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Spatial and temporal distribution of dissolved inorganic nutrients and phytoplankton in Mida Creek, Kenya

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Abstract

The spatial and temporal distributions of dissolved inorganic nutrients were investigated between May 1996 and April 1997 in Mida Creek, a mangrove area along the north coast region of Kenya. The nutrient levels of pore water from boreholes/wells within the surrounding area of the creek were also investigated for comparison. In addition, phytoplankton distribution in Mida Creek was assessed in three stations within the creek in order to determine the structure and succession stages of the phytoplankton community and to provide an indication of the status of primary productivity of the creek.

Measurements carried out within the creek revealed that the mean concentration ranges for NH_4^+–N, $(NO_2^- + NO_3^-)$–N, PO_4^{3-}–P and SiO_3^{2-}–Si were: 0.002–5.45; 0.12–5.63; 0.10–0.58 and 1.31–81.36 μM, respectively. For the case of boreholes/wells found in the surrounding area, their respective nutrient levels were found to lie in the ranges 0.4–907.0; 16.7–4897.0; 1.09–22.39 and 83.9–596.0 μM.

A total of 295 species of phytoplankton belonging to 78 genera were identified with great temporal variability in abundance in all the stations sampled. The most dominant algal members in the Creek included *Chaetoceros* spp., *Chroococcus limneticus* and *Oscillatoria* spp. The diversity values recorded were indicative of mesotrophic conditions.

The highest nutrient concentration levels within the creek were measured during the wet season as compared to dry season and this trend closely corresponded with that of the phytoplankton productivity. However, no significant variation ($p > 0.05$) was found in all cases with respect to the tidal cycles. On the contrary, diurnal nutrient concentrations especially in areas with high flooding duration (>12 h) were found to be highest during the dry season as opposed to wet season for all nutrients except for SiO_3^{2-}. The relatively high nutrient laden groundwater outflow into the creek water, coupled with surface runoff events during wet season, are the two main factors responsible for the elevated nutrients in the creek waters in the absence of river inflow into the creek.

Introduction

The distribution of dissolved inorganic nutrients in tropical coastal marine ecosystems can be influenced by a wide range of factors including tidal (hydrodynamic) processes (Bowman 1977; Ho 1977), physical stirring by currents and benthic invertebrates (Hammond et al. 1977; Vandebrorght et al. 1977; Hammond and Fuller 1979; McCaffery et al. 1980) as well as rainfall and river transport of nutrients from upland sources (Lugo and Snedaker 1974; Alongi et al. 1992). The tidal water movement characterised by ebb and flood flows, serves as a vehicle for fluxes of nutrients between the different coastal ecosystems (Wolanski et al. 1980). The incoming flood tide is considered to be a source of dissolved nutrients to the mangroves, seagrass beds and the coral reef ecosystems while the outgoing ebb tide water could leach nutrients from the mangrove swamp soils and act as a net exporter of dissolved nutrients from one locality to the adjacent ecosystems (Boto 1982; Mwashote 1997; Ohowa et al. 1997).

Mida Creek forms part of the Watamu Marine National Reserve (WMNR). WMNR in general supports a rich and diverse community of both flora and fauna which gained international recognition in 1976 when UNESCO awarded the reserve a biosphere reserve status. At present, a part of this area has been upgraded into a marine park while a part of it remains as a marine reserve. Human impacts on natural resources are more pronounced within the agricultural, forestry and fisheries sector. Unchecked exploitation of any resource may lead to overexploitation. In order to ensure that these resources are exploited in a sustainable manner, it is important to study and monitor the resource being exploited as well as gathering relevant environmental scientific information concerning this important creek. Specifically, the richness of the creek in its fishery and other biodiversity makes the creek an important fishing and eco-tourism area. As part of an effort to collect scientific information on this area, this particular study was initiated to examine nutrient distribution in relation to the phytoplankton productivity and the general biodiversity as well as the pollution status of Mida Creek.

For the general aim of the project to be realised, studies were conducted specifically to: (1) assess the standing stock of dissolved inorganic N ($=NO_2^- + NO_3^- + NH_4^+$), P ($=PO_4^{3-}$) and Si ($=SiO_3^{2-}$) in the water column and sediment of Mida Creek, from the creek mouth (Station 6) to the shores of Kirepwe island within the creek (Station 1), during the period, May 1996 to April 1997; (2) assess spatial and temporal variation of N, P and Si in the Mida Creek, within the time framework and the area of study; and (3) assess the spatial and temporal variation of plankton productivity and diversity in the Mida Creek.

Material and methods

Study area

Mida Creek (03° 22′ 729″ S and 039° 58′ 200″ E) is located in the north coast region of Kenya, 100 Km Northeast of the city of Mombasa (Figure 1). The total area including that covered by the mangroves is 32 km^2. There is no river drainage and the mangrove ecosystem is totally sustained by groundwater outflow. The main channel is 11 km long. This main channel is relatively narrow at the entrance, being less than 500 m wide, but it widens to about 1500 and 2600 m in the central and northern region, respectively. The lower parts of the creek are relatively shallow with a maximum depth of about 7.0 m, but this increases to a depth of 11.0 m in the central lower region and to about 4 m in the shallow wide basin to the north (Figure 1). Partially submerged sills near the entrance limit to a certain extent inflow and outflow of the water in the creek. Apart from the mangrove situated in the north, there are seagrass beds and coral reef in the offshore water in the central and lower regions of the creek. The mangroves are flanked landward by Arabuko-Sokoke forest (41,000 ha), which is also believed to be sustained by groundwater (GOK 1989). The dominant water circulation forcing is the astronomical semi-diurnal tide with a tidal range of 3.2 m at the entrance and 2.0 m in the middle section of the creek next to Sudi Island (Figure 1). The climatic conditions are characterised by two dominant monsoon seasons: the Southeast monsoon (March–September) and the Northeast monsoon (September–March). The total annual rainfall is 1041 mm with over 60% of the rain falling in April, May and June during the Southeast monsoon, and less than 40% falling in November and December during the Northeast monsoon. The highest monthly rainfall is recorded in May during Southeast monsoon (GOK 1989). The creek is located in an area with the lowest wind speeds in Kenya. Wind speed ranges between 0.05 and 0.13 m s^{-1} (GOK 1989). The annual evaporation rate is 1800 mm year^{-1} and air temperatures range between 24.0 °C in July to 33.0 °C in February. The creek is an important marine protected area as it forms part of Watamu Marine National Park and Reserve (GOK 1989).

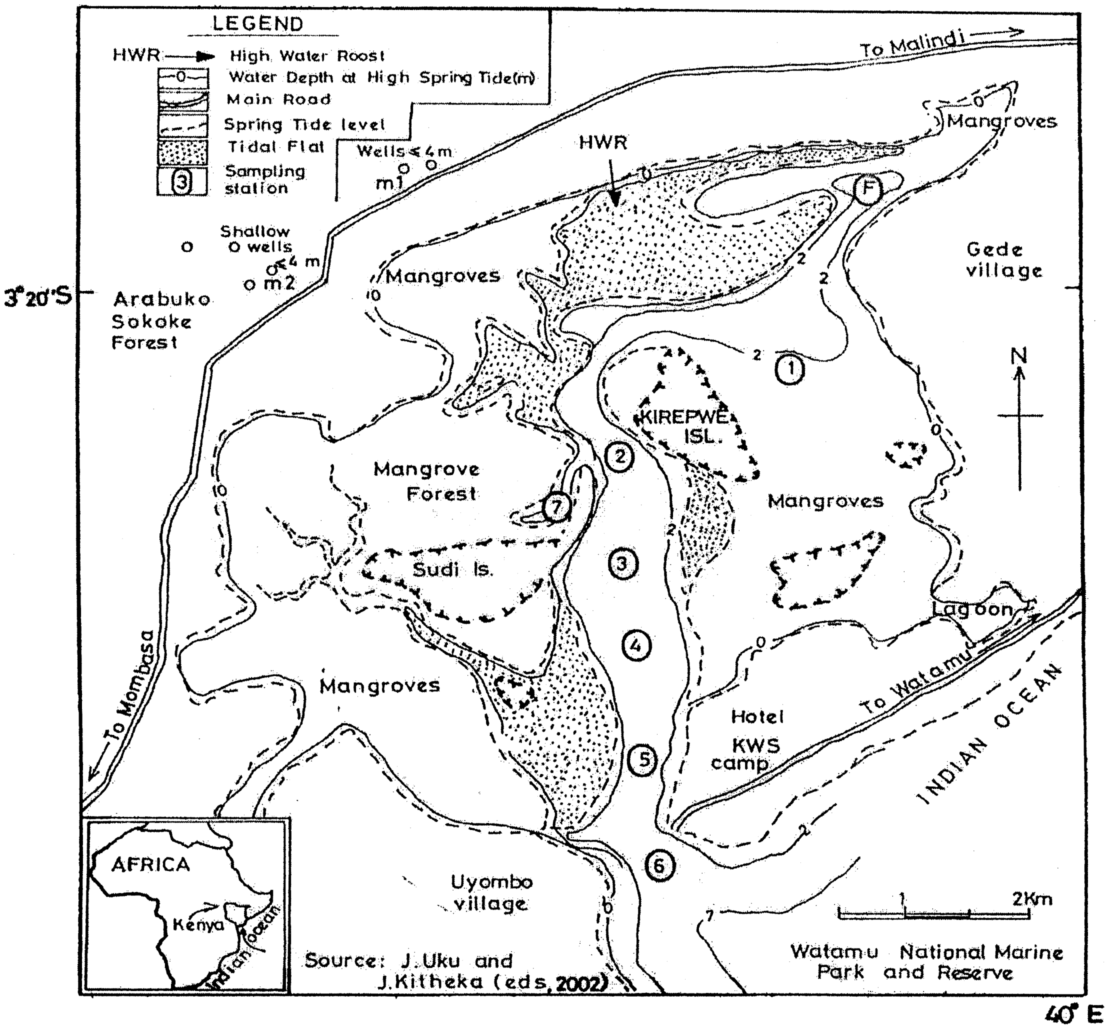

Figure 1. The location of Mida Creek in Kenya and the general bathymetry. Sampling stations are also shown.

Sampling

Sampling was done on an average frequency of once every month at low and high tides during the period of May 1996 to April 1997, which covered both dry and wet seasons.

Water and sediment samples were collected from specific stations which were seven in number (1, 2, 3, 4, 5, 6 and 7) and found within the study area (Figure 1). Water samples in the creek waters were taken using a water sampler (Nansen bottle), at mid-depth since the general depth of most sampled stations were $\leq$10 m. Monthly replicate samples within each station in Mida Creek were such that $n \geq 12$, where n is the sample size. In addition, some water samples were also collected using the water sampler from a few boreholes/ wells found in the vicinity of Mida Creek at the same sampling interval (monthly basis), in order to assess their nutrient levels in relation to the creek waters (the monthly replicates for every sampled borehole/well were such that $n \geq 4$). During the same period, replicate sediment cores ($n \geq 3$) of 5 cm in diameter were collected randomly at selected sampling stations within the creek using a plexiglass coring tube of internal diameter 3.6 and 30 cm long. Sediment samples were collected at the field using the plexiglass corers by diving where necessary, and pushing the corers to the required depth and pulling out gently. They were immediately secured at both ends of the corer using aluminium foils and kept in the icebox before transportation to the laboratory for analyses.

For the determination of diurnal variations, measurements on water quality variables were carried out at station 2 in the months of October, November, December and January (for each of the monthly time series variable, $n \geq 6$). All diurnal measurements were carried out at mid-depth (<5 m) at the middle of the creek.

Water samples, which were kept in 0.5 and 1 l polythene bottles, were transported in a cool-box containing ice and processed in the laboratory immediately. Those requiring storage were kept in a deep freezer at <−15 °C prior to analysis but in any case, all sample analysis was accomplished at most within three days of sampling.

Phytoplankton population estimates were done on surface water samples on a monthly basis from three stations in Mida Creek, extending from the creek mouth to the head. Station 6 was situated at the creek mouth while stations 3 and 1 were situated off Sudi Island and in the region of the sandbanks respectively.

Measured volumes of water were collected using a Niskin vertical sampler and passed through a plankton net (20 μm mesh). The samples were preserved in 5% buffered formalin for further analysis in the laboratory.

Sediment processing

Sub-samples of 2 cm thickness were taken at different depths up to 12 cm; by aid of a rubber piston and stainless steel blade, both of which were previously thoroughly cleaned and rinsed using distilled deionised water. The water from each sub-sample was isolated by centrifuging at 3000 RPM for 10 min. Samples were diluted 10–20 times or to any other appropriate dilution using 1 M KCl solution immediately before analysis. The dilution was necessary because the nutrient concentrations found in interstitial waters was relatively higher than the calibration range suitable for the water column nutrient levels.

Dissolved nutrients and oxygen determinations

The concentration of dissolved inorganic nutrients viz. ammonium (NH_4^+–N), nitrate + nitrite {(NO_3^- + NO_2^-)–N}, orthophosphate (PO_4^{3-}–P), silicate (SiO_3^{2-}–Si), dissolved oxygen (DO) and other associated measurements were determined according to methods described by APHA (1995), Parsons et al. (1984), and UNEP (1988).

Ammonium (NH_4^+–N)

NH_4^+–N was determined by the modified procedure of Parsons et al. (1984), where ca. 1.43 ml of reagent 1 (phenol + sodium nitroprusside) and ca. 1.43 ml of reagent 2 (trisodium citrate + sodium hydroxide + sodium hypochlorite) were added to 50 ml of sample in 100 ml glass bottle and shaken vigorously after each addition. The mixture was left to react for at least 6 h (usually overnight) at ambient temperature. The absorbance was then measured spectrophotometrically at a wavelength of 630 nm. Calibration standards were prepared using analytical-grade ammonium sulphate. The limit of detection is 0.005 μM N and precision is at 0.25 μM N.

Nitrate-nitrite {(NO_3^- + NO_2^-)–N}

(NO_3^- + NO_2^-)–N was analysed by quantitatively reducing it to nitrite by running the sample through a reduction column containing copper-coated cadmium filings. The nitrite was diazotized with sulphanilamide and coupled with *N*-(1-naphthyl)-ethylene diamine. The resulting coloured complex was measured spectrophotometrically at a wavelength of 543 nm. Alternatively, measurements were made using Technicon Autoanalyzer II system. Calibration standards were prepared using analytical-grade potassium nitrate. The limit of detection is 0.05 μM N and precision is at 5 μM N.

Orthophosphate (PO_4^{3-}–P)

PO_4^{3-}–P was measured by reacting the water sample with a composite reagent consisting of molybdic acid, ascorbic acid and trivalent antimony. The absorbance of the resulting reduced blue-coloured complex was measured spectrophotometrically at a wavelength of 885 nm. Calibration standards were

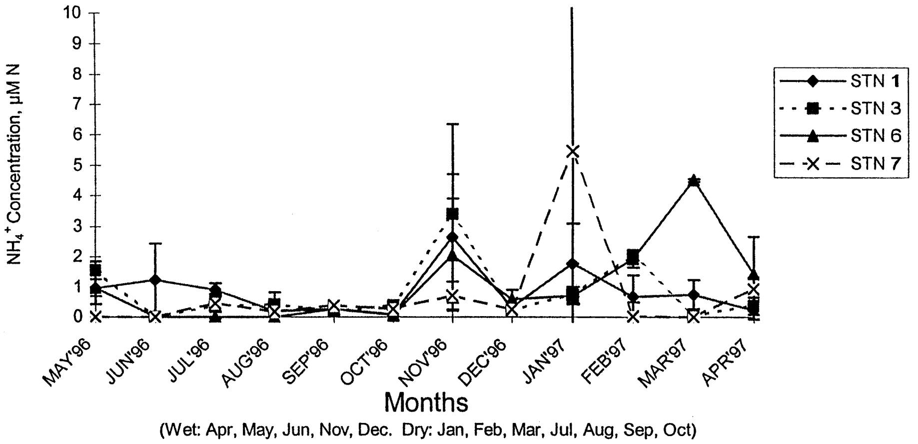

Figure 2. Mean monthly water column ammonium concentration in Mida Creek.

prepared using analytical grade potassium dihydrogen phosphate. The limit of detection is 0.03 μM P and precision is at 3 μM P.

Silicate (SiO_3^{2-}–Si)

The method used measures reactive silicate. The seawater is allowed to react with molybdate ions in solution. Presence of free silicate, phosphate or arsenate ions results in the formation of silicomolybdate, phosphomolybdate and arsenomolybdate complexes, respectively. When a solution containing metol and oxalic acid is added, the silicomolybdate complex is selectively reduced to give a blue colour leaving phosphomolybdate and arsenomolybdate intact. The resulting colour intensity is measured spectrophotometrically at 810 nm using 1 cm cells. Calibration standards were prepared using analytical grade sodium fluorosilicate. The limit of detection is 0.1 μM Si and precision is at 10 μM Si.

Dissolved oxygen (DO)

DO was measured at ambient conditions using the classical Winkler titrimetric procedure as described by Parsons et al. (1984) and modified by APHA (1995). Titration was done in the field.

Phytoplankton analysis

The phytoplankton population density was estimated based on concentrating the sample and taking 1ml aliquots of the concentrate in a Sedgwick rafter cell and counting under an inverted microscope. Species composition and identification were carried out according to taxonomic techniques described in Hasle (1978), Fukuyo et al. (1990), Oshima (1995), and Scholin and Anderson (1996).

Data analysis

Data obtained was subjected to analysis of variance (ANOVA) to determine the spatial and temporal variations in dissolved inorganic nutrients with respect to sampling stations and seasons. All statistical analyses were based on the significant level at $p = 0.05$ and critical values of F at $\alpha = 0.05$ (Yule and Kendall 1993).

Results

The mean monthly water column nutrient concentrations measured in the Mida Creek are depicted in Figures 2 and 3.

Most nutrient concentrations measured in Mida Creek were higher during the wet season as compared to the dry season. However, ANOVA on the nutrients data revealed no significant difference ($p > 0.05$) with respect to the tidal cycle but there was significant variation with respect to sampling stations ($p < 0.05$). The observed increase in nutrient concentration in the water column during the wet season is more evident for SiO_3^{2-} (Figure 3) than is the case for other nutrients. Indeed there

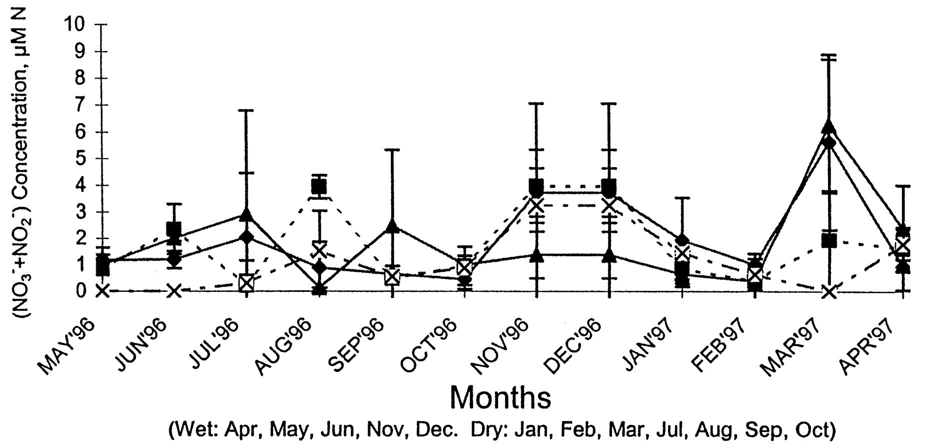

Figure 3. Mean monthly water column nitrate + nitrite concentration in Mida Creek.

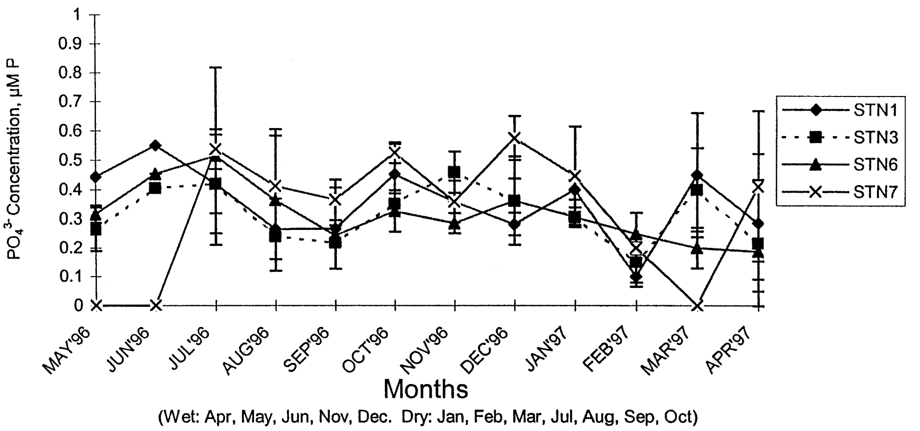

Figure 4. Mean monthly water column phosphate concentration in Mida Creek.

even seems to be a reversed trend for some of the nutrients such as NH_4^+ (Figure 2). Although salinity is expected to influence SiO_3^{2-} levels, there was no evidence of significant salinity variability during the dry and wet seasons (Figure 7) due to absence of river drainage into the creek.

The diurnal variation in water quality variables at station 2 as they vary with tide and current is given in Figures 4–6 during both the dry and wet seasons, while the abundance of phytoplankton is shown in Figure 7. Salinity, temperature, rainfall and other environmental variables are shown in Figures 8 and 9. Typical interstitial-water nutrient levels for Mida Creek sediments are given in Table 1 and the nutrient levels of the boreholes/wells in vicinity of the creek are in Table 2. The mean diurnal nutrient variations depict highest nutrient concentration levels in N, P and DO during the dry season (Figures 4 and 5) whereas highest values in Si were in the wet season (Figure 5). Due to the general shallowness of Mida Creek (mean depth $\leq$ 5 m), the water within the creek was generally well mixed and no stratification was expected.

During the study period a total of 295 species of phytoplankton belonging to 78 genera were identified (the whole list is available on request). The total number of cells in the creek mouth (station 6) ranged from a minimum value of 1614 cells l^{-1} in December to 68,515 cells l^{-1} in May with a mean value of 15,548 cells l^{-1}. In station 2, abundance values ranged from 1136 cells l^{-1} in December to 27,000 cells l^{-1} in January. The mean value recorded during the study period in this station was 9502 cells l^{-1}. In the region of the sandbanks

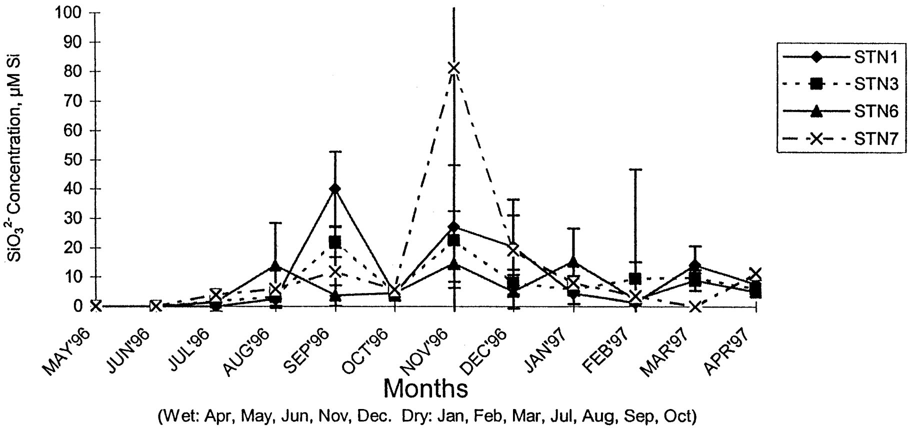

Figure 5. Mean monthly water column silicate concentration in Mida Creek.

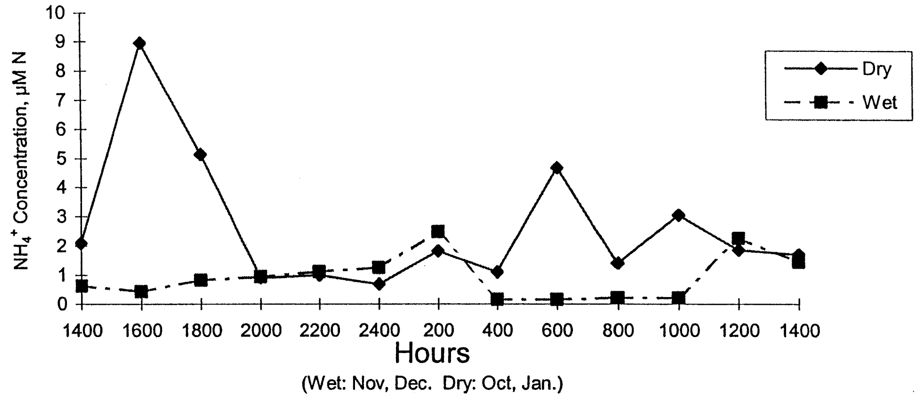

Figure 6. Mean diurnal water column ammonium variation in Mida Creek (Station 2).

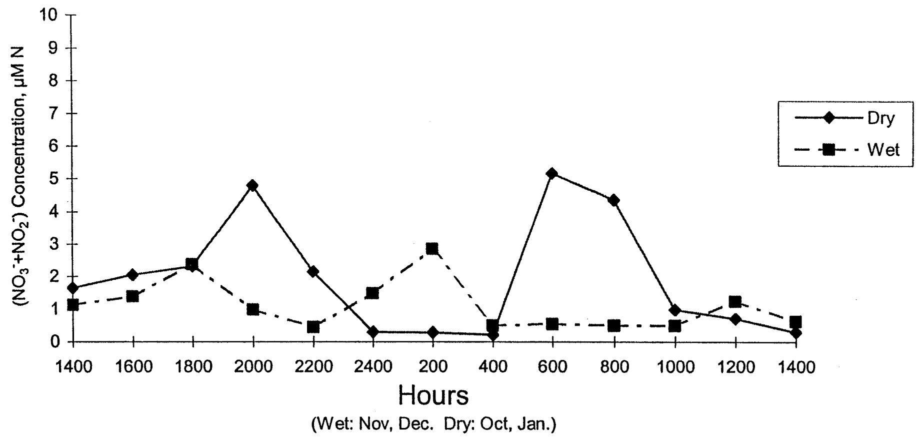

Figure 7. Mean diurnal water column nitrate + nitrite variation in Mida Creek (Station 2).

(station 1) abundance values ranged from 909 cells l^{-1} in November to 65,260 cells l^{-1} in January with a mean value of 13,662 cells l^{-1}. A great variability was observed in the monthly abundance values of the populations in all the three stations which in all cases registered a coefficient of variation (CV) exceeding 100% except in the case of the station 2 where it was 76%.

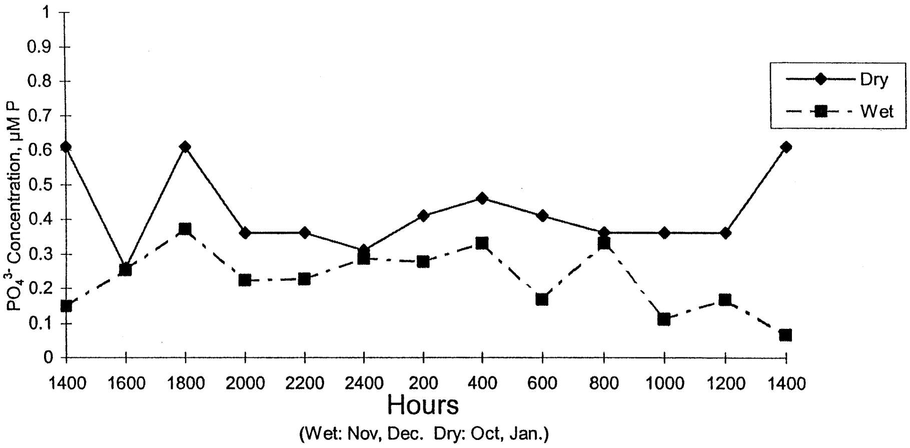

Figure 8. Mean diurnal water column phosphate variation in Mida Creek (Station 2).

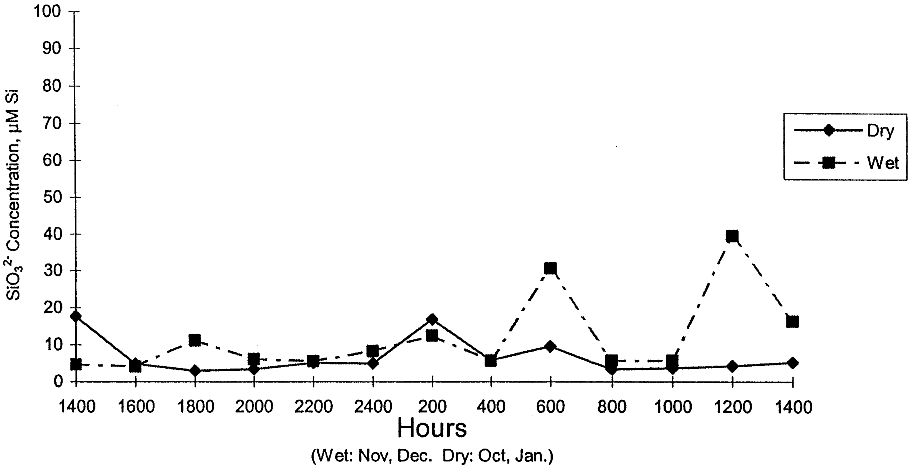

Figure 9. Mean diurnal water column silicate variation in Mida Creek (Station 2).

With regards to spatial distribution, station 6 was dominated by *Chaetoceros* spp., *Bacteriastrum* spp. and *Oscillatoria* spp. While station 3 was dominated by *Chaetoceros* spp. and *Oscillatoria* spp., it was noted that *Rhizoselenia imbricata* also occurred abundantly in this particular station. On the other hand, *Melosira islandica*, *Chaetoceros* spp. and *Oscillatoria* spp. were more prevalent in station 1 compared to the other two stations. In sharp contrast to the other stations, there was a marked presence of dinoflagellates namely *Prorocentrum lima* and *Protoperidinium* spp. in station 1, which although also recorded in the other stations, were in significantly minimal in their occurrence. *Rhizoselenia imbricata* was however noticeably absent in station 1 but occurred in negligible numbers at station 6 (see Figures 10–15).

With respect to temporal distribution during the wet season, *Chaetoceros* spp., *Bacteriastrum* spp. and *Oscillatoria limosa* were the dominant species at station 6. *Chaetoceros* spp. and *Bacillaria paradoxa* were however the dominant species during the dry season in this particular station. It was also interesting to note that during the dry spell, *B. paradoxa* occurred in relatively large proportions in this station as compared to the wet season. There was however a great reduction in abundance of *Bacteriastrum* spp. during the dry season.

At station 3, *O. limosa* and *Chaetoceros* spp. were more abundant during the wet season, while *Chaetoceros* spp. and *R. imbricata* spp. were more prevalent during the dry season. While the occurrence of *O. limosa* was relatively low during dry spell, the converse was true for the case of *R. imbricata* whose presence was barely minimal during the wet season.

At station 1 during the wet period, *M. islandica*, *O. limosa Chaetoceros* spp. and *Protoperidinium* spp. were more common. The most abundant species during the dry period however were *P. lima*, *Protoperidinium* spp., *Chaetoceros* spp. and *Coscinodiscus concinnus*.

Some species like *R. imbricata* were observed to show signs of limited spatial and temporal endemism. However the period of study was too short for any conclusive remarks to be made.

In general, it was observed that, spatially the species richness decreased in the order: station 6 > station 3 > station 1 while temporally, the order was: station 1 > station 6 > station 3 during the wet season and station 3 > station 6 station 1 during the dry season.

Table 1. Mean interstitial-water nutrient concentrations for Mida Creek sediments (at each depth, $n \geq 3$).

Station	Depth (cm)	$NO_2^- + NO_3^-$ (μM N)	PO_4^{3-} (μM P)
1	0–2	136.7 ± 6.0	71.3 ± 7.3
	2–4	359.3 ± 21.9	47.3 ± 11.8
	4–6	70.9 ± 10.1	45.2 ± 21.6
	6–8	48.5 ± 13.9	59.9 ± 11.5
	8–10	55.3 ± 12.0	61.0 ± 2.6
	10–12	116.9 ± 7.2	81.1 ± 17.9
3	0–2	158.0 ± 25.2	164.7 ± 46.7
	2–4	109.0 ± 11.9	107.4 ± 30.1
	4–6	59.3 ± 5.8	107.4 ± 31.1
	6–8	149.8 ± 42.4	97.8 ± 19.0
	8–10	61.1 ± 2.0	78.7 ± 8.8
	10–12	70.1 ± 13.0	88.3 ± 4.8
6	0–2	152.3 ± 87.2	107.3 ± 28.7
	2–4	29.2 ± 9.0	14.1 ± 16.6
	4–6	616.6 ± 179.5	65.8 ± 20.6
	2–8	29.2 ± 12.0	40.5 ± 33.5
	8–10	21.3 ± 4.0	14.6 ± 12.9
	10–12	97.0 ± 21.9	42.0 ± 13.9
7	0–2	19.3 ± 13.9	50.1 ± 10.6
	2–4	61.1 ± 15.9	20.9 ± 13.2
	4–6	57.1 ± 17.9	21.3 ± 22.2
	2–8	21.3 ± 19.9	18.0 ± 11.3
	8–10	21.3 ± 13.0	34.3 ± 9.9
	10–12	17.3 ± 6.0	15.6 ± 13.2

Discussion

The water column nutrient levels measured in the Mida Creek are generally higher (Figures 2 and 3) than the usually low levels found in tropical mangrove waters, which typically lie within the μM range. Variations in dissolved inorganic nutrients in marine waters can be ascribed to a number of factors including the extent of freshwater and groundwater input, degree of insolation, oxygen availability, standing stocks and productivity of phytoplankton and bacterioplankton (Boto and Wellington 1988).

The elevated nutrient levels experienced in Mida Creek are likely to be attributed to seepage into the creek of nutrient rich groundwater and runoff during the rainy season, since there is absence of river flow into the creek. For all the nutrients studied, the highest values were observed during the rainy season as compared to the dry season, with dissolved N species depicting much higher concentrations than the orthophosphates.

The observed high water column Si levels during the wet season could be related to the fact that there is

Table 2. Mean nutrient concentration levels for boreholes/wells found around Mida Creek during dry and wet seasons (for each case, $n \geq 10$).

	NH_4^+ (μM N)		$NO_2^- + NO_3^-$ (μM N)		PO_4^{3-}(μM P)		SiO_3^{2-} (μM Si)	
Borehole/well	Dry	Wet	Dry	Wet	Dry	Wet	Dry	Wet
M1	4.7 ± 1.8	1.8 ± 1.6	506 ± 351	1209 ± 717	1.9 ± 0.9	4.6 ± 0.9	154 ± 117	344 ± 71
M2	11.3 ± 6.8	20.3 ± 20.1	1743 ± 71	77 ± 215	4.9 ± 2.5	5.2 ± 4.6	145 ± 47	597 ± 232
W1	0.7 ± 0.3	7.1 ± 2.7	1729 ± 266	2921 ± 330	1.6 ± 0.9	1.4 ± 0.8	86 ± 44	228 ± 77
W4	907.0 ± 881.0	0.4 ± 0.7	3348 ± 544	4897 ± 775	22.4 ± 6.0	11.6 ± 6.7	162 ± 31	343 ± 39
W6	221.6 ± 28.9	0.4 ± 0.1	22603 ± 366	4126 ± 389	14.0 ± 3.7	17.7 ± 1.6	145 ± 49	298 ± 30

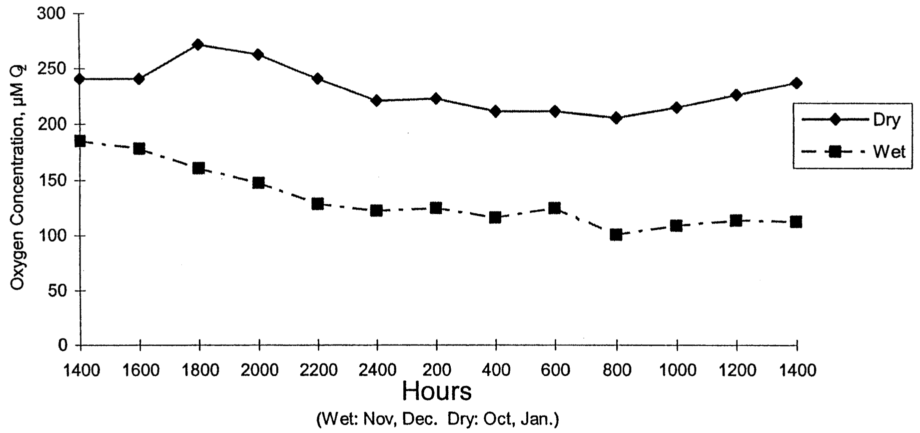

Figure 10. Mean diurnal water column dissolved oxygen variation in Mida Creek (Station 2).

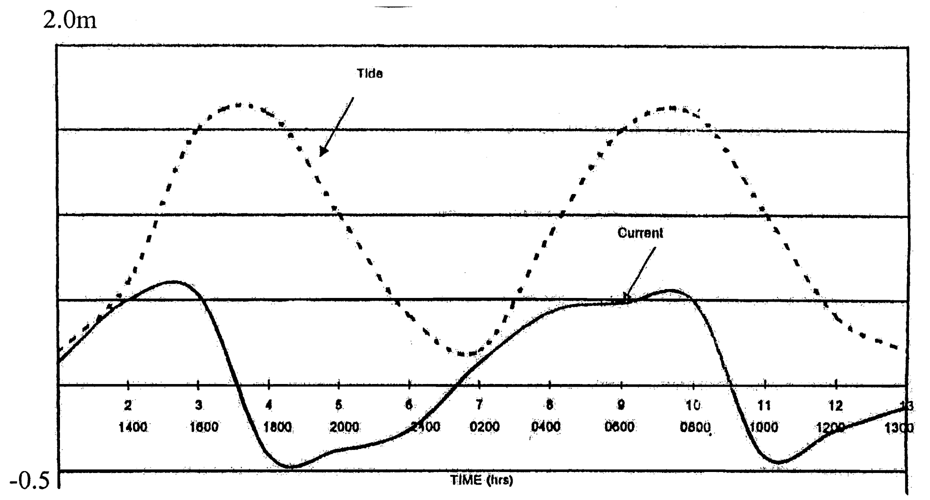

Figure 11. The time-series of tides and currents at station 2 (Mida Creek) in 28–29 October 1996 and 28–29 January 1997 (source: Kitheka et al. 1999).

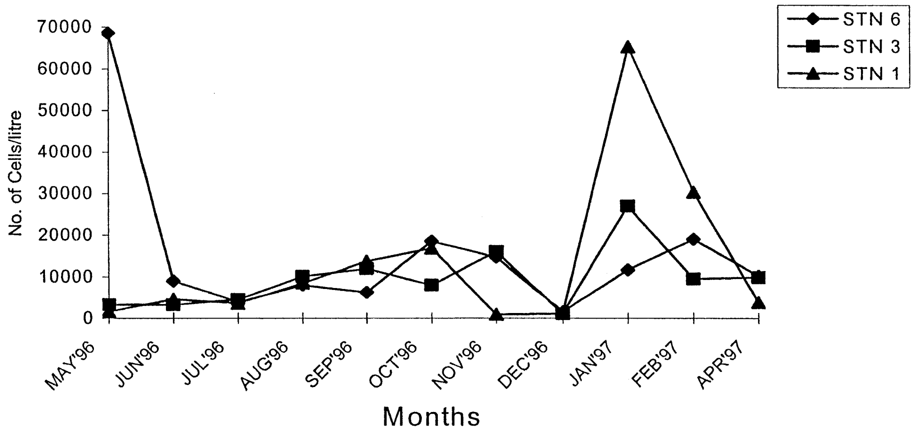

Figure 12. Monthly variation in cell abundance values in the three stations (1, 3 and 6).

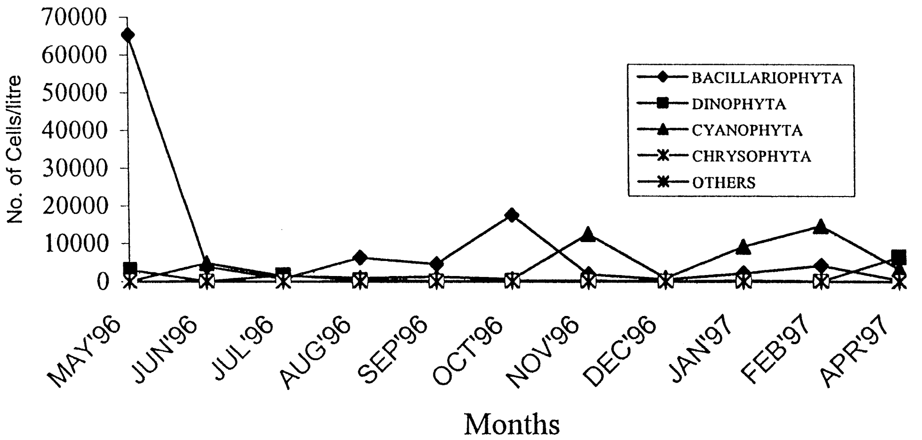

Figure 13. Monthly variation in algal numbers of various taxonomic groups in station 6.

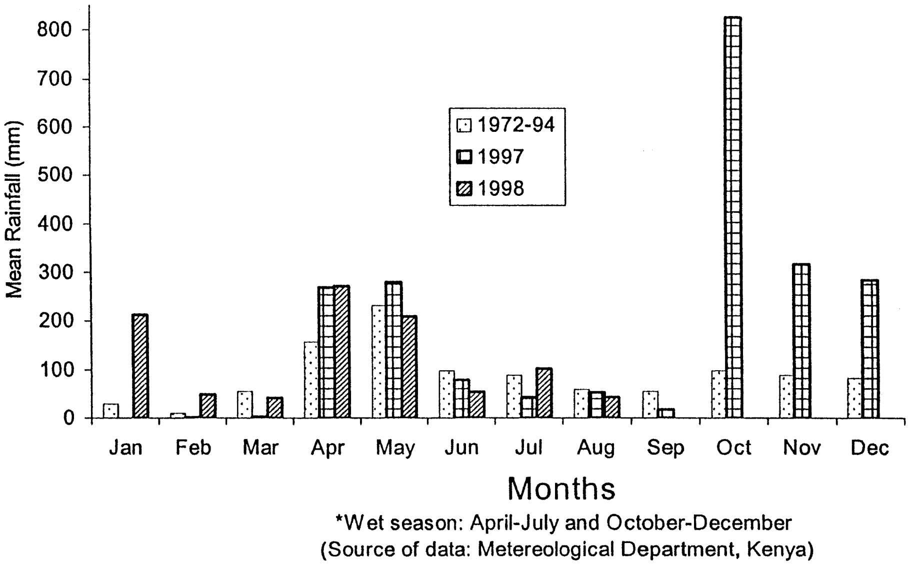

Figure 14. Mean annual rainfall at the study area (Kilifi/Mombasa District) for the period 1972–1998.

greater abundance of this nutrient arising from diffuse land-based sources, which are being washed into the creek through increased surface runoff during the wet season. However, it is to be observed that the variations in interstitial water nutrients (Table 1) do not seem to necessarily directly correspond with some of the water column nutrient distribution. One of the main reasons for this could be related to the difference in benthic communities found at the different stations. For instance it is likely that the benthic conditions found at station 7 are more reducing relative to the other stations as a result of higher water residence time, hence the disparity observed in their relative levels especially for nitrates and phosphates.

The variable nature of vertical distribution for pore water NO_2^- + NO_3^- concentrations observed in stations 1, 3 and 6 compared to station 7 could be attributed to the difference in the nature of the sediments in these stations. Studies conducted in tropical mangrove environment elsewhere have reported similar irregular patterns (Hines and Lyons 1982; Kristensen et al. 1988). Concentrations of NH_4^+ and NO_2^- + NO_3^- are known to be significantly lower in sediments in which mangrove roots are found, the reduction probably reflecting the uptake by the plants. This is likely to hold for Mida Creek because its fringing vegetation is predominantly mangrove. Other influencing factors include the

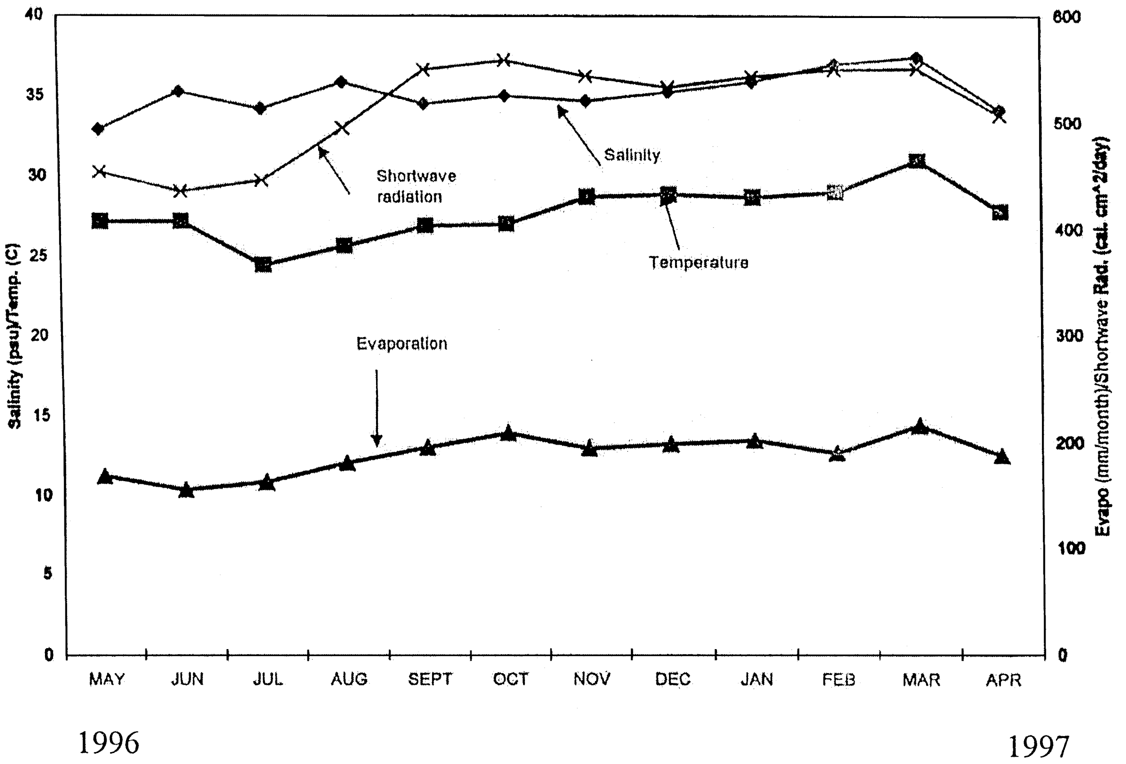

Figure 15. The combined stations mean seasonal variations of creek's water salinity and temperature between May 1996 and April 1997. Evaporation and solar radiation data are based on long-term averages for the region. Data represents the mean conditions in both fronrwater and backwater zones (source: Kitheka et al. 1999).

degree of tidal wetting, microbial decomposition, seasonal changes, rainfall and adsorption on sediment solids (Boto 1984; Boto et al. 1985; Mackin and Aller 1984).

The sediment PO_4^{3-} distribution generally decreased with depth at stations 3, 6 and 7 as compared to station 1 where there seemed to be a reversed trend with respect to the former stations. The trend observed may again be indicative of differences in sediment type. It is known that through chemical and physical interactions, the readily available phosphate ions in solution are prone to be strongly adsorbed to clay particles, particularly to clay containing iron or manganese oxyhydroxides (Boto and Wellington 1984). Phosphate immobilization by precipitation or adsorption on clays results in significant net removal of P to the larger mineral pool, limiting the available pool. Clays such as kaolinite abundant in tropical soils and sediments (Kennett 1982) are particularly efficient in phosphate adsorption.

On the contrary, the conspicuously lower mean diurnal dissolved oxygen levels and the relatively low concentrations of some water column nutrients (notably NH_4^+ and PO_4^{3-}) during the wet season compared to dry season, are most likely attributable to a combination of factors arising from the effect of dilution, refractory terrigenous debris and turbidity associated with major runoff events (Berner 1978; Aller et al. 1985; Torgersen and Chivas 1985) which also to a large extent, lead to a higher oxygen demand. The latter effect which is mainly associated with situations of increased turbidity than the other mentioned factors, is enhanced by the fact that reduced light penetrability directly affects phytoplankton photosynthesis, a process that leads to the generation of oxygen within the water column. Elsewhere within the region, for instance, in Gazi Bay and Tudor Creek (Kazungu et al. 1989; Mwashote 1997; Ohowa et al. 1997) where riverine contribution is significant, elevated concentration in dissolved inorganic N and Si have consistently been observed during the wet seasons, especially in areas within the estuarine vicinity. Similar observations have also been recorded in other regions (Duinker 1989; Wright 1989).

It is worth noting that the mean levels for PO_4^{3-} (Figure 3) were generally higher in station 7 in comparison to the rest of the sampled stations. Incidentally, the highest mean values for the other nutrients were also recorded in this station (Figures 2 and 3). This observation is related to the fact that station 7 is rather unique in a sense that it is found within a mangrove environment where the residence time of the waters in this station is relatively longer (>12 h) compared to that of the rest of the sampled stations in Mida Creek (Kitheka et al. 1999). The nature of the resulting environment in station 7 forms a favourable habitat for the thriving of a wide range of biota diversity including plankton and fisheries.

DO variations in Mida Creek, which were determined in the months of October–January ranged from 6.6 to 8.7 mg $O_2\ l^{-1}$ during dry season and 3.2 to 5.9 mg $O_2\ l^{-1}$ during the wet season. The mean lower DO values observed during the wet season are most probably an indication of the higher oxygen demand experienced during this season, arising mainly from increased organic matter inflow during runoff events.

There was great variability in the monthly population abundance in all the stations. It was evident that the observed phytoplankton productivity closely corresponded to nutrient levels. For instance increased abundance of phytoplankton coincided with the elevated nutrient presence in the water column in the creek, with inner stations depicting higher abundance of particular species almost in exclusion of others. Such species belonged mainly to members of the blue green algae of the genus: *Oscillatoria* spp. and the diatom *Chaetoceros* spp.

At the Creek mouth (station 6), the predominating diatoms were of the order Centrales. The members of Cyanophyta, which were dominant, are of the genus *Oscillatoria* which are capable of nitrogen fixation and whose population growth has been shown to be stimulated by organic substances (Fogg et al. 1973). The population found at station 3 differed qualitatively from that at station 3 though quantitatively, Bacillariophyta was able to favourably exploit the environment. In September (within the dry season), Centric diatom, *Rhizoselenia hebetata*, was the dominant member. It appeared just before the onset of North East Monsoon when the conditions were calmer. *Chaetoceros* spp. and *Rhizoselenia* spp. do not normally constitute typical benthic flora and *Tabellaria fenestrata* is widely distributed in fairly nutrient-rich freshwaters (Van den Hoek et al. 1995), and their peaks at station 1 in the month of September could have some ecological implications. In this station, during the month of January (dry season), *Chaetoceros* spp. had again become the most abundant. It would seem that among the Bacillariophyta members of the genus *Chaetoceros* spp. and *Bacteriastrum* spp. were best represented in most of the Mida Creek, while among the Cyanophyta, the genus *Chrococcus* spp. and *Oscillatoria* spp. had the most representation with Chrococcales dominating at station 3 and *Oscillatoria* spp. well represented throughout the Creek. The tendency by these algae to form large proportions of the algal populations in the water column could have far reaching implications towards sustaining the biodiversity at higher trophic levels due to predator preference of certain food types.

In general however, the nutrient and plankton variation trends for the waters of Mida Creek are similar to those obtained in other relatively pristine marine environments in the region (Mwashote 1997; Ohowa et al. 1997) and also within those of unpolluted areas elsewhere (Meybeck 1982). The nutrient levels in wells and boreholes found in the area around Mida Creek (Table 2) reveal that although the mean salinity was found to be almost zero (mean values < 2 PSU), their nutrient concentration levels are relatively higher than the creek waters. It is in fact evident that some of the nutrient levels are well above the WHO maximum allowable levels (WHO 1996) in drinking water. This should prompt concern on the suitability of the use of such water for consumption.

The elevated levels of some of the nutrients in the boreholes/wells is most likely attributed to contamination arising from pit latrines or refuse disposal pits which are rampant within the area where these water sources are located. The general location of these boreholes/wells is partially indicated in Figure 1. Those located in the inner stations 1–3 are labelled M1–M2 (shown in Figure 1) while the outer stations 3–6 are nearer to those labelled W1–W6 (not shown in Figure 1). It is interesting to note the significant differences in $NH_4{}^+$ concentrations between dry and wet seasons for W4 and W6 boreholes/wells. There is no obvious explanation for this observation (especially the very low NH_4^+ levels of 0.002 μM N, obtained by calibration extrapolation), but most probably this could have partially arisen from the infiltration of large volumes of rainfall water into these water sources during the wet season.

In view of the shallowness of the boreholes/wells around Mida Creek, it had been postulated that there may be appreciable contribution of nutrients through groundwater outflow into the creek waters may occur, as suggested by salinity measurements carried out within the creek (Kitheka et al. 1999). Indeed the relatively high levels of nutrients measured within Mida Creek waters compared to the open waters, points to sources within the creek. In the absence of rivers draining into the creek, groundwater outflow remains the most probable significant source of nutrients in the creek. Other supporting evidence to this fact is the luxuriant mangrove forest along the creek, believed to be partly sustained by groundwater outflow, so is the terrestrial Arabuko-Sokoke forest, one of the Eastern Africa's remaining terrestrial coastal forests (Kitheka et al. 1999). In addition, the occasional surface run off during the wet seasons also inevitably contribute to the nutrient budget in the creek.

Conclusions

The highest levels of nutrient concentrations within Mida Creek waters were generally experienced during the wet season in comparison to dry season and the general phytoplankton variation trend corresponded to that of nutrients.

Diurnal nutrient concentration in areas with high residence times were found to be highest during dry season rather than wet seasons for all nutrients except SiO_3^{2-}.

The high nutrient concentration levels in borehole/well water is mainly associated with sources arising from various anthropogenic activities within the area of study as well as underground seepage through pit latrines or refuse disposal pits which are rampant within the area where they are located.

The sources contributing significantly to the nutrient distribution in Mida Creek include nutrient laden groundwater outflow into the creek and occasional surface runoff events during the wet seasons.

Although nutrient concentration levels for the waters of Mida Creek are comparable to those found in relatively pristine marine environments within the region and elsewhere, the presence of high nutrients in the surrounding boreholes/water-wells raise concern especially with regard to human use of such water and its seepage into the creek system, a likely cause of high nutrient levels in the inner area of the creek waters.

A total of 295 species of phytoplankton belonging to 78 genera were identified with great temporal variability in abundance in all the stations sampled.

Although Mida Creek is not to be classified as polluted, there is a tendency for certain phytoplankton species to occur in very large proportions almost to the exclusion of others, the most notable of these being members of the blue green algae of the genus *Oscillatoria* spp. and the diatom *Chaetoceros* spp. Bacillariophyta members of the genus *Chaetoceros* spp. and *Bacteriastrum* spp. were the most represented in most of the Mida Creek.

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