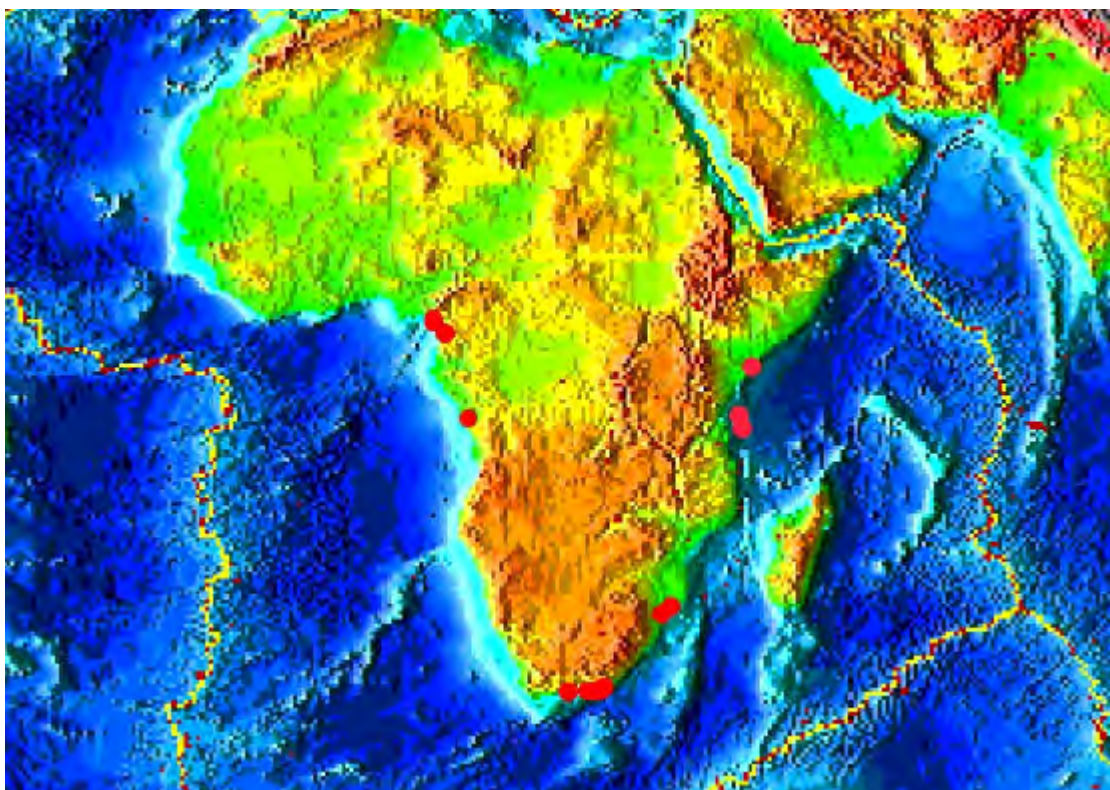


LAND-OCEAN INTERACTIONS IN THE COASTAL ZONE (LOICZ)  
Core Project of the  
International Geosphere-Biosphere Programme: A Study of Global Change (IGBP)  
and

UNITED NATIONS ENVIRONMENT PROGRAMME (UNEP)  
Supported by the Global Environment Facility (GEF)



ESTUARINE SYSTEMS OF SUB-SAHARAN AFRICA: CARBON, NITROGEN AND  
PHOSPHORUS FLUXES

*Compiled and edited by V. Dupra, S.V. Smith, J.I. Marshall Crossland and C.J. Crossland*

**LOICZ REPORTS & STUDIES NO. 18**

# ESTUARINE SYSTEMS OF SUB-SAHARAN AFRICA: CARBON, NITROGEN AND PHOSPHORUS FLUXES

*V. Dupra & S.V. Smith  
School of Ocean and Earth Science and Technology  
Honolulu, Hawaii, USA*

*J.I. Marshall Crossland & C.J. Crossland  
LOICZ International Project Office  
Texel, The Netherlands*



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Email: loicz@nioz.nl

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**Cover:** The cover shows an image of Africa (GTOPO30 elevation map), with the budgeted estuaries circled.

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# 1. OVERVIEW OF WORKSHOP AND BUDGETS RESULTS

The key objectives of the Land-Ocean Interactions in the Coastal Zone (LOICZ) core project of the International Biosphere-Geosphere Programme (IGBP) are to:

- gain a better understanding of the global cycles of the key nutrient elements carbon (C), nitrogen (N) and phosphorus (P);
- understand how the coastal zone affects material fluxes through biogeochemical processes; and
- characterise the relationship of these fluxes to environmental change, including human intervention (Pernetta and Milliman 1995).

To achieve these objectives, the LOICZ programme of activities has two major thrusts. The first is the development of horizontal and, to a lesser extent, vertical material flux models and their dynamics from continental basins through regional seas to continental oceanic margins, based on our understanding of biogeochemical processes and data for coastal ecosystems and habitats and the human dimension. The second is the scaling of the material flux models to evaluate coastal changes at spatial scales to global levels and, eventually, across temporal scales.

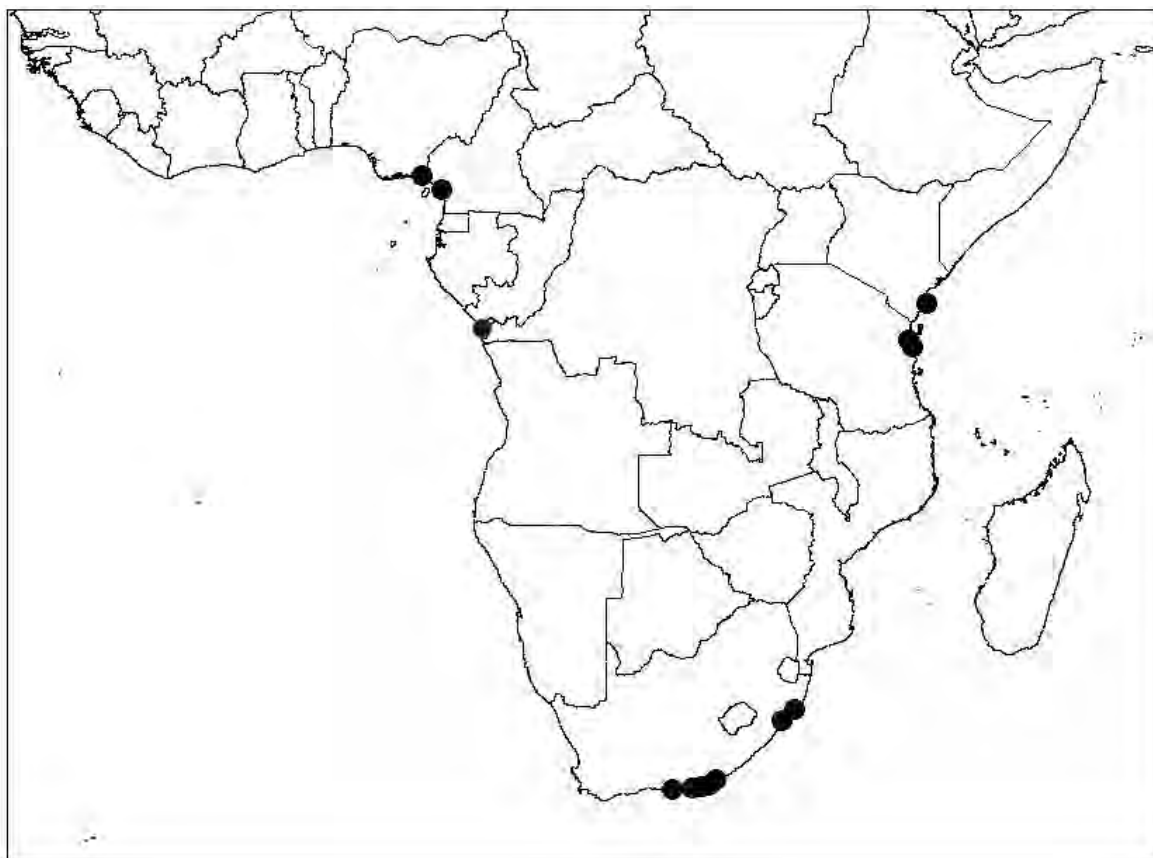
It is recognised that there is a large amount of existing and recorded data and work in progress around the world on coastal habitats at a variety of scales. LOICZ is developing the scientific networks to integrate the expertise and information at these levels in order to deliver science knowledge that addresses our regional and global goals.

The United Nations Environment Programme (UNEP) and the Global Environment Facility (GEF) have similar interests through the sub-programme: “Sustainable Management and Use of Natural Resources”. LOICZ and UNEP, with GEF funding support, have established a project: “The Role of the Coastal Ocean in the Disturbed and Undisturbed Nutrient and Carbon Cycles” to address these mutual interests. This Workshop is the fifth of a series of regional activities within the project.

Sub-Saharan Africa extends across 50 degrees of latitude (about 15°N to 35°S) and about 70 degrees of longitude. Coastal regions include tropical to temperate climate regimes and feature river catchments ranging from arid to wet monsoonal systems. The influence of large ocean current systems and their interplay with climatic patterns confers great diversity to the shelf physics, and the chemistry and biology of the shelf and marine coastal systems. Riverine inputs are highly diverse, with some regions driven by major monsoon patterns and events, frequently modified by cyclonic weather systems (especially in the eastern African region). By contrast, arid catchments and ephemeral river flows are characteristic of a number of regions. Major river systems are common near the tropics and in western Africa; damming, irrigation uptake and groundwater withdrawal are common modifiers. There is a huge number of smaller rivers discharging to estuarine and shelf areas. Land use pressures and change is a characteristic of the river catchments and with increasing population trends, changing and intensifying human resource uses and pockets of industrialisation, the region offers a tapestry for a diverse range of biogeochemical estuarine functions, patterns and changes. Comprehensive data and information on estuarine processes and coastal ecosystems are limited. While this situation often reflects limited effort and opportunity for research and measurement of these systems, much historical data has been dispersed (or lost) in transitions of countries in the Sub-Saharan region. Concerted effort is being made by scientists and governments, together with international agencies, to reclaim available information, to build and improve capacity and to initiate scientific study of ecosystems. This Workshop is a contribution to these efforts.

The Workshop was held at the Fisherman’s Resort, Zanzibar on 12-14 September 2000. The terms of reference for the Workshop (Appendix IV) and a summary of activities (Appendix I) are contained in this report. The resource persons worked with Workshop participants (Appendix III) from five countries (Tanzania, Kenya, Cameroon, Guinea and South Africa) to develop and assess biogeochemical budgets for eleven coastal systems in the region, ranging from estuarine environments associated with large and small river catchments to large bays. Further site budgets are being

developed at home institutions and through additional contact within the region initiated by workshop participants.



**Figure 1.1 Map of budget sites developed by the sub-Saharan Africa regional workshop.**

Dr Amani Ngusaru, Zanzibar Institute of Marine of Sciences, University of Dar es Salaam, will take up the LOICZ/UNEP Regional Training Scholarship (Africa) in early 2001, for additional training in budget analysis at the University of the Philippines (with the Regional Mentors) and at the University of Hawaii (with Professor Stephen Smith). Dr Howard Waldron (University of Cape Town) has accepted the role of Regional Mentor – Africa, and has planned a series of activities and network building in the region to expand both training and awareness in biogeochemical budgets development, and site budget derivations for the region.

The initial plenary session of the Workshop outlined the LOICZ approach to biogeochemical budget modelling of nutrient fluxes in estuaries, and described tools that have been developed for site assessment and budget derivations. Presentation of the CABARET software programme (for calculation of sites budgets and models) by Dr Laura David, added a further dimension to the tools and training elements. Up-scaling tools and approaches being developed and applied by LOICZ as part of the UNEP GEF project were described along with the planned agenda for regional and global integration by way of four workshops in 2001. The pivotal role of the LOICZ Budgets and Modelling electronic web-site was emphasised along with its use by global scientists in making budget contributions to the LOICZ purpose. In the web-site publication, contributing scientists are clearly attributed as authors of their budgets, and there is provision to update and provide additional assessment of their budgets.

The group moved from the plenary session to develop further the site budgets individually and in small working groups, returning to plenary sessions to discuss the budget developments and to debate

points of approach and interpretation. Eleven budgets were developed during the Workshop (Figure 1.1, Table 1.1), with additional sites identified for future work.

The common element in the site descriptions is the use of the LOICZ approach for biogeochemical budget development, which allows for global comparisons and application of the typology approach. The differences in the descriptive presentations reflect the variability in richness of site data, the complexity of the sites and processes, and the extent of detailed process understanding for the sites. Support information for the various estuarine locations, describing the physical environmental conditions and related forcing functions including history and potential anthropogenic pressure, is an important part of the budgeting information for each site. These budgets, data and their wider availability in electronic form (CD-ROM, LOICZ web-site) will provide opportunities for further assessment, comparisons and potential use across wider scales of pattern assessment for system response and human pressures.

The biogeochemical budget information for each site is discussed individually and reported in units that are convenient for that system (either as daily or annual rates). To provide for an overview and ease of comparison, the key data are presented in an “annualised” form and nonconservative fluxes are reported per unit area (Tables 1.1 and 1.2).

Key outcomes and findings from the Workshop include:

1. Sites for which budgets and models were developed represent a range of locality and climatic settings including an array of small to large estuaries and coastal bays in monsoonal climates and austral temperature conditions. The nutrient models cover wet-dry seasonality and a range of land N and P input situations yielding budget descriptions for land-dominated and ocean-dominated systems; in some the dominance changes with season. Several of the budgets are partially developed (e.g., Chwaka Bay, Zanzibar; Knysna Estuary, South Africa) and, while further fieldwork will provide requisite data and information, this reflects the disparity in data and coastal system research in much of the region.
2. Dry – wet season net metabolic performance changes were shown in some cases, wherein values changed (e.g., Malindi Bay, Kenya) and sign changed (e.g., Rio del Rey, Cameroons; Kromme Estuary, South Africa). These changes reflected a combination of forcing from seasonal precipitation and the interactions of river flow/flushing with tides and ocean inputs affecting water residence times and nutrient loading.
3. Inner and outer estuaries often differed in their estimated net metabolic performance e.g., Knysna Lagoon, South Africa. Water exchange and mixing patterns undoubtedly influence these settings. The Congo River estuary provided an unusual case with the estuary being influenced by deep ocean waters and an apparent remineralisation zone associated with a continental shelf submarine canyon.
4. The estuarine and coastal sites exhibited an array of nutrient regimes, modified by waste discharges from population and land use and in several cases by water management (dams) of terrestrial inflows to the estuaries. Generally there were limited population inputs (see DIP/DIN loads as indicators) but clearly population effects were apparent.

LOICZ is grateful for the support and efforts of Dr Amani Ngusaru and the staff of the Zanzibar Institute of Marine Sciences in hosting the Workshop, and to the resource scientists for their contributions to the success of the Workshop. LOICZ particularly acknowledges the effort and work of the participants not only for their significant contributions to the workshop goals, but also for their continued interaction beyond the meeting activities.

The workshop and this report are contributions to the GEF-funded UNEP project: *The Role of the Coastal Ocean in the Disturbed and Undisturbed Nutrient and Carbon Cycles*, recently established

with LOICZ and contributing to the UNEP sub-programme: “Sustainable Management and Use of Natural Resources”.

**Table 1.1      Budgeted regional sites for Sub-Saharan Africa - locations, system dimensions and water exchange times.**

System Name	Long. (E)	Lat. (S)	Area (km <sup>2</sup> )	Depth (m)	Exchange Time (days)
<b>Tanzania</b>					
Chwaka Bay, Zanzibar	39.47	6.19	50	3	30
Makoba Bay, Zanzibar	39.22	5.92	15	5	63
<b>Kenya</b>					
Malindi Bay	40.15	3.2	18	2	3
<b>Cameroon</b>					
Cameroon estuarine system	9.70	3.90 (N)	2850	15	48-315
Rio-del-Rey system <sup>a</sup>	8.28	4.80 (N)	3300	14	38
<b>Congo</b>					
Congo (Zaire) River estuary <sup>b</sup>	12.30	6.05	241	6-260	2
<b>South Africa</b>					
Knysna River system	23.00	34.10	48	3	97
Kromme estuary	24.85	34.15	3	3	87
Gamtoos estuary	25.07	33.97	2	2	26
Swartkops estuary	25.63	32.87	4	3	34
Sundays estuary	25.42	33.72	3	4	42
Mhlathuze estuary	32.05	28.80	12	2	1-4
Thukela estuary	30.50	29.22	0.6	1.5	<1

**a** water exchange times show the range estimated for wet and dry seasons

**b** average depth: shallow estuary, 6m; deep canyon in outer estuary, 260m.

**Table 1.2 Budgeted regional sites for sub-Saharan Africa - loads and estimated (*nfix-denit*) and (*p-r*).**

System	DIP load	DIN load	DDIP	DDIN	( <i>nfix-</i> <i>denit</i> )	( <i>p-r</i> )
	mmol m <sup>-2</sup> yr <sup>-1</sup>					
<b>Tanzania</b>						
Chwaka Bay, Zanzibar <sup>a</sup>	7	37	+36	+584	0	-4000
Makoba Bay, Zanzibar <sup>a</sup>	27	117	-25	+730	+1100	+2550
<b>Kenya</b>						
Malindi Bay	1360	5200	-330	-585	+4380	+33200
<b>Cameroon</b>						
Cameroon estuarine system <sup>e</sup>	33	50	-7	+73	+146	+730 <sub>p</sub> to +7300 <sub>m</sub>
Rio-del-Rey system <sup>e</sup>	18	21	+18	+330	+36	-1820 <sub>p</sub> to -18200 <sub>m</sub>
<b>Congo</b>						
Congo (Zaire) River estuary <sup>f</sup>	5450	42400	-2270	-31800	+4540	+240000
<b>South Africa</b>						
Knysna River estuary <sup>b</sup>	<1	1	+7	+26	-73	-730
Kromme estuary	<1	30	+7	+159	+73	-730
Gamtoos estuary	16	1265	-6	+199	+365	+730
Swartkops estuary	138	10800	-62	-10	-9125	+6570
Sundays estuary	12	1435	+5	-226	-329	-365
Mhlathuze Estuary <sup>b,d</sup>	<30	334	+3050 to +950	+6800 to +1850	-14600 <sub>p</sub> to -7300 <sub>m</sub>	-109500 <sub>p</sub> to >-500000 <sub>m</sub>
Thukela Estuary	1825	49275	+9125	242700	<b>c</b>	<b>c</b>

**a** annualised values estimated from budget developed for wet season only.

**b** annualised values estimated from budget developed for dry season only.

**c** system has a low exchange time and materials will probably behave conservatively, “jetting” through the estuary to the nearshore waters.

**d** DIP and DIN provide range of values, reflecting different water and mixing calculation.

**e** system metabolism values reflect use of phytoplankton or mangrove elemental ratios in stoichiometric estimates.

**f** deep ocean canyon intrusion and apparent remineralisation processes influence estimates.

## **2. ESTUARIES OF TANZANIA AND KENYA**

Tanzania, comprising 945,000 km<sup>2</sup> 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<sup>2</sup>. 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*

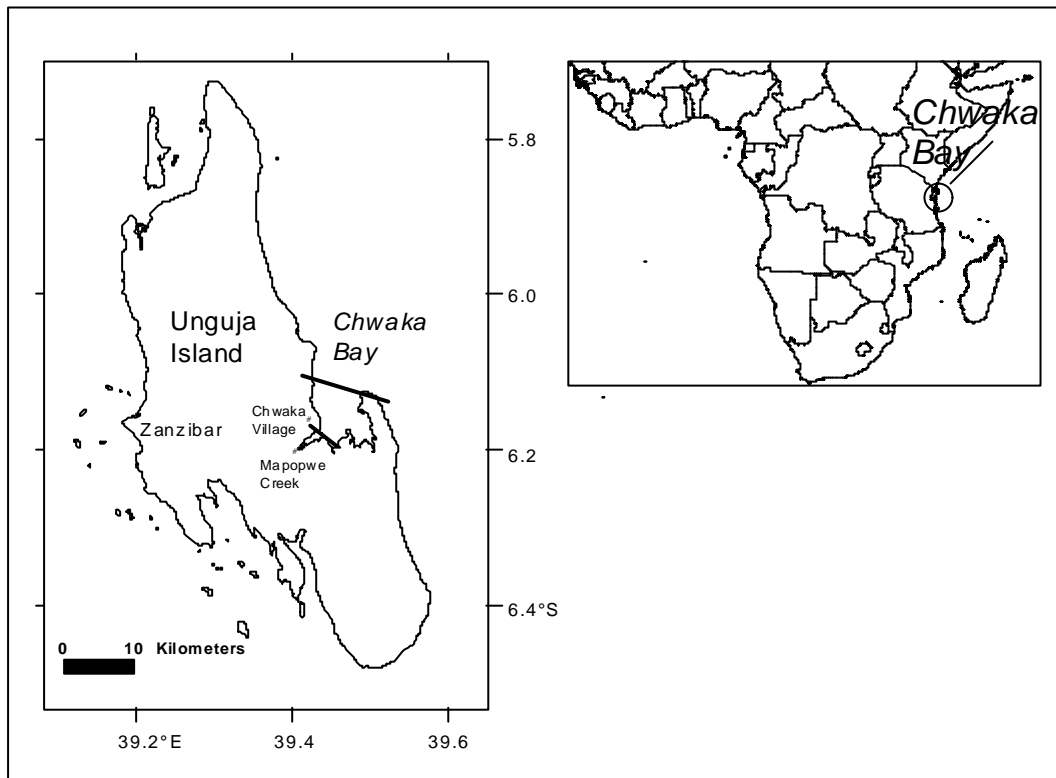
#### *Study area description*

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<sup>2</sup> with a depth of about 2 m, and total volume of the inner system 10x10<sup>6</sup> m<sup>3</sup>. The surface area of the outer system is about 45 km<sup>2</sup> with a depth of about 4 m, and total volume 180x10<sup>6</sup> m<sup>3</sup>.

#### 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<sup>-1</sup> and that for November 17 mm d<sup>-1</sup>. The average pan evaporation for all seasons were equal, estimated at about 5 mm d<sup>-1</sup>. 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:

$$PC = (\text{evaporation from a free water surface})/(\text{evaporation from a pan})$$

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

Month	Rainfall (mm month <sup>-1</sup> )	Evaporation (mm month <sup>-1</sup> )
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
<b>Mean</b>	<b>183</b>	<b>150</b>

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<sup>-1</sup> to 3.5 mm d<sup>-1</sup>, 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<sup>-1</sup> was obtained using the temperature data for Zanzibar during the dry season.

The rainfall value of 12 mm d<sup>-1</sup> and 17 mm d<sup>-1</sup> for June and November respectively and evaporation of 3.5 mm d<sup>-1</sup> 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:

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

where  $K$  is the hydraulic conductivity given to be  $6 \times 10^{-4}$  m sec<sup>-1</sup> 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:

$$V_{G(\text{Inner Chwaka})} = 0.3 \times 10^3 \text{ m}^3 \text{ d}^{-1}$$

$$V_{G(\text{Outer Chwaka})} = 1.5 \times 10^3 \text{ m}^3 \text{ d}^{-1}$$

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  $S_{\text{ocn}}$  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):

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

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:

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

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 [ $S_R = (S_1 + S_2)/2$ ].

$$dVS/dt = V_Q S_Q + V_P S_P + V_G S_G + V_O S_O + V_E S_E + V_R S_R + V_X (S_2 - S_1) \quad (3)$$

where  $V_X$  represents the mixing volume exchanged between the ocean and the bay, 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 [ $V_X (S_2 - S_1)$ ] 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:

$$dVS/dt = V_R S_R + V_X (S_2 - S_1) \quad (4)$$

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

$$0 = + V_R S_R + V_X (S_2 - S_1) \quad (5)$$

By re-arrangement:

$$V_X = -V_R S_R / (S_2 - S_1) \quad (6)$$

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  $V_R$ :

$$t = V_{\text{sys}} / (V_X + |V_R|) \quad (8)$$

$V_{\text{sys}}$  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 ( $V_R = -42 \times 10^3 \text{ m}^3 \text{ d}^{-1}$  for inner bay and  $V_R = -426 \times 10^3 \text{ m}^3 \text{ d}^{-1}$  for outer bay). Similarly, there is a net flux of water from the bay to the ocean during November ( $V_R = -67 \times 10^3 \text{ m}^3 \text{ d}^{-1}$  for inner bay and  $V_R = -676 \times 10^3 \text{ m}^3 \text{ d}^{-1}$  for outer bay). The corresponding residual fluxes of salt ( $V_R S_R$ ) 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  $V_{X1} = 1,200 \times 10^3 \text{ m}^3 \text{ d}^{-1}$  and  $V_{X2} = 4,000 \times 10^3 \text{ m}^3 \text{ d}^{-1}$  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  $\text{PO}_4$  concentration and DIN as the  $(\text{NO}_3^- + \text{NO}_2^- + \text{NH}_4^+)$ . The data from Chwaka Bay show the concentration of DIP in the inner and outer bay to be  $\text{DIP}_1 = 2.0 \text{ } \mu\text{M}$  and  $\text{DIP}_2 = 1.2 \text{ } \mu\text{M}$ , respectively (Figure 2.3). Likewise, the concentration of DIN in the inner and outer bay are  $\text{DIN}_1 = 23 \text{ } \mu\text{M}$  and  $\text{DIN}_2 = 18 \text{ } \mu\text{M}$ , respectively (Figure 2.4). Following Wyrki (1971) the concentration of DIN and DIP in the open ocean (Zanzibar Channel) are  $\text{DIP}_{\text{ocn}} = 0.1 \text{ } \mu\text{M}$  and  $\text{DIN}_{\text{ocn}} = 0.5 \text{ } \mu\text{M}$ , 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  $V_Q \text{DIP}_Q$  and  $V_Q \text{DIN}_Q$

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 ( $V_oDIP_o$ ,  $V_oDIN_o$ ) were considered here because the initial estimates of  $\ddot{A}DIP$  and  $\ddot{A}DIN$  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  $V_oDIP_o = 900 \text{ mol d}^{-1}$  and  $V_oDIN_o = 4,000 \text{ mol d}^{-1}$  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  $\mu\text{M}$  and 2  $\mu\text{M}$  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  $\mu\text{M}$ ; Lewis 1985; Tribble and Hunt 1996). Similarly,  $DIN_G$  concentrations of 25  $\mu\text{M}$  and 37  $\mu\text{M}$  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  $\ddot{A}DIP_1$  and  $\ddot{A}DIP_2$  for the wet season are  $+1,700 \text{ mol d}^{-1}$  ( $+0.3 \text{ mmol m}^{-2} \text{ d}^{-1}$ ) and  $+2,600 \text{ mol d}^{-1}$  ( $+0.06 \text{ mmol m}^{-2} \text{ d}^{-1}$ ), respectively, indicating that there is a net DIP flux from the bay to the ocean for the month of November (i.e.  $\ddot{A}DIP$  is positive). The calculated  $\ddot{A}DIP_{sys} = +4,300 \text{ mol d}^{-1}$  or  $+0.1 \text{ mmol m}^{-2} \text{ d}^{-1}$ . Chwaka Bay acts as a DIP source during the wet season.

The calculated  $\ddot{A}DIN_1$  and  $\ddot{A}DIN_2$  for the wet season are  $+11,000 \text{ mol d}^{-1}$  ( $+2.2 \text{ mmol m}^{-2} \text{ d}^{-1}$ ) and  $+68,000 \text{ mol d}^{-1}$  ( $+1.5 \text{ mmol m}^{-2} \text{ d}^{-1}$ ), respectively, indicating that there is a net DIN flux from the bay to the ocean during the wet season (i.e.  $\ddot{A}DIN$  is positive). The calculated  $\ddot{A}DIN_{sys} = +79,000 \text{ mol d}^{-1}$  ( $+1.6 \text{ mmol m}^{-2} \text{ d}^{-1}$ ). 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  $\ddot{A}DIP$ . The basic formulation is as follows:

$$(p-r) = -\ddot{A}DIP \times (C:P)_{part}$$

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:

$$(nfix-denit) = \ddot{A}DIN - \ddot{A}DIP(N:P)_{part}$$

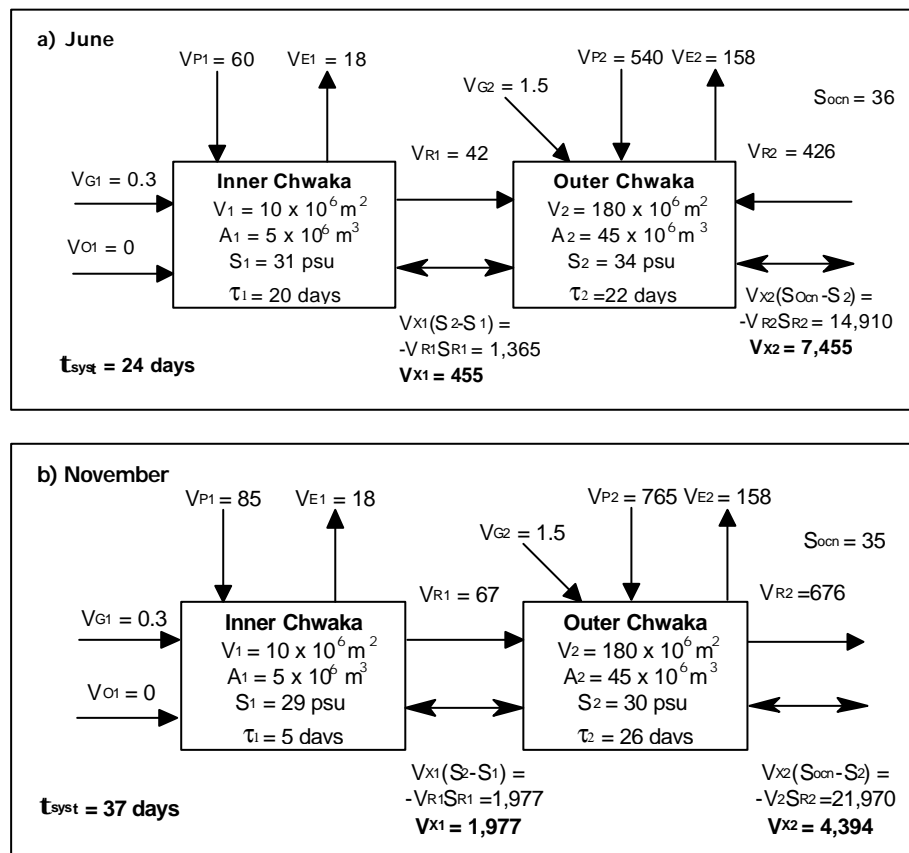
where  $(N:P)_{part}$  represents the ratio of both planktonic and waste derived organic matter reacting in the system, which is expected to be near 16:1. Table 2.2 shows the stoichiometric calculations made for Chwaka Bay for November 1998.

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).

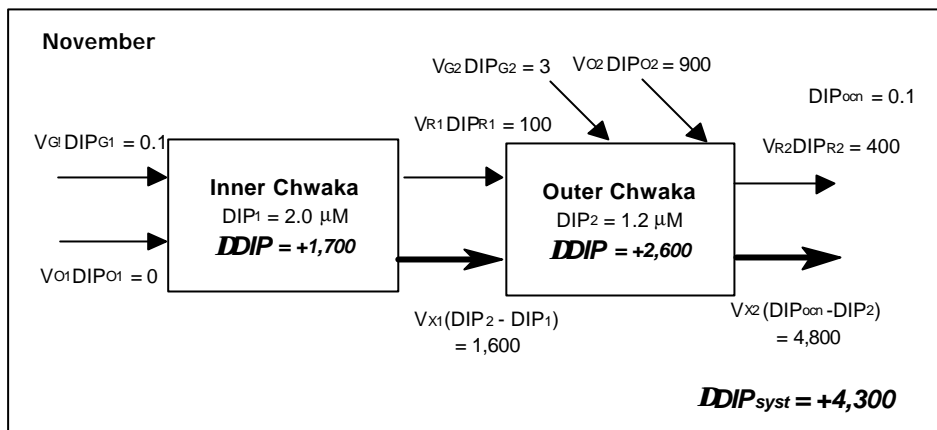
This indicates that Chwaka Bay is net heterotrophic during the wet season. Chwaka Bay seems to have net denitrification in the inner bay as indicated by the negative (*nfix-denit*) value and the outer bay to be net nitrogen-fixing at a slower rate (Table 2.2). However, the entire bay seems to balance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

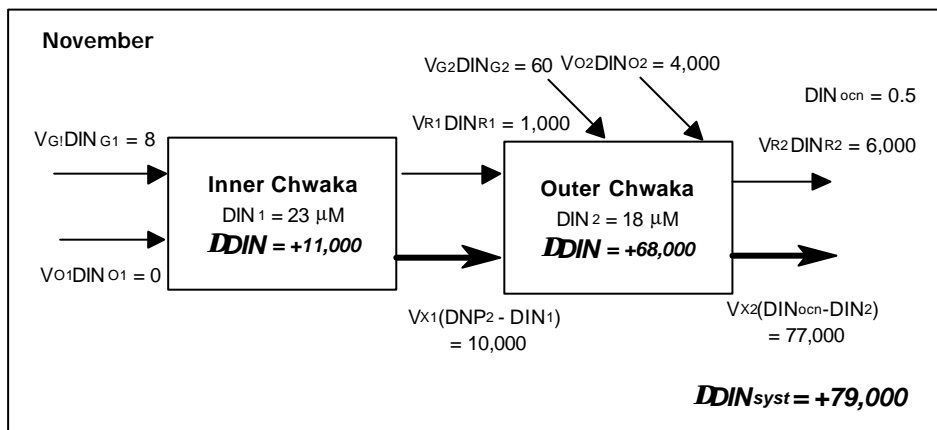
Calculated Values	Inner Chwaka Bay	Outer Chwaka Bay	Entire bay
$\dot{A}DIP$ (mol d <sup>-1</sup> )	+1,700	+2,600	+4,300
$\dot{A}DIP$ (mmol m <sup>-2</sup> d <sup>-1</sup> )	+0.3	+0.06	+0.1
$\dot{A}DIN$ (mol d <sup>-1</sup> )	+11,000	+68,000	+79,000
$\dot{A}DIN$ (mmol m <sup>-2</sup> d <sup>-1</sup> )	+2.2	+1.5	+1.6
<i>(p-r)</i> (mmol C m <sup>-2</sup> d <sup>-1</sup> )	-32	-6	-11
<i>(nfix-denit)</i> (mmol N m <sup>-2</sup> d <sup>-1</sup> )	-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  $10^3 \text{ m}^3 \text{ d}^{-1}$  and salt flux in  $10^3 \text{ psu-m}^3 \text{ d}^{-1}$ .



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



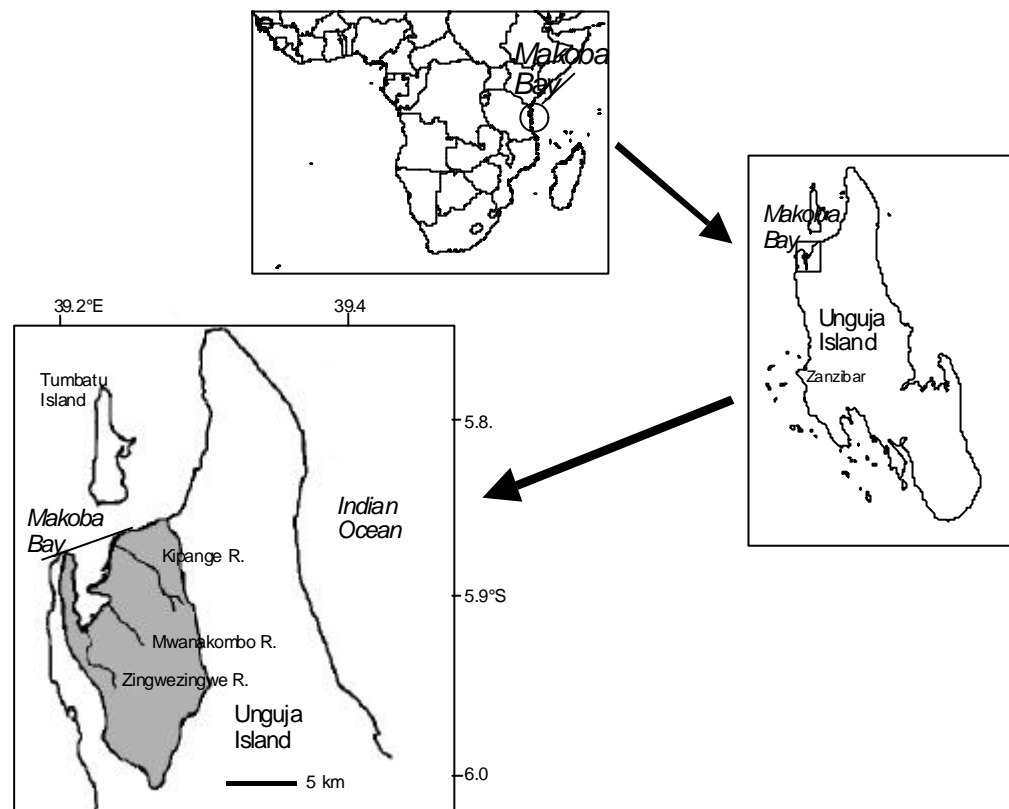
**Figure 2.4. DIN budget for Chwaka Bay for November 1998 (wet season).** Flux in  $\text{mol d}^{-1}$  and concentration in  $\mu\text{M}$  or  $\text{mmol m}^{-3}$ .

## 2.2 Makoba Bay, Zanzibar

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

### Study area description

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<sup>2</sup> and average depth of 5 m with a volume of about 75x10<sup>6</sup> m<sup>3</sup>. 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.

### Water and salt balance

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<sup>2</sup> with a total mean discharge of 24x10<sup>6</sup> m<sup>3</sup> yr<sup>-1</sup> or about 70x10<sup>3</sup> m<sup>3</sup> d<sup>-1</sup>.

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<sup>-1</sup> was used in this budget. Mean pan evaporation rate is 5 mm d<sup>-1</sup>, 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:

$$PC = (\text{evaporation from a free water surface})/(\text{evaporation from a pan})$$

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<sup>-1</sup> to 3.5 mm d<sup>-1</sup>, 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<sup>-1</sup> 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
<b>Mean</b>	183	221

The rainfall value of 14 mm d<sup>-1</sup> and evaporation of 3.5 mm d<sup>-1</sup> 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<sup>-4</sup> m sec<sup>-1</sup> 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 than those during the dry season. The calculations done for Makoba Bay gave:

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

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  $S_{\text{syst}}$  and  $S_{\text{ocn}}$ , respectively. Similarly, the volume and surface area of the bay are indicated as  $V_{\text{syst}}$  and  $A_{\text{syst}}$  respectively.

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

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

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:

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

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.

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

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

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 [ $V_X (S_{\text{ocn}} - S_{\text{syst}})$ ] 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:

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

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

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

By re-arrangement:

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

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  $V_R$ :

$$t = V_{\text{sys}} / (V_X + |V_R|) \quad (8)$$

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 ( $V_R = -223 \times 10^3 \text{ m}^3 \text{ d}^{-1}$ ). The residual fluxes of salt ( $V_R S_R$ ) 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.

### Budgets of nonconservative materials

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  $\text{PO}_4^{-3}$  concentration and DIN as the  $(\text{NO}_3^- + \text{NO}_2^- + \text{NH}_4^+)$ .

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  $\text{DIP}_{\text{sys}} = 0.2 \text{ } \mu\text{M}$  during the wet season (Figure 2.7). Likewise, the concentration of DIN in the bay is  $\text{DIN}_{\text{sys}} = 32 \text{ } \mu\text{M}$  for the wet season (Figure 2.8). Following Wyrski (1971) the concentration of DIN and DIP in the open ocean (Zanzibar Channel) are  $\text{DIP}_{\text{ocn}} = 0.1 \text{ } \mu\text{M}$  and  $\text{DIN}_{\text{ocn}} = 0.5 \text{ } \mu\text{M}$ . The concentrations in the rivers were estimated at  $\text{DIP}_Q = 0.3 \text{ } \mu\text{M}$  and  $\text{DIN}_Q = 6 \text{ } \mu\text{M}$ .

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  $\text{DIP}_{\text{atm}}$  and  $\text{DIN}_{\text{atm}}$  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  $V_O \text{DIP}_O = 1,100 \text{ mol d}^{-1}$  and  $V_O \text{DIN}_O = 4,400 \text{ mol d}^{-1}$  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  $\text{DIP}_G$  flux in groundwater flowing through carbonate terrain is known to be low, the concentration of nitrogen ( $\text{DIN}_G$ ) in the underground water could not be neglected. For the nutrient calculations reported here,  $\text{DIP}_G$  concentration of  $2 \text{ } \mu\text{M}$  and  $\text{DIN}_G$  concentration of  $37 \text{ } \mu\text{M}$  were used. These values are comparable to reported groundwater  $\text{PO}_4$  for similar systems ( $\text{DIN}_G = 1\text{-}10 \text{ } \mu\text{M}$ ;  $\text{DIP}_G = 37\text{-}72 \text{ } \mu\text{M}$ : 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  $\text{DDIP}$  and  $\text{DDIN}$  for the wet season is  $-990 \text{ mol d}^{-1}$  and  $+29,400 \text{ mol d}^{-1}$ , 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 ( $\text{DDIP}$  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 ( $\text{DDIN}$  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,

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

where  $(C:P)_{\text{part}}$  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:

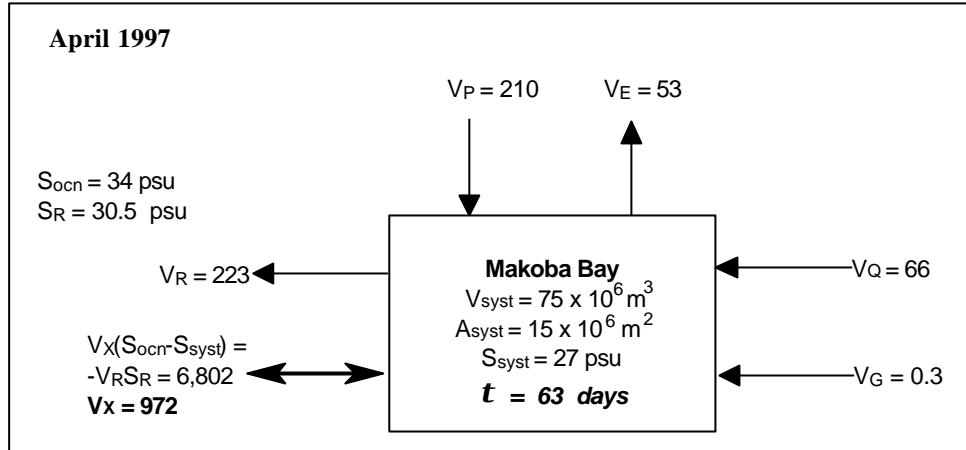
$$(nfix-denit) = \mathbf{DDIN} - \mathbf{DDIP}(N:P)_{\text{part}}$$

where  $(N:P)_{\text{part}}$  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.

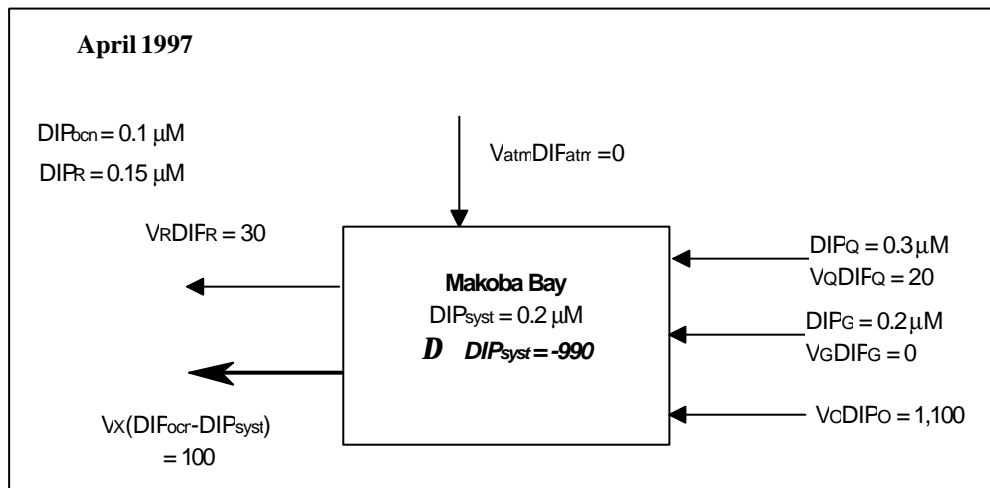
Stoichiometric calculations suggest that  $(p-r)$  is positive during the wet season (Table 2.4). This indicates that Makoba Bay is net autotrophic during the wet season. Makoba Bay is fixing nitrogen during wet season, where  $(nfix-denit)$  is estimated to be 3 mmol m<sup>-2</sup> d<sup>-1</sup> in 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 calculated  $(p-r)$  and  $(nfix-denit)$  values for Makoba Bay for April 1997 (wet season).**

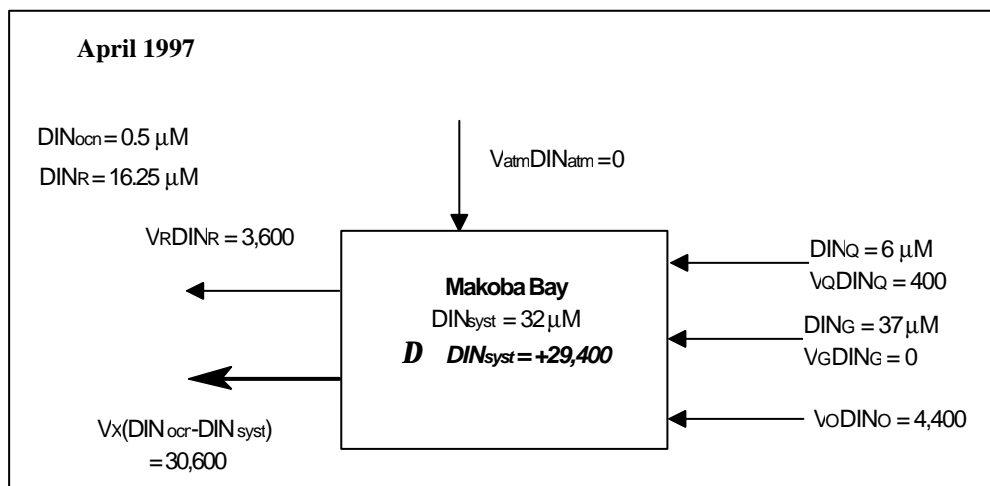
Parameters	Calculated values
<b>DDIP</b> (mol d <sup>-1</sup> )	-990
<b>DDIP</b> (mmol m <sup>-2</sup> d <sup>-1</sup> )	-0.07
<b>DDIN</b> (mol d <sup>-1</sup> )	+29,400
<b>DDIN</b> (mmol m <sup>-2</sup> d <sup>-1</sup> )	+2
<b>(p-r)</b> (mmol C m <sup>-2</sup> d <sup>-1</sup> )	+7
<b>(nfix-denit)</b> (mmol N m <sup>-2</sup> d <sup>-1</sup> )	+3



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



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



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

## 2.3 Malindi Bay, Kenya

*Mwakio P. Tole*

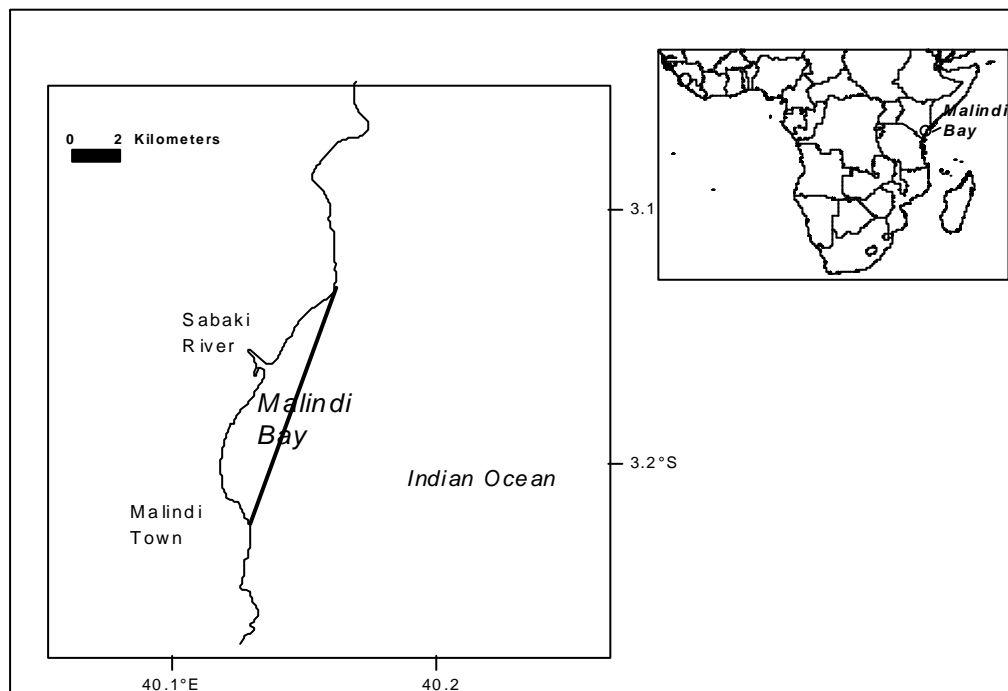
### Study area description

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<sup>2</sup>.

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<sup>3</sup> s<sup>-1</sup> in the driest periods, to 758 m<sup>3</sup> s<sup>-1</sup> during times of flood. Mean flow rate was 48.8 m<sup>3</sup> s<sup>-1</sup> 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  $0.5 \text{ m}^3 \text{ s}^{-1}$  ( $40 \times 10^3 \text{ m}^3 \text{ d}^{-1}$ ) in the driest periods to  $760 \text{ m}^3 \text{ s}^{-1}$  ( $70 \times 10^6 \text{ m}^3 \text{ d}^{-1}$ ) during times of flood. Mean flow rate was  $50 \text{ m}^3 \text{ s}^{-1}$  ( $4 \times 10^6 \text{ m}^3 \text{ d}^{-1}$ ) 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  $20 \times 10^3 \text{ m}^3 \text{ d}^{-1}$ .

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  $10^6 \text{ m}^3 \text{ d}^{-1}$ ) and water exchange time ( $t$ ).**

	<b>Oct–Dec</b> (wet)	<b>Jan–Mar</b> (dry)	<b>Apr–Jun</b> (wet)	<b>Jul–Sep</b> (dry)	<b>Annual</b>
<b>Surface runoff (<math>V_Q</math>)</b>	6	5	5	5	5
<b>Groundwater (<math>V_G</math>)</b>	0	0	0	0	0
<b>Precipitation (<math>V_P</math>)</b>	0	0	0	0	0
<b>Evaporation (<math>V_E</math>)</b>	0	0	0	0	0
<b>Outfall (<math>V_O</math>)</b>	0	0	0	0	0
<b>Residual flow (<math>V_R</math>)</b>	6	5	5	5	5
<b>Mixing (<math>V_X</math>)</b>	11	9	8	9	9
<b><math>t</math> (days)</b>	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 Wyrki *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 ( $\mu\text{M}$ )	River	Ohowa 1993	0.9	25
	Bay		0.5	10
	Ocean	Wyrski <i>et al.</i> 1988	0.2	2.5
DIN ( $\mu\text{M}$ )	River	Ohowa 1993	0.01	97
	Bay		0.2	40
	Ocean	Wyrski <i>et al.</i> 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.

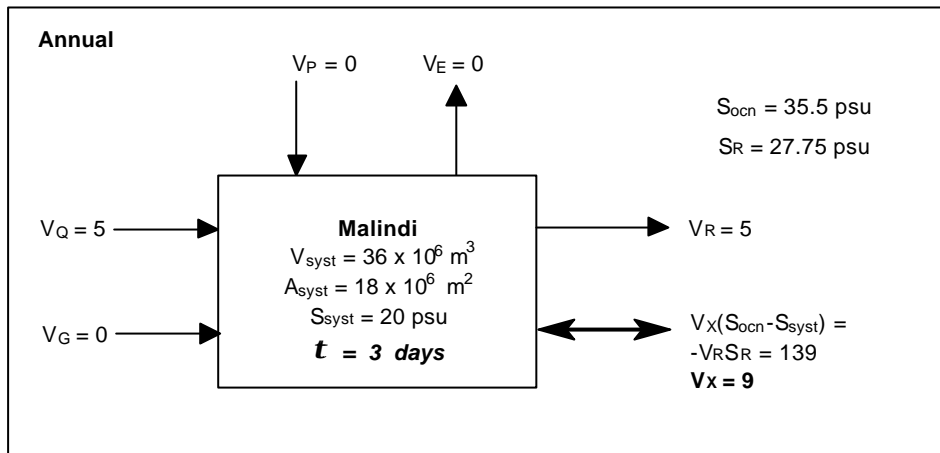
Table 2.7 summarizes the fluxes of DIP and DIN for Malindi Bay. The system appears to be a net sink for both DIP and DIN. However, there is a large amount of uncertainty in these budgets because of the extreme range in estimated nutrient concentrations.

**Table 2.7. Summary of nutrient fluxes and stoichiometrically 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
$V_oDIP_o (10^3 \text{ mol d}^{-1})$	5	125	65
$V_oDIP_o (10^3 \text{ mol d}^{-1})$	2	2	2
$V_RDIP_R (10^3 \text{ mol d}^{-1})$	-2	-31	-17
$V_X(DIP_{ocn}-DIP_{syst})$ ( $10^3 \text{ mol d}^{-1}$ )	-3	-68	-36
$DDIP (10^3 \text{ mol d}^{-1})$	-2	-28	-15
$DDIP (\text{mmol m}^{-2} \text{ d}^{-1})$	-0.1	-1.6	-0.9
$V_oDIN_o (10^3 \text{ mol d}^{-1})$	0	485	243
$V_oDIN_o (10^3 \text{ mol d}^{-1})$	13	13	13
$V_RDIN_R (10^3 \text{ mol d}^{-1})$	-2	-101	-52
$V_X(DIN_{ocn}-DIN_{syst})$ ( $10^3 \text{ mol d}^{-1}$ )	3	-356	180
$DDIN (10^3 \text{ mol d}^{-1})$	-14	-41	-28
$DDIN (\text{mmol m}^{-2} \text{ d}^{-1})$	-0.8	-2.3	-1.6
$(p-r)_{\text{plankton}}$ ( $\text{mmol m}^{-2} \text{ d}^{-1}$ )	+11	+170	+91
$(nfix-denit)_{\text{plankton}}$ ( $\text{mmol m}^{-2} \text{ d}^{-1}$ )	+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  $+91 \text{ mmol m}^{-2} \text{ d}^{-1}$  and  $(nfix-denit)$  is  $+12 \text{ mmol m}^{-2} \text{ d}^{-1}$  (Table 2.7).



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

### 3. CAMEROON AND CONGO ESTUARINE SYSTEMS

#### Cameroon's coastal zone and estuarine systems

Cameroon (8-16°E; 2-13°N) is situated on the extreme north-eastern end of the Gulf of Guinea with a surface area of 469,440 km<sup>2</sup>. The main topographical regions are: the low coastal plain covered by equatorial rain forests in the south, the mountain forests peaking at the active Mount Cameroon (4,070 m) in the west, the transitional plateau rising to the Adamaoua Mountains in the centre, and rolling savannah slopes gradating down to the marshlands surrounding Lake Tchad to the north of the Adamaoua Mountain range. Cameroon is drained by four major drainage basins: Atlantic, Zaire/Congo, Niger and Tchad. A watershed exists along the southern Cameroon plateau separating the coastal from the Congo system, with freshwater input into the Atlantic drainage basin.

Cameroon's coastal zone (Figure 3.1), extends along 402 km (Sayer *et al.* 1992), from latitude 2.30°N at the Equatorial Guinea borders to 4.67°N at the Nigeria borders. The coastal zone area is estimated at 9,670 km<sup>2</sup> (Adam 1998) representing 22% of the Gulf of Guinea countries.



Figure 3.1. Cameroon and the Gulf of Guinea.

Cameroon's coastal climate is of an equatorial type and is influenced by the meteorological equator, being the meeting point between the anticyclone of Azores (North Atlantic) and that of Saint Helen (South Atlantic). This climate results from the combined effect of convergence of the tropical oceanic low-pressure zone and the inter-tropical front within the continent. There are two distinct seasons: a long rainy season of more than 8 months (March-October) and a dry season of four months (November-

February) exist. Air temperatures are high throughout the year. South-westerly monsoon winds predominate, modified by land sea breezes causing humidity values to almost saturation point. Wind speeds exceptionally reach values of  $18 \text{ m sec}^{-1}$  (April, 1993) with average values recorded over a period of 10 years (1983 – 1993) varying between  $0.5\text{--}2.5 \text{ m sec}^{-1}$ . The rainy season is hot and dry with a north-easterly harmattan when the inter tropical convergence zone deviates from its normally southern position at  $5\text{--}7^\circ\text{N}$ .

Cameroon's coastal tropical rainforest is interrupted at the active Cameroon Mountain and within the mangrove estuarine complexes. These complexes are characterized by very low altitudes (0-20 m), developed on low soils (generally less than 5 m high) with primary stages of mangroves developed at 0-5 m while mature ones reach 2 m. Mangrove estuarine complexes in Cameroon occupy approximately 30% ( $3,500 \text{ km}^2$ ) of Cameroon's coastal zone. There are about 38 species of mangrove, dominated by *Rhizophora* (*R. racemosa* and *R. harrisianii*) species (Gabche 1997). This is followed by the Atlantic forest dominated by families of *Caesalpinacea* and *Guttiferae*, *Euphorbiaceae*; swamp forest dominated by *Rapphia* spp., *Matritia quadricorius*, *Clenolephon englerianus*, and seasonally inundated forests of *Guibortia demoussei* and *Oxystigma menil*. Phytoplankton species (Folack 1991) are dominated by diatoms such as *Chaetoceros testissimus*, *Nitzschia closterium*, *Diatoma vulgare*, *Trachyneis* and *Coscinodiscus*.

Dense river networks flow into three estuarine systems along the coast. The West/Rio-del-Rey system has several rivers (Cross, Ndian and Meme) that discharge at the Rio-del-Rey Point ( $4.8^\circ\text{N}$ ;  $8.3^\circ\text{E}$ ). The Cameroon estuary complex with several rivers (Mungo, Wouri, Dibamba etc) discharges at Douala Point ( $3.8\text{--}4.1^\circ\text{N}$  and  $9.25\text{--}10^\circ\text{E}$ ). This extends towards the west at Bimbria and south to the Sanaga River estuary. The third estuary complex in the south is made up of several rivers (Nyong, Lokoundje, Kienke, Lobe and Ntem) which discharge independently into the Atlantic Ocean. Some physical characteristics of the Cameroon and Rio-del-Rey estuarine complexes are given in Table 3.1. The rivers of these estuaries have watersheds from high altitudes (2,000–2,500 m) at the Adamawa plateau, Rumpi Hills and Manegumba Mountains. The mangroves of the Rio-del-Rey cover an area of about  $1,500 \text{ km}^2$  with 50 km of coastline and a landward extension of 30 km. The Cameroon estuary has a coastline of 60 km from the Sanaga to the Bimbria estuary and 30 km into the hinterlands giving area of  $1,800 \text{ km}^2$ . The southern river systems at the Ntem also has estuarine mangrove swamps. The supplies from the dense river network, groundwater and rainfall are major sources of freshwater into the continental shelf (area =  $15,400 \text{ km}^2$ ) (Gabche and Folack 1997). The gradual descent (10, 30, 50 and 100 m depth) of the continental shelf results in generally weak circulation with subsequent high sedimentation rates.

Hydrodynamic processes within the estuarine complexes indicate that semi-diurnal tidal wave action can be felt a long distance from the sea in the rivers (40 km in the Wouri; 35 km up the Dibamba), with wave height recordings ranging from 1.5–4.5 m. There is an enormous propagation of waves and ebb-tides through the estuarine complexes (Olivry 1986; Morin *et al.* 1989). Tidal currents are strong:  $1\text{--}1.5 \text{ m s}^{-1}$  for flood and up to  $2.6 \text{ m s}^{-1}$  for ebb. Chaubert *et al.* (1977) noted that sea swells in vicinity of the Rio-del-Rey are from south to south-west and distant in origin. This peculiarity results from the double obstacle created by Bioko Island and the wide continental shelf at the Rio-del-Rey (80 km as compared to 40 km at the Kribi coast). Swells of greater magnitude (226 m long) are common between June and September with lesser ones between November and April.

Salinity distribution within Cameroon's estuarine complexes is determined by huge inputs of freshwater from rivers, rainfall and groundwater. Salinity is generally low with values at the Douala Port of 9-12 psu. Lafond (1967) showed maximum values of 20 psu at 15 km from the port offshore during the dry season and less than 12 psu in the rainy season. These values decrease towards the port to average values of 0 psu for every 100 m (2.6 psu for each km) near Japoma on the Dibamba River, and maximum values as low as 6.5 psu at low tide. Values of between 12.0-17.5 psu have been recorded within the Mungo River, with increased values due to seawater intrusion during the dry season and mixture with freshwater. Salinity distributions are in line with regional surface values which show

significant fresh water in the Gulf of Guinea and in particular, in the Bight of Biafra, with values lower than 29 psu (ICITA 1973; GATE 1980).

**Table 3. 1. Physical characteristics of some Cameroon's coastal zone estuarine systems.**

Estuarine System	Long (°E+)	Lat (°N+)	River	Catchment Area (km <sup>2</sup> )	Estuarine Area (km <sup>2</sup> )		Mean Depth (m)
					Mangrove	Water	
Cameroon	9.25-10.00	3.83-4.10	Mungo	4,200			15
			Wouri	8,250			15
			Dibamba	2,400			15
<b>Total/Mean</b>				14,850	1,800	1,500	15
Rio-del-Rey	8.28	4.83	Cross	800			14
			Ndian	2,500			13
			Meme	500			14
<b>Total/Mean</b>				<b>3,800</b>	<b>1,500</b>	<b>1,350</b>	<b>14</b>

The high nutrient loads (Table 3.5) derived from land support high productivity and relatively large fish catches (more than 60,000 tons per year) as compared to other countries of the Gulf of Guinea (Schneider 1992). These are comparable to those in the countries where upwelling occurs. In recent years (1980 to present) there has been a trend of decreasing marine fish catch in Cameroon. This is partially due to reduced fishing effort. The decline may also be partly due to pollution by agricultural and industrial waste and municipal discharge into the ocean. A detailed elaboration using methods in WHO (1989) on this is given in UNEP (1984) and Angwe and Gabche (1997).

Leaf litter from mangroves and estuaries forms an important nutrient base for food webs leading to commercially important food fishes and invertebrates (Snedaker and Snedaker 1984). The mangrove leaves become nutritious through microbial enrichment processes. Higher rates of leaf fall occur in the dry season than in the rainy season. However, because studies have not been carried out on mangrove litter decomposition and nutrient enrichment, in this study they are assumed to be zero.

Faunal species within the mangroves and estuarine complexes are dominated by the forest elephant (*Eoxondonta africana*), the giant forest hog (*Hylochoerus meinertzhageni*), the endangered drill (*Mandrillus leucophaeus*), the highly vulnerable black colobus (*Colobus satanas*) and Upper Guinea primates (*Cercopithecus mitis martini*, *C. erythrotis camerunensis* and *C. pogonius pogonius*). There is a significant population of the highly vulnerable African manatee (*Trichechus senegalensis*) within the Sanaga estuary.

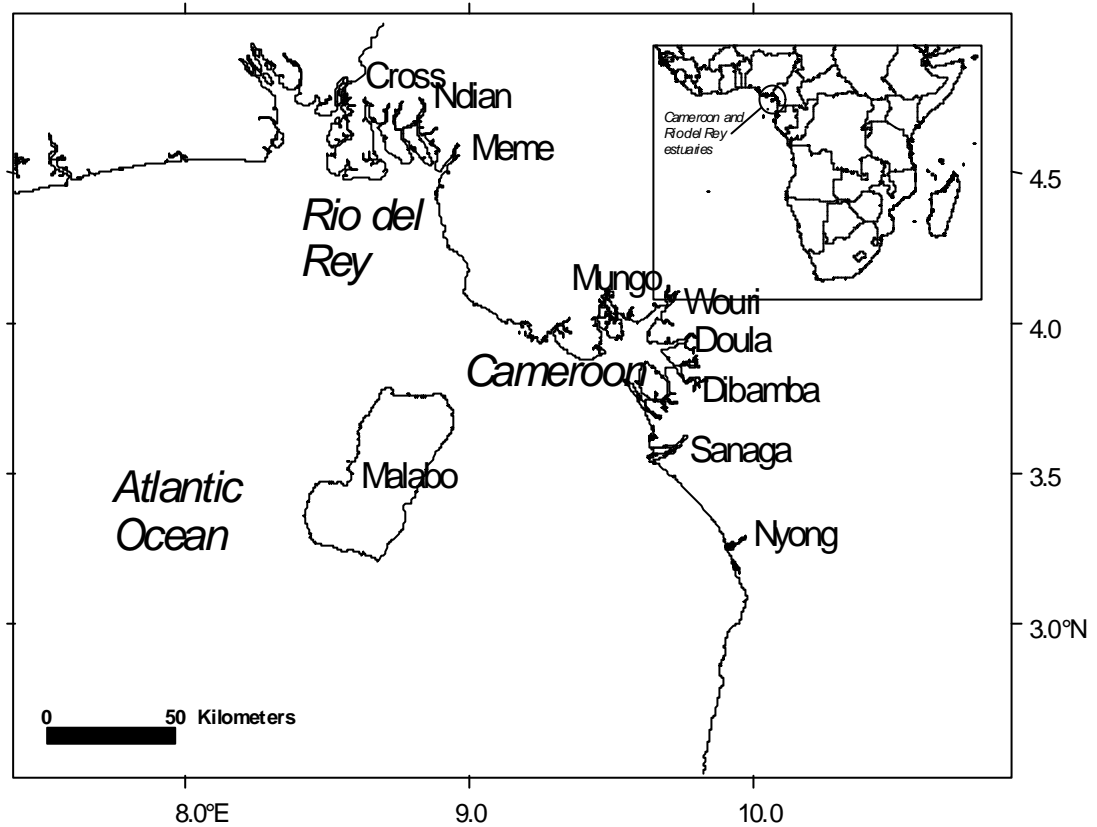
Cameroon's estuarine complexes and mangroves serve as habitats for meiofauna taxa such as nematodes, copepods, amphipods and protozoans which assist in the conversion of mangrove primary production to detritus. The benthic fauna is made up of polychaetes (*Amphiura* sp., *Nephtys*, etc), bivalves (*Arca nuculana*, *Aloides*, *Nassa* sp., oysters (*Crassostrea gasar*) etc) and sponges (e.g. *Holothurids*). They also serve as breeding grounds and nurseries for crustaceans (crabs e.g. *Grapsidae*, *Ocypodidae* and *Portunidae*; shrimps e.g. *Peneidae* and *Palaemonidae*) and fin-fish species including mud skippers *Periophthalmus* sp., *Cichlidae*, *Scianidae*, *Polynemidae*, *Clupeidae* and *Drepanidae*.

The physical characteristics of Cameroon's estuarine systems were determined from the scientific literature (Gabche and Folack 1997; Angwe and Gabche 1997; UNEP 1984; ICITA 1973; GATE 1980; Van den Bosche and Bernacell 1990; Sayer *et al.* 1992; Mahé 1987; Folack 1988, 1989; Gabche and Hockey 1995; Folack *et al.* 1999). Hydrological data such as river discharge, rainfall and evaporation came from Cameroon's annual hydrological handbook (1997) and the meteorological services in Douala with some modifications. Data on nutrient levels (Table 3. 4) came from monitoring by

government services such as the Ministry of Environment and Forestry in Douala and the Research Station for Fisheries and Oceanography Limbe, Cameroon.

Budgetary estimations for the Cameroon and Rio-del-Rey estuary systems were separated into four months (120 days: November – February) of dry season and eight months (245 days: March – October) of rainy season.

*C.E. Gabche and S.V. Smith*



**Figure 3.2. The Cameroon and Rio-del-Rey estuarine systems.**

### 3.1 Cameroon estuary complex, Cameroon

*C.E. Gabche and S.V. Smith*

#### Water and salt balance

The Cameroon estuary complex has three main rivers (Mungo, Wouri and Dibamba) with input directly into the estuary. The volume of runoff ( $V_Q$ ) calculated from mean discharge (Table 3.2) gives total volumes of  $120 \times 10^6 \text{ m}^3 \text{ d}^{-1}$ ;  $20 \times 10^6 \text{ m}^3 \text{ d}^{-1}$  and  $170 \times 10^9 \text{ m}^3 \text{ d}^{-1}$  for annual, dry and rainy seasons, respectively. River runoff, rainfall and evaporation with seasonal values (where available) are given in Table 3.2.

**Table 3.2. River runoff, rainfall and evaporation data for the Cameroon estuary complex.**

Cameroon rivers	River Runoff ( $\text{m}^3 \text{ s}^{-1}$ )			River Runoff ( $V_Q$ ) ( $10^6 \text{ m}^3 \text{ d}^{-1}$ )			Rainfall ( $\text{mm month}^{-1}$ )			Evaporation ( $\text{mm month}^{-1}$ )
	Annual	Dry	Rainy	Annual	Dry	Rainy	Annual	Dry	Rainy	Annual
Mungo	420	50	520	40	4	45				
Wouri	740	90	920	60	10	80				
Dibamba	480	60	520	40	5	45				
<b>Total</b>				<b>140</b>	<b>20</b>	<b>170</b>	<b>270</b>	<b>40</b>	<b>390</b>	<b>100</b>

Total evaporation ( $V_E$ ) for the dry season and rainy seasons is calculated with the assumption of mean monthly values of 100 mm for the  $1,500 \text{ km}^2$  Cameroon estuary area. This gives a mean evaporation of  $5 \times 10^6 \text{ m}^3 \text{ d}^{-1}$  for both the dry and rainy seasons. The precipitation ( $V_P$ ) values for the dry and rainy seasons are obtained from rainfall for Douala. These gave mean monthly values of 40 mm and 390 mm for the dry and rainy seasons, respectively (Table 3.2). The mean precipitation values are  $2 \times 10^6 \text{ m}^3 \text{ d}^{-1}$  and  $20 \times 10^6 \text{ m}^3 \text{ d}^{-1}$  for the dry and rainy seasons, respectively. Salinity values with seasonal variations at different depths and various stations (fresh, estuarine and marine) of the Cameroon estuary complex are given in Table 3.3. Areas of high input of freshwater have low salinity with higher values at the Cameroon estuary due to salt water intrusion.  $V_G$  (groundwater inflows) and  $V_o$  (other inflows) like sewage are assumed to be zero. The water exchange time ( $t$ ) was 315 and 48 days in the dry and rainy seasons, respectively.

**Table 3.3. Mean temperature, salinity and nutrient levels of the Cameroon estuary complex.**

Parameter	River		Estuary		Ocean	
	Dry	Wet	Dry	Wet	Dry	Wet
Temp ( $^{\circ}\text{C}$ )	29.9	21.7	25.0	21.1	30.4	27.5
Salinity (psu)	0	0	15.8	8.7	21.4	16.5
Si ( $\mu\text{M}$ )	26	27	24.5	24	20	18.1
$\text{NO}_3$ ( $\mu\text{M}$ )	2.6	2.4	3.8	3.6	2.5	2.5
$\text{PO}_4$ ( $\mu\text{M}$ )	2.1	2.0	1.2	1.1	0.6	0.5

#### Balance of nonconservative materials

##### *DIP balance*

The population of Douala city within the estuary estimated at 1.4 million inhabitants. The human waste is discharged directly into the system hence wastewater loading is considered an important contributor to nutrient loading to the estuary. DIP equivalent of the domestic sewage from the population was estimated based in McGlone *et al.* (2000).

Nonconservative flux of DIP (**DDIP**) was calculated for the Cameroon estuary. DIP fluxes are presented in Table 3.4. The system is a net sink of DIP both in the dry and rainy seasons.

#### *DIN balance*

Waste load for DIN from the human population was considered (McGlone *et al.* 2000). DIN fluxes are summarized in Table 3.4. The system is a net sink in the dry season and a net source in the rainy season for DIN.

**Table 3. 4. Water, salt and nutrient budgets for the Cameroon estuary complex.**

Parameter	Dry	Rainy	Annual
$A_{\text{syst}}$ (km <sup>2</sup> )	1,500	1,500	1,500
$V_{\text{syst}}$ (10 <sup>9</sup> m <sup>3</sup> )	23	23	23
$V_O$ (10 <sup>6</sup> m <sup>3</sup> d <sup>-1</sup> )	20	170	120
$V_E$ (10 <sup>6</sup> m <sup>3</sup> d <sup>-1</sup> )	-5	-5	-5
$V_P$ (10 <sup>6</sup> m <sup>3</sup> d <sup>-1</sup> )	2	20	14
$V_R$ (10 <sup>6</sup> m <sup>3</sup> d <sup>-1</sup> )	-17	-185	-129
$V_X$ (10 <sup>6</sup> m <sup>3</sup> d <sup>-1</sup> )	56	299	218
$t$ (days)	315	48	137
$V_O \text{DIP}_O$ (10 <sup>3</sup> mol d <sup>-1</sup> )	15	15	15
$V_O \text{DIP}_O$ (10 <sup>3</sup> mol d <sup>-1</sup> )	42	340	241
$V_R \text{DIP}_R$ (10 <sup>3</sup> mol d <sup>-1</sup> )	-15	-148	-104
$V_X (\text{DIP}_{\text{ocn}} - \text{DIP}_{\text{syst}})$ (10 <sup>3</sup> mol d <sup>-1</sup> )	-34	-179	-131
<b>DDIP</b> (10 <sup>3</sup> mol d <sup>-1</sup> )	-8	-28	-21
<b>DDIP</b> (mmol m <sup>-2</sup> d <sup>-1</sup> )	-0.01	-0.02	-0.02
$V_O \text{DIN}_O$ (10 <sup>3</sup> mol d <sup>-1</sup> )	104	104	104
$V_O \text{DIN}_O$ (10 <sup>3</sup> mol d <sup>-1</sup> )	52	408	289
$V_R \text{DIN}_R$ (10 <sup>3</sup> mol d <sup>-1</sup> )	-54	-564	-394
$V_X (\text{DIN}_{\text{ocn}} - \text{DIN}_{\text{syst}})$ (10 <sup>3</sup> mol d <sup>-1</sup> )	-73	-329	-244
<b>DDIN</b> (10 <sup>3</sup> mol d <sup>-1</sup> )	-29	+381	+244
<b>DDIN</b> (mmol m <sup>-2</sup> d <sup>-1</sup> )	-0.02	+0.3	+0.2
$(p-r)_{\text{plankton}}$ (mmol m <sup>-2</sup> d <sup>-1</sup> )	+1	+2	+2
$(p-r)_{\text{mangroves}}$ (mmol m <sup>-2</sup> d <sup>-1</sup> )	+10	+20	+20
$(\text{nfix} - \text{denit})_{\text{plankton}}$ (mmol m <sup>-2</sup> d <sup>-1</sup> )	+0.1	+0.6	+0.4

#### *Stoichiometric calculation of aspects of net system metabolism*

The net ecosystem metabolism (NEM =  $p-r$ ) can be estimated as negative of the **DDIP** flux multiplied by the C:P ratio of the reacting organic matter. If the dominant reacting material is plankton, the particulate C:P ratio is about 106:1; ( $p-r$ ) is +1 mmol m<sup>-2</sup> d<sup>-1</sup> in the dry season and +2 mmol m<sup>-2</sup> d<sup>-1</sup> in the rainy season. If it is dominantly mangrove, then the ratio may be as high as 1000:1 which gives a ( $p-r$ ) of +10 mmol m<sup>-2</sup> d<sup>-1</sup> in the dry season and +20 mmol m<sup>-2</sup> d<sup>-1</sup> in the rainy season. The system seems to be autotrophic for both seasons.

The net nitrogen fixation minus the denitrification ( $\text{nfix} - \text{denit}$ ) is expressed as the difference between observed and expected **DDIN**. Expected **DDIN** is **DDIP** multiplied by the N:P ratio of the reacting particulate organic matter. The system appears to be a net nitrogen fixing; ( $\text{nfix} - \text{denit}$ ) = +0.1 mmol m<sup>-2</sup> d<sup>-1</sup> in the dry season and +0.6 mmol m<sup>-2</sup> d<sup>-1</sup> in the rainy season.

### 3.2 Rio-del-Rey estuary complex, Cameroon

*C.E. Gabche and S.V. Smith*

#### Water and salt balance

The Rio-del-Rey estuary of the west coast of Cameroon has relatively low anthropogenic influence. It is dominated by fishing activities dominated by shrimps, offshore petroleum drilling, and some industrial agricultural palm plantations of the Cameroon Development Cooperation (CDC). Water, salt and nutrient budgets for this estuary were treated for the three main rivers (Cross, Ndian and Meme) which discharge at the point mentioned earlier into the Atlantic Ocean. River runoff, rainfall and evaporation with seasonal values (where available) are given in Table 3.5.

**Table 3.5. River runoff, rainfall and evaporation data for the Rio-del-Rey estuary complex.**

Rio-del-Rey rivers	River runoff ( $\text{m}^3 \text{s}^{-1}$ )			River runoff ( $V_Q$ ) ( $10^6 \text{m}^3 \text{d}^{-1}$ )			Rainfall ( $\text{mm month}^{-1}$ )			Evaporation ( $\text{mm month}^{-1}$ )
	Annual	Dry	Rainy	Annual	Dry	Rainy	Annual	Dry	Rainy	Annual
Cross	580	140	730	50	12	60				
Ndian	250	60	310	20	5	30				
Meme	300	70	380	30	6	30				
Others	100	20	120	10	8	10				
<b>Total</b>				<b>110</b>	<b>30</b>	<b>130</b>	<b>250</b>	<b>90</b>	<b>330</b>	<b>120</b>

Salinity values with seasonal variations at different depths and various stations (fresh, estuarine and marine) of the d Rio-del-Rey estuary complex are given in Table 3.6.

**Table 3.6. Mean temperature, salinity and nutrient levels of the Rio-del-Rey estuary complex.**

Parameter	River		Estuary		Ocean	
	Dry	Wet	Dry	Wet	Dry	Wet
Temp ( $^{\circ}\text{C}$ )	29.2	28.4	28	27	30	29
Salinity (psu)	0	0	17.8	11.3	19.2	15.3
Si ( $\mu\text{M}$ )	32	30	26	25	24	23
$\text{NO}_3$ ( $\mu\text{M}$ )	1.9	1.8	3.2	3.1	0.4	0.3
$\text{PO}_4$ ( $\mu\text{M}$ )	2.0	1.6	0.9	0.8	0.5	0.4

The total average discharge ( $V_Q$ ) as  $30 \times 10^6 \text{m}^3 \text{d}^{-1}$  and  $130 \times 10^6 \text{m}^3 \text{d}^{-1}$  for the dry and rainy seasons, respectively. The total evaporation ( $V_E$ ) for the dry and rainy seasons was calculated for the mangrove area of  $1,350 \text{km}^2$ . The monthly mean evaporation is 120 mm (Table 3.5). This gave  $V_E$  values of water evaporated from the estuary area of  $5 \times 10^6 \text{m}^3 \text{d}^{-1}$  for the dry and rainy seasons. The total precipitation values were obtained from rainfall data for Calabar, which has a monthly mean of 90 mm for the dry and 330 mm for the rainy season (Table 3.5). These values gave volumes of  $4 \times 10^6 \text{m}^3 \text{d}^{-1}$  for the dry season and  $15 \times 10^6 \text{m}^3 \text{d}^{-1}$  for the rainy season. The groundwater inflows ( $V_G$ ) and others ( $V_o$ ) such as sewage are considered to be zero. The water exchange time ( $\tau$ ) was 48 days and 33 days for the dry and rainy seasons, respectively.

#### Balance of nonconservative materials

##### *DIP balance*

The Rio-del-Rey estuary has a population dominated by fishermen estimated at 150,000 discharging directly into the system. Computed  $V_o \text{DIP}_o$  from the population based on McGlone *et al.* (2000) is

$2 \times 10^3 \text{ mol d}^{-1}$ . DIP fluxes are summarized in Table 3.7. Nonconservative DIP, **DDIP** of the system shows that the system is a net source of DIP for both seasons.

#### *DIN balance*

DIN fluxes are presented in Table 3.7. DIN flux from the population was considered. The system seems a source for DIN in both seasons.

**Table 3.7. Water, salt and nutrient budgets for the Rio-del-Rey estuary complex.**

Parameter	Dry	Rainy	Annual
$A_{\text{syst}}$ (km <sup>2</sup> )	1,350	1,350	1,350
$V_{\text{syst}}$ ( $10^9 \text{ m}^3$ )	20	20	20
$V_O$ ( $10^6 \text{ m}^3 \text{ d}^{-1}$ )	30	130	97
$V_E$ ( $10^6 \text{ m}^3 \text{ d}^{-1}$ )	-5	-5	-5
$V_P$ ( $10^6 \text{ m}^3 \text{ d}^{-1}$ )	4	15	11
$V_R$ ( $10^6 \text{ m}^3 \text{ d}^{-1}$ )	-29	-140	103
$V_X$ ( $10^6 \text{ m}^3 \text{ d}^{-1}$ )	384	466	439
$t$ (days)	48	33	38
$V_O \text{DIP}_O$ ( $10^3 \text{ mol d}^{-1}$ )	2	2	2
$V_O \text{DIP}_O$ ( $10^3 \text{ mol d}^{-1}$ )	60	208	159
$V_R \text{DIP}_R$ ( $10^3 \text{ mol d}^{-1}$ )	-20	-84	-63
$V_X (\text{DIP}_{\text{ocn}} - \text{DIP}_{\text{syst}})$ ( $10^3 \text{ mol d}^{-1}$ )	-154	-186	-175
<b>DDIP</b> ( $10^3 \text{ mol d}^{-1}$ )	+112	+60	77
<b>DDIP</b> ( $\text{mmol m}^{-2} \text{ d}^{-1}$ )	+0.08	+0.04	+0.05
$V_O \text{DIN}_O$ ( $10^3 \text{ mol d}^{-1}$ )	11	11	11
$V_O \text{DIN}_O$ ( $10^3 \text{ mol d}^{-1}$ )	57	239	178
$V_R \text{DIN}_R$ ( $10^3 \text{ mol d}^{-1}$ )	-52	-238	-176
$V_X (\text{DIN}_{\text{ocn}} - \text{DIN}_{\text{syst}})$ ( $10^3 \text{ mol d}^{-1}$ )	-1,075	-1,304	-1,228
<b>DDIN</b> ( $10^3 \text{ mol d}^{-1}$ )	+1,059	+1,297	+1,218
<b>DDIN</b> ( $\text{mmol m}^{-2} \text{ d}^{-1}$ )	+0.8	+1	+0.9
$(p-r)_{\text{plankton}}$ ( $\text{mmol m}^{-2} \text{ d}^{-1}$ )	-8	-4	-5
$(p-r)_{\text{mangroves}}$ ( $\text{mmol m}^{-2} \text{ d}^{-1}$ )	-80	-40	-50
$(n\text{fix}-\text{denit})_{\text{plankton}}$ ( $\text{mmol m}^{-2} \text{ d}^{-1}$ )	-0.5	+0.4	+0.1

#### *Stoichiometric calculation of aspects of net system metabolism*

The net ecosystem metabolism for the estuarine area ( $\text{NEM} = [p-r]$ ) is estimated as  $-8 \text{ mmol m}^{-2} \text{ d}^{-1}$  in the dry season and  $-4 \text{ mmol m}^{-2} \text{ d}^{-1}$  using plankton C:P ratio of 106:1 (Table 3.7). If the system is dominated by mangrove,  $(p-r)$  is estimated as  $-80 \text{ mmol m}^{-2} \text{ d}^{-1}$  in the dry season and  $-40 \text{ mmol m}^{-2} \text{ d}^{-1}$  using C:P ratio of 1000:1. It appears that the system is a net heterotrophic for both seasons.

The estimation of net nitrogen fixation minus denitrification ( $n\text{fix}-\text{denit}$ ) is made from the difference between the observed and expected DIN, where the expected value is given by **DDIP** x N:P ratio of decomposing organic matter. It is assumed that the N:P ratio is 16:1 (Redfield ratio for plankton). ( $n\text{fix}-\text{denit}$ ) is  $-0.5 \text{ mmol m}^{-2} \text{ d}^{-1}$  in the dry season and  $+0.4 \text{ mmol m}^{-2} \text{ d}^{-1}$  in the rainy season. The system seems to behave as net denitrifying in the dry season and nitrogen fixing in the rainy season.

## Congo River

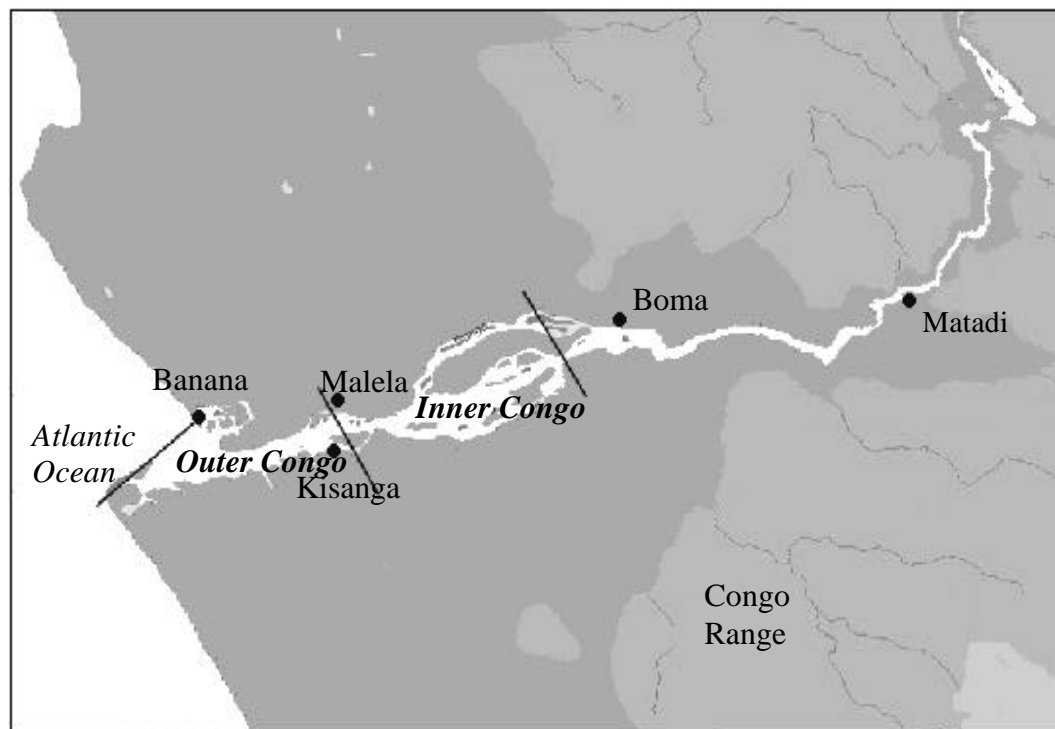
Tropical rivers bring more than half of the total global runoff to the ocean (Milliman and Meade 1983). The Congo River is the second largest river in the world, draining into the Atlantic Ocean from a vast area (3.8 million km<sup>2</sup>) of monsoonal sub-Saharan Africa. This includes the Central African Basin that borders on the Rift Zone to the east, and extends southward to Angola and Zambia and northwards into the Cameroon and Central Africa Republic. Various lakes, reservoirs and swamplands occur along its length before the river drops to the relatively narrow coastal plain incorporating the estuary. The human pressures and changes are variable. The catchment has a population density of 15 people km<sup>-2</sup>, it contains 18 major cities, and only about 8% of its area is under cropland agriculture. Approximately 43% of the basin area is forested, while 46% of the original forest cover has been deforested (World Resources Institute 1998). The climate in the region is extremely hot and humid, with a mean annual temperature of about 27°C in the coastal lowlands, and an average annual rainfall of about 1,524 mm north of the equator and 1,270 mm south of the equator. Frequent heavy rains occur from April to November north of the equator, and from October to May south of the equator.

### 3.3 Congo (Zaire) River Estuary, Democratic Republic of the Congo

*J.I. Marshall Crossland, C.J. Crossland and D.P. Swaney*

#### Study site description

Estuarine structure, details of oceanographic and other characteristics were described from two oceanographic cruises (November 1976 and May 1978) in a special volume of the Netherlands Journal of Sea Research (Vol. 12 (3/4) 1978). Here, we have drawn details of nutrient data and process regimes especially from Eisma and Bennekom (1978), and Bennekom *et al.* (1978) to derive a first-order assessment of nutrient fluxes.



**Figure 3.3. Map and location of the Congo River estuary.** Solid lines indicate boundaries of the inner and outer estuarine zones, the budgeted areas.

The Congo River estuary (6.05°S, 12.30°E) comprises two regions (Figure 3.3): the shallow inner estuarine region is dissected into channels with associated islands and swamps, and mangrove forests abut the outer estuary. A significant feature of the outer estuary is a deep central canyon that extends through most of the zone dropping abruptly to 100m depth and continuing to deepen as it extends offshore as a trench to the Angola Basin (3500m depth).

The canyon has a relatively unique and marked effect not only on the hydrographic characteristics of the outer estuarine system but also on nutrient processes, and thus the metabolic performance of the estuary as a whole. The shallow inner estuary swamps yield “black water”, rich in organic matter, which add organics to the relatively high inorganic nutrient load. Compared with other tropical rivers, phosphorus is high (0.4-0.9  $\mu\text{M}$  DIP, 0.7-1.0  $\mu\text{M}$  suspended P) and measured DIN includes nitrate (5-8  $\mu\text{M}$ ), nitrite (0.1-0.2  $\mu\text{M}$ ) and ammonium ions (0.5  $\mu\text{M}$ ). Due to physical supersaturation in river rapids, dissolved oxygen is high, up to 140%.

The central outer estuary is deep (more than 300m in the trench; average depth, 270m) with few tidal flats or shallow mud banks. Two townships, Malela and Kisanga (or Quissanga) potentially contribute effluent and runoff to the outer estuary region, but their population centers have less than 20,000 inhabitants, so the nutrient load is negligible compared with that of the upstream flow. The estuary has a small tidal range (0.3-1.9 m neap-spring; semidiurnal) and a high current velocity and discharge rate (annual average, 45, 000  $\text{m}^3 \text{s}^{-1}$ ) in the river producing a stratified estuary with very short residence time in the mixed surface layer (Eisma and Bennekomp 1978). Congo River water is confined to the upper 5-10 m depth forming a lens above the “canyon” waters, that extends offshore. Both DIP (e.g., 0.4 - 1.0  $\mu\text{M}$ ) and DIN can vary markedly over a few days, and oxygen concentration remains relatively high. Primary production is low and is confined to surface (turbid) waters; supersaturation with oxygen is greater at 10 m (140%) than at the surface (130%).

Bottom waters of the Congo canyon exhibit some key features. Isotherms slope upward: there is a net up-canyon bottom current. Temperature data suggest that coastal upwelling is more important in May than in November (when southerly winds dominate), and there is relatively high suspended material of organic origin near the head of the canyon. Indeed, Bennekomp *et al.* (1978) showed *in situ* processes involving consumption of oxygen and production of DIN. This is good evidence of a major zone of at least partial remineralisation of river-derived particulate organic matter on the inner face of the canyon (to 250m depth), from which derived inorganic nutrients may become mixed into the estuarine and immediate subsurface waters. Such entrainment of subsurface waters, or river-induced upwelling, is not unusual in plumes of large rivers, and in these cases the composition of the seawater end-member may be quite variable, depending on the source of upwelling. In May, the coastal upwelling yielded greater DIP and DIN concentrations in surface waters along the coast. Thus, the hydrography of the estuary has a vital influence on the advective quantities beyond those expected from simple mixing of river and seawater

Nitrate is near zero in coastal waters, DIP and silicate concentrations are low, and a sharp nutricline occurs at 30 m depth. The river plume is initially narrow, dominated by the high velocity of river water and entrainment of subsurface seawater. Offshore, the river plume broadens under wind influence. Congo River water has been detected more than 700km from the estuary.

Recognising the hydrographic characteristics of the estuary, we have developed an annual budget using a stratified (outer estuary), multiple horizontal box model.

**Table 3.8. Area, volume and depth estimates for the budget boxes of the Congo River estuary.**

Parameter	Outer estuary (surface)	Outer estuary (deep-canyon)	Inner estuary
Surface area ( $\text{km}^2$ )	146	46	95
Volume ( $\text{m}^3$ )	$1.2 \times 10^9$	$12 \times 10^9$	$0.47 \times 10^9$
Average depth (m)	8	260	5

### Water and salt balance

Water and salt budgets (Figure 3.4) are calculated from average annual data. The estimated annual river discharge of water was  $1,450 \times 10^9 \text{ m}^3 \text{ yr}^{-1}$  or  $4 \times 10^9 \text{ m}^3 \text{ d}^{-1}$ . Average annual precipitation and potential evaporation values were measured at Matadi, Democratic Republic of the Congo, approximately 100 km upstream ( $5^\circ 47' \text{ S}$ ,  $13^\circ 26' \text{ E}$ ) as precipitation =  $1,011 \text{ mm yr}^{-1}$  and evaporation =  $1,703 \text{ mm yr}^{-1}$ . Hamon's equation used with monthly temperature measured at Matadi, provides an estimate of evaporation  $\sim 1,350 \text{ mm yr}^{-1}$ . These values are generally consistent with regional values as they appear on global maps (e.g. see <http://data.ecology.su.se/mnode/Methods/precevap.htm>). The estimated net atmospheric flux, precipitation-evaporation, of  $-240$  to  $-600 \text{ mm yr}^{-1}$  over the area of the estuary is insignificant in relation to river inflow.

### Budgets of nonconservative materials

Budgets for DIP (Figure 3.5) and DIN (Figure 3.6) show that the Congo River is a major source of both P and N to the estuary (average daily fluxes of 3.6 million moles and 28 million moles, respectively). Somewhat surprisingly, the inflow from the ocean to the deeper waters of the canyon associated with the estuarine circulation also makes a significant contribution to the budgets, partly because the nutrient concentrations of seawater at depth are high relative to the concentrations in the river. An upper estimate of the direct local contributions from sewage, assuming a contributing population of 40,000 inhabitants in the coastal zone of the estuary and annual per capita loads of  $\sim 5 \text{ kg N}$  and  $1.5 \text{ kg P}$ , yields an insignificant contribution of  $\sim 40,000 \text{ moles N d}^{-1}$  and  $\sim 5,000 \text{ moles P d}^{-1}$ . Summing over both layers of the outer estuary, there is a net nutrient outflow to the ocean from the estuary. The net consumption of DIP and production of DIN in the deep canyon implies microbial action during organic remineralisation of organic material, described earlier by Bennekom *et al.* (1978). The surface waters of the outer estuary are a sink for both DIP and DIN, and the inner estuary is also a lesser sink for DIN. The total estuary system is a sink for DIP and DIN (i.e. the amount of nutrients injected into the ocean from the surface layer of the estuary is less than the sum of fluxes into the system from the Congo River and circulation from the ocean).

### Stoichiometric calculations of aspects of net system metabolism

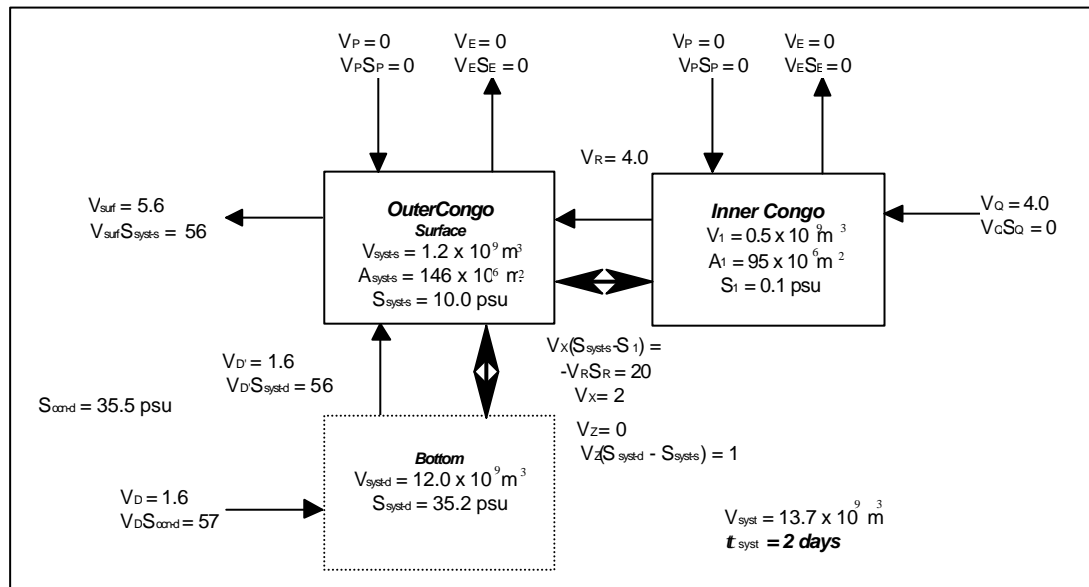
Stoichiometric calculations can be based on the molar ratio of material likely to be transported into the system and reacting therein (Gordon *et al.* 1996). We assume that this material is plankton, with C:N:P ratio of 106:16:1.

**Table 3.9. Net metabolism estimates for the Congo River estuary system**

	N or C per budget box ( $10^6 \text{ mol d}^{-1}$ )	N or C per unit area ( $\text{mmol m}^{-2} \text{ d}^{-1}$ )
Net ( <i>nfix-denit</i> ) - nitrogen		
Inner	-3	-32
Outer	-28	-192
Deep	+34	+739
Total system	+3	+12
Net ( <i>p-r</i> ) -carbon		
Inner	0	0
Outer	+21	+144
Deep	+138	+3,000
Total system	+159	+660

Nitrogen fixation minus denitrification (*nfix-denit*) provides an estimate of net nitrogen flux for the system and can be estimated as the difference between observed and expected *DDIN*, where *DDIN<sub>exp</sub>* is  $16 \times \text{DDIP}$  (Table 3.9). The total estuarine system is calculated as slightly net nitrogen fixing, with net denitrification exhibited in the surface (river) waters and shallows. Estimates for the deep canyon element exhibit strong net nitrogen fixation, probably reflecting microbial activity associated with the remineralisation zone near the head of the submarine canyon.

Net ecosystem metabolism (NEM =  $[p-r]$ ) or net production minus respiration) is derived from  $(p-r) = 106 \times \text{DDIP}$  (Table 3.9). The total system yields a picture of net autotrophy, with moderate net production rates in the surface waters of the outer estuary and apparent extreme values demonstrated for the deep canyon waters, where strong microbial activity is inferred. However, some caution is placed on this interpretation. In a large, sediment-dominated system such as this, the P budget may be compromised by sediment reactions, such that the relatively high (p-r) estimates reflect a sediment effect from P adsorption. Such processes could also contribute to the relatively high net nitrogen fixation values.



**Figure 3.4. Water and salt fluxes of the Congo River estuary.** (Units of volume and salinity flux are  $10^9 \text{ m}^3 \text{ d}^{-1}$ ,  $10^9 \text{ psu-m}^3 \text{ d}^{-1}$ )

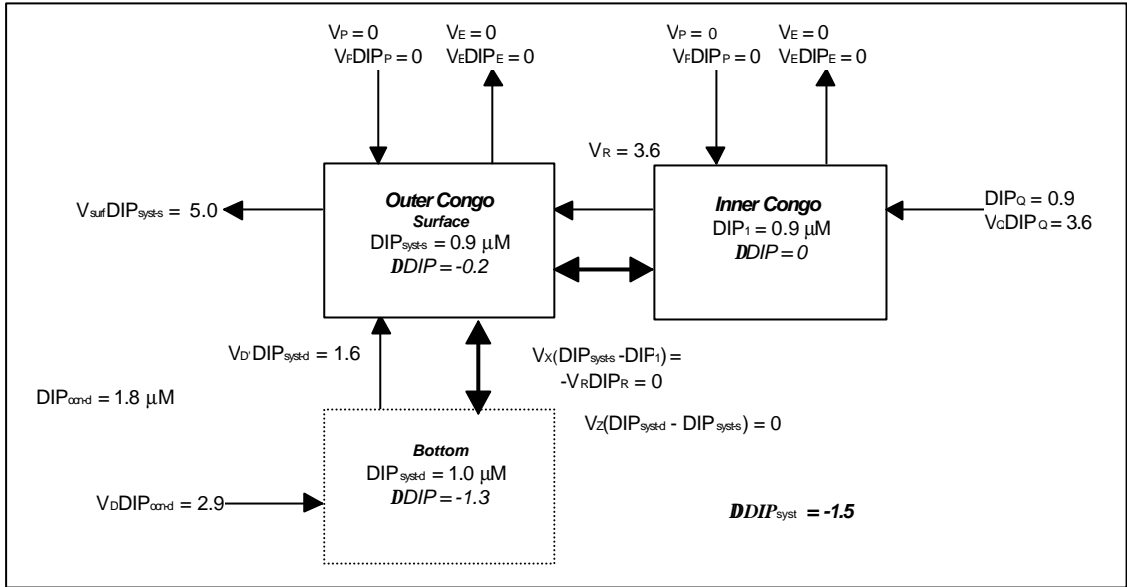


Figure 3.5. DIP flux for the Congo River estuary. Units of flux are  $10^6 \text{ mol d}^{-1}$ .

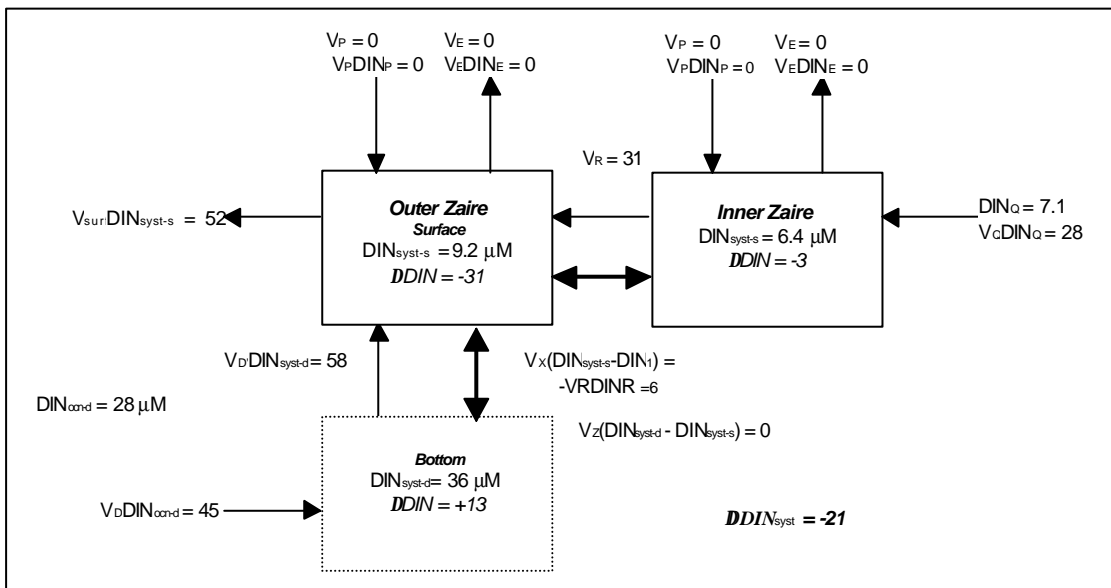
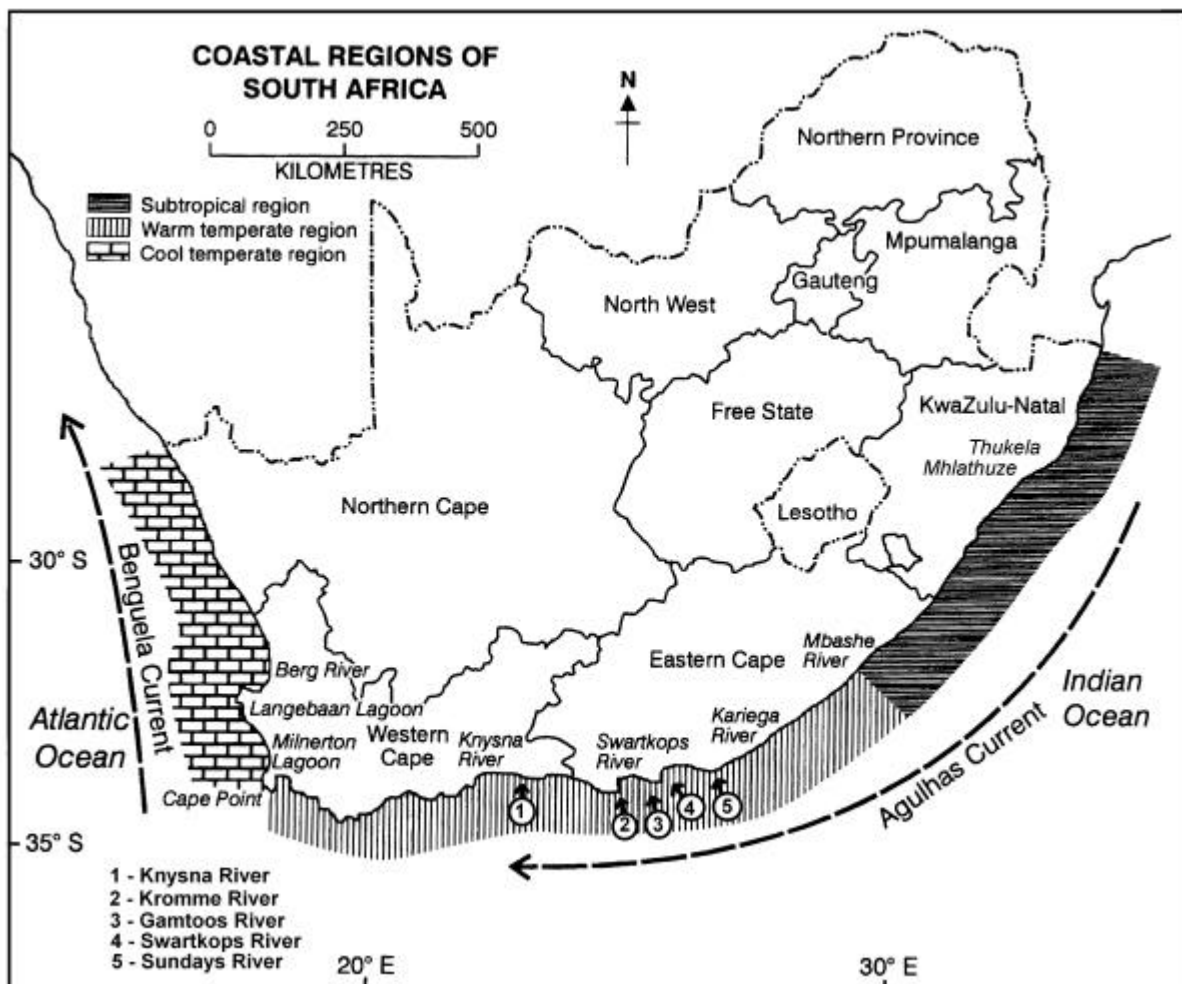


Figure 3.6. DIN flux for the Congo River estuary. Units of flux are  $10^6 \text{ mol d}^{-1}$ .

#### 4. ESTUARIES OF SOUTH AFRICA

The South African coastal area contains a wide variety of ecosystems, including 465 estuaries along its 3000 km coastline. South African estuaries have almost all originated in formerly incised bedrock valleys cut during periods of lowered sea levels during the Pliocene and Pleistocene epochs. Of most importance to their present configuration and morphology is the change in sea level during the Holocene, when the sea level rose by approximately 130 m about 13,000 years ago. Present sea levels along the coast were reached between 5000 and 6000 years ago (Cooper *et al.* 1999).

A wide variety of estuarine types can be found in South Africa, reflecting substantially different physical environments. The eastern seaboard has the steeply tilted coastal plains subject to heavy summer rainfall, whereas the arid west coast is less tilted, and estuaries become functional only during events of exceptional precipitation. Although numerous, South African estuaries are generally small and cover only some 600 km<sup>2</sup> of coastline. Compared with the USA where estuaries cover an area of 107,722 km<sup>2</sup> along a 10,000 km coastline, South African estuaries are indeed rather small (Allanson *et al.* 1999).



**Figure 4.1.** Climatological/biogeographical regions and ocean currents along the South African coast.

The morphology of South African estuaries is largely determined by climate, hinterland topography, wave energy, sediment supply and coastal lithology (Cooper *et al.* 1999). A wide range of estuarine types can be found in South Africa, reflecting the substantially different physical environments. The characteristics of these estuaries are dependent on where they are, and thus on the climate of the region.

Climatic regions and rainfall in catchments determine to a large degree the size, shape, and nature of the estuaries. Rainfall over South Africa is particularly erratic and unevenly distributed over the country with the 40 cm isohyet dividing the country into wetter, humid, subtropical eastern region, and a dry, semi-desert western region with almost complete aridity in places. The average annual rainfall of about 500 mm for the country as a whole is well below the global average of 800 mm. Periods of severe and prolonged drought occur from time to time, which are often terminated by severe floods. Rainfall is also highly seasonal. More than 80% of the rainfall occurs during summer (October–March) in the northern regions, while the situation is reversed in the south (Western Cape, Figure 4.1). The topography strongly influences rainfall, and the mountain ranges along the east coast of the country enhance precipitation, with marked spatial differences in rainfall (Schumann *et al.* 1999).

Freshwater flow into South African estuaries is generally low and limited. In many estuaries inflow rates average less than  $1 \text{ m}^3 \text{ sec}^{-1}$ . The inflow of fresh water into estuaries is further compounded by dams built in catchment areas to supply water for agricultural, industrial and domestic use. The recently promulgated Water Act of 1998, however, provided for the ecological freshwater requirements of estuaries.

Based on average seawater temperatures, the coast can be subdivided into three broad climatological regions (de Villiers and Hodgson 1999) as illustrated in Figure 4.1. These three climatological/biogeographic regions are (1) the subtropical region from the northern border of KwaZulu-Natal to the Mbashe River and (2) the warm temperate region from the Mbashe River to Cape Point in the south. Both these regions are under the influence of the warm Agulhas Current. The third cool temperate region occurs along the west coast and is under the influence of the Benguela current, an area of intense upwelling. The boundaries between these regions are not well defined and may vary within a distance of 50-100 km. Because of the climate, rainfall patterns and coastal morphology, not all estuaries are permanently open to the sea. The physical classification of estuaries is therefore not straightforward. However, Whitfield (1992) and Wooldridge (1994) have classified South African estuaries according to the state of the estuary mouths and identified five types useful in ecological and management studies:

- permanently open estuaries
- temporarily open/closed estuaries
- river mouths
- estuarine lakes
- estuarine lagoons

These five types occur with various frequencies in any of the three biogeographic regions. Less than 20% of the 465 estuaries is permanently open to the sea. The rest are open or closed for various periods of time, while some are artificially breached when water levels increase to unacceptable heights. There are only two systems which can be classified as “river mouths”, namely the Thukela River in the north-eastern, subtropical climate region and the Orange River (which forms the border between South African and Namibia) on the west coast in the cool temperate region. In both rivers the estuarine phase is very brief and they are for most of the year fresh to the sea.

Since much of southern Africa is semi-arid and prone to extremes of drought and floods, and with a growing population, South Africa is faced with the task of providing water to all users. The abstraction of water from rivers for human needs resulted in gross interference with the hydraulic structure of estuaries, and in some instances lead to the destruction of the ecosystem. As well as the influence of activities in the catchments of estuaries, there is also direct pressures on them. Because of the rugged coastline, the limited number of truly sheltered embayments, the high energy wave regime and strong winds throughout the year, development pressure has focused on estuaries. Most of South Africa's major industries are located in the interior, so that this pressure is mainly in the form of residential and recreational developments (Morant and Quinn 1999). They have not, in general, attracted large settlements of people with the exception of important estuarine settlements including urban and industrial developments at Richards Bay (near Lake St. Lucia) and Durban in KwaZulu-Natal, the Buffalo and Swartkops rivers in the Eastern Cape Province, Knysna and Saldanha in the Western Cape (Allanson *et al.* 1999). The condition of South African estuaries varies from “excellent” (i.e. in a nearly

pristine condition) to “poor” (i.e. where major ecological degradation occurs due to a combination of anthropogenic influences). About 30% of estuaries are considered to be in an “excellent” condition, 31% in a “good” condition, 24% are considered to be “fair” and 15% “poor”. Management of South African estuaries has in the past mainly been undertaken on a piecemeal basis, dependent on and driven by sectoral interests such as fishermen, property developers and owners, and local interest groups. More recently the management and research of estuaries have been incorporated into legislation and policy, such as the Marine Living Resources Act (No. 18 of 1998), the National Water Act (No. 36 of 1998), and the White Paper for Sustainable Coastal Development in South Africa. An authoritative and comprehensive review of the status of estuarine research and management in South Africa is given by Allanson and Baird (1999).

*Dan Baird*

#### **4.1 Knysna Lagoon, Western Cape**

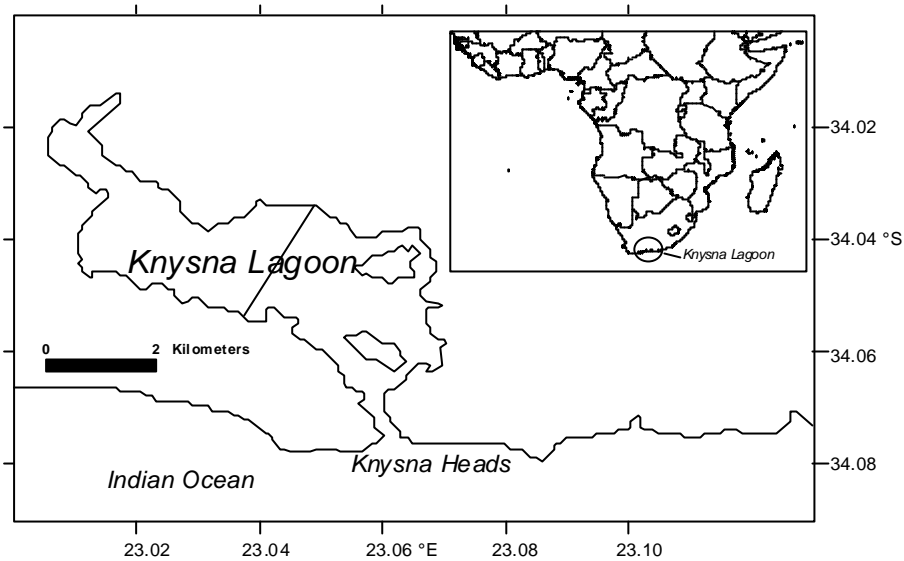
*Todd Switzer and Howard Waldron*

##### Study area description

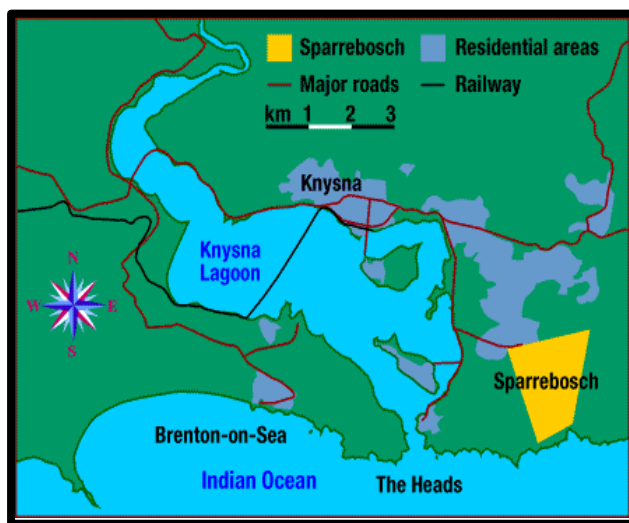
Knysna Lagoon is located in Western Cape province on the southern coast of South Africa (34.1°S, 23.0°E; Figures 4.2 and 4.3). It lies to the east of Cape Agulhas and therefore, geographically, falls within the domain of the south-west Indian Ocean. The dominant freshwater source of the estuary is the Knysna River; saltwater exchange occurs at Knysna Heads, the abrupt and perennially open interface between estuary and sea (Figure 4.2). The tide in the estuary is semi-diurnal with a range of approximately 0.5 m-2.0 m. The tidal influence extends 19 km inland from Knysna Heads (Largier *et al.* in press) and is prevented from further incursion by a weir. The area of water formed by tidal flow at high water spring tide is approximately 20 km<sup>2</sup> (Allanson *et al.* in press). The climate at Knysna is transitional between the summer rainfall dominated region of eastern South Africa and winter rainfall area of the western Cape. The average air temperature is 20.8°C (maximum monthly average 24.6°C in February, minimum monthly average 16.6°C in July). The average annual precipitation is 1,000 mm with highest monthly averages (100 mm to 130 mm) occurring between October and March in the austral summer. Average (1961-1990) monthly austral winter precipitation varies between 30 mm and 70 mm during April to September (Table 4.1, from Waldron 1999).

Knysna Lagoon is immediately adjacent to the medium-sized town of Knysna, which has a permanent population of 39,800 (1998 statistics). It is subjected to the usual suite of pressures exerted by an urban and industrialised population, and the region is also a hugely popular tourist destination. The catchment area of the estuary has extensive forestry and agricultural activities. All these activities are likely to increase in the future, placing the estuarine environment under increasing anthropogenic pressure.

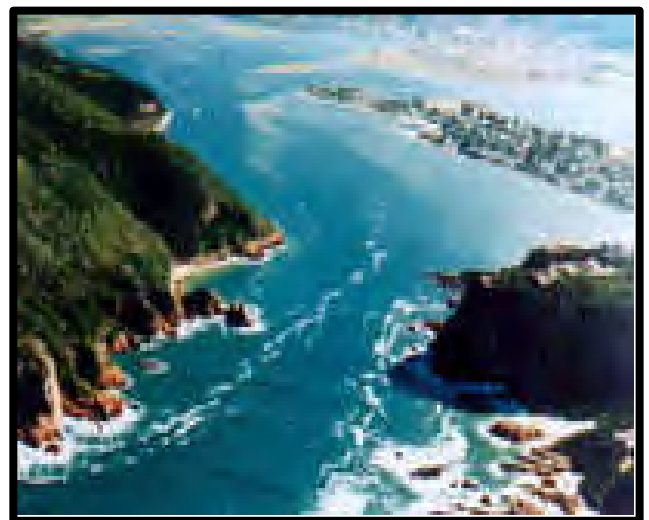
A LOICZ budgeting exercise was completed for the Knysna estuary (Figure 4.2). Available data constrained the preliminary budget to one season (winter). The system was divided into a two-box model on the basis of salinity gradients down the navigable channel from the Knysna River's source to the ocean at Knysna Heads. The estuary (Box 1) extended from the head of the estuarine system at the river input to a position slightly seaward of the N2 road bridge, which crosses the estuary at its upper end. From salinity sections a haline front of 1.7 psu was evident at this position at low water. The bay (Box 2) extended from this position to the mouth of the system (Knysna Heads) where there was another haline front of approximately 1.2 psu between bay and oceanic waters. Ambient salinity of oceanic water was 35.2 psu. This is the dry season and further data collection in the next six months will permit the addition of the summer season when higher rainfall is the anticipated norm. River flow rates for the Knysna River have been taken from Largier (in press), with direct measurements of river flow from the Salt River (Box 2) included.



**Figure 4.2. Location and map of Knysna Lagoon.**



**Figure 4.3. Detailed map of Knysna Lagoon.**



**Figure 4.4. Aerial view of Knysna Heads.**

### Water and salt balance

Based on data relating to riverine input, precipitation, evaporation and salinity, there was a residual flux of water ( $V_R$ ) of  $-37 \times 10^3 \text{ m}^3 \text{ d}^{-1}$  between estuary and the bay and  $-43 \times 10^3 \text{ m}^3 \text{ d}^{-1}$  between bay and the ocean. The negative value of these numbers denotes residual flow of water from the estuary to the bay, and from the bay to ocean waters.

The salt flux carried by this residual flow ( $V_R S_R$ ) was  $-1,227 \times 10^3 \text{ psu} \cdot \text{m}^3 \text{ d}^{-1}$  between estuary and bay and  $-1,487 \times 10^3 \text{ psu} \cdot \text{m}^3 \text{ d}^{-1}$  between bay and ocean.

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 estuary 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 the figures given in the model for  $V_X(S_{ocn}-S_{syst})$  between estuary and bay and between the bay and the ocean. Minimal salt fluxes from the rivers ( $V_{Q2}S_{Q2} + V_{Q3}S_{Q3}$ ) were considered in Box 2 (Figure 4.5). The mixing fluxes ( $V_X$ ) between estuary and bay and between bay and ocean were  $722 \times 10^3 \text{ m}^3 \text{ d}^{-1}$  and  $1,193 \times 10^3 \text{ m}^3 \text{ d}^{-1}$ , respectively.

The water exchange times for water in the estuary and bay for the winter were approximately 32 days and 49 days, respectively. It should be noted that this reflects background conditions for the dry season when river flow and rainfall were minimal.

**Table 4.1. Meteorological data for Knysna Estuary, from George Airport (averages, from Waldron 1999).**

	Air Temperature (°C)	Precipitation (mm)	Air Pressure (hPa)
January	24.4	134	991.7
February	24.6	113	991.5
March	23.9	120	992.8
April	21.7	73	993.5
May	19.1	59	994.7
June	16.8	28	997.3
July	16.6	39	997.9
August	17.7	62	997.8
September	19.3	73	996.1
October	20.4	98	995.7
November	21.8	108	994.0
December	23.4	102	991.9
Annual	20.8 (mean)	1009 (total)	994.6 (mean)

#### Budgets of nonconservative materials

The criteria established in the water and salt budgets also apply to exchanges of dissolved N and P with the caveat that deviations result from net non-conservative reactions of N and P in the system. Concentrations of  $\text{NO}_3$ ,  $\text{NO}_2$ ,  $\text{NH}_4$  (DIN) and  $\text{PO}_4$  (DIP) were available from samples taken at stations spaced at intervals of approximately 800 meters along the navigable channel of the bay and estuary. These 14 stations were sampled quasi-synoptically.

In order to obtain a single representative value for the bay and estuary in this model, the full suite of nutrient concentrations from each station sampled at low water was averaged. This gave a single mean value for DIN and DIP in the estuary and bay, respectively.

The nutrient concentrations were also determined for river inputs, point sources (including sewage) and the adjacent ocean. The average nutrient concentrations of point source water ( $n=10$ ), weighted for their respective flow volumes, were calculated and this value used in the model as representative of all point source input. Point source water only impacted on the bay area during the dry season.

#### *DIP balance*

The residual fluxes of DIP ( $V_R \text{DIP}_R$ ) between the estuary and bay, and bay and the ocean were  $-35 \text{ mol d}^{-1}$  and  $-28 \text{ mol d}^{-1}$  respectively, representing a loss of DIP across each boundary.

**DDIP** values of  $-90 \text{ mol d}^{-1}$  and  $+891 \text{ mol d}^{-1}$  were obtained for the estuary and bay (see Figure 4.6). This indicates that the estuary is experiencing a net loss of DIP while the bay realises a net gain at the

annual time scale. Given the system's total surface area of 48 km<sup>2</sup> this translates to a system average uptake of 0.02 mmol m<sup>-2</sup> d<sup>-1</sup>. These values are unrealistically low due to the fact that one dry season is being extrapolated to a full year.

#### *DIN balance*

The residual DIN fluxes ( $V_R \text{DIN}_R$ ) between estuary and bay and bay and the ocean were -133 mol d<sup>-1</sup> and -97 mol d<sup>-1</sup>, respectively.

**DDIN** values of -141 mol d<sup>-1</sup> and +3,542 mol d<sup>-1</sup> were obtained for the estuary and bay, respectively (see Figure 4.7). This indicates that the estuary is experiencing a net loss of DIN and the bay realises a net gain of DIN at the annual time scale. Given the entire system's surface area of 48 km<sup>2</sup> this translates to a system average DIN gain of 0.07 mmol m<sup>-2</sup> d<sup>-1</sup>.

#### *Stoichiometric estimates of aspects of net system metabolism*

Assuming that all the non-conservative behaviour is of biological origin, and for the purpose of this LOICZ budgeting exercise, the Redfield ratio applies to the system. The observed **DDIP** values in the Knysna system can be used to estimate the net production of organic matter. However, values of 8:1 or 10:1 for N:P may apply to the Knysna system upon further study (Allanson *et al.* in press). Using the Redfield ratio, the nonconservative flux can be calculated using the formula:

$$(nfix - denit) = \text{DDIN}_{obs} - \text{DDIN}_{exp}$$

The expected **DDIN** ( $\text{DDIN}_{exp}$ ) can be determined using the Redfield ratio of 16:1 for N:P, and the observed value for **DDIP** ( $\text{DDIP}_{obs}$ ). This allows  $\text{DDIN}_{exp}$  to be expressed as 16( $\text{DDIP}_{obs}$ ), yielding values of +0.1 mmol N m<sup>-2</sup> d<sup>-1</sup> for the estuary and -0.3 mmol N m<sup>-2</sup> d<sup>-1</sup> for the bay. This indicates that the estuary is fixing nitrogen while the bay is denitrifying during the winter season. Thus, on balance, the system is a denitrifying environment ( $[nfix - denit]_{syst} = -0.2 \text{ mmol N m}^{-2} \text{ d}^{-1}$ ). We would expect that the characteristics of nonconservative flux will change with the pending summer (wet) season data.

In order to express the net ecosystem metabolism (NEM) in terms of carbon, we make the assumption that NEM is the result of organic matter production - respiration ( $p-r$ ) and that the Redfield Ratio between carbon and DIP is 106:1.

$$\text{NEM} = (p-r) = -106(\text{DDIP})$$

Values of +1 mmol C m<sup>-2</sup> d<sup>-1</sup> for the estuary and -3 mmol C m<sup>-2</sup> d<sup>-1</sup> for the bay were obtained. The estuary is a net producer of organic matter in the winter, while the bay is a net consumer of organic matter during this period. The system is a net heterotrophic, ( $p-r$ ) is -2 mmol C m<sup>-2</sup> d<sup>-1</sup>. Given that the anthropogenic inputs of organic matter into the bay, and the inputs from the bay-ocean interface are much higher relative to those same inputs into the estuary these values are seasonally appropriate.

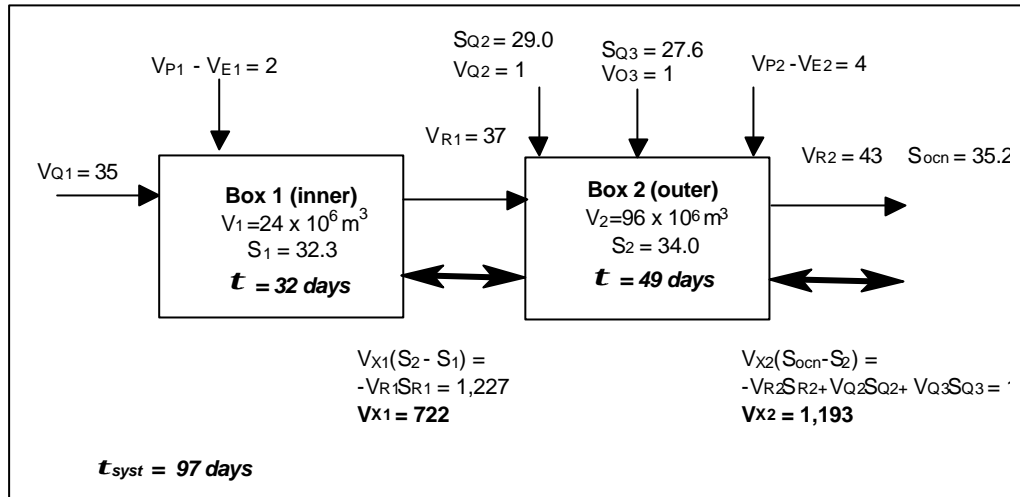


Figure 4.5. Water and salt budgets for Knysna Lagoon in the winter. Water and salt fluxes in  $10^3 \text{ m}^3 \text{ d}^{-1}$  and  $10^3 \text{ psu-m}^3 \text{ d}^{-1}$ , respectively.

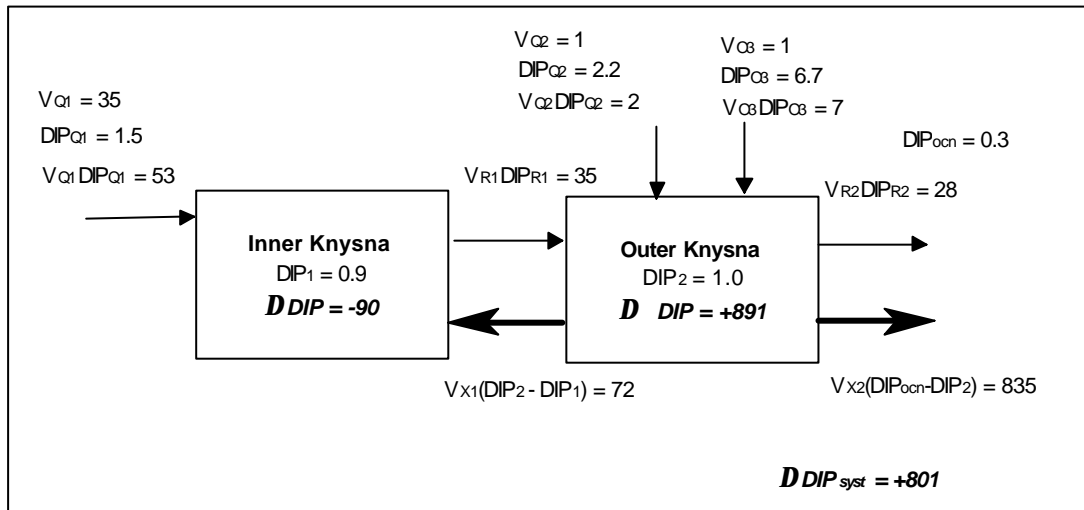


Figure 4.6. DIP budget for Knysna Lagoon in the winter. DIP flux in  $\text{mol d}^{-1}$ .

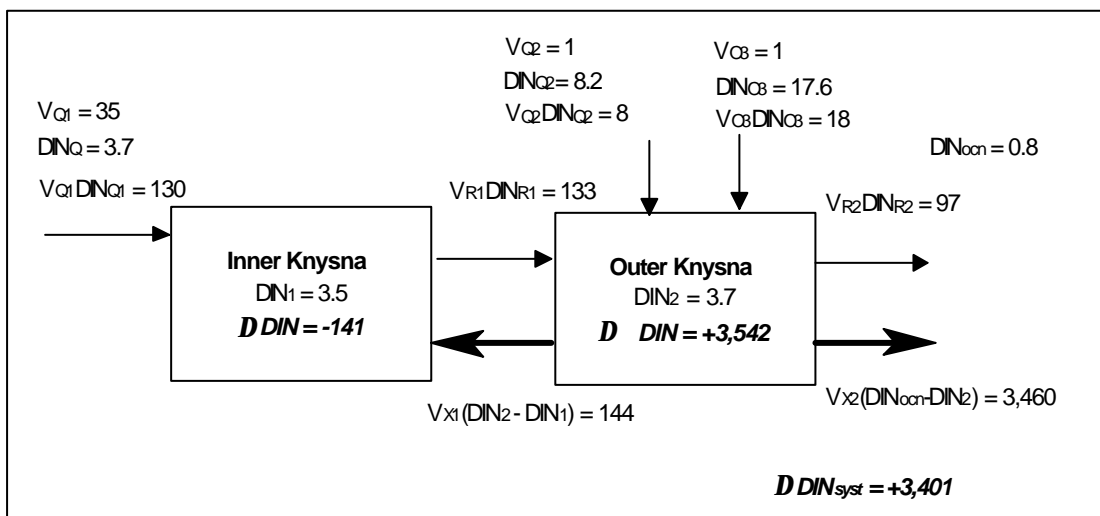


Figure 4.7. DIN budget for Knysna Lagoon in the winter. DIN flux in  $\text{mol d}^{-1}$ .

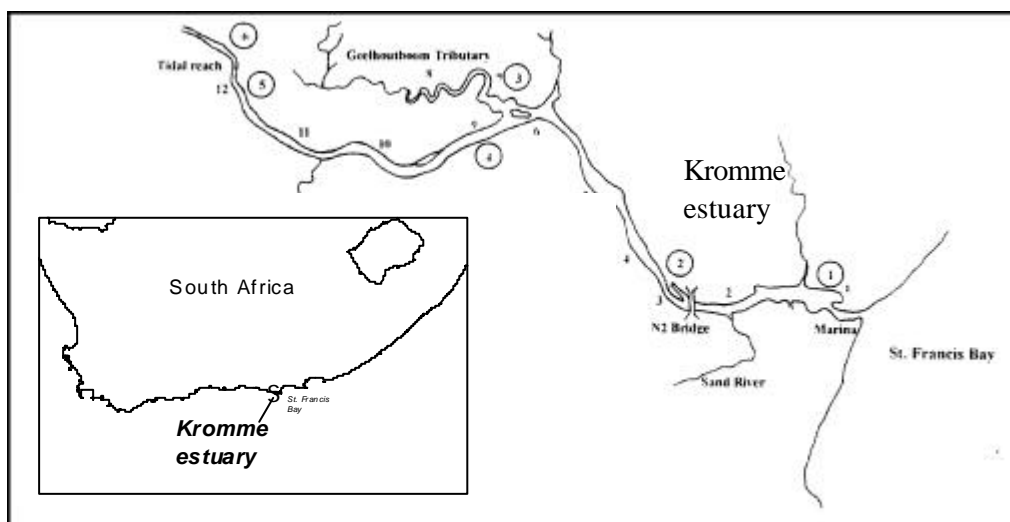
## 4.2 Kromme River Estuary, St Francis Bay, Eastern Cape

*Dan Baird*

### Study area description

The Kromme River estuary is a permanently open system, discharging through a constricted inlet into St Francis Bay, on the south-east coast of South Africa (34.15°S, 24.85°E; see Figure 4.8).

The 95 km long Kromme River originates in a coastal mountain range (the Tsitsikamma Mountains) and drains a catchment of about 936 km<sup>2</sup> (Reddering and Esterhuysen 1983), which is partly vegetated by fynbos vegetation and natural forest. Limited areas in the catchment are utilized for stock raising and grain cultivation. No industrial activities occur in the catchment or in the estuarine floodplain (Baird, Marais and Bate 1992), so that this estuary is considered to be one of the few relatively pristine systems in the country. Rainfall occurs throughout the year, with lowest precipitation during summer (December to February) (Bickerton and Pierce 1988) and peaks during the austral spring and autumn. Annual rainfall varies between 700 mm and 1,200 mm with a mean annual runoff (MAR) of about  $106 \times 10^6 \text{ m}^3$  (Reddering and Esterhuysen 1983). The high MAR is a consequence of the geomorphological characteristics of the catchment, i.e. high relief, rocky slopes and sparsely vegetated areas. Alterations to the river flow in the Kromme River as a result of two dams have severely reduced freshwater input into the estuary. The dams have the combined capacity of storing ca 133% of the MAR of the Kromme River catchment. The runoff into the estuary prior to the construction of the second dam in 1982 was about  $117 \times 10^6 \text{ m}^3 \text{ yr}^{-1}$  was subsequently drastically reduced to  $1 \times 10^6 \text{ m}^3 \text{ yr}^{-1}$ . Freshwater inflow into the Kromme estuary is low and irregular with a mean annual flow rate of about  $11 \times 10^3 \text{ m}^3 \text{ d}^{-1}$ . The flow rate during the rainy months increases to about  $13 \times 10^3 \text{ m}^3 \text{ d}^{-1}$  and decreases to about  $6 \times 10^3 \text{ m}^3 \text{ d}^{-1}$  during the dry months. The system is effectively freshwater-starved, with relatively low concentrations of DIN and DIP reaching the estuary from the catchment (Scharler *et al.* 1998), despite the fact that, in addition to the natural freshwater runoff, about  $2 \times 10^6 \text{ m}^3 \text{ yr}^{-1}$  are released from the upstream impoundments to compensate for evaporation in the estuary (Jezewski and Roberts 1986) (EMATEK (CSIR) 1994).



**Figure 4.8. Map and location of the Kromme River estuary.**

The estuary is about 14 km long, with a surface area of about 3 km<sup>2</sup> (Bickerton and Pierce 1988). The estuary is shallow (average depth at low water spring 3 m), with tidal amplitude of 2 m at the mouth. The tidal prism during spring tides is on average  $2 \times 10^6 \text{ m}^3$  and during neap tides about  $1 \times 10^6 \text{ m}^3$  in volume. The average flushing time at spring tide is about 27 h. The water temperature fluctuates

between 12°C in winter and 27°C in summer (Baird and Pereyra-Lago 1992). The salinity has rarely dropped below 30 psu since the completion of the dams in 1984. Salinity in the Kromme estuary ranges from 32.8 psu in the lower reaches to 31.1 psu in the upper reaches. Salinity stratification may occur in the upper and middle reaches of the estuary during low to moderate freshwater inflow (Scharler *et al.* 1998). The data on the salinity structures of the estuary, and on the concentrations of dissolved inorganic nutrients in both the freshwater reaches and the estuary considered in this study, were obtained from various theses and published information. Most of this information was collected during the years 1996-1999 (*cf.* Baird and Pereyra-Lago 1992, Scharler *et al.* 1998, Allanson and Baird 1999, Scharler 2000, Scharler and Baird 2000). The physical characteristics of the Kromme estuary are given in Table 4.2.

**Table 4.2. Physical characteristics of the Kromme River estuary.**

Characteristic	Value
Catchment (km <sup>2</sup> )	936
Length of estuary (km)	14
Surface area (km <sup>2</sup> )	3
Average depth (m)	3
Average system volume (10 <sup>6</sup> m <sup>3</sup> )	9

#### Water and salt balance

Two water and salt budgets are provided for this estuary: one each for the dry and wet seasons. Rainfall patterns are rather variable, but, in general, most of the precipitation occurs along the Eastern Cape coastal region during the months March to June, and again from August to November. Data used are given in Table 4.3.

The system is fairly pristine with no wastewater or industrial discharges into the river and estuary. The evaporation rate exceeds precipitation during the austral summer months, when hypersaline conditions may occur from time to time in the upper reaches of the estuary. Precipitation barely exceeds evaporation on an annual scale.

The results of the water and salt balance are illustrated in Figure 4.9. The residual water ( $V_R$ ) and salt fluxes ( $V_R S_R$ ), as well as the exchange flows of salt water ( $V_X$ ) and salinity [ $V_X(S_{ocn} - S_{syst})$ ] are highest during the wet season. The water exchange time [ $t$ ] of water in the system ranges from 66 days during the wet season to 130 days in the dry season. The long water exchange time during the dry periods is probably due to the low rate of fresh water inflows and low precipitation. The major input and output terms show that the residual flows are from the system.

**Table 4.3. Variations of physical properties, water budgets and water exchange times in the Kromme River estuary and adjacent St. Francis Bay.**

Season	Freshwater input (10 <sup>3</sup> m <sup>3</sup> d <sup>-1</sup> )			Residual flow (10 <sup>3</sup> m <sup>3</sup> d <sup>-1</sup> )	River salinity (psu)	Ocean salinity (psu)	Lagoon salinity (psu)	Exchange volume (10 <sup>3</sup> m <sup>3</sup> d <sup>-1</sup> )	$\delta$ (day)
	$V_Q$	$V_P$	$V_E$						
Dry	6	5	6	5	0.6	35.3	32.7	64	130
Wet	13	9	6	16	0.6	35.3	31.0	121	66
<i>Annual Mean</i>	11	8	6	12	0.6	35.3	31.6	102	87

### Budgets of nonconservative materials

#### *DIP balance*

Water flux data from Table 4.3 and Figure 4.9 were used to construct the DIP budget under well-mixed conditions. The mean annual nonconservative flux (**DDIP**) of +56 mol d<sup>-1</sup>, exceeds the river input of 7 mol d<sup>-1</sup>, which suggests that the estuary behaves as a source for DIP (see Table 4.4) and Figure 4.10.

#### *DIN balance*

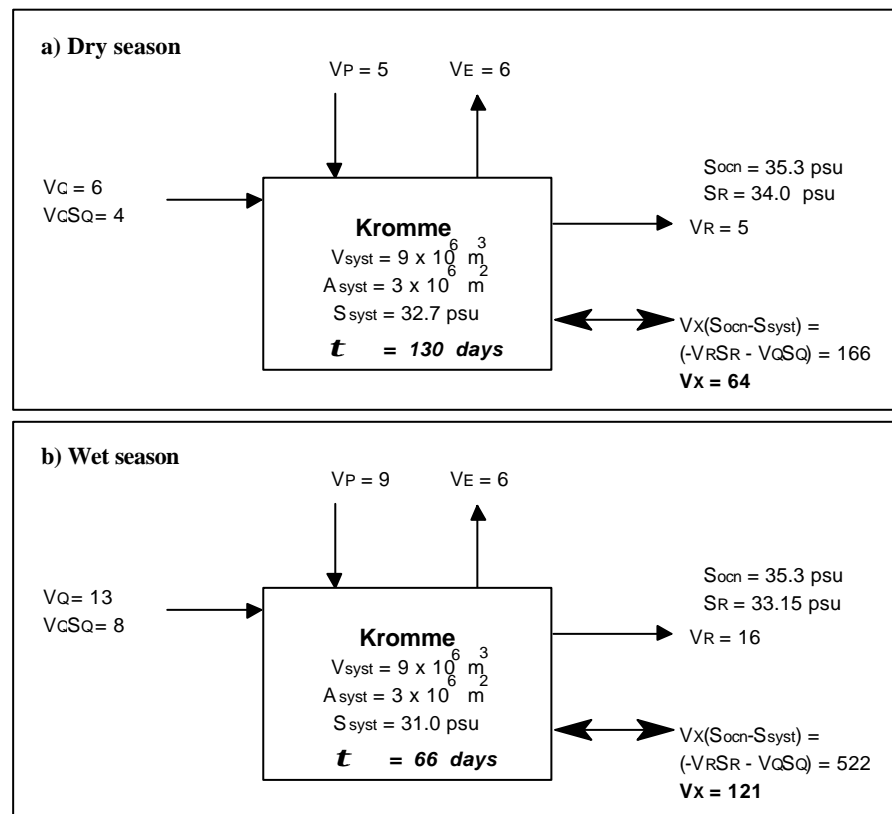
Budgeting results show that the estuary is also a net source of DIN on an annually averaged basis (see Table 4.4 and Figure 4.11).

**Table 4.4. Nonconservative fluxes of C, N and P in the Kromme River estuary.**

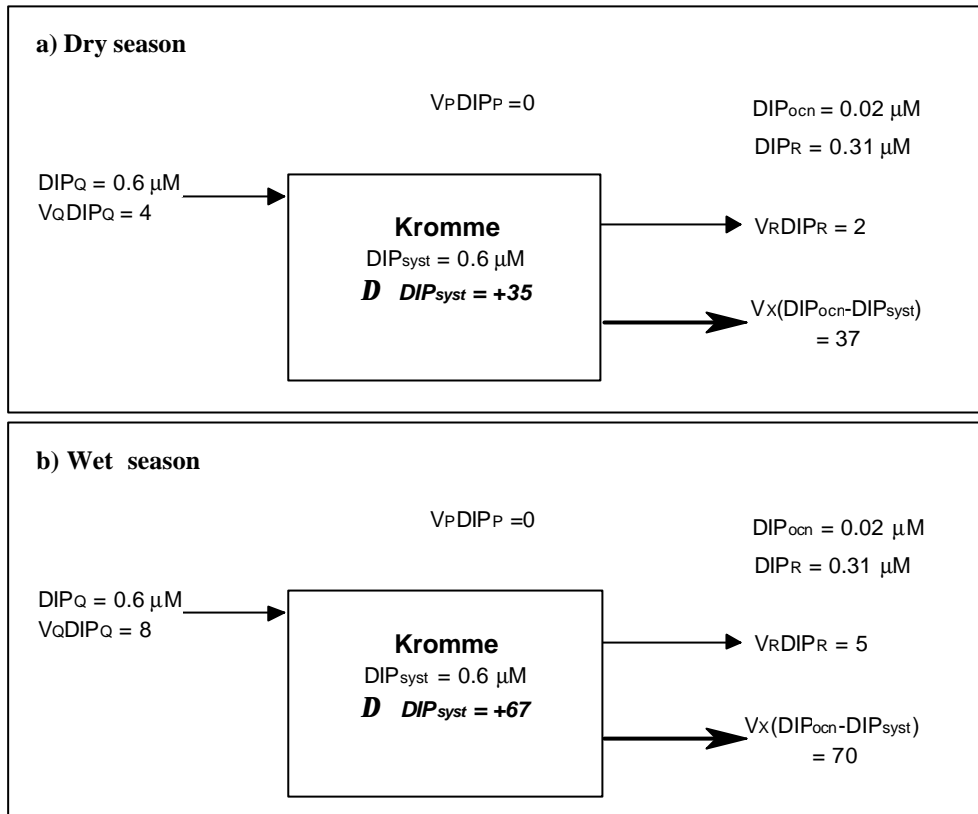
Time	<b>DDIP</b> (mol d <sup>-1</sup> )	<b>DDIN</b> (mol d <sup>-1</sup> )	( <i>p-r</i> ) (mol d <sup>-1</sup> )	( <i>nfix-denit</i> ) (mol d <sup>-1</sup> )	( <i>p-r</i> ) (mmol m <sup>-2</sup> d <sup>-1</sup> )	( <i>nfix-denit</i> ) (mmol m <sup>-2</sup> d <sup>-1</sup> )
Dry	+35	+817	-3,710	+257	-1	+0.1
Wet	+67	+1,552	-7,102	+480	-2	+0.2
<b>Annual mean</b>	<b>+56</b>	<b>+1,307</b>	<b>-5,971</b>	<b>+406</b>	<b>-2</b>	<b>+0.2</b>

#### *Stoichiometric calculations of aspects of net system metabolism*

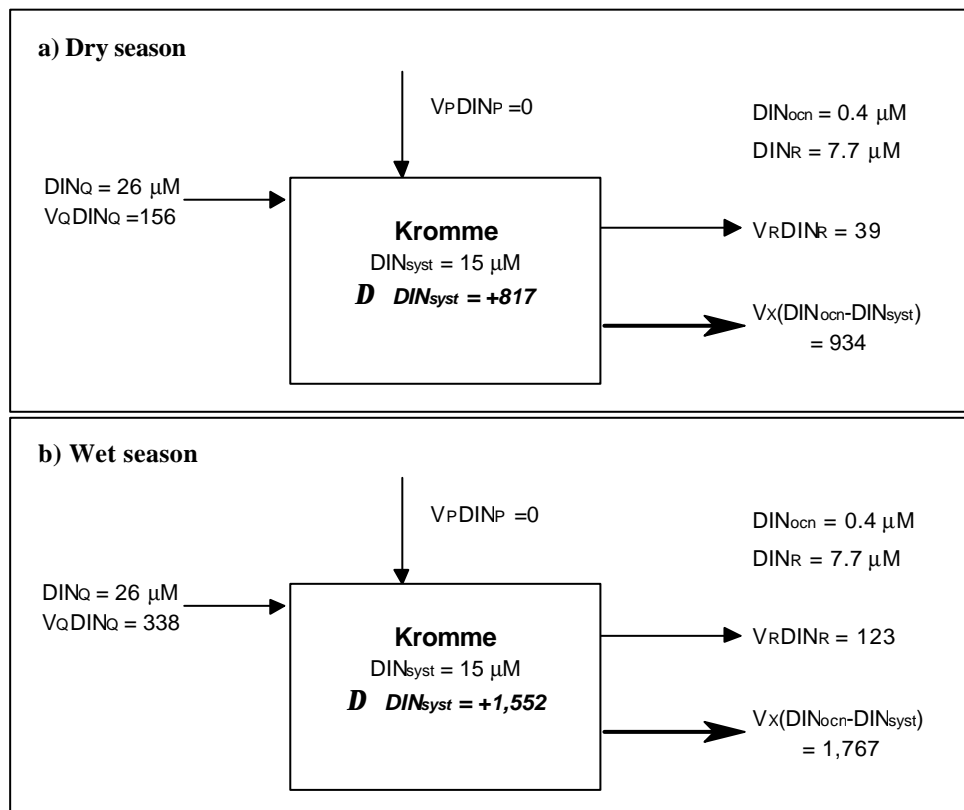
The net ecosystem metabolism (*p-r*), estimated from Redfield stoichiometric ratios and **DDIP** is -2 mmol m<sup>-2</sup> d<sup>-1</sup>. These negative values indicate that the estuary is net heterotrophic. Nitrogen fixation minus denitrification (*nfix-denit*), calculated as the difference between the observed and expected **DDIN**, amounts to +0.1 mmole m<sup>-2</sup> d<sup>-1</sup>. These results show that the estuary is, on annual average, a net nitrogen fixing system.



**Figure 4.9. Water and salt budgets for Kromme River estuary in the dry (a) and wet (b) seasons. Water flux in 10<sup>3</sup> m<sup>3</sup> d<sup>-1</sup> and salt flux in 10<sup>3</sup> psu·m<sup>3</sup> d<sup>-1</sup>.**



**Figure 4.10. DIP budget for Kromme River estuary in the dry (a) and wet (b) seasons.**  
 Flux in  $\text{mol d}^{-1}$ .



**Figure 4.11. DIN budget for Kromme River estuary in the dry (a) and wet (b) seasons.**  
 Flux in  $\text{mol d}^{-1}$ .

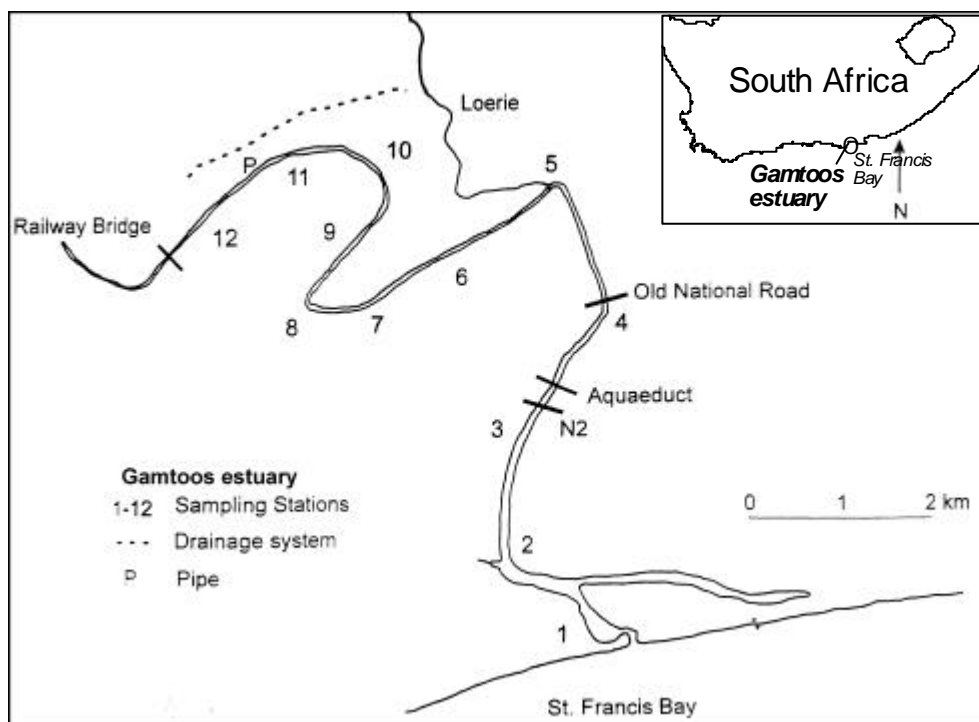
### 4.3 Gamtoos River Estuary, St. Francis Bay, Eastern Cape

*Dan Baird*

#### Study area description

The Gamtoos River estuary (33.97°S, 25.07°E) discharges through a permanently open mouth into St. Francis Bay (Indian Ocean) in Eastern Cape province on the south-east coast of South Africa. The catchment area of the Gamtoos River system is about 34,400 km<sup>2</sup> (Heydorn and Tinley 1980) and features a bimodal rainfall pattern typical of the southeast coastal region of the country (Heydorn and Tinley 1981) with a mean annual runoff of 485x10<sup>6</sup> m<sup>3</sup> (Noble and Hemens 1978). The mean annual rainfall is about 400 mm, and the mean annual evaporation 1,400 mm. Freshwater inflow into the Gamtoos River estuary range between 35x10<sup>3</sup> m<sup>3</sup> d<sup>-1</sup> during base flow conditions (dry season) to 138x10<sup>3</sup> m<sup>3</sup> d<sup>-1</sup> during the rainy season. The average annual discharge rate is about 86x10<sup>3</sup> m<sup>3</sup> d<sup>-1</sup> (Scharler and Baird 2000).

Major agricultural activities (mainly vegetable crops, and to a lesser extent stock farming) occur all along the river as well as on the estuarine flood plain. Natural fringing vegetation is absent in most parts along the estuary and agricultural fields reach up to the steep banks of the estuary. Crop-growing involves the extensive application of fertilizers and sprinkle irrigation throughout the year. A large part of the cultivated lands is drained by a complex drainage system which discharges at a point about 19 m from the mouth. The drainage system drains an area of about 0.5 km<sup>2</sup> to a depth of 1m during non-flood conditions (Pearce and Schumann 1997). The volume of the water entering the estuary via the pipe ranges between 0.8 and 5 litres sec<sup>-1</sup>, with an average point-source discharge of about 3 litres sec<sup>-1</sup>, or about 0.3 m<sup>3</sup> d<sup>-1</sup>. The estuarine waters are further enriched through groundwater seepage from the cultivated fields at a rate of about 0.3x10<sup>3</sup> m<sup>3</sup> d<sup>-1</sup> (Pearce and Schumann 1997, Scharler *et al.* 2001). Apart from the agricultural activities, no industry or human settlements occurs along the river and estuary (Heydorn and Grindley 1981).



**Figure 4.12. Map and location of the Gamtoos River estuary.**

The mean salinity (integrated over depth) gradient within the estuary ranges from 30.6 psu at the mouth to 0.6 psu at the head of the estuary (19.5 km from the mouth). The mean annual axial salinity of the system is 16.7, 18.5 in the dry season, and 14.6 in the wet season. The water temperature varies between 12°C in winter to 27°C in summer. Salinity and temperature stratification occur from time to time in the middle reaches of the estuary (Scharler *et al.* 2001). The physical characteristics of the Gamtoos River estuary are summarized in Table 4.5.

**Table 4.5. Physical characteristics of the Gamtoos River estuary.**

Characteristic	Value
Catchment (km <sup>2</sup> )	34,400
Length of estuary (km)	20
Surface area (km <sup>2</sup> )	2
Average depth (m)	2
Average system volume (10 <sup>6</sup> m <sup>3</sup> )	4

#### Water and salt balance

Water and salt budgets are provided for the wet and dry seasons, respectively (Figure 4.13). The residual water [ $V_R$ ] and salt fluxes [ $V_R S_R$ ] are negative (i.e., oceanward flow), so salt is imported to maintain the salinity of the system. The water exchange time in the estuary is 49 days in the dry season and 14 days in the wet season.

#### Budgets of non-conservative materials

##### *DIP balance*

Results show (Table 4.7 and Figure 4.14) a nonconservative DIP flux of -32 mol d<sup>-1</sup> or -0.02 mmol m<sup>-2</sup> d<sup>-1</sup>. It would appear that the system acts as a sink of DIP.

**Table 4.6. Variations of physical properties, water budgets and water exchange times in the Gamtoos River estuary and adjacent St. Francis Bay.**

Season	Freshwater input (10 <sup>3</sup> m <sup>3</sup> d <sup>-1</sup> )				Residual flow (10 <sup>3</sup> m <sup>3</sup> d <sup>-1</sup> )	River salinity (psu)	Ocean salinity (psu)	Lagoon salinity (psu)	Exchange volume (10 <sup>3</sup> m <sup>3</sup> d <sup>-1</sup> )	t (days)
	V <sub>Q</sub>	V <sub>O</sub>	V <sub>P</sub>	V <sub>E</sub>						
Dry	35	0.3	2	-5	32	0.6	35.3	18.5	50	49
Wet	138	0.3	3	-5	136	0.6	35.3	14.6	160	14
<b>Annual mean</b>	<b>104</b>	<b>0.3</b>	<b>3</b>	<b>-5</b>	<b>101</b>	<b>0.6</b>	<b>35.3</b>	<b>15.9</b>	<b>123</b>	<b>26</b>

##### *DIN Balance*

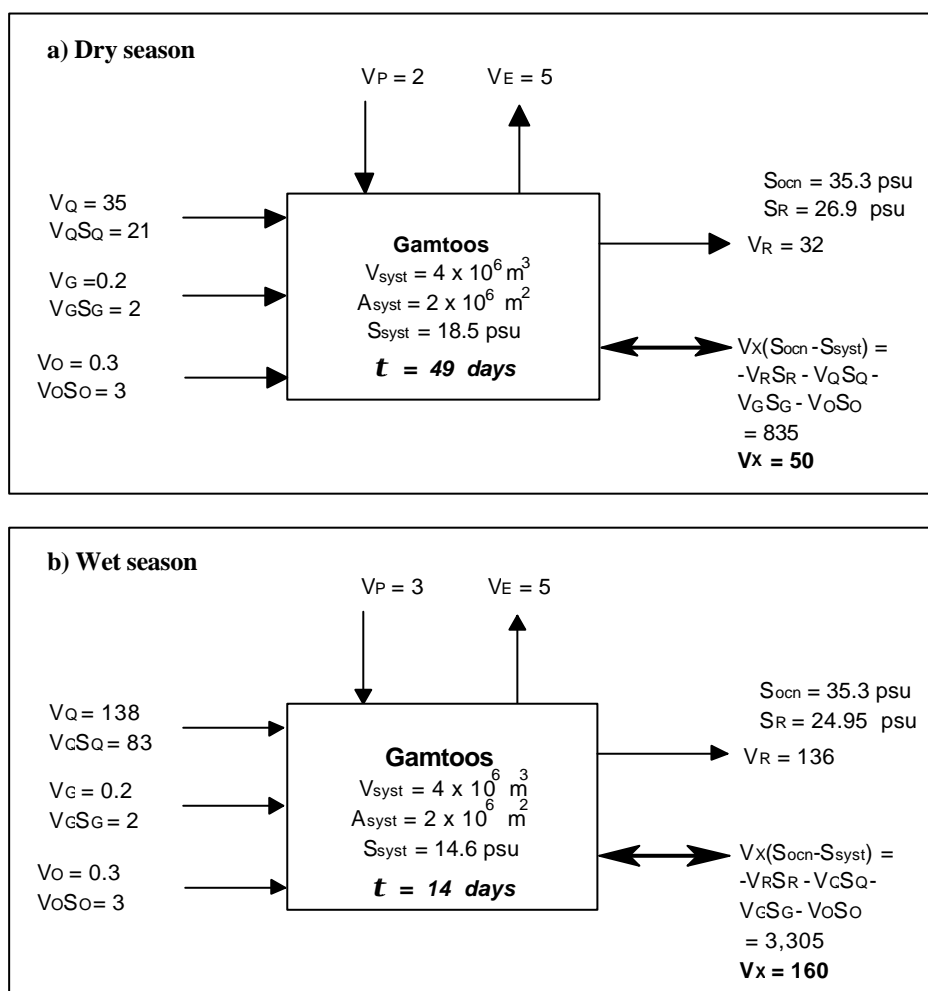
From the results, the Gamtoos River estuary is a net source of DIN (See Table 4.7 and Figure 4.15).

#### *Stoichiometric calculations of aspects of net system metabolism*

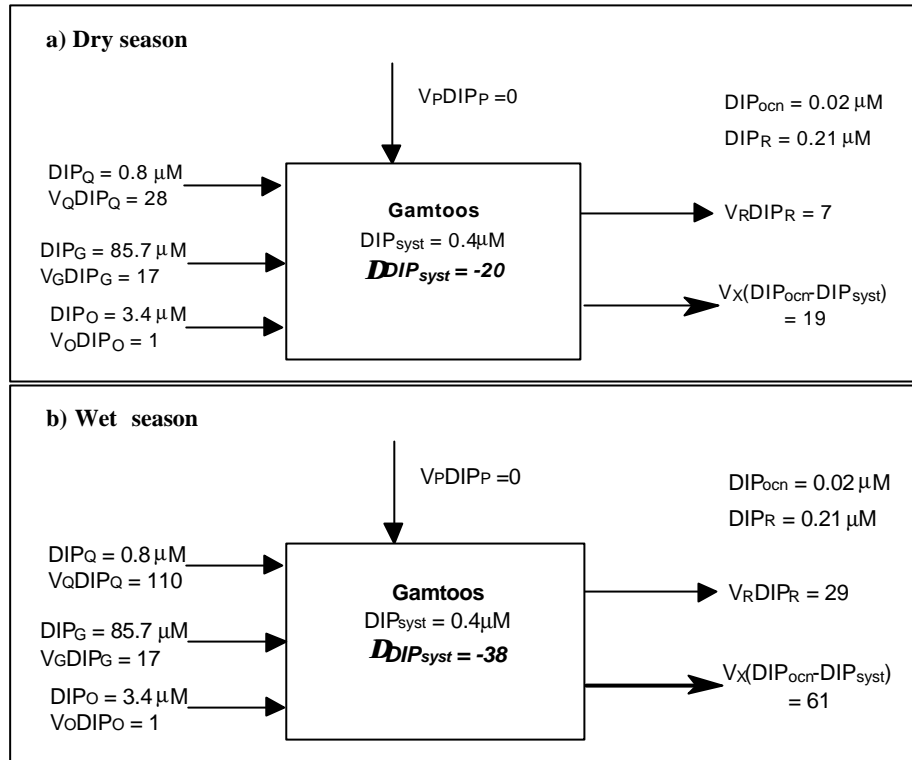
Table 4.7 presents the net system metabolism of the Gamtoos River estuary. It appears that the system is net autotrophic; ( $p-r$ ) = +2 mmol C m<sup>-2</sup> d<sup>-1</sup> and net nitrogen fixing; ( $nfix-denit$ ) = +1 mmol N m<sup>-2</sup> d<sup>-1</sup>.

**Table 4.7. Nonconservative fluxes of C, N and P in the Gamtoos River estuary.**

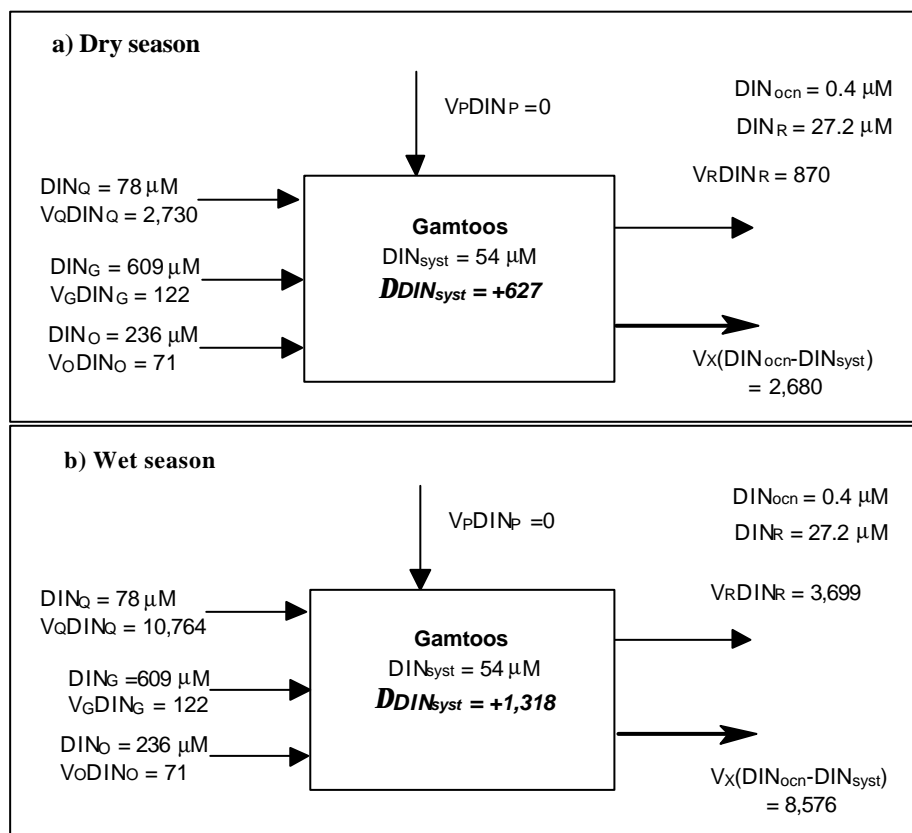
Time	<u>DDIP</u>		<u>DDIN</u>		<u>(p-r)</u>	<u>(nfix-denit)</u>
	(mol d <sup>-1</sup> )	(mmol m <sup>-2</sup> d <sup>-1</sup> )	(mol d <sup>-1</sup> )	(mmol m <sup>-2</sup> d <sup>-1</sup> )	(mmol m <sup>-2</sup> d <sup>-1</sup> )	(mmol m <sup>-2</sup> d <sup>-1</sup> )
Dry	-20	-0.01	+627	+0.3	+1	+0.5
Wet	-38	-0.02	+1,318	+0.7	+2	+1
Annual	<b>-32</b>	<b>-0.02</b>	<b>+1,088</b>	<b>+0.5</b>	<b>+2</b>	<b>+1</b>



**Figure 4.13. Water and salt budgets for Gamtoos River estuary in the dry (a) and wet (b) seasons. Water flux in  $10^3 \text{ m}^3 \text{ d}^{-1}$  and salt flux in  $10^3 \text{ psu} \cdot \text{m}^3 \text{ d}^{-1}$ .**



**Figure 4.14. DIP budget for the Gamtoos River estuary in the dry (a) and wet (b) seasons.**  
Flux in  $\text{mol d}^{-1}$ .



**Figure 4.15 DIN budget for the Gamtoos River estuary in the dry (a) and wet (b) seasons.**  
Flux in  $\text{mol d}^{-1}$ .

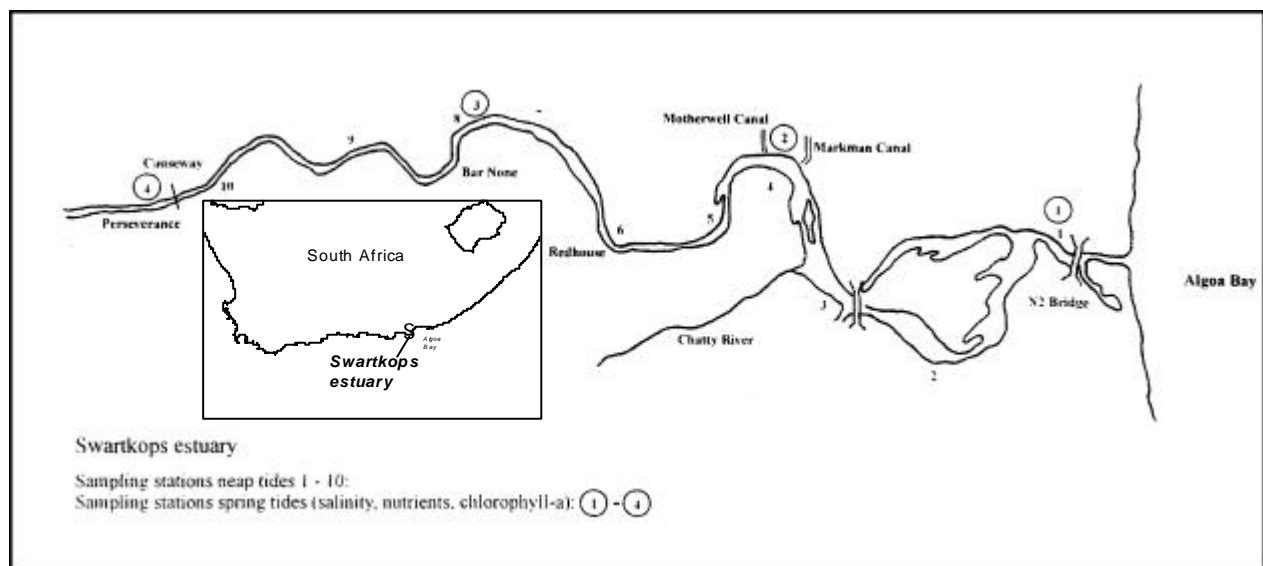
#### 4.4 Swartkops River Estuary, Algoa Bay, Eastern Cape

*Dan Baird*

##### Study area description

The Swartkops River estuary (32.87°S, 25.63°E; Figure 4.16) is located in Eastern Cape province on the south-east coast of South Africa and opens into Algoa Bay, in the Indian Ocean, about 15 km from the harbour of the city of Port Elizabeth (Baird *et al.* 1986). The Swartkops River and its main tributary (the Elands River) originate in the Great Winterhoek Mountains and meander for about 155 km to the estuary. The total catchment of both rivers is about 1,400 km<sup>2</sup>. The mean annual rainfall (MAR) is about 636 mm (range 500 mm–1,000 mm), or about  $84 \times 10^6$  m<sup>3</sup>; about 17% of the MAR is retained by impoundments in the catchment (Reddering and Esterhuysen 1981). Freshwater inflow into the estuary at spring tides was measured at  $130 \times 10^3$  m<sup>3</sup> d<sup>-1</sup> (Scharler *et al.* 1998).

There are numerous industrial and agricultural activities in the catchment and on the estuarine floodplain. These include sand and clay mining, sewage treatment works, saltworks, a tannery, a large industrial area discharging effluents in the river about 5 km upstream from the tidal reach, a large stormwater canal entering the estuary and draining a large urban settlement, etc. (Baird *et al.* 1986). There are also informal and formal settlements along the banks of the estuary, which contribute to the wastewater inputs into the system. The total human population in the Swartkops River catchment and floodplain is estimated to be approximately 1 million (Horenz 1987).



**Figure 4.16. Map and location of the Swartkops River estuary.**

The estuary is about 15 km long and has a total surface area of 4 km<sup>2</sup>. The tidal prism during spring tides is on average  $3 \times 10^6$  m<sup>3</sup> and the average flushing time during spring tides about 22 h. The estuary is shallow, turbid and well-mixed during periods of low river flow (Winter and Baird 1991). During floods, the estuary may exhibit highly stratified waters (Scharler *et al.* 1998). It attracts thousands of migrating Palearctic birds (Martin and Baird 1987) and is a popular recreational area for boating, angling and swimming (Lord and Thompson 1987). The estuary exhibits a salinity gradient along its longitudinal axis throughout the year, but this gradient may be reversed at times due to its high evaporative water requirement (Jezewski and Roberts 1986). The salinity ranges from 35 psu at the mouth to 10 psu at the head, while the temperature fluctuates between 28°C in summer to 13.5°C in winter (Baird and Ulanowicz 1993).

The Swartkops River estuary represents an impacted system, mainly through industrial effluent inputs, and to a lesser degree from stormwater pollution. Nutrient inputs are substantial, but there are no signs of eutrophication (Lord and Thompson 1987). Despite these inputs and the urbanization of the catchment area and floodplain, the system nevertheless abounds with productive and diverse plant and animal communities (Emmerson 1985; Baird and Ulanowicz 1993). This system is probably one of the best studied in the country because of its importance as an ecological and recreational asset to Port Elizabeth and its proximity to the University of Port Elizabeth. The physical characteristics of the Swartkops River estuary are summarized in Table 4.8.

**Table 4.8. Physical characteristics of the Swartkops River estuary.**

Characteristic	Value
Catchment (km <sup>2</sup> )	1,400
Length of estuary (km)	16
Surface area (km <sup>2</sup> )	4
Average depth (m)	3
Average system volume (10 <sup>6</sup> m <sup>3</sup> )	12

#### Water and salt budgets

Water and salt budgets were constructed representing typically dry and wet seasons. Budget data are given in Table 4.9 and illustrated in Figure 4.17. The water exchange time fluctuates between 22 days during the rainy season, to 45 days in the dry period. The annual average for water exchange time is about 34 days.

**Table 4.9. Variations of physical properties, water budgets and water exchange times in the Swartkops River estuary and adjacent Algoa Bay.**

Season	Freshwater input (10 <sup>3</sup> m <sup>3</sup> d <sup>-1</sup> )				Residual flow (10 <sup>3</sup> m <sup>3</sup> d <sup>-1</sup> )	River salinity (psu)	Ocean salinity (psu)	System salinity (psu)	Exchange volume (10 <sup>3</sup> m <sup>3</sup> d <sup>-1</sup> )	t (days)
Dry	71	25	5	35	66	5	35.3	27.3	198	45
Wet	164	25	9	35	163	5	35.3	25.0	385	22
<b>Annual mean</b>	118	25	7	35	115	5	35.3	26.2	292	34

#### Budgets of nonconservative materials

##### *DIP balance*

The DIP balance is given in Table 4.10 and Figure 4.18. The major input of DIP, in terms of concentration levels, is of anthropogenic origin from the informal settlements in the flood plain and stormwater inflows. The budgeting results show that the system acts as a sink for DIP.

**Table 4.10. Nonconservative fluxes of C,N and P in the Swartkops River estuary.**

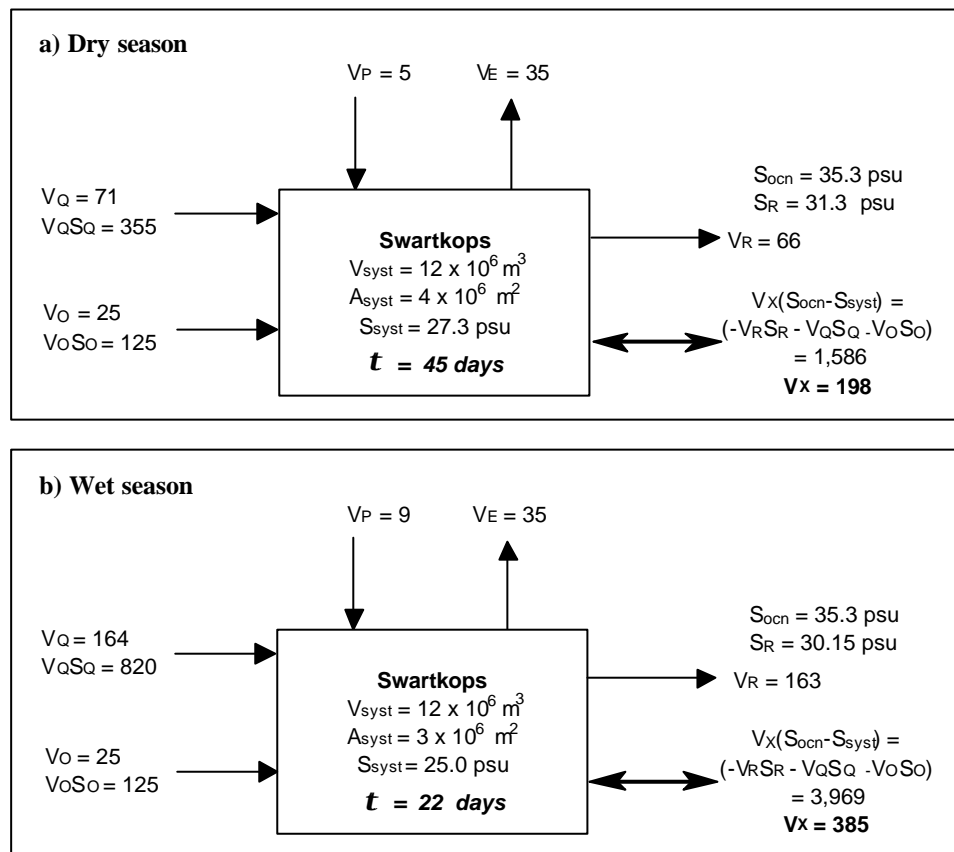
Season	<b>DDIP</b> (mol d <sup>-1</sup> )	<b>DDIN</b> (10 <sup>3</sup> mol d <sup>-1</sup> )	(p-r) (10 <sup>3</sup> mol d <sup>-1</sup> )	(nfix-denit) (10 <sup>3</sup> mol d <sup>-1</sup> )	(p-r) (mmol m <sup>-2</sup> d <sup>-1</sup> )	(nfix-denit) (mmol m <sup>-2</sup> d <sup>-1</sup> )
Dry	-649	-112	+69	-101	+17	-25
Wet	-719	-110	+76	-98	+19	-25
<b>Annual mean</b>	<b>-684</b>	<b>-111</b>	<b>+73</b>	<b>-100</b>	<b>+18</b>	<b>-25</b>

### DIN balance

The DIN budget (Table 4.10 and Figure 4.19) shows the Swartkops River estuary is a net sink for DIN, as for DIP. The principal load of DIN is by means of the wastewater flux ( $V_O \text{DIN}_O$ ).

### Stoichiometric calculations of aspects of net system metabolism

The positive net ecosystem metabolism ( $p-r$ ) values of  $+73,776 \text{ mol d}^{-1}$  (or  $+18 \text{ mmol m}^2 \text{ d}^{-1}$ ) indicate that the system is net autotrophic (see Table 4.10). Nitrogen fixing minus denitrification ( $nfix-denit$ ) results in a negative value of  $-100 \times 10^3 \text{ mol d}^{-1}$  (or  $-25 \text{ mmol m}^2 \text{ d}^{-1}$ ) indicating the Swartkops to be a net denitrifying system (see Table 4.10).



**Figure 4.17. Water and salt budgets for the Swartkops River estuary in the dry (a) and wet (b) seasons.** Water flux in  $10^3 \text{ m}^3 \text{ d}^{-1}$  and salt flux in  $10^3 \text{ psu-m}^3 \text{ d}^{-1}$ .

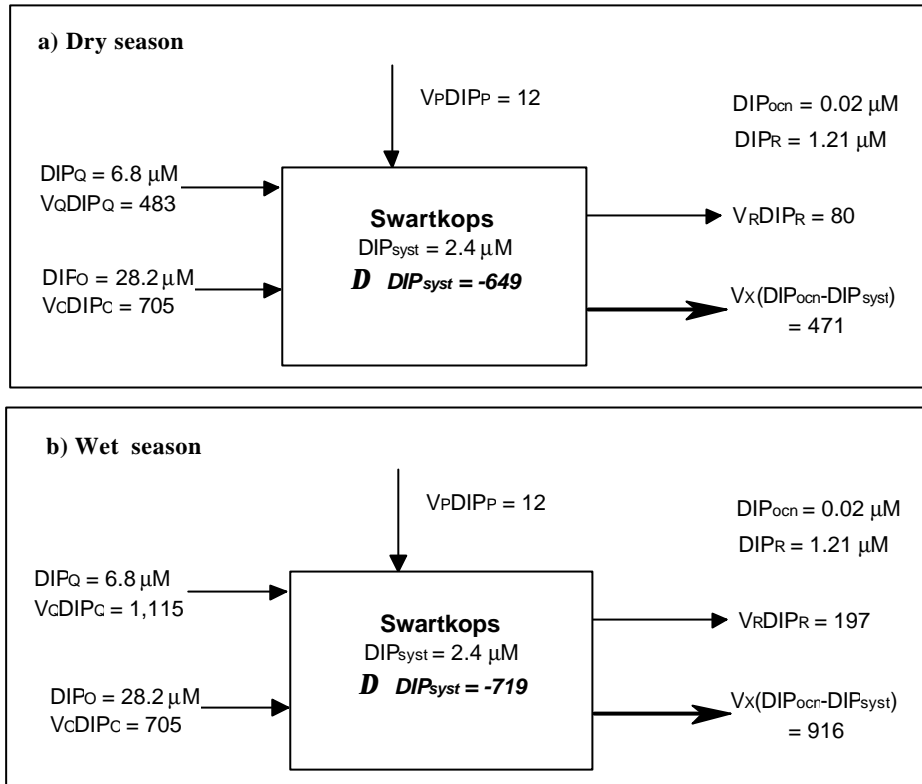


Figure 4.18. DIP budget for Swartkops estuary in the dry (a) and wet (b) seasons. Flux in  $\text{mol d}^{-1}$ .

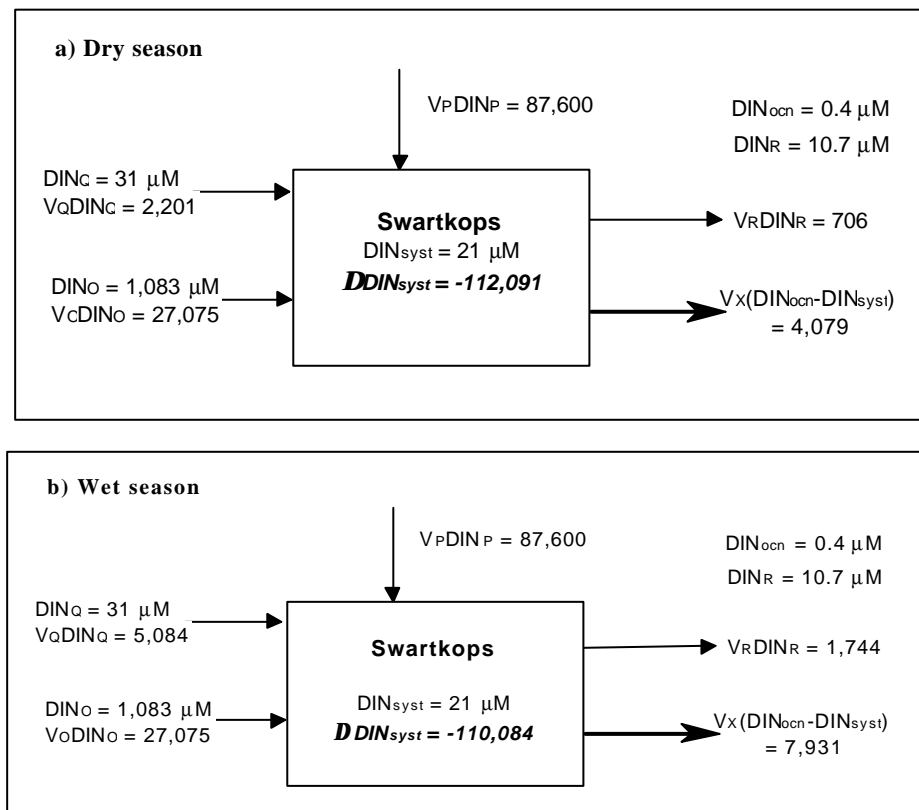


Figure 4.19. DIN budget for the Swartkops River estuary in the dry (a) and wet (b) seasons. Flux in  $\text{mol d}^{-1}$ .

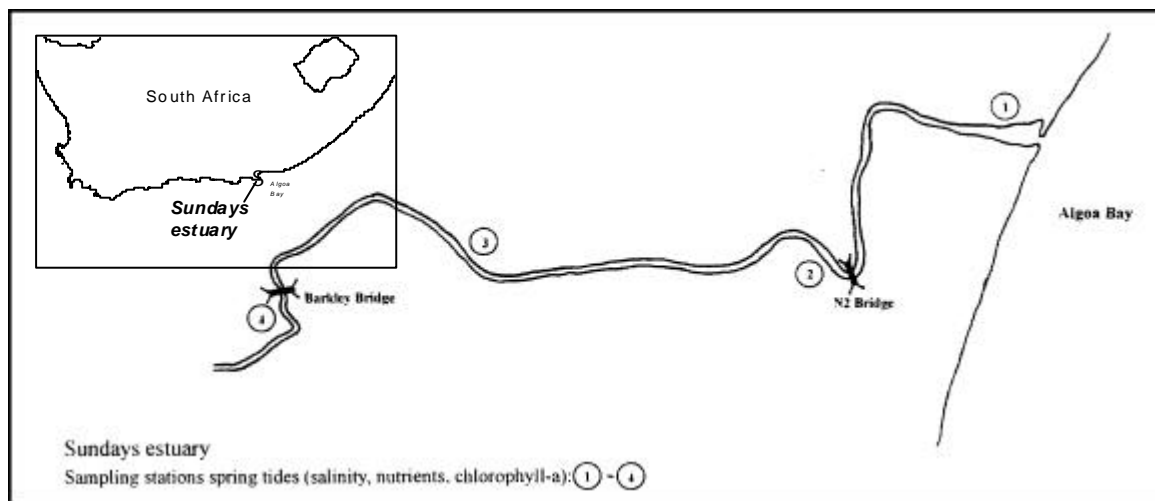
## 4.5 Sundays River Estuary, Algoa Bay, Eastern Cape

*Dan Baird*

### Study area description

The Sundays River estuary (33.72°S, 25.42°E) is about 20 km long (MacKay and Schumann 1990) and discharges through a permanently open mouth into Algoa Bay (Indian Ocean) about 30 km north-east of the city of Port Elizabeth, South Africa (Figure 4.20). It receives freshwater enriched by residues of fertilizers and pesticides used in citrus orchards in the catchment.

The Sundays River has a catchment area of 22,000 km<sup>2</sup>. Sheep farming and citrus cultivation are the main activities in the catchment and along the entire river, which is about 310 km in length. The mean annual precipitation in the region is about 320 mm, categorizing the catchment as semi-arid. The mean annual runoff (MAR) is about  $186 \times 10^6 \text{ m}^3$  while the two dams in the catchment retain collectively about 140% of the MAR (Reddering and Esterhuysen 1981). The river receives water from one of the largest rivers in South Africa, the Orange River, through an inter-basin water transfer scheme to provide irrigation water for the extensive citrus farming industry in the Sundays River catchment area. Because of the inter-basin water transfer scheme, the Sundays River estuary has a rather regular pattern of freshwater input, leading to a dilution of the natural saline regime of the estuary (Emmerson 1989). Recreation (sailing, fishing) is the main activity on the estuary, with limited farming practised in the flood plain. There are no industrial activities, and very low human habitation along the river and estuary. It is thus a relatively “pristine” estuary, although elevated levels of N and P have been measured from time to time due to agricultural practices within the catchment (Emmerson 1989).



**Figure 4.20. Map of Sundays River estuary, Algoa Bay.**

The Sundays River estuary receives freshwater at an annual mean inflow rate of about  $59 \times 10^6 \text{ m}^3 \text{ yr}^{-1}$  or  $162 \times 10^3 \text{ m}^3 \text{ d}^{-1}$ . Rates of freshwater inflow are available for most months of the year (Scharler *et al.* 1998), but the estuary receives about  $237 \times 10^3 \text{ m}^3 \text{ d}^{-1}$  during the rainy season and  $86 \times 10^3 \text{ m}^3 \text{ d}^{-1}$  during the dry season. The salinity range in this estuary from 28 psu in the lower reaches to 5.3 psu at the head. The salinity structure does not vary drastically between summer and winter within the various reaches of the estuary. The mean annual axial salinity is 16.4 psu, varying from 15.1 to 17.6 psu during the wet and dry seasons, respectively. Stratification of the water column occurs rarely, so that the water in the system is well-mixed throughout the year. Temperatures fluctuate from 17°C in winter to 24°C in summer (Scharler *et al.* 1998). The physical characteristics of the Sundays River estuary are summarized in Table 4.11.

**Table 4.11. Physical characteristics of the Sundays River estuary.**

Characteristic	Value
Catchment (km <sup>2</sup> )	22,000
Length of estuary (km)	20
Surface area (km <sup>2</sup> )	3
Average depth (m)	4
Average system volume (10 <sup>6</sup> m <sup>3</sup> )	12

Water and salt balance

Water and salt fluxes for the Sundays River estuary are illustrated in Figure 4.21, and some results are also given in Table 4.12. The water exchange time during the rainy season is about 23 days, 61 days during the dry season, and average at about 42 days over a year.

**Table 4.12. Variations of physical properties, water budgets and water exchange times in the Sundays River estuary and adjacent Algoa Bay.**

Season	Freshwater input (10 <sup>3</sup> m <sup>3</sup> d <sup>-1</sup> )			Residual flow (10 <sup>3</sup> m <sup>3</sup> d <sup>-1</sup> )	River salinity (psu)	Ocean salinity (psu)	System salinity (psu)	Mixing volume (10 <sup>3</sup> m <sup>3</sup> d <sup>-1</sup> )	$\hat{\theta}$ (day)
	V <sub>Q</sub>	V <sub>P</sub>	V <sub>E</sub>						
Dry	86	2	8	80	0.5	35.3	17.6	117	61
Wet	237	2	8	231	0.5	35.3	15.1	282	23
<b>Annual mean</b>	<b>162</b>	<b>2</b>	<b>8</b>	<b>156</b>	<b>0.5</b>	<b>35.3</b>	<b>16.4</b>	<b>200</b>	<b>42</b>

Budgets of nonconservative materials

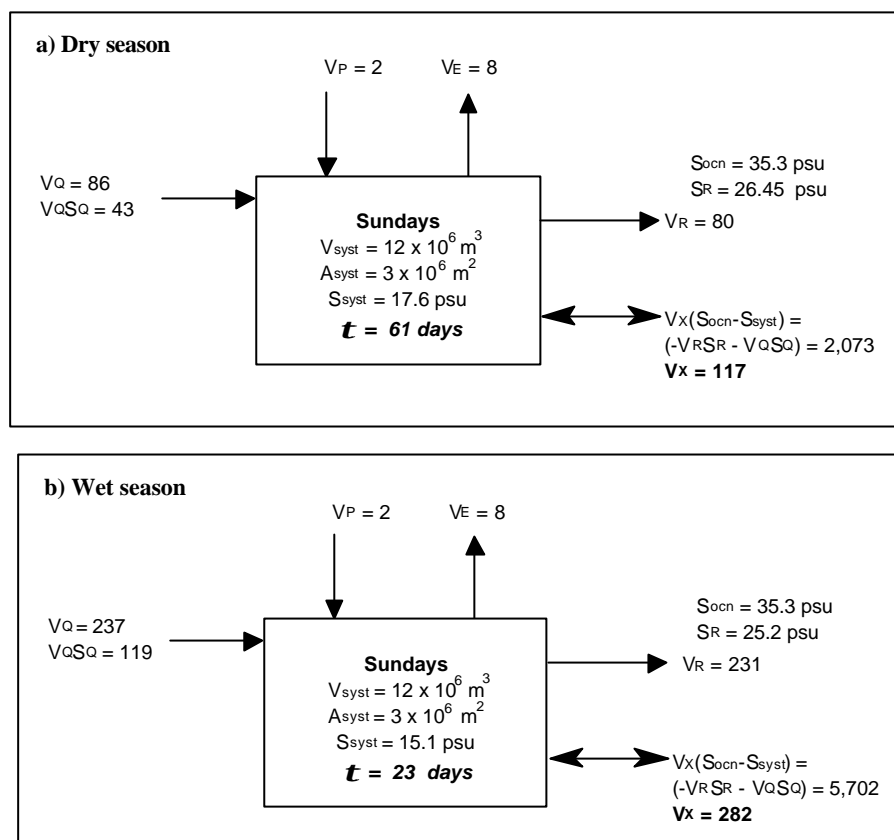
The nonconservative nutrient budgets indicate that the system is a source of DIP (**DDIP** = +39 mol d<sup>-1</sup>), but a net sink of DIN at a rate of -1,858 mol d<sup>-1</sup> (see Table 4.13 and Figures 4.22 and 4.23).

Stoichiometric calculations of aspects of net system metabolism

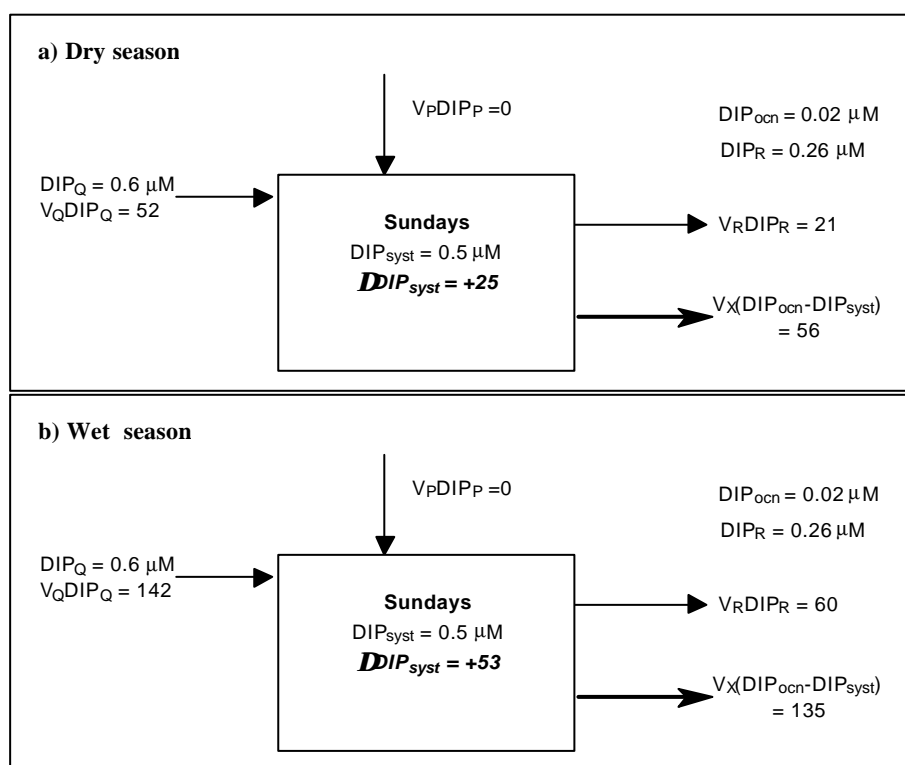
Net ecosystem metabolism (*p-r*) estimated from Redfield stoichiometrics is -4,134 mol d<sup>-1</sup>, or -1 mmol m<sup>-2</sup> d<sup>-1</sup>. Results also show that the difference between nitrogen fixation and denitrification (*nfix-denit*) is -2,482 mol d<sup>-1</sup> (or -0.9 mmol m<sup>-2</sup> d<sup>-1</sup>). The net system metabolism is thus heterotrophic, and it is also net denitrifying (see Table 4.13).

**Table 4.13. Nonconservative fluxes of C, N and P in the Sundays River estuary.**

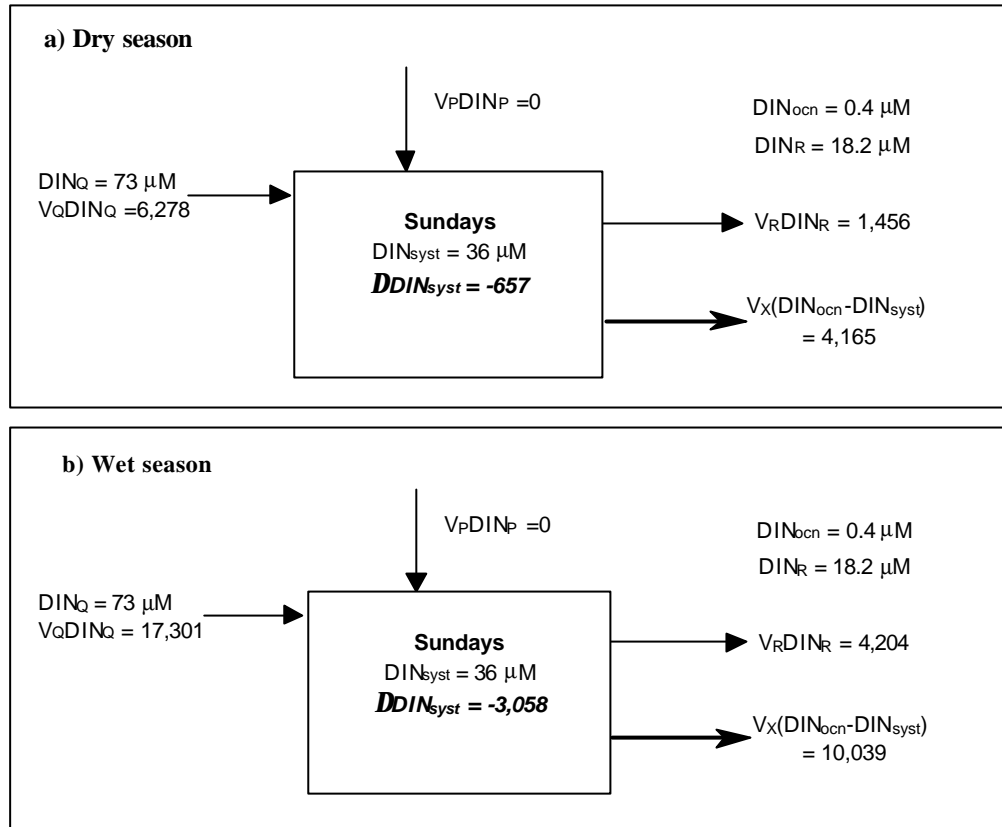
Time	<b>DDIP</b> (mol d <sup>-1</sup> )	<b>DDIN</b> (mol d <sup>-1</sup> )	<b>(p-r)</b> (mol d <sup>-1</sup> )	<b>(nfix-denit)</b> (mol d <sup>-1</sup> )	<b>(p-r)</b> (mmol m <sup>-2</sup> d <sup>-1</sup> )	<b>(nfix-denit)</b> (mmol m <sup>-2</sup> d <sup>-1</sup> )
Dry	+25	-657	-2,650	-1,057	-0.8	-0.4
Wet	+53	-3,058	-5,618	-3,906	-1.9	-1.3
<b>Annual mean</b>	<b>+39</b>	<b>-1,858</b>	<b>-4,134</b>	<b>-2,482</b>	<b>-1</b>	<b>-0.9</b>



**Figure 4.21. Water and salt budgets for Sundays River estuary in the dry (a) and wet (b) seasons.** Water flux in  $10^3 \text{ m}^3 \text{ d}^{-1}$  and salt flux in  $10^3 \text{ psu} \cdot \text{m}^3 \text{ d}^{-1}$ .



**Figure 4.22. DIP budget for Sundays River estuary in the dry (a) and wet (b) seasons.** Flux in  $\text{mol d}^{-1}$ .



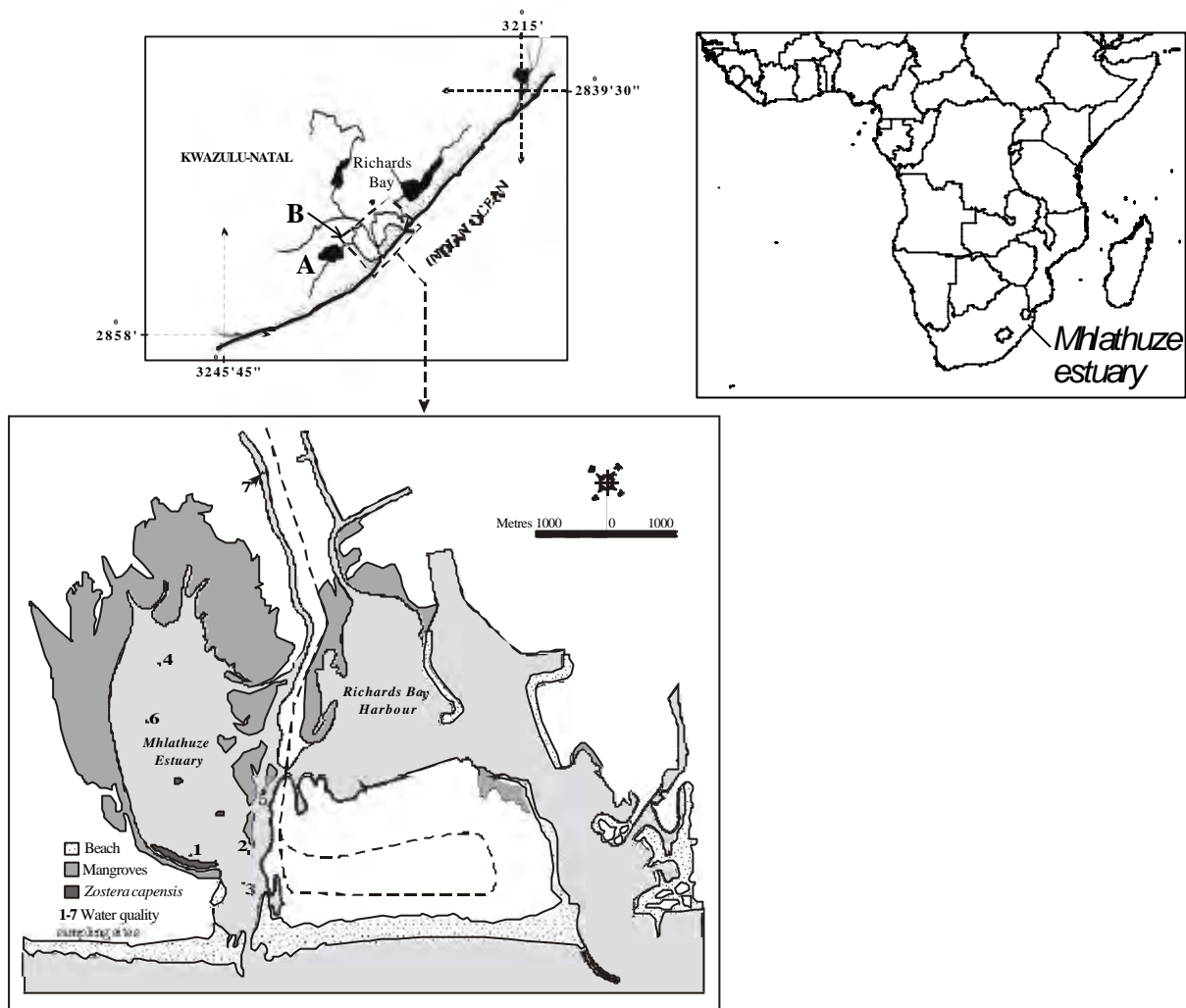
**Figure 4.23. DIN budget for Sundays River estuary in the dry (a) and wet (b) seasons .**  
Flux in  $\text{mol d}^{-1}$ .

#### 4.6 Mhlathuze River Estuary, KwaZulu-Natal

*V. Wepener*

##### Study area description

The Mhlathuze River estuary (28.80°S, 32.05°E; Figure 4.24) is situated in the subtropical coastal zone of KwaZulu-Natal province, South Africa and could be regarded as a permanently open estuarine bay (Whitfield 1992). The estuary covers an area of approximately  $12 \text{ km}^2$  (Cooks and Bewsher 1993), has an axial length of 6 km, a width of 3 km, and a total shoreline length of 30 km (Begg 1978). With the development of a deep-water harbour at Richards Bay in the 1970s, the original Richards Bay estuary was divided into two distinct sections by means of a 4 km berm wall. This divided the original estuary into the new harbour area and a sanctuary area, which was intended to protect the estuarine character of the original system. The Mhlathuze River was canalized, diverting the natural flow of the river into the “sanctuary” or estuary. During 1975 a new mouth was dredged through the sandbar approximately 5 km to the south of the original mouth.



**Figure 4.24. Map and location of Mhlathuze River estuary.** In the upper map, A indicates the position of Lake Chubu and B the Mtantatweni River. In the lower diagram, the dotted lines indicate the margins of the estuary.

The estuary can be divided into a “true estuarine area” displaying a salinity gradient, and a marine-dominated embayment. The canalized lower reaches of the Mhlathuze River (Site 7 on Figure 4.24) through to the mouth constitute the “true estuarine area”. The canalised Mhlathuze River drains the sugar-cane fields situated between the Mhlathuze and Mtantatweni Rivers. The large marine-dominated embayment (the south-westerly part of the estuary, represented by Sites 1 - 6 on Figure 4.24) receives only limited freshwater input from the Mtantatweni River (B in Figure 4.24), which drains Lake Chubu (A in Figure 4.24). The new harbour and mouth have increased the tidal prism in the Mhlathuze estuary from 0.4 m before the development to 1.8 m. According to Huizenga and Van Niekerk (1998) the wide, open mouth, which was developed after the breaching of the new mouth, provided a much shorter connection with the sea than was the case for the old bay and as a consequence increased the tidal variations in the new estuary. At the time of this study the mouth was approximately 300 m in width. Modelling of the physical dynamics of the mouth indicated that closure would not take place even if there were a total cessation of freshwater input into the estuary (Quinn 1999). The wide open mouth is mainly maintained by strong tidal flows related to the considerable size of the estuary and the large vertical tidal variation. Mouth closure could, however, be expected sometime in the future if the estuary filled with sediment, reducing the tidal flows through the mouth (Quinn 1999).

Sugar-cane is cultivated extensively on the floodplain of the estuary. In recent years the number of informal settlements and subsistence farms on the eastern shore of the estuary has increased drastically. On the southern and western banks are mangrove swamps, dominated by *Avicennia marina* and, to a lesser extent, by *Bruguiera gymnorhiza*. These mangrove stands represent 80% of the mangroves found in South African estuaries and bays. Other emergent and submerged macrophytes include *Phragmites australis* and eelgrass (*Zostera capensis*).

The substratum is a sequence of graded fluvial sand interspersed with silts and clay (Orme 1973). The alluvial deposits from the Mhlathuze River are extending the silt delta gradually into the estuary, with accompanying mangrove encroachment. This high degree of siltation has a pronounced effect on the volume of the estuary, resulting in a water exchange of about 90 % at each tidal cycle (Oliff 1977). There is a very limited salinity gradient in the greater part of the estuary. This is due to a number of factors including the mouth dynamics, the shallow nature of the estuary and the extent of water exchange. This results in the greater part of the estuary exhibiting marine salinities. The only salinity gradient is found along the canal of the Mhlathuze River. The Mhlathuze estuary is therefore not an axial system.

Very little information is available on the water quality of the Mhlathuze estuary. Hemens *et al.* (1971) analysed physico-chemical variables as part of a biological and sediment survey of the original Richards Bay during 1969. Follow-up studies, investigating pre- and post-harbour development conditions and conditions following the dredging of a new mouth for the estuary, were undertaken during 1974 (Hemens and Connell 1975), 1975 and 1976 (Hemens *et al.* 1976a; Hemens *et al.* 1976b). These data were collated and summarised by Begg (1978).

In 1996 the Coastal Research Unit of Zululand (CRUZ) initiated a programme to investigate the effects of an intrabasin transfer scheme on the water quality and biology of the Mhlathuze estuary (Cyrus *et al.* 2000). Quarterly sampling was undertaken from April 1996 to August 1998. No known water quality data (physico-chemical parameters) exist for the period between the pre-harbour development study (1976) and the 1996 programme. Estuarine water quality data reported in this paper are based on the results obtained from a CRUZ monitoring programme between 1996 and 1998, whereas the water quality data for the Mhlathuze River were obtained from the water quality database of the Department of Water Affairs and Forestry (DWAF), Pretoria, and from CRUZ between 1996 and 1998 in the lower reaches of the river (Cyrus *et al.* 2000). Nutrient data for groundwater were obtained from a database that forms part of a heavy-mineral mining operation biomonitoring programme (Clean Stream 2000).

### Water and salt balance

The assumption required to apply the steady-state water balance equation to a system is that the water level is steady over time. The Mhlathuze estuary undergoes marked water level changes due to tidal action through the permanently open mouth. Thus the assumption of a steady water level is not valid over short (i.e. daily) time-frames and it is thus necessary to average the water balance equation over an entire year, over which time the water level does remain essentially constant.

For LOICZ biogeochemical modelling, it is important to estimate the mixing volume ( $V_x$  in  $\text{m}^3 \text{d}^{-1}$ ) across the open boundary of the system. The basis for calculating the flux is the presence of a quantifiable salinity gradient. However, since there is a limited gradient in the Mhlathuze system, an alternative procedure to calculating the  $V_x$  is also included. That procedure (Yanagi 2000a) makes use of the dispersion process where the magnitude of the horizontal dispersion coefficient ( $D_h$  in  $\text{m}^2 \text{d}^{-1}$ ) is estimated from the current shear and the diffusivity normal to current shear. For wide and shallow estuaries the following equation is used:

$$D_h = W^{0.85} U^2 / 2180 \quad \text{where:} \quad (1)$$

W denotes the width of the estuary mouth in m and U is the residual flow velocity at the surface layer of the open boundary in  $\text{m d}^{-1}$ . Since this value is not independently known, a numerical value of 8,640 m

$d^{-1}$  was applied (Yanagi 2000a). In order to express  $D_h$  in LOICZ notation, the following equation was used for calculating  $V_X$  (Yanagi 2000b):

$$V_X = D_h (A/F) \quad \text{where:} \quad (2)$$

A denotes the cross section area of the open boundary of the system ( $m^2$ ) and F is the distance (m) between the geographic center of the system and the observation point for oceanic salinity (typically near the mouth of the system).

The following results for  $D_h$  and  $V_X$  were calculated for the Mhlathuze estuary using equations (1) and (2).

$$D_h = (200^{0.85} (0.1 \times 86,400)^2) / 2180$$

$$D_h = 3,100 \times 10^3 \text{ m}^2 \text{ d}^{-1}$$

$$V_X = D_h (A/F)$$

$$V_X = 3,100 \times 10^3 \text{ m}^2 \text{ d}^{-1} (5,000 \text{ m}^2 / 3,000 \text{ m})$$

$$V_X = 5,200 \times 10^3 \text{ m}^3 \text{ d}^{-1}$$

Figure 4.25 shows the water and salt balance for the Mhlathuze estuary with annual averages using the two methods described above.  $V_X^a$  is volume mixing calculated using water and salt balance and  $V_X^b$  is calculated using dispersion coefficient. For the purposes of this paper, the conservative estimate for total water exchange time ( $\tau$ ) calculated using  $V_X^b$  was used, was and calculated as four days. The relatively rapid exchange period is attributed to the large tidal prism of 1.8 m in this shallow estuary (average depth at high tide of 2 m). The system is therefore dominated by tidal mixing in the form of inflow of marine water in the greatest proportion of the estuary (i.e., the embayment area). Although there is significant freshwater outflow from the canalized area of the estuary, mixing of marine water and freshwater only occurs during high tide. During low tide the marine (estuarine brackish water) is replaced by freshwater flow from the river. The freshwater is mainly restricted to the canalized area, with the embayment remaining marine-dominated.

#### Budgets of nonconservative materials

Assuming a steady state for both dissolved inorganic nitrogen (DIN) and dissolved inorganic phosphorus (DIP) over an entire year, and that the nutrient concentration in evaporated water and the nutrient contribution from groundwater and rainwater are negligible, the nutrient budget equation can be simplified to:

$$DY = -V_R Y_R - V_G Y_G - V_Q Y_Q - V_X (Y_{ocn} - Y_{syst}) \quad (3)$$

It is known that nearby coastal lakes are affected by significant aerial deposition of nutrients from surrounding industries. However the prevailing wind conditions are such that the estuary should not be affected.

The values required for the application of this equation are given Table 4.14. Nutrient budgets are illustrated in Figures 4.26 and 4.27. Nonconservative fluxes with superscript (<sup>a</sup>) and (<sup>b</sup>) were derived using  $V_X^a$  and  $V_X^b$ , respectively.

**Table 4.14. Water fluxes, salinity and nutrient concentrations for the Mhlathuze River estuary.**

Quantity	Value	Data source
$V_Q$ ( $10^3 \text{ m}^3 \text{ d}^{-1}$ )	438	Average annual flow as measured at DWAF weir W1H032 for the period 1995-1998 (Cyrus <i>et al.</i> 2000).
$V_P$ ( $10^3 \text{ m}^3 \text{ d}^{-1}$ )	39	Average yearly rainfall from the South African Weather Bureau as supplied by the Computing Center for Water Research (CCWR) for the Mhlathuze catchment.
$V_E$ ( $10^3 \text{ m}^3 \text{ d}^{-1}$ )	-42	Average yearly evaporation rates from the South African Weather Bureau as supplied by the Computing Center for Water Research (CCWR) for the Mhlathuze catchment.
$V_G$ ( $10^3 \text{ m}^3 \text{ d}^{-1}$ )	12	Ground water recharge calculated for the Mhlathuze coastal plain as approximately 30% of the mean annual precipitation (Louw 1998).
$S_{\text{ocn}}$ (psu)	35.4	CSIR off-shore sampling.
$S_{\text{syst}}$ (psu)	34.5	Average salinity at all sites sampled at the surface when the mouth is open. Quarterly data from March 1996 to April 1998. This represents the average salinity of the outflowing surface layer.
$\text{DIP}_G, \text{DIN}_G$ ( $\mu\text{M}$ )	1.0, 14	Bore-hole monitoring results from the Mhlathuze floodplain for the period 1986-2000 (Clean Stream, 2000).
$\text{DIP}_Q, \text{DIN}_Q$ ( $\mu\text{M}$ )	0.7, 25	Monthly averages of six sites sampled in the lower reaches of the Mhlathuze River from 1996-1998 (Cyrus <i>et al.</i> 2000).
$\text{DIP}_{\text{syst}}, \text{DIN}_{\text{syst}}$ ( $\mu\text{M}$ )	5.8, 14	Averages of seven sites sampled in the Mhlathuze Estuary (Cyrus <i>et al.</i> 2000).
$\text{DIP}_{\text{ocn}}, \text{DIN}_{\text{ocn}}$ ( $\mu\text{M}$ )	0.1, 0.7	Readings at Site 3 when completely flushed with fresh seawater (Wepener and Vermeulen 1999).

For the purposes of calculating nutrient balances and system metabolism the results based on the most conservative of the flux calculations were used (i.e., fluxes based on current shear).

#### *DIP balance*

The system is a net source of nutrients and can be interpreted to indicate that heterotrophic processes prevail. The potential for aerial deposition could overestimate the heterotrophy. The differences in **DDIP** based on the derivation of  $V_x$  are shown in Figure 3.

#### *DIN balance*

The positive **DDIN** indicates that Mhlathuze estuary seems a source for DIN. However this should be regarded with the same degree of caution as expressed for the DIP about potential aerial deposition.

#### *Stoichiometric calculations of aspects of net system metabolism*

Because of time constraints for biological processes to occur, it is not reliable to estimate system metabolism in systems with rapid water exchange. However, assuming that the Mhlathuze estuary behaves more as having  $V_x^b$  and a longer water exchange time, net system metabolisms are calculated below.

The net ecosystem metabolism (NEM = primary production-respiration =  $p-r$ ) is calculated as the negative of **DDIP** multiplied by the C:P ratio of the reacting organic matter. Thus:

$$(p-r) = -\text{DDIP} \cdot (\text{C:P})_{\text{ratio}}$$

It is not completely obvious whether mangroves or phytoplankton are the dominating reactive organic matter, so two N:P ratios are used.

1) Assuming the bulk of the reacting organic matter is phytoplankton, the C:P ratio is 106:1, then for the Mhlathuze estuary, net ecosystem metabolism

$$(p-r) = -300 \text{ mmol m}^{-2} \text{ d}^{-1}$$

2) Assuming the bulk of the reacting organic matter is mangroves, the C:P ratio is 1000:1 ([Atkinson and Smith, 1983](#)) and for the Mhlathuze, the net ecosystem metabolism

$$(p-r) = -3,000 \text{ mmol m}^{-2} \text{ d}^{-1}$$

Both  $(p-r)$  values indicate that there is a net loss of organic matter from the Mhlathuze estuary.

If the **DDIP** values in Mhlathuze estuary are a measure of the net production of organic matter in the system, the expected **DDIN** ( $DDIN_{exp}$ ) would be **DDIP** multiplied by the N:P ratio of the reacting organic matter. Large differences between  $DDIN_{obs}$  and  $DDIN_{exp}$  are indicators of processes other than organic metabolism, which alter fixed nitrogen. As nitrogen fixation and denitrification are important processes in coastal systems, the difference is taken as a measure of net nitrogen fixation minus denitrification.

Again, because the major source of reacting matter is unclear, two N:P ratios are used.

1) If phytoplankton is the principal form of organic matter in the Mhlathuze estuary then, based on the Redfield ratio  $DDIN_{exp} = 16 \text{ DDIP}$ :

$$(nfix-denit)_{phytoplankton} = -40 \text{ mmol m}^{-2} \text{ d}^{-1}$$

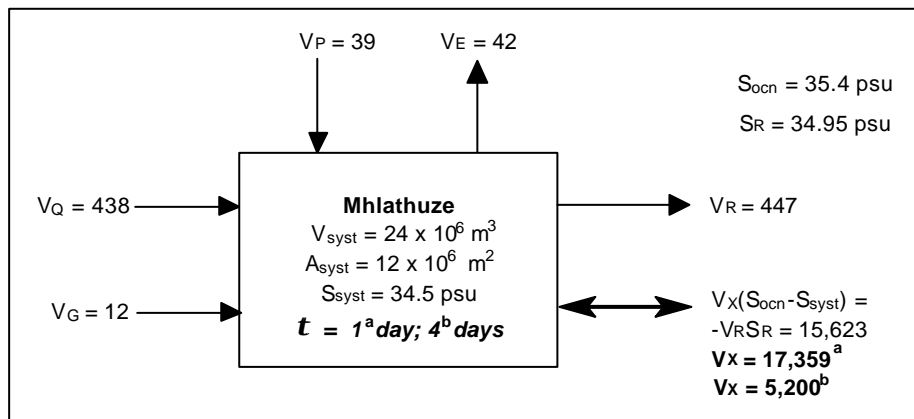
2) If the *Avicennia* mangroves are the principal form of organic matter then, based on a median ratio for mangroves of C:N:P 1000:11:1 (Atkinson and Smith 1983),  $DDIN_{exp} = 11 \text{ DDIP}$ , so that:

$$(nfix-denit)_{mangroves} = -20 \text{ mmol m}^{-2} \text{ d}^{-1}$$

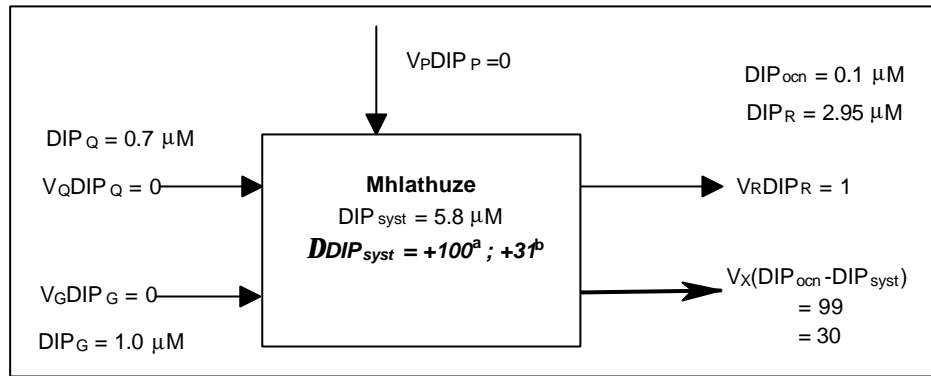
The negative values indicate that denitrification processes are responsible for smaller  $DDIN_{obs}$  than  $DDIN_{exp}$ .

### Comments

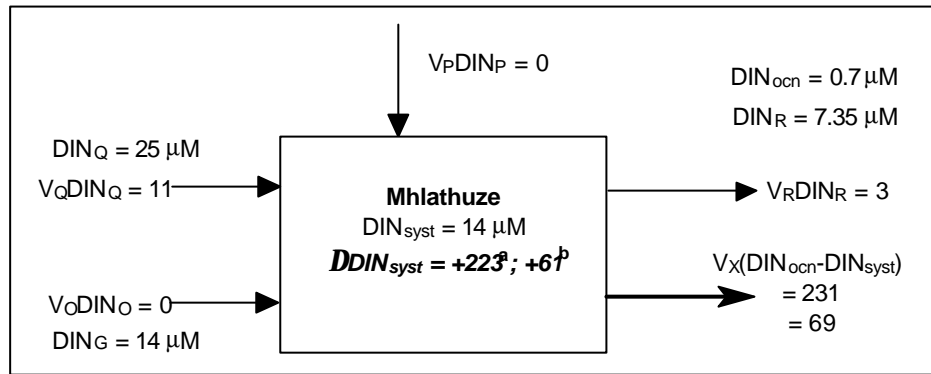
A single box LOICZ budget was set up for the Mhlathuze estuary due to the nature of the available estuarine data. During the study period, (1996-1997) the inflow from the Mhlathuze River was very constant and did not display any seasonal fluctuation (i.e. wet/dry seasonal flow patterns). This is because the Mhlathuze River is highly regulated and during wet cycles the winter and summer flows are similar. Since the monitoring of the Mhlathuze estuary is an ongoing project, it is anticipated that seasonal models will be developed once nutrient data from dry cycles are available.



**Figure 4.25. Water and salt budgets for Mhlathuze River estuary.** Water flux in  $10^3 \text{ m}^3 \text{ d}^{-1}$  and salt flux in  $\text{psu-m}^3 \text{ d}^{-1}$ .



**Figure 4.26. DIP budget for Mhlathuze River estuary.** Flux in  $10^3 \text{ mol m}^3 \text{ d}^{-1}$ .



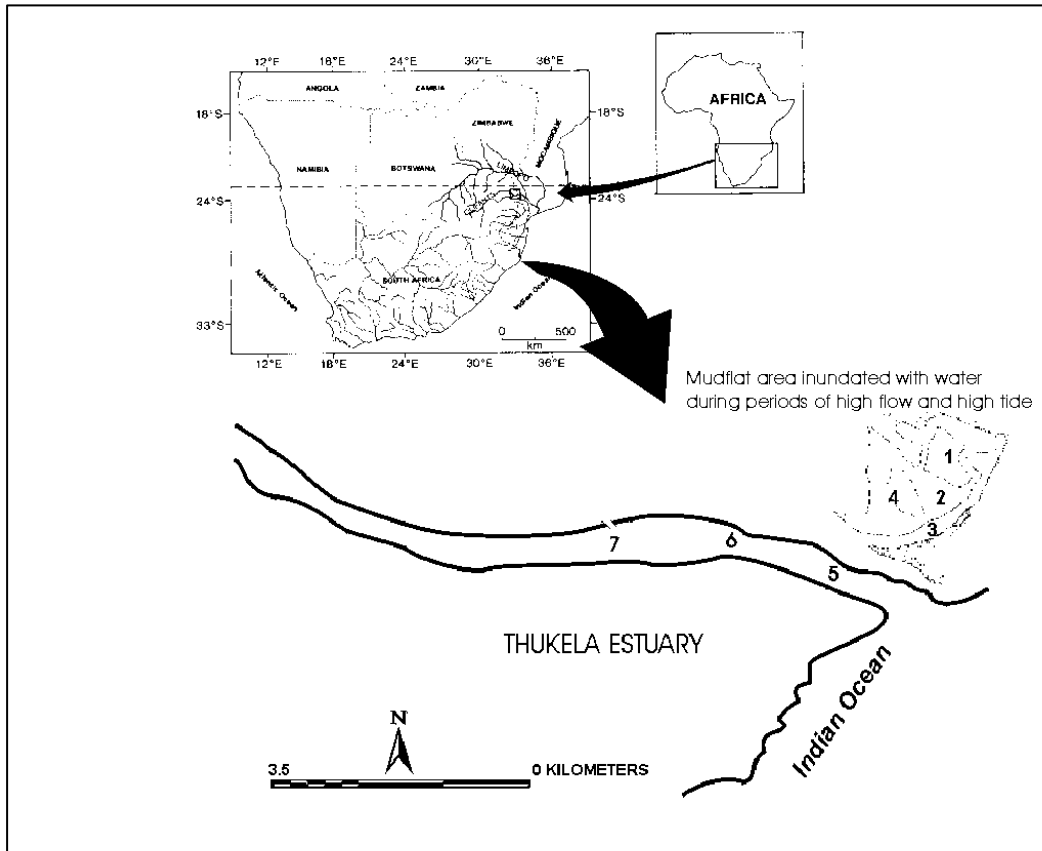
**Figure 4.27. DIN budget for Mhlathuze River estuary.** Flux in  $10^3 \text{ mol m}^3 \text{ d}^{-1}$ .

#### 4.7 Thukela River Estuary, KwaZulu-Natal

*V. Wepener*

##### Study area description

The Thukela River estuary is situated approximately 100 km north of the city of Durban on the east coast of South Africa (29.22°S, 30.50°E; Figure 4.28). Based on the classification by Whitfield (1992), the estuary is one of only two examples of an open river mouth estuarine system in South Africa. The Thukela River system forms a very important component of water resource utilization in South Africa with a number of large inter-basin transfer schemes responsible for transferring water from the Thukela basin across the escarpment into the Vaal river system (Davies and Snaddon 2000). The Thukela River originates in the Drakensberg Mountains (Begg 1978). From the Drakensberg range the river meanders for 520 km through the KwaZulu-Natal midlands before flowing into the Indian Ocean. The total catchment area is approximately 29,100 km<sup>2</sup>. Land uses in the catchment are mainly rural subsistence farming and commercial forestry. It is only on the coastal plain that the river flows through urbanised areas. The only industries associated with the urban development are paper and sugar mills with large scale commercial sugar cane farming along the banks of the lower reaches of the river.



**Figure 4.28. Map and location of the Thukela River estuary.**

Due to the high riverine runoff, the estuarine area of the Thukela River is small. The surface area of the estuary during low flow periods is approximately 0.6 km<sup>2</sup>. However, changes in river flow cause considerable changes in the morphometry of the estuary, and during periods of high flows the estuary extends out to sea and becomes unconfined by banks (Begg 1978). The axial length is estimated to be 800 m during low flow, with a shoreline length of approximately 2 km. The maximum width during natural flow periods is approximately 350 m with a channel width of 50 m, which increases to over 1,000 m during floods (Begg 1978). Initial observations on the bathymetry of the estuary indicated that it was relatively deep (Begg 1978), but surveys undertaken by the Coastal Research Unit of Zululand (CRUZ) from March 1997 to April 1998 (reported in Archibald 1998) showed an average depth of less than 1.5 m.

According to Begg (1978) the sandbar has a 700 m stable component on the floodplain (carrying a coastal dune forest) extending in a generally northern direction. There is also a 700 m unstable component without vegetation, that forms across the mouth. This bar is periodically removed by flood discharges. During flood conditions an offshore bar is formed, directing floodwater into the sea in a southerly direction. It is unlikely that mouth closure occurred during virgin conditions. More frequent mouth closures recorded in recent times (for only a few days) are probably due to the significant abstraction of water from the system via inter-basin transfer schemes to the Gauteng province. However, under future transfer schemes and runoff scenarios it is predicted that a drastic increase in mouth closure conditions will occur, for prolonged periods of up to 4 or 5 months (Quinn 1997).

Although very little is known about the biological condition of the estuary, recent surveys have shown that it plays an important role as habitat for water birds along the KwaZulu-Natal coast (Quinn 1997) and that fish and benthic estuarine invertebrates were found to be poorly represented. The same study found that very little natural vegetation remains, due to encroachment of sugar cane and forestry. However, there are still some stands of the brackwater mangrove (*Barringtonia racemosa*) and a small

*Phragmites*-dominated wetland on the south bank close to the mouth. According to MacKay and Cyrus (1998) the paucity of benthic fauna points to the estuary being plankton-dominated.

A water quality survey of the estuary highlighted the paucity of data (Archibald 1998). The only data available for the estuary were collected during a crab megalopa and benthic invertebrate survey undertaken by the CRUZ between 1997 and 1998. During this study, water quality was assessed at five sites in the estuary. Comprehensive data were obtained from the Department of Water Affairs and Forestry (DWAF) in Pretoria, South Africa. Biweekly water quality analyses were carried out at a number of stations in the Thukela River catchment. However, for the purposes of this assessment, the data from Weir V5H002, the gauging weir closest to the estuary, were analyzed. Daily flow records were also available for this station. The dataset from 1994 to 1998 were analyzed to represent present day conditions of the runoff to the estuary. These data were taken during an extended wet period and therefore no dry period results are presented.

### Water and salt balance

The assumption required to apply the steady-state water balance equation to a system is that the water level is steady over time. The Thukela estuary undergoes marked water level changes due the effects of the incoming and outgoing tides. Thus, the assumption of a steady water level is not valid over short time frames and it is necessary to average the water balance equation over an entire year, over which time the water level does remain essentially constant.

Figure 4.29 illustrates the water and salt balance for the Thukela estuary with annual averages using the LOICZ methodology. Residual water flux ( $V_R$  in the notation of Gordon *et al.* 1996) from this system, to balance freshwater inflow, is approximately  $3 \times 10^6 \text{ m}^3 \text{ d}^{-1}$ , while exchange flux ( $V_X$ ) is  $2 \times 10^6 \text{ m}^3 \text{ d}^{-1}$ . The system volume ( $0.9 \times 10^6 \text{ m}^3$ ) divided by the sum of these water fluxes gives an estimate of water exchange time of less than a day. These results indicate an extremely rapid seawater exchange within the estuary, which is caused by the significant freshwater outflow. It is this abundant freshwater supply from the Thukela River, which has led to the large inter-basin water transfer schemes currently in place and planned for the future.

### Budgets of nonconservative materials

Assuming a steady state for both dissolved inorganic nitrogen (DIN) and dissolved inorganic phosphorus (DIP) over an entire year, and that the nutrient contribution from groundwater is not known and rainwater is considered to be negligible, the nutrient budget equation can be simplified to:

$$DY = -V_R Y_R - V_Q Y_Q - V_X (Y_{ocean} - Y_{out}) \quad (1)$$

It should be borne in mind that nitrate in runoff is likely to be important since there are large sugar-cane fields on the banks of the lower reaches of the river and the estuary. However, no quantifiable data are available and consequently, nitrate concentrations were estimated from the mean  $\text{NO}_3$  to  $\text{NH}_4$  data described in the introduction. DIP and DIN concentrations of the various systems are shown in Table 4.15. The nonconservative fluxes of DIP and DIN (**DDIP**, **DDIN**) calculated for this one-box model is positive, indicating that the estuary is a net source of nutrients (Figures 4.30 and 4.31). The flux of nonconservative DIP, **DDIP**, is  $+15 \times 10^3 \text{ mol d}^{-1}$  or  $25 \text{ mmol m}^{-2} \text{ d}^{-1}$ ; and nonconservative DIN, **DDIN**, is  $+399 \times 10^3 \text{ mol d}^{-1}$  or  $665 \text{ mmol m}^{-2} \text{ d}^{-1}$ .

**Table 4.15. Water fluxes, salinity and nutrient concentrations, and data sources for Thukela River estuary.**

Quantity	Value	Data source
$V_Q$ ( $10^3 \text{ m}^3 \text{ d}^{-1}$ )	3,014	Average annual flow as measured at DWAF weir V5H002 for the period 1970-1996 presented by Roussouw and Claasen (1998) as reported by Archibald (1998).
$V_P$ ( $10^3 \text{ m}^3 \text{ d}^{-1}$ )	1.64	Average yearly rainfall from the South African Weather Bureau as supplied by the Computing Center for Water Research (CCWR) for the Thukela catchment.
$V_E$ ( $10^3 \text{ m}^3 \text{ d}^{-1}$ )	-2.14	Average yearly evaporation rates from the South African Weather Bureau as supplied by the Computing Center for Water Research (CCWR) for the Thukela catchment.
$V_G$ ( $10^3 \text{ m}^3 \text{ d}^{-1}$ )	0.08	Groundwater recharge calculated for the Thukela catchment as approximately 5% of the mean annual precipitation.
$S_{\text{ocn}}$ (psu)	35.4	CSIR off-shore sampling.
$S_{\text{syst}}$ (psu)	2.2	Average salinity of site 1 in surface when the mouth is open. Monthly data from April 1997 to March 1998. This represents the average salinity of the outflowing surface layer.
$\text{DIP}_Q, \text{DIN}_Q$ ( $\mu\text{M}$ )	0.9, 27	Average biweekly water quality data (1994-1998) from DWAF sampling site Weir V5H002 (Archibald 1998).
$\text{DIP}_{\text{syst}}, \text{DIN}_{\text{syst}}$ ( $\mu\text{M}$ )	5.5, 137	CRUZ monthly data from April 1997-March 1998 collected from 7 sites in the estuary and reported by Archibald (1998).
$\text{DIP}_{\text{ocn}}, \text{DIN}_{\text{ocn}}$ ( $\mu\text{M}$ )	1.3, 2	Readings at Site 5 when completely flushed with fresh seawater.

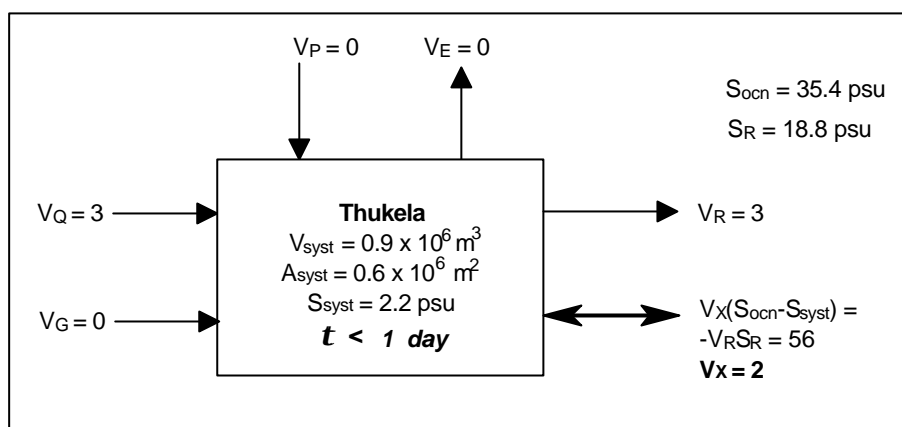
Estuarine systems with very short water exchange time either behave as high sinks or sources of DIP and DIN e.g., Camboriu estuary (Dupra *et al.* (2000b) or rapidly flush out all the nutrients as in the case of Mamberamo and Kuala Terengganu estuaries (Dupra *et al.* 2000a).

#### *Stoichiometric calculations of aspects of net system metabolism*

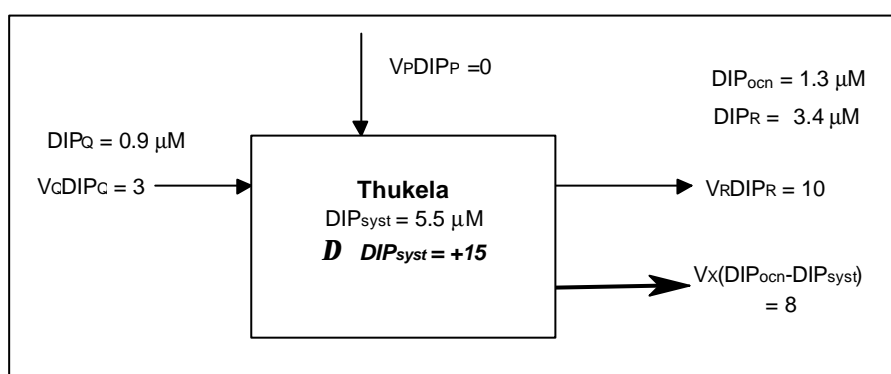
As is the case with many of the permanently open river-driven estuarine systems along the east coast of South Africa, the water exchange is very rapid, resulting in a time constraint for biological processes to take place.

#### Comments

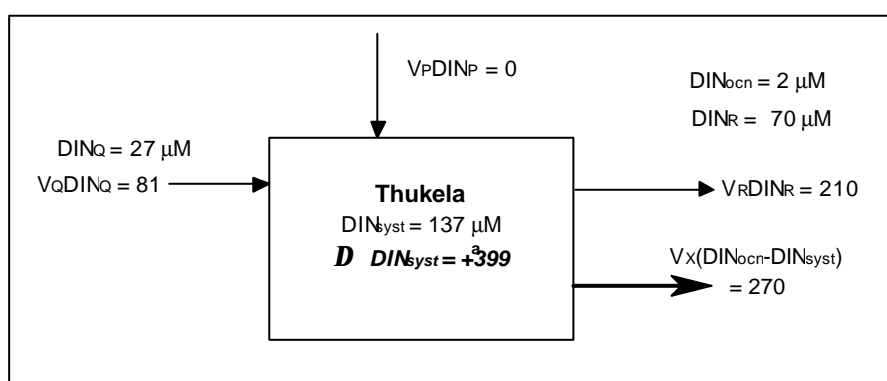
A single box LOICZ budget was set up for the Thukela estuary due to the nature of the available estuarine data. During the study period (1997-1998), very little seasonal fluctuation (i.e. wet/dry season flow patterns) was recorded. An extensive study of the Thukela River and its estuary is currently being undertaken as part of the Estuarine Freshwater Requirements (EFR) of the Resource Directed Management division of DWAF, South Africa. The envisaged sampling would allow for extensive nutrient surveys on the mudflats, off the mouth of the estuary and on the offshore Thukela banks. This would allow for the development of a three-box budget, which would be a better representation of the nutrient fluxes taking place.



**Figure 4.29. Water and salt budgets for Thukela River estuary.** Water flux in  $10^6 \text{ m}^3 \text{ d}^{-1}$  and salt flux in  $10^6 \text{ psu-m}^3 \text{ d}^{-1}$ .



**Figure 4.30. DIP budget for the Thukela River estuary.** Flux in  $10^3 \text{ mol m}^3 \text{ d}^{-1}$ .



**Figure 4.31. DIN budget for the Thukela River estuary.** Flux in  $10^3 \text{ mol m}^3 \text{ d}^{-1}$ .

## 5. REFERENCES

- Adam, S.K. (ed.) 1998 Towards Integrated Coastal Zone management in the Gulf of Guinea. A framework document. UNIDO/UNDP-GEF. Les Editions du Flamboyant, 86 pages.
- Allanson, B.R. and Baird, D. (eds) 1999 *Estuaries of South Africa*. Cambridge University Press, Cambridge, UK, 340 pages.
- Allanson, B.R., Baird, D. and Heydorn, A.E.F. 1999 Perspectives. Pages 321-327 in: Allanson, B.R. and Baird, D. 1999. (eds): *Estuaries of South Africa*. Cambridge University Press, Cambridge, UK.
- Allanson, B.R., Maree, B. and Grange, N. (in press) An introduction to the chemistry of the water column of the Knysna River estuary with particular reference to nutrients and suspended solids. *Proceedings of the Royal Society of South Africa*.
- Angwe, C.A., Gabche, C.E. 1997 Quantitative estimation of land based sources of Pollution to the coastal and marine environment of the republic of Cameroon. *Report on FAO WACAF II Project. Regional office for Africa*, Accra, Ghana, 72 pages.
- Archibald, C. 1998 Estuarine flow requirements of the Thukela River: water quality issues. *CSIR Report ECP-6000/6E03/JEA12/020*. Durban, South Africa.
- Atkinson, M.J. and Smith, S.V. (1983) C:N:P ratios of benthic marine plants. *Limnology and Oceanography* **28**:568-574.
- Baird, D. and Pereyra-Lago 1992 Nutrient status and water quality assessment of the Marine Glades canal system, Kromme estuary, St Francis Bay. *WaterSA* **18**:37-42.
- Baird, D. and Ulanowicz, R.E. 1993 Comparative study on the trophic structure, cycling and ecosystem properties of four tidal estuaries. *Marine Ecology Progress Series* **99**:221-237.
- Baird, D. and Winter, P.E.D. 1990 Annual flux budgets of dissolved inorganic nutrients through a well-mixed estuary. Pages 335-340 in Michaelis, W. (ed.) *Estuarine water quality management: monitoring, modelling and research*. Springer-Verlag, Heidelberg.
- Baird, D., Hanekom, N.M. and Grindley, J.R. 1986 Report No. 23: Swartkops (CSE 3). In: Heydorn, A.E.F. and Grindley, J.R. (eds). *Estuaries of the Cape. Part 2. Synopses of available information on individual systems*. *CSIR Research Report No. 422*.
- Baird, D., Marais, J.F.K. and Bate G.C. 1992 *An environmental analysis for the Kromme River estuary to assist in the preparation of a structure plan*. Institute for Coastal Research, University of Port Elizabeth, Port Elizabeth.
- Begg, G.W. 1978 *Estuaries of Natal*. Natal Town and Regional Planning Report No. 41.
- Bennekom, A.J. van, Berger, G.W., Helder, W. and de Vries, R.T.P. 1978 Nutrient distribution in the Zaire estuary and river plume. *Netherlands Journal of Sea Research* **12** (3/4): 296-323.
- Bickerton, I.B. and Pierce, S.M. 1988 Report No. 33: Krom (CMS 45), Seekoei (CMS 46) and Kabeljous (CMS 47). In: Heydorn, A.E.F. and Morant, P.D. (eds). *Estuaries of the Cape. Part 2. Synopses of available information on individual systems*. *CSIR Research Report No. 438*.
- Chambers, G. and Garrand, P. 1977 Conditions de houle a la Pointe Limbo. *Rapport de Synthese*. ONPC, Sogreah, Grenoble.
- Clean Stream 2000 Iscor Heavy Minerals Project: KwaZulu-Natal. *Integrated Biological, Water Quality, Water Quantity and Statistical Evaluation Report: Second quarter 2000*. Clean Stream Environmental Services, Pretoria, South Africa.
- Cooks, J. and Bewsher, P. 1993 Environmental reaction to human intervention in the Mhlathuze River Estuary, Richards Bay, South Africa. *Geoökodynamik* **14**:61-74.
- Cooper, A., Wright, I. and Mason, T. 1999 Geomorphology and sedimentology. Pages 5-25 in: Allanson, B.R. and Baird, D. (eds): *Estuaries of South Africa*. Cambridge University Press, Cambridge, UK.
- Cyrus, D.P., Wepener, V., MacKay, C.F., Vos, P.M., Viljoen, A. and Weerts, S.P. 2000 Effects of inter-basin water transfer on the hydrochemistry, benthic invertebrates and ichthyofauna of the Mhlathuze estuary and Lake Nseze. *WRC Report No. K2/720*, Water Research Commission, Pretoria, South Africa.
- David, L.T., Crossland, C.J. and Smith, S.V. 2000 *LOICZ Biogeochemical Budgeting Procedure: A Tutorial Pamphlet*. LOICZ, Texel, The Netherlands, 29 pages.

- Davies, B.R. and Snaddon, K. 2000 Ecological effects of interbasin water transfer schemes in dryland environments. *Water Research Commission Report K5/665*, WRC, Pretoria, South Africa.
- De Villiers, C., Hodgson, A. and Forbes, A. 1999 Studies on estuarine macroinvertebrates: The macrobenthos and nektonic invertebrates. Pages 167-207 in: Allanson, B.R. and Baird, D. (eds) *Estuaries of South Africa*. Cambridge University Press, Cambridge, UK.
- Dupra, V., Smith, S.V., Marshall Crossland, J.I. and Crossland, C.J. 2000a Estuarine systems of the South China Sea region: carbon, nitrogen and phosphorus fluxes. *LOICZ Reports and Studies* **14**, LOICZ, Texel, The Netherlands, 156 pages.
- Dupra, V., Smith, S.V., Marshall Crossland, J.I. and Crossland, C.J. 2000b Estuarine systems of the South American region: carbon, nitrogen and phosphorus fluxes. *LOICZ Reports and Studies* **15**, LOICZ, Texel, The Netherlands, 87 pages.
- Eisma, D. and Bennekou, A.J. van 1978 The Zaire River and estuary and the Zaire outflow in the Atlantic Ocean. *Netherlands Journal of Sea Research* **12** (3/4): 255-272.
- EMATEK, CSIR. 1994 Algoa Water Resources system. Modeling salinity distributions in the Kromme estuary under different freshwater inflow scenarios. *DWA Report B33/1/1200*; *CSIR Report EMAS-C-94051*, Stellenbosch.
- Emmerson, W.D. 1985 The nutrient status of the Swartkops River estuary, Eastern Cape. *Water SA* **11**:189-198.
- Emmerson, W.D. 1989 The nutrient status of the Sundays River estuary, South Africa. *Water Research* **23**: 1059-1067.
- Folack, J. 1988 Estimation et degradation de la chlorophyll dans une zone crevettecole: Kribi-Cameroon (Golfe de Guinée). *Cameroon Journal of Biological and Biochemical Sciences* **1**(2): 35-43.
- Folack, J. 1989 Etude préliminaire du phytoplancton d'une zone côtière d'exploitation crevettecole (Kribi – Cameroun, Golfe de Guinée – Atlantique centre Est. *Cameroon Journal of Biological and Biochemical Sciences* **2**(1): 51-65.
- Folack, J. Mbome, I/L Bokwe, A. and Tangang, A. (eds) 1999 Cameroon Coastal Profile. Ministry of the Environment, Large marine Ecosystem Project for the Gulf of Guinea. *MINEF – C/UNIDO/UNDP-GEF*, 102 pages.
- Gabche, C.E. 1997 *An appraisal of fisheries activities and evaluation of economic potential of the fish trade in the Douala – Edea reserve – Cameroon*. Cameroon Wildlife and conservation society consultancy report, June 1997, 39 pages.
- Gabche, C.E. and Folack, J. 1997 Cameroon coastal river network and its impact on the coastal and marine environment. 27<sup>th</sup> Liege Colloquium on Ocean Hydrodynamics. Liege Belgium, 8-12 May 1995. *IRMA Report No. 9*, 12 pages.
- Gabche, C.E. and Hockey, H-U.P. 1995 Growth and mortality of the giant African river prawn *Macrobrachium vollenhovenii* (Herklots: Crustacea, Palaemonidae) in the Lobe River, Cameroon: a preliminary evaluation. *Journal of Shellfish* **16** (1): 185-190.
- GATE 1980 Physical oceanography of the tropical Atlantic during GATE, GARP/ATE, Miami, USA, 89 pages.
- Giesen, W. and Kerkhof, K. 1984 The impact of river discharges on Kenya coral reef ecosystem - the physical processes: Effects on the Malindi Watamu coastal environment. *Laboratorium voor aquatische oecologie, Katholieke Universiteit, Nijmegen*, report No **194**.
- Gordon, D.C. Jr., Boudreau, P.R., Mann, K.H., Ong, J.-E., Silvert, W.L., Smith, S.V., Wattayakorn, G., Wulff, F. and Yanagi, T. 1996. LOICZ Biogeochemical Modelling Guidelines. *LOICZ Reports and Studies* **5**, LOICZ, Texel, The Netherlands, 96 pages.
- Hamon, W.R. 1961 Estimating potential evapotranspiration. *Journal of the Hydraulics Division, ASCE* **87** (HY3): 107-120.
- Hanisak, M.D. 1993 The nitrogen relationships of marine macroalgae. Pages 699-730 in Carpenter, E.J. and Capone, D.G. (eds): *Nitrogen in the Marine Environment*. Academic Press.
- Heip, C.H.R., Hemminga, M.A. and Bie, M.J.M. (eds) 1995 Monsoon and coastal ecosystems in Kenya. *Netherlands Indian Ocean Programme. Netherlands Museum of Natural History Cruise Report No. 5*.
- Hemans, J. and Connell, A.D. 1975 Richards Bay: Southern Bay Conservation Area. *Progress Report No 29*, Thirtieth Steering Committee Meeting, *CSIR/NIWR*.

- Hemens, J., McClurg, T.P. Simpson, D.E., Warwick, R.J. and Muller, M.S. 1976a Richards Bay Sanctuary Area: Report on field surveys in October 1975 and February 1976. *Progress Report No 31*, Thirty-Second Steering Committee Meeting, CSIR/NIWR, Durban, South Africa.
- Hemens, J., McClurg, T.P., Simpson, D.E. and Warwick, R.J. 1971 Detailed survey of Richards Bay. *Progress Report No. 21*, Twentieth Steering Committee Meeting, CSIR/NIWR.
- Hemens, J., Simpson, D.E. and Warwick, R.J. 1976b Richards Bay Sanctuary Area: Report on field surveys in May and June 1976. *Progress Report No 32*, Thirty-Third Steering Committee Meeting, CSIR/NIWR, Durban, South Africa.
- Heydorn, A.E.F. and Grindley, J.R. (eds) 1981 *Estuaries of the Cape. Part II. Synopses of available information on individual systems*. Report No. 7: Gamtoos (CMS48). *CSIR Research Report No. 406*, 76 pages.
- Heydorn, A.E.F. and Tinley, K.L. 1980 *Estuaries of the Cape. Part I. Synopsis of the Cape coast: natural features, dynamics and utilization*. Stellenbosch: National Research Institute for Oceanology.
- Horenz, J.W.G. 1987 Land use planning in the greater Algoa Bay metropolitan area with special reference to the Swartkops estuary. Pages 57-63 in: Baird, D., Marais, J.F.K., Martin, A.P. (eds): *The Swartkops estuary*. Proceedings of a symposium held on 14 and 15 September 1987 at the University of Port Elizabeth. South African National Scientific Programmes Report No. **156**.
- Huizenga, P. and Van Niekerk, L. 1998 Mhlathuze Estuary - Physical aspects. *CSIR Report ENV/S-C98*. CSIR, Stellenbosch, South Africa.
- ICITA 1973 *Oceanographic Atlas, Equalant I and II*. UNESCO, Paris, 237 pages.
- Jezewski, W.A. and Roberts, C.P.R. 1986 Estuarine and lake freshwater requirements. *Technical Report No. TR 129*, DWA, Pretoria.
- Lafond, L.R. 1967 Etudes littorales estuariennes en Zone intertropical Humide. *These d'Etat*, Université de Paris.
- Largier, J.L., Attwood, C. and Harcourt-Baldwin, J-L. (in press) The hydrographic character of Knysna Estuary. *Proceedings of the Royal Society of South Africa*.
- Lewis, J.B. 1985 Groundwater discharge into coral reefs, Barbados (West Indies). *Proceedings of the Fifth Coral Reef Congress, Tahiti 6*: 477-481.
- Lord, D.A. and Thompson, G.A. 1987 The Swartkops estuary: Pollution status. Pages 16-24 in Baird, D., Marais, J.F.K. and Martin, A.P. (eds): *The Swartkops estuary*. Proceedings of a symposium held on 14 and 15 September 1987 at the University of Port Elizabeth. South African National Scientific Programmes Report No. **156**.
- Louw, D. (1998). *Mhlathuze ecological (quantity) reserve study IFR*. Unpublished starter document for IFR specialist meeting held in Mtunzini, KwaZulu-Natal, South Africa, 26–30 October 1998.
- MacKay, C.F., and Cyrus, D.P. 1998 A review of the potential impact of reduced river runoff on the bird and macrobenthic fauna of the Thukela River. *CRUZ Investigational Report No. 61*: 1-52.
- MacKay, H.M. and Schumann, E.H. 1990 Mixing and circulation in the Sundays River estuary, South Africa. *Estuar. Coast. Shelf Sci.* **31**: 203-216.
- Mahe, G. 1987 Etude de la variabilite des apports hydriques continentaux dans le Golfe de Guinee, en liaison avec son hydrologie oceanique de surface. *Memoire de D.E.A. National d'Hydrologie, filiere "Resources en Eau"*. Université d'Orsay (Paris XI), Centre ORSTOM de Montpellier, 138 pages.
- Martin, A.P. and Baird, D. 1987 Seasonal abundance and distribution of birds from the Swartkops estuary. *Zool. afr.* **1**: 203-208.
- Milliman, J.D. and Meade, R.H. 1983 World-wide delivery of river sediment to the oceans. *J. Geol.* **91**: 1-21.
- Morant, P. and Quinn, N. 1999 Influence of man and management of South African estuaries. In: Morin, Kuete M. 1989 Le littoral Camerounais: Prolems morphologiques. *Trav. Labo. Geogr. Phys. Appliquee*. Inst. Geogr. Univ. Bordeaux II No. **11**:5-33.
- Munga, D., Yobe, A.C., Owili, M. and Mwanguni, S.M. 1993 Assessment of land-based sources of marine pollution along the Kenyan coast. *Report for the WHO Regional Office, Brazzaville*, 60 pages.

- Munyao, T.M. 2000 Dispersion of Sabaki River sediments in the Indian Ocean. *D.Phil. thesis*, Moi University, 127 pages.
- Noble, R.J. and Hemens, J. 1978 *Inland water ecosystems in South Africa: a review of research needs*. CSIR, Pretoria.
- Nolte and Associates 1998 *Sacramento regional wastewater treatment plant constructed wetlands demonstration project*. Five year summary report, 1994-1998.
- Ohowa, B.O. 1993 *Seasonal variations of the nutrient fluxes into the Indian Ocean from the Sabaki River, Kenya*. Unpublished report, Kenya Marine Fisheries Research Institute, Mombasa.
- Oloff, W.D. 1977 Environmental pollution studies, C: Estuarine surveys, III: Richards Bay southern sanctuary. *Progress report, CSIR/NIWR 34th steering committee meeting: Marine disposal of effluents* (33): 57-59.
- Olivry, 1986 Fleuves et rivières du Cameroun. *ORSTOM, MESIRES*, Mem. No 9, 733 pages.
- Orme, A.R. 1973 Barrier and lagoon systems along the Zululand coast, South Africa. Pages 181-217 in Coates, D.R. (ed.): *Coastal geomorphology*. Binghamton, State University of New York.
- Pearce, M.W. and Schumann, E.H. 1997 The effect of land use on the Gamtoos estuary water quality. *Water Research Commission Report No 503/1/97*, 23 pages.
- Quinn, N. 1997 *Thukela estuarine freshwater requirements: An initial assessment*. Department of Water Affairs and Forestry, Pretoria, South Africa.
- Quinn, N. 1999 Mhlathuze estuarine flow requirements: An initial assessment. *Mhlathuze Ecological Reserve Study*, IWR Environmental.
- Reddering, J.S.V. and Esterhuysen, K. 1981 Sedimentation in the Swartkops estuary. *ROSIE Report No. 1*, University of Port Elizabeth.
- Reddering, J.S.V. and Esterhuysen, K. 1981 Sedimentation in the Sundays estuary. *ROSIE Report No. 3*, University of Port Elizabeth.
- Reddering, J.S.V. and Esterhuysen, K. 1983 Sedimentation in the Kromme estuary. *ROSIE Report No. 6*, University of Port Elizabeth.
- San Diego-McGlone, M.L., Smith, S.V. and Nicolas, V. 2000 Stoichiometric interpretations of C:N:P ratios in organic waste materials. *Marine Pollution Bulletin* 40:325-330.
- Sayer, J.A., Harcourt, C.S. and Collins, N.M. (eds) 1992 *The conservation atlas of tropical forest – Africa*. Macmillan Publishing Ltd., London.
- Scharler, U.M. 2000 Response of nutrient status and biotic communities to variable freshwater input regimes in eastern Cape estuaries, South Africa, including a network analysis approach. *PhD thesis*. Department of Zoology, University of Port Elizabeth.
- Scharler, U.M. and Baird, D. 2000 The effects of a single freshwater release into the Kromme Estuary. 1: general description of the study area and physio-chemical responses. *WaterSA* 26:291-300.
- Scharler, U.M., Baird, D. and Winter P.E.D. 1998 Diversity and productivity of biotic communities in relation to freshwater inputs in three Eastern Cape estuaries. *Water Research Commission Report # 463/1/89*: 1-197.
- Scharler, U.M., Baird, D.H., Astill, H. and Adams, J. (in press) Water column and nutrient status in and around the river-estuary interface (REI) zone of the Gamtoos estuary. In: Whitfield, A.K. and Wood, A.D. (eds): *Studies on the river-estuarine interface region of selected Eastern Cape estuaries*. Final Report to the Water Research Commission.
- Schneider, W. 1992 Guide de terrain des ressources marines commerciales du golfe de Guinée. *Fiches FAO d'identification des espèces pour le besoins de la pêche*. FAO, Rome, 268 pages.
- Schumann, E., Largier, J. and Slinger, J. 1999 Estuarine hydrodynamics. Pages 27-52 in Allanson, B.R. and Baird, D. (eds): *Estuaries of South Africa*. Cambridge University Press, Cambridge, UK.
- Shaw, E.M., 1996 *Hydrology in Practice*. Chapman and Hall, London, 569 pages.
- Smith, S.V., Ibarra - Obando, S., Boudreau, P.R. and Camacho Ibar, V.F. 1997 Comparison of carbon, nitrogen and phosphorus fluxes in Mexican coastal lagoons. *LOICZ Reports and Studies* 10, 84 pages, LOICZ, Texel, The Netherlands.
- Snedaker, S.C. and Snedaker, J.G. (eds) 1984 *The mangrove ecosystem: research methods*. UNESCO/ SCOR Working Group 60 on Mangrove Ecology, 251 pages.
- Tribble, G.W. and Hunt, C.D. Jr. 1996 Nutrient flux from an atoll island compared with nutrient delivered by seawater. Pages 108-112 in Buddemeier, R.W. (ed.) *Groundwater discharge in the coastal zone*. *LOICZ Reports and Studies* 8, LOICZ, Texel, The Netherlands, 179 pages.

- UNEP, 1984 The marine and coastal environment of West and Central region and its state of pollution. *UNEP Regional Seas Reports and Studies* No. **46**.
- Van den Bossche, J.-P. and Bernacsek, G.M. 1990 Source book for inland fishery resources of Africa: 2. *CIFA Technical Paper* No. **18.2**, Rome, FAO, 411 pages.
- Waldron, H.N. 1999 *South African National Report on the southern African tide gauge network. Western Indian Ocean Sea Level Project*. Intergovernmental Oceanographic Commission, UNESCO, Paris.
- Wepener, V. and Vermeulen, L.A. 1999 Comments on the water quality of the Mhlathuze Estuary in relation to determining the ecological integrity class. *South African Journal of Aquatic Sciences* **24**(1/2): 18-27.
- Whitfield, A.K. (1992) A characterisation of southern African estuarine systems. *South African Journal of Aquatic Sciences* **18**(1/2): 89-103.
- Whitfield, A.K. and Wooldridge, T.H. 1994 Changes in freshwater supplies to southern African estuaries: some theoretical and practical implications. Pages 41-50 in Dyer, K.R. and Orth, R.J. (eds): *Changes in fluxes in estuaries: implications from science to management*. Fredensborg: Olsen and Olsen.
- WHO, 1989 *Management and control of the environment. WHO/PEP/89.1. Evaluation rapides des sources de pollution de l'air, de l'eau et du sol*. OMS Publication Offset No. **62**.
- William, J. 1997 05-365 Hydrology web site. University of Guelph, School. of Engineering. [www.eos.uoguelph.ca/webfiles/james](http://www.eos.uoguelph.ca/webfiles/james)
- Winter, P.E.D. and Baird, D. 1991 The exchange of phosphate between the Swartkops estuary and Algoa Bay. *S. Afr. J. Sci.* **87**: 192-197.
- Woodward-Clyde 1999 *Environmental impact assessment of the construction and abandonment of the proposed concrete gravity structure, Sitio Agusuhin, Subic Bay*. Volume 1-3.
- World Resources Institute. 1998 *World Resources 1998-99. A guide to the global environment*. Oxford University Press, New York, 369 pages.
- Wyrski, K. 1971 *Oceanographic Atlas of the International Indian Ocean Expedition*. NSF-IDOE-1, Washington, D.C., 531 pages.
- Wyrski, K., Bennett, E.B. and Rochford, D.J. 1988 *Oceanographic Atlas of the International Indian Ocean expedition*. National Science Foundation, Washington, D.C.
- Yanagi, T. 2000a *Coastal Oceanography*. Kluwer Publishers, Dordrecht, 162 pages.
- Yanagi, T. 2000b Simple method for estimating  $V_x$  from mixing equations in a 1-dimensional, steady-state system for LOICZ biogeochemical modelling. Pages 108-110 in Dupra, V., Smith, S.V., Marshall Crossland, J.I. and Crossland, C.J. 2000c Estuarine systems of the East Asia region: carbon, nitrogen and phosphorus fluxes. *LOICZ Reports and Studies* **16**, LOICZ, Texel, The Netherlands, 127 pages.

## **Appendix I**

## **Workshop Agenda**

### **Monday, 11 September**

Participants arrive in Zanzibar.

### **Tuesday, 12 September**

- 0900 Welcome and announcements – Dr Amani Ngusaru, Institute of Marine Science, Zanzibar
- Introduction of participants
- 0930 Introduction to LOICZ and IGBP – Chris Crossland
- 1000 Introduction to LOICZ budgeting approach and project overview – Stephen Smith
- 1030 Biogeochemical budgets calculation and web information – Vilma Dupra
- 1100 Coffee break
- 1115 Typology and scaling in LOICZ – Dennis Swaney
- 1145 Outline of the LOICZ biogeochemical budgets web site – Dennis Swaney
- Discussion
- 1230 Lunch
- 1330 Tools: Presentation of CABARET budgeting software – Laura David
- 1400 Tools: Calculation of river discharge values – Laura David
- 1415 Tools: Calculation of waste loads – Laura David
- 1430 Participant presentation of sites and preliminary budgets
- 1800 Session close

### **Wednesday, 13 September**

- 0900 Plenary discussion of continuing work plan and resource person collaborations
- 0930 Breakout groups working on site budget preparation
- 1230 Lunch
- 1330 Plenary discussion of status of work and problems
- 1345 Break out groups resume work on budget derivation.
- 1745 Plenary review of status of work for evening continuation

### **Thursday, 14 September**

- 0900 Breakout groups continue
- 1115 Budgets presentations by participants
- 1230 Lunch
- 1330 Budget presentations continue
- Identification of additional sites for budget estimates
- 1630 Synthesis and wrap-up session, and discussion of future activities of the group
- 1730 Workshop close

### **Friday, 15 September**

Participants depart Zanzibar

**Welcome**

Participants (see Appendix III) were welcomed to Zanzibar and the venue at the Fisherman's Resort by Dr Amani Ngusaru, on behalf of the Zanzibar Institute of Marine Sciences, University of Dar es Salaam, and meeting support arrangements were reviewed. The workshop agenda (Appendix I) was introduced, and working documents, electronic information and tutorial materials were distributed.

**Introduction and Background**

LOICZ goals and approaches were presented by Dr Chris Crossland and a context for the workshop activities and outcomes was provided against the wider questions of the LOICZ core project and the UNEP project. Emphasis was given to the central questions of evaluating material fluxes, the influence of human dimensions on global changes in processes within the coastal zone, and the use of a typology approach to develop a global picture of systems responses and changes. A round-table introduction of participants was made. The purpose of the workshop was outlined by Prof. Stephen Smith within an overview presentation of the LOICZ budgeting and modeling approach for nutrient flux and net ecosystem metabolism of estuarine and coastal sea systems.

In an introductory tutorial, Vilma Dupra provided participants with a description of the development and calculation of nutrient budgets models, including single box, stratified and multi-compartment assessments. A tutorial handbook (LOICZ Biogeochemical Budgeting Procedure: A Tutorial Pamphlet, prepared for the UNEP GEF project by the Marine Science Institute, University of the Philippines) was provided to all participants and supported the tutorial presentation.

The typology approach being developed by LOICZ for up-scaling local and regional material flux assessments to global scale was outlined by Dennis Swaney. The LOICZView tool and the extensive database for half-degree description of the global coastal zone were discussed and the planned integration of regional data through thematic workshops in 2001, as part of the project, was highlighted.

Various tools developed by LOICZ to assist in estimating water and biogeochemical material inputs to systems were reviewed by Dr Laura David. Calculation parameters, location and access to the tools were identified and examples proved as case evaluations. Electronic versions of the biogeochemical budget calculation software (CABARET), waste load estimations, and river discharge evaluation were provided to participants.

**Presentation of Biogeochemical Budgets**

The contributing budgets brought by the participants were briefly considered, including an overview of the system settings, data availability and quality, approaches being taken to build budgets, and the status and problems in making the model assessments. System sites included:

*Tanzania*

Chwaka Bay, Zanzibar

*Kenya*

Malindi Bay (Sakaki River system)

*Cameroon*

Bouche du Cameroon mangrove systems including:

Cameroon estuary

Lobe estuary

*Guinea*

Korikaufe estuary

*South Africa*

Knysna estuary

Swartkops estuary

Kromme estuary

Gamtoos estuary

Sundays River estuary  
Thukela estuary  
Mhlathuze estuary  
Nhlabane estuary

### **Budgets Development**

Break-out groups worked interactively on the development of these site budgets, supplemented with methodological and site/issue-based tutorials and discussions. Estimates for sites, and budgets refinement emerged from resolution of techniques, application of derivative data and assessment of watershed information.

Plenary and discussion sessions were held throughout the workshop. These enabled review of the status of budgets development and discussion of key issues raised by participants, as well as allied topics, such as: C:N:P ratio and stoichiometry, limits and “reasonable” values in budget assessments, scaling variables and typology.

### **Outcomes and Wrap-up**

Budgets for all systems were developed to a final or interim draft stage of completion during the workshop; additions to text descriptions and a check on data sources were required by most budgets before final contribution. A schedule for contribution and publication of the printed and CD-ROM report, and posting to the LOICZ website, was agreed:

20 October	revised final budgets to Prof. Smith and Vilma Dupra
30 November	final budgets to IPO for LOICZ R&S preparation
15 January	draft R&S report to UNEP for comment
29 January	R&S to printer

A number of additional sites was identified for which data is available and which may yield budgets. Participants committed to making other site budgets, subject to data availability, and to encourage others to make further site assessments. Prof. Howard Waldron, University of Cape Town, accepted the role of Regional Mentor – Africa for the project, with support from Prof. Baird, and participants discussed possibilities to expand the network of researchers and site budget potential for the region.

The participants joined with LOICZ in expressing thanks to Dr Amani Ngusaru and Edna Nyika from the Zanzibar Institute of Marine Sciences for support and hosting of a very fruitful training and information workshop. The financial support of the Global Environment Facility was gratefully acknowledged.

**Resource Persons**

Professor Stephen Smith  
 Department of Oceanography  
 University of Hawaii  
 1000 Pope Road  
 Honolulu, Hawaii 96822  
 United States of America  
 Phone: +1-808-956 8693  
 Fax: +1-808-956 7112  
 Email: [svsmith@soest.hawaii.edu](mailto:svsmith@soest.hawaii.edu)

Ms Vilma Dupra  
 Department of Oceanography  
 University of Hawaii  
 1000 Pope Road  
 Honolulu, Hawaii 96822  
 United States of America  
 Phone: +1-808-956 2354  
 Fax: +1-808-956 7112  
 Email: [vdupra@soest.hawaii.edu](mailto:vdupra@soest.hawaii.edu)

Dr. Laura David (*regional resource person*)  
 Marine Science Institute  
 University of the Philippines  
 Quezon City  
 Philippines  
 Phone: +632-922 3544  
 Fax: +632-924 7678  
 Email: [LTdavid@eudoramail.com](mailto:LTdavid@eudoramail.com)  
[ldavid@msi01.cs.upd.edu.ph](mailto:ldavid@msi01.cs.upd.edu.ph)

Dr Chris Crossland  
 LOICZ IPO  
 PO Box 59  
 1790 AB Den Burg, Texel  
 The Netherlands  
 Phone: +31-222-369403  
 Fax: +31-222-369430  
 Email: [loicz@nioz.nl](mailto:loicz@nioz.nl) or [ccross@nioz.nl](mailto:ccross@nioz.nl)

Mr Dennis Swaney  
 Boyce Thompson Institute  
 Cornell University  
 Tower Rd  
 Ithaca, NY 14853 USA  
 Phone: +1-607-254 1368  
 Fax: +1-607-254 1325  
 Email: [dps1@cornell.edu](mailto:dps1@cornell.edu)

**Participants**

*Tanzania*  
 Dr Amani Ngusaru  
 Institute of Marine Sciences  
 University of Dar es Salaam  
 PO Box 668 Zanzibar  
 Tanzania  
 Phone: +255-24-2232128 or 2230741  
 Fax: +255-24-2233050  
 Email: [angusaru@zims.udsa.ac.tz](mailto:angusaru@zims.udsa.ac.tz)

Dr S.M. Mohammed  
 Institute of Marine Sciences  
 University of Dar es Salaam  
 PO Box 668 Zanzibar  
 Tanzania  
 Phone: +255-24-2232128 or 2230741  
 Fax: +255-24-2233050  
 Email: [salim@zims.udsm.ac.tz](mailto:salim@zims.udsm.ac.tz)

Mr Oberth U. Mwaipopo  
 Institute of Marine Sciences  
 University of Dar es Salaam  
 PO Box 668 Zanzibar  
 Tanzania  
 Phone: +255-24-2232128 or 2230741  
 Fax: +255-24-2233050  
 Email: [mwaipopo@zims.udsm.ac.tz](mailto:mwaipopo@zims.udsm.ac.tz)

*Kenya*  
 Professor Mwakio P. Tole  
 School of Environmental Studies  
 Moi University  
 P.O.Box 3900 Eldoret  
 Kenya  
 Phone: +254-321-43263  
 Fax: +254-321-43047  
 Email: [Tole@Form-Net.com](mailto:Tole@Form-Net.com)

*Guinea*  
 Mr Pierre Koivogui  
 CERESCOR  
 BP 1615  
 Conakry Republic of Guinea  
 West Africa  
 Phone: +224-221908  
 Fax: +224-462112  
 Email: [Cerescor.padre@mirinet.net.gn](mailto:Cerescor.padre@mirinet.net.gn)

*South Africa*

Professor Dan Baird  
Head of Zoology Department  
University of Port Elizabeth  
PO Box 1600 Port Elizabeth  
South Africa  
Phone: +27-41-5042341  
Fax: +27-41-5042317  
Email: [zladdb@ZOO.upe.ac.za](mailto:zladdb@ZOO.upe.ac.za)

Professor Howard Waldron  
Dept of Oceanography,  
University of Cape Town,  
Rondebosch 7700,  
South Africa.  
Phone: +27-21-650 3284  
Fax: +27-21-650 3979  
Email: [waldron@physci.uct.ac.za](mailto:waldron@physci.uct.ac.za)

Mr Todd Switzer  
PO Box 748 Knysna 6570  
South Africa  
Phone: +27-44-343 2172 (Home)  
Fax: +27-82-4026198 (Cell)  
Email: [TODD@physci.uct.ac.za](mailto:TODD@physci.uct.ac.za)  
[Todd@cyberperk.co.za](mailto:Todd@cyberperk.co.za)

Dr Victor Wepener  
Departement Dierkunde  
Randse Afrikaanse Universiteit  
Posbus 524, Aucklandpark, 2006  
Phone: +27 (0)11 489-3373  
Fax: +27 (0)11 489-2286  
Email: [vw@na.rau.ac.za](mailto:vw@na.rau.ac.za)

*Cameroon*

Mr Charles Emene Gabche  
IRAD-Fisheries and Oceanography Research  
Station  
PMB 77 - Limbe, South-West Province  
Cameroon  
Fax: +237-33 23 76  
Email : [cemenegab@yahoo.com](mailto:cemenegab@yahoo.com)

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**LOICZ/UNEP WORKSHOP ON ESTUARINE SYSTEMS  
OF THE SUB-SAHARAN AFRICA & WESTERN INDIAN OCEAN REGION**

**Institute of Marine Science,  
University of Dar es Salaam  
ZANZIBAR, TANZANIA  
12-14 September 2000**

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**Primary Goals:**

To work with researchers dealing with estuarine systems of the Sub-Saharan Africa and western Indian Ocean region, in order to extract C,N,P budgetary information from as many systems as feasible using existing data. The Sub-Saharan Africa and western Indian Ocean systems include one of the major coastal regions of the world oceans and are heavily influenced by anthropogenic activity. The workshop provides the opportunity to characterize terrigenous inputs to the estuaries of the region, and outputs from the estuaries – hence, the net role of the estuarine zone of this region as a source or sink for carbon, nitrogen, and phosphorus.

This workshop will complement earlier, successful workshops in Ensenada, Mexico, in June 1997, a second Mexico workshop in January 1999 (Merida, Mexico), an Australasia workshop (Canberra, Australia) in October 1998, a South China Sea workshop (Manila, Philippines) in July 1999, a South America workshop in November 1999 (Bahia Blanca, Argentina), a South Asia workshop in February 2000 (Goa, India) and an East Asia workshop in Hong Kong in June 2000, by the analysis of data from another important coastal region.

It is hoped that each workshop participant will be able to bring the available data for at least two budgets: one from one of the "pollution hot spot" regions within their country, and one for a physiographically fairly similar region which is apparently subjected to less pollution. By this strategy, we hope to compile a set of sites that will represent a relatively wide range of human pressures in the Sub-Saharan Africa and western Indian Ocean region.

**Anticipated Products:**

1. Develop budgets for as many systems as feasible during the workshop.
2. Examine other additional data, brought by the researchers, or provided in advance, to scope out how many additional systems can be budgeted over an additional 2 months.
3. Prepare a LOICZ technical report and a CD-ROM summarizing this information.
4. Contribution of these sites to 1-2 papers to be published in the refereed scientific literature.
5. It is anticipated that one participant from the workshop will be offered the opportunity to spend up to two months in Hawaii and/or Manila, getting further experience and developing additional budgets for the region.

**Participation:**

The number of participants will be limited to fewer than 18 persons, to allow the active involvement of all participants. Nominees include:

- Resource persons (possible participants are Stephen Smith, Vilma Dupra, Laura David, Chris Crossland, Dennis Swaney);
- Up to 13 researchers from the region.

**Workplan:**

Participants will be expected to come prepared to participate in discussions on coastal budgets. Preparation should include reading the LOICZ Biogeochemical Modelling Guidelines (Gordon *et al.* 1996), the Mexican Lagoons Workshop Report (Smith *et al.* 1997), examination of the budgets and

tutorials presented on the LOICZ Modelling web page (<http://data.ecology.su.se/MNODE/>), and arriving with preliminary budgets, electronic maps, and 1-3 page writeups from “their sites.” In order to be included in the workshop report, the budgets should conform as best possible to the budgeting protocol laid out in the above documentation. Guidelines for budget preparation and writeups and a tutorial package entitled CABARET can (and should) be downloaded from the LOICZ Modelling web site.

**NOTE:** Please try to conform to materials on that web site as closely as possible, because this will greatly aid in report preparation. We anticipate structuring the workshop very strongly towards instruction and then working with individuals to complete budgets during the workshop.

### **Further Details:**

At an absolute minimum, each participant is expected to arrive at the workshop (or send in advance) the following materials:

1. A 1-3 page description of the area (see materials posted on the Web and in the various workshop reports) and a map of the site. These should be in electronic format.
2. Within the context of needs for the overall LOICZ project, some estimate of water exchange (most commonly via water and salt budgets) and budgets for the dissolved inorganic nutrients, nitrogen and phosphorus, constitute the minimum useful derivations from the biogeochemical budgeting. Budgets of other materials, while potentially interesting for other purposes do not satisfy this minimum requirement. The minimum data requirements are as follows:
  - a. The primary seasonal pattern of the region is at least one wet season and one dry season per annum. Ideally, a budget for each season would be developed. If a system is vertically stratified, then a 2-layer budget is preferred over a single-layer budget. If a system has a strong land-to-sea salinity gradient, then it is preferable to break the system along its length into several boxes.
  - b. Data requirements to construct a satisfactory water and salt budget include: salinity of the system and the immediately adjacent ocean, runoff, rainfall, evaporation, and (if likely to be important) inputs of other freshwater sources such as groundwater or sewage. Preferably, the salinity and freshwater inflow data are for the same time period (for example, freshwater inflow data for a month or so immediately prior to the period of salinity measurement). In the absence of direct runoff estimates for small catchments, estimations can be made from a knowledge of catchment area and monthly rainfall and air temperature for the catchment. See materials on the LOICZ biogeochemical modeling web site.
  - c. Data requirements for the nutrient budgets are: concentrations of dissolved nutrients (phosphate, nitrate, ammonium, and if available dissolved organic N and P) for the system and the adjacent ocean, concentrations of nutrients in inflowing river water (and if important, in groundwater), some estimate of nutrient (or at least BOD) loading from sewage or other waste discharges. If atmospheric deposition (particularly of N) is likely to be important, an estimate of this is also useful. If direct waste load measurements are not available, estimations can be made from a knowledge of the activities contributing to the waste loads and the magnitudes of those activities. See the materials on the web site.

### **Workshop Schedule**

(All final participants are expected to stay for the entire workshop):

September 11: Arrival

September 12: General introduction to the budgeting procedure and related issues; presentation of preliminary budgets (no details, simply a quick summary to see who has what).

Breakout groups to revise, refine budgets. This will vary, as needed, from tutorial, through detailed help, to procedural discussions.

September 13: Continue breakouts; afternoon plenary to evaluate progress.

September 14: Breakouts/plenary as required to develop synthesis.

September 15: Departure.

**Background Documents:**

Gordon, D.C. Jr., Boudreau, P.R., Mann, K.H., Ong, J.-E., Silvert, W.L., Smith, S.V., Wattayakorn, G., Wulff, F. and Yanagi, T. 1996. LOICZ Biogeochemical Modelling Guidelines. *LOICZ Reports and Studies* **5**, LOICZ, Texel, The Netherlands, 96 pages.

Smith, S.V., Ibarra - Obando, S., Boudreau, P.R. and Camacho Ibar, V.F. 1997 Comparison of carbon, nitrogen and phosphorus fluxes in Mexican coastal lagoons. *LOICZ Reports and Studies* **10**, LOICZ, Texel, The Netherlands, 84 pages.

LOICZ Modelling web page, for everyone with www access:( <http://data.ecology.su.se/MNODE/>).

- The web pages, including the guidelines, are frequently updated. If you have not looked at them within the last two weeks, you should go through them again (For example, there are recent additions on estimation of runoff and estimation of waste loads).
- If you do not have access to the worldwide web but do have access to a computer with a CD-ROM, please let us know; we will send you a CD with the web page. Please do not request the CD at this time if you have access; you will be furnished one during the workshop.
- CABARET (Computer Assisted Budget Analysis, Research, Education, and Training). Note: a version of this software is available on the web-site.

## Appendix V Glossary of Abbreviations

NH <sub>4</sub>	Ammonium
NO <sub>3</sub>	Nitrate
DIN	Dissolved inorganic nitrogen
DON	Dissolved organic nitrogen
DIP	Dissolved inorganic phosphorus
DOP	Dissolved organic phosphorus
PTN	Particulate total nitrogen
PTP	Particulate total phosphorus
POP	Particulate organic phosphorus
PON	Particulate organic nitrogen
ON	Organic nitrogen
OP	Organic phosphorus
TN	Total nitrogen
TP	Total phosphorus
DOC	Dissolved organic carbon
DIC	Dissolved inorganic carbon
POC	Particulate organic carbon
OC	Organic carbon
SiO <sub>4</sub>	Silicate
nfix	Nitrogen fixation
denit	Denitrification
p	Primary production
r	Respiration
TDN	Total dissolved nitrogen
TDP	Total dissolved phosphorus
CTD	Conductivity Temperature Depth