

Assessment of land-based pollution problems in Kenyan marine environments to facilitate adaptive management of coral reef systems

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Abstract

Coral reefs are sensitive to environmental perturbations, and an unprecedented decline in corals has been reported globally as a result of increasing global and local stressors including excessive input of anthropogenic nutrients. This study investigated the effect of land-based sources of nutrients (N and P) associated with sewage, on ocean water quality and the health of corals in Mombasa Marine National Park and Reserve in Kenya to inform integrated coastal zone management and ocean governance. A year-long study was conducted to determine water quality according to protocols described in Grasshoff *et al.* (2007). Coral health status was also monitored using Underwater Visual Census (UVC) to record coral reef ecological parameters. The study area's temperature, salinity, pH and dissolved oxygen were within the recommended standards for healthy coral reefs. The study indicated that land-based nutrients, Chlorophyll-*a* (*Chl a*) and total suspended solids (TSS), are the key factors affecting corals and could be the reason for the observed coral health, which ranged from fairly healthy to unhealthy. On average, nutrient concentrations were higher than recommended to maintain at least 50% coral coverage. Ammonia was the dominant form of nitrogen ranging from 0.105 to 0.4130 mg/l, while nitrate concentrations were 0.0348-0.0468 mg/l, indicating the possibility of blooming algal species in the area. Total suspended solids were above the recommended values, ranging between 33.5 and 79.3mg/l and *Chl a* 0.7114 and 1.58 µg/l. The study concluded that land-based nutrient load influenced coral reef health during the study period. It recommends that land-based pollution needs to be addressed as part of a holistic, integrated coastal zone management approach supporting practical, sustainable and legal management of nutrient discharge into the marine environment to preserve the water quality of Mombasa Marine National Park and Reserve.

Keywords: water quality, pollution, nutrient enrichment, coral health, governance

Introduction

Coral reefs play an important role in marine ecosystem functioning and service provision (Tan *et al.*, 2020; Hughes *et al.*, 2017; MEA, 2005). In recent years, corals have continued to degrade (reducing at a rate of 1-2 % per year) due to numerous anthropogenic stressors, such as overfishing, global climate change, and environmental pollution (Hughes *et al.*, 2017). The loss and degradation of coral reefs results in the loss

of livelihoods of millions of people living along tropical coastlines (Hoegh-Guldberg *et al.*, 2019). It will also hamper the achievement of the Sustainable Development Goal 14 and the Aichi Target 10, which aim to reduce the pressures on coral reefs (UN-GA, 2015, CBD, 2020). Along with increasing human population and urbanisation, unregulated coastal development puts pressure on the marine and coastal environment in the Western Indian Ocean (WIO) region, including

Kenya. These pressures include resource exploitation and discharges of poorly treated or untreated industrial, agricultural and urban wastes (ASCLME, 2012; Bhatnagar and Sangwan, 2009; Seitzinger *et al.*, 2005; Shanmugam *et al.*, 2007).

Approximately 80% of marine pollution originates from land-based sources that reach coastal waters via diffuse run-off, direct waste deposit, and atmospheric fallout (Daoji and Daler, 2004; McIntyre, 1990). Most eutrophication and organic pollution in coastal regions in the world is linked to the discharge of sewage (defined as a cocktail of waste from food preparation, dishwashing, garbage-grinding, toilets, baths, showers and sinks) effluent and dumping of sewage sludge (Okuku *et al.*, 2011). Moreover, an increase in food production due to population growth has resulted in a concentration of these nutrients on land as well as changes in the global hydrological cycle, doubling the rate at which biologically available nitrogen and phosphorus enter the marine ecosystems (Galloway *et al.*, 2004; Seitzinger *et al.*, 2005). This is compounded by poorly developed sewage waste management infrastructure and inadequate domestic waste management facilities, with much of the effluent from industries and tourist hotels emitted directly into the coastal waters (Okuku *et al.*, 2011).

Nutrients such as nitrogen (N) and phosphorous (P) are essential for supporting the productivity of coral reef ecosystems. However excessive enrichment of marine and coastal waters by these nutrients associated with anthropogenic activities can cause deleterious effects, making them one of the major threats facing coral reefs globally (Lapointe *et al.*, 2010). By stressing coral physiology and functioning through increased water temperature, increased algae cover, and seaweed development that competes with the corals for space and light, excess nutrients can cause coral ecosystems to collapse (Smith *et al.* 1981). A reduction in light penetration results in reduced zooxanthellae photosynthesis, which reduces coral productivity (DeGeorges *et al.*, 2010). Enhanced macro-algae growth can smother and kill corals (Littler *et al.*, 2006), negatively affecting them by shading/overtopping, reducing water exchange, and causing mechanical abrasion or chemical disturbance. Besides enhancing the susceptibility of coral reefs to bleaching (Mangi *et al.*, 2007), algae can also release toxins, deplete oxygen and increase the risk of bacterial and fungal infections contributing to the spread

of coral diseases (D'Angelo and Wiedenmann, 2014). Lower calcification rates, reduced reproductive success, altered skeletal density, and linear extension in response to heat and light stress are some of the observed reactions of corals to elevated nutrient levels. Studies have shown that anthropogenic nutrient enrichment of reef waters contributes to the deterioration of coral reefs close to urbanised and heavily populated areas. (Fabricius *et al.*, 2003; Wagner *et al.*, 2010; Wooldridge, 2009).

To conserve marine ecosystems from land-based pollution, governance institutions should develop policies to monitor and regulate the quality and quantity of nutrients released into coastal areas. There is limited data on the link between coral health and nutrient load in the WIO. At the same time, many global marine regulations do not integrate land-based controls, making them prone to failure (Carlson *et al.*, 2019). Marine reserves tend to be static (e.g., hotspots for marine biodiversity) rather than representing the time-variant dynamics that define land-sea processes, such as contaminant flows (Stoms *et al.*, 2005, Arias-González *et al.*, 2017). These issues are among several that have hindered the design and implementation of the regulation of discharges and management of wastes from urban developments and agricultural inputs in reef catchments. This highlights the need to couple land-sea planning while recognising the complexities associated with executing ridge-to-reef conservation approaches (Carlson *et al.*, 2019; Arias-González *et al.*, 2017; Stoms *et al.*, 2005).

This study provides information on the water quality status in coral reef ecosystems. Nutrient quality and quantity and coral reef health were assessed in the Mombasa Marine National Park and Reserve in Kenya. The study also aimed to establish the relationship between water quality, in terms of nutrient concentrations, and coral reef health. This is useful for managers and decision-makers in formulating holistic and best practices in management and governance for the conservation and sustainability of coral reefs.

Materials and methods

Study area

Mombasa Marine National Park and Reserve (MMN-P&R) is a marine protected area (MPA) between Mtwapa Creek and Tudor Creek in the north of Mombasa County, Kenya. It lies between 3° 57'S and 4° 9'S, and 39° 41'E and 39° 52'E, covering an area of 210 km². The MMNP&R, managed by the Kenya Wildlife

Services (KWS), is zoned into the Marine Park and the Marine Reserve (Fig. 1). The Park measures 10 km² and is open to public recreation, but extractive uses are prohibited (“no-take” zone). The Reserve measures 200 km², allowing public access and controlled extractive use of resources. It has coral reefs in its waters and encloses part of the lagoon, back reef and reef crest habitats of the Bamburi-Nyali fringing reef. The MPA has other critical habitats – seagrass

Water quality

The year-long study was carried out between September 2017 and August 2018 to measure seasonal variation in water quality and its potential impact on coral reef health. Samples were collected once a month on the first Tuesday/Wednesday of the month. Seasons were classified as short rains (September to November), dry (December to February), long rains (March to May), and cold (June to August).

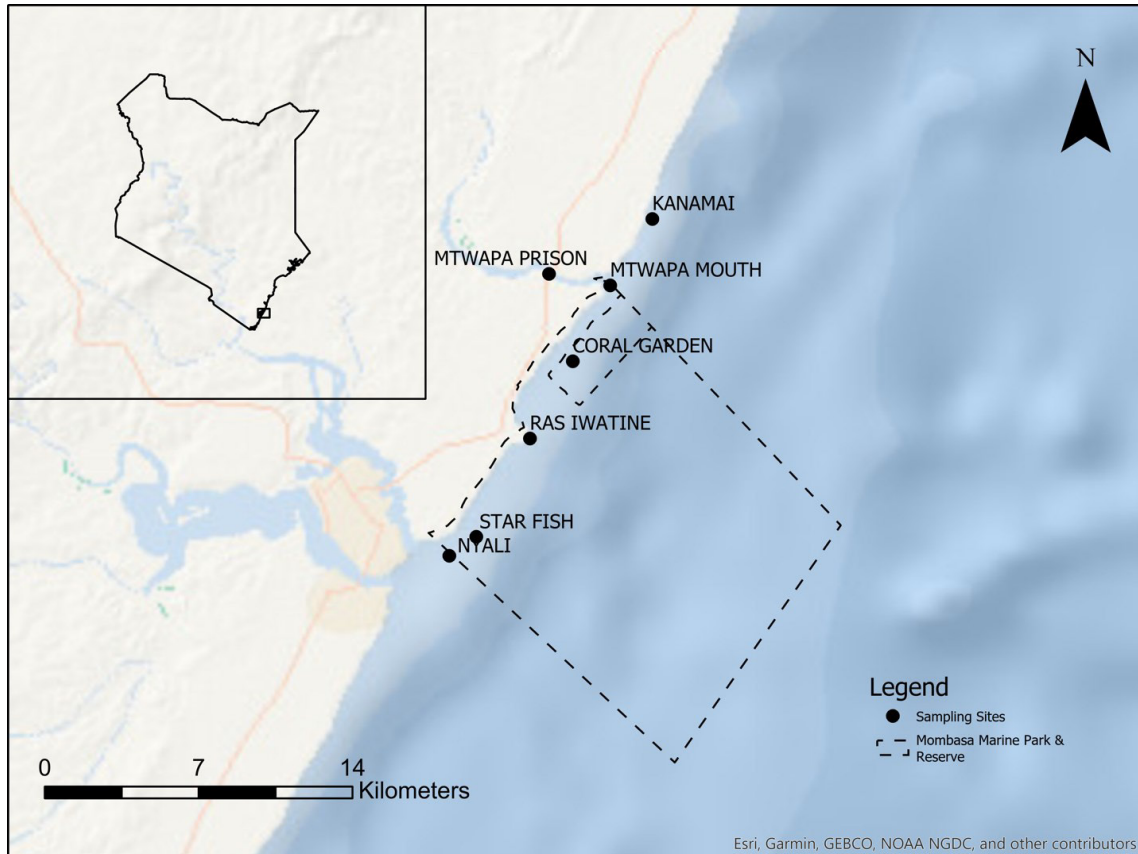


Figure 1. Map of the Mombasa Marine National Park and Reserve and sampling stations at Nyali, Star Fish, Coral Garden, Mtwapa Prison and Mouth and the control site in Kanamai.

beds, sandy beaches and intertidal flats – that are an essential source of coastal livelihoods such as fishing and tourism. The MMNP&R is adjacent to Mombasa city, making it vulnerable to numerous threats (Tuda *et al.*, 2007).

The area is characterised by warm tropical conditions varying between 25 °C and 31 °C throughout the year. It experiences bimodal rainfall, with long heavy rains falling between April to July and short rains between October and December. The rainfall surface run-off transports anthropogenic pollutants into the Mtwapa Creek and the MMNP&R (Pole *et al.*, 2016).

Seven stations were selected and clustered into three distinct groups for water sample collection and coral health monitoring (Fig. 1):

- Two sampling stations in Mtwapa Creek were selected after being identified as a potential point source of nutrient input. Mtwapa Prison station is close to the Shimo La Tewa prison, where raw, untreated sewage was observed entering the Creek (Fig. 2). The Mtwapa Mouth station was chosen because it is the point where potentially polluted water from the Creek enters the open ocean and the adjacent MPA.

- Two sampling stations rich in corals in the Marine Park (Coral Garden and Ras Iwatine) and Marine Reserve (Nyali and Starfish)
- One sampling station in Kanamai served as the control site and was characterised by a low human population, less anthropogenic influence and community-led conservation efforts.

The study examined the potential effects of nutrient pollution on corals by carrying out assessments of coral reef health and water quality in terms of nutrient (N and P) quality and quantity, usually measured as *Chl a* in the water column, which is a robust indicator of increased nitrification (Brodie *et al.*, 2007; Furnas *et al.*, 2005). Data collection were done both *in situ* and *ex-situ*. Measurements of physico-chemical properties of the water, including salinity, temperature, conductivity, pH and dissolved oxygen (DO), were carried out *in situ* using an AZ86031 digital handheld water meter. Water quality around the reefs was further determined by focusing on priority nutrients, i.e., dissolved inorganic nitrogen (DIN) [ammonium (NH_4^+ -N), nitrate + nitrite ($\text{NO}_3^- + \text{NO}_2^-$)-N] and phosphates (PO_4^{3-} -P), and *Chl-a*, with sampling and analysis done according to protocols described in Grasshoff *et al.* (2007).

Triplicate surface water (0.5 m) samples at each site were collected in pre-cleaned polypropylene sample bottles for the nutrients. The samples were fixed *in situ* with mercury chloride (HgCl) to prevent any further biological activities and kept at -20°C until analysis. The PO_4^{3-} -P was determined using the ascorbic acid method at 885 nm, while NH_4^+ -N was determined using the indophenol method at 630 nm after at least six hours. Dissolved ($\text{NO}_3^- + \text{NO}_2^-$)-N was determined

using the cadmium reduction method and measured calorimetrically at 543 nm and Genesys 10S Vis spectroscopy (Thermo Scientific™). Triplicate samples were also collected at each sampling point for *Chl-a*. One litre (1L) of seawater was filtered through a synthetic filter (GF/C) after a few drops of a suspension of magnesium carbonate were added to prevent acidity on the filter. The filter was drawn dry, removed and folded in half using forceps, then stored and fastened in a vial for storage in a freezer at -20°C until analysis. The pigments were extracted from the filter in 90% acetone. Their concentration was estimated spectrophotometrically at selected wavelengths of 750 nm, 664 nm, 647 nm, and 630 nm using a Genesys 10S Vis spectroscopy (Thermo Scientific™).

The same volume of 1L of the sample was passed through a prepared, pre-weighed filter paper. The filter was then dried at $104 \pm 1^\circ\text{C}$. After drying, the filter was reweighed, and the TSS was calculated. For all the analyses, procedural blanks were included. The accuracy and consistency of the analytical procedures were determined by analysing check standards (which had an absorbance at the middle range of the calibration curve) analysed after every ten samples.

Coral health

Of the seven sampling stations, only four had coral reefs (i.e., Ras Iwatine, Coral Garden, Nyali and Starfish). The coral health status was monitored monthly using an aquatic survey, which entails the Underwater Visual Census (UVC) method to monitor and record coral reef ecological parameters. The point intersect method was used to record benthic substrates along a 40 m permanent line transect laid parallel to the reef crest. Benthic substrates were recorded at every 1 m interval in 10 categories of hard coral, soft coral,



Figure 2. photos of the point of pollution where raw sewage is released into Mtwapa Creek (left) and filtered concentrated Total Suspended Solids (TSS) from water samples collected from the same sampling site (right)

seaweeds, seagrass, coralline algae, rubble, sand, bare rock, and *Halimeda* spp. as described by Obura and Grimsditch (2009). Percentage coral cover value was obtained by simply dividing the total number of point intercept records belonging to hard corals by 40, which is the total number of valid point intercept records for all the substrates at the transect, multiplied by 100.

The basic bleaching and mortality monitoring level developed by CORDIO (Kawaka *et al.*, 2016) for monitoring coral reefs in Eastern Africa was modified to include healthy, partially bleached, and fully bleached categories only and used to assess coral health conditions. Coral bleaching was evaluated using a 40 m permanent line transect laid parallel to the reef crest. Each coral colony intercepting the 40 m permanent transect was counted and classified into three bleaching categories. The percentage value of each bleaching category was obtained by dividing the total number of line intercept records belonging to a given bleaching category by the total number of corals intercepting the 40 m line transect.

Trophic state index (TSI) classification

The trophic state index (TSI), developed by Carlson (1977), is used to measure the water quality of water bodies. It has three states: **oligotrophic** (low primary productivity due to nutrient deficiency); **mesotrophic** (intermediate level of productivity); or **eutrophic** (high biological productivity due to excessive nutrients, especially nitrogen and phosphorus, and can support an abundance of aquatic plants). This study used the trophic status measured by Carlson's trophic state index (CTSI) which examines several criteria such as the oxygen concentration, species composition of the bottom fauna, concentrations of nutrients, and multiple measures of biomass or production as multi-parameter indices computed from the three interrelated water quality parameters of Turbidity (Secchi disk depth - SDD), chlorophyll-*a* concentration (Chl-*a*), and total phosphorous (TP) concentration as described by EPA (2000) and Carlson *et al.* (1977). The water bodies are classified as oligotrophic, mesotrophic or eutrophic based on the values of CTSI.

Data analysis

Microsoft® Excel 2010 was used to tabulate all the parameter data obtained, after which the different variables from different stations were subjected to quantitative analysis. One-way Analysis of Variance (ANOVA) at p -value = 0.05 was computed using the

Statistical Analysis System (SAS) to determine the variations between and within sampling stations and over time. Analysis of the means was computed using a t -test at a p = 0.05 significant level. A comparison of the levels of different nutrients with threshold levels for various nutrients was then made against standard water quality variables criteria.

PAST Statistical Package (Version 2.10) was used for the Shannon-Wiener Index ranking that considered species diversity (H') and species richness (MI) indices. Shannon-Weaver's diversity index, H' (Ortiz *et al.*, 2016) was calculated as $H' = -\sum P_i \log_2 P_i$, where P_i was the frequency of presence for I species. MI was calculated according to Margalef (1961): $MI = (S-1)/\ln N$, where S was the number of identified species for the total counted colony (N). The variable data was used to carry out correlation and multivariate analysis between other physical variables using Canonical correspondence analysis (CCA) (Orfanidis *et al.*, 2007). Carlson's TSI was calculated using the following formulas, ignoring the negative results:

- a. TSI for Chlorophyll-*a* (CA) $TSI = 9.81 \ln \text{Chlorophyll-}a(\mu\text{g/L}) + 30.6$
- b. TSI for Secchi depth (SD) $TSI = 60 - 14.41 \ln \text{Secchi depth (Meters)}$
- c. TSI for Total phosphorus (TP) $TSI = 14.42 \ln \text{Total phosphorous } (\mu\text{g/l}) + 4.15$

where TSI is Carlson's Trophic State Index, and \ln is Natural logarithm;

Carlson's trophic state index (CTSI) = $[TSI (TP) + TSI(-CA) + TSI(SD)]/3$

With TP and Chlorophyll-*a* measured in micrograms per litre ($\mu\text{g/L}$), and SD transparency in meters.

Assumptions

The study was carried out to investigate the impact land-based nutrient loads would have on marine systems, with corals being used as indicator species. While there are many factors such as human activities within the study area that impact coral reef health, the focus of this study was on nutrient concentrations. Temperature was also considered as it is a standard parameter when analysing water quality. The study did not consider previous bleaching events, rather focusing on the parameters that were measurable during the study period. The results and conclusions presented here are those observed during the study period. Furthermore, the study recognizes the need for continuous monitoring to establish long term

coral health parameters and differentiate chronic and acute impacts of nutrient load on coral reef health.

Results and discussions

Water quality

The physico-chemical properties of the sampling sites showed that the average monthly temperature ranged from 22.7 ± 10.0 to 28.2 ± 0.1 °C observed at Nyali and Mtwapa Prison. Studies conducted by Hoegh-Guldberg (1999) in similar coral ecosystems show similarities to the study area and describe these temperature ranges as ideal for coral's optimal growth (Hoegh-Guldberg and Bruno, 2010). Typically, the temperature range for the formation of corals is 18 – 36 °C, with the optimal temperature between 22° and 28 °C (Wilkinson, 1999; Hubbard, 1997). Further studies have found that photosynthesis pathways in zooxanthellae are impaired at temperatures above 30 °C; this could activate the dissociation of coral/algal symbiosis. Based on these figures, it can be concluded that the deterioration of coral health due to water temperature was unlikely in the study area during the study period. However, the comparatively higher temperatures observed at Mtwapa Prison, an area receiving untreated sewage effluents from Shimo la Tewa Prison, indicate the influence of sewage pollution on coastal water temperatures. Physico-chemical properties and nutrient concentrations of water samples collected from Mtwapa creek and MMNP&R are summarised in Table 1.

The average pH observed during the studies ranged from 7.7 ± 2.7 to 8.5 ± 0.1 . This is within the global average of the world's open oceans ranging from 7.9 to

8.3 ± 0.1 (Gagliano *et al.*, 2010; Hoegh-Guldberg *et al.*, 2007). There was a slight variation in salinity between the stations. The Mtwapa Prison station had the lowest salinity of 32.4 ± 9.2 ppt, while Ras Iwatine, located in the Marine Reserve, had the highest value of 39 ± 8.4 ppt of salinity. Studies have shown that most reef-building corals require saline water ranging from 28.7 – 40.4 PSU (Guan *et al.*, 2015), demonstrating that the salinity in the study area is ideal for the growth and development of corals and is therefore not a limiting factor for coral health.

Dissolved oxygen (DO) showed a wide variation ranging from 6.0 ± 2.1 mg/l to 15.7 ± 5.9 mg/l. The highest value was recorded in Ras Iwatine (MMNP&R) and the lowest at Mtwapa Mouth (Creek). Table 1 shows that the areas with high nutrient concentrations (Mtwapa Mouth and Prison) had lower concentrations of DO (6.0 mg/l and 6.3 mg/l), respectively. These stations are located in the Creek and are closest to the point source of pollution. Similarly, Ras Iwatine recorded lower levels of nutrients (0.0387 mg/l) and high DO levels (15.7 mg/l). During the study, there was no statistically significant correlation between DO and the measured nutrient concentrations (p -value > 0.05). Other studies found that excessive amounts of nitrogen and phosphorous have been linked with the reduction of DO in marine water systems to the point of causing hypoxia (Dodds, 2006). However, all stations had levels higher than the recommended standard of 4 mg/l (Shanmugam *et al.*, 2007) (Table 2). This implies that DO did not contribute to the deterioration of coral health in MMNP&R during the study period (Table 2).

Table 1. Mean physico-chemical and nutrient concentrations in water samples collected at the seven sampling stations in Mtwapa creek, Mombasa Marine National Park and Reserve.

	Control	Mtwapa creek			Marine Park and Reserve			Average
	Kanamai	Mouth	Prison	Coral Garden	Nyali	Starfish	Ras Iwatine	
Temp (°c)	27.8±1.17	27.7±1.19	28.2±1.28	27.9±1.32	22.7±10.00	27.9±1.27	27.9±1.66	27.5
pH	8.5±0.12	8.5±0.10	8.4±0.14	8.5±0.10	7.7±2.71	8.5±0.08	8.5±0.11	8.5
DO (mg/l)	8.3±2.40	6.3±1.88	6.0±2.10	7.5±2.44	14.28±11.2	7.4±2.39	15.85±15.7	9.1
Sal (ppt)	36.1±0.63	36.0±1.21	32.4±9.23	36.4±0.26	32.7±11.50	36.4±0.30	39.0±8.43	36.1
TSS (mg/l)	99.0±33.1	45.3±13.6	46.4±11.8	30.9±4.1	68.9±23.6	42.3±15.9	58.9±20.7	55.5
Chl-a (µg/l)	5.257±4.403	1.237±0.658	1.146±0.673	0.900±0.564	0.755±0.448	0.710±0.199	0.692±0.207	1.068
PO ₄ (mg/l)	0.014±0.0028	0.022±0.0044	0.03±0.0109	0.014±0.0031	0.03±0.0146	0.022±0.0213	0.011±0.0171	0.021
(NO ₃ ⁻ +NO ₂ ⁻)-N (mg/l)	0.0426±0.0139	0.0408±0.0165	0.0407±0.0234	0.0348±0.0238	0.0468±0.0245	0.0409±0.0145	0.0387±0.0125	0.0408
NH ₄ ⁺ -N (mg/l)	0.2338±0.0527	0.2496±0.069	0.2283±0.0547	0.2371±0.0805	0.2602±0.0853	0.2234±0.0437	0.2142±0.0351	0.2352

Table 2. Coastal water quality standards that are safe for swimming and support aquatic life (Shanmugam *et al.*, 2007).

Water quality parameters	Standards
pH	7.8–8.3
Temperature (°C)	30
Total Suspended Sediments (TSS)	<25 mg/l
Dissolved Oxygen (DO)	>4 mg/l
Nitrate/Nitrite (NO _x)	<10 mg/l
Phosphorus as Phosphate (PO ₄ ⁻³)	<0.1 mg/l
Chlorophyll- <i>a</i> (Chl <i>a</i>)	<15 mg/l

Total suspended solids (TSS) affect coral reef growth (Parwati *et al.*, 2014). Effects of sedimentation on the coral reef are a significant factor that results in the smothering and death of corals during the recruitment process (Fabricius *et al.*, 2003). The results for TSS ranged from 33.7 mg/l in the Mtwapa Mouth to 79.3 mg/l at Coral Garden, with an average of 55.5 mg/l across all seven stations. As shown in Table 2, the TSS across all stations is higher than the recommended standards of <25 mg/l (Shanmugam *et al.*, 2007). These values suggest that the high TSS levels in the study area could contribute to the deterioration of coral health during the study period. Proper sewage treatment to remove suspended solids, organic matter and nutrients is necessary before the effluent is discharged into aquatic bodies (Rono, 2017).

Nutrients

The net primary production of photoautotrophs in the ocean depends on nutrient availability, with some

nutrients limiting phytoplankton biomass production in a system at a given time. The water quality in marine regions can directly or indirectly be adversely affected by land-based and water-based anthropogenic activities, with most of the pollutants finding their way into the marine environment from land-based activities through sewerage drainage systems from the discharge of poorly or untreated wastewater. These activities can result in elevated nutrient concentrations (primarily nitrogen and phosphorus), leading to eutrophication. The increase in toxic algal blooms could cause the death of benthic fauna and can be a threat to human health and could limit recreational activities (Moreno-Díaz *et al.*, 2015; Pole *et al.*, 2016), which is a concern for Mombasa Marine National Park and Reserve.

The mean nutrient concentrations observed in the Mtwapa creek were NH₄⁺ - 0.253 ± 0.069 mg/l, (NO₃⁻ + NO₂⁻)-N 0.042 ± 0.017 mg/l, PO₄ - 0.028 ± 0.004 mg/l

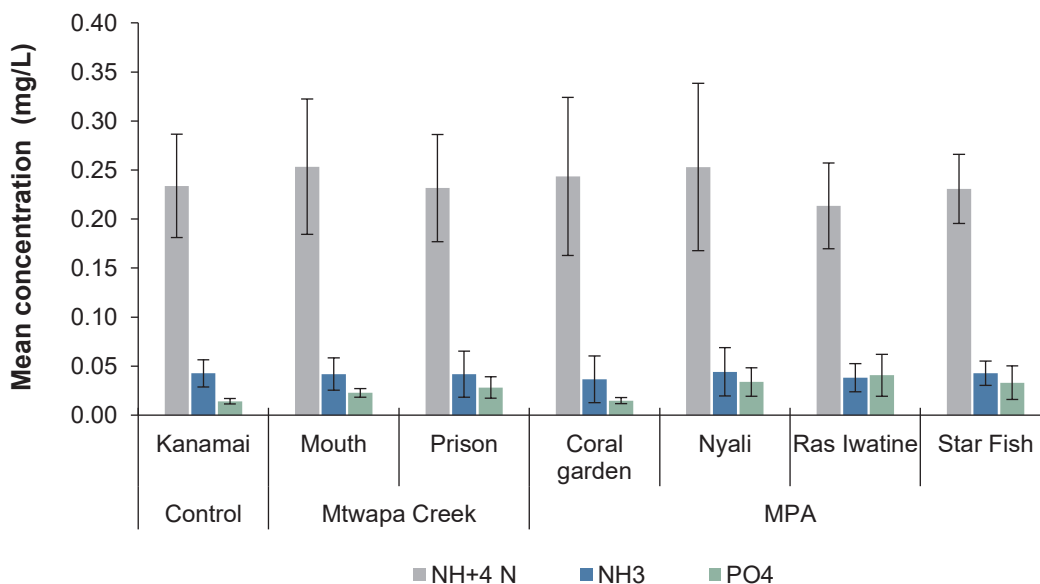


Figure 3. Mean ± standard deviation concentration of nutrients (dissolved inorganic nitrogen and phosphates) at the sampling stations.

at the Mtwapa Mouth station and $\text{NH}_4^+ - 0.042 \pm 0.055$ mg/l, $(\text{NO}_3^- + \text{NO}_2^-)\text{-N} 0.25 \pm 0.023$ mg/l, $\text{PO}_4 - 0.023 \pm 0.011$ mg/l at Mtwapa Prison. The results for the MPA stations ranged from $0.213 \pm 0.044 - 0.253 \pm 0.085$ mg/l for NH_4^+ , $0.037 \pm 0.014 - 0.044 \pm 0.025$ mg/l for $(\text{NO}_3^- + \text{NO}_2^-)\text{-N}$, and $0.014 \pm 0.003 - 0.041 \pm 0.021$ mg/l for PO_4 (Fig. 3).

1. Dissolved Inorganic Nitrogen (DIN)

DIN is composed of ammonium ($\text{NH}_4^+\text{-N}$), Nitrate plus Nitrite $(\text{NO}_3^- + \text{NO}_2^-)\text{-N}$. These forms of nitrogen are readily available to phytoplankton and often control the formation of blooms (Caffery *et al.*, 2007). The range of NH_4^+ was consistent throughout the study period, showing minimum variability across the sampling stations, ranging from 0.105 mg/l (Kanamai) to 0.4130 mg/l (Nyali). It was noted that there was some seasonal variation of NH_4^+ (Fig. 4). The highest levels were recorded between April and August 2018, during and after the long rain season. Statistical analysis of variance confirms no significant differences in NH_4^+ levels between the stations throughout the year.

Nitrates plus nitrites $(\text{NO}_3^- + \text{NO}_2^-)\text{-N}$ concentrations were lowest in Coral Garden (0.0348 mg/l), and the highest was recorded at the Nyali sampling station (0.0468 mg/l). The lowest amounts of $(\text{NO}_3^- + \text{NO}_2^-)\text{-N}$

concentrations were recorded between November 2017 and April 2018 (0.0074-0.1169 mg/l). Similarly, the highest levels were recorded between July and August 2018 (0.0321-0.0987 mg/l), after the long rain season (Fig. 5). There were no statistically significant differences (p-Value = 0.9853) of $(\text{NO}_3^- + \text{NO}_2^-)\text{-N}$ levels between the stations throughout the year.

2. Phosphates

Phosphorus is a limiting nutrient, particularly in tropical and subtropical estuarine and marine systems (Caffery *et al.*, 2007). Phosphates in the water samples ranged from 0.0138 mg/l in Coral Garden to 0.0430 mg/l in Ras Iwatine. There was a large seasonal variability across all stations, with peak amounts of phosphates recorded in October 2017, January and April 2018. This was more pronounced for Ras Iwatine and Nyali (spikes in January and April 2018) and Mtwapa Prison, which showed a spike in October 2017 (Fig. 6). The analysis of variance confirms that there are no significant differences in phosphate concentrations (mg/l).

3. Chlorophyll-a

Chlorophyll-a measures the green pigments in photosynthesising algae in the marine environment. The recommended scale for Chl-a in the marine environment ranges from good (<15 $\mu\text{g/l}$), fair (15-30 $\mu\text{g/l}$), and poor (>30 $\mu\text{g/l}$) (Shanmugam *et al.*, 2007). Ras Iwatine

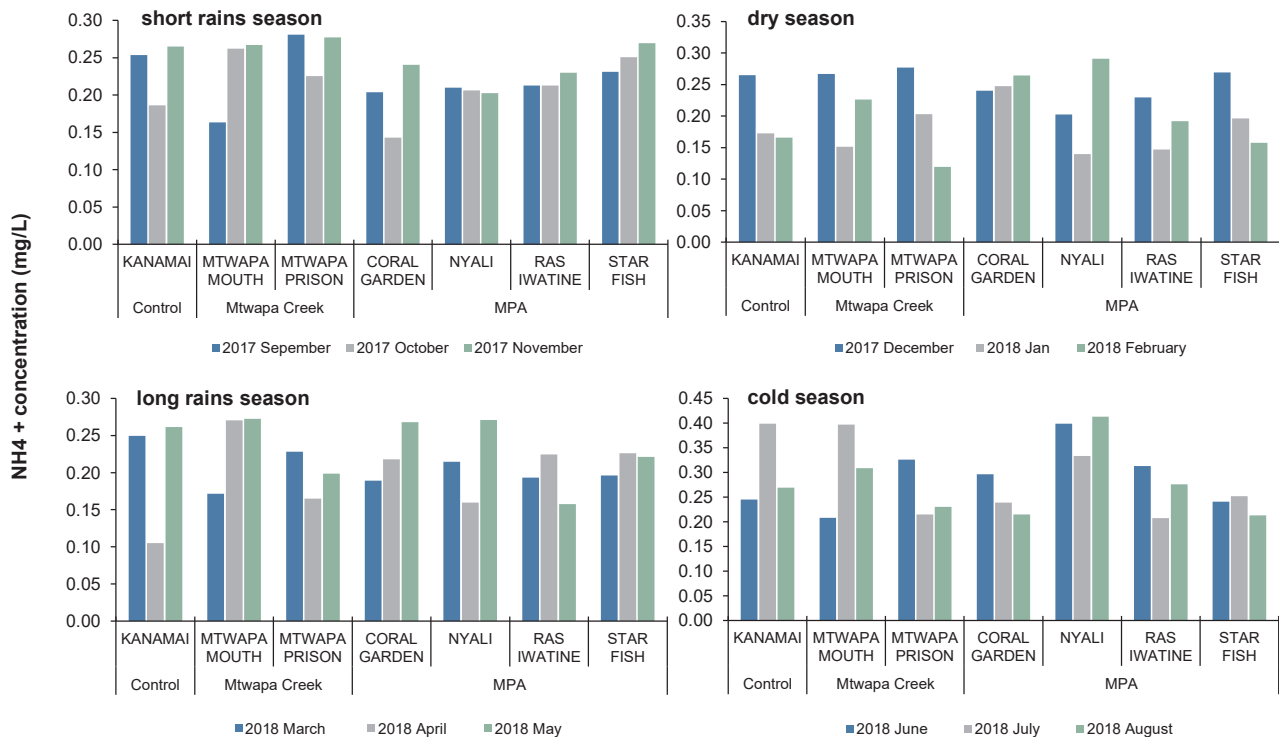


Figure 4. Monthly and seasonal variations of ammonium (NH_4^+) concentration from September 2017 to August 2018 at each sampling station.

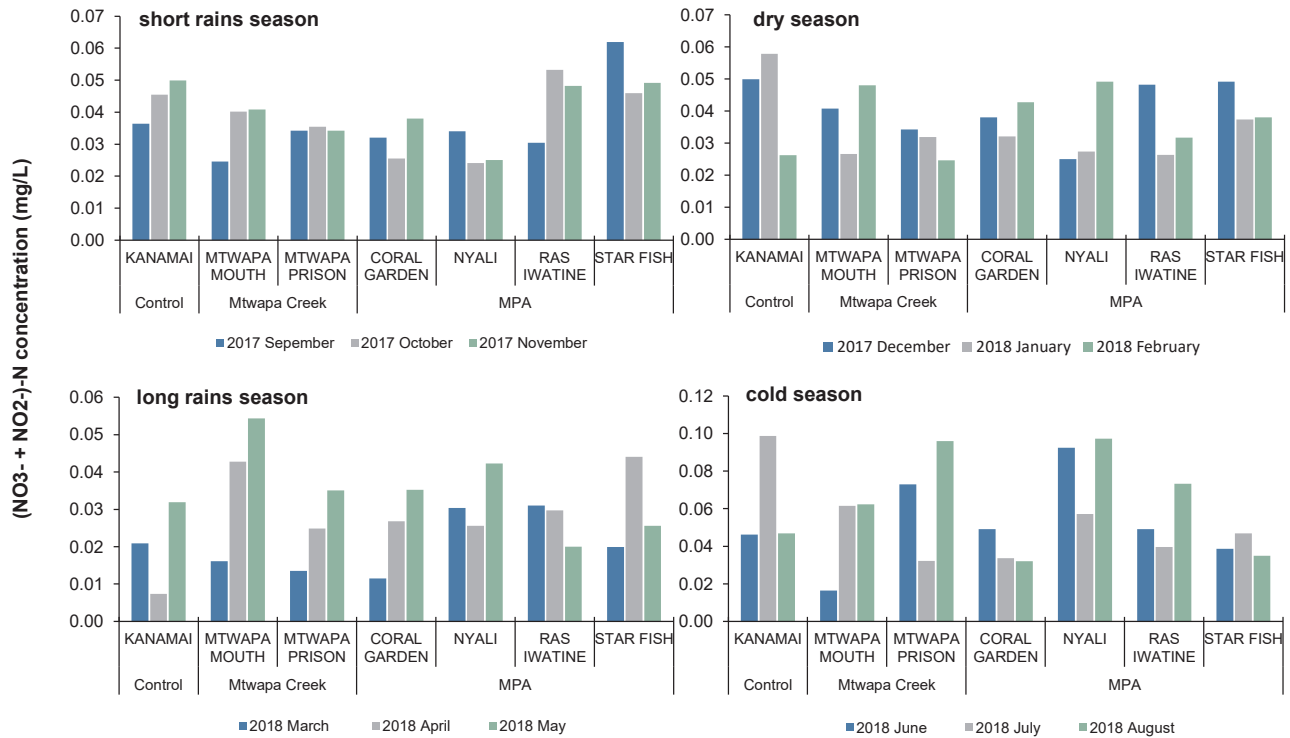


Figure 5. Monthly and seasonal variations of nitrates plus nitrites from September 2017 to August 2018 at each sampling station.

recorded the lowest average Chl-*a* amount of 0.7114 µg/l while Mtwapa mouth (Creek) had the highest value of 1.4942 µg/l. The levels of Chl-*a* appeared to be highest in the MPA stations close to the Mtwapa creek: Coral Garden (1.58 µg/l); Ras Iwatine (0.7114 µg/l); and

the control site of Kanamai (0.9591µg/l). This was also demonstrated when the seasonal variability of Chl-*a* was analysed (Fig. 7). April and August 2018 had the highest concentrations of Chl-*a* across all sampling stations (Fig. 7). Statistical analysis showed that, based on

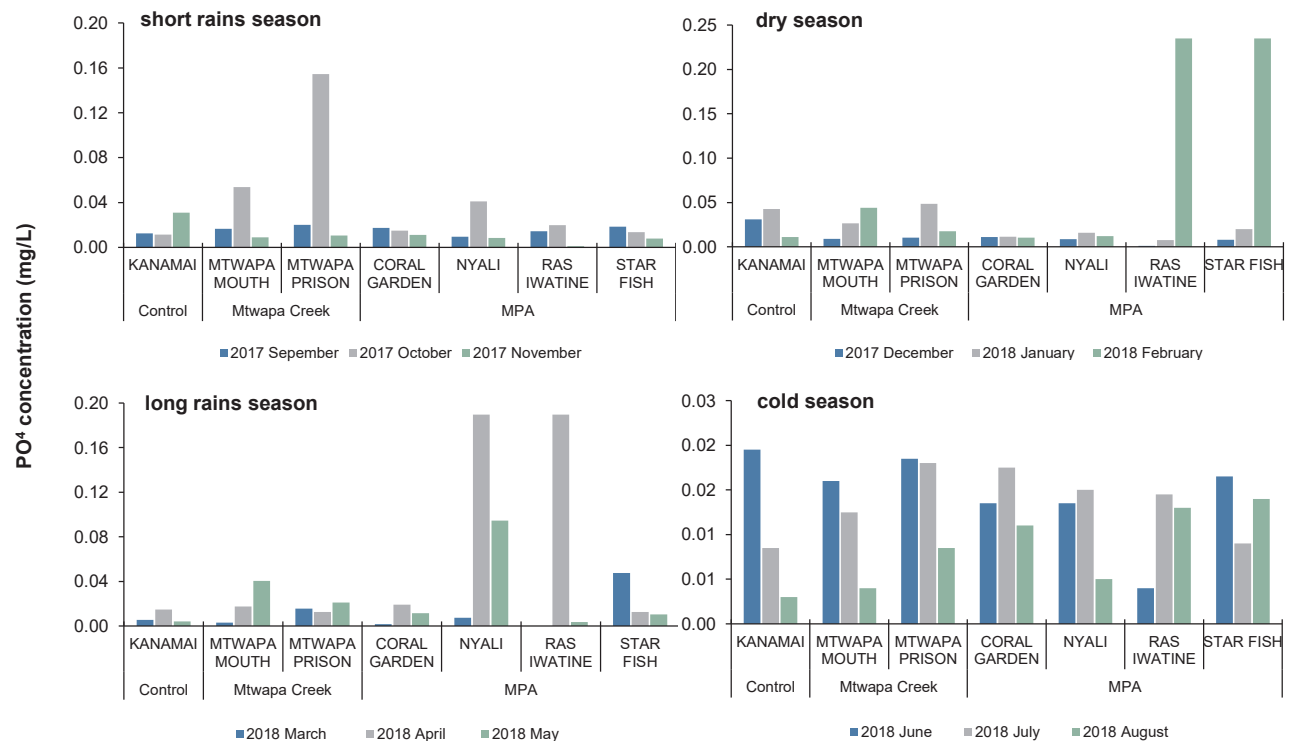


Figure 6. Monthly and seasonal variations of phosphates from September 2017 to August 2018 at each sampling station.

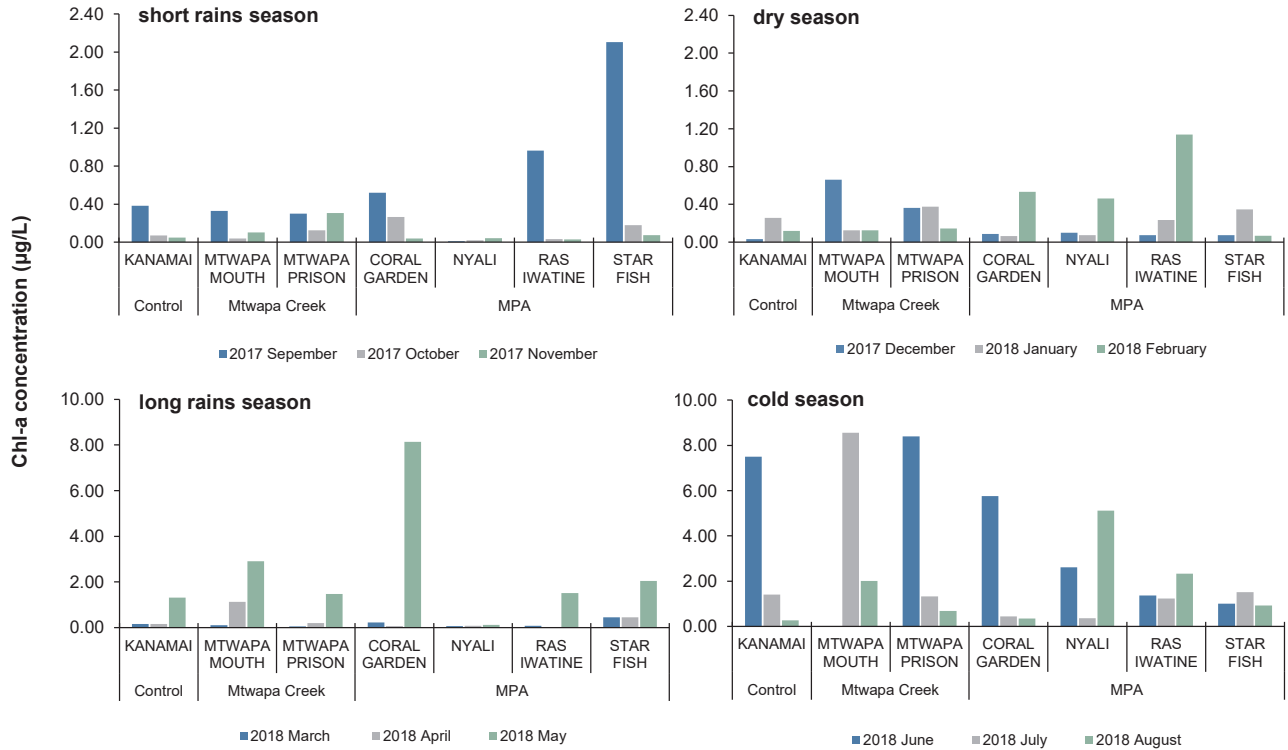


Figure 7. Monthly and seasonal variations of Chl-*a* in µg/L from September 2017 to August 2018 at each sampling station.

a p-value >0.05 in all sampling stations, there was no significant variance in Chl-*a* between the stations. Even though there was no significant difference in the level of all nutrients in the seven regions, Ras Iwatine, Nyali and Starfish had less Chl-*a* than the other four regions.

Kinjo (2017) presented a set of nutrient concentrations needed to maintain at least 50% coral reef coverage in a given area (Table 3). While the average amount of phosphates (0.021 mg/l) and nitrates + nitrites (0.0408 mg/l) were below the coastal water standards (Table 2), they are still higher than the concentration required to maintain 50% coral coverage (Kinjo 2017). These results suggest that, while the concentrations of these nutrients could not be harmful to most aquatic life, they would negatively impact corals. These observations are supported by Passy *et al.* (2016), who found that terrigenous nutrient delivery into the ocean

increases with the degree of eutrophication, which is sensitive to agricultural practices and wastewater treatments at the level of the watersheds. The over-enrichment of nutrients can result in toxic algal blooms, shellfish poisoning, coral reef destruction, and other harmful outcomes. Other studies have also observed a correlation between elevated nitrogen concentrations, increased phytoplankton densities and coral bleaching (Wagner *et al.*, 2010; Wooldridge, 2009; D'Angelo and Wiedenmann, 2014).

Enrichment of reef environments with dissolved inorganic nitrogen is considered a threat to the survival of corals. For those corals living in symbiosis with dinoflagellates (*Symbiodinium sp.*), enrichment can cause phosphorus starvation of the algal symbionts that can be caused by skewed nitrogen (N) to phosphorus (P) ratios (Rosset *et al.*, 2017). Nutrient enrichment plays

Table 3. Environmental guidelines for coral reef conservation for acceptable levels of P and N to maintain 50 % of coral coverage as highlighted by Kinjo (2017). The observed averages in the study areas and their molar ratios.

Water quality parameters	Water quality is required to maintain 50% of coral coverage	Observed averages	Moles (µM)
Phosphates	<0.006 mg/l	0.021 mg/l	0.00022
NO ₃	<0.01 mg/l	0.041 mg/l	0.00066
N:P molar ratio			3: 1

Table 4. Carlson's trophic state index (TSI) classification calculated from Chlorophyll-*a* (Chl-*a*) and total phosphorous (TP) concentration, ignoring the negative results.

Sampling Station		TSI (Chl- <i>a</i>)	TSI classification	TSI (TP)	TSI classification
Control	Kanamai	13.15	Oligotrophic	-57.29	Eutrophic
	Mouth	27.35	Oligotrophic	-50.41	Eutrophic
Mtwapa Creek	Prison	28.10	Oligotrophic	-47.35	Mesotrophic
	Coral garden	30.47	Oligotrophic	-56.62	Eutrophic
	Nyali	32.19	Mesotrophic	-44.70	Mesotrophic
MPA	Ras Iwatine	33.05	Mesotrophic	-42.03	Mesotrophic
	Star Fish	32.80	Mesotrophic	-45.03	Mesotrophic

Note: the scale of 0-30 TSI = oligotrophic, 31-49 TSI = mesotrophic and 50-100 TSI= eutrophic represent the trophic state classifications in reference to Carlson (1977) and KDHE (2001).

a role in determining coral reef resilience and overall health (Brodie *et al.*, 2009; D'Angelo and Wiedemann, 2014; Fabricius, 2005; Furnas *et al.*, 2005; Koop *et al.*, 2001). The ratio of N:P indicates the limiting nutrients for primary photosynthetic production in the marine environment. The approximate range of N:P ratios required for healthy coral reefs is from 4.3:1 to 7.2:1 (Smith *et al.*, 1981; Crossland *et al.*, 1984; Furnas *et al.*, 1995). The results recorded in this study showed an N:P ratio of 3:1, which is a lower ratio than those recommended by the previous studies. This lower ratio suggests that there is a higher concentration of phosphorous than nitrogen in the study area, which would negatively impact the health of corals. This is further supported by a study by Larned (1998) that concluded that higher concentrations of phosphorus, rather than nitrogen, are the primary limiting nutrient to coral and macroalgae productivity.

Carlson's TSI classification

According to Carlson (1977), the changes from oligotrophic to eutrophic do not occur at sharply defined

places or at the same location or rate. This implies that water bodies can be considered oligotrophic by one criterion and eutrophic by another. This is evident in the results from the current study in Table 4, where TSI classifications based on Chl-*a* differ from those based on total phosphorous concentrations.

The results based on Chl-*a* concentration show that the control site and the sampling stations in the Creek fell under oligotrophic TSI classifications. Except for Coral Garden (oligotrophic), the MPA sampling stations were all mesotrophic. The TSI classification based on concentrations of total phosphorous ranged from mesotrophic (Mtwapa Prison, Nyali, Ras Iwatine and StarFish) to eutrophic (Kanamai, Mtwapa Mouth and Coral Garden).

Coral Health

Ras Iwatine and Nyali had the highest average count of healthy corals (615) along the transect, followed by Coral Garden (608) and then Starfish (192). Coral Garden had the most partially bleached corals (16),

Table 5. Interpretation of benthic survey results based on Kawaka *et al.* (2016).

	Unhealthy	Fair	Healthy
Recommended levels according to Kawaka <i>et al.</i> (2016)	1% live coral cover >21% algae cover Characteristics: mainly rubble, broken, dead coral, bleached coral covered by algae	15-30% live coral cover 6-20% algae cover Characteristics: soft corals begin to grow on bare rock, and some live coral. an increasing proportion of live and soft coral, less rubble, dead and bleached coral	>30% live coral cover 0-5% algae cover Characteristics: high proportion of live & soft coral, very little rubble or bare rock, no brown or green algae covering coral
Observed Results	≈2% Live (soft) coral. ≈22% macroalgae	≈17% live (hard) coral	

followed by 15 in Ras Iwatine, 11 in Nyali, and then five in Starfish. In comparison, 19 corals were fully bleached in Coral Garden, 18 in Nyali, 17 in Starfish and 15 in Ras Iwatine. The mean percentage cover for hard coral in Mombasa National Marine Park and Reserve between October 2017 to September 2018 was $\approx 17\%$, while soft coral was $\approx 2\%$. Seaweed cover, which included macroalgae, was $\approx 22\%$ during the same period. Other benthic substrates covered were *Halimeda* with $\approx 1\%$, Coralline algae with $\approx 5\%$, sand with $\approx 6\%$, seagrass with $\approx 11\%$, bare rock with $\approx 22\%$, rubble with $\approx 16\%$ and other with $< 1\%$. Benthic substrate cover did not vary significantly from month to month (p-Value = 0.123). However, there was no consistent trend in the benthic substrate cover over the monitoring period. This inconsistency could be attributed to slow reef recovery after the 2016 bleaching event which affected Kenya's coral reefs. During the study period, there was no mass bleaching in the area (or elsewhere on the Kenyan coast).

Based on the study's results, it was inferred that the coral reef health in MMNP&R was fair to unhealthy (Table 5). While the health of the hard, live corals in the study area can be considered fair, it was still below Kenya's average coverage of 20% (Kawaka *et al.*, 2016). A report on coral health by Gudka *et al.* (2018) shows

similar results of hard live corals of $26 \pm 9.1\%$ following the bleaching event of 2016 in Mombasa.

Diversity Indices

The highest number of coral types recorded in this study was hard corals with 461 individuals, compared to the soft corals, with 89 individuals. The most dominant type was the soft corals with average *Dominance* ($D = 0.16 \pm 0.06$) compared to the hard corals with an average *Dominance* ($D = 0.07 \pm 0.02$). Based on the individuals recorded in various study sites, the Coral Garden had the highest diversity indices ($H = 2.9$) for the hard corals and the lowest diversity indices ($H = 1.7$) for soft corals (Table 6). On the other hand, the soft corals were low in percentage coverage, accompanied by a significant percentage coverage of macroalgae (tell-tale signs of eutrophic conditions), indicating unhealthy corals (Table 7).

Kanamai's (control) soft coral diversity index showed a positive canonical correspondence ($H = 0.11$), while the hard corals diversity index negatively correlated to the other physico-chemical parameters. Different results were found in the highly impacted Mtwapa Mouth station; the hard and soft coral diversity ($H = -36.84, -38.12$, respectively) negatively corresponded to the other physico-chemical parameters. The positive

Table 6. Principal component Canonical correspondence of the physico-chemical parameters and the Shannon-Wiener (H) diversity indices of the hard and soft corals recorded at the sampling sites.

	Control	Mtwapa Creek			MPA		
	Kanamai	Mouth	Prison	Coral garden	Nyali	Ras Iwatine	Starfish
	PC 3	PC 1	PC 2	PC 4	PC 5	PC 6	PC 7
DO (mg/l)	2.96	-25.40	-13.57	-0.78	1.12	0.11	-0.41
pH	-1.30	-29.74	-7.81	-3.21	0.74	0.58	0.35
Temp (°c)	4.28	12.41	18.19	-2.71	-0.48	1.48	-0.66
Cond (µs)	9.20	64.60	50.12	-4.63	2.68	-0.50	0.03
Sal (ppt)	8.20	33.47	25.64	-2.29	1.65	-0.38	0.30
Chl-a (mg/m ³)	-6.70	-44.54	-17.27	-4.21	-0.21	-1.03	-0.83
TSS (mg/L)	-28.74	101.10	24.14	-0.12	-3.15	0.00	0.10
NH ₄ N (mg/l)	-3.63	-48.23	-18.57	-3.64	0.52	0.06	0.33
NH ₃ (mg/l)	-3.68	-48.67	-18.84	-3.67	0.48	0.04	0.31
PO ₄ (mg/l)	-3.66	-48.70	-18.87	-3.67	0.48	0.05	0.32
Hard Corals (_I)	5.89	191.51	-50.47	3.31	1.52	0.01	-0.02
Hard Corals (_H)	-0.41	-36.84	6.98	5.82	0.59	0.06	0.11
Hard Corals (_D)	-0.40	-41.91	7.72	7.14	0.39	-0.16	-0.12
Soft Corals (_I)	18.37	0.77	-2.20	-0.67	-7.27	-0.25	0.14
Soft Corals (_H)	0.11	-38.12	7.06	6.27	0.54	0.12	0.19
Soft Corals (_D)	-0.48	-41.73	7.72	7.06	0.39	-0.17	-0.14

Table 7. Shannon-Wiener (H) diversity indices of the hard and soft corals recorded at the MPA sampling sites.

MPA	Hard Corals			Soft Corals		
	Individuals	Shannon_H	Dominance_D	Individuals	Shannon_H	Dominance_D
Coral garden	120	2.87	0.06	12.00	1.70	0.24
Nyali	132	2.78	0.06	16.00	2.19	0.13
Ras Iwatine	151	2.68	0.07	39.00	2.33	0.11
Starfish	58	2.56	0.10	22.00	2.02	0.19

canonical correspondence of the hard and soft coral diversity to other physico-chemical parameters in the MPA ranged from $H = 0.06$ - $H = 5.82$ and $H = 0.12$ - $H = 6.27$, respectively (Table 5).

Management of nutrient discharges

Land-based pollution needs to be addressed as part of a holistic, integrated coastal zone management approach supporting practical, sustainable and legal management of nutrient discharge into the marine environment to conserve corals. Efforts have been made to address land-based activities by formulating Strategic Action Plans (SAPs) to address the challenges of increased coastal water pollution in the Western Indian Ocean region (Pole *et al.*, 2016). Several methods to reduce nutrient discharge have also been developed around the world that can be adopted in Kenya (Aloe *et al.*, 2014). Encouragement of environmentally benign and economically viable technology, raising awareness and developing capacity for wastewater management are some methods for reducing effluent discharge. Kenya can follow the lead of many countries that have adopted Direct Toxicity Assessment (DTA) or Whole Effluent Toxicity (WET) testing to assess and manage effluents, leachates and contaminated ambient waters in marine and freshwater environments. These DTAs can serve as early warnings for the implementation of management actions and also provide a direct measure of toxicity and bioavailability of mixtures whose chemical composition is unknown (Pole *et al.*, 2016). Other available management options include land-based buffer zones along flow paths developed by Weller *et al.* (2011). Finally, Kenya should ensure the implementation of policy, legal, regulatory and institutional frameworks to protect and manage the coastal environment from land-based pollution. These frameworks would be an integral part of the country's ocean governance strategy.

Conclusions and recommendations

The study found that the land-based nutrient load would influence coral reef health during the study period. The temperature during the study period

was within normal ranges and was deemed to have little impact on coral health. The physico-chemical parameters of the study area and their effects on coral health were established. Nutrient quality and quantity were assessed and found to be higher than the recommended standards. This impacted the coral reef health within Mtwapa creek and MMNP&R, which was established to be fair to unhealthy. It was observed (and corroborated anecdotally) that despite efforts by KWS to manage MMNP&R, land-based pollution continues along the coastline. While it is easy to pinpoint the sewage discharged by the Shimo La Tewa prison as a point source of pollution, there are other diffuse and point sources of pollution along the coastline. Due to financial and technical limitations, the different sources were not considered in the study. While other direct human activities in the marine space contribute to coral health, the study did not consider them. More robust studies should be carried out in the future to include all these factors, including pollution from land-based sources.

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