Estuarine, Coastal and Shelf Science (1998) **47,** 63–75
Article No. ec980325

Groundwater Outflow and its Linkage to Coastal Circulation in a Mangrove-fringed Creek in Kenya

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Received 9 July 1997 and accepted in revised form 26 November 1997

Research into groundwater outflow and tidal circulation was undertaken in a 32 km^2 mangrove-fringed tropical creek in Kenya. The study involved measurement of the groundwater level, storage and outflow, tidal currents, salinity and temperature. The study shows that groundwater outflow in the creek occurs within the main tidal channels and is not restricted along the shoreline. Groundwater outflow is evidenced by: (1) the occurrence of vertical salinity anomalies; (2) ebb–flood tide salinity differences; (3) occurrence of groundwater in shallow wells a short distance from the mangroves; and (4) enormous groundwater recharge and storage in the Mida basin. Vertical salinity anomalies are characterized by the presence of a lens of low salinity water at the bottom water column and higher salinity at the surface. It is believed that this occurs since no major density differences develop despite vertical salinity differences of up to 1·58, possibly as a result of uniform distribution of water temperature vertically. In drought conditions, seepage reduces and hypersaline conditions (salinity in the range of 36·89 to 38·57) which mask groundwater outflow, develop in the backwater region as a result of intense evaporation and restricted circulation. The strong currents reaching 2·5 m s^{-1} occur in the frontwater zone and enhance the tidal flushing while lower currents <0·5 m s^{-1} occur in the backwater zone and promote trapping of water which thereby increase the residence time to 11 days. With flood currents being more dominant than ebb currents in the main creek channel, the seaward export of material derived from groundwater is limited.

Keywords: groundwater circulation; salinity anomalies; ebb- and flood tide currents; Kenya coast

Introduction

The outflow of groundwater into tropical coastal waters has long been thought to be important in the long-term sustainability of coastal and marine ecological systems (Valiela *et al.*, 1978). However, the interconnectivity between groundwater outflow and coastal water circulation is currently not well understood and not many studies have been undertaken to investigate and understand this linkage in the tropics (Kjerfve, 1994; Bokuniewuicz, 1980). In coastal lagoons with few natural streams, groundwater flow is thought to contribute a substantial fraction of the total freshwater input (Kjerfve, 1994; Smith, 1994; Bokuniewuicz, 1980). Groundwater seepage has been shown by Pandit and El-Khazen (1990) to be an integral part of lagoon hydrography, but as a result of difficulties in quantifying the actual flow, the subject, despite its significance has received very little attention among marine scientists (Pandit & El-Khazen, 1990). Bokuniewuicz (1980) made *in situ* measurements to record groundwater outflow through the sediments of Great South Bay along the south shore of Long Island, New York and found that although groundwater outflow occurs, there is a decrease in the seepage rate from the shore into the bay. Seepage was greatest on the land-ward side of the bay in a band several tens of metres wide running parallel to the shore. It was, however, not clear whether any seepage occurs within the channels of the bay.

In the evaluation of the role of groundwater outflow in coastal areas, research must, out of necessity, integrate terrestrial hydrological processes with coastal circulation processes. This therefore emphasizes the significance of multi-disciplinary approach to the study of groundwater outflow and its interconnection with the tidal dynamics and currents. Most research has been focused on the understanding of the groundwater aquifer dynamics, with very little consideration given to significance of the total groundwater flow on coastal circulation dynamics (Ferris, 1950; Banmann, 1953; Glovers, 1959, 1964; Bear & Dagan, 1963; Gardner & Kitchens, 1978; Raghunath, 1990). The extent to which groundwater outflow would influence (through supply of nutrients and other geo-chemicals) coastal marine ecosystems depends on the

The study on coastal hydrological processes and circulation in Mida Creek, conducted under the auspices of the Kenya Wildlife Service (KWS)–Kenya Marine & Fisheries Research Institute (KMFRI)–Mida Creek biodiversity project. May, 1996–June, 1997.

0272–7714/98/010063+13 $30.00/0

hydrodynamic processes within a mangrove creek. Studies by Wolanski *et al*. (1980), and Wolanski (1986) have demonstrated the physical processes that promote the trapping of brackish water in tropical mangrove estuaries. Coastal tidal dynamics, currents and water exchange patterns may promote or limit mixing and exchange of groundwater with tidal waters, and eventually between inshore and the offshore waters (Kjerfve, 1978) where seagrass beds and the coral reef ecosystems are found (Kitheka, 1996; Kitheka *et al*., 1996). Glovers (1959, 1964) has demonstrated the dynamic linkage between groundwater outflow and subterranean marine circulation. According to Glovers (1964) groundwater outflow occurs as a result of the interaction between subterranean marine circulation and groundwater circulation within the coastal aquifers. Hydraulic pressure and water density differences induces a net groundwater outflow which therefore occurs in a small zone where seawater–groundwater interphase emerges at the low tide margins of a beach. Below this interphase, there is a net landward flow of subterranean seawater and above it, is a net seaward flow of brackish groundwater. In this study, it is shown that groundwater seepage could also occur in the tidal channels and is not therefore concentrated just along the lower margins of the beach. However, not much is currently known as to the influence of this seepage on salinity and nutrient distribution in coastal waters (Gordon *et al*., 1996). Such influences greatly depend on the rate of groundwater discharge as well as its volume, water circulation and exchange processes in the coastal areas. Certainly, the study of groundwater outflow into the semi-enclosed tropical seas will be incomplete without establishment of the local hydrodynamic conditions. Hence, in this research, the two systems (groundwater and marine circulation) are treated together with a view to establishing the extent to which each of these systems responds to changes in another system. The objective of the present study is therefore to establish the significance and involvement of groundwater outflow in the overall coastal circulation processes. The extent to which land use, and channel bed alterations affect the linkage between the two systems is also dealt with.

The study area

Mida Creek (03°22′72″S and 039°58′20″N) is located in the north coast region of Kenya, approximately 100 km north-east 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 partly sustained by groundwater outflow. 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 occur near the entrance and control water exchange. Apart from the mangroves situated in the north, there are seagrass beds and a coral reef in the offshore water in the central and lower region of the creek. The mangroves are flanked landward by Arabuko–Sokoke forest (GOK, 1989; TARDA, 1983). 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 total annual rainfall is 1041 mm with over 60% of the rain occurring in the April–June period during the south-east monsoon. Less than 40% falls in the October–December period during the north-east monsoon (GOK, 1989). The creek is an important marine protected area as it is part of Watamu Marine National Park and Reserve under the management of Kenya Wildlife Service.

Materials and methods

Circulation and hydrography

Seven hydrographic stations shown in Figure 1 were set-up for measurement of currents, salinity, conductivity, temperature and bathymetry. Two transects were set across stations 6 and 2 at the creek entrance and in the middle part of the creek, respectively, for determination of volume fluxes during ebb and flood tides. Currents were measured in all these stations using drogues, Ottmolen and Toho Dentan current meters, while water salinity and temperature were measured using an Aanderaa salinity–temperature meter model 3315 (salinity and temperature accuracy: 0·01 and 0·01 °C), respectively. Conductivity was measured with a WTW conductivity meter (conductivity accuracy 0·1 mS cm^{-1}). These parameters were measured *in situ* at 0·2 *d*, 0·6 *d* and 0·8 *d* (where *d* is the water depth) from a flat-bottomed 5 m fibre-glass boat. Tidal elevations and water depths were determined using a tide pole and Plastimo echo-sounder, respectively. The measured depths were used to plot a generalized bathymetric chart shown in Figure 1. The tidal discharges in ebb and flood tides were determined in the two transects through measurement of current speed in four stations across the transect, and multiplying the mean current speed with the cross-sectional area to obtain tidal discharge. These methods are discussed in detail in Kjerfve (1978,

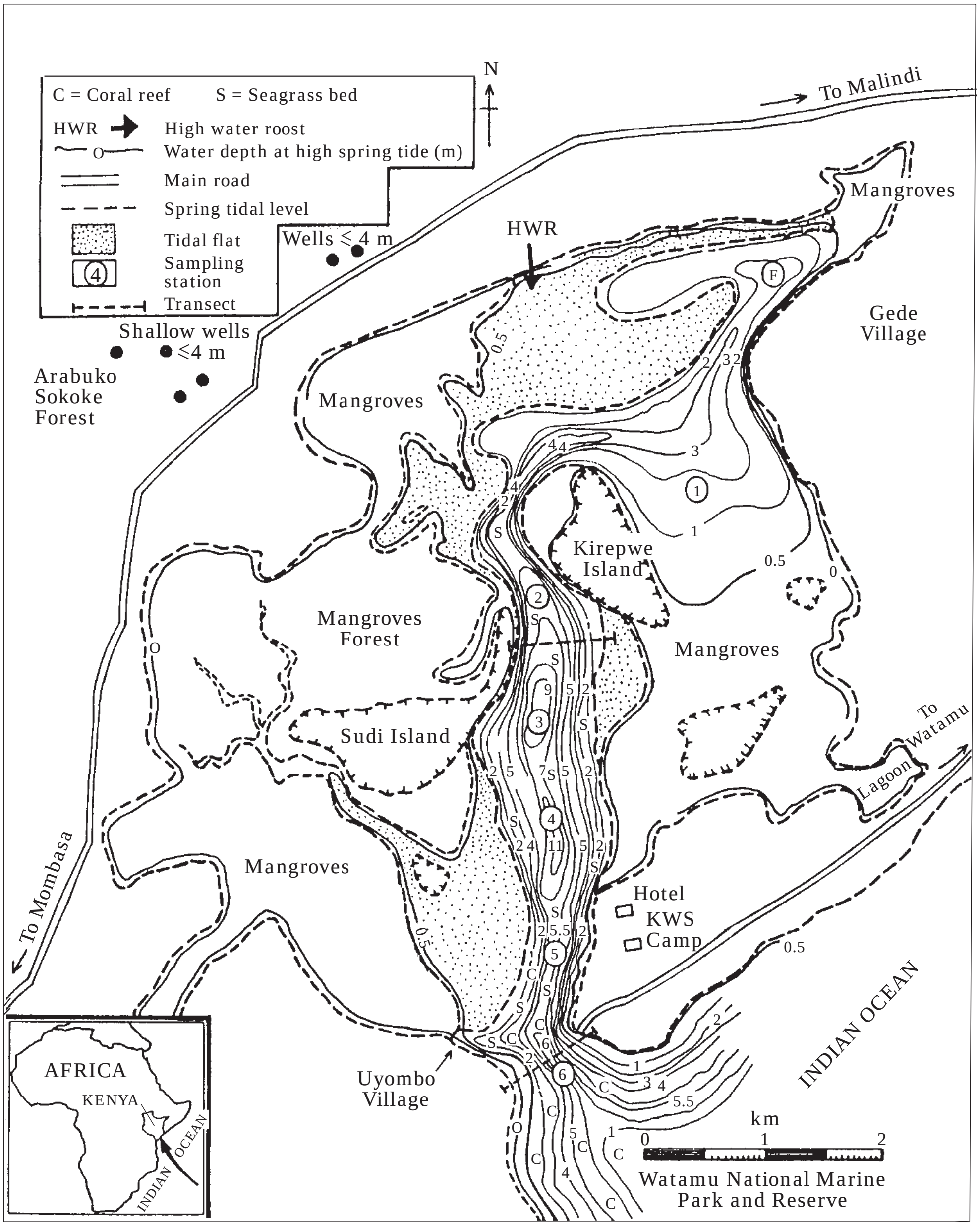

FIGURE 1. The location of Mida Creek in Kenya and the general bathymetry. The locations of the seagrass beds and the coral reef ecosystems as well as the main hydrographic stations are also shown.

1994), Smith (1994), Heinle and Flemer (1976), Swenson and Chuang (1983), and in Pond and Pickard (1983). Hydrographic measurements started in May 1996 and ended in April 1997. Sampling was carried out once a month and covered both neap and spring tides.

Water exchange

The exchange of water between different zones (backwater, frontwater and offshore zones) was determined using tidal prism and tidal flux methods. The modified tidal prism method involved the determination of water volumes in neap and spring tides using the mean spring and neap tidal ranges of 3·2 and 2·0 m measured with a tide pole at station 2. The tidal flux was computed as the exchange flux using the equation:

$$Q_o = (Axh)/(T/2) \qquad (1)$$

where A is the Creek's surface area (m^2), T is the tidal cycle (s), h is the tidal range (m) and Q_o is the oceanic water flux ($m^3\ s^{-1}$). Residence time (R in days) of water in the backwater and frontwater region of the Creek was calcualted using the relation:

$$R = V/Q \quad (2)$$

Groundwater Outflow

Groundwater outflow into Mida Creek was determined using methods described by Glovers (1964, 1959), Raghunath (1990) and Cooper (1964). A survey for the determination of groundwater level, total dissolved solids, temperature and salinity was conducted for the period July 1996–May 1997, mainly for wells located in the upper region of the Creek (Figure 1). Measurements were undertaken once per month using Aanderaa S-T meter and WTW LF 95 conductivity meter,

Groundwater storage was calculated using Walton (1990), Glovers (1964) and Raghunath's (1990) methods, represented as:

$$Q = A \times d \times S \quad (3)$$

where Q is the annual storage (m^3), d is the depth of groundwater fluctuation (m), and S is the specific yield of the aquifer. The specific yield of the aquifer was estimated using data from similar environments (GOK, 1989). The Creek area was determined from topographic maps at a scale of 1 : 50000. The groundwater discharge Q was calculated using:

$$Q = TiW \quad (4)$$

where Q is the groundwater flux (m^3 day^{-1}), T is the transmissibility (6×10^6 l day^{-1} m^{-1}), W is the aquifer width (m) and i is the infiltration rate (20% of rainfall). Glovers' (1964) equation described in Raghunath (1990) was used to determine the shape of the freshwater–seawater interphase. This equation is written as:

$$Y^2 - \frac{(2qX)}{K'} - \frac{q^2}{K'^2} = 0 \quad (5)$$

where when $X = 0$, $Y_o = q/K'$ and when $Y = 0$, $X_o = q/2K'$.

In the above equation, X_o is the width of gap through which groundwater escapes into the creek, X is the length of seawater intrusion and Y is the interphase depth (m), respectively. By establishing the co-ordinate distances (x,y) from the shoreline to any point in the interface, the freshwater supplied to the creek (q,Q) was determined. K' is the permeability rate which was determined from similar studies. The freshwater supplied to the creek is therefore calculated as:

$$q \approx \frac{(K'H^2)}{(2L)} = \frac{(K'y^2)}{(2x)} \quad (6)$$

Table 1. The mean monthly values of water temperature, salinity and conductivity at Mida Creek during the period May 1996–April 1997. The actual values on station basis are higher than the mean values provided in the table

Month	Mean temperature (°C)	Mean salinity	Mean conductivity (mS cm^{-1})
May 96	27·16	32·86	43·59
June	27·17	35·23	47·73
July	24·41	34·14	51·08
August	25·58	35·83	53·00
September	26·84	34·47	46·10
October	26·94	34·95	45·54
November	28·60	34·64	—
December	28·79	35·20	46·40
January 97	28·60	35·86	44·93
February	28·96	36·99	51·30
March	30·94	37·44	52·10
April	27·78	34·15	49·50

where (y) H is the depth to seawater–freshwater interphase (m), K is permeability (m day^{-1}) and (x) L is the intrusion length (m). The total volume of groundwater supplied to the creek is calculated as:

$$Q = q \times \text{permeable stretch of shoreline} \quad (7)$$

The width of gap through which groundwater escapes into the creek at the shore bottom is then calculated as:

$$X_o = q/2K' \quad (8)$$

The position of the tore to salt-water wedge was calculated as:

$$L = \frac{(K'H^2)}{(2q)} \quad (9)$$

For the determination of the depth to seawater–freshwater interphase, the Ghyben–Herzberg hydrostatic relation was applied. Computational methods of the interphase depth are discussed in detail by Raghunath (1990), Banmann (1953), Bear and Dagan (1963), Glovers (1964) and Cooper (1964).

Results

Hydrographic conditions and salinity anomalies

Table 1 shows the mean monthly values of water temperature, salinity and conductivity at Mida Creek during the May 1996–April 1997 period. The highest salinity in the range of 36·89 and 38·57 was recorded in the months of February and March 1997 in stations 1, 2, 3 and F in the backwater zone. This is attributed

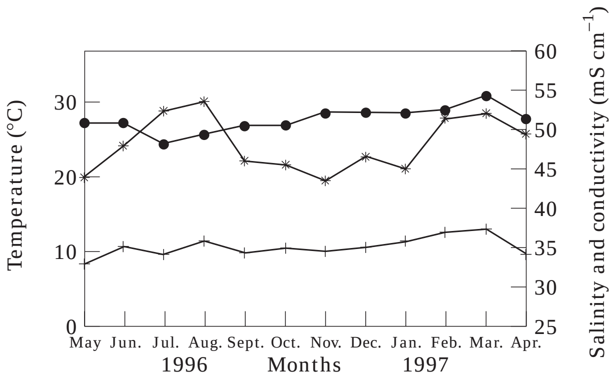

FIGURE 2 The variations of water salinity, conductivity and temperature between May 1996 and April 1997. Data represents the mean conditions in the creek. Temperature, —●—; Salinity, —+—; and Conductivity, —*—.

to high water temperature during the February–March period which ranged between 28·96 °C and 30·94 °C, and caused considerable heating of the water which enhanced evaporation to the tune of 7 mm day^{-1} and raised the salinity up to 38·57 (Figure 2). The effects of groundwater outflow were low as a result of reduced recharge during dry season and a small volume of groundwater discharged was quickly masked by major changes in water salinity. The lowest salinity and temperature were reported in the backwater zone of the creek. In the rainy season month of May 1996, water salinity and temperature ranged between 28·71 and 33·40 (monthly mean of 32·86) and 24 and 26 °C, respectively. The wet–dry season salinity range in the backwater region is high being 9·86 while in the frontwater region, it is only 2·61. The low temperature in July (24·41 °C) and August (25·58 °C) are associated with the influx of cool water-mass associated with the East African Coastal Current during the south-east monsoon (Table 1).

Data on differences between surface and bottom water salinity in stations with predominant groundwater outflow are shown in Table 2. The examination of data and spatial distribution of stations with vertical salinity anomalies showed that significant salinity anomalies are prevalent in stations 3, 2 and 1 in the backwater zone of the creek. The vertical salinity anomaly is essentially the difference between surface and bottom water salinity. In normal situations, the denser higher salinity water should occur within the bottom water column, while the relatively less dense water should be found at the surface water column as a result of buoyancy effects (Dyer, 1974; Wolanski *et al.*, 1980; Wolanski, 1986; Kjerfve, 1994). But, in Mida Creek, significant deviations from the traditional vertical distributions of water salinity were found, although the differences were not significantly very large. In these salinity anomalous conditions, a layer of relatively low salinity water is overlain by relatively higher salinity water. The highest vertical salinity anomaly was 1·58, but most anomalies were in the range of between 0·01 and 1·58 (Table 2). In conditions where these salinity anomalies occurred, there was no significant vertical temperature gradient.

Apart from vertical salinity anomalies, there were also flood–ebb tide salinity differences which are also linked to groundwater outflow. The ebb tides were characterized by relatively lower salinity as compared with flood tide. These differences imply an addition of a certain volume of brackishwater once the flood tide water enters the creek and this causes the lowering of salinity as a result of dilution effect. In the rainy season such a dilution could be a result of combined influences of groundwater outflow and surface runoff,

TABLE 2. The difference between surface and bottom water salinity in stations with predominant groundwater seepage

	1996						1997			
Station	29/5	17/6	18/6	21/7	28/8	29/8	12/2	18/3	28/4	Means
6					0·05	0·05	1·15		0·18	0·46
5		0·03	0·09	0·15			0·05			0·08
4	0·40		0·04	0·16	0·01	0·01				0·15
3	1·27	0·09		0·13	0·48	0·48		0·04		0·40
2			1·58	0·24	0·26	0·26		0·44	0·08	0·48
1	1·39	0·18		0·13	0·27	0·27		1·61	0·61	0·64
F	0·38	0·22		0·13			0·27			0·25
M				0·13	0·13	0·13	2·00		0·20	0·19
Mean	0·86	0·13	0·57	0·18	0·20	0·20	0·49	0·70	0·30	

Significant salinity anomaly occurs in stations 3, 2 and 1 in the backwater region of the creek.

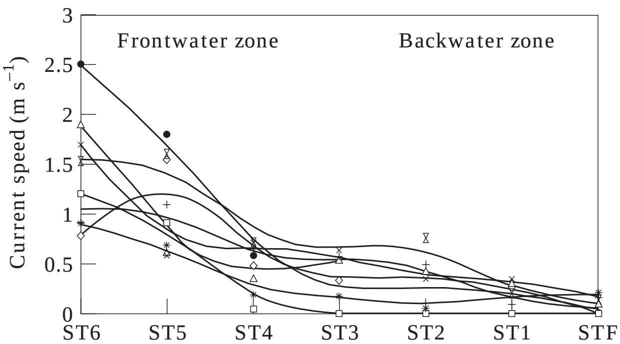

FIGURE 3. The distribution of the tidal current magnitudes in the frontwater and backwater zones of the creek. Lines represent the current magnitudes in various dates. 13/10/96, —●—; 14/10/96, —+—; 30/8/96, —✱—; 29/8/96, —□—; 29/8/96, —✖—; 30/7/96, —◇—; 28/7/96, —△—; 29/7/96, —⧗—.

but in dry periods of the year, these differences are entirely due to the effects of groundwater outflow. Typical flood–ebb tide salinity differences in dry season range between 0·02 and 1·72. In wet season however, these differences were much greater as they ranged between 0·89 and 2·13.

Figure 4 shows the tidal current patterns in different periods and as well as variations with the semi-diurnal tide at station 2. The higher magnitude currents occasionally reaching 2·5 m s^{-1} were measured in stations 6 and 5 in the frontwater zone (Figures 3 and 4). The lower magnitude currents which seldom reach 0·6 m s^{-1} occur in the backwater zone of the creek (stations 3, 2, 1 and F). The examination of current patterns showed that ebb tides are dominant in terms of duration, since they take a long period ranging from 6 to 9 h. But they are weaker in terms of magnitude since they only reach 0·50 m s^{-1} on average basis, whereas the mean flood tide currents reach 0·80 m s^{-1} (Figure 4). The flood tide currents are dominant in terms of magnitude as they have a mean of 0·80 m s^{-1}, but are of shorter duration ranging between 5 to 7 h. This is, therefore, a clear case of tidal current asymmetry where flood currents are dominant more than the ebb currents in terms of current magnitude. The prevalence of flood dominance in the creek is clearly evidenced by the distribution of carbonate sands which generally emanates from the coral reef complex offshore and are found right into the backwater zone of the creek in stations 2 and 1. This shows that carbonate sands are imported into the creek from offshore waters by a net inshore-directed flow.

Groundwater recharge and outflow

The total Mida Creek groundwater catchment covers an area of 700 km^2 and is dominated by sandy soils with ample rainfall of about 1041 mm and good infiltration rate (cf. Carruthers, 1995). There are seven shallow wells located about 150 m from the mangrove-fringed shoreline in the upper parts of Mida Creek. These wells provide the local inhabitants with water for domestic and livestock watering purposes. Groundwater abstraction rate is about 5000 l per day. The current rate of exploitation of groundwater is low as a result of low population and the availability of piped water supply in the area that supplements groundwater-based supply (GOK, 1989).

Table 3 presents data on groundwater physical and chemical parameters (salinity, temperature, conductivity and total dissolved solids) measured in shallow wells in the upper parts of the creek. There were no major variations in the levels of physical and chemical parameters. The wells in the upper parts of the creek are shallow with the water-table occurring 2–2·5 m below land surface in dry season. In wet season, the water table rose to 0·5 m below land surface. Groundwater was normally characterized by low salinity ranging from 0·10 to 0·48 and low conductivity ranging from 501 to 940 mS cm^{-1}. The dry–wet season groundwater level variation was seldom more than 1·0 m implying that the annual groundwater storage changes by about 50%. This is basically an indication of low groundwater abstraction and evapo-transpiration losses.

The annual groundwater storage calculated using the specific yield of 10%, depth of groundwater table fluctuation of 1·0 m and basin area of 700 km^2, yields an annual storage of 70×10^6 m^3 $annum^{-1}$ which is approximately equivalent to 50% of the total volume of water in Mida Creek. The annual recharge through annual rainfall of about 1000 mm is estimated to be 7×10^6 m^3 $annum^{-1}$. This means that rainfall recharge is equivalent to 1% of the total groundwater storage. While rainfall seems to be the main mode of groundwater storage replenishment in the Mida basin aquifer, seepage from effluent River Sabaki as it flows through porous coastal sedimentary formations could also be another mode in which recharge occurs.

The groundwater outflow to Mida Creek was determined according to Glovers' (1964) and Raghunath's (1980) methods. Glovers' (1964) equation for the shape of the freshwater–saltwater interphase was applied as described in the methodology section. The seawater–freshwater interphase depth calculated using the Ghyben–Herzberg relation is 25 m. The distance of the interphase from the mangrove-fringed shore was found to be about 100 m which explains the occurrence of groundwater with relatively low salinity in shallow wells in the upper parts of the creek, approximately 150 m from the mangroves. Since the

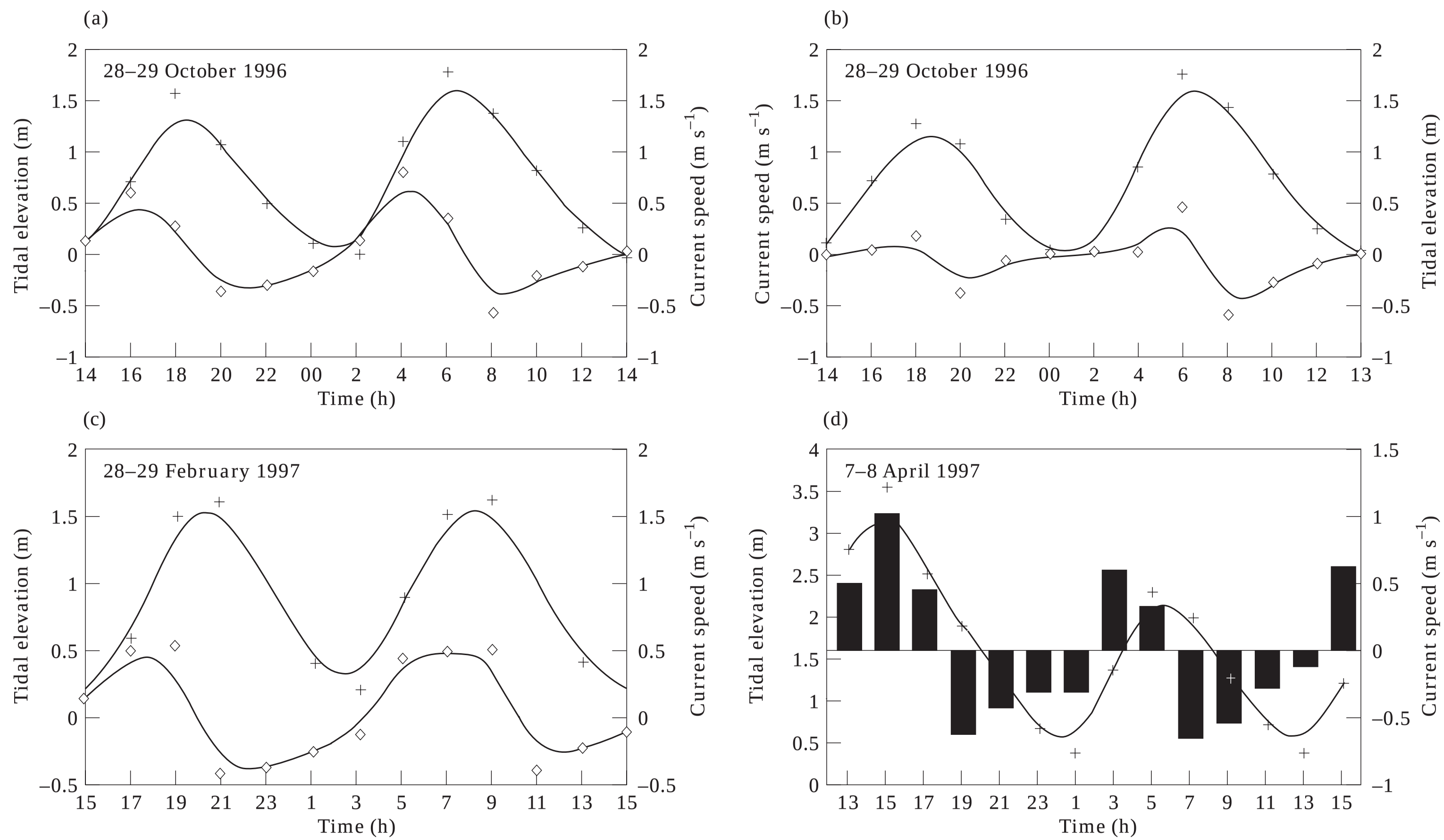

FIGURE 4. The patterns of tidal currents at station 2 in the main channel adjacent to Sudi Island. The upper right panel (b) represents current patterns in a mangrove channel. (a), (b) and (c): —+—, tidal elevation (m); —◇—, current speed (ms^{-1}). (d): —+—, tidal elevation (m); ■, current speed (ms^{-1}).

Table 3. The levels of groundwater physico-chemical parameters at Mtatani in the upper boundary of Mida Creek. Data represents conditions in dry and wet season conditions. The wells are located about 150 m from the mangrove-fringed shore

Date	Watertable depth (m)	Temperature (°C)	Conductivity (mS cm^{-1})	TDS (mg l^{-1})	Salinity (PSU)
Well A					
September 96	2·0	31·60	0·43	501	0·10
October 96	2·3	36·10	0·71	755	0·20
February 97	2·0	28·40	0·43	475	0·10
March 97	2·3	33·88	0·52	507	0·20
April 97	2·5	30·26	0·49	498	0·20
May 97	0·5	28·38	0·32	261	0·00
Well B					
September 96	2·0	34·10	0·47	668	0·30
October 96	2·3	36·10	0·71	755	0·35
February 97	2·2	28·60	0·80	940	0·48
March 97	2·2	33·31	0·67	803	0·48
April 97	2·0	30·47	0·93	896	0·41
May 97	1·0	27·00	0·32	326	0·14

depth of homogeneous aquifer is approximately 20 m and permeability is about 50 m day^{-1} it is possible to calculate the groundwater outflow. The results of computation gave a groundwater flow rate of 3·9 m^3 day^{-1} m^{-1} of shoreline. Groundwater discharge rate is normally expressed as per metre of the shoreline and the total groundwater outflow calculated using the above rate and 40 km perimeter is 156 000 m^3 day^{-1}. This total groundwater flow rate closely approximates a flux rate of 120 000 m^3 day^{-1} calculated using transmissibility of 6×10^6 l day^{-1} m^{-1} and infiltration of 20% of the annual rainfall. However, under the scenario of changed climate-reduced rainfall recharge and increased abstraction of groundwater as a result of population increase (UNESCO, 1993), there is high possibility of reduced groundwater outflow and increased seawater intrusion.

Discussions

The net groundwater flux in Mida Creek is seaward, and hence it is appropriate to determine its relationship with the water circulation since this determines its possible influence on hydrographic conditions. The calculated mean total daily groundwater outflow into the creek is 156 000 m^3 day^{-1} which when compared with the total high-water volume of the creek, is found to be a low volume representing 0·1% of the total creek water volume. According to Pandit and El-Khazan (1990), Kjerfve (1994) and Bokuniewuicz (1990), groundwater outflow commonly occurs in a narrow band along the shore. This band is normally only a few metres wide (Bokuniewuicz, 1980) and is referred to as the width of gap (Raghunath, 1980). Since the total perimeter through which seepage occurs is 40 km and the width of gap is about 1·6 m, the total area through which groundwater seepage occurs is estimated to be 64 000 m^2 which is roughly equivalent to about 0·2% of the total area of the creek. The outflow section does not, however, predominantly occur along the shore but extends into the tidal channels. Based on observations on the spatial distribution of stations with the vertical salinity anomalies, the active seepage zone could be located between stations 4 and 1 (Figure 5) and is not restricted along the shore as it has been reported elsewhere by Pandit and El-Khazen (1990). This observation is further supported by occurrence of vertical salinity anomalies and ebb–flood tide salinity differences in the main tidal channel of the creek. The significance of the groundwater outflow to the biotic functioning of the ecological systems at Mida Creek depends on: (1) the volume of groundwater supplied; (2) the residence time of groundwater; and (3) flushing mechanisms in the creek. The calculation of the groundwater turnover time was attempted by using the mean tidal volume conditions. After subtracting the tidal prism from the total volume, the spring and neap tide volumes reduce to $29{\cdot}4 \times 10^6$ m^3 and $44{\cdot}38 \times 10^6$ m^3 which allows the computation of turnover time using the total groundwater outflow per day. Since the total groundwater discharge in a 40 km perimeter is 156×10^3 m^3 day^{-1}, the calculated residence time is 188 days or roughly 6 months. These results show that groundwater-mixed backwater zone water is trapped and progressively exchanged slowly with the front waters. The low magnitude currents and a relatively small tidal range promote less efficient water circulation which reduces the flushing rate in the backwater zone and forces groundwater to remain in the mangrove-fringed zone for a relatively long period compared with the tidal water. The trapping of water in the upper parts of the creek is also enhanced by onshore north-east and south-east monsoon wind and long-shore currents which tends to confine the water along the mangrove-fringed shores. This probably explains why mangroves are able to survive in the creek despite occasional absence of the river discharge. Wolanski (1986) and Wolanski *et al.* (1980) have previously shown the trapping of tidal water in mangrove wetlands of Northern Australian creeks. This trapping retains river runoff from seasonal streams in the mangrove wetland and therefore sustains the mangroves. The trapping of groundwater-mixed backwater means that the mangroves at Mida Creek are never stressed for significantly long periods since there is a constant supply of brackish water which is necessary for their survival. In the absence of river discharge, the occurrence of dense mangrove vegetation would not have been possible. Seepage of groundwater in this region cause vertical salinity anomalies characterized by the presence of a layer of a relatively low salinity water at bottom water column and higher salinity in the surface water column. In stratified lagoons and estuaries, high salinity water occurs at the bottom water column and the low salinity water derived from river runoff occurs at the surface water column as a result of water density differences (Dyer, 1974; Pond & Pickard, 1983; Beer, 1993). But it was surprising that the anomalous non-estuarine conditions persisted throughout the sampling period at Mida Creek, even when there were significant spatial differences in the intensity of seepage between stations [Figure 5(a,b)]. This anomalous condition is not unexpected in a situation where significant seepage of ground-water occurs at the bottom of the channel (Cooper, 1964; Glovers, 1964). Beer (1993) has reported that it is the water density that controls the vertical distribution of salinity. Where there are major vertical temperature and salinity differences, the less dense water should be found overlying more saline dense water. However, salinity increase of 1·0 produces much the same density change as a 4 °C decrease in temperature, and if salinity changes are low and there is no vertical change in water temperature, no significant density differences would develop between the surface and the bottom water column (Beer, 1993). During the period of the study the vertical distribution of temperature remained uniform for all stations with salinity anomalies, and therefore very low vertical salinity differences of less than 1·0 that were measured could not cause major vertical density differences. It is therefore possible to find in tropical creeks with significant groundwater seepage, a relatively higher salinity water being underlain by water of slightly lower salinity particularly where there is no significant vertical temperature gradient. It is however important to note that in the rest of the creek particularly in the frontwater zone water is vertically well-mixed and homogeneous. In the latter it seems that strong tidal currents enhance vertical mixing of the bottom and surface water through turbulent diffusion and advection. Low current speed in the backwater zone, allows vertical salinity anomalies to develop since there is less efficient mixing of the surface and bottom water columns (Figure 5). The finding of relatively low salinity water near the bottom as an additional evidence for groundwater inflow in the creek should however have a caveat that the salinity was measured with an Aanderaa salinity–temperature sensor which may be affected by the suspended sediments near the bottom. Also the sensor may give a false reading if it touches the bottom. However, there is a very low possibility of the effect of the latter since the sensor was always carefully raised at least 10 cm from the bottom during measurement and there was persistence of the salinity anomalous conditions throughout the sampling period.

Water exchange

In this section, water exchange features of the creek are evaluated in order to determine whether groundwater-mixed water occurring in the upper zones of the creek is exported to the offshore waters. This is one way of assessing the possible influence of groundwater outflow on seagrass beds and the coral reef ecosystems found in the lower zones of the creek. Besides the fact that the creek frontwater is constantly being exchanged and mixed with the offshore water, there is also exchange and mixing between the groundwater dominated backwater zone and frontwater zone. Table 4 presents data on the volume of water involved in exchange in neap and spring tides. Since water volume changes are principally a result of the tidal influences, water exchange rates were calculated based on spring and neap tidal ranges of 3·2 and 2·0 m for frontwater zone and 1·7 and 0·8 m for the backwater zone, respectively. The results showed that in spring tide, 69% of the creek water is exchanged with the offshore waters per tidal cycle and in neap tide, only 50% of the creek water is exchanged per tidal cycle. In the backwater zone, the exchange during spring and neap tide reduces to 57 and 32%, respectively. This is a relatively lower rate of water

TABLE 4. The water volume and water exchange rates within the frontwater and backwater zones (in parentheses) of Mida Creek. The calculations are based on estimated creek tidal ranges and mean depths during low and high waters of neap and spring tides

	High waters Mean spring	Low waters Mean neap
Tidal range	3·2 m (1·7 m)	2·0 m (0·8 m)
Volume	$73·6 \times 10^6$ (48×10^6) m^3	$60·0 \times 10^6$ ($37·5 \times 10^6$) m^3
Tidal prism	$51·2 \times 10^6$ ($27·2 \times 10^6$) m^3	$30·0 \times 10^6$ (12×10^6) m^3
Exchange rate	69% (57%)	50·0% (32%)

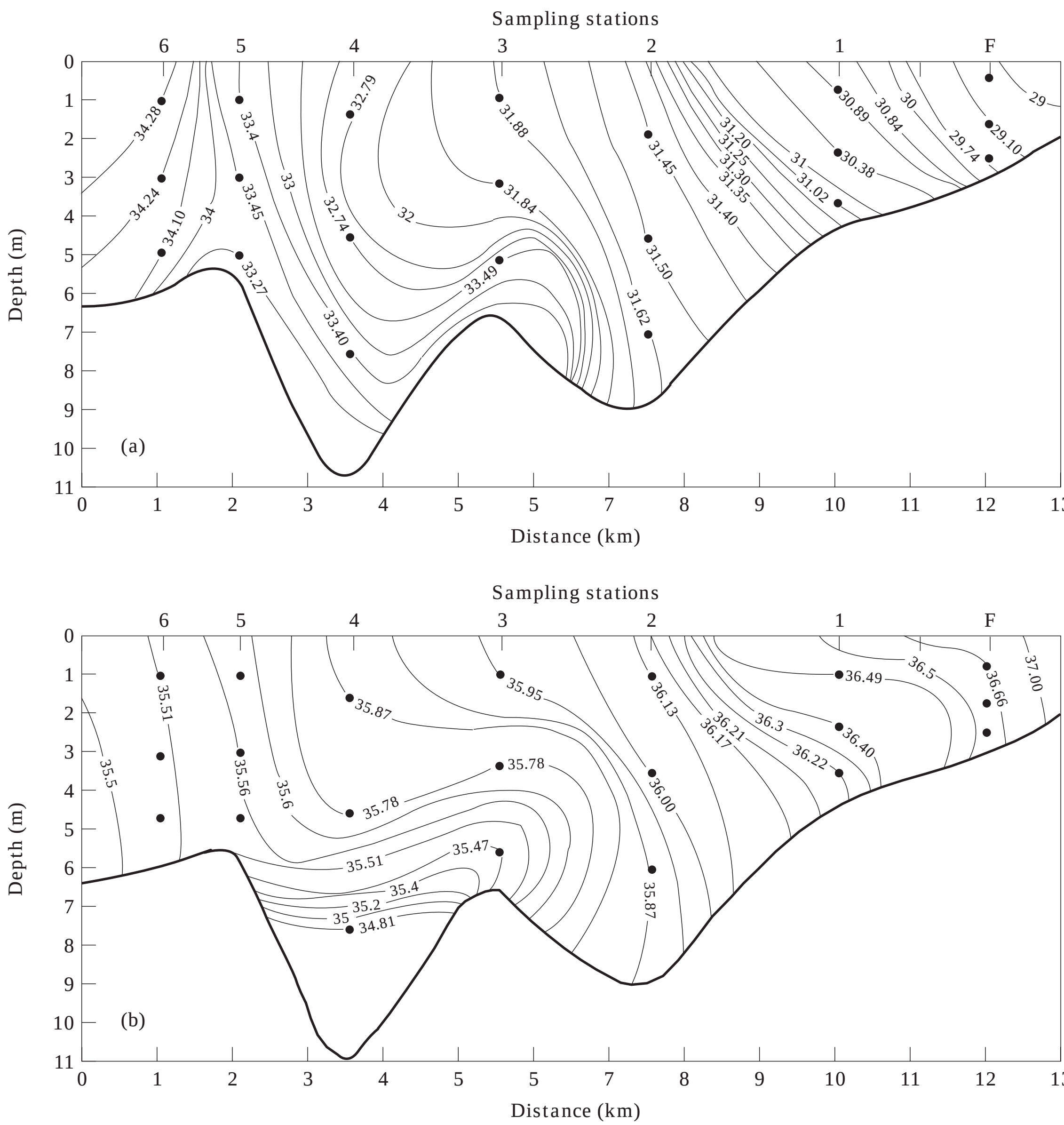

FIGURE 5. The synoptic view of the water column salinity structure in Mida Creek in (a) wet and (b) dry seasons.

exchange considering that, in a similar bay (Gazi Bay) on the south coast of Kenya, tidal water exchange rate is close to 90% per tidal cycle in spring tide because of the presence of a wide shallow entrance (Kitheka, 1996; Kitheka *et al.*, 1996). Low exchange rates at Mida Creek are probably a result of the presence of a narrow tidal inlet, absence of river inflow and the presence of submerged sills at stations 5 and 4. Partially submerged coral limestone sills near the entrance to a certain extent limits the exchange of water in ebb and flood tides [Figure 5(a,b)].

An attempt was made to estimate the volume exchange between backwater and frontwater zone of the creek based on measurements of tidal currents and determination of cross-sectional area at a transect located at station 2 next to Sudi Island. Across the Sudi Island at station 2, the mean ebb–flood tide current is 0·49 m s^{-1} with a cross-sectional area of 76·0 m^2. However, the maximum flood current reaches 1·0 m s^{-1} in spring tide. Therefore, the tidal discharge using the maximum current speed of 1·0 m s^{-1} in flood tide is 77·52 m^3 s^{-1} implying that tidal discharge in flood tide is seldom more than 80 m^3 s^{-1}. However, using the maximum ebb tide current speed of 0·65 m s^{-1}, the ebb tide discharge is calculated as being 49·4 m^3 s^{-1} which is significantly lower than the flood tide discharge. The mean tidal discharge calculated by considering both the ebb and flood discharges is 64 m^3 s^{-1}. Using the ebb tide discharge of 49·4 m^3 s^{-1} and the corresponding volume of water in backwater region (48×10^6 m^3), the residence time of tidal water in the backwater zone is calculated as being 11·24 days while that in the frontwater zone is only equivalent to half a tidal cycle. The differences in ebb–flood tidal discharges are balanced by the respective differences in the duration of ebb and flood currents. Ebb tidal discharge at the creek entrance is also much larger (2850 m^3 s^{-1}) than the ebb discharge past Sudi Island (49 m^3 s^{-1}). It is therefore certain that a considerable volume of water is exchanged between the offshore continental shelf zone and the frontwater zone of the creek. The exchange between frontwater zone water and groundwater outflow dominated backwater zone seems to be limited and this could reduce the influence on seagrass beds and the coral reef.

Management and development interventions

The seasonal rainfall recharge of Mida Creek groundwater basin occurs on land and is promoted by the interception and flow retardation effects of terrestrial vegetation particularly the Arabuko–Sokoke forest reserve. The changes in land-use systems in the Mida Creek catchment area will definitely interfere with the future groundwater outflow patterns since extensive clearance of terrestrial vegetation will drastically reduce the runoff retardation effects of the vegetation and eventually limit the percolation of rainwater into the groundwater aquifer. This is particularly so given the fact that the continued high population growth rate at a rate of between 2·78 and 3·5% p.a. will increase demand for groundwater and land for agriculture and settlement (cf. Tyson & Weber, 1964; GOK, 1989). It is important to note that the increased abstraction of the groundwater under scenario of increased population in the Mida Creek groundwater basin, will be a drastic lowering of the water table below sea level given that the land elevation is just about 4 m a.s.l. and water table occurs less than 2·5 m a.s.l. The resultant hydraulic pressure gradient changes will favour a net seawater intrusion which will increase the volume of seawater in the aquifer, and eventually, drastically reduce the groundwater outflow. An intrusion of seawater to a distance of 1 km inland could reduce the groundwater outflow by almost 90%. The clearance of coastal bushland and Arabuko–Sokoke forest will reduce the percolation of surface runoff and rainwater (as a result of blockage of soil pores through compaction) which is necessary for recharging the local groundwater aquifer. The resultant effect will be reduced groundwater storage, and eventually the outflow to Mida Creek will be extremely low, unable to sustain the mangroves and domestic water supply requirements of the local inhabitants. The reduced groundwater outflow coupled with increased seawater intrusion will reduce the supply of inorganic nutrients to the creek and this will negatively affect coastal marine bio-diversity, fisheries and tourism and eventually will disrupt the local socio-economic livelihood system which is dependent on local coastal and marine bio-diversity. Extensive removal of mangroves could also increase seawater intrusion into the aquifer and intensify the problem of shoreline erosion and promote extensive sedimentation in the creek that would eventually smother the seagrass beds and probably the coral reef ecosystems. Mida Creek being an important tourist site will increase a need in the near future to dredge and deepen the main tidal channel to facilitate entry of larger boats into the creek. Any future dredging operation of the main channel should be carried out after a thorough evaluation of its effects on groundwater outflow, water circulation and on biotic systems. Dredging could change the present ebb and flood tide circulation patterns and promote the net export of suspended matter to the offshore waters where they may affect the coral reef. Any major changes in the water circulation (both groundwater and coastal marine) will have a drastic effect on the biotic systems in the creek. There is therefore a need to protect the Mida Creek basin through initiation of sound integrated management programmes.

Conclusions

Mida Creek is a good example of coastal marine ecosystem principally sustained by groundwater outflow, since the occurrence of dense mangrove vegetation is only expected where there is a significant influx of groundwater. Vertical salinity anomalies that occasionally reach 1·58 are mainly as a result of groundwater seepage within the main tidal channel. Although there is a tidal current asymmetry in the creek it is not clear whether there could be net export of backwater zone water mixed with groundwater, since flood tide currents in the main tidal channel are dominant in terms of speed despite their shorter duration of between 5 and 7 h. Also, while there is considerable mixing of the backwater and frontwater zone water, the exchange and interlinkage between backwater and the offshore water is limited because of low volume of water involved in exchange per tidal cycle.

However, as a result of high groundwater recharge rate in the sandy soils found within the catchment and low rate of groundwater abstraction, there is sufficient groundwater in storage within the basin. Low hydraulic pressure gradient makes groundwater outflow to be relatively low and it therefore represents less than 1% of the total creek volume. The groundwater outflow is not restricted within a narrow band along the mangrove-fringed shore, but also occur within the main tidal channel where it causes vertical salinity and water density anomalies. Less efficient circulation caused by low current speeds $<0{\cdot}5\ \mathrm{m\,s^{-1}}$ in the backwater zone of the creek increases the residence time of tidal water to roughly 11 days. However, the turnover time of groundwater is longer and there is therefore a constant supply of brackish water into the creek. This could explain the existence of dense mangrove vegetation in the area despite the absence of river discharge in the creek. The groundwater outflow is evidenced by: (1) the occurrence of vertical salinity anomalies; (2) ebb–flood tide salinity differences; and (3) the existence of shallow wells with brackish groundwater (with low total dissolved solids concentration) about 150 m from the mangroves in the upper parts of the creek.

Acknowledgements

I thank Dr Else Martens—The Netherlands Wetland Programme co-ordinator and Dr Nyawira Muthiga—the Kenya Wildlife Service (KWS) Bio-diversity programme co-ordinator for supporting the broader project on Mida Creek bio-diversity. This study is part of that project.

References

Banmann, P. 1953 Experiments with freshwater barrier to prevent seawater intrusion. *Journal of American Water Works Association* **45,** 521–534.

Bear, J. & Dagan, G. 1963 Intercepting freshwater above the surface in a coastal aquifer, IASH publ. No. 64.

Beer, T. 1993 *Environmental Oceanography: An Introduction to the Behavior of Coastal Waters*. Pergamon, Oxford, U.K., 262 pp.

Bokuniewuicz, H. 1980 Groundwater seepage into great South Bay New York. *Estuarine and Coastal Marine Science* **10,** 437–444.

Carruthers, R. M. 1995 Report on geo-physical studies relating to the coastal aquifer of the Mombasa District, Kenya. *Regional Geophysics Research Group (BGS)*, Natural Environment Research Council, Report 85/4, London.

Cooper, H. H. J. 1964 Seawater in coastal aquifers. *U.S. Geological Survey Water Supply Paper* 1614-c, pp. 84.

Dyer, K. R. 1974 The salt balance in stratified estuaries. *Estuarine and Coastal Marine Science* **2,** 273–281.

Ferris, J. G. 1950 A quantitative method of determining groundwater characteristics for drainage basins. *Agriculture and Engineering* **30** (b).

Gardner, L. R. & Kitchens, W. M. 1978 Sediment and chemical exchanges between salt marshes and coastal waters. In *Estuarine Transport Processes* (Kjerfve, B., ed.). University of South Carolina Press, Columbia, pp. 191–207.

Glovers, R. E. 1959 The pattern of freshwater flow in a coastal aquifer. *Journal of Geophysical Research* **64,** 4.

Glovers, R. E. 1964 The pattern of freshwater flow in a coastal Aquifer. In *Seawater in Coastal Aquifer. U.S. Geological Survey Water Supply Paper* 1613-C, pp. C232–C35.

Gordon, D. C., Boundreau, P. R., Mann, K. H., Ong, J. E., Silvert, W. L., Smith, S. V., Wattayakorn, G., Wulff, F. & Yaragi, T. 1996 Land–Ocean Interactions in the Coastal Zone (LOICZ): LOICZ Biogeochemical modelling guidelines. *LOICZ Reports and Studies* No. 5, Texel, the Netherlands, 96 p.

GOK 1989 Kilifi District Development Plan, 1989–1993 Ministry of Planning and National Development, Nairobi, Kenya, 224 pp.

Heinle, D. R. & Flemer, D. A. 1976 Flows of materials between poorly flooded tidal marshes and an estuary. *Marine Biology* **35,** 359–373.

Kitheka, J. U. 1996 Water circulation and coastal trapping of brackishwater in a tropical mangrove-dominated Bay in Kenya. *Limnology and Oceanography* **41** (1), 169–176.

Kitheka, J. U., Ohowa, B. O., Mwashote, B. M., Shimbira, W. S., Mwaluma, J. M. & Kazungu, J. M. 1996 Water-circulation dynamics, water-column nutrients and plankton productivity in a well-flushed tropical bay in Kenya. *Journal of Sea Research* **35** (4), 257–268.

Kjervfe, B. (ed.) 1978 *Estuarine Transport Processes*. University of South Carolina Press, Columbia, 331 pp.

Kjervfe, B. (ed.) 1994 *Coastal Lagoon Processes*. Elsevier, London, pp. 1–127.

Pond, S. & Pickard, G. L. 1983 Introductory Dynamical Oceanography, 2nd Edition. Pergamon Press, New York, 239 pp.

Raghunath, H. M. 1990 *Groundwater*, 2nd edition. Wiley Eastern Ltd, New Delhi, 563 pp.

Smith, N. P. 1994 Water, salt and heat balance of coastal lagoons. In *Coastal Lagoon Processes*, Chapter 4 (Kjervfe, B., ed.). Elsevier, London, pp. 69–96.

Swenson, E. M. & Chuang, W. S. 1983 Tidal and sub-tidal water volume exchange in an estuarine system. *Estuarine, Coastal and Shelf Science* **16,** 229–240.

TARDA 1983 Resource Development Proposals. *Kilifi District main report*, Nairobi, Kenya, July, 1983.

Tyson, H. N. & Weber, E. N. 1964 Groundwater management for nation's future—future simulation of groundwater basins. *Journal of Hydro Division, Proceedings of the ASCE* **90,** 11–44.

UNESCO 1993 *The Development of Groundwater Resources with Special Reference to Deltaic Areas*. United Nations, NY.

Valiela, I., Teal, J. M., Volkman, S., Shaefer, D. & Carpenter, E. 1978 Nutrient and particulate fluxes in a salt marsh ecosystem: Tidal exchanges and inputs by precipitation and groundwater. *Limnology and Oceanography* **23,** 798–812.

Walton, W. C. 1970 *Groundwater Resource Evaluation*. McGraw-Hill, New York.

Wolanski, E. 1986 An evaporation-driven salinity maximum zone in Australian Tropical. *Estuarine, Coastal and Shelf Science* **22,** 415–424.

Wolanski, E., Jones, M. & Bunt, J. S. 1980 Hydrodynamics of a tidal creek mangrove swamp system. *Australia Journal of Marine and Freshwater Research* **13**, 431–450.