Gazi Bay mangrove creek

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Study area description

Gazi Bay (4.92°S, 39.50°E; Figure 1) is a shallow tropical coastal water system located on the southern coast of Kenya, approximately 50 km south of Mombasa. The total surface area of the bay including that covered by the mangrove forest is 15 km^2. The mangrove forest covers a surface area of about 7 km^2 (Kitheka 1996, 1997). Seagrass meadows and mangrove forest cover a surface area of about 12 km^2. The bay is open to the Indian Ocean through a relatively wide (3,500 m) entrance, and is mostly shallow with mean depth at the entrance about 5 m. There are several narrow shallow cuts through the reef, which is mostly submerged except during spring tide. The bay is drained by two main rivers, the Kidogoweni River on the north-west part of the bay and the Mkurumuji River on the south-west side of the bay.

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

The volume of the bay is $60x10^6$ m^3, given a surface area of 15 km^2 and mean depth of 4 m. The tidal prisms in spring and neap tides are $42x10^6$ m^3 and $21x10^6$ m^3, respectively. The two rivers are seasonal with variable discharges which reach a maximum of 5 and 17 m^3 sec^{-1} ($432x10^3$ m^3 day^{-1} and $1,500x10^3$ m^3 day^{-1}) for Kidogoweni and Mkurumuji Rivers, respectively (Kitheka 1997). The river discharge in the dry season is usually less than 1 m^3 sec^{-1} ($86x10^3$ m^3 day^{-1}) and completely absent in periods of serious droughts. River discharge usually occurs between October and December during the north-east monsoon and also between March and July during the south-east monsoon. The flow rate is usually much higher during the south-east monsoon than during the north-east monsoon. The drainage basins of the Kidogoweni and Mkurumuji rivers are 30 km^2 and 164 km^2, respectively. The two catchments extend into the Shimba Hills which receive rainfall of the order of 900 mm $year^{-1}$. Land use includes agriculture, wildlife conservation and forestry.

The tides in the bay are mainly semi-diurnal with a tidal range of 3 m (Kitheka 1996, 1997). The maximum current velocities are of the order of 0.6 m sec^{-1} in the narrow creek sections in the upper zone but are much lower in the broad and shallow lower sections of the bay, about 0.3 m sec^{-1}. The entrance of the bay is approximately 4 km wide.

The bay portrays both positive and negative estuarine characteristics. During dry periods it can be considered to be a negative estuary since its salinity (37.8 psu) is higher than that in the adjacent Indian Ocean (35.5 psu) (Kitheka 1996). In the dry season, salinity in the tidal creeks ranges 37.5-38.0 psu. Dry season precipitation is of the order 100 mm $year^{-1}$ (or 0.3 mm day^{-1}), while dry season evaporation totals 1,800-2,000 mm $year^{-1}$.

During the wet season, the bay can be considered to be a positive estuary, since estuary salinity is much lower than that of the adjacent Indian Ocean - in the mangrove-fringed tidal creeks, the wet season salinity range is 0-14 psu and in the bay 27-33 psu. The average salinity in the adjacent ocean during wet season is 35 psu. The average salinity in the tidal creek in wet season is 19 psu. Precipitation and evaporation during wet season are 900 and 1,800 mm $year^{-1}$ (or 2.5 mm day^{-1} and 5 mm day^{-1}), respectively.

Studies on water circulation in Gazi Bay have established that the low salinity water from the two rivers does not completely inundate the coral reef complex because the turbid plume associated with river discharge is confined to the south-western zone. In the upper mangrove zone, the plume is trapped within the mangrove-fringed tidal creeks. The trapping of the plume along the south-western zone of the bay has been attributed to the generation of westward flowing currents in the coral reef due to breaking waves as well as due to the generation of longshore currents along the coast (Kitheka 1996, 1997).

In the computation of the salt, water and nutrient budgets, it was realized that data derived from measurements conducted within the coral reef zone do not adequately represent the oceanic sector. Data derived from measurements conducted within the seagrass meadows in the central location of the bay were assumed to represent the bay conditions. Those measured within the tidal creeks fringing the mangrove forests were designated as representing the mangrove creek compartment. Since data derived from the coral reef zone does not adequately represent oceanic conditions, it was decided that the exchange of salt, water and nutrient be determined for the mangrove-fringed creek system.

The inner portion of the bay was considered for these budgets. The system is representative of the mangrove-fringed creeks found in Kenya. The mangrove creek system has an area of 7 km^2 and an average volume of $5x10^6$ m^3. The freshwater supply is mainly through the Kidogoweni River, with some groundwater. The estuary presents partial to well-mixed conditions, depending on the magnitude of river freshwater discharge and tidal volume flux. However, because of its shallow depth (less than 1 m), the system was treated as single-layer in this paper.

The budgets were developed for both dry and wet seasons. Fluxes and exchanges within the mangrove creek compartment and also at the boundaries were determined according to LOICZ biogeochemical budgeting guidelines (Gordon *et al*. 1996).

Water and salt balance

The total evaporation over the entire surface of the mangrove creek system is $35x10^3$ m^3 day^{-1} in both wet and dry seasons. Total precipitation over the area is $18x0^3$ m^3 day^{-1} in the wet season and $2x10^3$ m^3 day^{-1} in the dry season.

Based on wet season data relating to riverine input, precipitation, evaporation and salinity, there was a residual flux of water (V_R) of $-219x10^3$ m^3 day^{-1} in the mangrove-fringed tidal creek compartment. The negative value of this flux implies a loss of water from the mangrove-fringed tidal creek to the bay. However during the dry season, there was a positive residual flux of water (V_R) of $+31x10^3$ m^3 day^{-1} between the mangrove-fringed tidal creek and the bay. The positive flux during the dry season shows that there is net inflow of water into the mangrove-fringed tidal creek compartment.

During the wet season, the salt flux carried by the residual flow (V_RS_R) was $4,468x10^3$ psu-m^3 day^{-1} from the mangrove-fringed tidal creek compartment. During dry season, the salt flux carried into the system by the residual flow (V_RS_R) was $1,175x10^3$ psu-m^3 day^{-1}.

Following the underlying physical principles of the LOICZ budgeting method, salt must be conserved. The residual salt flux, denoting a loss of salt from the system, is brought back to balance in the system through the mixing flux of salt across intra- and inter-system boundaries. This can be seen in Figure 2 given in the model for $V_X(S_{ocn}-S_{syst})$ between mangrove-fringed tidal creek and the bay. During the wet season, the volume mixing (V_X) in the mangrove-fringed tidal creek compartment is $324x10^3$ m^3 day^{-1} (Figure 2a). On the other hand, during the dry season the mixing volume (V_X) between the mangrove-fringed tidal creek compartment and the bay is $5,875x10^3$ m^3 day^{-1} (Figure 2b).

The water exchange time in the mangrove-fringed tidal creek compartment was 9 days in the wet season and less than one day in the dry season.

Budgets of nonconservative materials

Nutrient concentrations have been determined for the nitrate-nitrogen, nitrite-nitrogen, ammonium, silicate and phosphate (Kitheka, *et al*. 1996; Ohowa *et al*. 1997). In general, nutrient concentrations are usually higher in the wet season than in the dry season, because nutrients are supplied into the creek not only directly from the Kidogoweni River, but also indirectly from the Mkurumuji River through the bay. The wet and dry season inputs of ammonium-nitrogen, nitrate-nitrogen, nitrite-nitrogen and orthophosphate from the Kidogoweni River are shown in Table 1. The fluxes shown in Table 1 were calculated using the mean river discharges during wet and dry seasons.

Table 1. River nutrient inputs from the Kidogoweni River in the wet and dry seasons.

	Phosphate (DIP) (mol day^{-1})	**Ammonium** (mol day^{-1})	**Nitrate+nitrite** (mol day^{-1})	**DIN** (mol day^{-1})
Wet	290±250	380 ± 340	700 ±610	1,080
Dry	30±20	20 ±10	20 ±10	40

The characteristic nutrient concentrations within the mangrove-fringed tidal creeks in both wet and dry seasons are shown in Table 2. There was a tendency for much higher nutrient concentrations during ebb tide than during flood tide, indicating that oceanic water inflow was low in nutrients in the wet season. In the dry season when there is no river discharge, there is no significant difference in nutrient concentrations in flood or ebb tide. The influence of the river is usually very low in dry seasons.

Table 2. Nutrient concentrations for the mangrove creek zone in wet and dry seasons.

	Phosphate (DIP) (mmol m^{-3})	**Ammonium** (mmol m^{-3})	**Nitrate+nitrite** (mmol m^{-3})	**DIN** (mmol m^{-3})
Wet				
Ebb	1.3	1.9	0.5	2.4
Flood	0.7	0.5	0.2	0.7
Mean	**1.0**	**1.2**	**0.4**	**1.6**
Dry				
Ebb	0.4	0.4	0.2	0.6
Flood	0.3	0.5	0.2	0.7
Mean	**0.4**	**0.5**	**0.2**	**0.7**

The mean nutrient concentrations in the mangrove-fringed tidal creeks, bay (seagrass meadows) and the coral reef zone are shown in Table 3. The mean concentrations of NH_3 and NO_3+NO_2 with their respective standard deviations in the coral reef zone, bay and mangrove-fringed tidal creeks for the wet season are also presented in Table 3.

Table 3. Mean nutrient concentrations for the different zones in wet and dry seasons.

	Phosphate (DIP)	**Ammonium**	**Nitrate+nitrit**	**DIN**

	(mmol m^{-3})	(mmol m^{-3})	e (mmol m^{-3})	(mmol m^{-3})
Wet				
Mangrove zone	0.9	0.82± 0.08	0.75±0.01	1.6
Seagrass zone (bay)	0.8	0.88±0.10	0.89± 0.19	1.8
Coral reef zone	0.9	0.90±0.08	0.97±0.01	1.9
Dry				
Mangrove zone	0.4	0.4	0.3	0.7
Seagrass zone (bay)	0.4	0.3	0.2	0.5
Coral reef zone	0.3	0.3	0.2	0.5

DIP and DIN balance

The criteria established in the water and salt budgets also apply to exchange of dissolved inorganic phosphorus and nitrogen within the mangrove creek compartment. Deviations result from net nonconservative reactions of P and N in the system (Table 4). Concentrations of NO_3 + NO_2 + NH_4 (DIN) and PO_4 (DIP) were available from samples taken at stations established in the mangrove-fringed tidal creek and the bay (seagrass zone) stations designated in Figure 1 as stations 3 and 2, respectively (Kitheka, *et al.* 1996; Ohowa *et al*. 1997). These stations were sampled quasi-synoptically. In order to obtain a single representative value for the bay and mangrove-fringed tidal creek, nutrient concentrations from each station sampled at both high and low water conditions were averaged (Table 3). This gave a single mean value for DIN and DIP in the mangrove-fringed tidal creek and bay sectors, respectively. The nutrient concentrations were also determined for river inputs (Table 1). Those for point sources such as sewage from Gazi Village were not determined, but it is suspected that the sewage load is very small considering that population in the village is also small. This term was therefore neglected in the calculations.

Table 4. Nonconservative fluxes of DIP and DIN for Gazi Bay mangrove creek in the wet and dry seasons.

	ΔDIP		ΔDIN	
	(mol day^{-1})	(mmol m^{-2} day^{-1})	(mol day^{-1})	(mmol m^{-2} day^{-1})
Wet	-28	-0.004	-773	-0.1
Dry	-42	-0.006	+1,116	+0.2

The residual fluxes of DIP ($V_R DIP_R$) in the wet season between the mangrove-fringed tidal creek compartment and the bay was -197 mol day^{-1} representing a transport of DIP from the mangrove creek to the bay. During the dry season, the residual flux of DIP ($V_R DIP_R$) in the mangrove-fringed tidal creek compartment was +12 mol day^{-1}

representing a transport gain of DIP from the bay into the mangrove-fringed tidal creek. DIP nonconservative flux (ΔDIP) in the wet season was -28 mol day^{-1} for the mangrove-fringed tidal creek-bay compartment (Figure 3a). The wet season ΔDIP value per unit area is -0.004 mmol m^{-2} day^{-1}. During dry season, ΔDIP for the mangrove creek compartment was -42 mol.day^{-1} or -0.006 mmol m^{-2} day^{-1} (Figure 3b). This indicates that the mangrove-fringed tidal creek compartment acts as a slightly net sink of DIP in both wet and dry seasons.

During the wet season, the residual DIN flux ($V_R DIN_R$) in the mangrove-fringed tidal creek compartment was -372 mol day^{-1} (Figure 4a), and ΔDIN was -773 mol day^{-1} or -0.1 mmol m^{-2} day^{-1} for the mangrove-bay system. This indicates that the mangrove creek system is experiencing a net sink of DIN during the wet season. During the dry season, the residual DIN flux ($V_R DIN_R$) for the mangrove creek compartment was +19 mol day^{-1}, and ΔDIN was +1,116 mol day^{-1} or +0.2 mmol m^{-2} day^{-1} (Figure 4b). This indicates that the mangrove creek compartment experiences a net release of DIN during the dry season.

The nonconservative fluxes (both ΔDIP and ΔDIN) in the wet season are within the uncertainties of the river nutrient inputs. In the dry season, about 50% of the nonconservative DIP flux (ΔDIP) may be due to the uncertainties of the DIP load. The nonconservative DIN flux (ΔDIN) in the dry season is highly dominated by net DIP exchange ($V_X(DIN_{ocn}$-$DIN_{syst})$.

Stoichiometric estimates of aspects of net system metabolism

Assuming that all the nonconservative behavior is of biological origin and the Redfield ratio applies to the mangrove-creek system as a whole, then the observed ΔDIP values in the system can be used to estimate net production or consumption of organic matter. In expressing the net ecosystem metabolism (NEM) in terms of carbon, it is assumed that NEM is the result of phytoplankton production–phytoplankton respiration and that the Redfield ratio between carbon and DIP is 106:1 (David *et al*. 2000).

$$NEM = (p\text{-}r) = -106(\Delta DIP_{\text{obs}})$$

During the wet season, the positive (p-r) of +0.4 mmol m^{-2} day^{-1} for the mangrove-fringed tidal creek compartment shows that the mangrove creek system is slightly net autotrophic in the wet season. If the higher C:N ratio of mangrove detritus were used, then the estimated autotrophy would be larger.

Net nitrogen metabolism can be calculated using the formula:

$$(nfix\text{-}denit) = \Delta DIN_{obs} - \Delta DIN_{exp}$$

The expected ΔDIN (ΔDIN_{exp}) can be determined using the Redfield ratio of 16:1 for N:P, and the observed value for ΔDIP(ΔDIP_{obs}). This allows ΔDIN_{exp} to be expressed as 16(ΔDIP_{obs}). During wet season, using the Redfield ratio of 106:16:1, (*nfix-denit*) = -0.04 mmol m^{-2} day^{-1} and using the typical mangrove C: N: P ratio of 1000:11:1, (*nfix-*

denit) = -0.06 mmol m^{-2} day^{-1} for the mangrove creek. The negative (*nfix-denit*) values indicate that the mangrove-fringed tidal creek compartment is net denitrifying during wet season.

Net system metabolism was not estimated for the dry season due to the short (less than one day) water exchange rate, which infers that the nutrient fluxes are conservative with respect to the system processes.

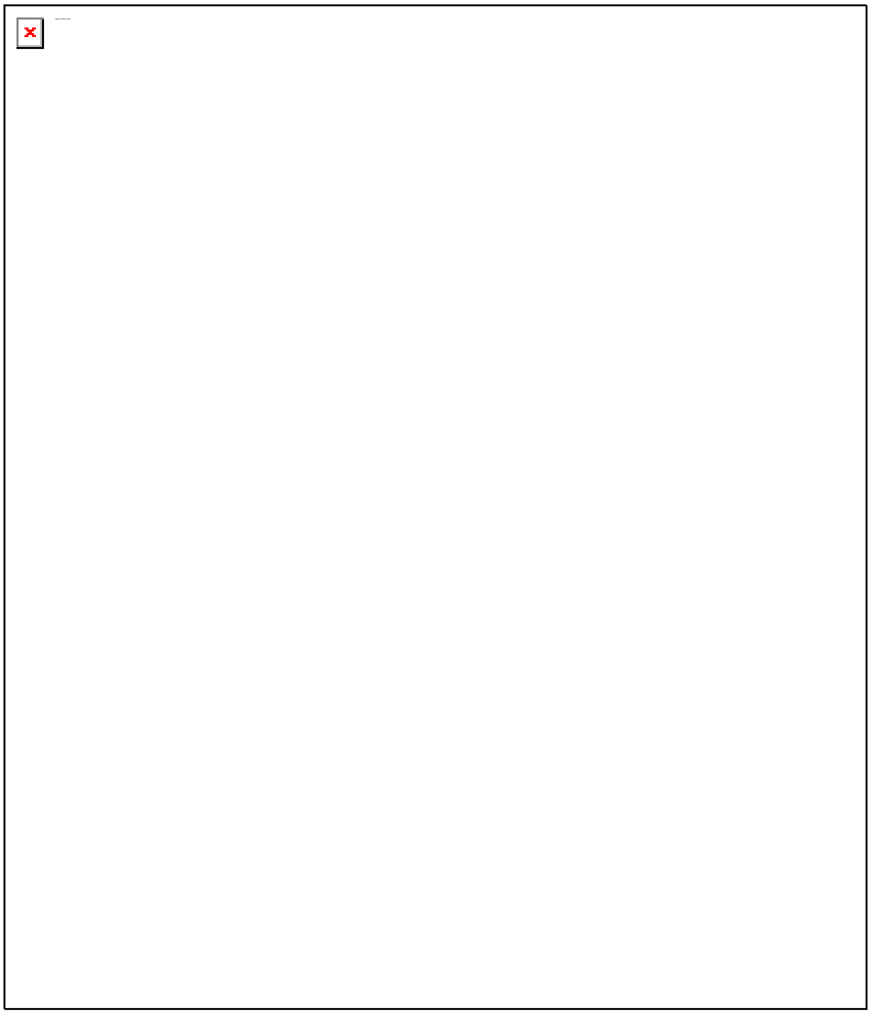

Figure 2. Salt and water budgets for Gazi mangrove creek in wet (a) and dry (b) seasons. Water flux in 10^3 m^3 day^{-1} and salt flux psu-m^3 day^{-1}.

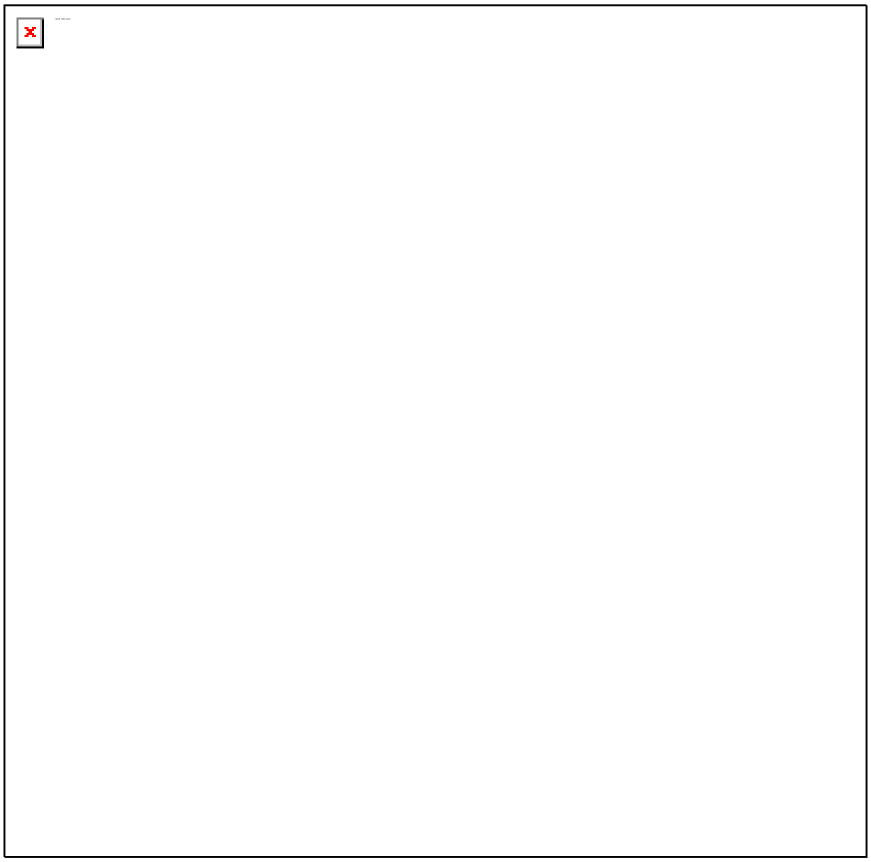

Figure 3. DIP budgets for Gazi mangrove creek in wet (a) and dry (b) seasons.
Flux in mol day^{-1}.

Figure 4. DIN budgets for Gazi mangrove creek in wet (a) and dry (b) seasons.
Flux in mol day^{-1}.

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