Dynamics of Suspended Sediment Exchange and Transport in a Degraded Mangrove Creek in Kenya

Author(s): Johnson U. Kitheka, George S. Ongwenyi, Kenneth M. Mavuti
Source: AMBIO: A Journal of the Human Environment, 31(7):580-587. 2002.
Published By: Royal Swedish Academy of Sciences
DOI: http://dx.doi.org/10.1579/0044-7447-31.7.580
URL: http://www.bioone.org/doi/full/10.1579/0044-7447-31.7.580

Johnson U. Kitheka, George S. Ongwenyi and Kenneth M. Mavuti

Dynamics of Suspended Sediment Exchange and Transport in a Degraded Mangrove Creek in Kenya

This study focuses on sediment exchange dynamics in Mwache Creek, a shallow tidal mangrove wetland in Kenya. The surface area of the creek is 17 km^2 at high water spring. The creek experiences semidiurnal tides with tidal ranges of 3.2 m and 1.4 m during spring and neap tides, respectively. The creek is ebb dominant in the frontwater zone main channel and is flood dominant in the backwater zone main channel. During rainy season, the creek receives freshwater and terrigenous sediments from the seasonal Mwache River. Heavy supply of terrigenous sediments during the *El Niño* of 1997–1998 led to the huge deposition of sediments (10^6 tonnes) in the wetland that caused massive destruction of the mangrove forest in the upper region. In this study, sea level, tidal discharges, tidal current velocities, salinity, total suspended sediment concentrations (TSSC) and particulate organic sediment concentrations (POSC) measured in stations established within the main channel and also within the mangrove forests, were used to determine the dynamics of sediment exchange between the frontwater and backwater zones of the main channel including also the exchange with mangrove forests. The results showed that during wet seasons, the high suspended sediment concentration associated with river discharge and tidal resuspension of fine channel-bed sediment accounts for the inflow of highly turbid water into the degraded mangrove forest. Despite the degradation of the mangrove forest, sediment outflow from the mangrove forest was considerably less than the inflow. This caused a net trapping of sediment in the wetland. The net import of the sediment dominated in spring tide during both wet and dry season and during neap tide in the wet season. However, as compared to heavily vegetated mangrove wetlands, the generally degraded Mwache Creek mangrove wetland sediment trapping efficiency is low as the average is about 30% for the highly degraded backwater zone mangrove forest and 65% in the moderately degraded frontwater zone mangrove forest.

INTRODUCTION

The direction and magnitude of sediment transport in mangrove creeks is critical in defining the sediment budget of an individual mangrove forest and the role it plays in the large coastal sedimentary system. Most mangrove creeks are characterized by the occurrence of time-velocity asymmetry in which ebb flow is more dominant than flood flow (1–4). Tidal asymmetry contributes to the maintenance of a deep self-scouring drainage channel, even in the presence of a large sediment input from surrounding coastal waters (5–6). Previous studies have shown that mangrove systems normally trap most of the incoming sediments during flood tide and there is no significant export of sediments during ebb tide (5, 7–10). Sediment trapping is believed to be an essential process by which mangroves build their own environment (11). However, little information exists on sediment fluxes in degraded mangrove wetlands of Africa since most of the previous studies on water exchange and suspended sediment fluxes in mangrove creeks, have mostly been conducted in dense, pristine mangrove systems (5, 7–9) and salt marshes (12, 13). The general objective of this study is to determine the patterns of sediment transport and exchange within the 17 km^2 Mwache mangrove wetland in the northern zone of Port-Reitz Ria in Kenya. The dominant mangrove species in the creek are *Avicennia marina*, *Rhizophora mucrunata* and *Ceriops tagal*. The creek is impacted by siltation and extensive clearance of mangroves for fuel-wood and timber.

MATERIALS AND METHODS

Measurement of Water and Sediment Exchange

This study was implemented in the period between October 2000 and July 2001. Hydrographic stations shown in Figure 1 were established in the main tidal channel. Stations 5, 6 and 7 were located in the frontwater zone while stations 1, 2, 3 and 4 were located in the backwater zone. At stations 1E to 6, in the thalweg of the main channel, vertical profiles of water salinity, total suspended sediment concentrations (TSSC), particulate organic sediment concentrations (POSC) and currents were obtained from a rubber dinghy at anchor. Salinity was measured using an Aanderaa Salinity sensor. Point-based water samples drawn from different levels of the water column at different stations using a Hydrobios water sampler, were integrated to obtain the depth-integrated TSSC and salinity. Within the main tidal channel, tidal elevations were measured at stations 1 and 6 using Divers Pressure gauges, while current velocities (speed and direction) and TSSC were measured with Aanderaa Recording Current Meter (RCM 9). Water samples were used to calibrate the output of the sensor on the Recording Current Meter to TSSC. These instruments recorded data at 5-min intervals after averaging data measured during 1 min at 1-sec intervals. The deployment period ranged from 3 to 21 days. At the 2 stations, the instrument depths were 2 and 4 m for stations 1 and 6 respectively.

TSSC within the main channel and tidal inlets were also determined by gravimetric method. The POSC were determined by loss on ignition to 0.0001 g (14). The instantaneous total suspended sediment concentrations (kg m^{-3}) were multiplied by the corresponding instantaneous velocities (m s^{-1}) to yield instantaneous total suspended sediment fluxes (kgm^{-2} s^{-1}). The instantaneous sediment fluxes for ebb and flood periods were summed to yield the total ebb and flood-tide sediment fluxes.

In the determination of the sediment and water exchange dynamics in mangrove forest inlets, measurements of water level, velocities, salinity, TSSC and POSC were made at 20 min intervals to cover the full tidal cycle. These measurements were done at the middle sections of the tidal inlets, about 100–150 m from main tidal channel, in both the backwater and frontwater mangrove forests (Fig. 1). In the inlets, tidal elevations were measured using a tide pole and tidal current velocities were measured using partially submerged drogues. The tidal inlets were usually of small cross-sectional areas (less than 4-m wide and less than 3-m deep) with no major vertical and lateral velocity variations. Thus a single point-based velocity measurement

The frontwater zone of Mwache Creek showing the main channel and mangrove forest fringing. The frontwater zone mangrove was not impacted by the El Niño floods, but excessive cutting of mangroves has caused some degradation. Photo: J. Kitheka.

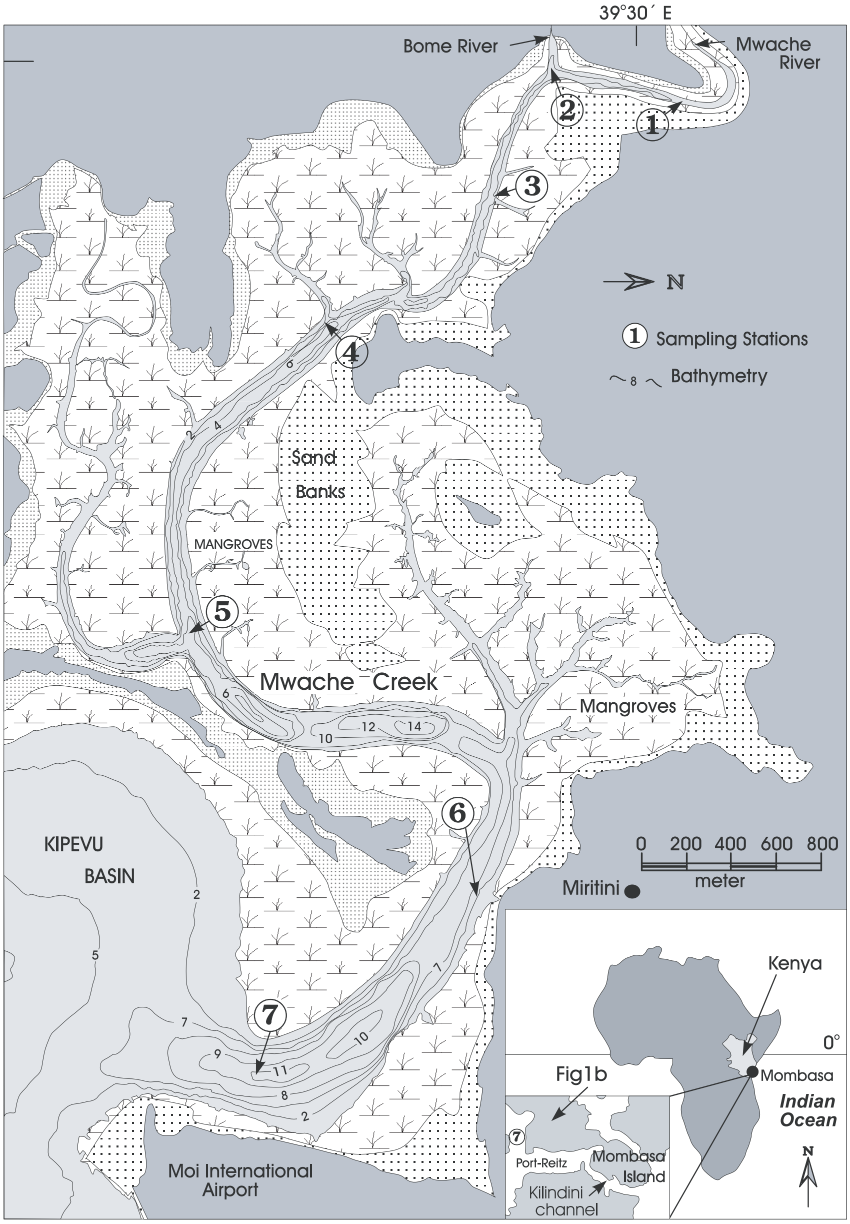


Figure 1. Map of Mwache Creek with the locations of sampling stations. The principal stations are Stns 1, 4, 6 and 8. For surface area and volume computations, the whole mangrove extent and associated tidal creeks above Stn 7 were considered.

at the middle of the channel, at an interval of 20 min was assumed to represent the average velocity within the cross-section. The ebb and flood tidal discharges in the inlets were determined using the cross-sectional area-velocity approach. Instantaneous velocities (m s^{-1}) within the cross-sections, were multiplied by the instantaneous cross-sectional areas (m^2) in order to obtain the instantaneous tidal discharges (m^3 s^{-1}). The instantaneous tidal discharges in both ebb and flood periods were multiplied by the corresponding instantaneous depth-integrated flood-ebb tide organic and inorganic sediment concentrations (g L^{-1} = kg m^{-3}) to determine the corresponding depth-integrated ebb-flood period total particulate organic and inorganic sediment loads in kg s^{-1} (13). The difference between ebb and flood particulate organic and inorganic sediment loads yielded the net organic and inorganic sediment fluxes (15–17). Information on the surface area of the mangrove forest basin drained by the respective inlet as well as the sediment bulk density enabled the determination of the net organic and inorganic sediment fluxes per unit area (g m^{-2} s^{-1}). The bulk density of sediment collected in different stations was determined in the laboratory as the ratio between dry weight of sediment and the corresponding sediment volume (18). For both the main channel and the tidal inlets, the positive sediment fluxes corresponded to sediment import and the negative ones corresponded to sediment export. Apart from the measurement of velocities within the main channel and tidal inlets, velocities were also measured inside the mangrove forest by timing the movement of partially submerged drogues over predetermined distances (5, 11).

Figure 2. Tidal current velocity and direction at station 1.

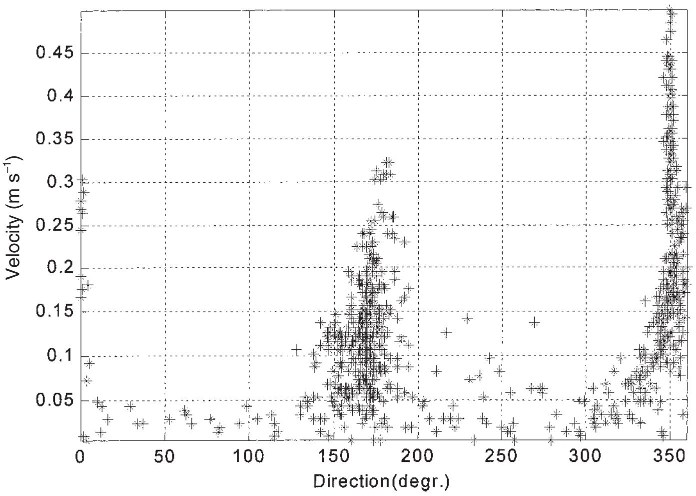
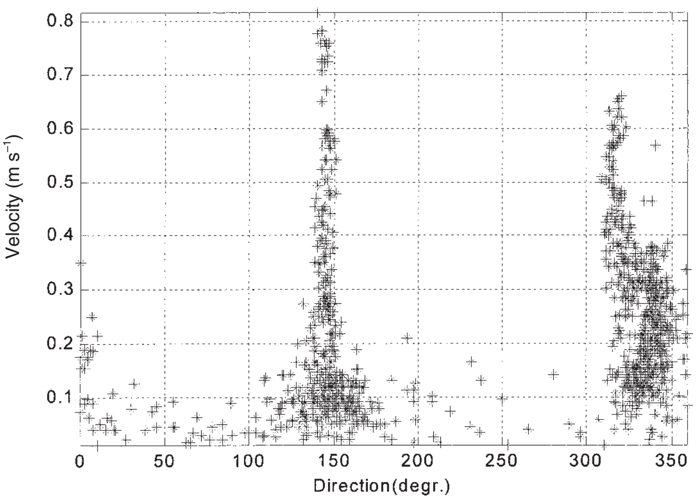


Figure 3. Tidal current velocity and direction at station 6.



RESULTS

Dynamics in the Main Channel

In the main channel at stations 1 and 6, the duration of flood and ebb tides are 6.6 and 6.2 hrs, respectively. Neap and spring tidal ranges are 1.3 and 3.1 m, respectively. These tidal ranges are comparable to those reported in other mangrove creeks along the Kenya coast (1–3). There was also a significant asymmetry in the current velocity (Figs. 2 and 3). As shown in Figure 3, the peak current velocities were measurably larger at ebb tide than at flood tide in the frontwater zone, which means that the main channel in the frontwater zone of the creek is ebb dominant. In dry seasons, the peak ebb current velocity was 0.85 m s^{-1} and the peak flood current velocity was 0.68 m s^{-1}. In the backwater zones, the peak currents (0.50 m s^{-1}) were measurably larger at the flood-tide than at the ebb tide during the dry season, which means that the main channel in the backwater zone is flood tide dominant during dry seasons (Fig. 2).

During periods of relatively high river discharge above 4 m^3 s^{-1} (Figs 4a–b), the zone above station 4 experienced low salinity ranging from 0 to 29 PSU, while that in the frontwater zone experienced salinity ranging from 30 to 35 PSU. Both the minimum and the maximum salinities were recorded in the backwater zone where peak salinities reached as high as 40 PSU and lowest reached 0.1 PSU in the zone above station 4.

Dynamics in the Mangrove Forest

Results of measurements of current velocities, tidal discharges and tidal range within the tidal inlets draining the backwater zone and frontwater zone mangrove forests are shown in Table 1. As shown in Figures 6a–b, the water level variation in the mangrove forests is unimodal. The duration of the flood and ebb tides is variable as it ranges from 2.0 to 4.3 hrs. There is also tidal elevation asymmetry in the mangrove forest with the duration of the flood period being slightly longer than that of the ebb period by about 30 minutes (Table 1). The ebb-flood tidal discharges portrayed a bimodal pattern as is shown in Figures 6a-b, being a function of velocity and tidal elevation variations (5, 11). The tidal range was variable as it ranged from 0.9 to 2.6 m. The peak current velocity within the inlets usually occurred during ebb tide. During ebb tide, current velocities ranged from 0.01 to 0.45 m s^{-1} and during flood tide, current velocities in the mangrove forest inlets ranged from 0.02 to 0.34 m s^{-1} (Table 1). However, within the mangrove forest, the velocities were less than 0.10 m s^{-1}.

Variability of the Suspended Sediment Concentrations in the Main Channel

The spatial distribution of TSSC within the main channel showed that TSSC decreases exponentially from the backwater zone to the frontwater zone main channel. The magnitude of the TSSC

Table 1. The duration of ebb-flood tide, velocity ranges and tidal discharges in the degraded mangrove forest inlets upstream of station 4.

Date	Flood period (Hrs)	Ebb period (Hrs)	Tidal Range (m)	Flood velocity range (m s^{-1})	Ebb velocity range (m s^{-1})	Flood tidal discharge range (m^3 s^{-1})	Ebb tidal discharge (m^3 s^{-1})
25 Oct. 00	3.3	3	1.43	0.03–0.22	0.12–0.30	0.0017–3.54	0.0024–3.52
24 Nov. 00	2.3	2.3	0.90	0.05–0.12	0.01–0.02	0.0756–1.08	0.004–0.216
28 Nov. 00	3.6	–	1.79	0.02–0.12	0.02–0.05	0.014–1.60	0.43–1.02
14 Dec. 00	3.7	–	1.60	0.08–0.34	–	0.014–3.80	–
9 Jan. 01	4.3	4.0	2.18	0.04–0.11	0.02–0.10	0.009–3.77	0.09–3.79
7 Feb. 01	4.3	4.0	2.45	0.02–0.19	0.06–0.45	0.0006–5.20	0.0003–9.56

in the backwater zone (stations 1–4) is much larger than in the frontwater zone (stations 5–7). Sediment grain size analysis revealed that sediment particle sizes increase towards the frontwater zone. The backwater zone main channel is essentially covered with very fine sediment consisting of clay, while the frontwater zone is dominated by fine sand and silt particles.

Figures 4a–b and 5a–b shows the vertical distribution of TSSC and salinity in both dry and rainy seasons. During the rainy seasons, the water column is poorly mixed with a significant vertical sediment stratification in the backwater zone between stations 1 and 3, and also in the estuarine zone between the stations 1E and 1A (Figs 4a–b). The water column in the frontwater zone is well-mixed and more-or-less homogenous. In dry season, sediment stratification exits in the backwater zone main channel but is of relatively much lower magnitude. The turbidity maximum zones (TMZ) were present in both the frontwater and backwater zones of the creek, but were better developed in the latter (Figs 4b and 5b). The backwater zone TMZ occurred in the zone between stations 1E and 2 and, that in the frontwater zone occurred in the zone between stations 5 and 6. In the backwater zone TMZ, TSSC ranged from 0.10 to 0.31 g L^{-1} while that in the frontwater zone ranged from 0.08 to 0.25 g L^{-1}.

Sediment Exchange in the Tidal Inlets and Mangrove Forest

Table 2 shows the results on measurements conducted on the variations of TSSC and POSC in the tidal inlets draining mangrove forests. In the highly degraded backwater mangrove forest, during a period of low tidal range (< 1.5 m) in dry season, the highest TSSC and POSC occurred at the early stages of flood tide (i.e., within 1 hr of commencement of flood tide) and at the last stages of ebb tide, 1 hr before the end of ebb tide (Fig. 6a).

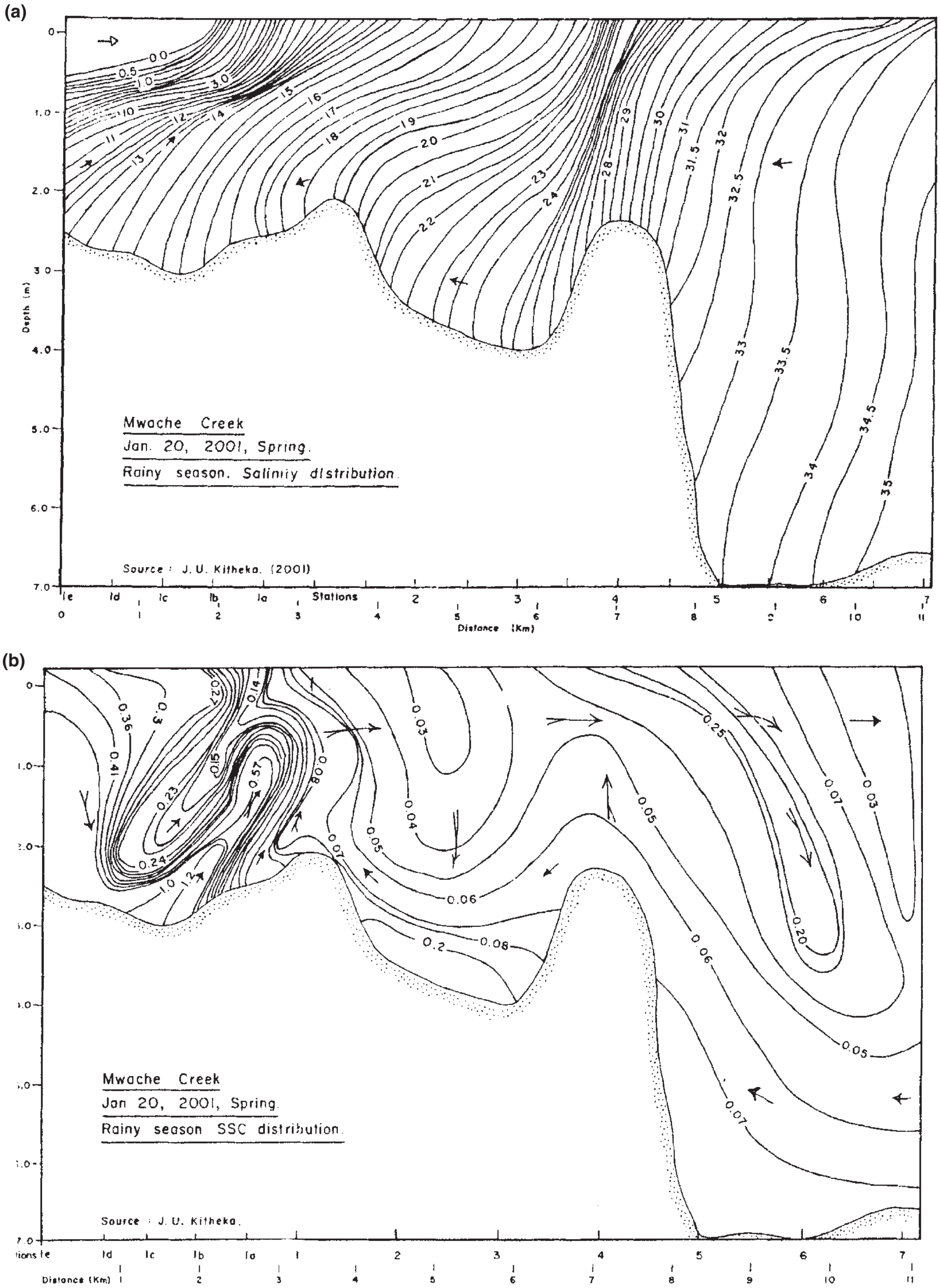


Figure 4. The contour plots of (a) salinity; and (b) TSSC variations in rainy season.

The peak TSSC recorded during the last stages of ebb tide was usually much higher than the peak TSSC recorded during the early stages of flood tide. However, this occurred when ebb tidal discharges were very low so that the corresponding ebb-tide sediment flux tended to be relatively low. The high TSSC at the beginning of flood tide was attributed to the inflow of turbid water from the main channel, and the peak TSSC during ebb tide was attributed to the resuspension of fine bottom sediment due to strong ebb tide velocities within the inlets. These results contrast findings of research conducted in the heavily vegetated mangrove forests in Australia where high TSSC was reported to occur during flood tide (5, 11). During ebb tide, TSSC in Australian mangrove forest is usually extremely low and there is no increase in TSSC during the last stages of ebb tide as is clearly evident at Mwache creek.

In the highly degraded backwater zone mangrove forest of Mwache creek, the flood- and ebb-tide sediment fluxes were of the same order of magnitude in dry seasons, but there was a significant difference in the rainy season when river discharge was higher than 0.15 $m^3 s^{-1}$ (Figs 6a–b). In the backwater zone mangrove forest, the flood tide TSSC flux reached as high as 2285 kg $tide^{-1}$ and the ebb period sediment fluxes reached 1897 kg $tide^{-1}$ (Tables 3 and 4). During wet seasons, the net sediment import was of the order 388 kg $tide^{-1}$, which is equivalent to net sediment deposition rate of about 4 gm^2 $tide^{-1}$. In the moderately degraded frontwater mangrove forest, the difference between flood and ebb tide sediment fluxes was more pronounced as compared to that in the degraded backwater zone mangrove forest fluxes (Figs 6a–b). However, there was a tendency for the peak TSSC to be much higher during flood tide and much lower during ebb tide. The flood tide sediment fluxes ranged from 1420 to 8573 kg $tide^{-1}$ and the ebb ones ranged from 400 to 2926 kg $tide^{-1}$. The net sediment import into the frontwater mangrove forest ranged between 400 to 5647 kg $tide^{-1}$. The peak sedimentation rate was 62.7 g m^{-2} $tide^{-1}$. In general, the net import of the total sediment and the net export

Figure 5. The contour plots of (a) salinity; and (b) TSSC variations in dry season.

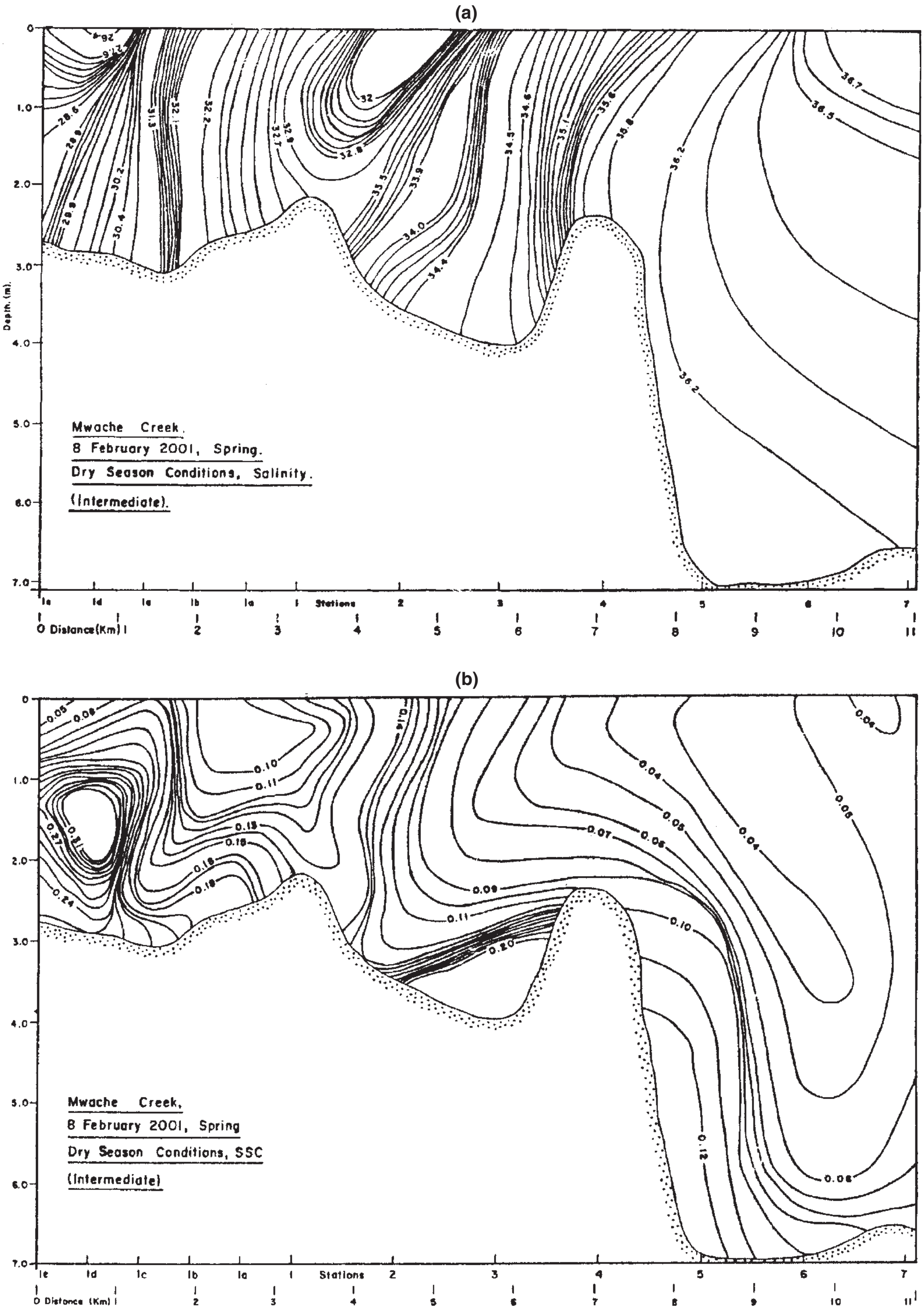


Table 2. The flood and ebb total suspended sediments concentrations (TSSC) and particulate organic sediment concentrations (POSC) ranges and percentages in inlets draining the degraded mangrove forest upstream of station 4.

Date	Flood TSSC ($g L^{-1}$)	Ebb TSSC ($g L^{-1}$)	Flood POSC ($g L^{-1}$)	Ebb POSC ($g L^{-1}$)	Flood POSC %	Ebb POSC %
25 Oct. 00	0.1757–0.0278	1.46–0.040	0.0155–0.0044	0.0861–0.0073	8.8–19.4	9.9–58.97
24 Nov. 00	0.113–0.0372	0.068–0.038	0.104–0.034	0.0637–0.0346	6.6	7.4
28 Nov. 00	0.229–0.048	0.052–0.051	0.064–0.007	0.009–	27.9	17.3
14 Dec. 00	0.220–0.050	–	0.037–0.009	–	14.3–20.0	
9 Jan. 01	0.742–0.052	0.294–0.0368	0.27–0.005	0.252–0.0034	3.6–42.5	8.5–13.0
7 Feb. 01	0.283–0.0411	0.781–0.0424	0.036–0.0047	0.099–0.0058	9.7–15.9	8.8–14.9

Figure 6a. The pattern of TSSC variability (5 April 2001) within the backwater zone mangrove forest inlet B in relation to changes in tidal discharge and elevation.

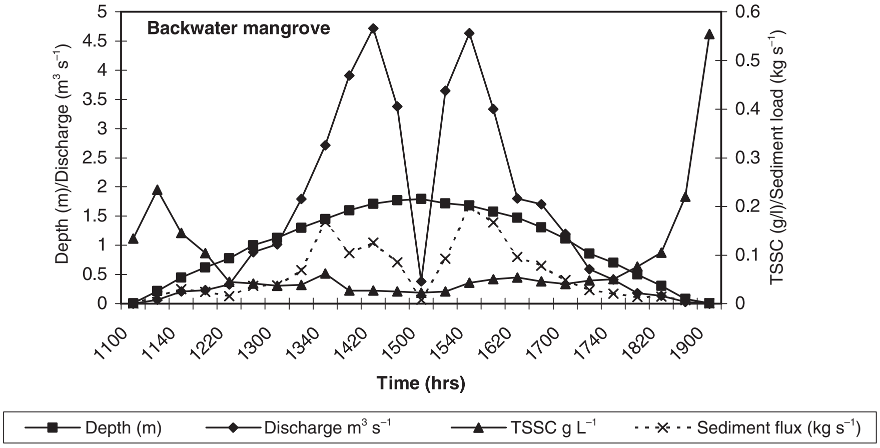


Figure 6b. The pattern of TSSC variability (8 May 2001) within the frontwater zone mangrove forest inlet D in relation to changes in tidal discharge and elevation.

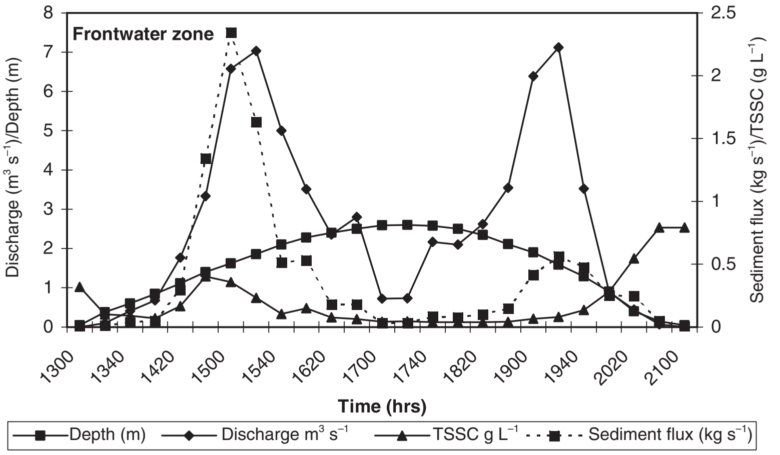


Table 3. River discharge, ebb–flood period total suspended sediment (TSS) fluxes. The negative net sediment fluxes represent export out of the mangrove forest to main tidal channel.

Date	Tidal range (m)	River discharge $m^3\ s^{-1}$)	Ebb TSS flux (kg $tide^{-1}$)	Flood TSS flux (kg $tide^{-1}$)	Net TSS flux (g m^{-3} $tide^{-1}$)
25 Oct. 00 (b)	1.4	0.8	1267.67	737.45	–8.83
24 Nov. 00 (b)	0.9	6	32.99	139.46	1.77
9 Jan. 01 (b)	2.2	3.7	1896.64	2284.64	4.31
7 Feb. 01 (b)	2.4	0.15	1436.64	1596.57	1.78
8 March 01 (b)	2.4	0.01	3206.35	3304.51	1.09
5 April 01 (b)	1.8	0.03	918.67	860.44	–0.65
8 May 01 (f)	2.6	0.01	2926.17	8573.15	62.74

(b) Degraded backwater mangrove forest inlets;
(f) moderately degraded frontwater mangrove forest inlets).

Table 4. River discharge, ebb–flood tide particulate organic sediment (POS) fluxes and net sediment fluxes. Negative net fluxes represent export out of the mangrove forest to the tidal channel.

Date	Tidal range (m)	River discharge ($m^3\ s^{-1}$)	Ebb POS flux (kg $tide^{-1}$)	Flood POS flux (kg $tide^{-1}$)	Net POS flux (g m^{-3} $tide^{-1}$)
25 Oct. 00 (b)	1.4	0.8	240	108	–2.20
24 Nov. 00 (b)	0.9	6	2.54	8.26	0.095
9 Jan. 01 (b)	2.2	3.7	1316.33	587.07	–8.103
7 Feb. 01 (b)	2.5	0.15	259.82	179.04	–0.897
8 March 01 (b)	2.4	0.01	445.79	429.51	–0.181
5 April 01 (b)	1.8	0.03	76.15	66.19	–0.111
8 May 01 (f)	2.6	0.01	483.99	968.79	5.387

(b) Degraded backwater mangrove forest inlets;
(f) moderately degraded frontwater mangrove forest inlets.

of the organic sediment occurred in spring tide during both wet and dry season and during neap tide in wet season. The export of the total sediment occurred in the dry season during neap tides.

Considering the flood and ebb sediment flux differences (see Tables 3 and 4), it was found that, the frontwater zone mangrove forest traps, on average, about 65% of the incoming sediments. In the backwater zone mangrove forest, the net sediment trapping is highly variable as it ranges from 3 to 76 %, but the average is about 30%. In heavily vegetated Australian mangrove forest, 80% of the incoming sediments are trapped within the mangrove forest (5, 11), and in these heavily vegetated Australian mangrove forests, the peak sedimentation rate is 270 g m^{-2} $tide^{-1}$ (5, 11), which is much higher than that at Mwache creek, which is about 63 g m^{-2} $tide^{-1}$. In Mexican mangrove forests, the rate of sediment export is 210 g m^{-2} yr^{-1} (19). In salt marshes, net TSS import range from 0.034 to 0.44 g m^{-2} hr^{-1} (18), which assuming that the inundation period is 4 hrs, is equivalent to net sediment import ranging from about 0.1 to 2.0 g m^{-2} $tide^{-1}$. The relatively low sediment trapping efficiency at Mwache creek was attributed to the low mangrove forest vegetation cover.

SEDIMENT DYNAMICS IN THE MAIN CHANNEL

Frontwater Zone Main Channel

Resuspension of the fine bottom sediment was dominant in the frontwater zone main channel where a significant increase in TSSC occurred as velocity rose above 0.25 m s^{-1} (Fig. 7a). The TSSC in the frontwater zone also varied at tidal frequency and there was also a neap-spring variability. The TSSC was relatively much higher during spring tide (> 0.20 g L^{-1}) as compared to neap tides. The strong tidal currents greater than 0.50 m s^{-1} caused resuspension of fine sediment at tidal frequency. The ebb sediment fluxes were high as they reached as high as 0.31 kg m^{-2} s^{-1} while the flood ones attained values of the order 0.1 kg m^{-2} s^{-1}. In dry seasons, the resuspension of the fine sediment was relatively larger in ebb tide than in flood tide. This caused net sediment export in the frontwater zone main channel. During periods of high resuspension, the net sediment export reached as high as 0.8 kg m^{-2} s^{-1}.

Backwater Zone Main Channel

The results of TSSC monitoring revealed that there is a neap-spring TSSC cycle in the backwater zone (Fig. 7b). The spring peak TSSC were generally greater than 0.5 g L^{-1} while the neap concentrations were less than 0.5 g L^{-1}. The highest sediment fluxes also occurred during spring tide when TSSC and current velocities were greater than 0.1 g L^{-1} and 0.25 m s^{-1}, respectively. As in the frontwater zone, the TSSC variability was also at tidal frequency. However, as compared to the frontwater zone where TSSC increased as current velocity increased, TSSC decreased as current velocities and elevation increased. The peak TSSC occurred at low tide or at the very last stages of the ebb tide (Fig. 7b). The ebb sediment fluxes were on average basis much higher as they ranged from 0.025 to 0.31 kg m^{-2} s^{-1} as compared to the flood tide sediment fluxes, which ranged from 0.01 to 0.16 kg m^{-2} s^{-1}. There is therefore a sustained net sediment export to the frontwater zone main channel of the creek. This export was further reinforced during periods of high river discharge because of the occurrence of frontwater zone directed residual current.

DISCUSSION

Most of the terrigenous sediments discharged into the creek by Mwache River are trapped within the backwater zone of the creek. The mechanisms of trapping within the main channel are related to tidal pumping as well as to estuarine circulation. Within the estuarine zone located above station 1, the classical estuarine circulation develops in periods of relatively high river discharge (Fig. 4a). Also sediment flocculation is important in the trapping of different classes of sediments. Because of their high settling velocities, the flocculated clay sediments are deposited rapidly within the main channel in the backwater zone while the silty sediments are transported downstream to the frontwater zone. The silty sediment eventually settle in the frontwater zone main channel during periods of sluggish current velocities during neap tide. However, during spring tide when strong spring-tide currents in the order of 0.85 m s^{-1} are experienced, the fine channel-bed sediments in the frontwater zone are resuspended and advected into the surface water column leading to the formation of the frontwater zone TMZ (Figs 4b and 5b).

The occurrence of high TSSC within the inlets draining the mangrove forest at the early stages of flood tide and subsequent decline as the water volume in the wetland increases can be attributed to the progressive settling of flocculated sediment and the influx of low TSSC water from the main channel. The lowest TSSC within the mangrove inlets occurred at high tide when most of the resuspended sediments have settled within the main channel or have entered into the frontwater zone mangrove forest. During ebb tide, the patterns of TSSC variations at the degraded Mwache mangrove forest were different from those described in heavily vegetated Australian mangrove forests (5, 11). At Mwache mangrove forest, instead of a sustained decrease of TSSC, there was instead a progressive increase in TSSC with the peak ebb tide TSSC occurring at the last stages of ebb tide. The ebb tide peak TSSC was much higher than the peak flood tide TSSC. Field data showed that the peak velocities and TSSC occurs when tidal elevation and tidal discharges are extremely low, particularly during the late stages of the ebb tide (see Figs 6a and 6b). In general, the average ebb sediment fluxes were much lower than the flood ones. On the other hand, the peak flood tide TSSC occurred when velocities, tidal elevation and, therefore, tidal discharges were high, resulting in high mean flood tide sediment fluxes in the frontwater zone mangrove forest. Relatively high flood tide TSSC is essentially not due to resuspension of fine sediment within the mangrove forest inlets, but can be attributed to *i*) the resuspension within the main tidal channel, which occurs adjacent to the mangrove forest; and *ii*) the inflow of highly turbid water trapped within the main channel in the backwater zone.

The net import of both of inorganic and organic sediments in both frontwater and backwater zone mangrove forest, occurs in most periods of the year in spring tides. However, the magnitude of import is much lower in the highly degraded backwater

Figure 7a. TSSC variation in relation to tidal current velocities and sediment flux at station 6 in the period between June 21–July 7, 2001.

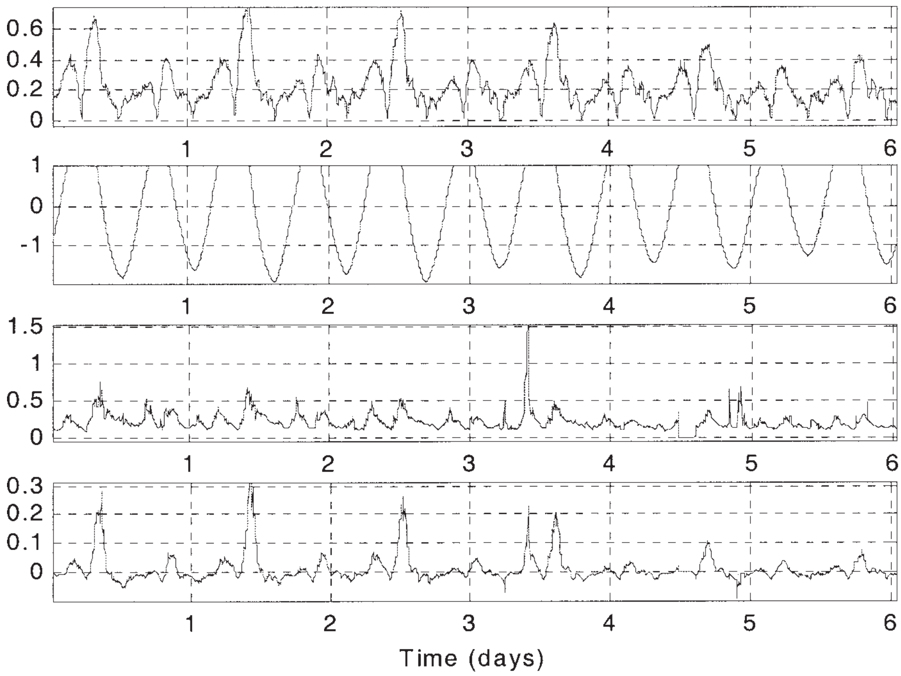
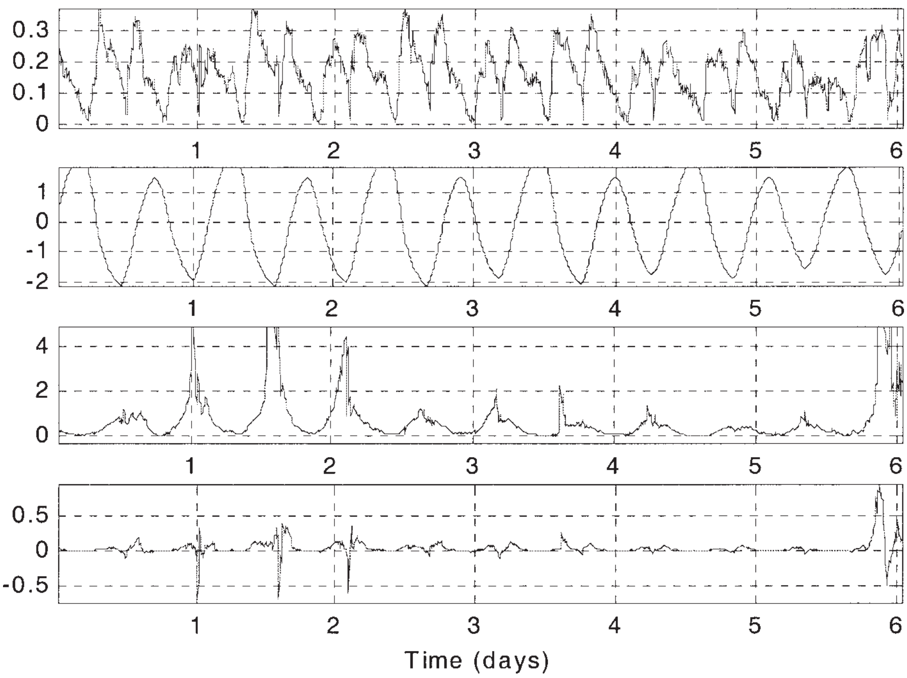


Figure 7b. TSSC variation in relation to tidal current velocities and sediment flux at station 1 in the period between June 21–July 7, 2001.



zone mangrove forest and is relatively higher in the moderately degraded frontwater mangrove forest. In both cases, net import is greater when tidal range is high and also when TSSC is high in the main channel. The trapping of sediment in the mangrove forest was attributed to the presence of mangrove vegetation as well as to the gentle slope. These induce friction on the flow, so that the resultant flow velocities within the mangrove forest are extremely low as they range from 0.005 to 0.20 m s^{-1}. The discharge of river water is also important as it results in relatively high water level within the main channel and therefore low tidal range in the mangrove forest. This causes the horizontal pressure gradient between the mangrove forest and the main channel to be low. In such cases, the ebb tidal flow tends to be weaker than flood ones, thus favoring net trapping of incoming sediments in the mangrove forest. It is important to note that, trapping of particulate inorganic sediments in the degraded mangrove forest zone, causes net build up of wetland sediment thus ensuring that the wetland keeps pace with sea-level rise. The finding of this study thus reinforces the knowledge that mangrove forests act as sediment traps (7–10). However, it is emphasized that although the trapping of incoming sediment is also important in degraded mangrove forests, the trapping efficiency is relatively low compared to that in highly vegetated pristine mangrove forests.

Trapping of sediment by the mangrove forest is important because it prevents the siltation of the main tidal channel and also reduces the export of sediment to the critical ecosystems (e.g. coral reef and seagrass meadows) located within the continental shelf of the Indian Ocean. Along the East African coast, mangrove forests are increasingly being degraded as a result of both natural and anthropogenic driven pressures. Population increase and poor land-use activities in river basins have in the recent past increased soil erosion which has consequently led to a large volume of sediments being discharged into the mangrove creek systems along the Kenyan coast. Apart from the threats related to the degradation of the river basins, wanton destruction of mangrove forests through excessive harvesting is also harming the long-term sustainability of the mangrove systems. This then calls for concerted integrated management of both the river basins and the associated mangrove-fringed creek wetlands.

CONCLUSIONS

This study on sediment exchange in Mwache creek showed that in the dry season, the occurrence of flood-tide dominance, estuarine circulation and flocculation in the backwater zone promotes the trapping of clay sediment in the backwater zone of the creek. The peak suspended sediment concentrations in the backwater zone main channel occur at low tide when current velocities are sluggish, but the peak TSSC in the frontwater zone occurs during periods of peak current velocities. The resuspension of fine sediments in the frontwater zone main channel is more dominant, compared to the backwater zone, because current velocities are of high magnitude (0.85 m s^{-1}) in the frontwater zone compared to those in the backwater zone main tidal channel, which are relatively low (0.50 m s^{-1}). The peak TSSC and POSC in the backwater zone main channel occur during low tide and during later stages of ebb tide. In the frontwater, the peak TSSC and POSC occur when tidal current velocities are at their peaks particularly at the mid-stages of ebb and flood tide. The intensity of sediment exchange between the main channel and the mangrove forest varies with tidal range and sediment concentrations in the main channel. Both the degraded backwater and frontwater mangrove forests trap suspended sediment at a rate of 30% and 60%, respectively. It is thus concluded that degraded mangrove forest sediment trapping efficiency is low and there is no complete trapping of the incoming sediment.

References and Notes

1. Kitheka, J.U. 1996. The dynamics of Mwache river basin sediment production and discharge and he flux of terrigenous sediments into the Port-Reitz creek, Kenya. *WIOMSA MARG 1 (SC-298-012-5) Report*.
2. Kitheka, J.U. 1996b Coastal tidally driven circulation and and the role of water exchange in the linkage between tropical coastal ecosystems. *Estuar. Coastal Shelf Sci. 45*, 177–187.
3. Kitheka, J.U. 1998 Groundwater outflow and its linkage to coastal circulation in a mangrove-fringed creek in Kenya. *Estuar. Coastal Shelf Sci. 47*, 63–75.
4. Kitheka, J.U., Cederlof, U. and Rydberg, L. 2000. Ebb-flood tide suspended sediment transport and import in a mangrove creek in Kenya. *J. Coastal Res*. (In press).
5. Furukawa, K., Wolanski, E. and Mueller, H. 1997. Currents and sediment transport in mangrove forest. *Estuar. Coastal Shelf Sci. 44*, 301–310.
6. Wolanski, E., Jones, M. and Bunt, J.S. 1980. Hydrodynamics of a tidal-creek mangrove swamp system. *Austral. J. Mari. Freshwater Res. 31*, 431–450.
7. Wattakayakorn, G., Wolanski, E. and Kjerfve, B. 1990. Mixing, trapping and outwelling in the long Ngao mangrove swamp, Thailand. Estuar. *Coastal Shelf Sci. 31*, 667–688.
8. Wolanski, E., Mazda, Y., King, B. and Gray, E. 1990. Dynamics, flushing and trapping in Hinchinbrook channel a giant mangrove swamp, Australia. *Estuar. Coastal Shelf Sci. 31*, 555–579.
9. Wolanski, E. and Ridd, P.V. 1986. Tidal mixing and trapping in mangrove swamps. *Estuar. Coastal Shelf Sci. 23*, 759–771.
10. Wolanski, E., Mazda, Y., Furukawa, K., Ridd, P., Kitheka, J., Spagnol, S. and Stieglitz, T. 2001. Water-circulation in mangroves and its implications for Biodiversity. In: *Oceanographic Processes of Coral Reefs: Physical and Biological Links in the Great Barrier Reef*. Wolanski, E. CRC Press, London. pp. 53–76.
11. Furukawa, K. and Wolanski, E. 1996. Sedimentation in mangrove forests. *Mangroves Salt Marshes 1*, 3–10.
12. Henle, D.R. and Flemer, A. 1976. Flows of materials between poorly flooded tidal marshes and an estuary. *Mar. Biol. 35*, 359–373.
13. Stevenson, J.C., Ward, L.G. and Kearney, M.S. 1988. Sediment transport and trapping in marsh systems: implications of tidal studies. *Mar. Geol. 80*, 37–59.
14. Bryce, S., Larcombe, P. and Ridd, P.V. 1998. The relative importance of landward-directed tidal sediment transport versus freshwater flood events in the Normady River estuary, Cape York Peninsula, Australia. *Mar. Geol. 149*, 55–78.
15. Spurrier, J.D. and Kjerfve, B. 1988. Estimating the net flux of nutrients between a Salt marsh and a tidal creek. *Estuaries 11*, 10–14.
16. Kjerfve, B. 1990. *Manual for Investigation of Hydrological Processes in Mangrove Ecosystems*. UNESCO-UNEP Regional projects: Research and its application to the management of the mangroves of Asia and the Pacific. RAS/86/120/UNESCO/COMAR/UNEP. 77 pp.
17. Wolaver, T.G., Dame, R.F., Spurrier, J.D. and Miller, A.B. 1988. Sediment exchange between a euhaline salt marsh in South Carolina and the adjacent tidal creek. *J. Coastal Res. 4*, 17–26.
18. Childers, D.N. and Day, J.W. 1990. Marsh-water column interactions in two Louisiana estuaries. I. Sediment dynamics. *Estuaries 13*, 393–403.
19. Rivera-Monroy, V.H., Day, J.W., Twilley, R.R., Vera-Herrera, F. and Coronado-Molina, C. 1995. Flux of nitrogen and sediment in a fringe mangrove forest in Terminos Lagoon, Mexica. *Estuar. Coastal Shelf Sci. 40*, 139–160.

20. This study was made possible through research grants issued by the International Foundation for Science (IFS Grant A/2716-2F) and the Kenya-Belgium VLIR-IUC-UON project. Maurice Obiero and Patrick Nthenge assisted with the field and laboratory investigations. Prof. Lars Rydberg and Dr. Ulf Cederlöf of Gothenburg University, Sweden, are thanked for their support.

Johnson U. Kitheka is a senior research scientist at the Kenya Marine and Fisheries Research Institute. His area of specialization is land-river-ocean interaction including tidal and estuarine circulation. His address: Ecology and Environment Research Programme, Kenya Marine and Fisheries Research Institute, P.O. Box 81651, Mombasa, Kenya.
E-mail: Jkitheka@recoscix.org

George S. Ongwenyi is an associate professor in hydrology and the coordinator of the Postgraduate Hydrology Programme of the University of Nairobi, Kenya. His area of specialization includes research on hydrological dynamics and sediment transport processes. His address: Postgraduate Hydrology Programme, Department of Geography, University of Nairobi, P.O. Box 30197, Nairobi, Kenya.
E-mail: gongwenyi@uonbi.ac.ke

Kenneth M. Mavuti is an associate professor in zoology and the coordinator of the Kenya-Belgium VLIR-IUC-UoN Project of the University of Nairobi. He specializes on the ecological dynamics of both freshwater and marine wetlands. His address: Department of Zoology, University of Nairobi, P.O. Box 30197, Nairobi, Kenya.
E-mail: kmavuti@uonbi.ac.ke