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Quantitative aspects of inorganic nutrient fluxes in the Gazi Bay (Kenya): implications for coastal ecosystems

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Abstract

Fluxes of dissolved inorganic nutrients: NH_4^+, NO_2^-, NO_3^-, PO_4^{3-} and $Si(OH)_4$ from nearshore sediments of Gazi Bay were measured in situ within mangrove, seagrass and coral reef biotopes using benthic flux bell-jar chambers of cross-sectional area 0.066 m^2 and volume 0.0132 m^3. The objectives were: (1) to determine the influence of benthic fluxes, fluvial discharge and seasonal variations on the nutrient budget in the Bay waters; (2) to determine the effect of tidal and spatial variations on nutrient loads in the water column and (3) to establish the relative importance of the nutrient sources with regard to total community production of the Bay.

The directly measured fluxes ranged from −270 to +148 μmol NH_4^+–N/m^2/h; −60 to +63 μmol NO_2^-–N/m^2/h; −79 to +41 μmol NO_3^-–N/m^2/h; −79 to +75 μmol PO_4^{3-}–P/m^2/h and +30 to +350 μmol $Si(OH)_4$–Si/m^2/h for and respectively. It was established that benthic fluxes are the major sources of dissolved inorganic NH_4^+, NO_2^- and $Si(OH)_4$ while fluvial sources are important for NO_3^- and PO_4^{3-} into Gazi Bay waters. Seasonal variations had an appreciable effect on the PO_4^{3-} fluxes, N:Si ratio, river nutrient discharge, plankton productivity and important environmental factors such as salinity and temperature. Tidal and spatial variations had no significant effect on nutrient concentrations and net fluxes within the water column. The results imply that benthic fluxes are largely responsible for the nutrient dynamics of the nearshore coastal ecosystems especially where direct terrestrial inputs do not contribute significantly to the nutrient budget.

Keywords: Gazi bay; Nutrient sources; Benthic fluxes; Fluvial discharge; Community production; Coastal ecosystems

1. Introduction

Mangroves, seagrass meadows and coral reefs form a marine ecosystem characteristic of the Eastern-African and other tropical coastlines. This ecosystem plays an important role in coastal stabilization processes and has a high economic value as it is a source of forestry and fishery products, coral blocks for building, and certain farming activities (Davies, 1940; Odum, 1969). In many areas however, these vulnerable ecosystems are today threatened by increasing resource consumption by the adjacent human populations.

Many interrelations which are considered as functional entities exist between mangroves, coral reefs and adjacent seagrass meadows (Lugo et al., 1976). The interrelations are both biotic and abiotic: Coral reefs are known for their diversity and abundance of their fish and invertebrate faunas; while mangroves and seagrass beds act as important nursery and feeding grounds for fishes and crustaceans (Weinstein and Heck, 1979; Pollard, 1984; Robertson and Duke, 1987; Flores-Verdugo et al., 1987). As a first major step in defining such interrelations, it is important to determine the rates and direction of material fluxes from these systems to adjacent coastal waters, especially with respect to nutrients as they play a vital role in the ecological balance of the systems (Mortimer et al., 1998).

Gazi Bay, which is comprised of vast areas of mangrove and seagrass vegetation, provides an interesting location for studies related to intersystem nutrient fluxes since all the three biotopes of interest (mangrove, seagrass and coral reef) co-exist at the same Bay. Nevertheless, studies previously carried out in Gazi Bay are of floristic and faunistic nature (Gallin et al., 1989) with

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majority of the results focusing on the former (Ruwa and Polk, 1986). Although information on abiotic intersystem linkages in coastal regions is vital for the functional understanding and management of the systems, there is scarce availability of such information for the Gazi Bay.

It is the conspicuous scarcity of this important information not only for Gazi Bay but also for the E. Africa coastal region as a whole, that necessitated the design and execution of experiments that would generate information to correct this scenario, hence the purpose of this study.

2. Materials and methods

2.1. Study area

The Gazi Bay is a shallow, tropical coastal water system with mean depth of less than 5.0 m. The Bay is situated in southern Kenya on longitude 39°30″E and latitude 4°22″S. It is approximately 50 km from Mombasa. The total area of the bay excluding the area covered by the mangroves is 10.0 km^2. The mangrove forest covers an area of 5.0 km^2, and is dominated by the species: *Rhizophora mucronata*, *Sonneratia alba*, *Ceriops tagal*, *Bruguieria gymnorrhiza* and *Xylocarpus granatum*. The seagrass zone which is dominated by *Thallasia* sp. is found in the central region and covers an additional area of 7.0 km^2 which is approximately equivalent to 70% of the total area of the Bay. The bay is open to the Indian Ocean through a relatively wide (3500 m) entrance in the south. This entrance is rather shallow with depths of about 3 m in the east, increasing to 8 m in the western region of the bay. There are also a number of narrow and shallow cuts through the coral reef ecosystem, which is submerged most of the time but emerges at spring low tide.

There are two tidal creeks draining the upper region (which is dominated by mangrove vegetation). These are the Kidogoweni and Kinondo creeks and measure about 5 and 2.5 km long respectively. The Kidogoweni creek receives fresh water from Kidogoweni river. By contrast, the Kinondo creek lacks direct surface freshwater input, although there may be groundwater influx as salinity of the water has been observed to fluctuate significantly during the wet season. Directly adjacent to the mangroves are the intertidal flats and shallow subtidal areas.

The Mkurumuji river with its higher flow rates, discharges into the south-western region of the Bay. The drainage basin of both Mkurumuji and Kidogoweni rivers extends into the coastal ranges of the Shimba Hills. The Mkurumuji river alone drains an area of 164 km^2, while the Kidogoweni river drains an area of 50 km^2 upcountry. River discharge fluxes during the wet seasons can reach up to 5.0 and 17.0 m^3 s^{-1} for the Kidogoweni and Mkurumuji rivers, respectively. The contribution of Kidogoweni and Mkurumuji rivers to the nutrient budget and distribution in the Gazi Bay is appreciable although there are no significant differences between seasonal concentrations for most nutrients in their waters. Differences in the total nutrient input could be attributed to the differences between daily volumes discharged by the two rivers into Gazi Bay. Mkurumuji river discharges a higher volume than Kidogoweni river during both the dry (3050 m^3 vs 714 m^3) and wet (1.61×10^5 m^3 vs 1.19×10^5 m^3) seasons. The freshwater influx is greatest during the wet season when discharge results in considerable amounts of nutrients derived from terrestrial run off and drainage of rich agricultural areas where there is measurable fertiliser and other agro-chemical use in the farms. However, when compared with nutrient inputs in other rivers, Kidogoweni and Mkurumuji rivers can be considered to be among the least polluted rivers in the world. The climatic seasons are attributed to the south-east monsoon which is responsible for the long-rains (April–June) and the north-east monsoon, which causes short-rains (November–December). The dry season is experienced in the months of August–October and January–March. Rainy seasons occur as a result of the location of the intertropical convergence zone (ITCZ) which covers the East Africa region. Mean annual rainfall varies from 1000 to 1500 mm, while the rates of evaporation range from 1950 to 2200 mm per annum.

The detailed description of the study area, Gazi Bay, has been given elsewhere (for instance, see Coppejans and Gallin, 1989; Kitheka et al., 1996). For the purposes of this study, a total of five sampling stations were identified. These were coded: S1, S2, S3, K1 and M1 (Fig. 1). Three of these stations (S1, S2 and S3) were chosen within the Gazi Bay, while the other two were on rivers Kidogoweni (K1) and Mkurumuji (M1). The former three stations are representative of the three biotopes of interest within the Gazi Bay: Coral reef, seagrass and mangrove respectively, while the latter two stations were chosen to represent riverine contribution into the Bay from rivers Kidogoweni and Mkurumuji respectively. In order for the three sampling stations within the Bay to be as representative of the three biotopes as possible, they were chosen roughly from central locations of the biotopes they represent. Similarly, the riverine sampling stations were located at mid depth within the central part of the river where the salinity level was zero, representing fresh water.

2.2. Sampling, nutrient flux and gross community production measurements

Sampling and flux studies were conducted at least fortnightly, during the period: November, 1994 to July, 1995. Flux measurements, water and sediment samples

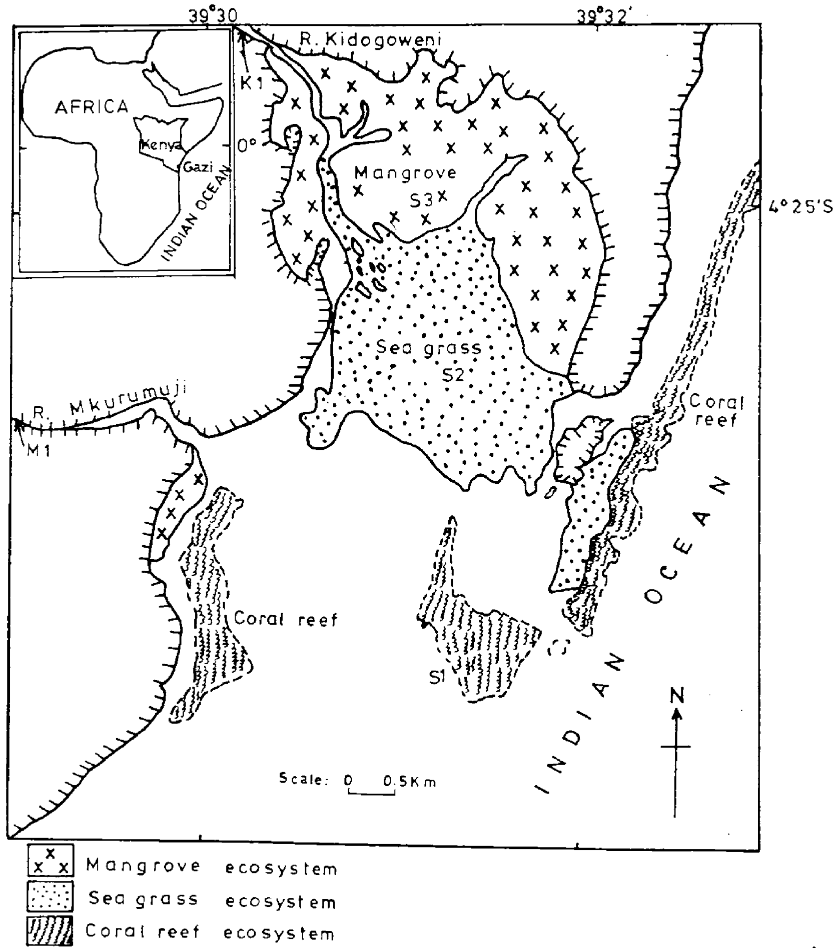

Fig. 1. The location of local and marine Coastal ecosystems in the Gazi Bay, Kenya.

collection were done at the three stations in Gazi Bay. The stations were chosen such that they were located within the mangrove, seagrass and coral-reef ecosystems. Replicate sediment cores of 5 cm in diameter were collected randomly at the three sampling stations (S1, S2 and S3) within the Bay using a coring device.

Water samples were also collected from the river stations at the same interval. Water samples from the river stations (K1 and M1) were collected at mid depth in the middle of the river channel using a water sampler (Nansen bottle). Since all sampled stations were shallow (<5 m), it was assumed that the water was well mixed. Temperature, salinity and dissolved oxygen variations were also closely monitored during the course of the study using mercury thermometer (0–50 °C), a hand held (Atago) refractometer and Winkler method respectively.

Samples were transported from the field in a cooler box containing ice. They were processed immediately. Those requiring storage were kept in a deep freezer at <-15 °C prior to analysis (which was usually accomplished within three days of sampling).

The in situ sediment–water nutrient exchange and benthic community production measurements were made using two transparent and two opaque plexiglass bell-jar chambers each covering 0.0660 m^2 of sediment and enclosing a total volume of 0.0132 m^3. The chambers were placed randomly at the bottom of each sampling station at the Bay. Water in each chamber and in the immediate surrounding was sampled during a full tidal cycle.

Duplicate water samples (100 ml) for analysis were withdrawn by syringe in 3 h intervals from sampling pots in each chamber. The volume of water during sampling was replenished with ambient seawater through one-way valves at the same periodic intervals. Changes in dissolved nutrient and oxygen concentrations with time were used to calculate rates of sediment–water column exchanges and benthic community production according to the method of Rizzo (1990).

Using the relationship described by Rutgers van der Loeff et al. (1984) shown below, theoretical calculations of the expected nutrient fluxes were made on the basis of interstitial-water nutrient concentrations and compared with the in situ flux measurements:

$$J = \acute{U} D_s \, dC/dx$$

where J is rate of flux, $\acute{U}$ is sediment porosity; D_s is effective diffusive coefficient of nutrient; dC/dx is concentration gradient across the sediment/water interface.

2.3. Dissolved inorganic nutrient analysis

The concentrations of dissolved inorganic nutrients viz. ammonia or ammonium (NH_3 or NH_4^+); nitrite (NO_2^-); nitrate (NO_3^-) and orthophosphate (PO_4^{3-}), were determined according to methods of Parsons et al., 1984) and APHA (1995) or the same methods but with minor modifications for use with Technicon Analyzer II system.

From the mean nutrient values obtained during preliminary recovery measurements, the capabilities of the analytical methods used were found to be of reasonably high precision for all the nutrients analysed. The summary of the various capabilities are NH_4^+: range 0.1–10 μM, precision 1 μM; NO_2^-: range 0.01–2.5 μM, precision 1 μM; NO_3^-: range 0.05–45 μM, precision 5 μM; PO_4^{3-}: range 0.03–5 μM, precision 3 μM; $Si(OH)_4$: range 0.1–140 μM, precision 10 μM. The correct values for the nutrient measurements are within: mean $\pm (0.03/n^{1/2}$ to $0.5/n^{1/2}$, depending on the nutrient, where n is the sample size).

2.4. Statistical analysis

Spatial and temporal variations in dissolved nutrients and flux measurements at different stations were carried out using Analysis of Variance (ANOVA). Various regression relationships were also calculated using a Minitab statistical computer package (Minitab Release 6.1.1, Minitab Inc., 1987). All statistical analyses are based on the significant level at $p = 0.05$ and critical values of F at $a = 0.05$ (Yule and Kendall, 1993).

3. Results and discussion

3.1. Environmental variables

3.1.1. Temperature

Temperature within complete tidal cycles in the Gazi Bay ranged from 24.1 to 30 °C (mean 28.2 ± 0.4 °C) for wet season and from 27.6 to 30.4 °C (mean 28.6 ± 4 °C) for dry season during the study period (November 1994–July 1995). The lowest temperatures were recorded in the wet season while the highest were recorded in the dry season (Fig. 2). Both of these extreme temperatures were however recorded at the same sampling station S3. Analysis of variance revealed significant differences in temperature between the sampled stations within the Bay, with respect to time of sampling during the dry season ($p = 0.01$), but there was no significant difference with respect to the stations ($p = 0.27$). For the wet season there was no significant difference for data within tidal cycle ($p = 0.16$) as well as between stations ($p = 0.57$).

There was evidence of a general drop in temperature in all the three stations within the Bay between the months of June 1995 and July 1995 which coincided with the peak of the wet season though seasonal differences were not significant ($p = 0.25$).

The temperature variations of Gazi Bay throughout the sampling period were typical of a tropical coastal environment and comparable to values obtained elsewhere within the region (Kazungu et al., 1989; Johnstone and Mohammed, 1995).

3.1.2. Salinity

Mean salinity variations during complete tidal cycles ranged from 26 to 37 PSU within the three sampled stations in Gazi Bay during the entire sampling period. Wet season mean was 34.1 (± 0.65) and dry season mean was 35.6 (±0.51) PSU. The highest salinities were realized during the dry season while the lowest were in the wet season (Fig. 3). Incidentally, both the highest and the lowest salinities were as in the case of temperatures, found in the sampling station S3, which is found in the vicinity of the Kidogoweni river estuary. For dry season data, analysis of variance revealed no significant difference with respect to time of sampling ($p = 0.15$) but there was a significant difference with respect to sampling stations ($p = 0.02$). For the wet season, there was no significant difference in salinity with respect to both time ($p = 0.10$) and stations ($p = 0.06$).

In general, the salinity values for the Gazi Bay during the entire sampling period were within the levels

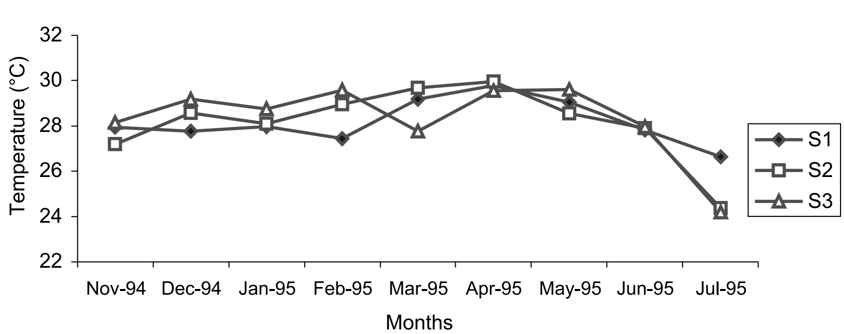

Fig. 2. Mean monthly temperature variations for the entire sampling period in Gazi Bay.

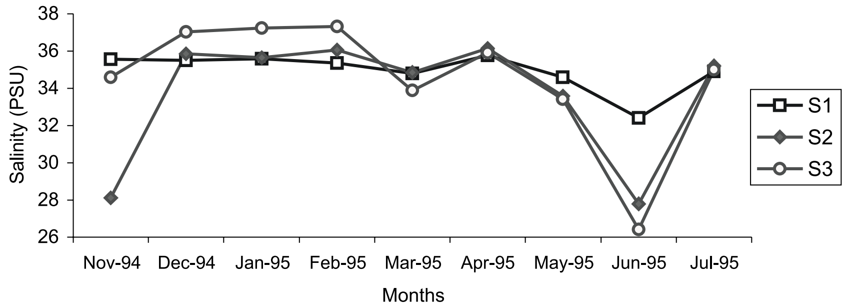

Fig. 3. Mean monthly salinity variations for the entire sampling period in Gazi Bay.

obtained before in the Bay (Osore, 1994; Kitheka et al., 1996; Kazungu, 1996; Middelburg et al., 1996) and elsewhere within the region (Kazungu et al., 1989; Johnstone and Mohammed, 1995).

3.1.3. Dissolved oxygen

The average dissolved oxygen (DO) in the waters of Gazi Bay during the study period varied between 4.9 and 10.5 mg O_2/l with mean of 6.8 ($\pm$1.8) mg O_2/l. These values are in agreement with previous measurements in the Bay (Osore, 1994; Kitheka et al., 1996).

3.2. Benthic nutrient fluxes

The mean NH_4^+–N seasonal flux variations in the Gazi Bay ranged from -270 to $+148$ µmol NH_4^+–N/m^2/h, with lowest flux values (in magnitude) being realised mainly during the wet season and highest values in the dry season. In general, however, there is evidence of greater degree of variation during the wet season as compared to dry season. Of the three sampling stations in the Gazi Bay, the NH_4^+–N fluxes in S3 were directed more into the sediment (negative fluxes on influxes) as compared to S1 and S2, whose fluxes were predominantly directed out of the sediment (positive fluxes or effluxes). The NO_2^-–N fluxes ranged from -60 to $+63$ µmol NO_2^-–N/m^2/h with lowest and highest values obtained during the wet season. The relative NO_2^-–N flux magnitudes are on average minimum in all the sampling stations during the dry season as compared to the wet season with variations greater in S2 than in S1 and S3. On the other hand, the NO_3^-–N mean fluxes were markedly variable during both dry and wet seasons in all the sampled stations in the Bay. The fluxes varied from -79 to $+41$ µmol N/m^2/h. In all the stations in the Gazi Bay, the fluxes were predominantly directed into the sediment. This is in contrast to the net fluxes observed for the other nitrogenous nutrients. The observed trend however, tends to agree with results of similar work obtained elsewhere. For instance, Hall et al. (1996) reported NH_4^+–N fluxes inversely related to the NO_3^-–N fluxes, with high influxes of NH_4^+–N correlated with high effluxes of NO_3^-–N. Mortimer et al. (1998) also found annual fluxes which are in line with observations of this study.

PO_4^{3-}–P mean fluxes were from -79 to $+ 75$ µmol PO_4^{3-}–P/m^2/h. There was no definite trend in the PO_4^{3-}–P flux variations, with magnitudes remaining relatively similar in all the sampled stations during both dry and wet seasons. During dry season however, there tended to be net influx for this nutrient in most of the biotopes while during the wet season the converse was true. The variable nature of PO_4^{3-}–P in the Gazi Bay may be reflective of the dynamic nature of the Bay. However, this is not a feature unique only to Gazi Bay for similar observations have also been reported elsewhere (Zwolsman, 1994; Mortimer et al., 1998). $Si(OH)_4$–Si mean fluxes ranged from +30 to +350 µmol $Si(OH)_4$–Si/m^2/h and are directed into the water column in all the sampling stations in Gazi Bay during both dry and wet seasons. Compared to the other nutrients, the average flux magnitudes for $Si(OH)_4$–Si were higher. The observation may be indicative of the fact that the siliceous material released (which is mainly controlled by temperature) is not significantly affected by uptake through phytoplankton. These results are in close agreement with those of similar work conducted elsewhere (Kemp et al., 1990; Hall et al., 1996).

The effect of environmental factors were examined by multiple linear regressions, treating the nutrient flux data as variable dependent on temperature, initial water column nutrient concentration, respiration rate and gross production rate (Table 1). These analyses showed existence of substantial correlations between NO_2^-–N and $Si(OH)_4$–Si with some of the independent variables as evidenced by their correlation coefficients (r^2). This was found to be in agreement with the observations of Hammond et al. (1985) in a similar work he conducted in San Francisco Bay, USA. It is most likely that the analytical problems in detecting small concentration changes during chamber deployments were the primary cause of the large variabilities observed in most of the nutrient flux results, given that precision capabilities of the analytical procedures employed for the majority of the nutrients analysed was not less than 1 µM.

Table 1
A summary of linear regression analyses relating temperature, benthic respiration, gross primary production, initial water-column nutrient concentration and benthic nutrient fluxes in Gazi Bay

Independent variables	Regression parameters	Benthic respiration ($gO_2/m^2/d$)	Gross production ($gO_2/m^2/d$)	Dependent variables: fluxes ($\mu mol/m^2/d$)				
				NH_4^+–N	NO_2^-–N	NO_3^-–N	PO_4^{3-}–P	$Si(OH)_4$–Si
Temperature (°C)	*b*	34.1	33.9	10497	102	1012	−3611	−59130
	m	−0.0004	−0.0003	−330	−3.6	−78	121	2037
	r^2	0	0.13	0.25	0	0	0	0.63
	n	12	12	15	15	15	15	15
Benthic respiration ($gO_2/m^2/d$)	*b*	–	−1982	−950	190	4941	2215	14738
	m	–	1.47	0.169	−0.02	−0.93	−0.3	−1.39
	r^2	–	0.76	0	0.20	0	0.15	0.37
	n	–	12	12	12	12	12	12
Gross production ($gO_2/m^2/d$)	*b*	–	–	−812	138	−1768	542	13267
	m	–	–	0.125	−0.01	−0.1	−0.1	−0.99
	r^2	–	–	0	0.07	0	0	0.61
	n	–	–	12	12	12	12	12
Initial nutrient concentration (μM)	*b*	–	–	1504	−202	3304	−357	423
	m	–	–	−466	1716	−358	274	244
	r^2	–	–	0.35	0.92	0	0.10	0.36
	n	–	–	15	15	15	15	12

b = y-intercept, m = slope, r^2 = coefficient of determination, n = sample size.

Variance analysis between flux rate data obtained for transparent or clear and darkened bell-jar chambers, as well as between nutrient concentration data for sampled waters from the different stations within Gazi Bay revealed no significant difference for all the nutrients considered ($p = 0.42$). In addition, the same analysis on all nutrient flux measurements between different seasons revealed no significant differences ($p = 0.66$). The values of the present work on these nutrients were found to be in reasonable agreement with those obtained in a similar previous study within the same Bay (Kazungu, personal communication, Table 7) and elsewhere within the region (Johnstone et al., 1989). There is also a close agreement with results of similar work conducted in other regions (Table 2).

3.3. Benthic production

The mean net production values ranged from 0.11 to 7.45 g $O_2/m^2/d$ while the mean daily respiration rates were from 5.44 to 8.06 g $O_2/m^2/d$ (Table 3). There was evidence of considerable variability in the mean net production and respiration rates in all the stations sampled in the Gazi Bay, during both dry and wet seasons, though there was lack of any definite trend. However, the overall results for daily gross production (P) and daily respiration (R) suggest that there is generally an autotrophic condition in the Gazi Bay as the P:R ratios were always greater than 1 (Table 3).

Analysis of variance on benthic gross production data revealed no significant difference with respect to both seasons ($p = 0.64$) and stations ($p = 0.61$). When the Gazi Bay data is compared with that of similar work done elsewhere, in the temperate regions (Boyton et al., 1980; Rizzo, 1990), it is found to be relatively higher. There is however, a paucity of this kind of work within the region to compare with.

3.4. Fluvial nutrient inputs

The mean nutrient concentration levels for Kidogoweni and Mkurumuji rivers indicated net elevation

Table 2
Ranges of mean dissolved nutrient benthic fluxes ($\mu mol/m^2/d$) for nearshore sediments from various studies

Location (author(s))	PO_4^{3-}–P	$Si(OH)_4$–Si	NH_4^+–N	NO_2^-–N	NO_3^-–N
Chesapeake Bay (Kemp et al., 1990)	–	–	800–8600	–	−2300–400
Tamar Estuary (Watson et al., 1995)	0–790	−500–17620	670–4090	380–630	−6830–8960
Skagerrak (Hall et al., 1996)	−20–100	550–4000	−60–50	−20–10	−140–300
Great Ouse (Nedwell and Trimmer, 1996)	–	–	−1200–3200	–	−47600–19400
Colen Estuary (Oglivie et al., 1997)	–	–	−1200–17900	–	−21800–2200
Humber Estuary (Mortimer et al., 1998)	−1100–2200	−5100–3600	−6700–25900	1500–1400	43000–15000

Table 3
Mean (±SD) daily net production, daily respiration, gross production (units are in mmol $O_2/m^2/d$) and P:R ratios in Gazi Bay

	Site					
	S1		S2		S3	
	DS	WS	DS	WS	DS	WS
Daily net production	59 ± 44	58 ± 44	37 ± 248	234 ± 456	35 ± 26	46 ± 217
Daily respiration (R)	–	–	252 ± 72	245 ± 64	170 ± 130	171 ± 129
Daily gross production (P)	–	–	289 ± 320	486 ± 520	206 ± 156	217 ± 151
R:P ratio	–	–	1:1.2	1:2	1:1.2	1:1.3

DS and WS are dry and wet seasons respectively.

(though not significantly different, $p > 0.1$) for all the nutrient concentrations in both rivers except for $Si(OH)_4$–Si, during the wet season as compared to dry season. The increased terrestrial run off during this period is thought to be the most likely cause of this observed effect. The river discharge data (Table 4) also showed that the nutrient discharge into the Gazi Bay from the two rivers is dependent on seasons. Wet season is marked with considerable increase in nutrient discharge into the Bay while the converse is true for the dry season.

The levels of NO_2^-–N and NO_3^-–N were higher in the Mkurumuji river than Kidogoweni river, while for $Si(OH)_4$–Si the Kidogoweni river showed higher levels than the Mkurumuji river during the whole sampling period. The levels for NH_4^+–N and PO_4^{3-}–P are more or less similar in both the rivers during both the dry and wet seasons. However, the trend observed in the variation of all nutrients in both rivers is similar during the entire sampling period.

Variance analysis performed on dry season mean data revealed no significant difference for all nutrients between the two rivers ($p = 0.33$) except for $Si(OH)_4$ which showed some significant difference ($p = 0.01$). The same analysis performed on wet season data revealed no significant difference for all nutrients between the two rivers ($p = 0.36$) except for NO_3^- where a significant difference was observed ($p = 0.04$). Previous work done in the same Bay also recorded similar observations (Kitheka et al., 1996). These observations were also comparable with that of similar work conducted in rivers found in other regions (Table 5).

3.5. Coupling nutrient fluxes and plankton

On the basis of the results discussed hitherto and considering each biotope in Gazi Bay on an individual basis, it would appear that most of the three biotopes (mangrove, seagrass and coral reef) found in the Bay act mainly as sources of the nutrients considered except for

Table 4
Mean (±SD) river nutrient discharges (g/day) during the dry and wet seasons for Kidogoweni and Mkurumuji rivers

River	NH_4^+–N		NO_2^-–N		NO_3^-–N		PO_4^{3-}–P		$Si(OH)_4$–Si	
	DS	WS	DS	WS	DS	WS	DS	WS	DS	WS
Kidogoweni	7.06	1563	1.79	336	41.7	6407	21.8	8578	10643	1096030
	(1.69)	(1496)	(0.62)	(109)	(1.2)	(941)	(0.4)	(10150)	(232)	(795420)
Mkurumuji	43.0	3015	15.00	1474	632	45169	83.3	8436	34864	78500
	(15.9)	(2172)	(0.01)	(1271)	(312)	(35000)	(15.8)	(5775)	(3029)	(566570)

DS and WS are dry and wet seasons respectively.

Table 5
A comparison of mean nutrient concentrations (μM) in some rivers in other world regions

River	PO_4^{3-}–P	NO_2^-–N	NH_4^+–N	NO_3^-–N	$Si(OH)_4$–Si
Aire, UK (summer means)	55	33	84	600	165
Derwent, UK (Summer means)	6	4	4	220	116
Don, UK (summer means)	80	18	21	580	130
Sondu-Miriu[a] (Kenya)	–	1.3	–	10	–
Kidogoweni[b] (Kenya)	1.7	0.2	0.8	0.4	429
Mkurumuji[b] (Kenya)	1.3	0.5	1.2	17	279

Sources: Uncles et al. (1998), Mwashote and Shimbira (1994) and Present study.
[a] Mwashote and Shimbira (1994).
[b] Present study.

NO_3^- for which they were all sinks. It was also apparent that the flux of NH_4^+ from the sediments (efflux) accounted for essentially all dissolved N exchange from the sediment to the water column since virtually all NO_3^- flux was directed into the sediments (influx). NO_2^- contribution was relatively insignificant. On the other hand, the flux direction for PO_4^{3-} was largely variable within the different biotopes. This variability seemed to be different from one biotope to the other and essentially depended on the season. For instance, the fluxes for PO_4^{3-} were basically into the sediments during dry season and out of the sediments during wet season (Table 6). For the case of NH_4^+ and $Si(OH)_4$ fluxes in all the Gazi Bay biotopes, these nutrients were entirely directed out of the sediments during both dry and wet seasons. This observation compares well with similar work conducted elsewhere (Hall et al., 1996; Mortimer et al., 1998).

Although the general Si:N:P ratio for in situ benthic fluxes appeared less variant for nearshore (S3) and inner (S1) stations, the individual Si:N, N:P and Si:P ratios showed a different trend. It is likely that these observations could be as a result of the types of the geochemical processes controlling the benthic flux of these nutrients, within the various biotopes of Gazi Bay. It was also clear that the N:Si ratio within these biotopes is influenced considerably by seasonal change. For instance, N:Si ratio for S1 was 49 during dry season but became 12 during wet season. The lack of a clear variation trend in Si:P and N:P ratios within individual biotopes and between seasons does not allow any general assertion in this regard to be drawn for Gazi Bay.

Since input of organic matter to the sediment surface is not deficient in nitrogen, some other process must have been operative in producing the generally low ratios observed. For instance, Nixon et al. (1976) reported preliminary results from Narragansett Bay, USA, which suggested that nitrogen flux from sediments to water was a mixture of both NH_4^+ and dissolved organic nitrogen (DON). They reckoned that partitioning of the flux into inorganic and organic fractions (as in our present situation) may have been responsible for the low N:P benthic ratios and, to a lesser extent, the low N/P ratios observed in the water column. However, in the present study DON was not determined since it was assumed to be negligible. This assumption was found reasonable on the basis of results of several related studies conducted elsewhere which have found this to be so. For example, Boyton et al. (1980) who studied the Patuxent Estuary, USA, found that DON flux was generally small and, on annual basis, was directed into the sediments. Similarly Hartwig (1976) also reported that DON flux was just a small portion of total nitrogen flux in a sandy system in California.

It has also been suggested elsewhere that interstitial phosphate may be controlled by both inorganic and organic processes but the flux of $Si(OH)_4$ and NH_4^+ are enhanced by macrofaunal irrigation (Callender and Hammond, 1982; Davey et al., 1990; Davey, 1994). Moreover, relatively large phosphorus fluxes may represent anoxic degradation of phosphorus containing iron oxyhydroxides (Krom and Berner, 1981). Our values for N:P ratios found in Gazi Bay, though seemingly low, are quite comparable to those found in studies elsewhere (Nixon, 1981; Klump and Martens, 1981). Hence, on a global perspective, the nutrient fluxes in Gazi Bay are within the normal levels.

The results of the present study have indicated that benthic input supplies a major fraction of the nutrients which are utilized in the water column. There are several ways in which to place the importance of benthic fluxes in perspective. Applying one crude method which was also used by Aller and Benninger (1981), the average water column nutrients in the sampled area through fluvial sources can be compared with that supplied by flux from the bottom sediment by simply considering data obtained and the areal coverage of the sampled stations of Gazi Bay. The results of this treatment revealed that with an exception of NO_3^- and PO_4^{3-} for which fluvial contribution is far more important in Gazi Bay, the benthic nutrient fluxes are of significantly greater magnitude to the Bay during both dry and wet seasons. In addition, if we assume that atmospheric inorganic nutrient inputs into Gazi Bay are relatively insignificant in comparison to fluvial and benthic flux sources, and considering that there is no evidence of groundwater contribution to the Bay (Kitheka et al., 1996), it is evident that on an overall basis, direct terrestrial inputs to the Bay are minor controls on dissolved inorganic nutrient distribution relative to the

Table 6
Summary of mean benthic nutrient fluxes for the different biotopes in Gazi Bay (μmol/m^2/d)

Biotope	NH_4^+–N		NO_2^-–N		NO_3^-–N		PO_4^{3-}–P		$Si(OH)_4$–Si	
	DS	WS	DS	WS	DS	WS	DS	WS	DS	WS
Coral reef (S1), 3 km^2	147	105	−11.1	−12.2	−79.0	−21.3	−54.9	16.1	36.2	109
Seagrass (S2), 7 km^2	72.3	17.0	3.6	−21.0	38.1	−52.5	19.0	−5.2	97.5	274
Mangrove (S3), 5 km^2	−25.2	140	23.4	61.8	−26.6	−65.7	−10.6	2.2	188	87.7
Net function for Gazi Bay	Source	Source	Source	Source	Sink	Sink	Sink	Source	Source	Source

DS and WS are dry and wet seasons respectively.

benthic flux processes within the Bay. In view of the small total area of Gazi Bay which is approximately 15 km^2 (mangrove = 5 km^2, seagrass = 7 km^2 and coral reef = 3 km^2) and its moderate mean annual rainfall (Kitheka et al., 1996), this observation is quite in conformity with results of studies done in other regions. For instance, a review study by Meybeck (1982) found that in 22 unpolluted stations around the world, dissolved inorganic nitrogen (DIN) fall-out was in between 300 and 600 $kg\,km^{-2}\,yr^{-1}$, the median being 450 $kg\,N\,km^{-2}\,yr^{-1}$, while the corresponding atmospheric input of P was only 5 $kg\,km^{-2}\,yr^{-1}$.

When we consider Gazi Bay in terms of its constituent biotopes, some degree of variation in their net nutrient benthic flux directions are observed. While the overall picture portrayed by the benthic fluxes of the Bay is that of behaving as a source for NH_4^+, NO_2^- and $Si(OH)_4$, and sink for NO_3^- and PO_4^{3-}, the scenario is not necessarily the same when each particular biotope is considered individually. For instance, during the dry season, the coral reef and seagrass biotopes act as sources for NH_4^+ while the mangrove biotope behave as a sink for the same nutrient. In the contrary, during the wet season, for the case of NO_2^-, the former two biotopes behave as sinks while the latter biotope acts as a source. These observations appear to suggest some kind of mutual concomitant antagonistic processes which take place in terms of source/sink function between some of the biotopes in Gazi Bay, with respect to particular nutrients. However, since many other processes such as denitrification and nitrification (Rivera-Monroy et al., 1995b) are involved in determining the net flux observed in any nearshore coastal system such as Gazi Bay, further work is needed in this regard to provide a better understanding of the observed effect.

Taken together these data, and considering the fact that the Bay has an overwhelmingly high rate of exchange between its waters and oceanic waters, accompanied by a relatively short residence time (Kitheka et al., 1996), all these facts suggest that Gazi Bay is a net exporter of inorganic NH_4^+, NO_2^- and $Si(OH)_4$ and a net importer of NO_3^- and PO_4^{3-}. Similar observations have also been made in the same Bay previously (Middelburg et al., 1996; Kazungu, 1996) and in other similar environments elsewhere (Rivera-Monroy et al., 1995b,a; Mortimer et al., 1998). However, it is also worthwhile to note that there are a few contrasting conclusions which have been reached in benthic nutrient studies elsewhere (Sanders et al., 1997). There is therefore need for further work in order to reconcile the underlying factors which lead to the apparent contrasting conclusions.

Both phytoplankton and zooplankton distribution in Gazi Bay have been found to be strongly influenced by seasonal changes (Kitheka et al., 1996). The increased river discharges which occur during rainy (wet) season have been found to have noticeable but different effects on the abundance of planktons. For example, in the mangrove station (S3), which has greater riverine influence from Kidogoweni river, has been found to record a low zooplankton count (as low as 2 individuals per m^3) due to the resulting low salinities (Mwaluma et al., 1993). Conversely, the same riverine influence favours phytoplankton production (up to 1110mg $C/m^3/day$) because of the overriding effect of increased nutrients resulting from higher river discharge. On an overall basis however the plankton production in the Bay has been found to be lower compared to similar environments within the region. For instance, gross phytoplankton production in the neighbouring Tudor Creek was estimated to be 350 $mg\,C/m^2/h$ (Okemwa, 1989). These observations are again mainly attributed to the high exchange rate between offshore and inshore waters and the short residence time found in the waters of Gazi Bay. The same factors are also thought to be responsible for the lack of any observable eutrophic conditions which would have otherwise arisen due to the nutrient enrichment from river discharges. In this respect, Gazi Bay can be listed among the unpolluted environments of the world (Meybeck, 1982). Incidentally, during the dry season, it has been found that the density distribution of planktons become more evenly distributed over all the different biotopes in the Bay because the river discharges are reduced considerably, hence the salinities become less variable (remain at approximately 35 PSU) except for areas which are just within the very vicinity of the river mouths (Kitheka et al., 1996). Unlike similar environments elsewhere (Ullman and Sandstrom, 1987), the lack of any significant difference in nutrient fluxes between the different biotopes ($p = 0.55$) and seasons ($p = 0.66$) in Gazi Bay gives the impression that there is little effect of dilution by refractory terrigenous debris and turbidity associated with major runoff events which often lead to reduction in sediment reactivity and nutrient remineralization rates. Such phenomena have been found to be a common occurrence in a number of other similar environments (Aller et al., 1985; Berner, 1978; Torgersen and Chivas, 1985).

Our nutrient flux study results have unequivocally demonstrated that all biotopes in Gazi Bay, in one way or the other import NO_3^- following the apparent deficit created by the directional NO_3^- flux into the sediments. Although the mean theoretical calculations showed reversed fluxes (Table 7) for this nutrient, this disparity is attributed to the effect of microbial processes prevalent at the sediment–water column interface (Johnstone et al., 1989; Santschi et al., 1990; Davey, 1994). It is however suggested that direct estimates of coupled nitrification–denitrification processes within the Gazi Bay biotopes are needed to evaluate the alternative source of N to the NO_3^- loss in the system. Moreover, studies of other similar systems in different geomorphological and

Table 7
Comparison between some calculated and experimental mean benthic nutrient flux rates (mol/m^2/d) in the Gazi Bay

Constitution	Present study			Previous study (Kazungu personal communication)	
	In situ flux	Calculated flux	Number of samples (*n*)	Experimental flux	Number of samples (*n*)
NH_4^+–N	-9 ± 27	0.4 ± 0.3	20	15 ± 61	84
NO_3^-–N	-68 ± 249	0.05 ± 0.02	20	3.3 ± 17.6	87

hydrological environments are required for a better understanding and elucidation of the function of mangrove, seagrass and coral reef biotopes such as those found in Gazi Bay, in the overall nutrient dynamics of the coastal zone.

4. Summary

1. Seasonal variations had a profound influence on the physical and chemical environmental properties of Gazi Bay, more so to areas within the vicinity of the river mouths. This effect was also strongly reflected in the plankton distribution of the Bay. While precipitation plays a significant role in this aspect due to the increased river discharge and surface runoff into the Bay during this period, tidal and spatial variations have little or no effect on both physical and water column nutrients of the Gazi Bay.
2. Benthic nutrient fluxes in Gazi Bay are a major supply for NH_4^+, NO_2^- and $Si(OH)_4$ compared to inputs from fluvial sources, which are relatively more important in the supply of NO_3^- and PO_4^{3-} into the Bay. Sediments therefore appear to be quite efficient at recycling organic matter received from the water column. In this respect, Gazi Bay sediments as a whole act as net sink for PO_4^{3-} and NO_3^- and a net source for NH_4^+, NO_2^- and $Si(OH)_4$.
3. Within experimental uncertainty, the different treatments for benthic chambers had no effect on the resultant benthic nutrient fluxes obtained in Gazi Bay and theoretically calculated fluxes were in agreement with the in situ measurements. There is however, considerable seasonal influence on PO_4^{3-} nutrient fluxes and N:Si ratio within the Bay.
4. In general, it is envisaged that any anthropogenic pressures at the catchment with respect to nutrients (for instance nutrient inputs arising from agricultural practice at the catchment) would have a direct bearing on the nutrients distribution of the Gazi Bay.

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