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Water circulation and coastal trapping of brackish water in a tropical mangrove-dominated bay in Kenya

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Abstract

Water circulation patterns in a tropical mangrove-fringed bay with seagrass and coral reef are driven by tides that generate strong reversing tidal currents. The wind, which has an onshore component, generates a net clockwise-rotating eddy. The dominant tidally driven water circulation pattern, coupled with the effects of onshore wind and alongshore current generated by wave breaking, promotes the coastal trapping of turbid brackish water and its inherent nutrient content. This brackish water inundates the mangrove swamp and seagrass beds but not the coral reef ecosystem. Weak stratification prevails during the wet season in the upper parts of Kidogoweni Creek as a result of freshwater influx from rivers. In the dry season, well-mixed homogeneous water is found in most regions of the bay. A small zone of hypersaline water (salinity reaching 38 PSU) is found in the upper region of the mangrove-dominated creeks during the dry season. The connection between the mangrove swamp, with its wide salinity variations, and seagrass beds is apparently through river plumes and tidal effects. The link between seagrass beds and coral reefs is mainly through tidal influences.

Research on water circulation in tropical regions is important because hydrodynamic processes influence the sustainability of marine ecological systems. Coastal water circulation also determines the interaction and therefore the linkage between coastal and marine ecosystems through nutrients and material exchanges (Wolanski et al. 1980; Wolanski 1994; Ho 1977; Kjerfve et al. 1981). The study of water circulation is also significant to environmentalists and land-use planners interested in determining the impact of coastal development projects on marine ecosystems. Thus, the description of coastal water circulation and exchange patterns in tropical waters is crucial to understanding the ecosystem dynamics.

With that in mind, research on water circulation and its role in the linkages between mangrove, seagrass beds, and coral reef biotopes was undertaken at Gazi Bay, southern Kenya. The dominant forcings in the bay are onshore wind, tides, and river runoff, each of which vary at different periods from semidiurnal to seasonal. The strength and significance of each of these forcing functions also vary depending on a wide range of topographic, hydraulic, and meteorologic controls. In the context of linkage between eastern Africa coastal ecosystems, the role of water circulation in linking the mangroves, seagrass beds, and the coral reef ecosystems formed the central focus of the EEC-STD 3 project in Kenya.

Methods and materials

Description of the study area—Gazi Bay (4°22′S, 39°30′E) is a tropical, semienclosed, shallow (mean depth <5 m) coastal water system in southern Kenya (Fig. 1). The total area of the bay, excluding the mangrove swamp, is 10 km^2 (Kitheka 1993). The mangrove forest covers an additional 5.0 km^2 and is dominated by *Rhizophora mucronata, Sonneratia alba, Ceriops tagal, Bruguieria gymnorrhiza,* and *Xylocarpus granatum.* The seagrass zone, which is dominated by *Thallassia* sp., is at the center of the bay and covers an area of 7 km^2, $\sim$70% of the total area of the bay. The bay is open to the Indian Ocean through an entrance in the south (Fig. 1). This entrance is wide, and depths vary between 3.0 and 8 m in the eastern and western regions, respectively. There are also several narrow, shallow cuts through the reef, which is mostly submerged except during spring tides. The bay is also open to the Indian Ocean through coral reef flats $\sim$1.0 km from the bay entrance. The current in this region is weak, and the flow is always westward as a result of breaking waves.

There are two tidal creeks (Kidogoweni and Kinondo) draining mainly the upper region of the bay, which is dominated by mangrove vegetation. Kidogoweni Creek is 4,500 m long and has meandering features similar to those of old-stage alluvial river systems. Kinondo Creek is 2,500 m long and lacks meandering features. Kidogoweni Creek receives river runoff from the Kidogoweni River, which is seasonal in its upper parts, but remains semiperennial in its lower section due to the presence of a swamp that stabilizes flow. Finally, there is the Mkurumuji River, which has higher flow rates and discharges into the southern region of the bay. The drainage basin areas of the Mkurumuji and Kidogoweni Rivers are 164 and 30 km^2, respectively. The discharge of the Kidogoweni and Mkurumuji Rivers reach peaks of 5.0 and 16.7 m^3 s^{-1} during the rainy season, but flows in most periods of the year are usually <1.0 m^3 s^{-1}.

The main climatic seasons are the southeast monsoon (March–September) and the northeast monsoon (October–March). An offshore (shoreward) wind prevails throughout the year. Rains occur in March–May and to

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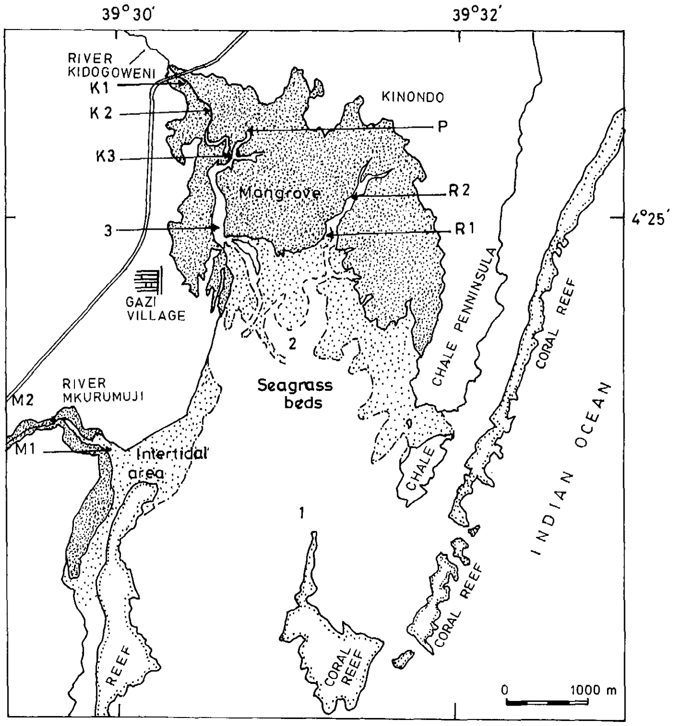

Fig. 1. Location of Gazi Bay and Kidogoweni and Mkurumuji Rivers. Sampling stations are also shown.

a lesser degree in October and November. However, interannual shifts in these seasons are common (East Africa Meteorol. Dep. 1980; Mwebesa 1978).

Sampling stations—Data were obtained at station 1 in the coral zone and station 2 in the seagrass zone, at five stations (K1, K2, K3, P, and 3) in Kidogoweni Creek, and at two stations (R1 and R2) in Kinondo Creek. There were also two stations in the lower course of the Mkurumuji River (M1 and M2). Stations M1 and K1 were used to measure runoff from the Mkurumuji and Kidogoweni Rivers.

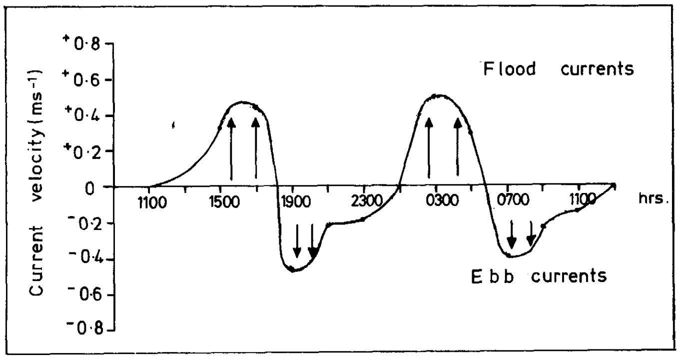

Fig. 2. Current patterns during flood and ebb periods at Kidogoweni Creek between 13 and 14 January 1994. Measurements were made after the northeast monsoon season at station 3.

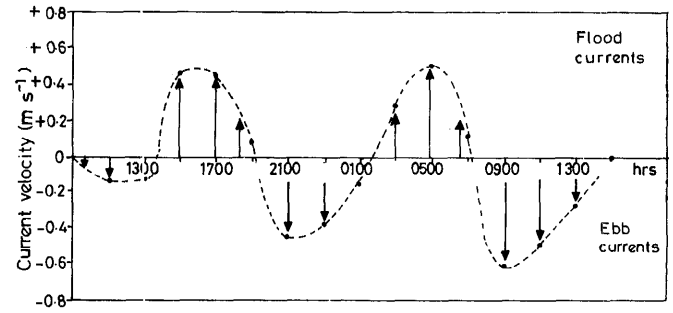

Fig. 3. As Fig. 2, but during the northeast monsoon season on 17 December 1993.

Hydrographic measurements—Field measurements included salinity, temperature, conductivity, current, and tidal elevation. For temperature and conductivity measurements, a WTW LF/95 electronic conductivity meter was used. Salinities were measured with a hand-held Atago refractometer and later with a salinity-temperature sond. Tidal current velocities were measured with three Ottmolen propeller current meters. Occasionally a direct-reading Dentan current meter was used. Tidal elevations were read from a tide pole installed at station 3 in the lower part of Kidogoweni Creek. Measurements were conducted during both neap and spring tides and in most cases involved surveys throughout the bay. However, once per lunar month, full tidal monitoring of all the above physical parameters was carried out at stations 3 and 2. Measurements for physical parameters were for surface, middle, and bottom waters; the middle and bottom water samples were drawn with a Nansen water sampler.

Freshwater influx measurements—Freshwater flows in the Kidogoweni and Mkurumuji Rivers were determined by river gauging at stations K1 and M2 (Fig. 1). The measurement process included measuring flow velocities with Ottmolen current meters, hydraulic radius, and effective width of the stream channel. The integration of the stream cross-sectional areas with the river flow rates provides a measure of instantaneous freshwater influx (Linsley et al. 1988).

Results and discussion

Tides and currents—The tide at Gazi Bay is normally mixed semidiurnal, with a range of 3 m at springs and 1.4 m at neaps. The tide generates strong reversing currents throughout the tidal creeks and relatively weaker currents in the open regions of the bay (Figs. 2, 3).

Tidal currents were more than 50% stronger during spring tides than during neap tides. On most occasions, peak ebb and flood currents were symmetrical, particularly in open waters, showing their duration and magnitudes to be equal (Figs. 2, 3). However, there was some asymmetry of tidal currents in the creeks, where current velocities peaked at 0.60 m s^{-1} and the duration of flood and ebb currents differed by up to 1 h (Table 1). The tidal

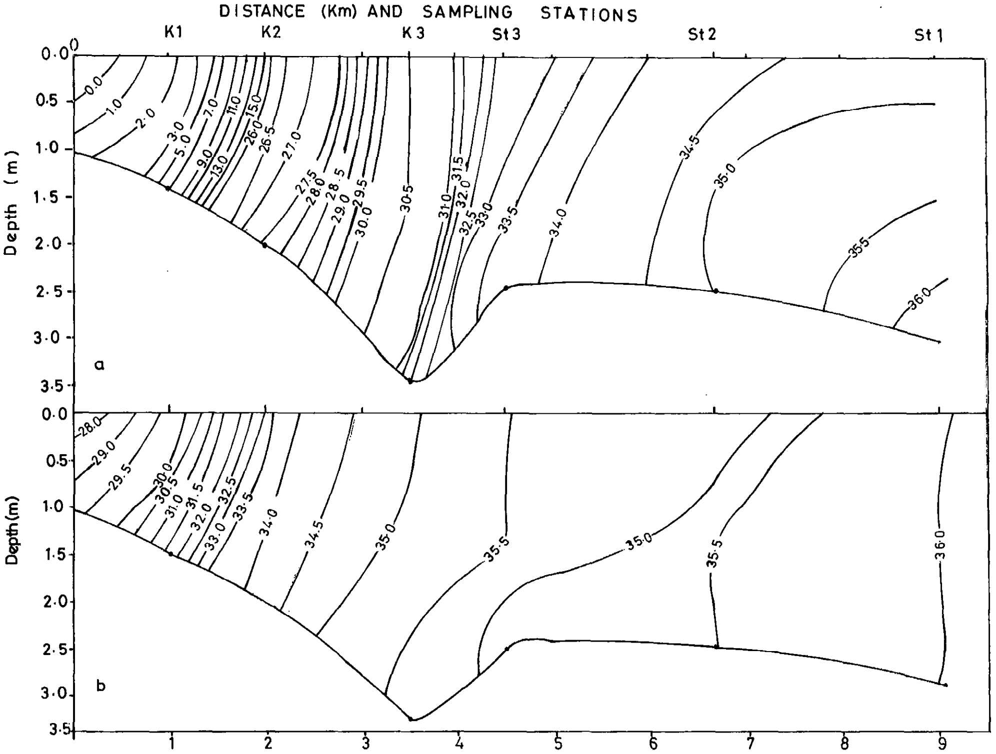

Fig. 4. Longitudinal distribution of salinity in the mangrove, seagrass, and coral reef zones of Gazi Bay between 27 and 28 April 1994. The two diagrams represent the vertical salinity distribution during the flood (a) and ebb (b) periods. (Salinity contours—‰.)

asymmetry in the mangrove creeks is attributed partly to the increase in flood flows due to river runoff and partly to the flow-retarding effects of the mangrove vegetation, especially during spring tides when water floods most areas of the mangrove swamp (*see Figs. 2, 3*). Drainage of water from the mangrove swamp tends to be slower than flow in the tidal creeks. This drainage from the mangroves, in addition to the presence of a positive hydraulic pressure head between the upper and lower regions of the bay, contributes to the observed tidal asymmetry in the creeks (Fig. 4).

Tidal current velocities were slower (<0.25 m s^{-1}) in open regions of the bay (seagrass and coral zones) compared with the tidal creeks (0.60 m s^{-1}). During neap tides, tidal currents in both the mangrove-dominated tidal creeks and open parts of the bay were much slower (<0.30 m s^{-1}).

Variability in physical parameters—Salinity, temperature, currents, and tidal elevations showed both semidiurnal and seasonal frequencies. The salinity changes during the wet season were mainly attributed to influx of runoff from the rivers, while the semidiurnal tides were responsible for diurnal salinity variabilities (Figs. 4, 5). In the wet season, low-salinity brackish water (10‰) was found in the tidal creeks (Figs. 4, 5), but this water was pushed back into the mangroves at high tide. This process results in trapping the brackish water in the mangroves, especially during neap tide when rates of water exchange are low (*see* Swenson and Chuang 1983). In general at stations K2 and K3, salinity was as low as 2.0‰ during the wet season but was hypersaline (37.5‰) during the dry season as a result of evapotanspiration in the mangrove zone (Figs. 6, 7). The rate of evapotranspiration reaches 7.0 mm d^{-1} along the semiarid Kenya coast during the dry season (East Africa Meteorol. Dep. 1980).

Table 1. The magnitude and duration of tidal currents in Gazi Bay. Highest current velocity recorded at station R1 in Kinondo Creek during spring tide (0.62 m s^{-1}). Kidogoweni Creek has a maximum current velocity of 0.60 m s^{-1} during spring tide. Current velocities for seagrass and coral zones are <0.25 m s^{-1}. A longshore current has a peak velocity of 0.34 m s^{-1}. In the Mangrove swamp, current velocities are <0.10 m s^{-1}.

	Tidal phase	Current (m s^{-1})	Duration (h)
23–24 Sep 93*	Flooding	0.19–0.12	8
	Ebbing	0.22–0.10	7
3–4 Nov 93*	Flooding	0.27–0.22	7
	Ebbing	0.20–0.10	5
17 Dec 93†	Flooding	0.55	6
	Ebbing	0.60–0.45	7.5
13 Jan 94†	Flooding	0.50–0.45	6
	Ebbing	0.50–0.45	6

* Before northeast monsoon.
† After northeast monsoon.

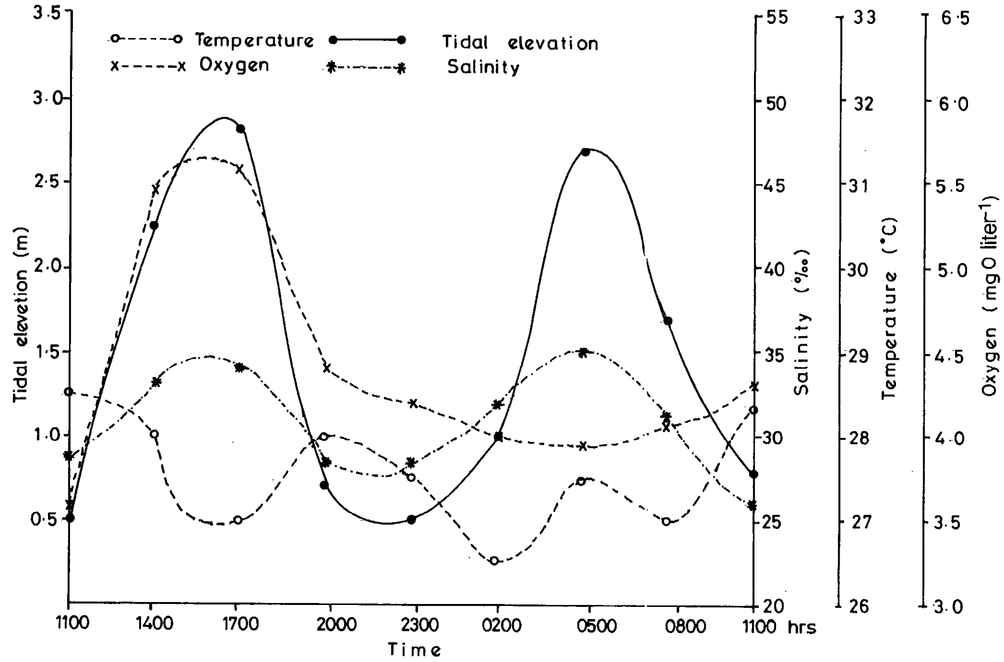

Fig. 5. Diurnal variability of salinity, temperature, and dissolved oxygen in relation to variations in tidal elevation at station 3 in Kidogoweni Creek. Measurements were made between 27 and 28 September 1993.

Compared to Kinondo Creek, at Kidogoweni Creek there were large fluctuations from brackish conditions (salinity, 5.0‰) in the wet season to moderate hypersaline conditions (salinity, 38.0‰) in the dry season. In the absence of direct runoff, the low-salinity water observed at Kinondo Creek (22.0‰) is attributed partly to the ebb flow of low-salinity water in the seagrass zone, which is subsequently pushed into the creek during the flood (Figs. 8, 9). The horizontal salinity gradient during the wet season is negative and of 2.0‰ km^{-1} magnitude in Kinondo Creek and 5.0‰ km^{-1} in Kidogoweni Creek. The dry-season lateral salinity gradients in both creeks are positive and <1.0‰ km^{-1}.

Temperature changes by up to 2.5°C in response to solar radiation in shallow waters, but there are exceptions. Within the shallow mangrove zone, temperature fluctuations show diurnal patterns (Fig. 5), while in the open waters (seagrass and coral reef zones) variations are semi-

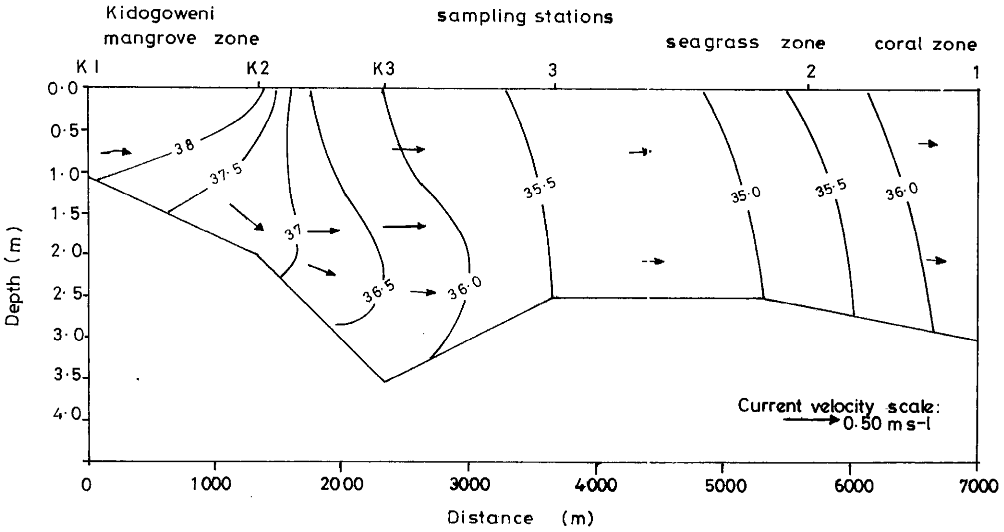

Fig. 6. Horizontal salinity (‰) distribution along the Kidogoweni transect during spring tide. Measurements were made in the dry season with no river freshwater influx. Arrows show the direction of water flow.

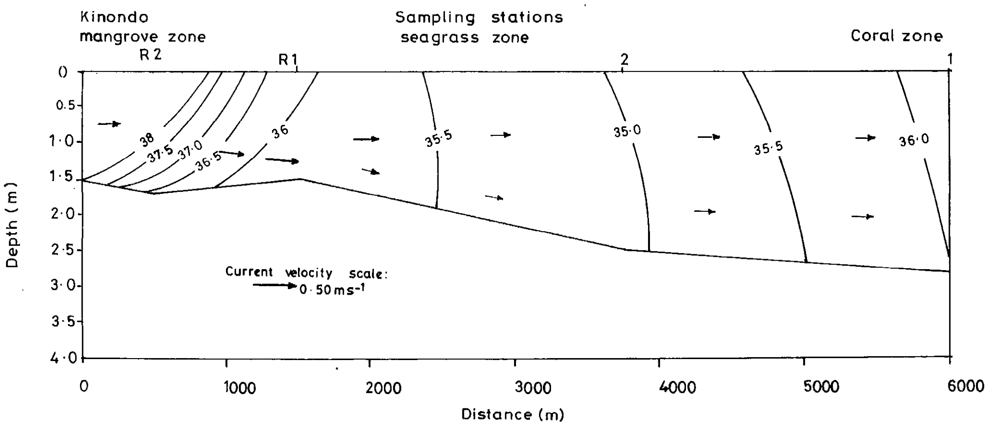

Fig. 7. As Fig. 6, but along the Kinondo transect.

diurnal and do not directly relate to solar radiation heating effects. These differences may be due to turbulent tidal mixing. There was a temperature difference between the mangrove and seagrass areas on the order of 0.6°C, and a salinity difference of 1.63 PSU during the dry season. However, temperature and salinity differences between mangroves and the coral zone were slightly higher (2.0°C and 2.4 PSU). On other hand, the differences between the coral and seagrass zone were 1.5°C and 0.7 PSU. Thus, water temperature differences among the coral, seagrass, and mangrove zones were generally small throughout the year. The vertical temperature differences between surface and bottom waters were also always minimal and in the range of 0.5–1.5°C in most periods of the year.

Freshwater influx effects—The influence of the Kidogoweni River is most evident in the mangrove-dominated tidal creeks and the backwater zone of the bay (Figs. 9, 10). Brackish water from the Mkurumuji River is trapped in the southwestern region of bay (Fig. 9) because of the dominant water circulation pattern. The ebb axial current is mainly southward alongshore and the flood axial current is northward alongshore. The coastal trapping of this plume is reinforced by the wind, which has a shoreward component. Breaking waves at the bay entrance also generate alongshore current that reinforces tidal current.

To determine whether the influx of freshwater into the bay causes any gravitational circulation, I attempted to compute both the circulation (U_f) and stratification (S_f) parameters (e.g. Pylee et al. 1990; Kjerfve 1976; Hansen and Rattray 1965, 1967). S_f was computed as the difference between bottom and surface salinity divided by depth-averaged salinity. U_f was computed as a ratio between the surface and depth-averaged velocity (Table 2). Values of U_f were below 1.75, while those of S_f were below 1.3. The highest value of U_f was at station 3, and the highest S_f value was at station K2, both in Kidogoweni Creek (Fig. 1). These computations show there are measurable buoyancy effects in this creek during wet seasons. The U_f for all stations in the bay during the dry season was <1.5 and in most cases <0.01, implying well-mixed homogeneous water conditions. High values of S_f during the dry season are a result of evapotranspiration, particularly in the mangroves.

Flow patterns and the brackish water plume—Oceanic water during floodtide enters the bay through a 4.0-km-wide entrance (Figs. 1, 9, 11). Wave orientation at the

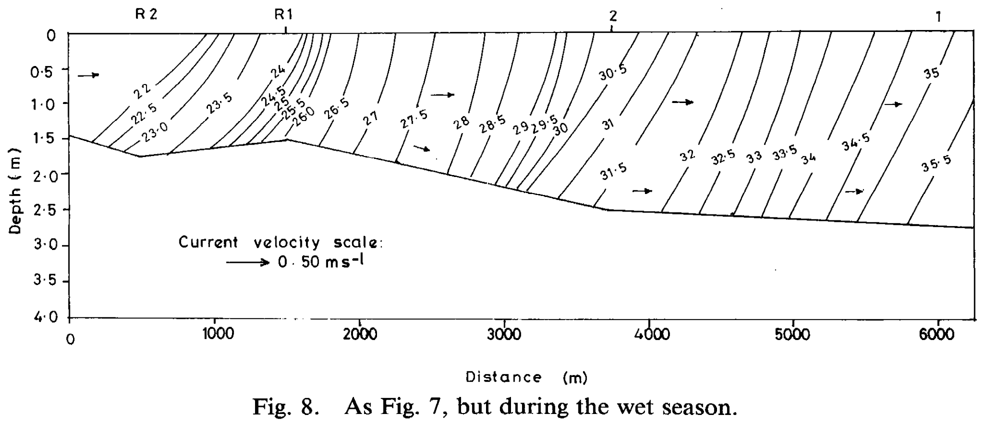

Fig. 8. As Fig. 7, but during the wet season.

entrance is normally oblique toward the southwestern shores of the bay. This orientation on a relatively straight sandy shore on the west mainland side generates a moderately strong alongshore current (littoral drift) with a magnitude ranging between 0.10 and 0.30 m s^{-1}. The alongshore current reaches greater magnitude during spring tides (0.30 m s^{-1}) and, in most cases during floodtide, tends to display a sustained flow direction toward the entrance of Kidogoweni Creek. These strong alongshore currents are partly responsible for the high rates of coastal erosion observed along the western shores of the bay, which are covered with unconsolidated sediments. Further observations on alongshore current show that these currents link with the tidal currents during the flood but become weaker during the ebb.

The bathmetry has a far-reaching influence on water movement because flows at the entrance of the bay at floodtide are toward the deeper southwestern shore (Figs. 9, 11). The water moves northward toward the central western sector, where flows are swifter (0.25 m s^{-1}) than in the eastern sector (0.17 m s^{-1}). A weak clockwise eddy is generated in the lower central region of the bay at floodtide (Fig. 9) and disappears on the ebb (Fig. 11).

The freshwater plume formed as a result of the Mkurumuji River runoff (peaking at 17 m^3 s^{-1}) is confined to the western region of the bay (Fig. 9), partly as a result of the effects of onshore wind. The tidal currents also contribute to this trapping, especially when they link with

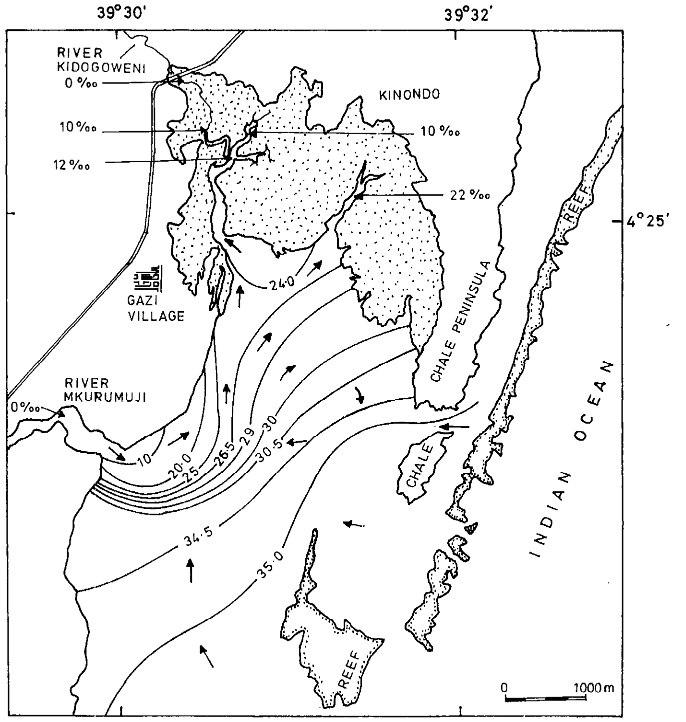

Fig. 9. Spatial distribution of salinity in Gazi Bay on 13 May 1994. Salinity values are shown for a wet period of the southeast monsoon. Arrows show the direction of water flow.

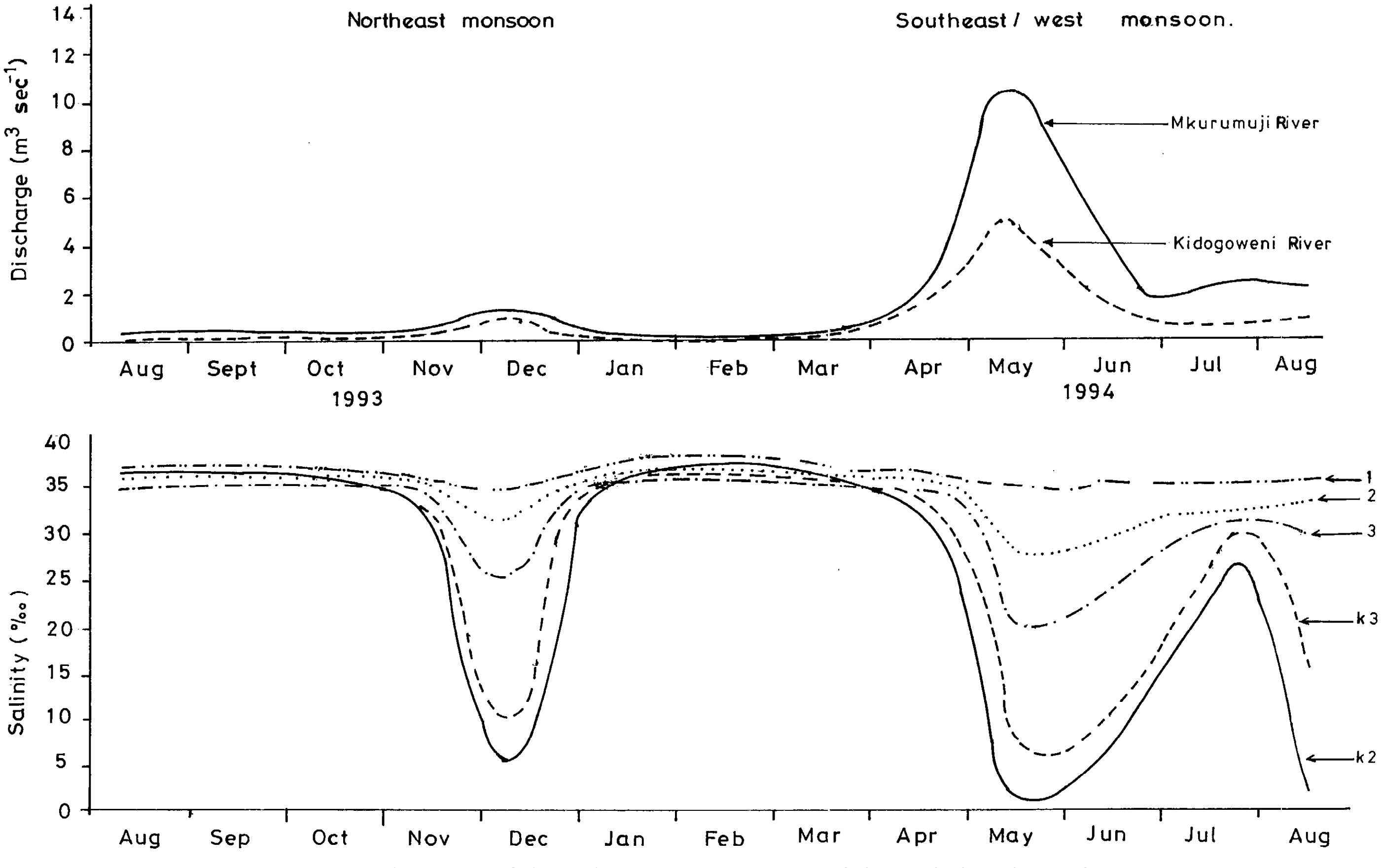

Fig. 10. The influence of river discharge on seasonal salinity variations in Gazi Bay.

Table 2. Water circulation (U_f) and stratification (S_f) parameters for various stations in Gazi Bay. Station locations shown in Fig. 1.

	U_f			S_f	
	Max	Min	Sta.	Max	Sta.
18 Aug 93	1.08	0.66	R1	0.068	R1
24 Aug 93	1.15	0.82	K2	0.045	2
10 Sep 93	1.33	0.97	2	0.033	2
23 Sep 93*	1.40	0.90	3	0.028	3
23 Sep 93†	1.75	0.92	3	0.028	2
4 Nov 93	1.32	0.80	3	0.015	3
12 Nov 93	1.11	1.00	K3	—	—
9 Dec 93	1.00	0.80	K2	—	—
28 Apr 94	1.23	0.01	3	0.125	K2
13 May 94	—	—	—	1.000	K2
28 Aug 94	1.24	0.00	2	0.020	2
30 Aug 94	1.00	1.00	R2	0.014	R2
31 Aug 94†	—	—	—	0.330	K4
31 Aug 94*	—	—	—	1.310	K2

* Ebbtide.
† Floodtide.

alongshore currents during the flood. As a result, the brackish water plume, with its high nutrient and suspended solids content, does not reach the coral reef ecosystem where it could have a detrimental effect because the coral reef ecosystem cannot withstand high-salinity variations and turbidity. Similar observations on plume dispersion patterns have been reported by means of remote-sensing imagery for Ngwana Bay in the north coast of Kenya, where the Tana and Sabaki Rivers discharge highly turbid water (Brakel 1984).

Strong tidal currents at floodtide in the wet season push brackish Mkurumuji and Kidogoweni River water into the backwater zones of the bay, which are covered with seagrass beds, and eventually into the mangroves (Figs. 7, 8). Similar tidal and wind-driven circulation patterns are seen during the dry season, but the obvious difference is that the plume is not observed because there is no significant river runoff (Figs. 10, 11). Salinity in most parts of the bay during this period ranges from 34.5 to 35.5‰ and reaches 38‰ in the upper zones of the mangrove creeks. The formation of a localized zone of maximum salinity (37.5–38.0‰) within the mangrove-dominated creeks is observed only during extended periods of dry conditions (with high evapotranspiration rate) in the bay, when there is no runoff from the rivers. In other studies, this salinity maximum zone has been found to act as a plug which isolates estuarine waters from coastal waters in the dry season (Wolanski 1986).

Conclusions

Gazi Bay can be considered an estuarine system in that it receives substantial freshwater input from Kidogoweni and Mkurumuji Rivers, during the wet seasons of both the northeast and the southeast monsoons. River runoff causes weak transient stratification in the mangrove-dominated Kidogoweni Creek during wet seasons. The other major forcings in the bay are shoreward wind and tide. This study established that tidal influences are dominant in Gazi Bay. The shoreward wind and the tidal currents combine to vertically mix the water column in the bay, leading to formation of homogeneous water, with a salinity range of 34.5–35.5 PSU. A significant lateral and vertical salinity gradient develops during the wet seasons as a result of increased river runoff. There is, however, no major salinity gradient (lateral and vertical) during the dry northeast and southeast monsoons in the seagrass and coral zone regions of the bay, but a significant lateral gradient develops within the mangrove-fringed creeks, which experience elevated salinity on the order of 37.0–38.0‰. The high salinity in the mangrove zone is attributed to high evapotranspiration during the dry season.

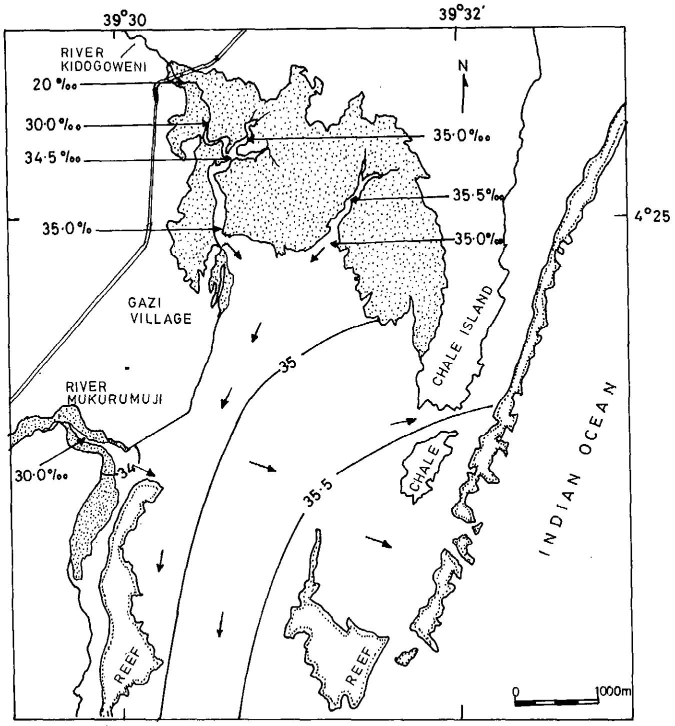

Fig. 11. Spatial distribution of salinity in Gazi Bay on 29 December 1993. Measurements were conducted during a period of low river discharge.

The tide, onshore wind, and breaking waves combine to trap the river plume in the mangroves and along the coast over the seagrass beds at high tide, but deflect the plume from the coral reef on the ebb. Thus, the coral reef and mangroves can coexist a few kilometers apart because they are essentially isolated from each other by hydrodynamic processes, while the seagrass beds act as a buffer zone (possibly trapping nutrients and suspended solids) between these two biotopes. This process works to maintain the ecological health of the coral reef by trapping turbid brackish water along the coast.

The flushing ability of mixed semidiurnal tides in the bay varies depending on tidal range, tidal elevation, and the nature of the tide. Spring tides are characterized by swift flows (velocity up to 0.60 m s^{-1}) and tend to rapidly disperse lower salinity water. The rates of water exchange are also high during spring tides compared to neap tides. On the other hand, currents at neaps are sluggish and inhibit flushing of brackish water. This flushing pattern of the tide combined with river runoff has a far-reaching effect in the form of nutrient and material exchanges on the linkage between mangrove, seagrass, and coral reef ecosystems (Haas 1977; Bowman 1977; Ho 1977). The river input of freshwater is normally associated with high nutrient (phosphates, nitrates, nitrites, and silicates) input that partly sustains the coastal biotopes (mainly seagrass and mangroves) in the bay.

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