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Coastal Tidally-driven Circulation and the Role of Water Exchange in the Linkage Between Tropical Coastal Ecosystems

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Water circulation and exchange processes in a shallow, semi-enclosed tropical bay were studied in southern Kenya (Gazi Bay) through measurements of tidal elevations, salinity, temperature, dissolved oxygen and current velocities at stations established in mangrove creeks, seagrass beds and coral reef zones. Occurrence of wide shallow entrance, lack of topographic controls (sills) and the orientation of the Bay entrance with respect to dominant tidal water circulation patterns, accounts for the high rates of exchange (60–90% of the volume per tidal cycle) between the inshore and offshore waters. High flushing rates are coupled with short residence times in the order of 3–4 h. The dominant water circulation driving force is the semi-diurnal tide, causing a strong reversing current in the mangrove creeks (0·6 $\mathrm{ms^{-1}}$) and low magnitude current in the seagrass and coral reef zones (<0·30 $\mathrm{ms^{-1}}$). Tidal asymmetry, characterized by stronger ebb flows than flood flows in the mangrove creeks, partly promotes the net export of organic matter to the seagrass beds. The brackish and turbid water plume in the mangrove creeks and south-western region of the Bay is trapped along the coast and in the mangrove swamp, and does not reach the coral reef. The freshwater influx via rivers and direct rainfall in the Bay accounts for a volume of 305 000 $\mathrm{m^3}$, of which 20% is lost as a result of enhanced evapotranspiration, which is also responsible for a salinity maximum zone (38) in the upper region of the Bay covered by mangroves.

Keywords: coastal circulation; water exchange; coastal ecosystems; river discharge

Introduction

Research on coastal water circulation dynamics in tropical waters has received considerable attention in the recent past because the hydrodynamic processes determine the short- and long-term sustainability of marine coastal ecological systems (Swenson & Chuang, 1983; Wolanski, 1986, 1994; Kruyt & van der Berg, 1993). The hydrodynamic processes also determine the linkage between coastal ecosystems such as mangroves, seagrass beds and coral reef. The description of water circulation and exchange patterns in tropical coastal waters is therefore crucial to the understanding of ecosystem dynamics and global ocean flux studies (Bowman, 1977; Ho, 1977; Swenson & Chuang, 1983). The main forcing functions responsible for coastal circulation in tropical waters are astronomical tide, river discharge and meteorological forcing of which wind is important (Joseph & Kurup, 1987; Denes & Caffrey, 1988; Pylee *et al.*, 1990). The strength, and therefore the significance, of each of the above forcing mechanism vary depending on a wide range of topographic, hydraulic and meteorological controls (Hansen & Rattray, 1965, 1967; Chandrakanth *et al.*, 1987). In the context of the linkages between the Eastern Africa Coastal ecosystems, the role of water circulation in linking mangroves, seagrass beds and coral reef ecosystems formed the central focus of the EEC-STD-3 project in Kenya (1993–1995).

The objective of the present study is to establish, by focusing on Gazi Bay, the influences of water circulation in tropical coastal waters in linking the mangroves, seagrass beds and coral reef ecosystems. These ecosystems occur adjacent to each other in tropical areas and are thought to be linked through movement of water which is tidally driven (Kruyt & van der Berg, 1993). The flow of water from the mangroves into the seagrass zone and eventually into the coral reef is thought to promote the interchange of materials, especially nutrients and organic matter. This also influences the ecological interaction between the three ecosystems which can, therefore, be considered to be interlinked. The degree of interlinkage, however, depends on the hydrodynamic processes operating in the coastal waters.

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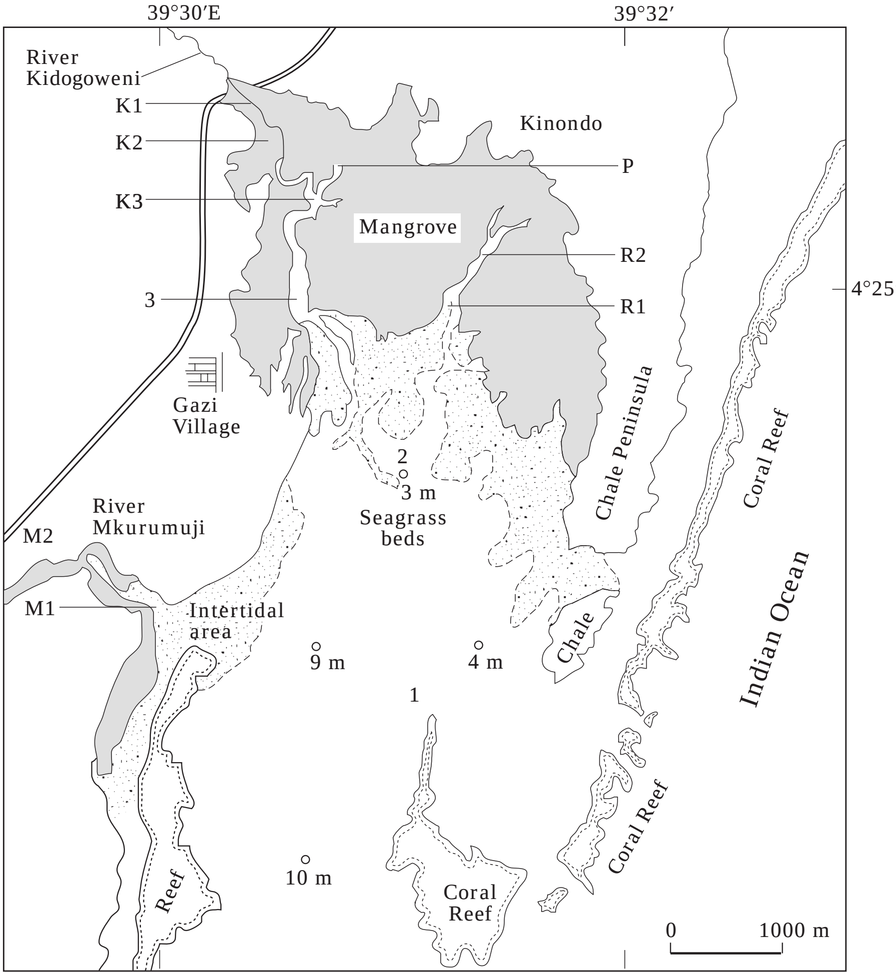

FIGURE 1. The location of Gazi Bay with Kidogoweni and Mkurumuji Rivers.

The description of the study area

The study area, Gazi Bay, is a shallow, tropical coastal water system with mean depth often less than 5·0 m. The Bay is in southern Kenya (39°30′E and 4°22′S), approximately 47 km from Mombasa (Figure 1). The total area of the Bay, excluding the area covered by the mangroves, is 10·0 km^2. The mangrove forest, covering an area of about 5·0 km^2, is dominated by *Rhizophora mucronata*, *Sonneratia alba*, *Ceriops tagal*, *Bruguieria gymnorrhiza* and *Xylocarpus granatum* (Slim & Gwada, 1993). The seagrass zone which is dominated by *Thallasia* sp, is found in the central region of the Bay and covers an additional area of 7·0 km^2 which is roughly equivalent to 70% of the total area of the Bay. The Bay is open to the Indian Ocean through a relatively wide (3500 m) and shallow entrance in the south (Figure 1). This entrance, which for the purpose of this study is represented by a transect running from the Chale peninsular headland to the Mkurumuji Estuary, is rather shallow, with depths ranging between 3·0 and 8·0 m in the eastern and western regions, respectively. There are also a number of narrow and shallow cuts through the coral reef, which is submerged most of the time but partly emerges at spring low tide. There are two tidal creeks (Kidogoweni and Kinondo) draining the upper region of the Bay, which is dominated by mangrove vegetation. Kidogoweni Creek receives fresh water from Kidogoweni River. However, Kinondo Creek lacks direct surface freshwater input but there may be groundwater influx as water salinity fluctuates significantly in the wet season. Finally, there is Mkurumuji River which has higher flow rates and discharges into the south-western region of the Bay. The drainage basin of Mkurumuji and Kidogoweni Rivers extends into the coastal ranges of Shimba hills with the drainage areas being 164 and 30 km^2, respectively. River discharge is important in wet seasons and occasionally reaches up to 5·0 and 17·0 $m^3 s^{-1}$ for the Kidogoweni and Mkurumuji Rivers, respectively. The climatic seasons are the south-east monsoon which is responsible for the ' long rains ' (March–May), and the north-east monsoon, which causes ' short rains ' (November–December). Rainy seasons are a result of the location of the intertropical convergence zone (ITCZ) in the East Africa region. Total annual rainfall based on data from the Meteorological Department, Nairobi, is between 1000 and 1500 mm. The rates of evaporation range between 1950 and 2200 mm per annum. Wind blows into the area with an easterly component and is always onshore (Meteorological Dept., 1964; EADBAP, 1995).

Materials and methods

Sampling stations

Hydrographic data on Gazi Bay were obtained in the mangroves, seagrass beds and coral reef zones by applying different standard hydrographic measurement techniques. Data were obtained at the coral reef zone at Station 1, seagrass bed zone at Station 2, and at five stations in the mangrove zone (K1, K2, K3, P and 3) in the Kidogoweni Creek; and Stations R1 and R2 in the Kinondo Creek. There were also two additional stations (K1 and M1) in the lower reaches of Mkurumuji and Kidogoweni Rivers for the measurement of freshwater influx into the Bay (Figure 1).

Hydrographic measurements

Hydrographic parameters that were measured in the field are water salinity, temperature, current speed and sea-level variations. Measurements of water salinity, temperature and dissolved oxygen were at three levels in order to represent surface, middle and bottom water column. Water samples were obtained by using a Nansen bottle. Salinity of water was determined in the field using a refractometer and a salinity-temperature sond. Temperature was measured using either a WTW LF/95 conductivity meter or a temperature-salinity sond. The dissolved oxygen (DO) in water samples was determined at the Kenya Marine and Fisheries Research Institute laboratories using the Winkler method. However, due to logistic problems, oxygen determination was restricted to samples obtained in the mangrove zone at Station 3. Tidal current velocities were also measured at three levels (surface, middle, bottom) using three C-31 Ottmolen current meters and a direct reading CM-2 Dentan current meter. The current flow direction was based on visual observation of the direction of the vane of the current meters suspended in water. Tidal elevations during neap and spring tides were measured at an interval of 2–3 h using a tide pole installed at Station 3. The sampling frequency for the measurement of above-water physical parameters was twice per month during neap and spring tide, in dry and wet seasons and in low and high waters. The mean current velocity over depth (ms^{-1}) was computed using the equation:

$$\overline{U}=1/h\int U_z \cdot d(z) \qquad (1)$$

where $\overline{U}$ is the mean current velocity over depth (ms^{-1}), U_z is the current velocity at z m above the bottom, and h is the water depth (m).

Freshwater influx measurements

The freshwater influx into Gazi Bay from Kidogoweni and Mkurumuji Rivers was determined through river gauging at Stations K1 and M1, respectively (Figure 1). The river discharge, Q_f, is computed using the following relation:

$$Q_f=\Sigma a_i \cdot v_i \cdot \cos(\theta\pi/180) \qquad (2)$$

where a_i is the stream channel cross-sectional area (m^2), v_i is the cross-sectional component of velocity (ms^{-1}) and θ is the deviation of the current velocity in relation to the flow direction (Linsley, 1988).

In the study of the influences of freshwater influx, it was also necessary to determine circulation and stratification parameters since these are the key indices of the influence of freshwater influx in coastal waters. The stratification and water circulation parameters (S_f and U_f, respectively) were calculated using the method of Hansen and Rattray (1965, 1967). The stratification parameter (S_f) was computed as the difference between bottom (S_b) and surface salinity (S_s) divided by the depth-averaged salinity (S_d). This relation is presented in the following equation:

$$S_f=(S_b-S_s)/S_d \qquad (3)$$

The circulation parameter (U_f) was calculated by dividing net surface velocity with the net depth-averaged velocity.

Water exchange

In the evaluation of the importance of water exchange in Gazi Bay, the salt and volume-conservation approach involving the determination of exchange fluxes as well as salinity changes was applied. The volume

TABLE 1. The magnitude and duration of flood and ebb currents

Date	Tidal phase	Current (ms^{-1})	Duration (h)
23–24 Sept 1993[a]	Flooding	0·19–0·12	8
	Ebbing	0·22–0·10	7
3–4 Nov 1993[a]	Flooding	0·27–0·22	7
	Ebbing	0·20–0·10	5
17 Dec 1993[b]	Flooding	0·55	6
	Ebbing	0·60–0·45	7·5
13 Jan 1994[b]	Flooding	0·50–0·45	6
	Ebbing	0·50–0·45	6

[a] Measurements during north-east monsoon, [b] measurements during north-east monsoon.
Highest current velocity recorded in Kinondo and Kidogoweni Creeks in the spring tide is 0·62 ms^{-1}.

conservation in semi-enclosed coastal waters is represented in the following modified equation (O'Kane, 1988; Rydberg, 1991):

$$V \cdot d_s/d_t = (Q_r \cdot S_r + Q_a \cdot S_o) - (Q_a \cdot + Q_r)\, S \quad (4)$$

where Q_r is the river freshwater supply ($m^3\, s^{-1}$), Q_a is the exchange flux ($m^3\, s^{-1}$), S_r is the salinity of river water (=0), V is the volume of the Bay (m^3), S is the salinity of the Bay, d_s/d_t is the salinity change with time (day^{-1}), S_o is the salinity of ocean water influx Q_o. The simplified version of Equation 4 is written as:

$$Q_a = (V \cdot d_s/d_t) + (Q_r \cdot S)/S_a - S \quad (5)$$

The oceanic water influx (Q_o) is equivalent to river influx (Q_f) and exchange flux (Q_a)[$Q_o = Q_r + Q_a$]. The residence time is then computed using the following relation V/Q_o, where V is the volume of the Bay (m^3) and Q_o is the oceanic water flux (O'Kane, 1988; Rydberg, 1991).

Results

Tidal dynamics and current patterns

The astronomical tide is the main forcing function driving water circulation in Gazi Bay. The tide generates strong reversing currents in the deep and narrow tidal channels in the mangrove zone, but not in the seagrass and coral reef. The Bay experiences semidiurnal tides (Kruyt & van den Berg, 1993) with a spring tide range of 3·2 m and neap tide range of 1·4 m. The strength and magnitude of tidal currents vary depending on the cross-sectional area of the channel, depth and tidal regime. The current speed is 90° out of phase with tidal elevations and is approximately 50% higher during spring tides than neap tides. On most occasions, the peak ebb and flood currents were symmetrical, particularly in open waters (seagrass and coral reef zone), implying that their durations and magnitudes are equal (Table 1). In the mangrove creeks, tidal asymmetry was more clearly defined, with ebb currents being stronger than flood currents (Figures 2 and 3). The peak current speed in the mangrove creeks reaches 0·60 ms^{-1}, and the duration of flood and ebb currents differs by up to 1 h (Table 1). The tidal asymmetry in the mangroves is partly attributed to the flow-retarding effects of the dense mangrove vegetation during spring high tide when flood waters inundate most parts of the mangrove forest. Tidal asymmetry has been known to contribute toward the maintenance of deep narrow tidal creeks through tidal flushing (Wolanski *et al.*, 1980). The current speed in the wide and shallow open region of the Bay covered with seagrass and coral reef is lower (<0·25 ms^{-1}). These current speeds, however, slacken to <0·40 ms^{-1} in neap tides, therefore reducing the rates of tidal flushing and water exchange. Current speeds in the seagrass and coral reef zone reduce to a peak of 0·25 ms^{-1} during neap tides, but reach 0·30 ms^{-1} during spring tides. The tidal asymmetry in the mangrove zone promotes the net-downstream longitudinal current which is responsible for carrying away organic detritus to the seagrass zones in the open region of Gazi Bay. This may enhance the export of nutrients from the mangrove zone to the seagrass beds (Van de Kreek, 1976; Wolanski *et al.*, 1980; Pylee *et al.*, 1990).

Response of salinity, temperature and oxygen to tidal forcing

The diurnal variations of salinity, dissolved oxygen and water temperature in Gazi Bay at Station 3 during a moderately wet season with river freshwater influx

TABLE 2. Water circulation (U_f) and stratification (S_f) parameters

	U_f			S_f	
Date	Max	Min	Station	Max	Station
18 Aug 1993	1·08	0·66	R1	0·068	R1
24 Aug 1993	1·15	0·82	K2	0·045	2
10 Sept 1993	1·33	0·97	2	0·033	2
23 Sept 1993[a]	1·40	0·90	3	0·028	3
23 Sept 1993[b]	1·75	0·92	3	0·028	2
4 Nov 1993	1·32	0·80	3	0·015	3
12 Nov 1993	1·11	1·00	K3	–	–
9 Dec 1993	1·00	0·80	K2	–	–
28 Apr 1994	1·23	0·01	3	0·125	K2
13 May 1994	–	–	–	1·000	K2
28 Aug 1994	1·24	0·00	2	0·020	2
30 Aug 1994	1·00	1·00	R2	0·014	R2
31 Aug 1994[b]	–	–	–	0·330	K4
31 Aug 1994[a]	–	–	–	1·310	K2

[a]Ebb tide measurements, [b]flood tide measurements.
Stations K2, K3, P and 3 are in Kidogoweni Mangrove Creek. Stations R1 and R2 are in Kinondo Mangrove Creek.

reaching 0·6 m^3 s^{-1} are presented in Figure 4. Results demonstrate that variations in the level of salinity is a result of the evaporation, freshwater and oceanic water influx. Oceanic water is flushed out of the Bay during the ebb period, paving the way for brackish water from the Kidogoweni River to occupy the mangrove creek. This leads to lowering of salinity in the tidal creeks. As the oceanic water starts to enter the Bay during flood tide, salinity rises from 28 to 34, reaching its peak at high water when most parts of the Bay are covered with oceanic water. The brackish water at this time is pushed back into the mangroves (Figures 4 and 5). This pattern is repeated in several tidal cycles until brackish water is totally mixed with oceanic water. The complete mixing of the different water masses happens mostly in dry seasons when freshwater influx becomes negligible as a result of decline in rainfall in the Kidogoweni and Mkurumuji River basins (Figures 5 and 6). In such periods, salinity variations are often moderate ranging from 34·5 to 35·5. The diurnal variations of temperature based on measurements at Stations 3 show that the main water temperature control is the intensity of solar radiation heating effect. However, there are also temperature variations which are essentially related to tidal dynamics (Figure 4). The highest temperature is reached in the afternoon during the day when cloud cover is low and the solar radiation heating effect is

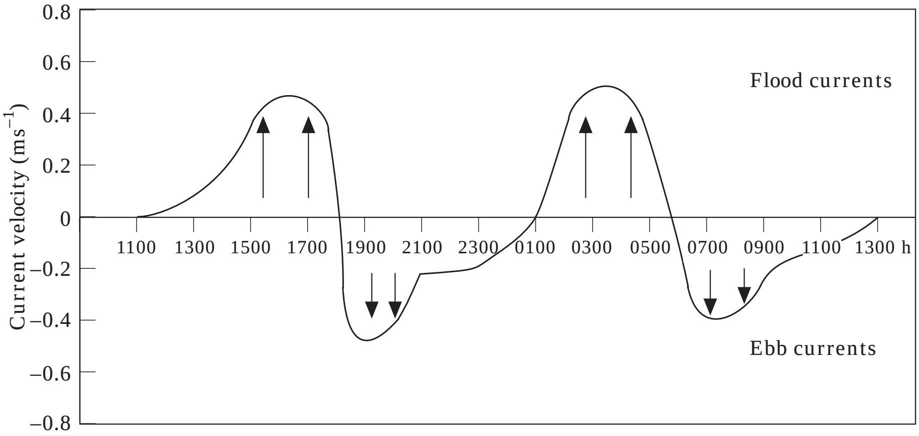

FIGURE 2. The distribution of flood and ebb currents during the post-north-east monsoon season at Station 3. Measurements were made between 13 and 14 January 1994.

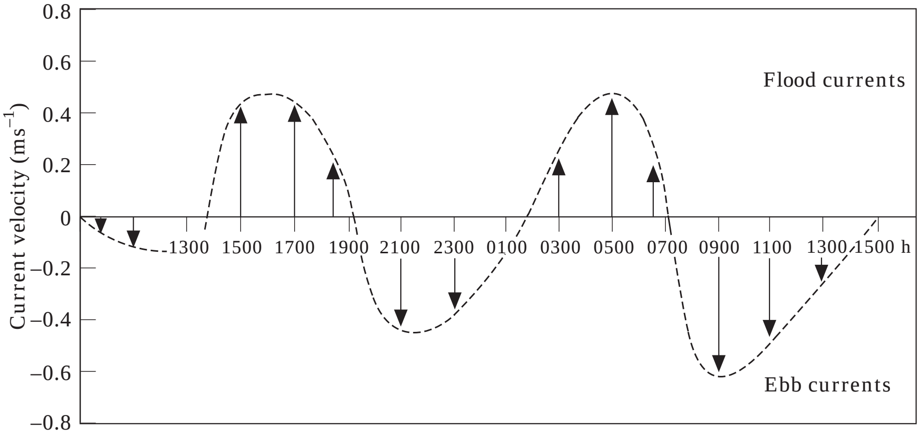

FIGURE 3. The patterns of flood and ebb currents during the north-east monsoon season based on measurements at Station 3 between 17 and 18 December 1993.

at its maximum. However, since the oceanic water is cooler (27·0–27·5 °C) than mangrove water (28–30 °C), the influx of oceanic water into the Bay often leads to slight lowering of water temperature from 27·5 °C to 27·0 °C. Observation of temperature distribution shows that water temperature changes associated with tidal inflow of water can be as large as 2·5 °C. In the shallow mangrove zone, such variations show diurnal patterns, while in the open ocean, semi-diurnal patterns which are a result of the tidal influences are observed. There are also spatial differences between the mangroves, seagrass beds and the coral reef in terms of temperature distribution. The water temperature difference between the mangroves and seagrass bed zone was in the order of 0·6 °C. It reached 2·0 °C for the differences between mangroves and the coral reef zones. Water temperature of the seagrass zone differed from that in the coral reef zone by as much as 1·5 °C, but these differences are minimal for most periods of the year. Although these spatial temperature differences between mangrove, seagrass beds and the coral reef seem small, they are important in the net export of heat energy from the inshore waters to offshore waters. The vertical

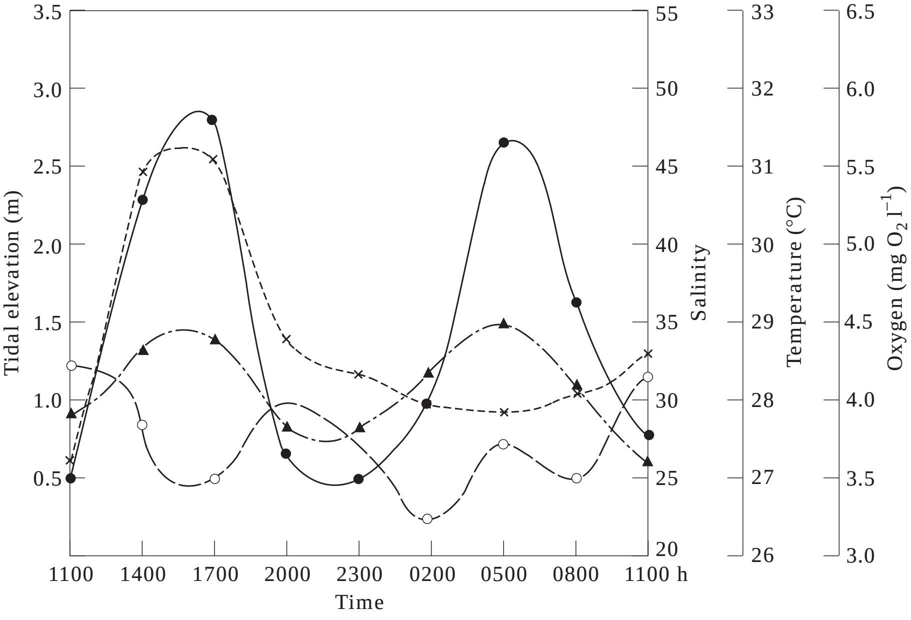

FIGURE 4. The variability of water salinity, temperature and oxygen with respect to tidal elevation at Station 3 during the south-east monsoon season. Measurements were in Kidogoweni Creek. ○, temperature; ●, tidal elevation; ×, oxygen; ▲, salinity.

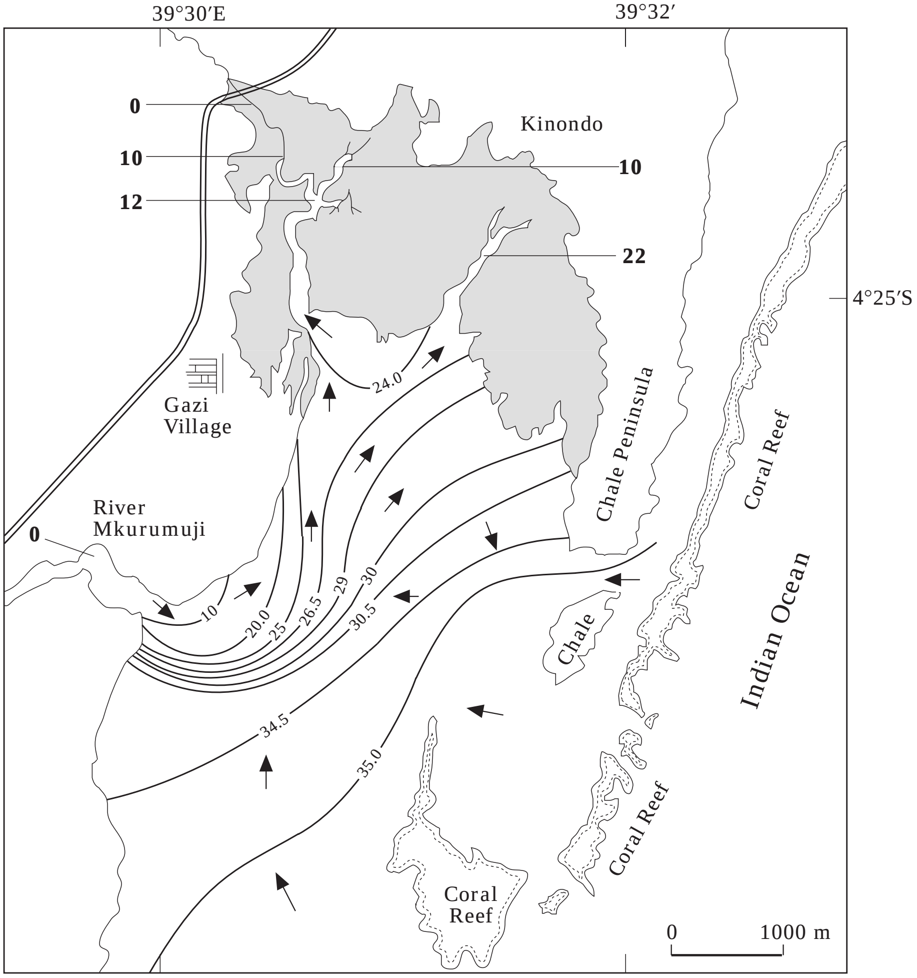

FIGURE 5. The distribution of water salinity (bold type) as a result of the influence of river freshwater input between 13 and 14 May 1994. The arrows indicate the direction of flow of water.

temperature differences are also small, in the range between 0·5 and 1·5 °C in most periods of the year, particularly in dry seasons. The dissolved oxygen varies diurnally in response to algal photosynthetic activity and turbulent tidal mixing. The dissolved oxygen, which is an important physicochemical factor for ecosystem sustainability, lies between 3·0 and $6{\cdot}0\ \mathrm{mg\ O_2\ l^{-1}}$. The maintenance of the dissolved oxygen level of $3{\cdot}0\ \mathrm{mg\ O_2\ l^{-1}}$ in the Bay at night, in the absence of sunlight, is partly facilitated by the turbulent tidal current mixing effects and the breaking waves in the coral reef zone, which tends to mix the atmospheric oxygen with water (Figure 4).

Freshwater influx and salinity distribution

The salinity of water in Gazi Bay varies both diurnally and seasonally. There are a number of factors affecting salinity distribution, of which evapotranspiration, oceanic water influx and river discharge have been known to play important roles in semi-enclosed coastal waters (Ketchum & Keen, 1955; Wolanski *et al.*, 1980; Jiahao, 1987; Denes & Caffrey, 1988). However, the most important factor causing wide salinity changes in Gazi Bay was found to be freshwater influx from Kidogoweni and Mkurumuji Rivers, particularly during wet seasons of both the south-east and north-east monsoons (Figures 4–6). The degree of salinity fluctuation depends on the magnitude of river discharge and turbulent mixing effects of the tide. Figures 5–7 are presentations of spatial salinity distribution in the mangroves, seagrass beds and the coral reef zones. The low-salinity, brackish water is found during wet seasons in the Kidogoweni Creek and in the south-western region of Gazi Bay (Figure 5). Salinity variations in the Kidogoweni Creek are very wide, ranging from as low as 2·0 to as high as 38·0. However, in the Kinondo Creek, the salinity

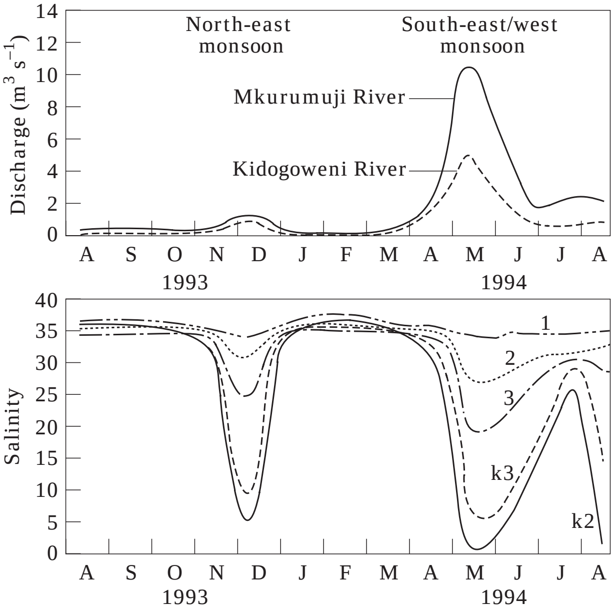

FIGURE 6. The response of different stations to seasonally varying input of fresh water from Kidogoweni and Mkurumuji Rivers. Note very high response in the mangrove zone (Stations K2, K3 and 3) as opposed to the coral reef zone (Station 1).

fluctuation is low, ranging between 22·0 and 38·0. The lowering of salinity in the Kinondo Creek is perplexing since this creek has no direct river discharge (Kruyt & van der Berg, 1993). The lowering of salinity may be as a result of groundwater influx or surface runoff input from the surrounding deforested mangrove areas.

It is also important to note that, as a result of freshwater influx, a negative horizontal salinity gradient of magnitude, 2·0 km^{-1} in Kinondo Creek and 5·0 km^{-1} in the Kidogoweni Creek was measured in the wet season. The dry season lateral salinity gradient in both creeks is often less than 1·0 km^{-1}. Whereas wet-season salinity fluctuations are mainly a result of freshwater influx from the rivers and surface runoff, including direct rainfall, dry-season variations are mainly a result of high evapotranspiration rates. This often reaches 7·0 mm day^{-1} in the southern coastal region of Kenya (cf. Wolanski *et al.*, 1980; Wolanski, 1986). In order to establish whether the freshwater influx in the Bay causes any measurable buoyancy effects, water stratification and circulation parameters (S_f and U_f) were calculated using procedures of Pylee *et al.* (1990) and Hansen and Rattray (1965, 1967). The results of calculation of these parameters show that U_f is often less than 1·75, while S_f is often less than 1·3. The maximum S_f and U_f values were both 1·31. These results indicate the existence of measurable buoyancy effects in the Kidogoweni Creek in the mangrove zone during the wet season, when the freshwater influx through the Kidogoweni River is greater than 3·0 $m^3 s^{-1}$. In both dry and wet seasons, U_f and S_f values for seagrass and coral reef zones were found to be often less than 0·01, implying there is no stratification and the Bay water is well mixed and homogeneous.

Discussion

Forcing functions controlling water circulation dynamics in Gazi Bay are river discharge, astronomical tide and onshore wind. Discharge of fresh water from Mkurumuji and Kidogoweni Rivers is responsible for limited gravitational circulation in the Kidogoweni Creek. This circulation is characterized by the presence of low-salinity river water (10) on the surface, and high-salinity water (35) at the bottom. During this period, the flow of bottom water during flood tide is towards the upper parts of the Creek, while the flow on the surface water column is always seaward. During the ebb period, the flow of water at all levels is seaward. This flow pattern was demonstrated by higher stratification parameters measured in the rainy season in stations located in the Kidogoweni Creek (Table 2). It is also important to note that in most parts of the Bay, as a result of the dominance of astronomical tide in water circulation, there is no stratification. The onshore wind, combined with the effects of breaking waves in the coastal reef zone generates longshore current which traps the brackish plume along the south-western coast of the Gazi Bay, thus ensuring that turbid water from the rivers does not reach the coral reef ecosystem (Figures 5 and 6). The breaking of waves along the coral reef flats also leads to the generation of westward-flowing current (cf. Wolanski, 1994), which seem to promote the coastal trapping of turbid brackish water along the south-west coast.

The total freshwater input through direct rainfall and river runoff was estimated to be in the order of 305 400 m^3 day^{-1} (rainfall, 1000 mm $year^{-1}$, freshwater influx rate, 3·4 $m^3 s^{-1}$) for the Mkurumuji and Kidogoweni Rivers. The freshwater influx volume accounts for 1·0% of the total volume of the Bay which is $49{\cdot}5 \times 10^6$ m^3. Based on the Penman (E_o) evaporation rate of 5·5 mm day^{-1}, the volume of fresh water removed through evapotranspiration is estimated to be in the order of 60 000 m^3 day^{-1}. This high evapotranspiration rate causes a salinity in maximum zone (38) in the dry season in the upper parts of the mangrove creeks. In periods with little freshwater input, the salinity maximum zone acts as a plug which

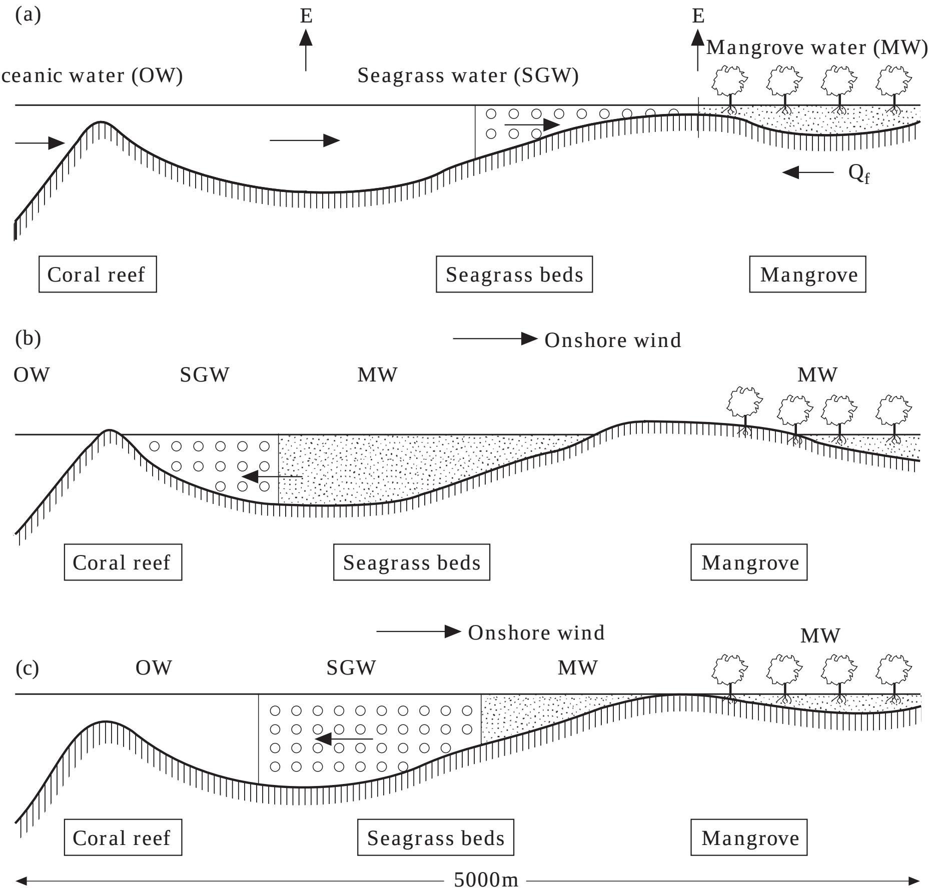

FIGURE 7. The interaction of the coral reef, seagrass and mangrove waters (OW, SGW and MW, respectively) in (a) neap high tide, (b) spring low tide, and (c) neap low tide conditions. E and Q_f refers to evaporation and freshwater input, respectively.

could limit the mixing of estuarine and oceanic water (Wolanski, 1986). However, this was found to be localized in a small area in the upper parts of the mangrove creeks, and was not apparent in the Mkurumuji Estuary where tidal excursion length is short being <500 m. The loss of fresh water through evapotranspiration is therefore equivalent to <20% of the total freshwater supplied through river runoff and direct rainfall falling into the Bay. The remaining 80% is retained in the Bay, and is transported through the seagrass beds by eddy diffusion and advection, and is eventually mixed away through tidal turbulence in the more saline water offshore. However, this study has not established the contribution of groundwater seepage to the total freshwater supply in the Bay.

In the determination of water exchange and flushing patterns in the Bay, the mass-balance approach discussed earlier is used. The following values are used to represent the different terms of the equation: V, $49{\cdot}5 \times 10^6$ m^3; d_s/d_t, 5·0 month^{-1}; Q_r, 10·0 m^3 s^{-1}; S, 35·0; S_a, 37·75. A higher river discharge rate of 10·0 m^3 s^{-1} was chosen to represent the long-term freshwater influx patterns. The mean values of freshwater influx (Q_f) were not used in the salt and volume-conservation equation because of wide seasonal river discharge variations which may underestimate the actual rates of water exchange. The exchange flux (Q_a) computed using data provided above is found to be 3800 m^3 s^{-1}. The mean ocean flux (Q_o) at the Bay entrance is computed using the following equation:

$$Q_o = A{*}h/T/2 \qquad (6)$$

where A is the Bay area (m^2), h is the tidal range (m) and T is the tidal period (s). The maximum ocean flux (Q_o) at the bay entrance is 4200 m^3 s^{-1}, since the Bay width is approximately 4·0 km at high tide, with mean depth of 3·0 m and maximum current speed in the order of 0·35 m s^{-1}. The comparison of ocean water flux (Q_o) and exchange flux (Q_a) yields a ratio of 0·9, which implies that about 90·0% of water in the Bay is

TABLE 3. Water volume and sea level in neap and spring tides

	High waters		Low waters		Mean waters
Type	Mean spring	Mean neap	Mean spring	Mean neap	Mean sea level
Sea level	3·3	2·4	0·5	1·0	1·8
Volume (m^3)	$49{\cdot}5 \times 10^6$	$36{\cdot}0 \times 10^6$	$7{\cdot}5 \times 10^6$	$15{\cdot}5 \times 10^6$	$27{\cdot}0 \times 10^6$
Tidal prism (m^3)	$42{\cdot}0 \times 10^6$	$21{\cdot}0 \times 10^6$			
Exchange	85·0%	58·0%			

The computations on water exchange were based on modified tidal prism method.

involved in the exchange. The residence time of the oceanic water, computed as V/Q_o is 3·6 h. However, the residence time, calculated using the advective time-scale approach is 3·1 h. The computation of exchange rates using the modified tidal prism approach (Norconsult, 1975; Rama-Raju *et al.*, 1979) yields an exchange rate of 85% in spring tide and 60% in neap tide. These results are presented in Table 3 which shows that the rates of water exchange in the Bay are very high (60–90%). The high exchange rates are a result of the presence of a wide shallow entrance, absence of topographic controls (sills), and the orientation of the Bay in respect to the dominant tidal water flow paths. Therefore, the modifications of turbidity, salinity, temperature and dissolved oxygen are promoted by turbulent mixing effects of the breaking waves on the coral reef flats and high exchange rates. The oceanic water flux computations were handicapped by the absence of self-recording current meters and micro-tide gauges, and therefore the long-term diurnal variations of currents, salinity, oxygen and temperature could not be determined, especially in the seagrass and coral reef zones.

The high rate of water exchange has significant implications in as far as the linkage between mangroves, seagrass beds and coral reef ecosystem is concerned. The turbid and brackish water from the mangroves and rivers is flushed into the seagrass beds where, as a result of low current speed, deposition of suspended solids occurs, reducing the turbidity of water. The large water volume in the seagrass area also had diluting effects. However, the linkage between the seagrass beds and the coral reef waters is limited as a result of tidal dynamics which tend to expose the coral reef flat at a time when seagrass water is approaching the coral reef zone, thereby trapping the seagrass water in the lagoon situated next to the reef (Figure 7). This naturally prevents the seagrass water from inundating the coral reef. However, there seems to be no direct link between the mangrove and the coral reef biotope waters, since turbid water from the mangroves and the associated rivers is modified in the shallow seagrass beds before it reaches the lagoon situated next to the coral reef flat at low tide (Figure 7).

The presence of the mangrove swamps influences water circulation through the maintenance of self-scouring deep drainage channels (Wolanski *et al.*, 1980). These drainage channels, coupled with the occurrence of dense mangrove vegetation, tend to promote the seaward transport of organic matter and nutrients, and therefore link the mangroves with the seagrass ecosystem. Previous research restricted to the Kinondo Creek area in the north-east of Gazi Bay has shown that the Kinondo Creek essentially acts as an export system with net seaward transport of organic matter and nutrients (Kruyt & van der Berg, 1993).

Conclusions

Gazi Bay is essentially a well-flushed estuarine coastal water system with a very high rate of water exchange between the inshore and offshore waters. The rates of water exchange are in the range of 60–90%, with residence times of between 3 and 4 h. The short residence time, coupled with the high rate of water exchange, promotes the linkage between the mangroves and seagrass beds in the Bay through the interchange of water. There is no direct linkage between mangroves and coral reef. Tidal influences which are dominant cause significant diurnal variations in salinity, dissolved oxygen and temperature. The semi-diurnal tide also generates strong reversing currents in the mangrove tidal creeks ($0{\cdot}60\ m\ s^{-1}$), and weaker currents in the seagrass and coral reef zones ($<0{\cdot}35\ m\ s^{-1}$). The influence of freshwater influx from the Kidogoweni and Mkurumuji Rivers is only important in the wet seasons of the north-east and south-east monsoons. The influx of freshwater only causes weak transient stratification in the deeper upper parts of the Kidogoweni Creek. The turbid, nutrient-laden brackish water plume is formed in the wet season along the coast, in the south-western region of the Bay. The tidal and longshore current facilitates the rapid mixing of the water column, thereby promoting the formation of the well-mixed homogeneous water observed in dry seasons in most parts of the Bay (salinity 34·5–35·5). Evapotranspiration which is greater than 5·0 mm year^{-1}, particularly in the mangrove zone, causes a salinity maximum zone (38) in the upper region of the mangrove tidal creeks. The existence of lateral and vertical salinity gradients in the Bay is a result of enhanced evaporation in the dry season and river freshwater influx in the rainy season. There is trapping of turbid, nutrient-laden brackish water in the mangroves and in the south-western parts of the Bay as a result of the onshore wind, the longshore current and dominant tidal water flow patterns. At low tide, turbid water reaches the seagrass beds where modifications to the water quality occur before this water reaches the coral reef zone. The modified seagrass zone waters reach the coral reef zone during spring low tide when the coral reef flat is exposed above the mean low water level. The water emanating from the seagrass beds and mangroves does not therefore inundate the coral reef ecosystem since this water is pushed back into the Bay on the flood tide, paving the way for the oceanic water to cover the coral reef flat. The coral reef is mostly covered with the clear oceanic (coral) water during high tide. This explains the existence of the mangroves, seagrass beds and the coral reef ecosystems near each other, the distance apart being less than 4000 m. The mangroves and the coral reef biotopes are, therefore, isolated from each other by hydrodynamic processes.

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