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Water circulation, groundwater outflow and nutrient dynamics in Mida creek, Kenya

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Abstract

The relationship between physical hydrodynamic processes and nutrients dynamics was investigated in Mida creek, a groundwater influenced mangrove-fringed creek in Kenya between March 1996 and May 1997. The research involved spot and time-series measurement of nitrate–nitrite, ammonia, silicates, phosphates, salinity, temperature, sea-level as well as tidal currents at seven stations located in the front, middle and backwater zones of the creek. Groundwater level as well as total dissolved solids' concentration, salinity, temperature and nutrients' concentration were also measured once every month in shallow wells (water-table $<$ -5 m) located in the upper region of the creek. Results of the study show that nutrient concentrations vary with the tide and that, though there is no river drainage, they are of the same magnitude as in mangrove creeks with substantial river runoff. The peak concentrations of NH_4^+-N (5.45 μM), $NO_2^- - NO_3^-$ (5.63 μM), $PO_4^{3-}-P$ (0.58 μM) and $SiO_3^{2-}-Si$ (81.36 μM) in the creek occurred during flood tide, 2–3 h before high waters. The ($NO_2^- + NO_3^-$)–N concentrations declined rapidly during ebb tide, reaching the minimum levels during low water. Contribution of groundwater seepage to the net nutrients flux (particularly on nitrite–nitrates) is largest in dry seasons. The study shows that groundwater outflow sustains the mangroves during periods of severe salinity stress and nutrients deficiency in dry seasons. This is essentially by limiting salinity increase and by boosting nutrient supply in dry seasons.

Introduction

Hydrodynamic processes have long been known to influence the sustainability of ecological systems in coastal waters (Wolanski et al., 1980); however, little is known about how tidally driven circulation influence the patterns of nutrients and plankton variability in mangrove creek systems receiving a significant volume of groundwater. The previous research on river-influenced mangrove creeks' hydrodynamics have mainly focussed on circulation processes as relates to nutrients and plankton dynamics (Bowman, 1977; Boto, 1982; Wolanski et al., 1980, 1998; Alongi et al., 1992). Little research on the same processes has been conducted in mangrove creeks with substantial seepage of groundwater. Thus, the importance of groundwater outflow on water circulation and nutrients' balance remains largely unknown in tropical coastal waters. This is despite the enormous discharge of groundwater into the oceans (Glover, 1959, 1964).

Groundwater is the largest source of fresh water on the planet Earth excluding the polar ice caps and glaciers. The amount of groundwater within 800 m from the ground surface is 30 times the amount in all fresh water lakes and reservoirs, and about 3000 times the amount in stream channels, at any one time. At present nearly one fifth of all the water used in the world is obtained from groundwater resources (Raghunath, 1990). Thus groundwater is an important component of the hydrological cycle and there is need for better understanding of the processes governing the exchange of materials between the ocean and coastal groundwater aquifers. As compared to river supply of freshwater, groundwater seepage in coastal zones is either diffuse or localized and its effect show great spatial variability (Mazda et al., 1990; Vanek, 1991;

Kitheka, 1998). Where groundwater seepage occurs, substantial nutrient contribution could come from the regional groundwater basins extending far inland (Valiela et al., 1978). Since groundwater seepage also occurs at the channel bed (Vanek, 1991), it is expected that significant anomalies will arise on water column stability. Despite the likelihood of an enormous groundwater supply to the oceans, the significance of groundwater seepage on hydrodynamic processes and nutrient fluxes in a mangrove-fringed tidal creek system are largely unknown. In the recent years there has been an effort to address the problem, although most of the studies have not being focussed on the mangrove wetlands (Valiela et al., 1978; Pandit and El-Khazen, 1990; Vanek, 1991; Kjerfve, 1994; Ridd and Sam, 1996). Previous studies in Kenya on nutrient dynamics and circulation in mangrove wetland creek system include those of Kazungu et al. (1989), Kitheka et al. (1996), Mwashote (1997), Ohowa et al. (1997). In this study, we attempt to demonstrate the link between groundwater outflow, coastal water circulation and variations of nutrient concentrations in a unique mangrove-fringed creek along the Kenya coast. The creek is unique in the sense that it has no river drainage.

Study area

Mida creek (Figure 1) is located in north coast region of Kenya in East Africa (03°22′ S and 039°58′ E). The total area including that covered by mangroves is 32 km^2 with a spring high tide volume of $124 \times 10^6\,\text{m}^3$. As previously mentioned, there is no river drainage but groundwater enters the creek through seepage along the shores and within channel bed. In addition to groundwater outflow, there is also surface runoff inflow in rainy seasons. The creek basin is located in area covered with Pleistocene sand and coral limestone rocks. The reef complex in the offshore waters occur mainly as scattered pockets which are partially exposed during spring low tide. The mangroves occur in the central and upper regions of the creek and are flanked landward by Arabuko–Sokoke forest; an important lowland tropical forest famous for wildlife conservation and high biodiversity. The dominant species of mangrove vegetation include *Rhizophora mucronata*, *Ceriops tagal*, *Avicennia marina*, *Sonneratia alba*, and *Bruguiera gymnorrhiza.*

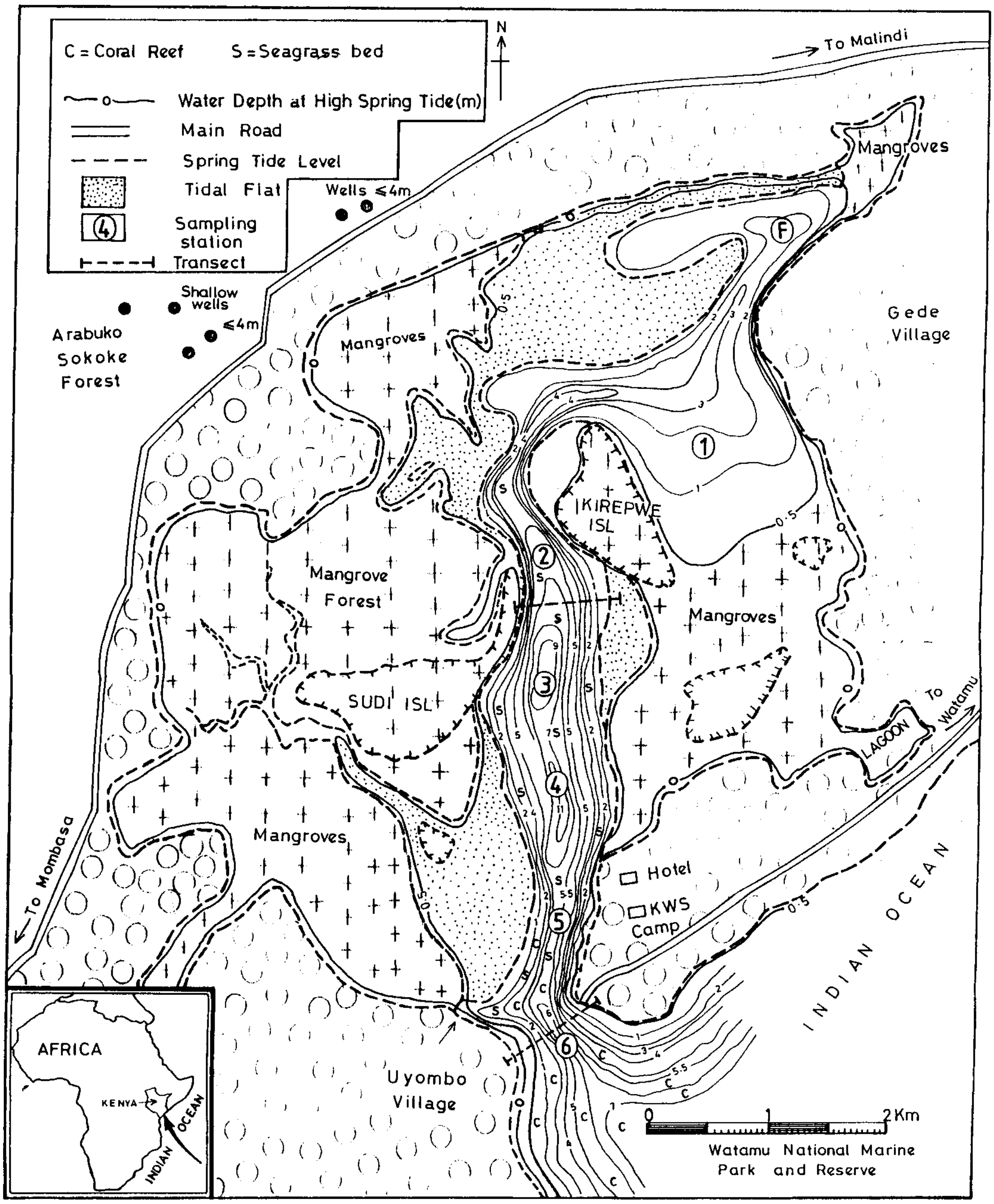
The creek experiences semi-diurnal tide with a range of 3.2 m at the entrance. The two dominant climatic seasons are the Southeast monsoon (March–September) and the Northeast monsoon (September–March). Annual rainfall is variable ranging from about 0.6 m to 1.0 m (GOK, 1989). The highest monthly rainfall is normally recorded in May. The evaporation rate is 2.0 m per year with a monthly range of 0.16–0.21 m per month. Air temperature range between 24.0 °C in July and 32.0 °C in February. The creek is also an important nature conservation site as it is part of the Watamu Marine National Park and Reserve under the management of the Kenya Wildlife Service (KWS).

Materials and methods

Tidal currents, water salinity, conductivity and temperature were measured at seven stations shown in Figure 1 (stations 1–6, F). Two transects were set across station 2 in the middle upper region and at station 6 at the entrance for determination of volume fluxes. Currents were measured from an anchored boat using partially-submerged floats and a Toho Dentan current meter, while salinity and temperature were measured using Aanderaa salinity-temperature meter model 3315. Conductivity was measured with a WTW conductivity meter. All variables were measured *in situ* at $0.2\,d$, $0.6\,d$ and $0.8\,d$ (d = water depth). Variation of tidal elevation was measured at station 2 using a tide pole installed at the lowest water point. Depths were determined using a Plastimo echo sounder and were corrected for tidal variations and used to plot the bathymetry of the creek as shown in Figure 1.

The measured mean tidal volume fluxes (based on current measurements) together with groundwater flux rates as well as the corresponding nutrients concentrations in wet and dry seasons were used to compute the ebb and flood fluxes of nutrients. Measurements of salinity, temperature and nutrients were conducted once a month at spring and neap tides in both flood and ebb periods of the tide. Twenty-four joint research cruises covering all seven stations were made from March 1996 to April 1997 period.

Calculations on rates of water exchange were carried out using the tidal prism, and modified salt-and-volume conservation methods of Gordon et al. (1996a, b). The tidal prism method involved the estimation of the rate of water exchange using the computed volumes and tidal ranges during low and high waters in neap and spring tides. The hydraulic residence times



Source: Kitheka J.U and Uku J.N (1997)

Figure 1. Map showing the location and bathmetry (in m) of Mida creek in Kenya. The sampling stations (1–6, F) are located within the main creek channel. Main station for time-series measurement of dissolved nutrients, sea level, currents, salinity and temperature is station 2.

R of water in the frontwater and backwater regions of the Creek were calculated using the relation

$$R = \frac{V}{Q_o}, \tag{1}$$

where V is the creek's water volume and Q_o is the ebb-flood tidal flux ($m^3\,s^{-1}$). The mean groundwater flux Q_f ($m^3\,day^{-1}$) was calculated using the equation

$$Q_f = TIW. \tag{2}$$

In the above equation, T is the transmissibility ($600\,m^{-3}\,day^{-1}\,m^{-1}$), W is the aquifer width (m) and I is the infiltration rate which is ~20% of rainfall. The shape of the freshwater–seawater interface was determined as

$$Y^2 - \frac{2Q_*X}{K'^3} - Q_*^2 = 0, \tag{3}$$

Where X is the distance (m) inland of seawater intrusion from shoreline and Y is the depth (m) of the interface, K' is the soil permeability, Q_* is the groundwater outflow per meter of shoreline. Groundwater outflow (Q_*) per meter of shoreline is

$$Q_* \approx \frac{K'H^2}{2L} = \frac{K'Y^2}{2X}, \tag{4}$$

Where H is the depth to seawater–freshwater interface (m), L is the horizontal length of seawater intrusion (m). Since the above equation yields the groundwater outflow per meter of shoreline, the total groundwater supplied to the creek (Q_t) is calculated as

$$Q_t = Q_*P, \tag{5}$$

where P is the permeable stretch (m) of shoreline. In addition, monthly surveys for the determination of groundwater level, as well as groundwater nutrients' concentration, total dissolved solids (TDS), temperature and salinity were conducted for the period between July 1996 and May 1997 in shallow wells located 100–300 m from the mangroves in the upper region of the creek. Measurements of groundwater quality variables were undertaken once a month using Aanderaa S-T meter and WTW LF 95 conductivity meter.

The concentration of dissolved inorganic nutrients; ammonium (NH_4^+–N), nitrite + nitrate ($NO_2^- + NO_3^-$)–N, orthophosphate (PO_4^{3-}–P) and silicate (SiO_3^{2-} Si) were determined according to methods described by Parsons et al. (1984) and APHA (1995). Water samples were drawn at the middle section of the channel using Hydrobios water sampler at $0.2\,d$ near the surface water column. Water samples were kept in cool boxes with ice-blocks and analyses were conducted within 48 h with an Auto-analyzer. Triplicate samples analyzed once had the relative error <10%. To estimate the net nutrient fluxes in ebb and flood tides, several time-series measurements at an interval of 2 h for 25 h were conducted at station 2. Time-series measurements were conducted for 25 h since a diurnal irregularity in tidal amplitudes associated with semi-diurnal tides causes varying current speeds and varying responses in nutrient transport in the creek. Dissolved nutrients data were subjected to correlation analysis and analysis of variance (ANOVA) to determine the association as well as the spatial and temporal variations. 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). The phytoplankton population was estimated after concentrating the sample and taking 1 ml aliquots of the concentrate in a Sedgwick rafter. Counting was done under a microscope and species diversity and evenness were calculated according to Shannon (1948) and Pielou (1966) methods.

Results

Groundwater flux, temperature and salinity changes

Within the shallow groundwater wells sampled in the period between August 1996 and April 1997, variations in the concentrations of groundwater temperature, conductivity, salinity and total dissolved solids (TDS) were detected (Table 1). Changes in groundwater salinity and total dissolved solids (TDS) were from 0.0 to 0.48 PSU and from 261 to 940 $mg\,l^{-1}$, respectively. Conductivity varied from 0.32 to 0.93 $mSc\,m^{-1}$. There were changes up to 8 °C in water temperature since most wells are wide and shallow and are effectively heated by direct solar radiation. In wet seasons, groundwater table rises to the surface and salinity, conductivity and total dissolved solids' concentration decline rapidly (Table 1). While groundwater salinities are much lower, the lowest recorded mean monthly creeks' water salinity is 32.9 PSU in the rainy season month of May 1996 (see also Figure 2). The dry season period between February and March 1997 had a mean salinity of 37.4 PSU.

The calculated groundwater outflow (Q_*) is about $3.9\,m^3\,day^{-1}$ per meter of shoreline which is equivalent to $2\,m^3\,s^{-1}$ over the entire 40 km permeable perimeter of the creek through which seepage occurs (Kitheka, 1998). To find out whether evaporation

Table 1. The groundwater quality in Mida basin. Data represents dry (Sept, Oct, Feb) and wet (Mar, Apr, May) season conditions. Data are based on sampling of two shallow wells M1 and M2 (in parentheses) located <300 m from the mangrove-fringed shore

Date	Water table depth (m)	Temp-erature (°C)	Conductivity (mS cm^{-1})	TDS (mg l^{-1})	Salinity (PSU)
Sept 96	2.0 (2.0)	31.60 (34.1)	0.43 (0.47)	501 (668)	0.10 (0.30)
Oct 96	2.3 (2.3)	36.10 (36.1)	0.71 (0.71)	755 (755)	0.20 (0.35)
Feb 97	2.0 (2.3)	28.40 (28.6)	0.43 (0.80)	475 (940)	0.10 (0.48)
Mar 97	2.3 (2.2)	33.88 (33.3)	0.52 (0.67)	507 (803)	0.20 (0.48)
Apr 97	2.5 (2.0)	30.26 (30.5)	0.49 (0.93)	498 (896)	0.20 (0.41)
May 97	0.5 (1.0)	28.38 (27.0)	0.32 (0.32)	261 (326)	0.00 (0.14)

TDS = total dissolved solids.

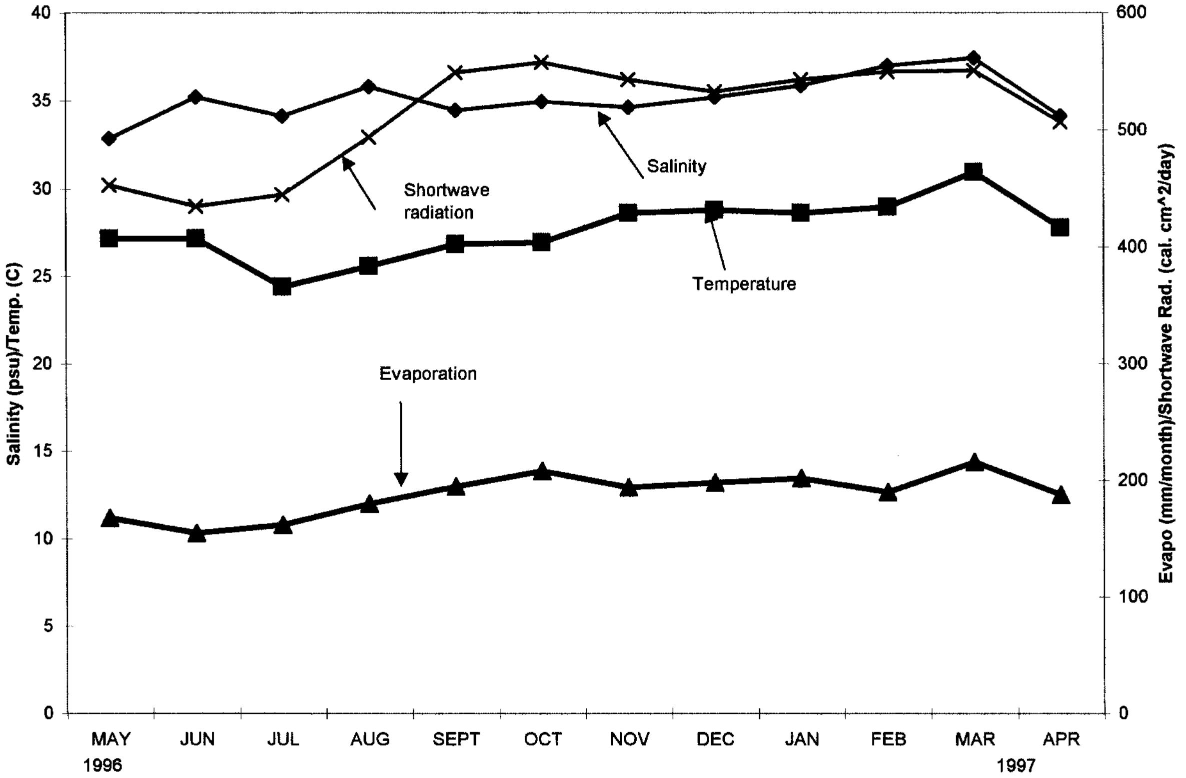


Figure 2. The combined stations mean seasonal variations of creek's water salinity and temperature between May and April 1997. Evaporation and solar radiation data are based on long-term averages for the region. Data represents the mean conditions in both frontwater and backwater zones.

could lead to increased salinity in dry season, we multiplied the typical dry season evaporation of 0.005 m day^{-1} by the wetted creek area and established that the effective evaporation water loss Q_{ev} is 160,000 m^3 day^{-1}. Since the volume of water entering the creek by groundwater Q_{t} is 155,520 m^3 day^{-1}, the net water flux in the system from the ocean Q_{in}, as given by $Q_{\mathrm{in}} = Q_{\mathrm{ev}} - Q_{\mathrm{t}}$ is 4480 m^3 day^{-1}, and since it is >0, the salinity is expected to increase in dry season. This prediction is in agreement with our field data. With evaporation varying from 0.17 m per month in May to 0.22 m per month in March and with no freshwater supply (Figure 2), the backwater region waters would become hypersaline with +40 salinity if there was no groundwater inflow. This hypersalinity would have a destructive effect on the mangrove vegetation. Thus the maximum salinity of 37.4 measured in the creek in dry season is principally a result of moderation by groundwater inflow.

Vertical salinity anomalies (difference between surface and bottom water salinity) were experienced in all stations in both dry and wet seasons. A near-bottom layer 2–3 m thick of less saline water overlain by relatively higher salinity water at the surface occurs in stations 3–5 (Figures 3a,b). The highest measured vertical salinity anomaly was 1.58 at station 2. Apart from vertical salinity anomalies, there were also significant ebb-flood tide salinity differences characterized by relatively lower salinity at ebb and higher salinity at flood tide. These ebb-flood tide salinity differences are due to groundwater seepage in the creek (Kitheka, 1998).

Variations in nutrients concentrations

In the creek, NH_4^+–N concentrations ranged from 0.002 to 5.45 μM and those for $(NO_2^- + NO_3^-)$–N, PO_4^{3-}–P and SiO_3^{2-}–Si were 0.12–5.63, 0.10–0.58 and 1.31–81.36 μM, respectively. Although there were seasonal variations in nutrient concentrations, there also were variations in ebb and flood tide. The relationship between tide and nutrient concentrations are however complex. The results for October 28–29, 1996 (Figure 4a,b) time-series measurements show that the peak concentrations of ammonium, nitrates–nitrites and silicates generally occurred 2–3 h after high water (Figure 4a). With few exceptions, the nitrate–nitrite, ammonium, silicates and orthophosphate concentrations declined quite rapidly during ebb tide reaching the minimum levels during low water. Silicates' concentration can increase or decrease rapidly 2 h before high water and afterwards remains constant even at low tide. In most cases, the flood tide silicate concentrations were much higher by as much as 50% than the values at ebb tide. Periods associated with high nitrate-nitrite and orthophosphate concentrations are also associated with either peak flood and ebb currents. As the current magnitude reduced with the fall in tide, there was also a corresponding time-lagged progressive decrease in nitrate–nitrite and orthophosphate concentrations (Figure 4a,b). The rapid decline in these nutrients during ebb tide could be attributed to very high nutrients uptake by the phytoplankton. However, in case of ammonium and silicates, the influence of the tide and current doesn't seem to be quite distinct. The correlation coefficients for the relationship between nitrate–nitrite, silicates and ammonium concentrations and tidal elevation ranged from 0.30 to 0.67 for nitrite–nitrates and from -0.21 to -0.44 for silicates. The correlation coefficients for ammonium-tide ranged from 0.19 to 0.22. Those for the relationship between nitrate–nitrite, silicate and ammonium concentration with tidal current ranged from 0.11 to 0.51 in case of nitrite–nitrate and from -0.27 to -0.48 in case of silicates. In case of ammonium the correlation coefficient ranged from 0.40 to 0.13. These low values of the correlation coefficients indicate the relationship between the above nutrients and tide is highly variable and suggests other factors are important. Similar patterns as described above were also observed in other nutrient time-series (Figure 4b) although patterns were not the same for all nutrients. The above pattern is characteristic of areas with groundwater seepage since in river-influenced mangrove systems studied elsewhere, nutrient concentrations increase during ebb tide (Ohowa et al., 1997; Kitheka et al., 1996) but this was not the case at Mida creek.

Dissolved nutrient concentrations were significantly higher during the wet (rainy) season as compared to dry season (Table 2). There was also a significant spatial variation. The backwater zones have a high nutrient concentration (but lower than those in groundwater) as compared to the frontwater zones. Groundwater nutrient concentrations were consistently higher than in the creek (Table 3). The ratio of nutrient concentration in groundwater divided by that in the creek for NH_4^+ was 1:0.028 in wet season and 1:0.035 in dry season. That for $NO_2^- + NO_3^-$ was 1:0.001 in dry season and 1:0.004 in wet season. For PO_4^{3-} the ratio was 1:0.10 in dry season and 1:0.09 in wet season. For SiO_3^{-2} the ratio was 1:0.042 for dry season and 1:0.034 for wet season. These ratios clearly show that most of the dissolved nutrients remain locked up in the groundwater system (Tables 2 and 3). It is likely that a large portion of the nutrients available in the groundwater is removed by the terrestrial vegetation (e.g. Arabuko–Sokoke tropical lowland forest) and also by the mangroves. In addition to above, it is also possible that groundwater nitrite–nitrate is also progressively removed by denitrification process.

Discussion

Backwater zone with low current speeds (<0.4 m s^{-1} at spring tide, <0.15 m s^{-1} at neap tide) are relatively poorly flushed (Table 5) and water is trapped

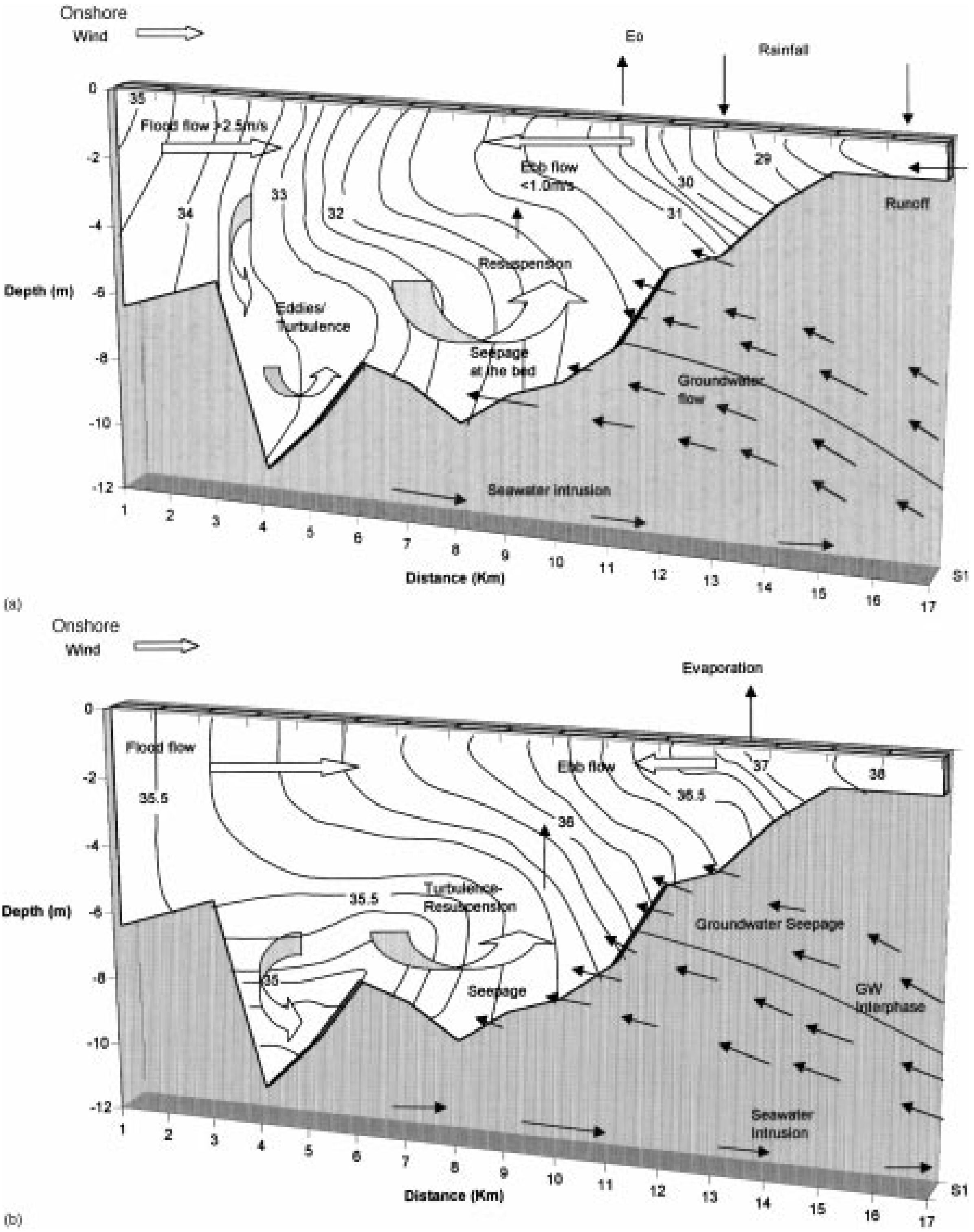


Figure 3. The water column salinity structure in Mida creek in (a) wet and (b) dry seasons. Note the vertical salinity anomalies and occurrence of relatively lower salinity water at the bottom water-column in some of the locations. Hypersaline and low salinity conditions develop in dry and wet seasons respectively, in the upper zones of the creek. Arrows shows the patterns of flow of water.

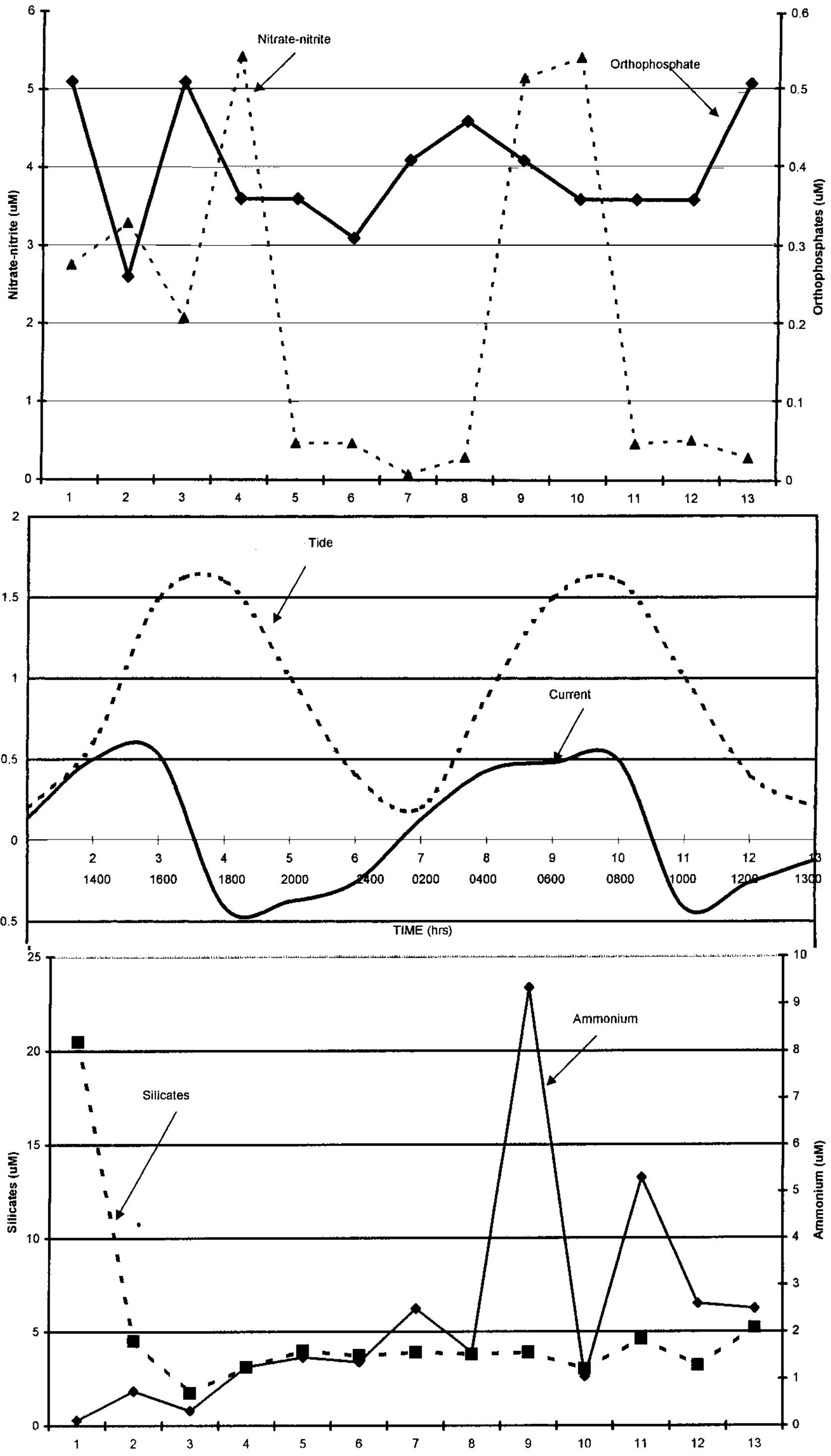


Figure 4. The time-series of tides, currents and variations in dissolved nutrient concentrations at station 2 in the middle zone of the creek in October 28–29, 1996 (a) and in January 28–29, 1997 (b).

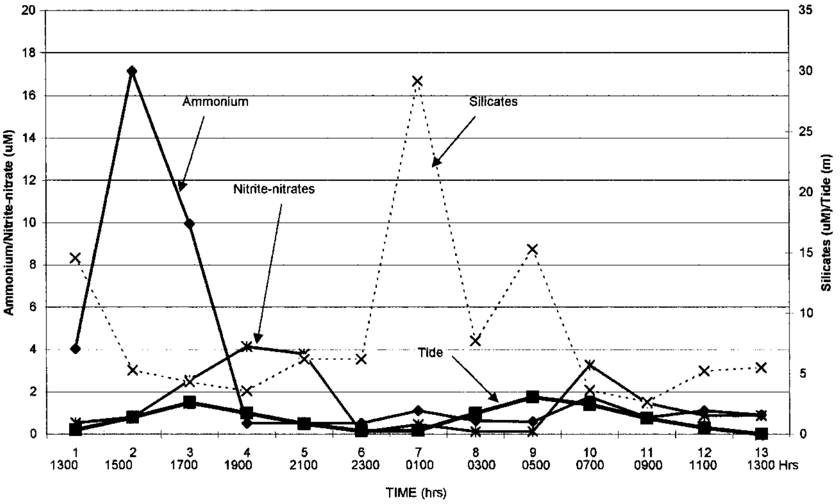


Figure 4. continued

Table 2. The mean values for creek's (all stations) water column nutrients and groundwater nutrient concentration in the Mida basin in dry and wet seasons. Note high concentration of nutrients in groundwater system as compared to those in the creek

	NH_4^+ (μM N)	$NO_2^- + NO_3^-$ (μM N)	PO_4^{3-} (μM P)	Si O_3^{2-} (μM Si)
Creek's water				
Dry season	0.22	1.52	0.34	6.35
Wet season	0.39	2.64	0.44	15.94
Groundwater				
Dry season	8.00	1124.10	3.41	149.80
Wet season	11.05	642.87	4.88	470.25

Table 3. Mean groundwater nutrient concentration in the Mida creek basin in dry and wet (in parenthesis) seasons. Note high concentration of nutrients in groundwater. Wells are located in areas dominated by highly porous Pleistocene sand. Wells marked M1 and M2 are shown as shallow wells in the upper zones of the creek in Figure 1

	NH_4^+ (μM N)	$NO_2^- + NO_3^-$ (μM N)	PO_4^{3-} (μM P)	Si O_3^{2-} (μM Si)
M1	4.7 (1.9)	505.7 (1209.0)	1.9 (4.6)	154.4 (343.6)
M2	11.3 (20.3)	1742.5 (76.7)	4.9 (5.2)	145.3 (596.9)

Table 4. The creek's water volumes and water exchange rates in the frontwater and backwater zones (parenthesis) of Mida creek based on neap and spring tidal ranges during high waters

	High waters	
	Mean spring	Mean neap
Tidal range	3.2 (1.7) m	2.0 (0.8) m
Volume	73 (48) ×10^6 m^3	60.0 (37.5) ×10^6 m^3
Tidal prism	57 (27) ×10^6 m^3	30.0 (12) ×10^6 m^3
Exchange rate	69 (57)%	50.0 (32)%
Area	29.4 × 10^6 m^2	14.46 × 10^6 m^2

for a period of between 10 and 14 days. Nutrients have more time leached from the mangroves channel bed, sediments and groundwater seepage are therefore bound to reside longer in this region. Sustained seepage of groundwater at the channel bed and lack of strong bottom current is probably the main cause of vertical salinity anomalies (Kitheka, 1998). The examination of the structure of isohalines in dry and wet seasons (Figure 3a,b) confirmed unstable stratification in salinity (Vanek, 1991). It is unlikely that the salinity stratification is caused by temperature since most sections of the creek are shallow with water depths ranging between 3 and 11 m and water temperature is usually vertically uniformly well-distributed.

The maximum ebb tidal discharge at the entrance (calculated using data derived from current and cross-sectional area measurements) is 2800 m^3 s^{-1} which is slightly lower than the flood tidal discharge. The duration of ebb tide (∼6.5 h) is longer than that at flood tide (∼5 h) although current tends to be stronger in flood tide as compared to ebb tide. This partly explains larger flood tide discharge. Since volume of water in the frontwater zone is 73.5 × 10^6 m^3 and ebb tidal discharge is 2800 m^3 s^{-1}, residence time of water was calculated using data shown in Table 4. The results of computation shows that, in the frontwater zone the

Table 5. The mean creeks' tidal (ebb and flood) and groundwater (GW) nutrients fluxes ($g\,s^{-1}$) in dry and wet seasons. In dry seasons, most of the nutrients emanate from the groundwater seepage while in wet season surface runoff influx adds additional nutrients into the creek

Season	NH_4^+ ($g\,s^{-1}$)			$NO_2^-+NO_3^-$ ($g\,s^{-1}$)			Si O_3^{2-} ($g\,s^{-1}$)		
	GW	Ebb	Flood	GW	Ebb	Flood	GW	Ebb	Flood
Dry	0.2	8.7	11.7	28.3	59.7	80.0	7.6	499.6	669.1
Wet	0.3	15.1	20.2	16.2	103.3	138.4	23.8	1254.2	1680.0

Table 6. (a) Tidal export, (b) Groundwater and (c) Oceanic inflow fluxes of nutrients at Mida creek in dry season (data in $kg\,m^{-3}$ day^{-1})

	NH_4^+	$NO_2^-+NO_3^-$	SiO_3^{2-}
(a) EA (dC/dx)	3.5×10^6	213.0×10^6	177.0×10^6
(b) Q_tPC_g	2.7×10^6	380.0×10^6	102.1×10^6
(c) $Q_{in}C_o$	4.5×10^6	30.9×10^6	258.9×10^6
	(Sink)	(Source)	(Sink)

residence time is 0.5–1 day, and that in the backwater zone is roughly 14 days. Thus different zones of the creek have water being exchanged at different rates. The highest mean values for the all nutrients were recorded in the backwater zone. This could be due to high residence time and trapping. Nutrients in the backwater zone are trapped there for relatively longer period. Also, as compared to the backwater region of the creek, strong currents in the order of $2\,m\ s^{-1}$ and high rates of water exchange in the frontwater zone flush nutrients rapidly (Kitheka, 1998), hence nutrients concentrations are usually relatively lower in the frontwater zone (Kitheka et al., 1996).

Attempt was made to determine the contribution of groundwater on the overall nutrient balance of the creek. As shown in Tables 2 and 5, groundwater seepage is estimated to contribute between 8% and 140% of the net NH_4^+ and $NO_2^- + NO_3^-$ flux but $< 5\%$ of the net silicate flux. In wet season, the contribution of groundwater seepage is additional to the supply by surface runoff, and it contributes $<5\%$ of NH_4^+ flux, 46% of net $NO_2^- + NO_3^-$ flux and 6% of the net silicate flux. The groundwater flux of ammonium and silicates shows a dry–wet season increase of between 26% and 32% while in case of nitrite–nitrates there is a dry–wet season decrease of about 43%. In both dry and wet season, flood tide is usually characterized by increased nutrient flux as compared to ebb tide (Table 5). It is worth noting that the levels for PO_4^{3-}–P were generally higher in the inner backwater zones of the creek (station 1), both in the sediments and in the water column. It is likely that there is an additional source of PO_4^{3-}–P in the creek since the corresponding concentrations in the groundwater system were relatively lower. For a conservative nutrient (dissolved form, no intake/outtake from plankton and no reaction with sediment), the nutrient budget of the creek can be expressed as

$$Q_tPC_g + Q_{in}C_o = EA(dC/dx), \qquad (6)$$

where C is the concentration in the creek, P is the permeable stretch of the shoreline (m), A the creek cross-sectional area ($1600\,m^2$), x the distance measured along the creek (10 km), C_g is the groundwater inflow and C_o is that in the ocean, E is the eddy diffusivity and Q_{in} is the net discharge at the mouth of the creek. The above equation states that the inflow of mass of nutrient from the open ocean and from groundwater has to equal the outflow to the open ocean by tidal diffusion and for a conservative nutrient, the three terms must balance. Where they do not balance, the creek functions as either a source or sink of nutrients. In order to determine different terms in equation (6), the horizontal eddy diffusion E was calculated from the equation

$$Q_{in}S_o = EA\left(\frac{dS}{dx}\right), \qquad (7)$$

where S_o is ocean salinity (35), S the dry season salinity in the creek along the creek axis (37 PSU). From salinity data, dS/dx was estimated as 0.0002 PSU m^{-1}. The calculated eddy diffusivity (E) is 6 $m^2\ s^{-1}$ which is on the lower side of the expected typical range 5–60 $m^2\ s^{-1}$. The wetted surface area A, ($\sim 25 \times 10^6\,m^2$) was calculated as the mean between wetted surface areas at high spring tide, low spring tide, high neap tide and low neap tide. The calculated eddy diffusivity (E) and other terms were applied in equation (7) and the three terms (in kg day^{-1}) for each nutrient in dry season were determined. C, C_g, C_o (at the mouth), and dC/dx were computed from data shown in Table 5. The three terms as expected were not equal indicating nutrients at the creek are not conservative. Tidal export fluxes are lower than groundwater and incoming oceanic fluxes in case of ammonium, nitrite–nitrate and silicates implying that there is more nutrients input than output (Table 6). These results basically show that the creek is a source of nitrite–nitrate (and probably orthophosphates) but is a sink of silicates and ammonium. Most of the nitrite–nitrate enters the creek through groundwater flow and only a very small percentage actually enters the creek with the oceanic inflow. A large percentage of Ammonium and silicates enters the creek with the oceanic inflow although groundwater supply of these two nutrients is still relatively high.

High concentrations of dissolved inorganic N and Si have consistently been observed during rainy seasons in river-influenced tidal mangrove-fringed creeks in Kenya (Kazungu et al., 1989; Kitheka et al., 1996; Mwashote, 1997; Ohowa et al., 1997). In the latter cases, processes controlling nutrients budget are predominantly those related to the seasonally variable input of freshwater by surface runoff and rivers. Of course other sources in the mangrove wetland itself cannot be under-estimated. Similar nutrient concentration levels have also been reported for other predominantly estuarine systems with perennial river flow regime (Ho, 1977; Duinker, 1989; Wright, 1989). There is however no data from mangrove creeks with groundwater outflow particularly those with a complete absence of river drainage. Mida creek basin lacks river drainage and it is possible to attribute the observed high nutrient concentrations to groundwater outflow. It is believed luxuriant mangrove forest at the creek is partly sustained by groundwater outflow, so is the terrestrial Arabuko–Sokoke forest-one of the Eastern Africa's remaining terrestrial coastal forests. The effects of groundwater seepage seem to be more crucial in the overall dry season nutrient budget although its contribution in rainy seasons is not negligible (Tables 5 and 6). Since the mangrove creek could experience shortage of nutrients in dry season, sustained groundwater outflow during that time boosts nutrient supply into the creek and also moderates the salinity which would otherwise reach hypersaline condition ($+40$ in view of high rates of evaporation). This helps in sustaining the mangroves and other marine ecosystems in the creek. Thus groundwater aquifer system management in this area should be one of the main focus of integrated coastal zone management. Beside being an important source of freshwater for various human uses (domestic, irrigation etc), groundwater is also important in sustaining coastal marine ecosystems such as the mangroves.

Conclusions

Despite the absence of river drainage in the Mida creek basin, the concentrations of nutrients in Mida creek are similar to those reported for creeks supplied with freshwater by seasonal and perennial river systems in the Eastern Africa region and other parts of the world. Groundwater inflow induces vertical salinity anomalies (stratifies the water column), limits the salinity in dry season and supplies nutrients into the creek. Low rates of water exchange in the backwater zone (residence time >14 days) encourage trapping of nutrients and therefore with low tidal flushing, higher nutrients concentration result. High rates of water exchange (residence time $<$ tidal cycle) coupled with high magnitude current (>1.0 m/s) encourage rapid flushing of nutrients in the frontwater zone and prevent anoxic conditions from developing. The contribution of groundwater seepage to nutrients budget is more prominent in dry season as compared to wet season when its effect is masked by surface runoff. Thus, groundwater outflow helps in dry season in sustaining the mangroves by providing nutrients and preventing hypersalinity ($+40$) which would otherwise occur since there is no river inflow. Groundwater basin management in Mida creek basin is necessary in order to safeguard against the loss of coastal biodiversity and associated socio-economic benefits.

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