## 2. ESTUARIES OF TANZANIA AND KENYA

Tanzania, comprising 945,000 km$^2$ on the east coast of Africa, lies mainly on a plateau at an average elevation of about 1,220 m. Isolated mountain groups rise in the north-east and south-west, including Mt Kilimanjaro, the highest mountain in Africa, near the north-eastern border. The western border is the Rift Valley, with lakes Malawi and Tanganyika. The Rift Valley is a drainage divide. Rivers to the east of it drain into the Indian Ocean, within the Rift Valley they drain into the Rift Lakes, (saline as they lack outlets), while to the west of the Rift Valley, rivers drain into Lake Victoria, and eventually into the Mediterranean Sea through the River Nile.

Along the Indian Ocean coast of Tanzania, the landscape is generally flat and low, with a warm and tropical climate, and rainfall varying from 1,016 to 1,930 mm.

Kenya sits astride the equator, and has an area of 582,600 km$^2$. It is bounded by latitudes 5°30' N and 4°40'S, and longitudes 33°50'E and 41°50'E. To the east is the narrow, low-lying Indian Ocean coast, stretching for 400 km. The altitude ranges from sea level in the south-east, to a broad arid plateau in the central part, and great volcanic mountain chains culminating in Mount Kenya at 5199 m above sea level. To the west is the Rift Valley, a structural feature that runs north-south right across the country. Further west are highlands which slope westwards.

The major river in Kenya that drains into the Indian Ocean is the Tana River, which rises from Mount Kenya and the Aberdare mountains, but it passes mainly through farmlands. Only the provincial towns of Nyeri (population 40,000); Embu (population 20,000); and Garissa (population 15,000) contribute effluents into the Tana River system. The Athi-Galana-Sabaki system is the second largest river, and the capital city, Nairobi (with a population of about 2 million), is situated on its upstream banks. In terms of nutrient loading into the Indian Ocean, therefore, the Athi-Galana-Sabaki system may be more important than the Tana River.

*Mwakio P. Tole and J.I. Marshall Crossland*

### 2.1 Chwaka Bay, Zanzibar

***A.S. Ngusaru, S.M. Mohamed and O.U. Mwaipopo***

*Study area description*

Zanzibar is an island group off the coast of east central Africa, 35 km from the mainland across the Zanzibar Channel. The islands were probably once part of mainland Africa. Unguja Island, the main island, is low-lying with a tropical marine environment. The air temperature ranges from 27-30°C and the average relative humidity from 85% in April to 75% in November. The winds are north-east (October-March) and south-east (March-October) monsoons, with short intermediate periods. Zanzibar has long been an important commercial centre in the Indian Ocean trading system. Coconuts, cocoa and cloves are grown for export; fishing is important for the local economy; sugar, rice and rubber are also grown and processed.

Chwaka Bay is located within 6.13-6.25°S and 39.37-39.58°E on the east coast of Unguja Island, about 34 km east of Zanzibar town. Large intertidal flats partly covered with mixed assemblages of algae and seagrass beds characterize the bay. On the landward side of its mouth, the bay is fringed by a dense mangrove forest, which is drained by a number of tidal creeks, the largest of which is Mapopwe Creek, which is the main water exchange route between the forest and the bay. A modest fragmented coral reef occurs at the entrance of the bay, which is part of the extensive reef that fringes the east of Unguja Island (Figure 2.1).

There are two rain seasons in Zanzibar: the first, during the months of March, April and May, is referred to as long rains, and the second, ‘short rains’, extends from October to December. Therefore

March-May and October-December constitute the wet season in Zanzibar. The months of January-February and June-September constitute the dry season. There are no major rivers that enter directly into the bay, except for some small seasonal streams that flow during rainy seasons. However, there seems to be a significant underground water flow into the bay, but this has not been measured. On the other hand, the bay does not have any significant industrial development. Therefore no effluents or pollutants directly associated with industries find their way into the bay. The estimated population at Chwaka village is about 9,000 people. Untreated sewage is commonly dumped directly into the bays. However, anthropogenic effects may not be an important factor in this bay. Other environmental pollutants such as agro-chemicals are also insignificant.

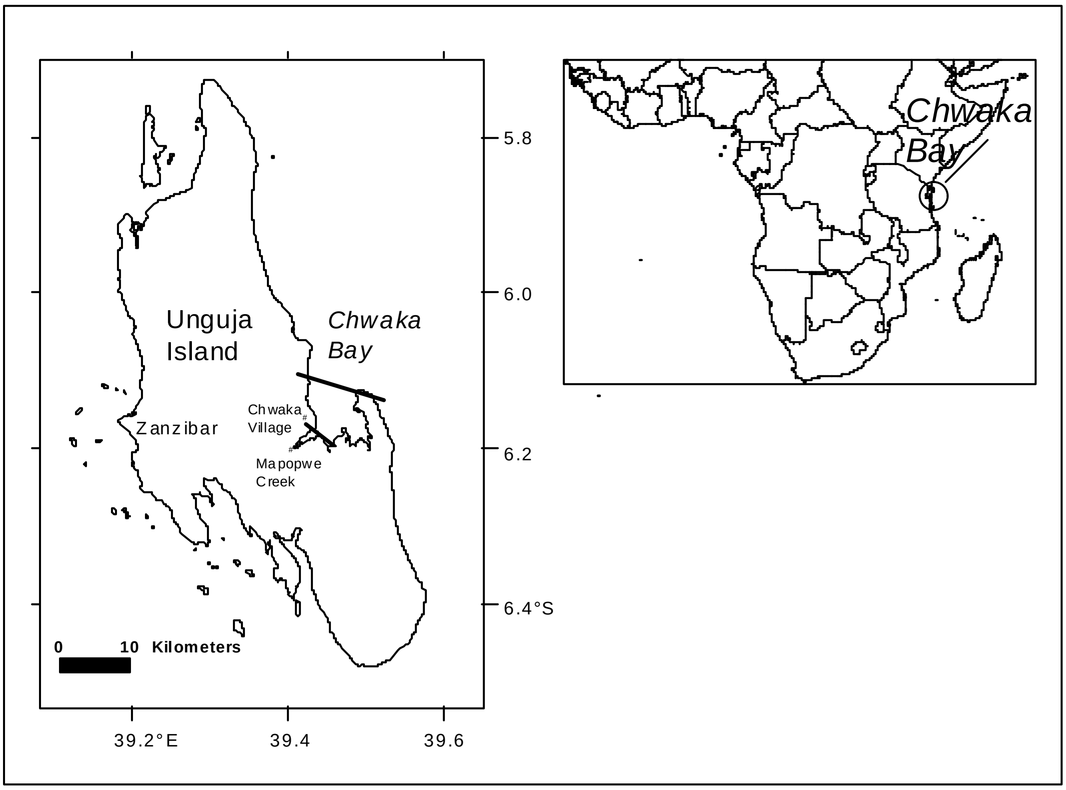


**Figure 2.1. Map of Chwaka Bay, Zanzibar.** Bars on the bay show the budgeted outer and inner compartments of the bay.

For the purpose of describing the salt, water and nutrient budgets in Chwaka Bay, it is convenient to separate the system into two compartments. The first compartment comprises the inner bay that includes Mapopwe Creek (Figure 2.1). The second compartment comprises the main outer bay, which opens into the open ocean. The two compartments are physically separated by a coral sill near the entrance to the creek, so that water exchange between the two compartments is only through the upper 1 m above the sill. There is also a marked salinity difference between the two compartments. The surface area of the inner system is about 5 $km^2$ with a depth of about 2 m, and total volume of the inner system $10x10^6$ $m^3$. The surface area of the outer system is about 45 $km^2$ with a depth of about 4 m, and total volume $180x10^6$ $m^3$.

*Water and salt balance*

The concept behind the water budgets is to establish the balance of freshwater inflow (such as runoff, precipitation, groundwater, sewage) and evaporative loss of freshwater. There must be a compensating outflow (or inflow) in order to balance the water volume in the system. Since salt must be conserved in the system, the salt fluxes accounted for by the salinity used to describe the fresh water advective flows must be balanced by mixing (Gordon *et al.* 1996).

The data used here were collected in June 1998, just after the end of long rains, and November 1998 during the wet season. Table 2.1 gives a summary of monthly averages of the rainfall for year 1998, and monthly averages of evaporation for Zanzibar. The average rainfall for June was 12 mm $d^{-1}$ and that for November 17 mm $d^{-1}$. The average pan evaporation for all seasons were equal, estimated at about 5 mm $d^{-1}$. However pan observations are known to be affected by a variety of factors: vapor pressure difference, wind, water temperature, pan diameter, air pressure, rim height, pan color, pan depth, pan immersion in the soil and exposure. Evaporation from a pan is usually greater than from larger water bodies because of higher water temperatures. The excess is corrected by a *pan coefficient* (PC), which is given by:

PC = (evaporation from a free water surface)/(evaporation from a pan)

**Table 2.1. Zanzibar mean monthly rainfall and evaporation (1998).**

| **Month** | **Rainfall** (mm $month^{-1}$) | **Evaporation** (mm $month^{-1}$) |
|---|---|---|
| January | 310 | 150 |
| February | 180 | 180 |
| March | 90 | 150 |
| April | 600 | 150 |
| May | 90 | 120 |
| June | 45 | 150 |
| July | 10 | 120 |
| August | 0 | 150 |
| September | 100 | 150 |
| October | 510 | 150 |
| November | 320 | 150 |
| December | 400 | 150 |
| **Mean** | **183** | **150** |

The correction depends on the size of the pan, e.g. for 4 ft diameter 10 inches deep pans use PC = 0.7 and for 10 ft diameter 24 inches deep pan use PC = 0.95 (William 1997; Nolte and Associates 1998). For this budget, the pan coefficient of 0.7 was applied to convert the measured daily evaporation value of 5 mm $d^{-1}$ to 3.5 mm $d^{-1}$, which is the free water surface evaporation value. The obtained free water surface evaporation is also consistent with the value obtained using Hamon's Equation (Hamon 1961) where estimated evaporation of 3.6 mm $d^{-1}$ was obtained using the temperature data for Zanzibar during the dry season.

The rainfall value of 12 mm $d^{-1}$ and 17 mm $d^{-1}$ for June and November respectively and evaporation of 3.5 mm $d^{-1}$ for both seasons, together with the data on the bay surface area, were used to calculate the precipitation and evaporation water volumes per day in the bay for the dry and wet seasons.

The estimation of the underground water flow ($V_G$) was a problem for this system, because the parameter has not been measured. Therefore the groundwater input was estimated using Darcy's Law (Shaw 1996). That empirical relationship is given by the following equation:

$$V_{G(Approx)} = -K[(h_2-h_1)/d]LW$$

where $K$ is the hydraulic conductivity given to be $6\times10^{-4}$ m $sec^{-1}$ for mainly coralline deposits (Woodward-Clyde 1999); $h_1$ and $h_2$ are the lower and upper hydraulic heads which for inner and outer bays the difference is estimated to be 2 m (tidal range); *d* is the watershed, which is 6 km and 2.5 km for the inner and outer bay, respectively; *L* is the length of the coastline, which is 9.5 km for the inner Bay and 18 km for the outer bay; and *W* is the width of the flow, which for Chwaka Bay is 2 m. The calculation using this relationship is good for estimation of typical annual groundwater flows only and unrealistic for estimating monthly averages. The same values were therefore applied for quantifying the average groundwater flow for both dry and wet seasons. It is noted however that the values for the wet season could be higher than those during the dry season. The calculations done for this system in the inner and outer bays gave:

$$V_{G(Inner\ Chwaka)} = 0.3x10^3\ m^3\ d^{-1}$$

$$V_{G(Outer\ Chwaka)} = 1.5x10^3\ m^3\ d^{-1}$$

Since the system is separated into two compartments, there are two salinity input values necessary for the calculation of salt balance between the compartments and between the big outer Chwaka Bay and the open ocean. These salinity values are shown in Figure 2.2. The salinity of the inner bay, outer bay and open ocean are indicated as $S_1$, $S_2$ and $S_{ocn}$ respectively. Similarly, the volume and surface area of the inner bay and outer bay are indicated as $V_1$, $A_1$ and $V_2$, $A_2$, respectively.

The water balance for each season is calculated using Equation (1) from Gordon *et al.* (1996):

$$dV/dt = V_Q + V_P + V_G + V_O + V_E + V_R \qquad (1)$$

where $V_Q$ is rate of river discharge, $V_P$ is precipitation, $V_O$ is sewage discharge, $V_E$ is evaporation and $V_R$ is residual flux. Assuming steady state (i.e. $dV/dt = 0$), then the residual flow is:

$$V_R = V_E - V_Q - V_P - V_G - V_O \qquad (2)$$

Substituting terms in Equation (2) with data in Table 2.2, the values of $V_R$ can be obtained for the wet and dry seasons.

On the other hand, the salt balance is calculated from Equation (3), in order to balance salt input via mixing with salt output from residual outflow. It is assumed that the salinity of out-flowing water ($S_R$) is the average of the salinities between the compartments under consideration [$S_R=(S_1+S_2)/2$].

$$dVS/dt = V_QS_Q + V_PS_P + V_GS_G + V_OS_O + V_ES_E + V_RS_R + V_X\ (S_2 - S_1) \qquad (3)$$

where $V_X$ represents the mixing volume exchanged between the ocean and the bay, and $V_RS_R$ is the salt flux carried by the residual flow. The general principle is that salt must be conserved so the residual salt flux is brought back to the system through the mixing salt flux across the boundary [$V_X\ (S_2 - S_1$] via the tides, wind and general ocean circulation pattern.

Since the salinity of freshwater inflow terms can be assumed to be 0, then Equation (3) can be simplified to:

$$dVS/dt = V_RS_R + V_X\ (S_2 - S_1) \qquad (4)$$

Assuming that $S_1$ remains constant with time (steady state):

$$0 = + V_RS_R + V_X\ (S_2 - S_1) \qquad (5)$$

By re-arrangement:

$$V_X = -V_RS_R / (S_2 - S_1) \qquad (6)$$

Substituting terms in Equation (6) with salinity data, the mixing volume ($V_X$) for different compartments can be obtained as illustrated in Figure 2.2 for the wet and dry seasons.

The water exchange or freshwater residence time ($t$) in days for both wet and dry seasons can be calculated from Equation 8, where $|V_R|$ is the absolute value of $V_R$:

$$t = V_{syst}/(V_X + |V_R|) \qquad (8)$$

$V_{syst}$ is the total volume of the bay or in our case the volume of the individual compartments. Figure 2.2 summarizes the water and salt flux for this two-box system and gives the water exchange time based on the data.

Chwaka Bay water and salt balance has demonstrated that in order to balance the inflow and outflow of water for June, there must be a net flux of water from the bay to the open ocean ($V_R$ = -42x$10^3$ $m^3$ $d^{-1}$ for inner bay and $V_R$ = -426x$10^3$ $m^3$ $d^{-1}$ for outer bay). Similarly, there is a net flux of water from the bay to the ocean during November ($V_R$ = -67x$10^3$ $m^3$ $d^{-1}$ for inner bay and $V_R$ = -676x$10^3$ $m^3$ $d^{-1}$ for outer bay). The corresponding residual fluxes of salt ($V_RS_R$) from the two boxes indicate advective salt export. However, the exchange of bay water with the open ocean plays a role of replacing this exported salt via mixing ($V_X$). In this data, the total exchange times (flushing time or freshwater residence time) were 20 and 22 days for the inner and outer bays, respectively for the month of June, and 5 and 26 days for the inner and outer bays respectively for the month of November. Water exchange time of the entire bay with the open ocean is 24 days in June and 37 days in November.

The mixing volumes were estimated from mixing equations in a 1-dimensional, steady state system (Yanagi 2000a) for comparison with the results obtained using water and salt balance method. The estimated mixing using Yanagi's method gave $V_{X1}$ = 1,200x$10^3$ $m^3$ $d^{-1}$ and $V_{X2}$ = 4,000x$10^3$ $m^3$ $d^{-1}$ for the inner and outer bay, respectively. These values were consistent with the $V_X$ obtained from the salt and water balance for both June and November.

This budget has demonstrated that it is difficult to obtain realistic budgets for systems that are dominated by evaporation that is almost comparable with net precipitation in the absence of runoff. It also showed that unrealistic budgets could be obtained by using the pan evaporation data. It is always important to convert the pan evaporation values to free water surface evaporation values. The use of pan coefficients ranging from 0.6-0.8 is recommended, depending on the size of the pans used. In this example, a pan coefficient of 0.7 was applied and provided realistic water and salt budgets for this system. It was also found that, in order to obtain realistic budgets, it is useful to compare the $V_X$ values obtained from salt-water balance with those obtained using Yanagi's method. The experience from this budget also showed that budgets for different seasons could be significantly different. It is therefore important to specify the seasons and preferably the month when the data used in budgets were taken.

*Budgets for nonconservative materials*

The nutrient data were only available for the month of November. The discussion in this section is therefore limited to the wet season. The general principle is that all the dissolved inorganic phosphorus (DIP) and dissolved inorganic nitrogen (DIN) will exchange between the system and the adjacent ocean according to the criteria established in the water and salt budget. Deviations are attributed to net nonconservative reactions of (DIP) and (DIN) in the system. DIP is defined as the $PO_4$ concentration and DIN as the ($NO_3^-$ + $NO_2^-$ + $NH4^+$). The data from Chwaka Bay show the concentration of DIP in the inner and outer bay to be $DIP_1$ = 2.0 ìM and $DIP_2$ = 1.2 ìM, respectively (Figure 2.3). Likewise, the concentration of DIN in the inner and outer bay are $DIN_1$ = 23 ìM and $DIN_2$ = 18 ìM, respectively (Figure 2.4). Following Wyrtki (1971) the concentration of DIN and DIP in the open ocean (Zanzibar Channel) are $DIP_{ocn}$ = 0.1 ìM and $DIN_{ocn}$ = 0.5 ìM, respectively.

This system poses a challenge for estimating fluxes of nutrients because the groundwater nutrient and nutrient loading associated with waste discharge concentration are unknown. The $V_QDIP_Q$ and $V_QDIN_Q$

were assumed to be zero since Chwaka Bay has no rivers. The $V_{atm}$DIP$_{atm}$ and $V_{atm}$DIN$_{atm}$ were assumed to be zero because atmospheric contribution is normally very small. However, although the population around Chwaka Bay is fairly small (9,000 people), the anthropogenic effects ($V_O DIP_O$, $V_O DIN_O$) were considered here because the initial estimates of *ÄDIP* and *ÄDIN* were relatively small. The waste load from solid waste, domestic waste and detergents could therefore be important for this system and were estimated using a method suggested by McGlone *et al*. (1999). Since the waste is dumped directly to the bay, it was assumed that 100% of the waste load does actually reach the bay waters. The values of $V_O DIP_O$ = 900 mol $d^{-1}$ and $V_O DIN_O$ = 4,000 mol $d^{-1}$ were obtained and used in the calculation of the budget for this system. Note that the waste load for the inner bay was taken to be zero because only the areas around the outer bay are inhabited.

Similarly, although the DIP$_G$ flux in groundwater flowing through carbonate terrain is known to be low, the concentration of nitrogen (DIN$_G$) in the underground water could not be neglected. For the nutrient calculations reported here, DIP$_G$ concentrations of 0.4 ìM and 2 ìM were used for the inner (DIP$_{G1}$) and outer (DIP$_{G2}$) systems, respectively. These values are comparable to reported groundwater $PO_4$ for similar systems (1-10 ìM: Lewis 1985; Tribble and Hunt 1996). Similarly, DIN$_G$ concentrations of 25 ìM and 37 ìM were used for the inner (DIN$_{G1}$) and outer (DIN$_{G2}$) systems, respectively.

*DIP and DIN balance*

DIP and DIN budget results for nonconservative materials in Chwaka Bay are illustrated in Figures 2.3 and 2.4. The calculated *ÄDIP$_1$* and *ÄDIP$_2$* for the wet season are +1,700 mol $d^{-1}$ (+0.3 mmol $m^{-2}$ $d^{-1}$) and +2,600 mol $d^{-1}$ (+0.06 mmol $m^{-2}$ $d^{-1}$), respectively, indicating that there is a net DIP flux from the bay to the ocean for the month of November (i.e. *ÄDIP* is positive). The calculated *ÄDIP$_{syst}$* = +4,300 mol $d^{-1}$ or +0.1 mmol $m^{-2}$ $d^{-1}$. Chwaka Bay acts as a DIP source during the wet season.

The calculated *ÄDIN$_1$* and *ÄDIN$_2$* for the wet season are +11,000 mol $d^{-1}$ (+2.2 mmol $m^{-2}$ $d^{-1}$) and +68,000 mol $d^{-1}$(+1.5 mmol $m^{-2}$ $d^{-1}$), respectively, indicating that there is a net DIN flux from the bay to the ocean during the wet season (i.e. *ÄDIN* is positive). The calculated *ÄDIN$_{syst}$* = +79,000 mol $d^{-1}$ (+1.6 mmol $m^{-2}$ $d^{-1}$). Thus as for DIP, Chwaka Bay is a net source of DIN during the wet season.

*Stoichiometric calculations of aspects of net system metabolism*

In general, the LOICZ Biogeochemical Modelling Guidelines (Gordon *et al.* 1996) were used to calculate the stoichiometrically linked water and salt-nutrients budgets. In these mass balance budgets, complete mixing of the water column is assumed. The general principle is that the nonconservative flux of DIP with respect to salt and water is an approximation of net ecosystem metabolism (production-respiration, *p-r*) at the scale of the system. The net ecosystem metabolism can be calculated from *ÄDIP*. The basic formulation is as follows:

*(p-r) = -ÄDIP* x *(C:P)*$_{part}$

where *(C:P)*$_{part}$ represents the C:P ratio of organic matter that is reacting in the system, which is expected to be near 106:1. On the other hand the nonconservative flux of DIN approximates net nitrogen fixation and denitrification in the system. The basic formulation is as follows:

*(nfix-denit) = ÄDIN - ÄDIP(N:P)*$_{part}$

where *(N:P)*$_{part}$ represents the ratio of both planktonic and waste derived organic matter reacting in the system, which is expected to be near 16:1. Table 2.2 shows the stoichiometric calculations made for Chwaka Bay for November 1998.

Because of unavailability of monthly nutrient data for the whole of 1997, the results from Chwaka Bay could not clearly demonstrate the dependence of seasonality in the nutrient budget. Stoichiometric calculations suggest that (*p-r*) is negative (Table 2.2) for all three regimes (inner, outer and entire bay).

This indicates that Chwaka Bay is net heterotrophic during the wet season. Chwaka Bay seems to have net denitrification in the inner bay as indicated by the negative (*nfix-denit)* value and the outer bay to be net nitrogen-fixing at a slower rate (Table 2.2). However, the entire bay seems to balance nitrogen fixing and denitrification, since (*nfix-denit*) for the entire bay is zero.

**Table 2.2. Summary of calculated (*p-r*) and (*nfix-denit*) values for Chwaka Bay for November 1998 (wet season).**

| Calculated Values | Inner Chwaka Bay | Outer Chwaka Bay | Entire bay |
|---|---|---|---|
| ***ÄDIP*** (mol $d^{-1}$) | +1,700 | +2,600 | +4,300 |
| ***ÄDIP*** (mmol $m^{-2}$ $d^{-1}$) | +0.3 | +0.06 | +0.1 |
| | | | |
| ***ÄDIN*** (mol $d^{-1}$) | +11,000 | +68,000 | +79,000 |
| ***ÄDIN*** (mmol $m^{-2}$ $d^{-1}$) | +2.2 | +1.5 | +1.6 |
| | | | |
| **(*p-r*)**<br>(mmol C $m^{-2}$ $d^{-1}$) | -32 | -6 | -11 |
| | | | |
| **(*nfix-denit*)**<br>(mmol N $m^{-2}$ $d^{-1}$) | -2.6 | +0.5 | 0 |

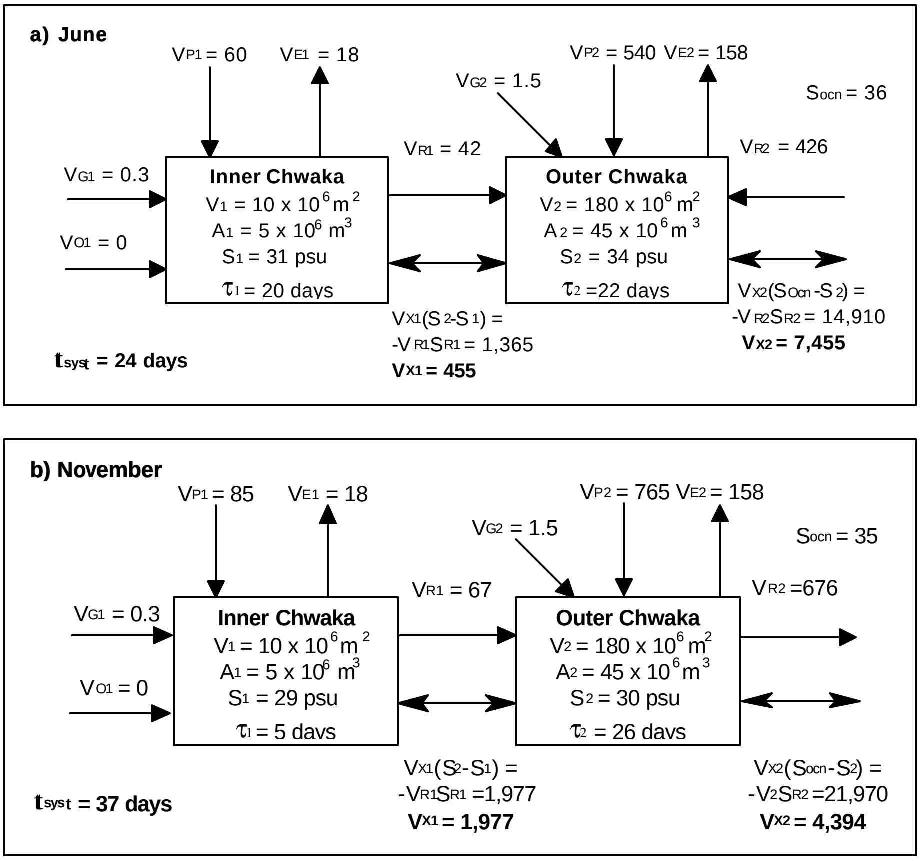


**Figure 2.2. Water and salt balance for Chwaka Bay for June 1998 (a) and November 1998 (b).** Water flux in $10^3$ $m^3$ $d^{-1}$ and salt flux in $10^3$ psu-$m^3$ $d^{-1}$.

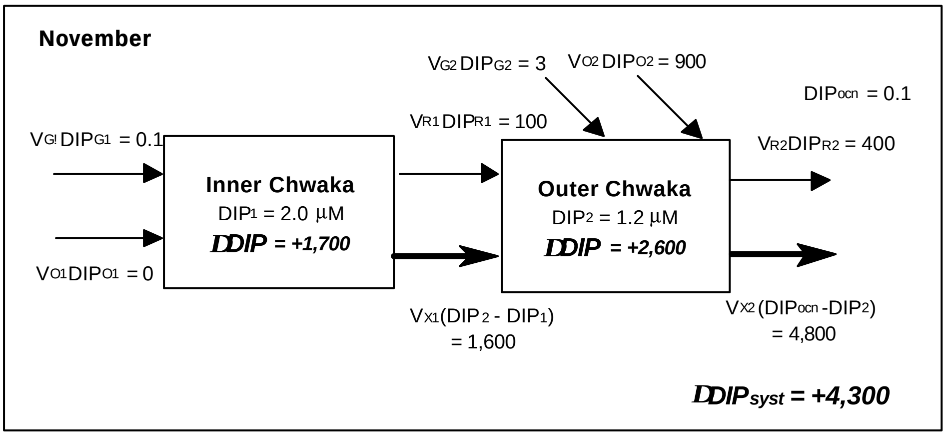


**Figure 2.3. DIP budget for Chwaka Bay for November 1998 (wet season).** Flux in mol d$^{-1}$ and concentration in μM or mmol m$^{-3}$.

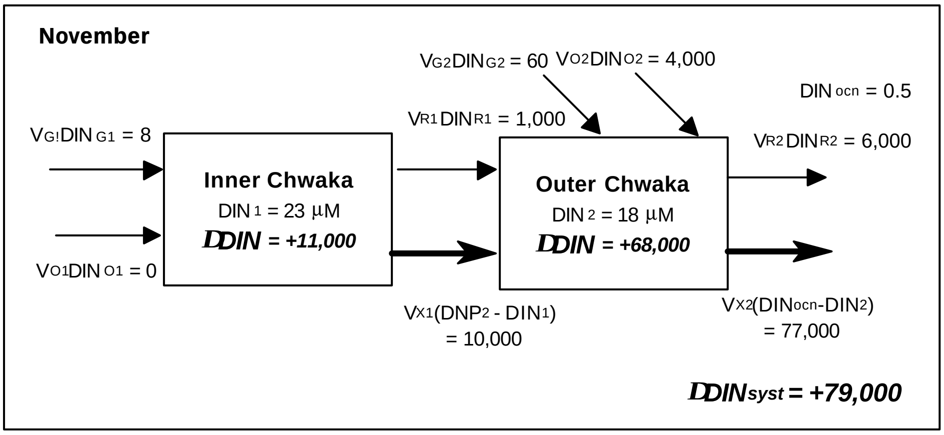


**Figure 2.4. DIN budget for Chwaka Bay for November 1998 (wet season).** Flux in mol d$^{-1}$ and concentration in μM or mmol m$^{-3}$.

## 2.2 Makoba Bay, Zanzibar

*A.S. Ngusaru and A.J. Mmochi*

<u>Study area description</u>

Makoba Bay is located within 5.90-5.95°S and 39.20-39.25°E on the northwest coast of Unguja Island, Zanzibar (Figure 2.5). It is sheltered by the much smaller Tumbatu Island, which is located about 5 km offshore to the north. The bay has a total surface area of about 15 $km^2$ and average depth of 5 m with a volume of about $75x10^6$ $m^3$. The tides in Makoba Bay are mainly semi-diurnal with a typical tidal range of about 2 m. Local climate is characterized by two rainy seasons: the long rains occur in March, April and May and the short rains during October, November and December. Therefore March-May and October-December constitute the wet season in Zanzibar. January-February and June-September constitute the dry season in Zanzibar. The estimated population around the bay is about 10,000 people. Untreated sewage is usually dumped directly into the bay. Industrial and agro-chemicals are also commonly applied, and the runoff from these also flows into the bay.

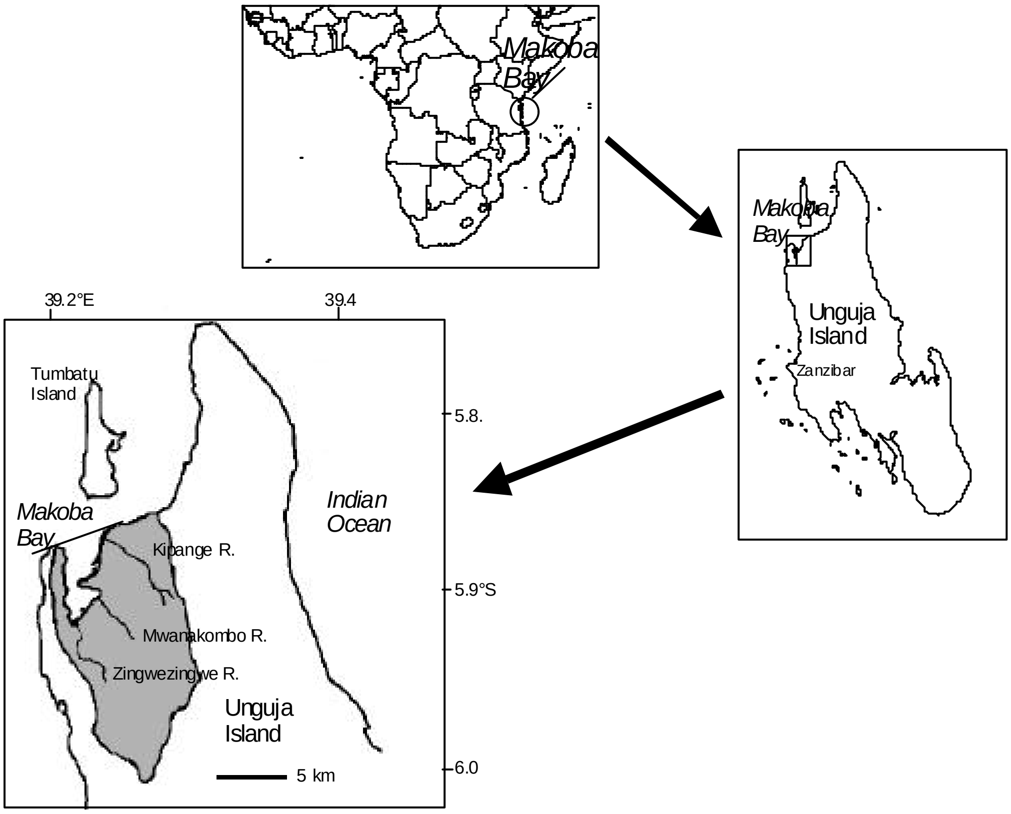


**Figure 2.5. Map and location of Makoba Bay, Zanzibar.** The bar at the mouth of the bay shows the budgeted area.

<u>Water and salt balance</u>

The basic principle for the water and salt budgets is to establish balance of freshwater inflow (such as runoff, precipitation, groundwater, sewage) and evaporative loss. Then compensating outflow (or inflow) is calculated to balance the water volume in the system. Since salt must be conserved in the system, the salt fluxes accounted for by the salinity used to describe the freshwater flows must be balanced by mixing (Gordon *et al.* 1996). Makoba Bay is the largest water catchment area in Zanzibar, referred to as the Mahonda-Makoba drainage basin. It drains rice farms, sugar cane plantations, a sugar factory and a rubber factory. Three main rivers with multiple rivulets provide a substantial amount of freshwater input directly to the bay, namely the Mwanakombo, Zingwezingwe and Kipange rivers. These rivers have a total watershed area of 150 $km^2$ with a total mean discharge of $24x10^6$ $m^3$ $yr^{-1}$ or about $70x10^3$ $m^3$ $d^{-1}$.

The data used for this budget were collected in April 1997, during the wet season in the area. Table 2.3 shows the monthly rainfall data for 1997; the average rainfall of 14 mm $d^{-1}$ was used in this budget. Mean pan evaporation rate is 5 mm $d^{-1}$, however pan observations are commonly affected by such factors as vapor pressure difference, wind, water temperature, pan diameter, air pressure, rim height, pan color, pan depth, pan immersion in the soil and exposure. Evaporation from a pan is usually greater than from larger water bodies because of higher water temperatures. The excess is corrected by a *pan coefficient* (PC), which is given by:

PC = (evaporation from a free water surface)/(evaporation from a pan)

The correction depends on the size of the pan, e.g. for 4 ft diameter 10 inches deep pans use PC = 0.7 and for 10 ft diameter 24 inches deep pan use PC = 0.95 (William 1997; Nolte and Associates 1998). For this budget, the pan coefficient of 0.7 was applied to convert the measured daily evaporation value of 5 mm $d^{-1}$ to 3.5 mm $d^{-1}$, which is the free water surface evaporation value. The obtained free water surface evaporation is also consistent with the value obtained using Hamon's equation (Hamon 1961) where estimated evaporation of 3.6 mm $d^{-1}$ was obtained using the temperature data for Zanzibar.

**Table 2.3. Zanzibar mean monthly rainfall and evaporation (1997).**

| **Month** | **Rainfall** (mm) | **Evaporation** (mm) |
|---|---|---|
| January | 0 | 150 |
| February | 50 | 180 |
| March | 425 | 150 |
| April | 310 | 150 |
| May | 250 | 120 |
| June | 215 | 150 |
| July | 40 | 120 |
| August | 40 | 150 |
| September | 0 | 150 |
| October | 510 | 150 |
| November | 315 | 150 |
| December | 45 | 150 |
| **Mean** | 183 | 221 |

The rainfall value of 14 mm $d^{-1}$ and evaporation of 3.5 mm $d^{-1}$ together with the data on the bay surface area were used to calculate the precipitation and evaporation water volume per day in the bay for the dry season as shown in Figure 2.6.

Unfortunately the underground water flow ($V_G$) was not measured. The groundwater input was therefore estimated using Darcy's Law (Shaw 1996). The empirical relationship is given by the following equation:

$$V_{G(Approx)} = -K[(h_2-h_1)/d]LW$$

Where $K$ is the hydraulic conductivity given to be $6x10^{-4}$ m $sec^{-1}$ for mainly coralline deposits (Woodward-Clyde 1999); $h_1$ and $h_2$ are the lower and upper hydraulic heads which for inner and outer bays the difference is estimated to be 2 m (tidal range); $d$ is the watershed which is 15 km; $L$ is the length of the coastline, which is about 20 km and $W$ is the width of the flow, which for Makoba Bay is about 2 m. The calculation using this relationship is good for estimation of typical annual ground water flows only and unrealistic for estimating monthly averages. The same obtained values were therefore used for quantifying the average groundwater flow for both dry and wet seasons. However, the values for the wet season should be higher that those during the dry season. The calculations done for Makoba Bay gave:

$V_G = 0.3 \times 10^3\ m^3\ d^{-1}$

The salinity-input values for the calculation of salt balance between Makoba Bay and the open ocean are shown in Figure 2.6. The salinity of the bay and open ocean is indicated as $S_{syst}$ and $S_{ocn}$, respectively. Similarly, the volume and surface area of the bay are indicated as $V_{syst}$ and $A_{syst}$ respectively.

The water balance for each season is calculated using Equation (1) from Gordon *et al.* (1996):

$$dV/dt = V_Q + V_P + V_G + V_O + V_E + V_R \qquad (1)$$

where $V_Q$ is rate of river discharge, $V_P$ is precipitation, $V_O$ is sewage discharge, $V_E$ is evaporation and $V_R$ is residual flux. Assuming steady state (i.e. $dV/dt = 0$), then the residual flow is:

$$V_R = V_E - V_Q - V_P - V_G - V_O \qquad (2)$$

Substituting terms in Equation (2) with data in Table 2.3, the values of $V_R$ can be obtained for the wet and dry seasons.

On the other hand, the salt balance is calculated from Equation (3), in order to balance salt input via mixing with salt output from residual outflow. It is assumed that the salinity of out-flowing water ($S_R$) is the average of the salinities between the bay and open ocean.

$[S_R = (S_{syst} + S_{ocn})/2]$.

$$dVS/dt = V_Q S_Q + V_P S_P + V_G S_G + V_O S_O + V_E S_E + V_R S_R + V_X (S_{ocn} - S_{syst}) \qquad (3)$$

where $V_X$ represents the mixing volume exchanged between the bay and the ocean, and $V_R S_R$ is the salt flux carried by the residual flow. The general principle is that salt must be conserved so the residual salt flux is brought back to the system through the mixing salt flux across the boundary [$V_X$ $(S_{ocn} - S_{syst}$] via the tides, wind and general ocean circulation pattern.

Since the salinity of freshwater inflow terms can be assumed to be 0, then Equation (3) can be simplified to:

$$dVS/dt = V_R S_R + V_X (S_{ocn} - S_{syst}) \qquad (4)$$

Assuming that $S_{syst}$ remains constant with time (steady state):

$$0 = + V_R S_R + V_X (S_{ocn} - S_{syst}) \qquad (5)$$

By re-arrangement:

$$V_X = -V_R S_R / (S_{ocn} - S_{syst}) \qquad (6)$$

Substituting terms in Equation (6) with salinity data, the mixing volume ($V_X$) can be obtained as illustrated Figure 2.6 for both wet and dry seasons.

The water exchange or freshwater residence time ($t$) in days for both wet and dry seasons can be calculated from Equation 8, where $|V_R|$ is the absolute value of $V_R$:

$$t = V_{syst}/(V_X + |V_R|) \qquad (8)$$

Figure 2.6 summarizes the water and salt flux for this system and gives the water exchange time based on the data. The Makoba Bay water and salt balance has demonstrated that in order to balance the inflow and outflow of water during the wet season there is net flux of water from the bay to the open ocean ($V_R$ = -223x$10^3$ $m^3$ $d^{-1}$). The residual fluxes of salt ($V_RS_R$) between the bay and the open ocean indicate advective salt export; the exchange of bay water with the open ocean plays a role of replacing this exported salt via mixing. The calculated water exchange time (flushing time or freshwater residence time) for Makoba Bay is 63 days during the wet season.

*<u>Budgets of nonconservative materials</u>*

The dissolved inorganic phosphorus (DIP) and dissolved inorganic nitrogen (DIN) budgets are termed the budgets of nonconservative materials. While this might be done with any reactive material, the particular interest here is in the balance among the essential elements C, N, and P. The general principle behind the budgets is that the DIP and DIN will exchange between the system and the adjacent ocean according to the criteria established in the water and salt budgets. Deviations are attributed to net nonconservative reactions of DIP and DIN in the system. DIP is defined as the $PO_4^{-3}$ concentration and DIN as the ($NO_3^- + NO_2^- + NH4^+$).

Due to limited data, the discussion of nutrient budgets for Makoba Bay is limited to the wet season only. The data from Makoba Bay show the concentration of DIP in the bay to be $DIP_{syst}$ = 0.2 µM during the wet season (Figure 2.7). Likewise, the concentration of DIN in the bay is $DIN_{syst}$ = 32 µM for the wet season (Figure 2.8). Following Wyrtki (1971) the concentration of DIN and DIP in the open ocean (Zanzibar Channel) are $DIP_{ocn}$ = 0.1 µM and $DIN_{ocn}$ = 0.5 µM. The concentrations in the rivers were estimated at $DIP_Q$ = 0.3 µM and $DIN_Q$ = 6 µM.

This system poses a challenge for estimating fluxes of nutrients because the groundwater nutrient and nutrient loading associated with waste discharge concentration are unknown. The $DIP_{atm}$ and $DIN_{atm}$ were assumed to be zero because atmospheric contribution is normally small. The population around Makoba Bay is fairly small (10,000 people); nevertheless the waste load from solid waste, domestic waste and detergents were estimated using a method suggested by McGlone *et al* (1999). Since the waste is dumped directly to the bay, it was assumed that 100% of the waste load does actually reach the bay waters. The values of $V_ODIP_O$ = 1,100 mol $d^{-1}$ and $V_ODIN_O$ = 4,400 mol $d^{-1}$ were obtained and used in the calculation for the budget. Because of lack of data, the DIP and DIN contributions from agricultural and industrial activities were not included in the budget. Although the $DIP_G$ flux in groundwater flowing through carbonate terrain is known to be low, the concentration of nitrogen ($DIN_G$) in the underground water could not be neglected. For the nutrient calculations reported here, $DIP_G$ concentration of 2 µM and $DIN_G$ concentration of 37 µM were used. These values are comparable to reported groundwater $PO_4$ for similar systems ($DIN_G$ = 1-10 µM; $DIP_G$ = 37-72 µM: Lewis 1985; Tribble and Hunt 1996).

*DIP and DIN balance*

The budget results for nonconservative materials in Makoba Bay are illustrated in Figures 2.6 and 2.7. The calculated *DDIP* and *DDIN* for the wet season is –990 mol $d^{-1}$ and +29,400 mol $d^{-1}$, respectively, indicating that there is a net DIP flux from the ocean to the bay during the wet season. Therefore Makoba Bay acts as a sink for dissolved inorganic phosphorus during wet season (*DDIP* is negative). There is also a net DIN flux from the bay to the open ocean during the wet season. Makoba Bay is therefore a source of dissolved inorganic nitrogen (*DDIN* is positive) during the wet season.

*Stoichiometric calculations of aspects of net system metabolism*

The LOICZ Biogeochemical Modelling Guidelines (Gordon *et al.* 1996) were used to calculate the stoichiometrically linked water-salt-nutrients budgets. In these mass balance budgets, complete mixing of the water column is assumed. The general principle is that the nonconservative flux of DIP with respect to salt and water is an approximation of net ecosystem metabolism (production-respiration, *p-r*) at the scale of the system in question. The net ecosystem metabolism can therefore be calculated from *DDIP* using the following basic formulation,

$$(p\text{-}r) = -DDIP \times (C{:}P)_{\mathrm{part}}$$

where $(C{:}P)_{\mathrm{part}}$ represents the C:P ratio of organic matter that is reacting in the system, which is expected to be near 106:1.

On the other hand the nonconservative flux of DIN approximates net nitrogen fixation and denitrification in the system. The basic formulation is as follows:

$$(nfix\text{-}denit) = DDIN - DDIP(N{:}P)_{\mathrm{part}}$$

*w*here $(N{:}P)_{\mathrm{part}}$ represents the ratio of both planktonic and waste-derived organic matter reacting in the system, which is expected to be near 16:1. Table 2.4 shows the stoichiometric calculations made for Makoba Bay.

Stoichiometric calculations suggest that (*p-r*) is positive during the wet season (Table 2.4). This indicates that Makoba Bay is net autotrophic during the wet season. Makoba Bay is fixing nitrogen during wet season, where (*nfix-denit)*is estimated to be 3 mmol $m^{-2}$ $d^{-1}$ in excess of denitrification. The summary of fluxes of nonconservative nutrients in Makoba Bay is given in Table 2.4. Nitrogen fixation is known to provide the nitrogen requirement in areas dominated by seagrass beds and mangroves (Hanisak 1993). The occurrence of mangroves and seagrass beds at Makoba Bay is a possible ecological reason behind the balance of nitrogen fixation over denitrification in the bay.

**Table 2.4. Summary of calculateded (*p-r*) and (*nfix-denit*) values for Makoba Bay for April 1997 (wet season).**

| **Parameters** | **Calculated values** |
|---|---|
| ***DDIP*** (mol $d^{-1}$) | -990 |
| ***DDIP*** (mmol $m^{-2}$ $d^{-1}$) | -0.07 |
| ***DDIN*** (mol $d^{-1}$) | +29,400 |
| ***DDIN*** (mmol $m^{-2}$ $d^{-1}$) | +2 |
| **(*p-r*)**<br>(mmol C $m^{-2}$ $d^{-1}$) | +7 |
| **(*nfix-denit*)**<br>(mmol N $m^{-2}$ $d^{-1}$) | +3 |

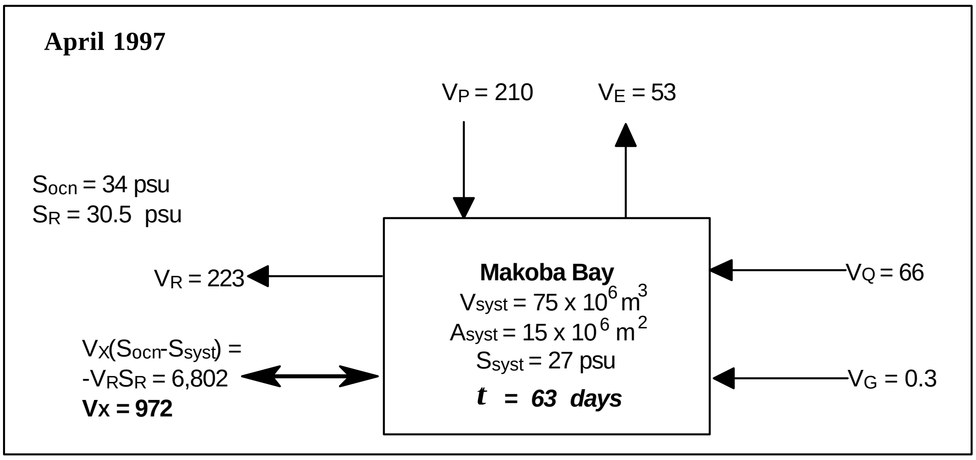


**Figure 2.6 Water and salt balance for Makoba Bay for April 1997 (wet season).** Water flux in $10^3$ $m^3$ $d^{-1}$ and salt flux in $10^3$ psu-$m^3$ $d^{-1}$.

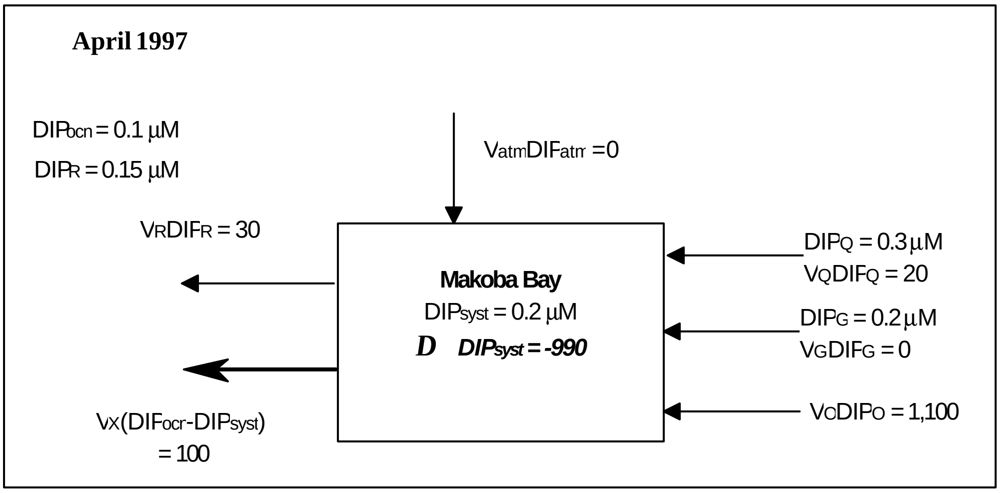


**Figure 2.7. DIP budget for Makoba Bay for April 1997 (wet season).** Flux is in mol $d^{-1}$ and concentration in µM or mmole $m^{-3}$.

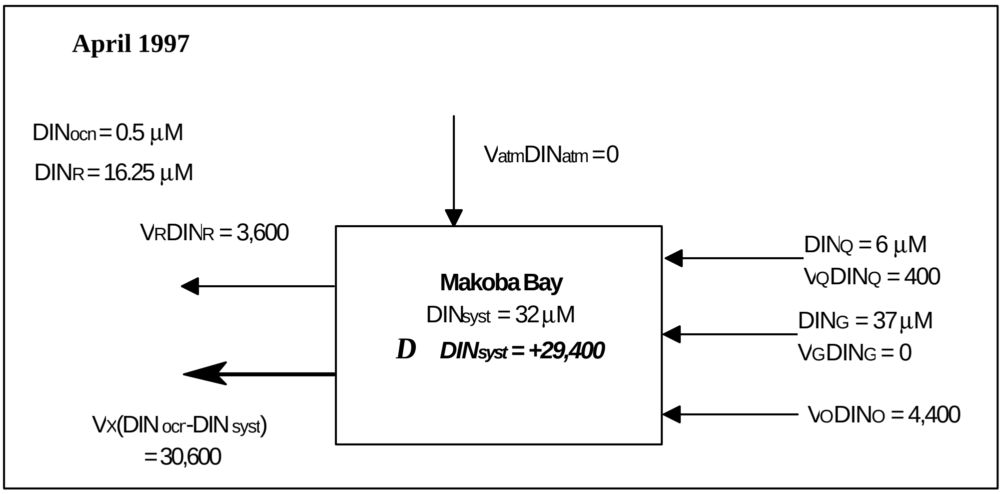


**Figure 2.8. DIN budget for Makoba Bay for April 1997 (wet season).** Flux is in mol $d^{-1}$ and concentration in µM or mmole $m^{-3}$.

## 2.3 Malindi Bay, Kenya

*Mwakio P. Tole*

<u>Study area description</u>

Malindi Bay, towards the south coast of Kenya, is semi-enclosed to the north and to the south, but open to the ocean over a patchy coral reef ecosystem. Sea grasses and algae are common in southern and northern ends of the bay. A small mangrove forest occurs on the banks of the Sabaki River about 1 km from the ocean. Figure 2.9 shows the location of the study area. The area is estimated to be 18 $km^2$.

Mean annual rainfall in the Malindi Bay area, and for most of the drainage basin, is 972 mm per annum, and ranges from 677mm during dry years to 1267mm during wetter years. Annual evaporation is much higher than the rainfall, at 1800 mm per year. Temperatures range from 28°±7°C at Malindi in the coast, to 20°±7°C in the highland areas around Nairobi.

The Athi-Galana-Sabaki River system rises from the highlands in the central part of the country, and is the second largest river draining into the Indian Ocean in Kenya. It has a length of 400 km, and drains a basin area of 70,000 square kilometers It enters the Indian Ocean at 3.2° S 40.15°E, just north of Malindi town (population approximately 50,000) in Malindi Bay. The Sabaki River flow rate ranges from a low of 0.52 $m^3 s^{-1}$ in the driest periods, to 758 $m^3 s^{-1}$ during times of flood. Mean flow rate was 48.8 $m^3 s^{-1}$ over the period 1957 to 1979.

Industrial and municipal wastes from Nairobi City (population approximately 2 million) drain into the river, sometimes with little treatment. The river also receives agrochemicals (fertilizers, pesticides) from farms that grow coffee, tea, horticultural crops (including cut flowers), and from maize farming. Dairy and beef farming is also practised along the river basin.

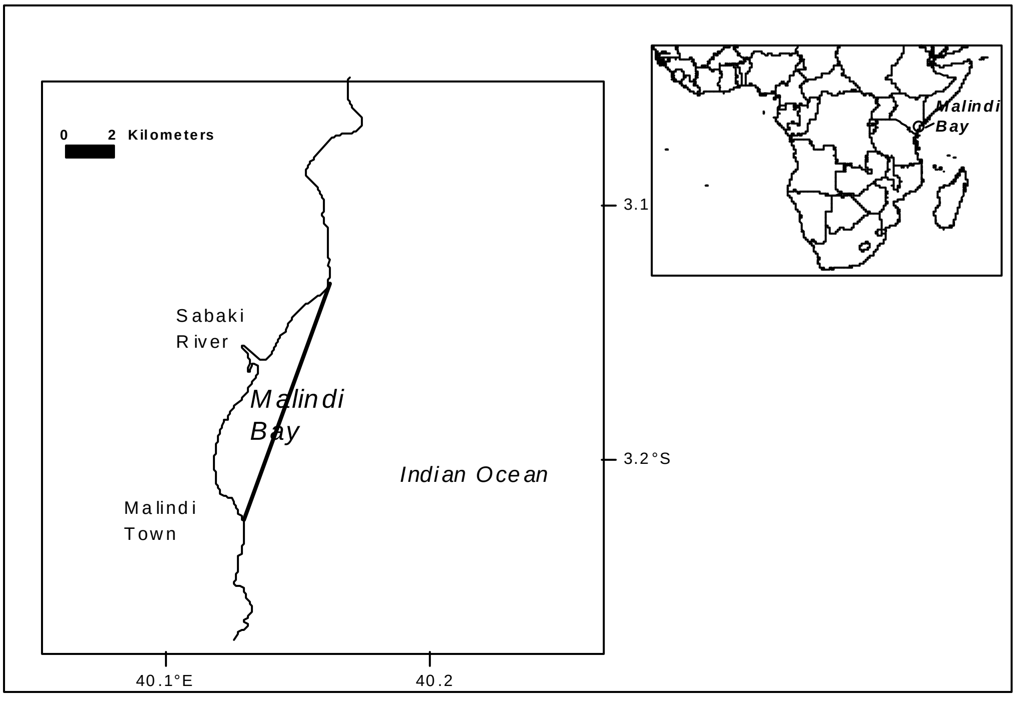


**Figure 1. Map of Malindi Bay.** Bar shows the boundary of the budgeted area.

Mean annual rainfall in the Malindi Bay region is 1,000 mm, and ranges from 700 mm during dry years to 1,300 mm during wet years. Annual evaporation is 1,800 mm.

The Sabaki River flow rate ranges from 0.5 $m^3$ $s^{-1}$ ($40x10^3$ $m^3$ $d^{-1}$) in the driest periods to 760 $m^3$ $s^{-1}$ ($70x10^6$ $m^3$ $d^{-1}$) during times of flood. Mean flow rate was 50 $m^3$ $s^{-1}$ ($4x10^6$ $m^3$ $d^{-1}$) over the period 1957 to 1979. Malindi Town has a population of approximately 50,000 people. Water abstracted upstream in the Sabaki River is used in the town, and becomes wastewater that is assumed discharged directly into the Malindi Bay. The volume of this has been estimated to be $20x10^3$ $m^3$ $d^{-1}$.

Tidal influence is high in Malindi Bay, with tidal ranges between 2 and 3 m. Waves, particularly during the SE monsoon period (April–September), range up to 2 m near the shore. The mean depth of the bay is 2 m. The system is well-flushed and fairly well-mixed.

*Water and salt balance*

The water and salt budgets describe the exchange of water and salt between the Malindi Bay and the Indian Ocean (Figure 2.10). Freshwater inputs are from the Sabaki River ($V_Q$), precipitation ($V_P$) and Malindi Town sewage ($V_O$), while loss is to the open ocean ($V_R$) and by evaporation ($V_E$). Salt must be conserved in the system, hence salt flux out from the system carried by the residual flow ($V_R$) must be balanced via mixing ($V_X$). There are two distinct wet seasons and two dry seasons each of about three months. Data were collected in 1997 and 1998, and were affected by unusually heavy El Nino rains, so that the dry seasons were masked by flooding rains. There were no distinct dry seasons during the El Nino rains in 1997-1998. Tables 2.5 and 2.6 indicate the data used to compile the water and salt budgets.

**Table 2.5. Malindi Bay water fluxes (in $10^6$ $m^3$ $d^{-1}$) and water exchange time ($\boldsymbol{t}$).**

| | **Oct–Dec** (wet) | **Jan–Mar** (dry) | **Apr–Jun** (wet) | **Jul–Sep** (dry) | **Annual** |
|---|---|---|---|---|---|
| **Surface runoff** ($V_Q$) | 6 | 5 | 5 | 5 | 5 |
| **Groundwater** ($V_G$) | 0 | 0 | 0 | 0 | 0 |
| **Precipitation** ($V_P$) | 0 | 0. | 0 | 0 | 0 |
| **Evaporation** ($V_E$) | 0 | 0 | 0 | 0 | 0 |
| **Outfall** ($V_O$) | 0 | 0 | 0 | 0 | 0 |
| **Residual flow** ($V_R$) | 6 | 5 | 5 | 5 | 5 |
| **Mixing** ($V_X$) | 11 | 9 | 8 | 9 | 9 |
| $\boldsymbol{t}$ (days) | 2 | 3 | 3 | 3 | 3 |

The water balance for each season is calculated based on Gordon *et al.* (1996). Precipitation, evaporation and sewage flow were considered insignificant compared to high river flow. Water fluxes and water exchange time ($t$) are summarized in Table 2.5. The water exchange time, based on the average data, was 2 to 3 days.

*Balance of nonconservative materials*

Available data for nutrient concentrations used in this budget were measured in different years. Nutrient concentrations for Sabaki River were taken from Ohowa 1993, Giesen and Kerkhof 1984, and Heip et al. 1995; and oceanic concentrations from Wyrtki *et al.* 1988 (see Table 2.6). The nutrient concentrations measured in those years vary significantly between dry and wet seasons with low concentrations during the dry seasons and high during the wet seasons. Nonconservative budgets were developed for the low and high nutrient concentrations using annual average water budget for 1997-1998 (Figure 2.10).

**Table 2.6. Salinity and nutrient concentrations for Sabaki River, Malindi Bay and adjacent ocean.**

| Parameter | Sector | Data source | Low nutrient | High nutrient |
|---|---|---|---|---|
| **Salinity** (psu) | Bay | Munyao 2000 | 19 | 20 |
| | Ocean | Munyao 2000 | 35.5 | 35.5 |
| | | | | |
| **DIP** (μM) | River | Ohowa 1993 | 0.9 | 25 |
| | Bay | | 0.5 | 10 |
| | Ocean | Wyrtki *et al.* 1988 | 0.2 | 2.5 |
| | | | | |
| **DIN** (μM) | River | Ohowa 1993 | 0.01 | 97 |
| | Bay | | 0.2 | 40 |
| | Ocean | Wyrtki *et al.* 1988 | 0.5 | 0.5 |

Estimated loads from all sources - domestic, hotels, storm runoff, solid wastes, industrial waste, agricultural waste, and livestock waste (modified after Munga *et al.* 1993) are 34 tonnes per annum of phosphorus and 168 tonnes per annum of nitrogen. These exclude what is inputted into the ocean through the Sabaki River. The estimated loads were converted to dissolved inorganic phosphorus (DIP) and dissolved inorganic nitrogen (DIN) using DIP:TP (0.5) and DIN:TN (0.4) in San Diego-McGlone *et al.* 1999 with the assumption that 100% of the estimated nutrient loads enter the bay.

Table 2.7 summarizes the fluxes of DIP and DIN for Malindi Bay. The system appears to be a net sink for both DIP and DIN. However, there is a large amount of uncertainty in these budgets because of the extreme range in estimated nutrient concentrations.

**Table 2.7. Summary of nutrient fluxes and stoichiometically derived (*p-r*) and (*nfix-denit*) for Malindi Bay, comparing results using the low and high nutrient concentrations data.**

| Fluxes | Low nutrient | High nutrient | Average |
|---|---|---|---|
| $V_Q DIP_Q$ ($10^3$ mol $d^{-1}$) | 5 | 125 | 65 |
| $V_O DIP_O$ ($10^3$ mol $d^{-1}$) | 2 | 2 | 2 |
| $V_R DIP_R$ ($10^3$ mol $d^{-1}$) | -2 | -31 | -17 |
| $V_X(DIP_{ocn}-DIP_{syst})$ ($10^3$ mol $d^{-1}$) | -3 | -68 | -36 |
| ***DDIP*** ($10^3$ mol $d^{-1}$) | -2 | -28 | -15 |
| ***DDIP*** (mmol $m^{-2}$ $d^{-1}$) | -0.1 | -1.6 | -0.9 |
| | | | |
| $V_Q DIN_Q$ ($10^3$ mol $d^{-1}$) | 0 | 485 | 243 |
| $V_O DIN_O$ ($10^3$ mol $d^{-1}$) | 13 | 13 | 13 |
| $V_R DIN_R$ ($10^3$ mol $d^{-1}$) | -2 | -101 | -52 |
| $V_X(DIN_{ocn}-DIN_{syst})$ ($10^3$ mol $d^{-1}$) | 3 | -356 | 180 |
| ***DDIN*** ($10^3$ mol $d^{-1}$) | -14 | -41 | -28 |
| ***DDIN*** (mmol $m^{-2}$ $d^{-1}$) | -0.8 | -2.3 | -1.6 |
| | | | |
| $(p-r)_{plankton}$ (mmol $m^{-2}$ $d^{-1}$) | +11 | +170 | +91 |
| $(nfix-denit)_{plankton}$ (mmol $m^{-2}$ $d^{-1}$) | +0.8 | +23 | +12 |

*Stoichiometric calculations of aspects of net system metabolism*

Net metabolism of the bay was stoichiometrically derived from the calculated nonconservative DIN and DIP. Assuming that the bay is primarily driven by phytoplankton and using C:N:P ratio of 106:16:1 for phytoplankton, the bay seems to be net autotrophic and fixing nitrogen. The average (*p-r*) is +91 mmol $m^{-2}$ $d^{-1}$ and (*nfix-denit*) is +12 mmol $m^{-2}$ $d^{-1}$ (Table 2.7).

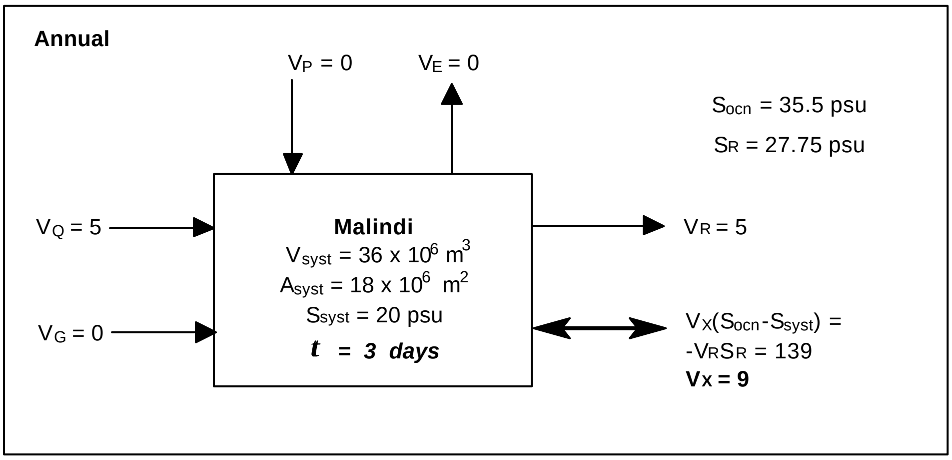


**Figure 2.10. Water and salt budgets for Malindi Bay for 1997-1998.** Water flux in $10^6$ $m^3$ $d^{-1}$ and salt flux in $10^6$ psu-$m^3$ $d^{-1}$.