I.A., Diedhiou, A., Djalante, R., Ebi, K., Engelbrecht, F., Guiot, J., Hijioka, Y., Mehrotra, S., Hope, C.W., Payne, A.J., Pörtner, H.-O., Seneviratne, S.I., Thomas, A., Warren, R., Zhou, G., 2019. The human imperative of stabilizing global climate change at 1.5°C. Science 365, eaaw6974. https://doi.org/10.1126/science.aaw6974.

Hussain, F., Clasen, T., Akter, S., Bawel, V., Luby, S.P., Leontsini, E., Unicomb, L., Barua, M.K., Thomas, B., Winch, P.J., 2017. Advantages and limitations for users of double pit pour-flush latrines: a qualitative study in rural Bangladesh. BMC Publ. Health 17, 515. https://doi.org/10.1186/s12889-017-4412-7.

Jenkins, Jupiter, Jenney, Naucukidi, Prasad, Vosaki, Mulholland, Strugnell, Kama, Crump, Horwitz, 2019. Environmental foundations of typhoid fever in the Fijian residential setting. IJERPH 16, 2407. https://doi.org/10.3390/ijerph16132407.

Jonsson, H., Richert Stinzing, A., Vinneras, B., Salomon, E., 2004. EcoSanRes: Guidelines in the Use of Urine and Faces in Crop Production. EcoSanRes programme and the Stockholm Environment Institute.

Jung, M., Dahal, P.R., Butchart, S.H.M., Donald, P.F., De Lamo, X., Lesiv, M., Kapos, V., Rondinini, C., Visconti, P., 2020. A global map of terrestrial habitat types. Sci. Data 7.

Jupiter, S.D., Jenkins, A.P., Negin, J., Anthony, S., Baleinamau, P., Devi, R., Gavidi, S., Mailautoka, K.K., Mangubhai, S., Naivalu, K., Naivalulevu, T., Naivalulevu, V., Nasim, N., Naucunivanua, S., Nelson, S., Qauqau, I., Ratu, A., Ravoka, M., Thomas, J., Tukana, A., Van Nimwegen, P., Wakwella, A., Wenger, A., Wilson, D., Horwitz, P., 2023. Transforming place-based management within watersheds in Fiji: the Watershed Interventions for Systems Health project (preprint). EarthArXiv. https://doi.org/10.31223/X56S9M.

Lapointe, B.E., Brewton, R.A., Herren, L.W., Porter, J.W., Hu, C., 2019. Nitrogen enrichment, altered stoichiometry, and coral reef decline at Looe Key, Florida Keys, USA: a 3-decade study. Mar. Biol. 166, 108. https://doi.org/10.1007/s00227-019-3538-9.

Leder, K., Openshaw, J.J., Allotey, P., Ansariadi, A., Barker, S.F., Burge, K., Clasen, T.F., Chown, S.L., Duffy, G.A., Faber, P.A., Fleming, G., Forbes, A.B., French, M., Greening, C., Henry, R., Higginson, E., Johnston, D.W., Lappan, R., Lin, A., Luby, S.P., McCarthy, D., O'Toole, J.E., Ramirez-Lovering, D., Reidpath, D.D., Simpson, J.A., Sinharoy, S.S., Sweeney, R., Taruc, R.R., Tela, A., Turagabeci, A.R., Wardani, J., Wong, T., Brown, R., RISE Consortium, 2021. Study design, rational and methods of the Revitalising Informal Settlements and their Environments (RISE) study: a cluster randomised controlled trial to evalutae environmental and human health impacts of a water-sensitive intervention in information settlemetns in Indonesia and Fiji. BMJ Open 11.

Lehner, B., Grill, G., 2013. Global river hydrography and network routing: baseline data and new approaches to study the world's large river systems: global river hydrography and network routing. Hydrol. Process. 27, 2171–2186. https://doi.org/10.1002/hyp.9740.

Linke, S., Lehner, B., Ouellet Dallaire, C., Ariwi, J., Grill, G., Anand, M., Beames, P., Burchard-Levine, V., Maxwell, S., Moidu, H., Tan, F., Thieme, M., 2019. Global hydro-environmental sub-basin and river reach characteristics at high spatial resolution. Sci. Data 6.

Mangubhai, S., Sykes, H., Lovell, E., Brodie, G., Jupiter, S., Morris, C., Lee, S., Loganimoce, E.M., Rashni, B., Lal, R., Nand, Y., Qauqau, I., 2019. Fiji: coastal and marine ecosystems. In: World Seas: an Environmental Evaluation. Elsevier, pp. 765–792. https://doi.org/10.1016/B978-0-08-100853-9.00044-0.

McFarlane, R.A., Horwitz, P., Arabena, K., Capon, A., Jenkins, A., Jupiter, S., Negin, J., Parkes, M.W., Saketa, S., 2019. Ecosystem services for human health in Oceania. Ecosyst. Serv. 39.

Ministry of Economy, 2017. Transforming Fiji: 5-Year and 20-Year. National Development Plan.

Montangero, A., Belevi, H., 2007. Assessing nutrient flows in septic tanks by eliciting expert judgement: a promising method in the context of developing countries. Water Res. 41, 1052–1064. https://doi.org/10.1016/j.watres.2006.10.036.

Mosley, L.M., Aalbersberg, W.G.L., 2003. Nutrient levels in sea and river water along the "coral coast" of Viti Levu. Fiji. S. Pac. J. Nat. Sci. 21, 35–40.

Mrimi, E.C., Matwewe, F.J., Kellner, C.C., Thomas, J.M., 2020. Safe resource recovery from faecal sludge: evidence from an innovative treatment system in rural Tanzania. Environ. Sci.: Water Res. Technol. 6, 1737–1748. https://doi.org/10.1039/C9EW01097A.

Nasim, N., Anthony Anthony, S., Daurewa, T., Sikeli, G., Horwitz, P., Jenkins, A., Jupiter, S., Liu, S., Mailautoka, K., Mangubhai, S., Naivalu, K., Naivalulevu, T., Naivalulevu, V., Naucunivanua, S., Negin, J., Ravoka, M., Tukana, A., Wilson, D., Thomas, J., 2023. Understanding On-Site Sanitation in Rural Fiji: where Defintions of Sanitation Back-Ends Differ. Environmental Science: Water Research and Technology.

Nasim, N., El-Zein, A., Thomas, J., 2022. A review of rural and peri-urban sanitation infrastructure in South-East Asia and the Western Pacific: highlighting regional inequalities and limited data. Int. J. Hyg Environ. Health 244, 113992. https://doi.org/10.1016/j.ijheh.2022.113992.

Nyenje, P.M., Foppen, J.W., Kulabako, R., Muwanga, A., Uhlenbrook, S., 2013. Nutrient pollution in shallow aquifers underlying pit latrines and domestic solid waste dumps in urban slums. J. Environ. Manag. 122, 15–24. https://doi.org/10.1016/j.jenvman.2013.02.040.

Okaali, D.A., Kroeze, C., Medema, G., Burek, P., Murphy, H., Tumwebaze, I.K., Rose, J.B., Verbyla, M.E., Sewagudde, S., Hofstra, N., 2021. Modelling rotavirus concentrations in rivers: assessing Uganda's present and future microbial water quality. Water Res. 204, 117615 https://doi.org/10.1016/j.watres.2021.117615.

Pacific Data Hub, 2020. Population Raster Fiji 2020.

Samonte-Tan, G., 2008. Economic Values of Coral Reefs, Mangroves, and Seagrasses A Global Compilation 2008 23.

Singh, S., Aalbersberg, W.G.L., Morrison, R.J., 2009. Nutrient pollution in Laucala Bay, Fiji Islands. Water Air Soil Pollut. 204, 363–372. https://doi.org/10.1007/s11270-009-0050-8.

Singh, R.B.K., Hales, S., de Wet, N., Raj, R., Hearnden, M., Weinstein, P., 2001. The influence of climate variation and change on diarrheal disease in the Pacific Islands. Environ. Health Perspect. 109.

SPREP, 2007. Fiji National Liquid Waste Management Strategy and Action Plan.

Spuhler, D., Scheidegger, A., Maurer, M., 2021. Ex-ante quantification of nutrient, total solids, and water flows in sanitation systems. J. Environ. Manag. 280, 111785 https://doi.org/10.1016/j.jenvman.2020.111785.

Suárez-Castro, A.F., Beyer, H.L., Kuempel, C.D., Linke, S., Borrelli, P., Hoegh-Guldberg, O., 2021. Global forest restoration opportunities to foster coral reef conservation. Global Change Biol. 27, 5238–5252. https://doi.org/10.1111/gcb.15811.

Tamata, U., Morrison, J., 2012. Anthropogenic factors and nutrient variability along the Coral Coast. Fiji 7.

Thomas, J., Gold, M., 2021. Resource recovery from human excreta in urban and regional settlements. In: The Palgrave Encoclopedia of Urban and Regional Futures.

Tilley, E., Ulrich, L., Luethi, C., Reymond, P., Zurbruegg, C., 2014. Compendium of Sanitation Systems and Technologies. Swiss Federal Institute of Aquatic Science and Technology, Dubendorf, Switzerland.

Tuholske, C., Halpern, B.S., Blasco, G., Villasenor, J.C., Frazier, M., Caylor, K., 2021. Mapping global inputs and impacts from of human sewage in coastal ecosystems. PLoS One 16, e0258898. https://doi.org/10.1371/journal.pone.0258898.

UNESCO, 2023. United Nations World Water Development Report 2023: Partnerships and Cooperation for Water. UNITED NATIONS, S.l.

Van Drecht, G., Bouwman, A.F., Harrison, J., Knoop, J.M., 2009. Global nitrogen and phosphate in urban wastewater for the period 1970 to 2050. Global Biogeochem. Cycles 23. https://doi.org/10.1029/2009GB003458.

Vermeulen, L.C., Hofstra, N., 2014. Influence of climate variables on the concentration of Escherichia coli in the rhine, meuse, and drentse aa during 1985–2010. Reg. Environ. Change 14, 307–319. https://doi.org/10.1007/s10113-013-0492-9.

Wakwella, A., Wenger, A., Jenkins, A., Lamb, J., Kuempel, C.D., Claar, D., Corbin, C., Falinski, K., Rivera, A., Grantham, H.S., Jupiter, S.D., 2023. Integrated watershed management solutions for healthy coastal ecosystems and people. Camb. prisms Coast. futures 1, e27. https://doi.org/10.1017/cft.2023.15.

Wang, X., Daigger, G., de Vries, W., Kroeze, C., Yang, M., Ren, N.-Q., Liu, J., Butler, D., 2019. Impact hotspots of reduced nutrient discharge shift across the globe with population and dietary changes. Nat. Commun. 10, 2627. https://doi.org/10.1038/s41467-019-10445-0.

Wear, S.L., 2019. Battling a common enemy: joining forces in the fight against sewage pollution. Bioscience 65.

Wear, S.L., Vega Thurber, R., 2015. Sewage pollution: mitigation is key for coral reef stewardship. Ann. N. Y. Acad. Sci. https://doi.org/10.1111/nyas.12785.

Wenger, A.S., Harris, D., Weber, S., Baghi, F., Nand, Y., Naisilisili, W., Hughes, A., Delevaux, J.M.S., Klein, C.J., Watson, J., Mumby, P.J., Jupiter, S.D., 2020. Best-practice forestery management delivers diminishing returns for coral reefs with increased land-clearing. J. Appl. Ecol. 57, 2381–2392.

WHO, 2018. World Health Statistics 2018: Monitoring Health for the SDGs, Sustainable Development Goals. World Health Organization, Geneva.

WHO and UNICEF, 2019. Progress on Household Drinking Water, Sanitation and Hygiene: 2000-2017.

WHO and UNICEF, 2021. Estimates on the Use of Water, Sanitation and Hygiene in Fiji.

Withers, P.J., Jordan, P., May, L., Jarvie, H.P., Deal, N.E., 2014. Do septic tank systems pose a hidden threat to water quality? Front. Ecol. Environ. 12, 123–130. https://doi.org/10.1890/130131.