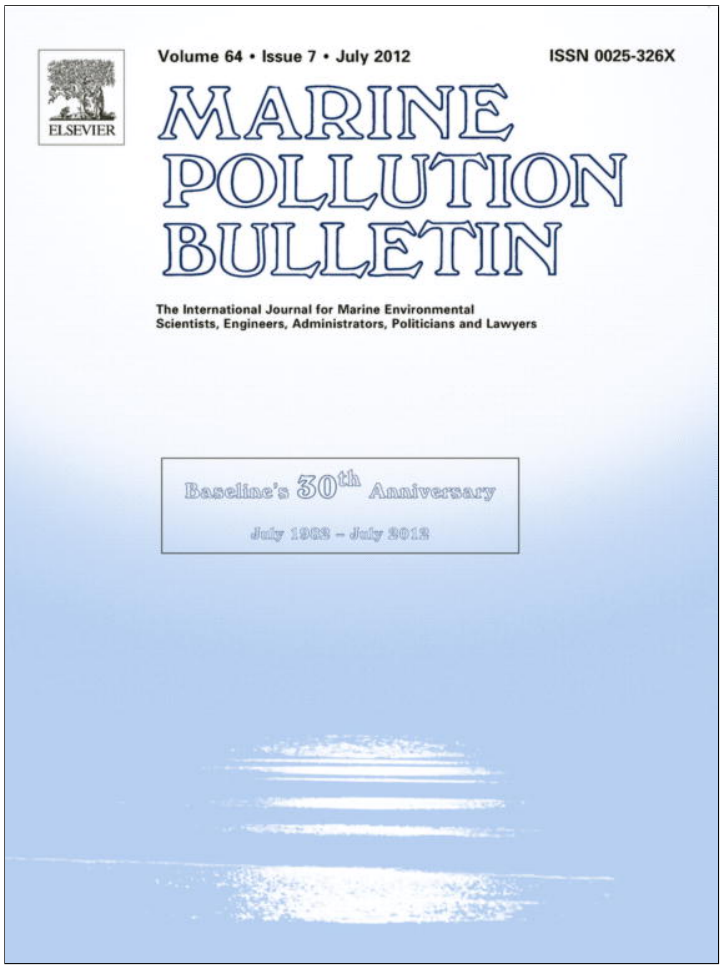
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Isotopic and microbial indicators of sewage pollution from Stone Town, Zanzibar, Tanzania

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ABSTRACT

In Stone Town, Zanzibar, sewage treatment is minimal, with a biological oxygen demand reduction to 60% and no removal of bacteria or nutrients. Here, Stone Town's sewage pollution was studied by measuring *Enterococci* and NH_4^+ concentrations in seawater and $\delta^{15}N$ of benthic organisms; samples were collected along the Stone Town shoreline and from offshore coral reefs. Public perceptions of sewage pollution were investigated via interviews. *Enterococci* from the Stone Town shoreline exceeded USEPA guidelines for recreational use. Benthic organisms from two of the four reefs were relatively enriched ($\delta^{15}N > 10‰$), indicative of sewage derived N. $\delta^{15}N$ values of organisms from Stone Town exceeded 16‰. A strong correlation was found between *Enterococci* and $\delta^{15}N$ across sites, while step-wise regression indicated rainfall and tidal stage as important predictors for bacterial concentrations. These data provide an important impact assessment from which the efficacy of future policy and management change can be assessed.

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1. Introduction

Along the East African Coast, many cities are developing tourism without concomitant development of wastewater treatment. Consequently, the increasing influx of sewage to coastal waters poses a direct threat to human health and the environment upon which the economy relies (Murray, 2007). Ingestion of sewage-contaminated water increases the incidence of gastroenteritis, symptoms of which include: nausea, vomiting, fever, diarrhea, and dysentery (Cabelli et al., 1982; Noble et al., 2003; Wade et al., 2003). Sewage polluted waters spread more severe diseases as well, such as typhoid fever, dysentery, hepatitis, and cholera (Ashbolt, 2004). Each year, poor water sanitation results in approximately 4 billion cases of diarrhea and 2.2 million deaths, most of which are children under the age of five (WHO & UNICEF, 2000). In addition, sewage contaminated waters can cause eye and skin infections, such as trachoma and schistosomiasis. As of 2000, 6 million people were estimated to be blind from trachoma and 200 million people infected with schistosomiasis (WHO & UNICEF). Thus, improved sanitation via improved wastewater management is one of the most pressing issues of modern times.

Aside from the health risks to humans, sewage pollution also threatens community structure, biodiversity, and services provided by marine ecosystems, (Harvell et al., 2004; Pastorok and Bilyard, 1985), and it is regarded as the most significant local factor threatening coral reefs worldwide (Halpern et al., 2008; Fabricius, 2005). Reefs are particularly sensitive to changes in nutrient concentrations. Nutrients decrease coral calcification and fertilization rates and increase the abundance of macroalgae and heterotrophic filter feeders (Fabricius, 2005). Moreover, sewage pollution and runoff have been linked to several coral diseases (Baker et al., 2007; Harvell et al., 2004; Bruno et al., 2003; Pastorok and Bilyard, 1985). Such deleterious effects of sewage pollution on coral reefs can have a strong impact on economies dependent upon marine tourism.

However, despite these human and environmental health hazards, sewage pollution is a local stressor, and with proper research, policy, and management, it can be effectively mitigated. Recreational water quality is often monitored via fecal indicator bacteria, such as *Enterococcus* (ENT) and *Escherichia coli*, as used by the USEPA (Gronewold et al., 2008). In marine waters, ENT is considered a better indicator for sewage as it has a higher salinity tolerance (Hanes and Fragala, 1967; United States Environmental Protection Agency, 1986; Noble et al., 2003). According the USEPA protocol, short-term water quality is based on Single Sample Maximum (SSM) values, and long-term monitoring relies on the geometric mean of no less than five samples taken within a 30-day period. For safe recreational waters, the USEPA recommends that

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single sample value should not exceed 104 CFU × 100 mL^{-1} (United States Environmental Protection Agency, 1986), and geometric means should not exceed 35 CFU × 100 mL^{-1}. Above these thresholds, swimmers face a high risk of gastrointestinal illnesses (Haile et al., 1999; Noble et al., 2003).

Nevertheless, given that fecal bacteria concentrations can be temporally variable, it is difficult to thoroughly evaluate the long-term environmental impacts of sewage pollution using this metric alone, particularly when sewage-derived nutrients may travel beyond the distribution of bacteria. In areas where fecal indicator bacteria cannot be detected using culture dependent methods, stable isotope analysis can be used to detect the presence of sewage-derived nitrogen within an ecosystem. This technique can accurately distinguish between different sources of nitrogen, even where indicator bacteria are too dilute to detect, have settled to the benthos, or died (Baker et al., 2010). Generally, sewage pollution contains a higher proportion of ^{15}N than marine sources, making $\delta^{15}N$, the ratio of ^{15}N:^{14}N, a direct indicator of nitrogen from sewage (Heikoop et al., 2000; Risk, 2009; Baker et al., 2010). Untreated wastewater may have a ^{15}N:^{14}N ratio >10‰, whereas upwelling typically results in $\delta^{15}N$ values between 4‰ and 7‰ (Katz, 2004; Leichter et al., 2007). In this study, we use a combination of *Enterococcus* and stable isotope analysis to examine the relationship between sewage pollution, environmental health, and human health in Stone Town, Zanzibar.

Zanzibar, a semi-autonomous State of the United Republic of Tanzania, consists of two main islands, Unguja and Pemba, as well as several smaller islands (Fig. 1A). According to a census conducted by the Tanzanian government in 2002, Zanzibar has an urban population of 206,292. This figure is considered to be a gross underestimate (Bissell et al., 2011), and the urban population of Zanzibar is predicted to reach at least 470,000 by 2015 (Zanzibar Sustainable Programme (ZSP), 1998; Bissell et al., 2011). Located within Zanzibar's urban area, Stone Town is a subsection of the larger Zanzibar Town. Only the residences of this subsection (i.e. Stone Town) are sewered.

In Stone Town, there are currently 2289 septic tanks and 27 sewage outfalls (Fig. 1C). Each sewage outfall extends 55 m along the ocean floor from the point of low tide, and pipes are open throughout the day (Muhsin, Personal communication). The biological oxygen demand (BOD) of the sewage is reduced to 60% (Muhsin, Personal communication), yet this technique does not significantly reduce nutrients, pathogens, or contaminants. The Zanzibar Municipal Council estimates that 2.2 × 10^6 L d^{-1} of liquid waste are discharged into the sea via sewage outfalls (Muhsin, Personal communication). Additional non-point sources of sewage enter the ocean from unsewered residences. The Municipal Council advises against swimming in Stone Town's nearshore waters, but little effort has been made to increase awareness of this issue.

This study was conducted in Stone Town between April 1st and April 27th, during the peak of the southeast monsoon rainfall (McClanahan, 1988). Due to Stone Town's lack of sewage treatment and an increase in rainfall, it was hypothesized that significant levels of fecal indicator bacteria (*Enterococci*) would be found in waters around Stone Town and that $\delta^{15}N$ values of common benthic organisms collected near Stone Town would be more enriched relative to more distant sites, reflecting the influence of sewage derived N on ecosystem productivity. Additionally, we examine public perceptions of water quality in Zanzibar, in the context of both human and environmental health.

2. Methods

2.1. Location

Surface water samples from five sites along the Stone Town shoreline were used to assess the town's sewage sources. These sites include: Kizingo (6.173°S, 39.194°E), Africa House (6.165°S, 39.187°E), Shangani (6.161°S, 39.188°E), Port (6.158°S, 39.192°E), and Maruhubi Ruins (6.145° S, 39.208°E) (Fig. 1C). These sites are frequented by Zanzibari swimmers, with the exception of Maruhubi. Samples were collected approximately 5 m from the shoreline.

Four coral reef sites were selected for surface water sampling with varying distances from Stone Town: Chumbe (6.278°S, 39.175°E); Chapwani (6.127°S, 39.197°E); Changuu (6.114°S, 39.165°E); and Bawe (6.145°S, 39.136°E) (Fig. 1B; Fig. 2; Table 2). Because Chumbe Island is a Marine Protected Area (MPA) and the farthest site from Stone Town, it was designated as a reference site. Bawe, Changuu, and Chapwani are popular reefs for day snorkeling trips. Changuu has 15 small cottages and a giant tortoise conservation area, which tourists on the main island often visit during day trips. Septic tanks are used on Changuu and waste is taken off the island for disposal. Site maps (Fig. 1) were constructed on ArcMap using GPS points gathered in the field and online data

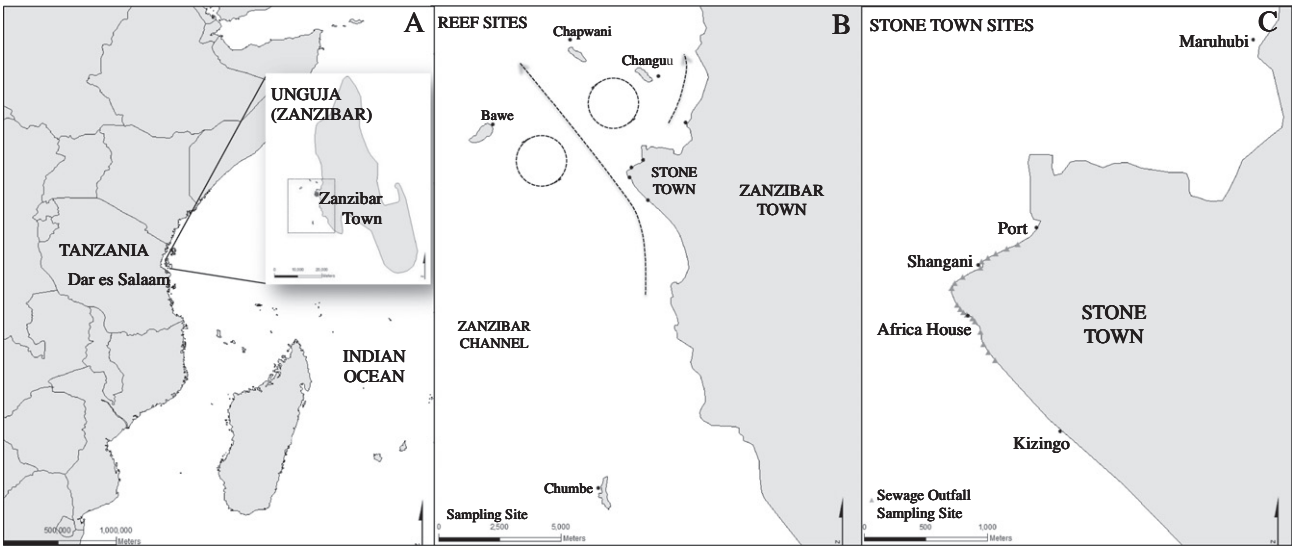


Fig. 1. Map of study area. (A) Tanzania and Unguja, the main island of the Zanzibar Archipelago. (B) Close up reef sites and major current flow (Mohammed et al., 1993). (C) An overlay of Stown Town sites with sewage outflow locations.

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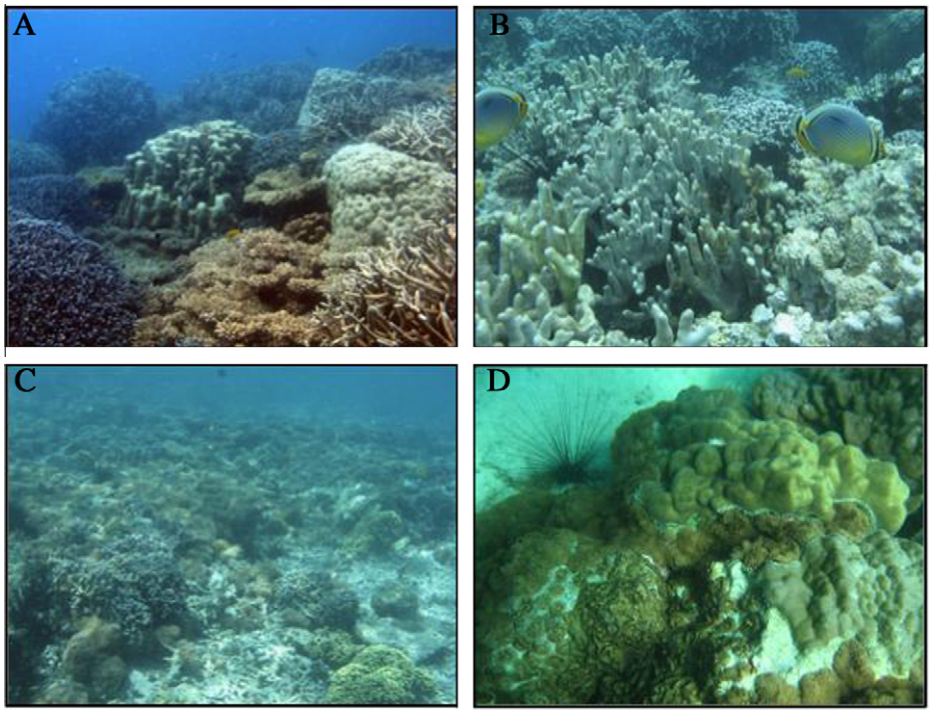


Fig. 2. Coral reef sampling sites. (A) Chumbe, (B) Bawe, (C) Changuu and (D) Chapwani. Photographs credited to Dr. Muhando of the Zanzibar Institute of Marine Sciences.

from ReefBase (http://www.reefbase.org).

2.2. Water quality determination

At each site, pH, temperature, and salinity measurements were taken using a Hanna hand-held pH meter and a refractometer. Weather conditions were noted on site, and tidal phase was recorded using local tide tables. At each site, a 500 mL surface water grab sample was collected and transported on ice to the Institute of Marine Science (IMS). Fecal indicator bacteria inoculations were performed within 6 h of sampling. Between 2 and 4 replicate membrane filtrations were performed per grab sample depending on available supplies. Water samples were frozen for later analysis of ammonium (NH_4^+) concentrations. Daily and monthly rainfall data were obtained from the Zanzibar Meteorological Department's rainfall sampling. Bawe, Changuu, and Chapwani sites were sampled on three different days, and the Port and Maruhubi were sampled on two different days. The remaining sites were sampled once.

Enterococci were enumerated using membrane filtration (USEPA Method 1600, 2002). For each surface water sample, water was filtered over a sterile membrane, and filters were placed on Difco m-enterococcus selective media. Plates were incubated for 48 h, and subsequently, all red colonies were counted and normalized to colony forming units per 100 mL (CFU $\times$ 100 mL^{-1}). Mean ENT values were based on 2–4 replicate filters from the same surface water sample. NH_4^+ concentrations were quantified using the Indophenol method with UV–visible spectrophotometry with a detection range between 0.1 and 10 μM/L.

2.3. Stable isotope analyses

Common benthic organisms were collected from all coral reef sites and one Stone Town site (i.e. Chumbe, Changuu, Bawe, Chapwani, and Maruhubi). Scleractinian corals (*Acropora*, *Pocillopora*), seagrass (*Thalassia*, *Cymodocea*, *Thalassodendron*) macroalgae (*Halimeda*, *Udotea*, *Avrainvillea*) and/or sponges were collected depending on what was present at each site. Dried samples were transported to the Carnegie Institution of Washington for stable isotope analysis. Scleractinian coral samples were rehydrated in nanopure H_2O, and sonicated for 20 min to remove surface tissues. Approximately 70 mL of this homogenate was loaded into a 4 $\times$ 6 mm silver capsule and dried overnight at 60 °C. Dried sponge and algae samples were homogenized by grinding into a powder, using a mortar and pestle. Liquid nitrogen was used to aid in the grinding process. Powder from individual samples was then weighed into 4 $\times$ 6 silver capsules. All samples were directly acidified with 2 $\times$ 20 mL aliquots of 6 N HCl to remove excess $CaCO_3$. Excess acid was allowed to evaporate in a fume hood between additions, and then re-dried overnight at 60 °C. All samples were then combusted in a Carlo-Erba NC2500 elemental analyzer, and the resulting gas analyzed by a Thermo Delta V isotope ratio mass spectrometer coupled via a Conflo III open-split interface. $\delta^{15}N$ was calculated using the equation:

$$\delta^{15}N(‰) = \left(\frac{(^{15}N/^{14}N)_{sample}}{(^{15}N/^{14}N)_{standard}} - 1 \right) \times 1000$$

Precision of this analysis is routinely ±0.2‰.

2.4. Statistical analyses

To test the hypothesis that variation in ENT was affected by temporal and spatial factors associated with point and non-point source inputs from Stone Town, we examined the correlation between ENT and (1) 1, 2, and 3-day rainfall sums, (2) distance from Stone Town, and (3) day of sampling using pair-wise correlation analysis. We then used a step-wise regression analysis to assess the degree to which these variables accounted for variation in ENT.

2.5. Public surveys

Surveys were conducted by the author on both tourists and Zanzibaris to determine the level of water quality safety awareness in Stone Town.

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Table 1
Data from Stone Town shoreline water sampling.

Site	Date	Tide	Precip. (mm)	pH	Salinity (‰)	Mean ENT (CFU × 100 mL^{-1})	Ammonium (μM/L)	Perceived impact
MARUHUBI	Day 8	Ebb	1.8	8.52	33	43.0 ± 3.0	0.77 ± 0.16	High
	Day 15	Flood	55.1	8.21	32	1831.0 ± 111.6	0.95 ± 0.13	
PORT	Day 8	Ebb	1.8	8.09	34	84.5 ± 0.4	0.06 ± 0.22	High
	Day 15	Flood	55.1	8.16	32	1716.0 ± 427.1	1.30 ± 0.44	
SHANGANI	Day 15	Flood	55.1	8.16	33	456.0 ± 2.7	BDL[a]	High
AFRICA HOUSE	Day 15	Flood	55.1	8.19	33	377.5 ± 29.9	0.26 ± 0.25	High
KIZINGO	Day 15	Flood	55.1	8.29	32	140.5 ± 11.3	BDL[a]	High

[a] BDL = below detectable levels. Day *X* = April *X*th 2010.

3. Results

3.1. Water quality results

At Stone Town sites, water samples had ENT concentrations ranging from 40.0 to 2208 CFU × 100 mL^{-1}. On Day 15, water samples from Maruhubi and Port had mean ENT values of 1831 and 1716 CFU × 100 mL^{-1}, respectively, greatly exceeding the USEPA single-sample cutoff for safe recreational waters (104 CFU × 100 mL^{-1}). Maruhubi and Port also had the highest concentrations of NH_4^+ (Table 1). Shangani had relatively high mean ENT (456.0 ± 2.7 CFU) while [NH_4^+] was below detectable levels. No clear correlation between ENT and NH_4^+ was found.

At coral reef sites, all ENT values were <104 CFU × 100 mL^{-1} (Table 2). Results ranged from 0.25 to 13.0 CFU × 100 mL^{-1}. ENT from sites sampled during ebb tide were much higher than those of flood tide. On two of the sampling days, Changuu's ENT results were greatest, (mean ± standard error) 11.0 ± 2.0 and 8.8 ± 0.4 CFU × 100 mL^{-1}. However, on Day 17 Chapwani had the greatest concentration of ENT (2.7 ± 0.4 CFU). NH_4^+ at reef sites ranged from undetectable to 2.18 μM/L. At Chumbe, Bawe and Changuu, NH_4^+ was undetectable on at least one sampling day. The highest NH_4^+ concentration was found at Chapwani (2.18 μM/L).

During the period of study, the heaviest rainfall occurred from Day 14 to Day 16 (Fig. 3). The sum of precipitation during this period was 67.2 mm, which accounts for 44% of all rainfall recorded during April. The highest ENT values found in this study were from sampling on Day 15 in Stone Town. The second largest precipitation event occurred between Day 4 and Day 5. Rainfall during these two days totaled 29.6 mm (19% of monthly rainfall). At each reef site, mean ENT was greatest on Day 6.

Significant correlations were detected between all precipitation variables, but not day of sampling (Table 3). The correlation between 1-day precipitation estimates and ENT was strongest, relative to the multi-day rainfall sums. In the step-wise regression, all factors contributed to the explained variance with a maximum R^2 = 0.91. Given that the rainfall estimates were auto-correlated, and that the 1-day values yielded the strongest correlation with ENT, we removed the 2-day and 3-day sums from the regression, resulting in a slight drop in R^2 (=0.87). To test for the combined effects of these fixed continuous factors, in addition to site (random factor) and tidal stage (fixed, categorical) we used a random effects model. The model explained 96.5% of the variation in ENT values.

3.2. Stable isotope results

δ^{15}N values of all benthic organisms sampled ranged from 0.0 to 18.2 ‰. Consistent with our hypothesis, Chumbe had the lowest overall δ^{15}N (3.5 ± 3.1‰). Benthic organisms from the Stone Town site, Maruhubi, had the highest overall δ^{15}N, with a mean of 16.3‰ and maximum of 18.2‰. At reef sites, Changuu had the highest mean coral δ^{15}N (11.2 ‰), followed by Bawe (8.2 ‰), and then Chapwani (7.2‰). δ^{15}N results were highly correlated with ENT (R^2 = 0.89, p < 0.0001; Fig. 4).

3.3. Interview results

A total of 43 surveys were completed, 20 by tourists and 23 by Zanzibaris. Summaries of questions and results can be found in Tables 4 and 5.

4. Discussion

4.1. Water quality, precipitation, and hydrodynamics

In Zanzibar, the Indian Ocean monsoon causes a heavy rain season from mid-March to May which delivers ~49% of annual rainfall (Suleiman, Personal communication). Intense precipitation events drastically affect water quality, as flooding streets cause a large influx of garbage, agricultural runoff, and sewage to enter the ocean around Stone Town. The influence of precipitation on water quality was evident throughout this study. ENT concentrations from Stone Town sites greatly increased after heavy rains, with Maruhubi

Table 2
Data from nearshore coral reef water sampling.

Site	Date	Tide	Precip. (mm)	Distance from Stone Town (km)	pH	Salinity (‰)	Mean ENT (CFU ∗ 100 mL^{-1})	Ammonium (μM/L)	Perceived impact
BAWE	Day 6	Ebb	16.2	5.75	8.13	32	8.3 ± 0.8	0.32 ± 0.66	Medium
	Day 17	Flood	0.0		8.16	33	0.9 ± 0.2	1.02 ± 1.75	
	Day 20	Flood	12.2		8.36	32	0.4 ± 0.1	BDL[a]	
CHANGUU	Day 6	Ebb	16.2	5.81	8.09	32	11.0 ± 2.0	0.12 ± 0.07	Medium-High
	Day 17	Flood	0.0		8.23	33	1.6 ± 0.3	BDL[a]	
	Day 20	Flood	12.2		8.22	32	8.8 ± 0.4	0.12 ± 0.55	
CHAPWANI	Day 6	Ebb	16.2	4.11	8.14	31	5.3 ± 1.3	2.18 ± 0.47	High
	Day 17	Flood	0.0		8.20	33	2.7 ± 0.4	0.68 ± 1.20	
	Day 20	Flood	12.2		8.21	32	0.9 ± 0.1	0.83 ± 1.07	
CHUMBE	Day 12	Flood	3.3	12.82	8.22	32	4.2 ± 0.7	BDL[a]	Low

[a] BDL = below detectable levels. Day *X* = April *X*th 2010.

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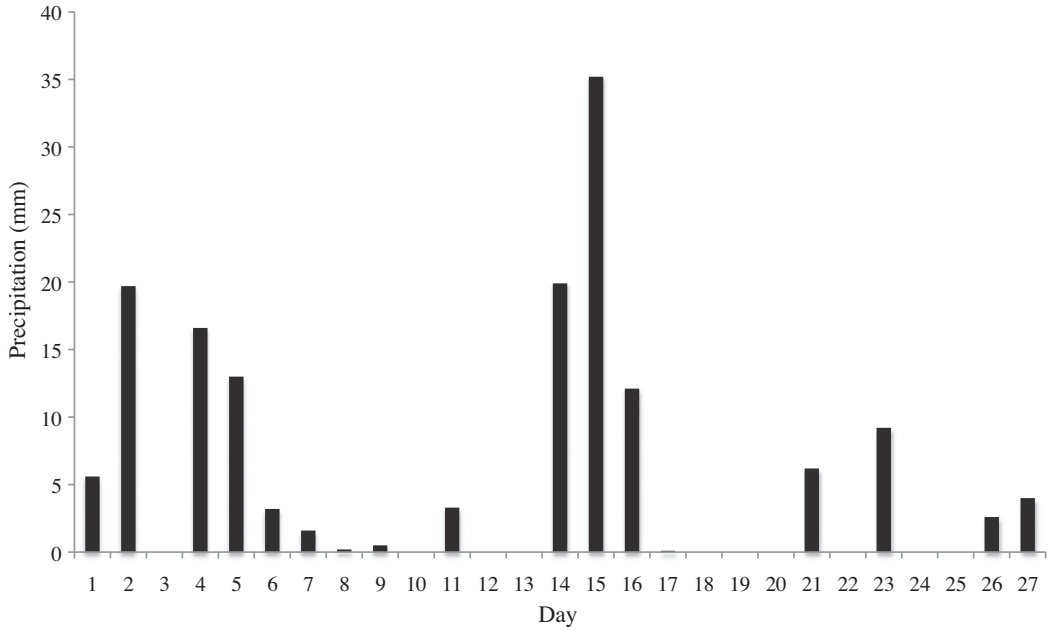


Fig. 3. Daily precipitation in millimeters on Unguja Island (Zanzibar) during April, 2010.

showing a 43-fold increase in ENT and Port a 20-fold increase (Days 8 and 15; Table 1). At reef sites, high ENT values from sampling on Day 6 at Bawe, Changuu, and Chapwani correlated with heavy precipitation. Although there was not enough data to calculate the geometric means of 5 different water samples per site (according to USEPA protocol), all ENT results from Stone Town's sampling sites exceeded USEPA single-sample limits, with those of Maruhubi and Port being over 10-times the level for safe recreational waters. These results clearly indicate that the waters around Stone Town were unsafe for swimming during the sampling period of this study. Yet, swimmers were commonly seen in the water at every site in Stone Town.

The influence of precipitation on water quality is also apparent in our regression analysis. The use of regression-based analysis of precipitation versus bacteria is widely found in literature (Eleria and Vogel, 2005; Kelsey et al., 2004); however, such studies typically have a large sampling size. Despite the small sample size in this study, we conducted a regression-based analysis to serve as a basis for future work and to provide insight into an understudied region. Our results indicate that precipitation and distance from Stone Town significantly affect variation in ENT (Table 3). These correlations are not surprising given that wastewater inputs from highly concentrated point-sources such as outfalls increase with stormwater input. We found that the 1-day sum of precipitation had a stronger correlation with ENT than 2- or 3-day sums. This suggests that sewage inputs increase rapidly around Stone Town during precipitation events.

Hydrodynamics in the vicinity of Stone Town may also explain some observed variation in water quality. In the northern part of Stone Town, waters have higher retention times, especially in the bay areas on either side of the harbor (Mohammed et al., 1993). Samples from these areas (Maruhubi & the Port) had the highest ENT concentrations. Moreover, although it was predicted that reefs closest to Stone Town would have the most severe sewage pollution, Changuu's δ^{15}N and ENT values were consistently higher than those of Chapwani, the reef closest to Stone Town. Changuu's high ENT and δ^{15}N values may be a result of the island's small tourist population. However, currents around the island may also impact water quality. An eddy (Fig. 1) proposed by Mohammed et al. (1993) may be accumulating sewage effluents and producing a sink for bacteria and nutrients. Further research should be conducted to determine how currents in Zanzibar Channel control pollution dispersal.

In addition to currents, tidal flow also plays a role in sewage dispersal. Water diverges from the Zanzibar channel during ebb tide, flowing simultaneously to the north and south of Stone Town, and during flood tide, these two currents are reversed (Shaghude et al., 2002). During ebb tide, ENT concentrations from Bawe were approximately 1.6 times greater than Chapwani's. During flood tide samplings, ENT concentrations from Chapwani's were over 2 times greater than Bawe's (Table 2). Thus, Bawe may experience a greater influx of polluted water from Stone Town during ebb tide, when water is diverging away from Stone Town, whereas during flood tide, water converging towards Stone Town may prevent pollution from moving out into the channel. Furthermore, it is probable that during the dry season water quality fluctuations are more closely linked with the tidal phase. This relationship could be studied by establishing seasonal or monthly water quality and reef monitoring programs around Stone Town.

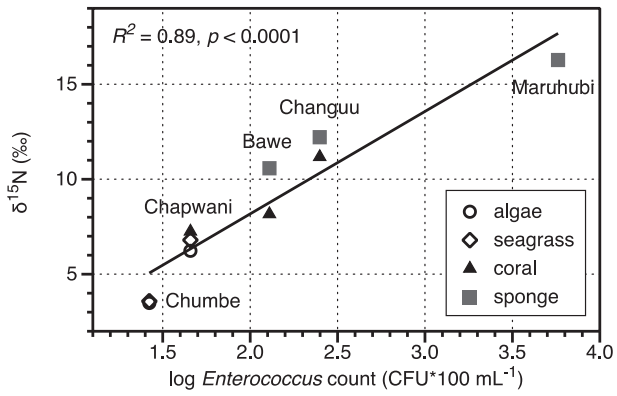


Fig. 4. Regression of mean *Enterococcus* results and mean δ^{15}N values from Bawe, Changu, Chapwani, and Maruhubi.

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Table 3
Correlation analyses between log *Enterococcus* and precipitation, distance, and time.

Factor	r	*p*-Value
1 DAY PRECIP	0.88	<0.001
2 DAY PRECIP	0.85	<0.001
3 DAY PRECIP	0.48	<0.001
DISTANCE	−0.74	<0.001
DAY	−0.22	0.1

4.2. Water quality and coral reefs

At offshore coral reef sites, waters posed no direct threat to human health, as all ENT samples were well below USEPA cutoffs. Nevertheless, it is difficult to assess the magnitude of sewage pollution on offshore coral reefs using surface water sampling alone, as fecal indicator bacteria die off rapidly in marine waters (Lipp and Griffin, 2004). Similarly, δ^{15}N values >4.0‰ alone are often considered to be indicative of sewage pollution, though natural enrichments could arise from high rates of denitrification or strong upwelling (Valiela, 1995). We were able to circumvent these issues by simultaneously analyzing ENT and the δ^{15}N of benthic organisms. The strong, positive correlation between δ^{15}N and ENT concentrations is powerful evidence for sewage pollution. Based on the correlation between ENT and δ^{15}N (Fig. 4), it is clear that isotope enrichments and ENT concentrations are a result of sewage pollution, not denitrification (Baker et al., 2010).

This strong correlation between ENT and δ^{15}N indicates that sewage pollution and runoff from Stone Town potentially threaten Zanzibar's reefs. Moreover, in comparison with δ^{15}N samples taken at Zanzibar in 1998 and 2000, it is evident that water quality around Stone Town has degraded. Samples taken from offshore fringing reefs in Zanzibar (Heikoop et al., 1998) yielded a δ^{15}N range of 4.7–5.4‰. A second study of the hard coral, *Porites lobata*, from Changuu and Chumbe (Heikoop et al., 2000) reported δ^{15}N of 4.2‰ for both sites. Results from our study indicate that sewage-derived nitrogen has not increased at Chumbe (δ^{15}N = 3.5‰, Fig. 4). However, in comparison to Heikoop et al., 2000, our hard coral data suggest a marked increase in sewage-derived nitrogen reaching Changuu, as evidenced by a nearly a three-fold increase in δ^{15}N (12.2‰).

Ammonium concentrations corroborate the threat that Stone Town's sewage pollution is posing to the marine environment. Studies from the Caribbean and Great Barrier Reef have established that dissolved inorganic nitrogen (NO_3^+, NH_4^+ and NO_2) should not exceed 1.0 μM to maintain healthy a reef ecosystem (Bell, 1992; Goreau et al., 1994). Water samples from Chapwani on Day 6 during ebb tide exceed this threshold for NH_4^+ alone, reaching 2.18 μM (Table 2).

Although we did not quantify benthic community composition or health, visual observations and local knowledge suggest that our observed variation in water quality is linked to reef health. Eutrophication of reef ecosystems is characterized by a dominance of fast-growing macroalgae (Bjork et al., 1995), and urchins are often indicative of fishing pressure (Tyler, 2005). Chumbe was perceived to be the healthiest reef, with 69.1% live coral cover recorded by Lokrantz et al. (2010). Chapwani and Changuu were overgrown with algae and sea urchins were abundant (Fig. 2). Bawe appeared to be healthier than both Chapwani and Changuu, yet Changuu had lower NH_4^+ concentrations than Bawe on two of the three sampling days. Conversely, Changuu's ENT and δ^{15}N values were the highest of all reef sites. This discrepancy between NH_4^+ concentrations, ENT, and δ^{15}N results could be due to (1) the presence of other N or P species not measured, (2) episodic inputs or, (3) rapid assimilation of NH_4^+ by the large community of autotrophs found here. Surface water samples only represent snapshots of water quality. Even long-term monitoring could miss important episodic inputs of nutrients. Here, the δ^{15}N measurements are critical, integrated measurements which indicate that Changuu is chronically impacted by sewage derived N. Thus, Changuu's waters may have large fluctuations in nutrient concentrations, which are dominated by Stone Town's sewage pollution and/or pollution from the island's tourism industry.

At our reference site, Chumbe, we predicted that all indicators of water quality (ENT, NH_4^+ and δ^{15}N) would be the low, given the distance between Chumbe and development around Stone Town and the perception of relatively healthy coral reefs. During ebb tide, ENT results from Chumbe were less than those of Bawe, Changuu, and Chapwani (Day 6), and δ^{15}N values from Chumbe were not indicative of sewage pollution (δ^{15}N < 4‰). However, due to Chumbe's status as an MPA, only sea grass from outside of the MPA was analyzed from this site. Further isotope analysis should be conducted on corals and sponges from within Chumbe's MPA, as certain species of benthic organisms are better recorders of ^{15}N than others (Baker et al., 2010). Water quality sampling during flood conditions should also be conducted at Chumbe to determine the extent to which tidal parameters influence water quality. Investigating any possible source of pollution influencing Chumbeis of concern, as Chumbe is one of only 3 MPAs in Zanzibar (Marine Parks, 2007), and thus represents an important site for environmental monitoring.

4.3. Water quality and public awareness

Results from Zanzibari surveys in Stone Town reveal that there is limited public concern about water quality impacts on human health. The Municipal Council advises against swimming around Stone Town and has prohibited swimming in certain areas, yet only 22% of local interviewees were aware that swimming in town unadvised (Table 5). Most interviewees were aware that sewage enters the ocean without treatment and that it is a health hazard, but all of the Zanzibari men interviewed (except one) swam

Table 4
Survey questions asked of tourists and local Zanzibaris.

Questions for Zanzibaris	Questions for tourists
Mwanaume au mwanamke? (Male or female?)	Male or female?
Una miake mingagi? (Age?)	Age?
Umemaliza miaka mingapi skuli? (How many years of schooling have you completed?)	Have you gone swimming in Zanzibar? If yes, where?
Umewahi kusikia kumekatazwa kuogelea mijini? (Have you ever heard that it is prohibited to swim in town?)	If you have gone snorkeling here, what did you think of the reefs?
Unajua maji machafu yanakwenda wapi? (Do you know where sewage water goes?)	Have you been told not to swim in the waters around Stone Town? If yes, from whom?
Unafikiri maji machafu ni hatari kwa afya yako? Kwa nini? (Do you think that sewage water is dangerous to your health? Why?)	Before this survey, were you aware that there is no proper sewage treatment in town?
Unafikiri maji machafu ni hatari kwa mazingira? Kwa nini? (Do you think that sewage water is dangerous to the environment? Why?)	Would you be more likely to come back to Stone Town if the waters and beaches around the town were cleaner?

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Table 5
Results (A) and responses (B) from surveys of Zanzibaris and of (C) international tourists in Zanzibar.

(A) Zanzibari survey		(B) Zanzibari responses: Why swim in town if water is polluted?	(C) Tourist survey	
Average age	30	It costs money to go elsewhere	Average age	26.7
Number of females	12	Bacteria die in salt water	Number of females	13
Number of males	11	There is a lot of water and just a little pollution, so it is safe	Number of males	7
Average years of schooling	10.36	Tide takes pollution far out to sea	Aware of sewage issues	40%
Swims in town	48%	You need to enjoy the present and not worry about the future	Has been told not to swim in town	35%
Has been told not to swim in town	22%	The ocean cannot be polluted, it will always be clean	More likely to return to Stone Town if waters were cleaner	50%
Aware that sewage goes into ocean	83%	Peer pressure		
Thinks sewage is bad for health	91%			
Things sewage is bad for environment	100%			

frequently in the ocean and had little concern about adverse health effects. Responses from the survey indicate that the local attitude towards pollution is one in which humans cannot have a significant impact on their environment (Table 5B).

Despite the fact that the Zanzibaris interviewed were not very concerned about sewage pollution, 30% of Zanzibar's GDP is dependent on marine resources (Marie-Lange and Jiddawi, 2008). Tourism is Zanzibar's most important marine ecosystem service, followed by seaweed farming, fishing, and mangrove harvesting (Marie-Lange and Jiddawi, 2008). Because marine resources are central to Zanzibar's traditional culture, disruptions in the integrity of the island's marine ecosystems would be detrimental to many of the island's practices.

The impact of pollution on tourist arrivals was also apparent our survey. Many tourists were unaware that Stone Town lacks a sewage treatment system, and 50% of tourist interviewees said they would be more likely to return to Zanzibar if waters were cleaner. Although the sample size for this survey was limited, results suggest that without clean beaches and spectacular reefs, Zanzibar could quickly lose its tourism appeal.

5. Conclusion

As areas like Stone Town continue to experience rapid development, finding practical solutions to deal with sewage pollution is critical for the sustainability of human and environmental health as well as economic security. Without healthy marine ecosystems, Zanzibar will be suffer economic loss due to decreases in tourism and fisheries productivity; decreased use of the ocean for cultural activities; and an increase in health costs associated with insufficient sanitation. However, despite Zanzibar's economic dependence on marine ecosystems, public awareness of these issues in Stone Town is low. With respect to climate change, reefs in southern Kenya and Zanzibar have been found to be more resilient to thermal stress than other reefs in East Africa, due in part to the seasonality of the Indian Ocean Monsoon (Maina et al., 2008; McClanahan et al., 2007). Given this, and the high biodiversity found here, Zanzibar has been identified as an area of high conservation priority (McClanahan et al., 2007). The potential for resilience to climate change places even more emphasis on alleviating local stressors given that increased nutrient inputs can lower the thermal threshold for bleaching in hard corals by up to 2 °C (Wooldridge and Done, 2009). Based on data collected during this brief period, our analysis of sewage pollution distribution exposes the significant impact of precipitation events on Stone Town's near shore water quality. Thus, to progress with waste and resource management, it is necessary to understand the relationship between sewage pollution and monsoonal patterns in Zanzibar. This study was done during the height of seasonal monsoon precipitation, when runoff and sewage outflow rates are at their yearly maxima. To determine how water quality fluctuates, a more detailed and long-term study should be conducted. Understanding seasonal variability in water quality is vital to Stone Town's public health and to the health of coral reefs. Monitoring techniques used in this study are simple, cost-effective, and relatively easy to perform with limited laboratory equipment. Stable isotope analysis of benthic organisms can be outsourced for <$10 per sample, and shipping dried algae in particular is relatively easy. ENT and $\delta^{15}N$ data presented in this study unquestionably indicate that sewage is having a detrimental effect on the waters surrounding Stone Town. Significant improvements in wastewater management are a critical next step for mitigating the effects of nutrient pollution. Unless basic sanitation access and treatment are addressed in a timely manner, sewage pollution in Stone Town is likely to have severe economic and environmental consequences.

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