ESTUARINE SYSTEMS OF AFRICA (Regional Workshop II): CARBON, NITROGEN AND PHOSPHORUS FLUXES

by

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

L.T. David
Marine Science Institute, College of Science,
University of the Philippines
Quezon City, The Philippines

H. Waldron
Dept of Oceanography
University of Cape Town
Rondebosch, South Africa

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

United Nations Environment Programme
Supported by financial assistance from the Global Environment Facility

LOICZ REPORTS & STUDIES NO. 20

Published in the Netherlands, 2002 by:
LOICZ International Project Office
Netherlands Institute for Sea Research
P.O. Box 59
1790 AB Den Burg - Texel
The Netherlands
Email: loicz@nioz.nl

The Land-Ocean Interactions in the Coastal Zone Project is a Core Project of the "International Geosphere-Biosphere Programme: A Study Of Global Change" (IGBP), of the International Council of Scientific Unions.

The LOICZ IPO is financially supported through the Netherlands Organisation for Scientific Research by: the Ministry of Education, Culture and Science (OCenW); the Ministry of Transport, Public Works and Water Management (V&W RIKZ); and by The Royal Netherlands Academy of Sciences (KNAW), and The Netherlands Institute for Sea Research (NIOZ).

This report and allied workshops are contributions to the project: The Role of the Coastal Ocean in the Disturbed and Undisturbed Nutrient and Carbon Cycles (Project Number GF 1100-99-07), implemented by LOICZ with the support of the United Nations Environment Programme and financing from by the Global Environment Facility.

Citation: **Dupra, V., Smith, S.V., David, L.T., Waldron, H., Marshall Crossland, J.I. and Crossland, C.J. 2002 Estuarine systems of Africa: carbon, nitrogen and phosphorus fluxes. LOICZ Reports & Studies No. 20, i + 81 pages, LOICZ, Texel, The Netherlands.**

ISSN: 1383-4304

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

The LOICZ Reports and Studies Series is published and distributed free of charge to scientists involved in global change research in coastal areas.

TABLE OF CONTENTS

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 eighth in a series of regional activities within the project and derives from efforts by the LOICZ Regional Mentor (Africa), Dr Howard Waldron, University of Cape Town, to extend training and scientific information development in estuarine processes in Africa. It builds on interests, skills and an initial network of researchers established at an earlier workshop that addressed sub-Saharan African biogeochemical budgets held in Zanzibar, September 2000 (LOICZ R&S 18, 2001).

Coastal regions of Africa include tropical to temperate climates and feature river catchments ranging from arid to wet monsoonal systems. Large ocean current systems interact with climate and with coastal and shelf systems. A diversity of estuarine types occurs along the coastline of Africa, together with an array of human influences and pressures that affect loads of nutrients and water flows into the coastal seas. This interplay confers a variety of biogeochemical estuarine functions, patterns and changes. Comprehensive data and information on estuarine processes and coastal ecosystems are limited. This Workshop is a contribution to further understanding the status and performance of coastal systems of Africa.

The Workshop was held at Simonstown, Republic of South Africa, 3-6 September 2001. A summary of activities (Appendix II) and the terms of reference for the Workshop (Appendix III) are contained in this report. The resource persons worked with Workshop participants (Appendix I) from four countries (South Africa, Kenya, Angola and Egypt) to develop and assess biogeochemical budgets for nine coastal systems in continental Africa. Further site budgets have been/are being developed at home institutions.

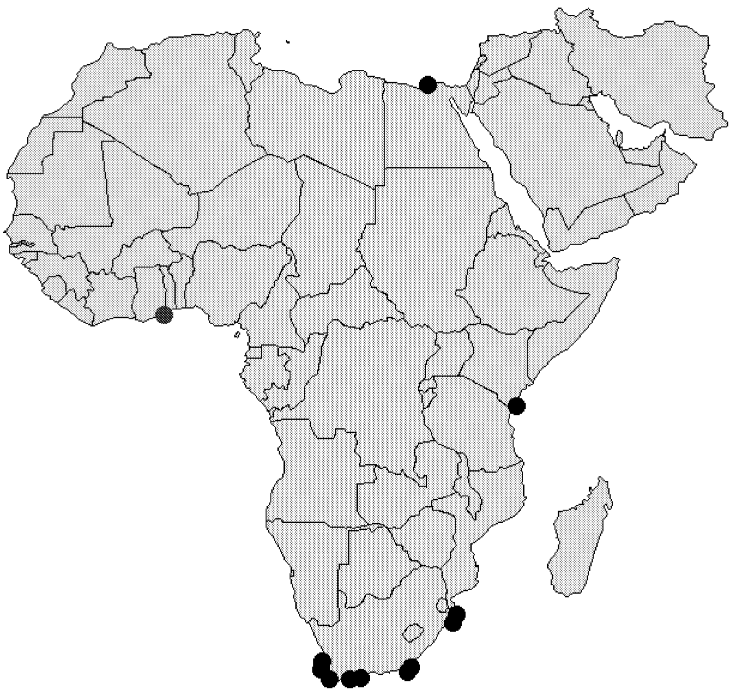


Figure 1.1 Map of budget sites developed by the African estuaries workshop.

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 an outline of the sequence of and their outcomes. 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 and published report, contributing scientists are clearly attributed as authors of their budgets, and there is provision to update and provide additional assessment of budgets through the web-site.

The group moved from the plenary session to small working groups in order to develop further the identified site budgets, returning to plenary sessions to discuss the budget developments and to debate points of approach and interpretation. Nine budgets were developed during the Workshop (Figure 1.1, Table 1.1), with additional sites identified for future work. Some of the latter are included here. The budget for False Bay, South Africa, has not been included in the printed report as the salinity data need reworking; it will be posted on the LOICZ web-site when it is finalised. The budget for the Quanza River estuary in Angola was not able to be completed due to lack of data.

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 reported here 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 regional and global assessment, comparisons and potential use in evaluating patterns of coastal system responses to 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. The estuarine systems exhibited a wide range of N and P loads and marked seasonality especially between wet and dry season flow conditions in the across the temperate, sub-temperate and tropical locations. In most cases, the wet season flow or rivers or land storage systems was of such magnitude that the conservative dilution of nutrients dominated the signal for calculation of non-conservative fluxes i.e., where water exchange times are calculated as less than about 2 days.

2. Several of the estuaries were subject to human control of flow rates, for example, the Great Fish River, the Knysna system and the Kariega system in the Republic of South Africa. The modified flow rates have implicit effects on the net metabolism of the systems.

3. In the assessment of estuarine metabolic performance, it was necessary to consider the estuarine systems as a multiple set of horizontal biogeochemical budget boxes to encompass the physical circumstances of salinity and mixing. In these cases, the inner (landward) and outer (seaward) "boxes" often showed different tendencies for relative heterotrophy and net nitrogen balance.

LOICZ is grateful for the support and efforts of Dr Howard Waldron and the staff of the Department of Oceanography, University of Cape Town in hosting the Workshop, and to the resource scientists for their contributions to the success of the Workshop. LOICZ particularly acknowledges the efforts of the participants not only for their contributed work, 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*, established with LOICZ and contributing to the UNEP sub-programme: "Sustainable Management and Use of Natural Resources".

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

System Name	**Long.** (E)	**Lat.** (S)	**Area** (km^2)	**Depth** (m)	**Exchange Time** [a] (days)
Ghana					
Angaw Lagoon	0.45	5.60 (N)	8	2	27
South Africa					
Berg River system	18.17	32.78	0.1	4	<1
Langebaan Lagoon	18.05	33.13	38	2.5	49; 10
Breede River estuary	20.85	34.40	6	2.7	8; <2
Knysna Lagoon	23.00	34.10	48	3	119; 40
Kariega River estuary	26.70	33.68	1.6	2.4	10; 1
– dry season					
– wet season					
Great Fish River system	27.13	33.50	1	2.2	<2
Mvoti River estuary – wet season	31.35	29.40	0.2	<0.4	<1
Nhlabane River estuary	32.35	28.65	0.1	2	5
Kenya					
Gazi Bay mangrove creek	39.50	4.92	15	4	9; <1
Egypt					
River Nile delta					
– Rosetta Nile estuary	30.35	31.50 (N)	40	3	3; <1
– Lake Edku	30.15	31.15 (N)	126	1	42; 16

a - annual value or dry (summer); wet (winter) season

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

System	**DIP load**	**DIN load**	**ΔDIP**	**ΔDIN**	**(*nfix-denit*)**	**(*p-r*)**
	mmol m^{-2} yr^{-1}					
Ghana						
Angaw Lagoon	<1	<1	15	438	292	-18900
South Africa						
Berg River system [a]	3540	95000	-1490	-16300	N sink	C sink
Langebaan Lagoon [b]	2	4	58	-290	-1220	-6200
Breede River estuary [c]	80	3230	0	26	26	0
Knysna Lagoon	<1	<1	22	-69	-220	-1095
Kariega River estuary						
– Dry season	<1	<1	15	146	-365	-1460
– Wet season	<1	5	-	-	N sink	C sink
Great Fish River system	3150	1160	-	-	N sink	C sink
Mvoti River estuary – wet season	1940	18900	1240	3065	N sink	C sink
Nhlabane River estuary [c]	16	2145	290	6200	1460	-30650
Kenya						
Gazi Bay mangrove creek [c]	4	16	-2	-7	-15	146
Egypt						
River Nile delta						
– Rosetta Nile estuary [c]	1890	66200	-	-	N sink	C sink
– Lake Edku	23	11	3	-150	-146	-365

a – system has a low water exchange time and materials will probably behave conservatively, jetting through the estuary to the nearshore waters.

b – loads are oceanic inputs.

c – annualised values estimated from dry season only.

2. ESTUARIES OF SOUTH AFRICA

A comprehensive description of South African estuarine types was given in Dupra *et al.* (2001). A summary of that information is repeated here, and the map of South Africa reproduced in this report shows the estuarine systems budgeted here.

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).

The South African coastal area contains a wide variety of ecosystems, including 465 estuaries along its 3000 km coastline. The wide variety of estuarine types reflects 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^2 of coastline. Compared with the USA where estuaries cover an area of 107,722 km^2 along a 10,000 km coastline, South African estuaries are indeed rather small (Allanson *et al.* 1999).

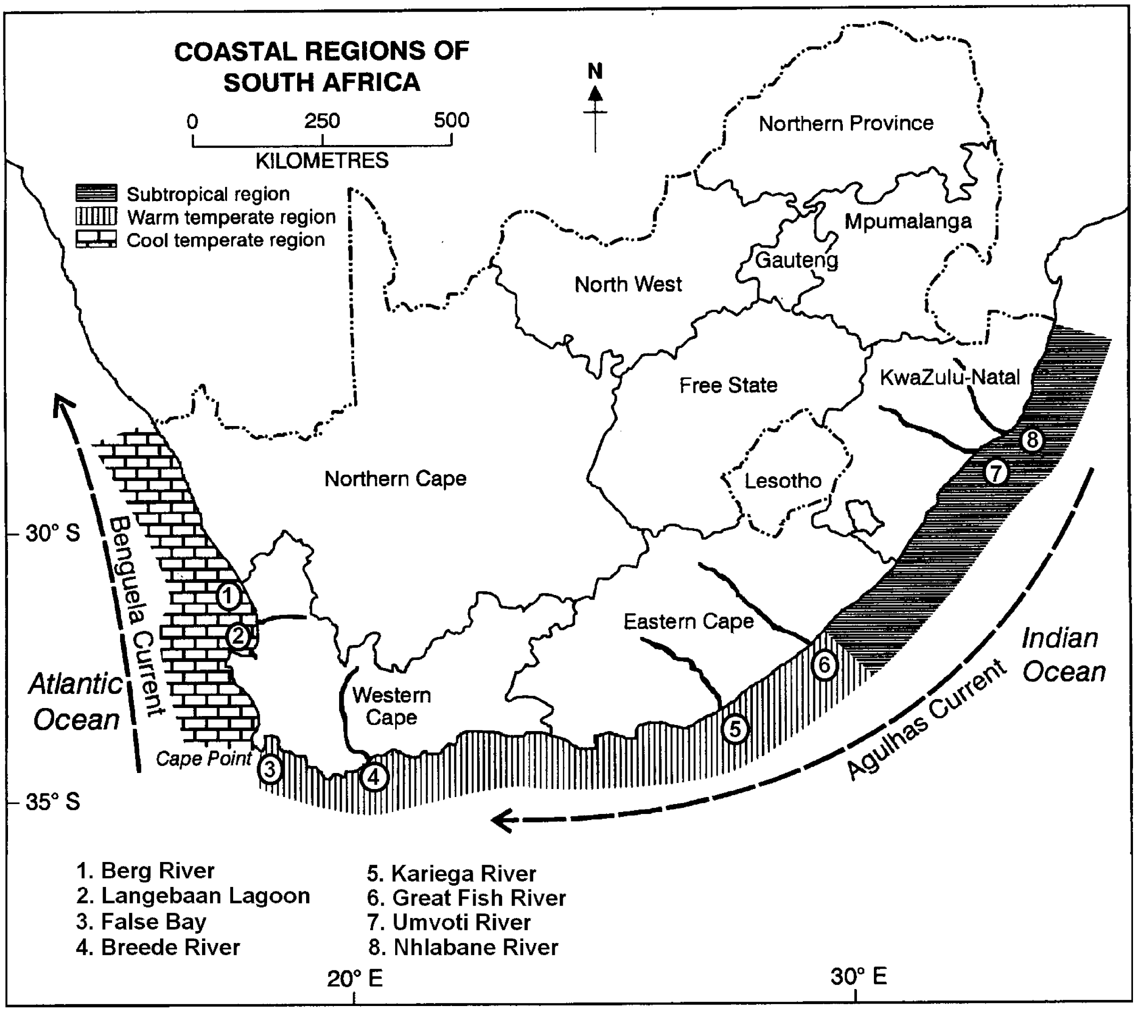


Figure 4.1. Climatological/biogeographical regions and ocean currents along the South African coast, indicating the locations of the estuarine systems budgeted in this report.

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 are 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.

Important estuarine settlements include 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

2.1 Berg River system, Western Cape

Craig Attwood, Susan Taljaard and Howard Waldron

Study area description

The Berg River rises in the Groot Drakenstein Mountains near the town of Franschoek, approximately 60 km east of Cape Town. The system drains a catchment area of about 7,720 km^2 before entering the sea at St. Helena Bay on the west coast of South Africa (32.78°S, 18.17°E; Figure 2.1).

The Berg River system flows through numerous towns as well as agricultural areas, made up mainly of vineyards and wheat fields. The estuary meanders through flat terrain, rising only 1 m in the first 50 km. Extensive flood plains which are subjected to occasional episodic flooding lie adjacent to the channel and support a rich bird population. Flow in the 294 km long river is very seasonal, with low flows in the dry summer period and higher flows during the wet winter season. The high concentration of dissolved inorganic nitrogen (DIN) in the winter runoff is largely attributed to fertilizer entering the river through the agricultural runoff. In winter the river flow is often strong and will, on occasions, prevent the incursion of the ocean through the mouth, even on high tides. The mouth of the estuary has been stabilized about 1 km north of the original mouth to provide access to the fishing harbour at the town of Laaiplek, just upstream of the mouth.

Because the river has strong seasonal characteristics, the study area was modelled for two seasons, i.e. summer (dry season) and winter (wet season). The dry season stretches from October to April (7 months), while the wet season occurs between May and September (5 months).

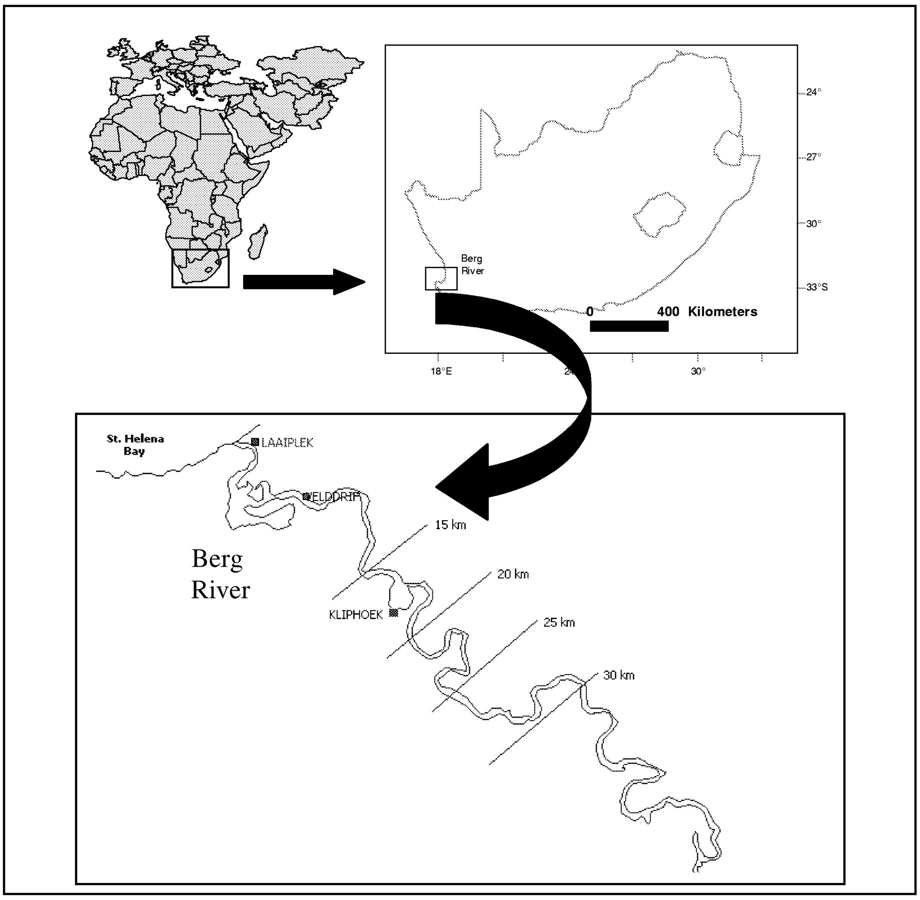


Figure 2.1: Map and location of the Berg River system.

Salinity profiles measured during field studies (Slinger and Taljaard 1994; Slinger and Taljaard 1996; Slinger *et al.* 1996) were used to select the boundaries of the three boxes in the dry season, and the one-box system in the wet season. Details of the multi-box, single-layer model for the dry season and one-box, single-layer model for the wet season are listed in Table 2.1.

Table 2.1. Details on the model set-up for the Berg River system in the dry and wet seasons.

Season	**Box**	**Boundaries**	**Depth** (m)	**Area** (km^2)	**Volume** (10^3 m^3)
Dry	Box 1	Between 25 km and 20 km from the mouth	4	0.1	400
	Box 2	Between 20 km and 15 km from the mouth	4	0.1	400
	Box 3	Between 15 km and 10 km from the mouth	3	0.15	450
Wet	Box 3	Between 15 km and 10 km from the mouth	3	0.15	450

The data on the Berg River study area were obtained from various sources. River flow, for just downstream of the Misverstand weir (~ 130 km from the mouth) was derived from simulated monthly runoff data (Huizinga, CSIR Stellenbosch, pers. comm.). Table 2.2 shows the mean monthly runoff for present conditions, which has been simulated over a 50-year period for the catchment area downstream of the Misverstand weir. This shows that the runoff downstream of the Misverstand weir contributes a negligible amount to the total Berg River runoff (DWAF 1993).

Table 2.2. Simulated monthly runoff (in m^3 sec^{-1}) for the Berg River system just downstream of the Misverstand weir.

Dry season							**Wet season**				
Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep
14	8	4	4	3	4	9	18	32	38	43	31
Average: 6 m^3 sec^{-1} or 518x10^3 m^3 day^{-1}							Average: 32 m^3 sec^{-1} or 2,760x10^3 m^3 day^{-1}				

Evaporation and precipitation data were obtained from the Department of Water Affairs and Forestry (DWAF). The precipitation data was measured at Laaiplek (near the mouth of the estuary), while the evaporation was measured at Langebaanweg (Table 2.3). The contribution of precipitation and evaporation to the water budget is however insignificant compared to the river runoff.

Table 2.3. Summary of the precipitation and evaporation for the Berg River system.

	Precipitation (mm day^{-1})	**Evaporation** (mm day^{-1})
Dry season (October - April)	0.3	6.5
Wet season (May - September)	1.1	2.0

Table 2.4 shows the salinity, dissolved inorganic phosphorus (DIP) and dissolved inorganic nitrogen (DIN) data for the dry season from a field survey conducted in February 1996 (Slinger *et al.* 1996), and the data from a field survey conducted in September 1989 was used to calculate the wet season budget

(Taljaard and Slinger 1992). The values were compared to a monthly time series data for DIP and DIN that was collected from a monitoring station on the Berg River at Jantjiesfontein (about 46 km from the mouth). The Jantjiesfontein dataset shows dry season concentration averages for DIP and DIN to be 0.7 mmol m^{-3} and 11.3 mmol m^{-3}, respectively, while DIP and DIN concentrations for the wet season were 1.0 mmol m^{-3} and 49.6 mmol m^{-3}, respectively. These long-term data set concentrations were similar to those measured during the one-off surveys, for both the dry and wet seasons.

Table 2.4. Salinity, DIN and DIP concentrations used in the budget for the Berg River system in the dry and wet seasons.

	Dry season (February 1996)			**Wet season (September 1989)**		
	Salinity (psu)	DIP (mmol m^{-3})	DIN (mmol m^{-3})	Salinity (psu)	DIP (mmol m^{-3})	DIN (mmol m^{-3})
River	0	3	13	0	0.9	42
Box 1	10	2.5	3.4	10	-	-
Box 2	15	1.6	3	15	-	-
Box 3	25	0.8	9	25	2	34
Ocean	34.8	0.4	17	35.2	2.6	32

Water and salt balance

Water and salt budgets for the dry and wet seasons are presented in Figure 2.2. Water fluxes and water exchange time are summarized in Table 2.5. Water exchange rates for both seasons were very short (<1 day).

Table 2.5. Water flux and water exchange time for Berg River system in dry and wet seasons.

	Water Flux (10^3 m^3 day^{-1})					**Water exchange time** (days)
	V_Q	V_P	V_E	V_R	V_X	τ
Dry						
Box 1	518	0.03	-0.7	-518	1,295	<1
Box 2	0	0.03	-0.7	-518	1,036	<1
Box 3	0	0.05	-1.0	-518	1,580	<1
Whole system	518	0.1	-2.4	-518	1,580	<1
Wet						
Box 3	2,760	0.2	-0.3	-2,760	8,145	<1

Budgets of nonconservative materials

DIP and DIN balance

DIP and DIN budgets are presented in Figures 2.3 and 2.4. Nonconservative fluxes for DIP (*ΔDIP*) in the dry and wet seasons were -2 mmol m^{-2} day^{-1} and -7 mmol m^{-2}day^{-1}, respectively (Table 2.6), while nonconservative fluxes for DIN (*ΔDIN*) in the dry and wet seasons were -36 mmol m^{-2} day^{-1} and -57 mmol m^{-2} day^{-1}, respectively. The system seems to behave as sink for both DIP and DIN with very rapid rates. Further stoichiometric calculations of the nonconservative fluxes to derive net system metabolism are not reliable because of the very short water exchange time.

Table 2.6. Nonconservative fluxes of DIP and DIN for the Berg River system in dry and wet seasons.

	ΔDIP		*ΔDIN*	
Dry	(10^3 mol day^{-1})	(mmol m^{-2} day^{-1})	(10^3 mol day^{-1})	(mmol m^{-2} day^{-1})
Box 1	+0.7	+7	-4.6	-46
Box 2	-0.8	-8	-5.3	-53
Box 3	-0.5	-3	-2.8	-17
Whole system	-0.6	-2	-12.6	-36
Wet				
Box 3	-1.0	-7	-8.6	-57

NOTE: The field survey data that was used for the budget calculations did NOT coincide with an ocean upwelling event, a regular occurrence during the dry season (summer) along the Cape West Coast. This might be a further source of DIN for the estuary, which makes the system more of a sink for DIN.

Acknowledgements

Our thanks go to Piet Huizinga and Lara van Niekerk of the CSIR for help and advice, Steve Smith and Laura David for pointing us in the right direction and Mrs Petro Diedericks at the Department of Water Affairs and Forestry for the supply of archived data.

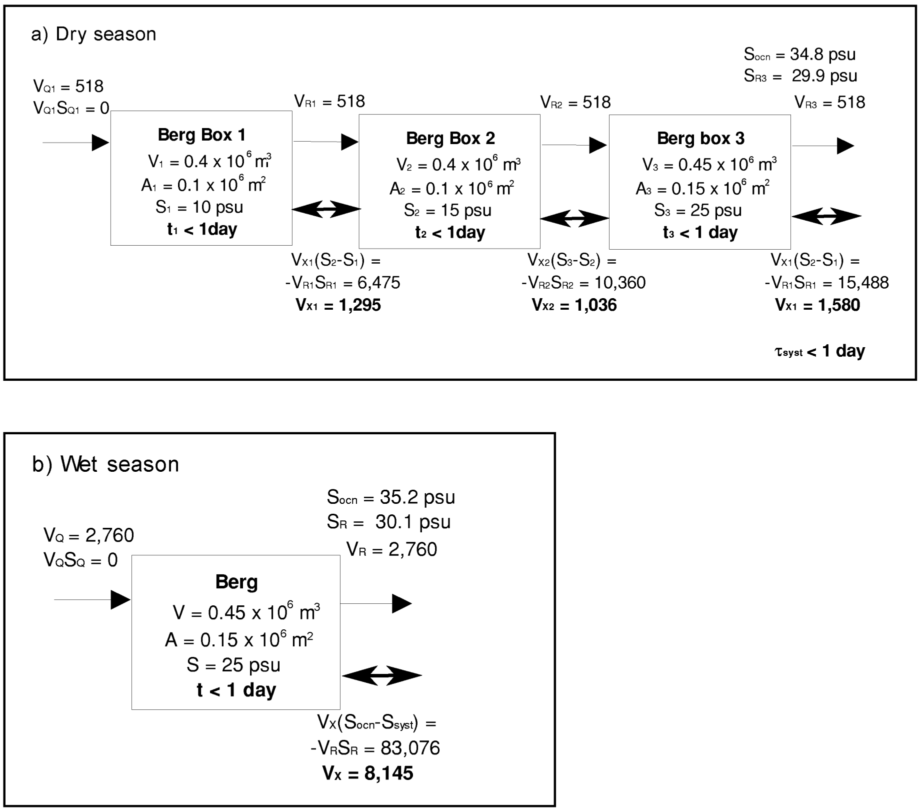


Figure 2.2. Water and salt budgets for the Berg River system in the dry (a) and wet (b) seasons. Water flux in 10^3 m^3 day^{-1} and salt flux in 10^3 psu-m^3 day^{-1}.

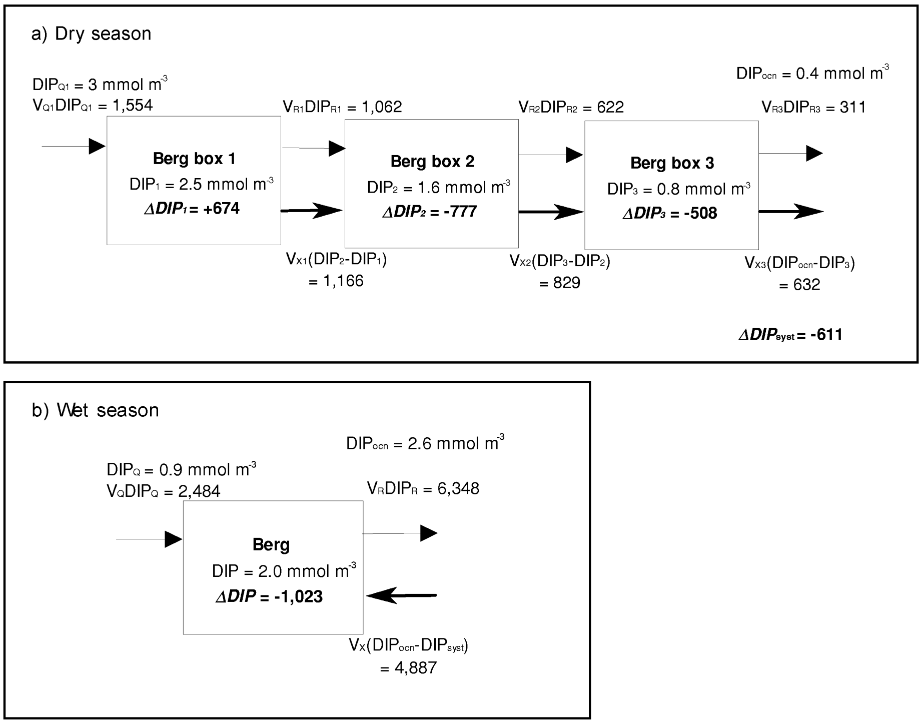


Figure 2.3. DIP budgets for the Berg River system in the dry (a) and wet (b) seasons. Flux in mol day^{-1}.

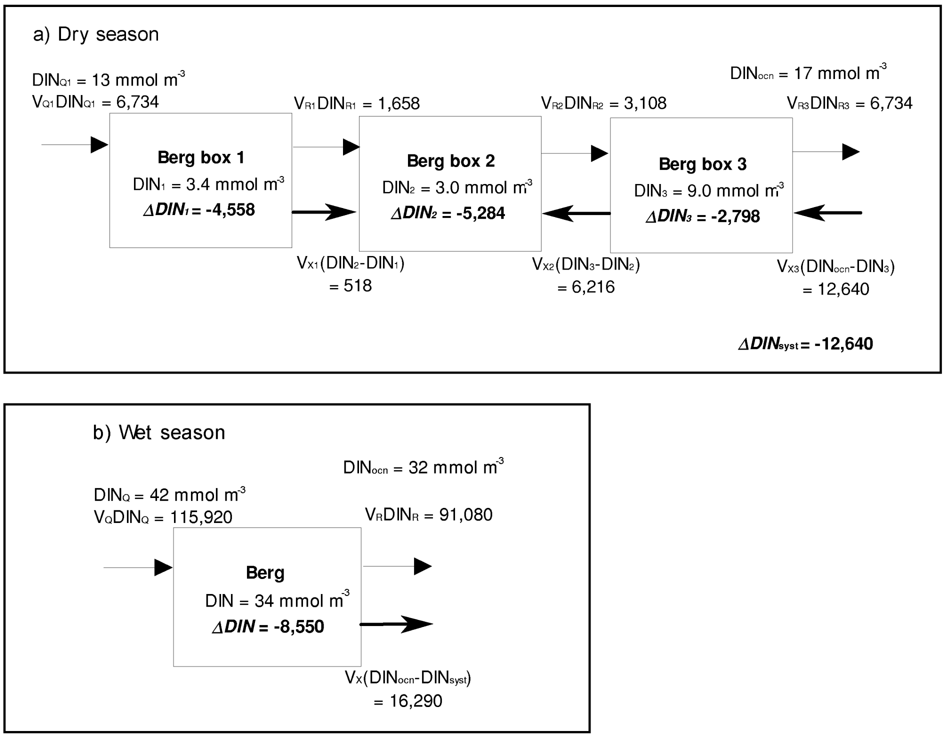


Figure 2.4. DIN budgets for the Berg River system in the dry (a) and wet (b) seasons. Flux in mol day^{-1}.

2.2 Langebaan Lagoon, Western Cape

H. Waldron, S.V. Smith and V. Dupra

Study area description

Langebaan Lagoon (33.13°S; 18.05°E) is situated on the west coast of South Africa approximately 100 km north of Cape Town (Figure 2.5). It is a meridionally orientated and sheltered arm of Saldanha Bay, a large natural embayment embedded in the southern Benguela upwelling system (Figure 2.5). The lagoon is about 15 km in length with a mean width of approximately 2.5 km, an area of 38 km^2 and average depth of 2.5 m. It is completely dominated by its adjacent marine environment and has no riverine input. The lagoon is situated in a winter rainfall area, the wet season being of about 4 months duration from May to August inclusive. The dry summer period results in the lagoon waters tending towards hypersalinity.

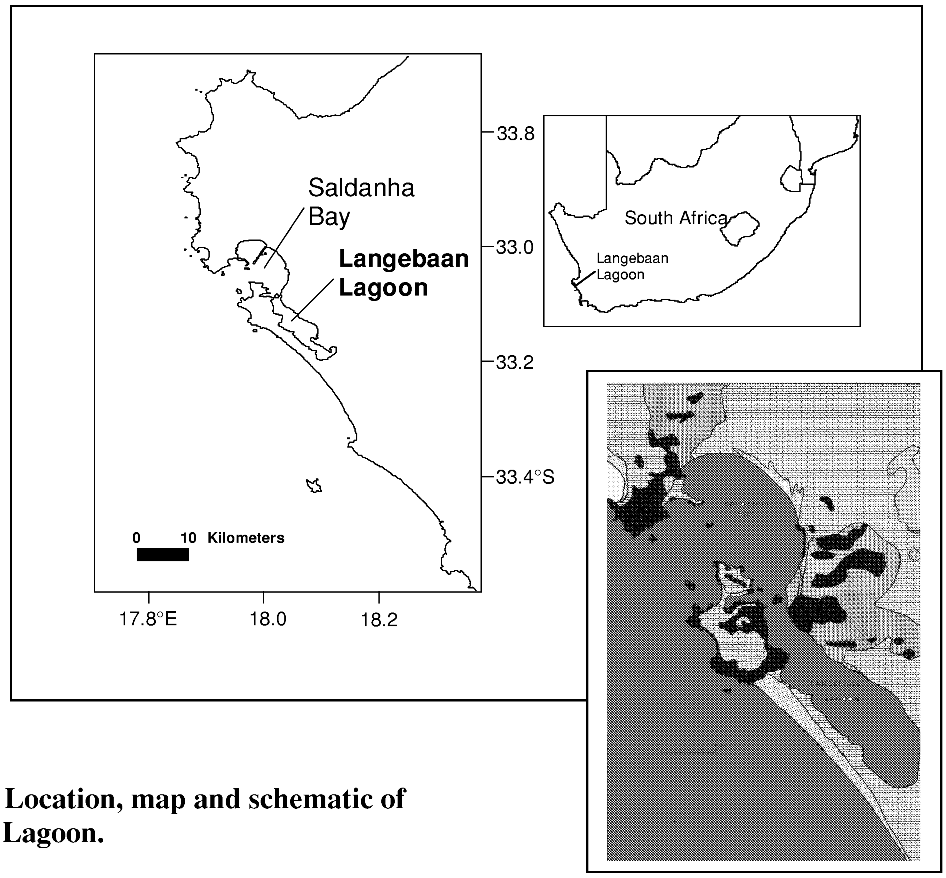


Figure 2.5. Location, map and schematic of Langebaan Lagoon.

A schematic representation of the lagoon as a system box and Saldanha Bay as the outer system is given below. Relevant seasonal data has been included so that winter and summer budgets for water, salt, dissolved inorganic phosphorus (DIP) and dissolved inorganic nitrogen (DIN) may be constructed according to the LOICZ budgeting guidelines. Data for this study were obtained from Christie (1981).

Water and salt balance

Figure 2.6 presents the water and salt budgets for Langebaan Lagoon in summer (a) and winter (b). Water fluxes and water exchange times are summarized in Table 2.7. The LOICZ approach based on the principle of conservation of mass was applied to develop the budgets. There is no river water input to the lagoon. Precipitation was three times higher in the winter and evaporation was assumed the same for the summer and winter. Salinity in the lagoon was higher than salinity of the adjacent bay for both seasons which indicates hypersalinity in the lagoon. Water fluxes in the lagoon are clearly dominated by water exchange with the outer bay. The water exchange times were 49 days in the summer and 10 days in the winter. The annual water exchange is 21 days calculated through the system volume divided by the sum of annual residual flow (V_R) and mixing volume (V_X) (Table 2.7).

Table 2.7. Water flux and water exchange time for Langebaan Lagoon in summer (September-April) and winter (May-August).

	Water flux (10^3 m^3 day^{-1})				**Water exchange time** (days)
	V_P	V_E	V_R	V_X	
Summer (8 months)	15	130	115	1,797	49
Winter (4 months)	49	130	81	9,463	10
Annual	26	130	104	4,352	21

Budgets of nonconservative materials

DIP and DIN balance

DIP and DIN budgets are shown in Figures 2.7 and 2.8, respectively. The same principle of mass conservation was applied for the nutrient budgets. The water flux data and nutrient concentrations of the system and the adjacent bay were used to develop the budgets. There were no estimated land-derived nutrient loads in the system and they were assumed insignificant in this budget. The lagoon nutrient budgets were primarily influenced by the nutrient exchange between the lagoon and the bay.

Nonconservative DIP (ΔDIP) for Langebaan Lagoon was +2,960 mol day^{-1} or +0.08 mmol m^{-2} day^{-1} in the summer and +12,090 mol day^{-1} or +0.32 mmol m^{-2} day^{-1} in the winter (Table 2.8). The lagoon appears to be a net source of DIP for both seasons.

Nonconservative DIN (ΔDIN) was -15,050 mol day^{-1} or -0.4 mmol m^{-2} day^{-1} in the summer and -59,120 mol day^{-1} or -1.6 mmol m^{-2} day^{-1} in the winter (Table 2.8). The lagoon on the other hand appears to be a net sink of DIN for both seasons.

Table 2.8. Nonconservative DIN fluxes for Langebaan Lagoon in summer (September-April) and winter (May-August).

Seasons	ΔDIP		ΔDIN	
	(mol day^{-1})	(mmol m^{-2} day^{-1})	(mol day^{-1})	(mmol m^{-2} day^{-1})
Summer (8 months)	+2,960	+0.08	-15,050	-0.4
Winter (4 months)	+12,090	+0.32	-59,120	-1.6
Annual	+6,000	+0.16	-30,000	-0.8

Stoichiometric calculations of aspects of net system metabolism

Stoichimetric calculations using the Redfield ratio (C:N:P = 106:16:1) reveal that the lagoon seems to behave as net heterotrophic both in summer and winter by 8 mmol C m^{-2} day^{-1} and 34 mmol C m^{-2} day^{-1}, respectively. The annual weighted average net system metabolism (*p-r*) was -17 mmol C m^{-2} day^{-1} using the length of the seasons as 8 months in the summer and 4 months in the winter (Table 2.9).

Nitrogen fixing minus denitrification (*nfix-denit*) was -1.7 mmol N m^{-2} day^{-1}in the summer and -6.7 mmol N m^{-2} day^{-1} in the winter. The system is net denitrifying for both seasons with an annual average of -3.4 mmol N m^{-2} day^{-1}.

Table 2.9. Apparent net system metabolism for Langebaan Lagoon in summer (September-April) and winter (May-August).

Seasons	**(*p-r*)**	**(*nfix-denit*)**
	(mmol m^{-2} day^{-1})	(mmol m^{-2} day^{-1})
Summer (8 months)	-8	-1.7
Winter (4 months)	-34	-6.7
Annual	-17	-3.4

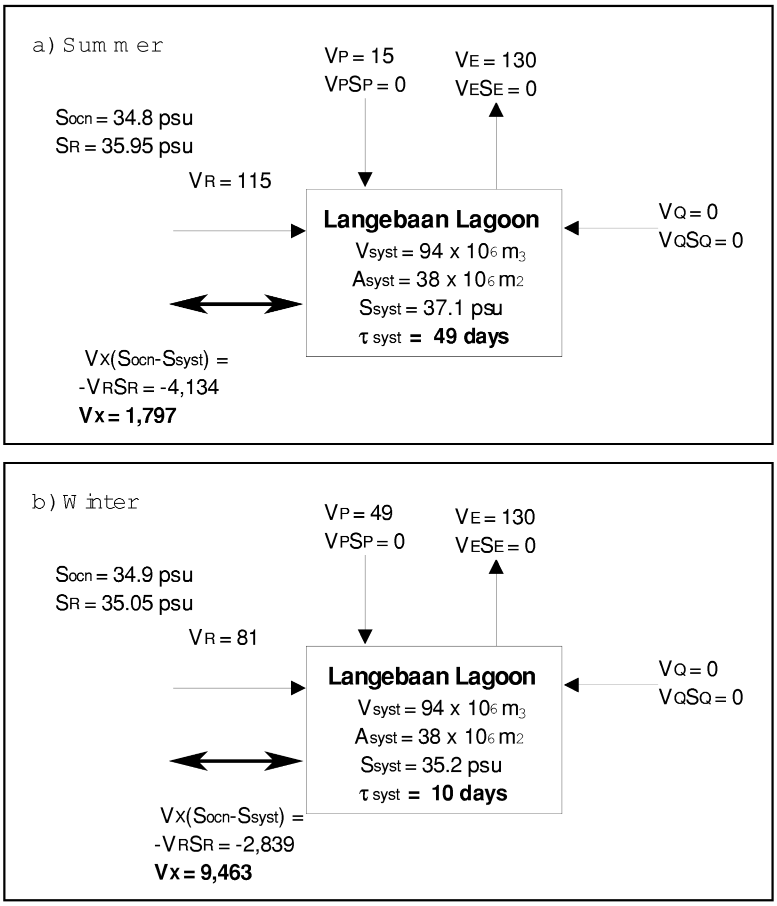


Figure 2.6. Water and salt budgets for Langebaan Lagoon in the summer (a) and winter (b). Water flux in 10^3 m^3 day^{-1} and salt flux in 10^3 psu-m^3 day^{-1}.

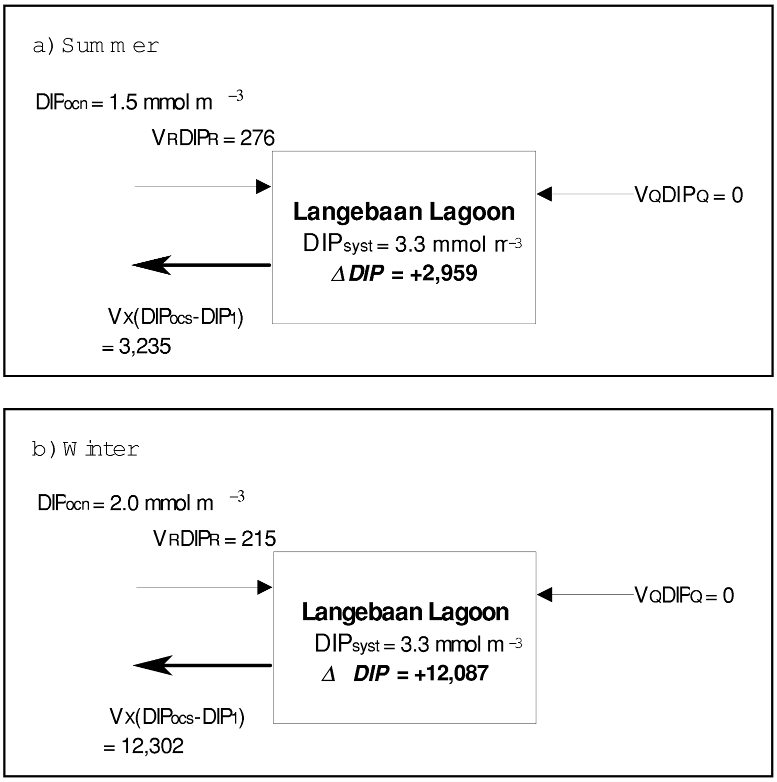


Figure 2.7. DIP budget for Langebaan Lagoon in the summer (a) and winter (b). Flux in mol day^{-1}.

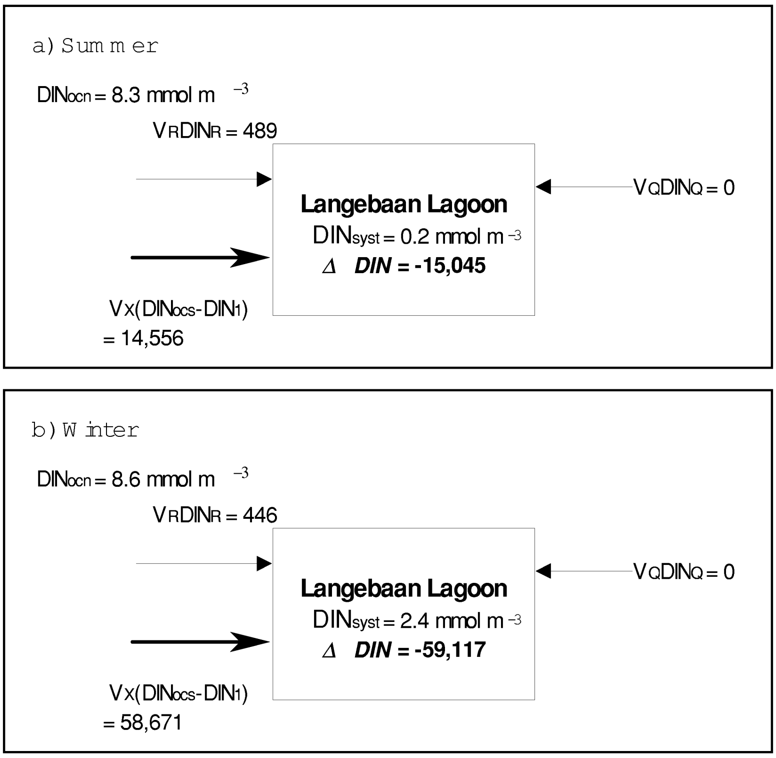


Figure 2.8. DIN budget for Langebaan Lagoon in the summer (a) and winter (b). Flux in mol day^{-1}.

2.3 Breede River system, Eastern Cape

Susan Taljaard and Craig Attwood

Study area description

The Breede River is about 260 km long with a catchment area of about 12,630 km^2. Runoff from the catchment is strongly seasonal, with high flows and major floods during winter months (June to August) and low flows during the summer (February to March) (Carter 1983). The catchment is mainly used for agriculture, in particular vineyards and wheat farming. The high concentrations of dissolved inorganic nitrogen (DIN) in the winter runoff are largely attributed to fertilizer entering the river through the agricultural runoff.

The river mouth (34.40°S, 20.85°E; Figure 2.9) is at the town of Witsand, some 220 km east of Cape Town. The estuary enters the sea through a permanently open mouth located at the southern edge of an extensive sand spit. The channel of the estuary is between 3 and 6 m deep. Seawater intrusion usually only reaches between 25 to 30 km upstream but tidal influence can extend beyond 50 km.

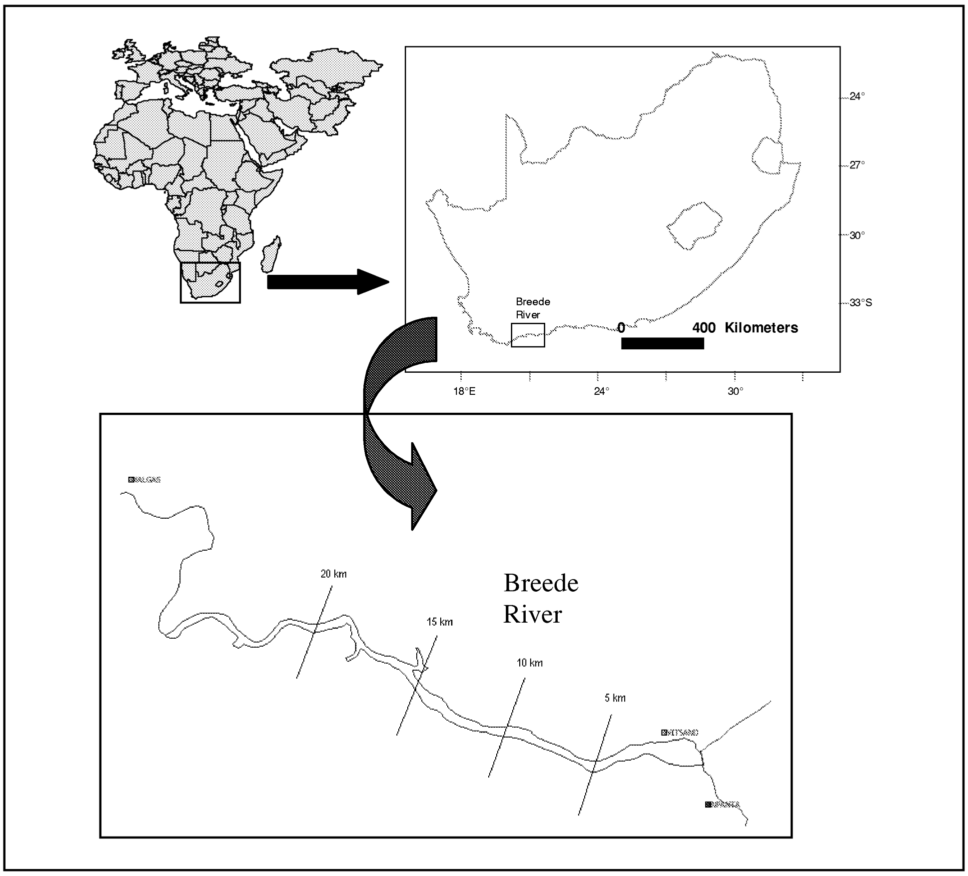


Figure 2.9. Map and location of the Breede River study area.

Because the Breede River system has strong seasonal characteristics, both in terms of runoff and DIN concentrations, the study area was modelled for three seasons: Season 1 is from January to April (4 months), Season 2 from May to August (4 months) and Season 3 from September to December (4 months).

For Seasons 1 and 3, the Breede River system was divided into two boxes (two-box, single-layer model), while for Season 2 only one box was used (one-box, single-layer model). Details on the model set-up for the different seasons are provided in Table 2.10. Salinity profiles measured during field studies were used to select the boundaries of the boxes (Taljaard *et al.* in prep.). Cross-section measurements were made along the length of the estuary (Taljaard *et al.* in prep.) and simulated using a 1-dimensional hydrodynamic model (MIKE-11).

Table 2.10. Details on the model set-up for the Breede River system.

Season	Compartment	Boundaries	Depth (m)	Area (km^2)	Volume (10^3 m^3)
Season 1 (Jan-Apr)	Box 1	Between 20 km and 10 km from the mouth	3.4	3	11
	Box 2	Between 10 km and 0 km from the mouth	2.6	6	16
Season 2 (May-Aug)	Box 1	Between 5 km and 0 km from the mouth	2.3	4	9
Season 3 (Sep-Dec)	Box 1	Between 10 km and 5 km from the mouth	3.2	2	7
	Box 2	Between 5 km and 0 km from the mouth	2.3	4	9

River inflow was derived from simulated monthly runoff data produced for the Breede River where it enters the estuary, i.e. about 50 km upstream of the mouth. The mean monthly runoff for present conditions, simulated over a 64-year period is listed in Table 2.11.

Table 2.11. Simulated runoff (in m^3 sec^{-1}) for the Breede River system (from Taljaard *et al.* in prep.).

Season 3				**Season 1**				**Season 2**			
Sep	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug
51	32	21	8	7	7	6	18	33	50	67	90
Average mid-season flow: 28 m^3 sec^{-1} or 2.4x10^6 m^3 day^{-1}				Average dry season flows: 10 m^3 sec^{-1} or 0.8x10^6 m^3 day^{-1}				Average wet season flows: 60 m^3 sec^{-1} or 5.2x10^6 m^3 day^{-1}			

NOTE: Although runoff of the month of August is typically within the range of Season 2, the river inflows at the time of the August 2000 field survey were more characteristic of Season 3. Runoff in Season 3 was also used for Season 2.

Evaporation data were taken from Taljaard *et al.* (in prep.) (Table 2.12). Precipitation data for the lower reaches of the system were not available and, as a result, data from George, a nearby city, was used (Switzer and Waldron 2001).

Table 2.12. Summary of precipitation and evaporation for the Breede River system.

	Precipitation (mm day^{-1})	**Evaporation** (mm day^{-1})
Season 1	3.7*	3.8
Season 2	1.6*	0.2
Season 3	3.2*	3.0

**The seasonality of the Breede River flows are largely influenced by the precipitation characteristics of the larger catchment, i.e. Breede River has a high winter rainfall (i.e. from June to August) and low flows during summer (i.e. January to March). However, the lower reaches near the estuary have a different precipitation pattern as indicated in the table. Therefore, these local precipitation numbers were used to calculate the precipitation on the study area.*

Salinity, dissolved inorganic phosphorus (DIP) and dissolved inorganic nitrogen (DIP) data collected during a field survey in February 2000 and August 2000, were used for seasons 1 and 3, respectively (Taljaard *et al.* in prep.). Only the nutrients for the river inflow and ocean were available. No nutrient measurements were available for the modelled area for Season 1. These parameters were derived using expert opinion which is based on an understanding of the Breede River system. The data used are listed in Table 2.13.

Table 2.13. Salinity, DIN and DIP concentrations for the Breede River system.

Salinity (psu)	**Season 1**		**Season 2**		**Season 3**	
	DIN (mmol m^{-3})	DIP (mmol m^{-3})	DIN (mmol m^{-3})	DIP (mmol m^{-3})	DIN (mmol m^{-3})	DIP (mmol m^{-3})
0 (river)	4*	0.6*	33*	0.6*	16*	0.6*
10	-	-	26	0.6	-	0.6
15	10	0.6	-	0.6	16	0.6
25	6	0.6	-	0.6	10	0.6
35 (ocean)	6	0.6	6	0.6	6	0.6

**DIN and DIP concentrations in river inflow for the different seasons were taken from a long-term data record of the DWAF measured at a station near Swellendam, some 70 km from the mouth (Taljaard et al. in prep).*

Water and salt balance

Water and salt budgets for the three seasons are illustrated in Figure 2.10. Water fluxes and water exchange time are summarized in Table 2.14. Net contribution of precipitation and evaporation were considered negligible compared to the river runoff. The water exchange times of the system boxes considered in Season 1, Season 2 and Season 3 were 8, 2 and 2 days, respectively.

Table 2.14. Water flux and water exchange time for Breede River system.

	Water flux (10^3 m^3 day^{-1})					**Water exchange time** (days)
	V_Q	V_P	V_E	$\boldsymbol{V_R}$	$\boldsymbol{V_X}$	τ
Season 1						
Box 1	800	11	11.4	800	1,600	5
Box 2	0	22	22.8	800	2,400	3
Whole system	800	33	34.2	800	2,400	8
Season 2						
Box 1	2,400	6	0.8	2,400	2,160	2
Season 2						
Box 1	2,400	7	6	2,400	4,800	1
Box 2	0	13	12	2,400	7,200	1
Whole system	2,400	20	18	2,400	7,200	2

Budgets of nonconservative materials

DIP and DIN balance
Budgets for DIP and DIN for the three seasons are presented in Figures 2.11 and 2.12, respectively. Nonconservative DIP flux (*ΔDIP*) was zero in all seasons. It appears that DIP loads via river just flow through the system and there was no net flux of nutrients between the system and the adjacent ocean as

shown by the invariable DIP concentration between compartments in all seasons. Table 2.15 summarizes the nonconservative DIN flux. The system seems a net source of DIN in all seasons.

Table 2.15. Nonconservative DIN flux for the Breede River system.

	ΔDIN	
	(10^3 mol day^{-1})	(mmol m^{-2} day^{-1})
Season 1		
Box 1	+9.6	+3.2
Box 2	-8.0	-1.3
Whole system	+1.6	+0.2
Season 2		
Box 1	+2.4	+0.6
Season 3		
Box 1	+21.6	+11
Box 2	-12.6	-3.2
Whole system	+9.6	+1.6

Stoichiometric calculations of aspects of net system metabolism

During Season 1, (*p-r*) is 0 mmol C m^{-2} day^{-1} and (*nfix-denit*) is +0.2 mmol N m^{-2} day^{-1}. This indicates that net ecosystem production is 0 and the system is net nitrogen fixing.

No apparent net system metabolism was estimated for seasons 2 and 3 for the Breede River system due to the very short water exchange time.

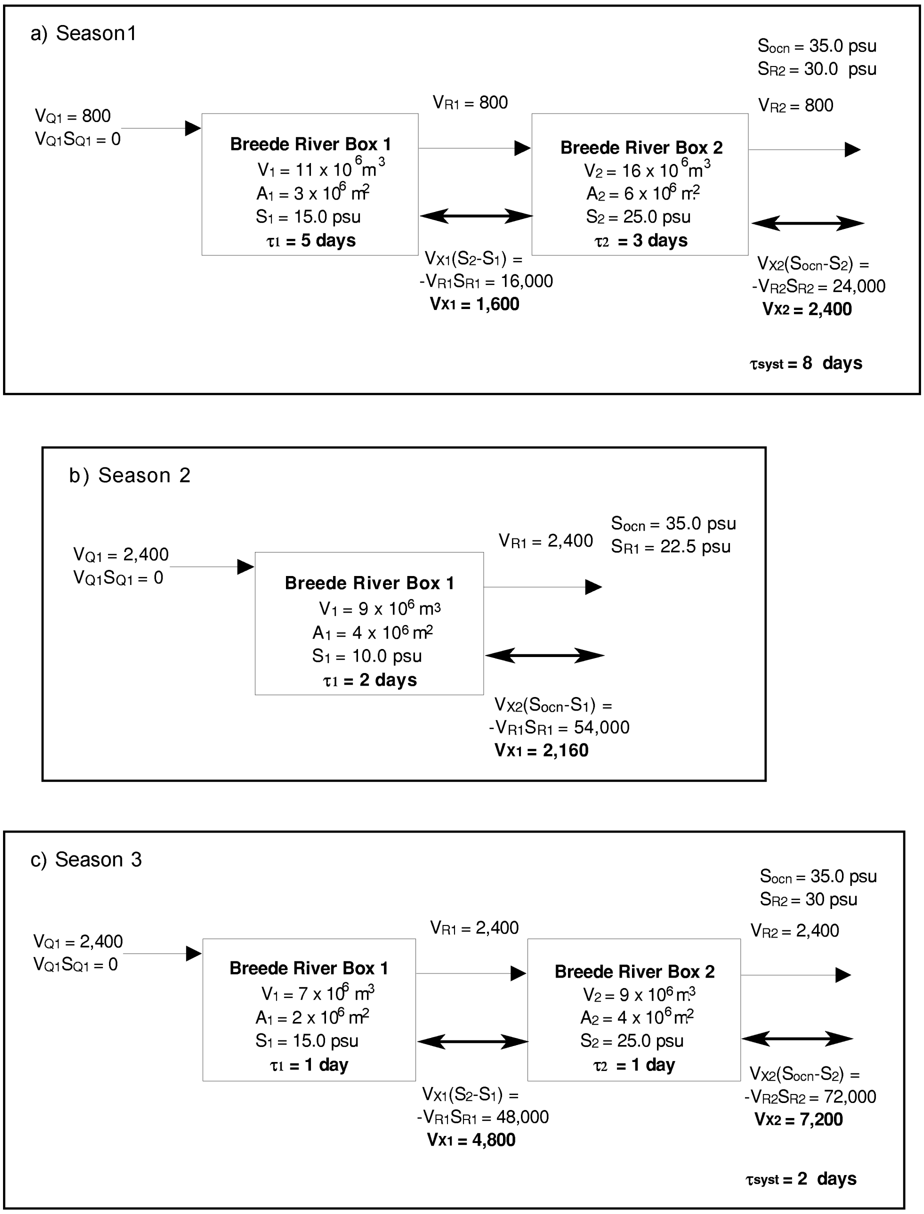


Figure 2.10. Water and salt budgets for the Breede River system in Season 1 (a), Season 2 (b) and Season 3 (c). Water flux in 10^3 m^3 day^{-1} and salt flux in 10^3 psu-m^3 day^{-1}.

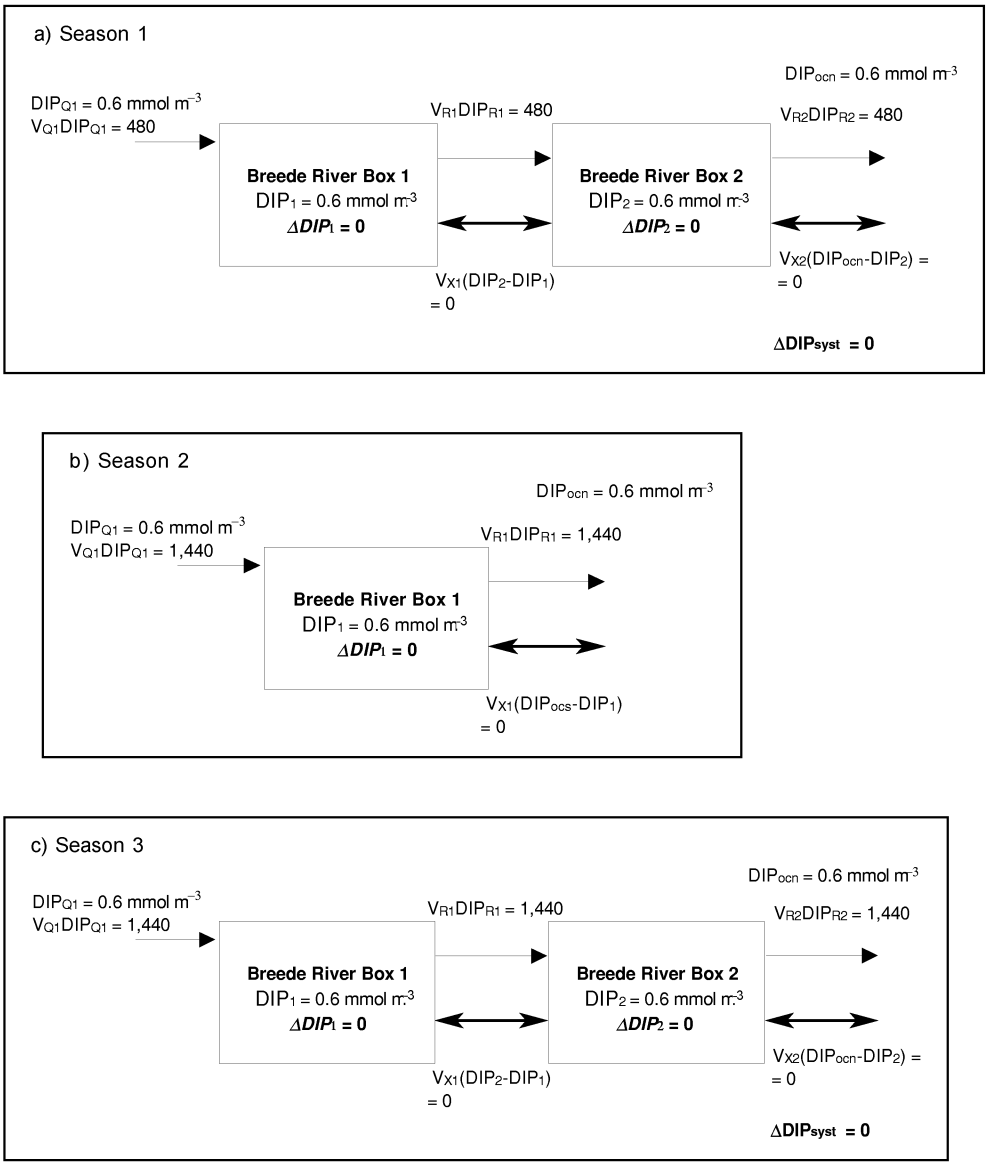


Figure 2.11. DIP budgets for the Breede River system in Season 1 (a), season 2 (b) and Season 3 (c). Flux in mol day^{-1}.

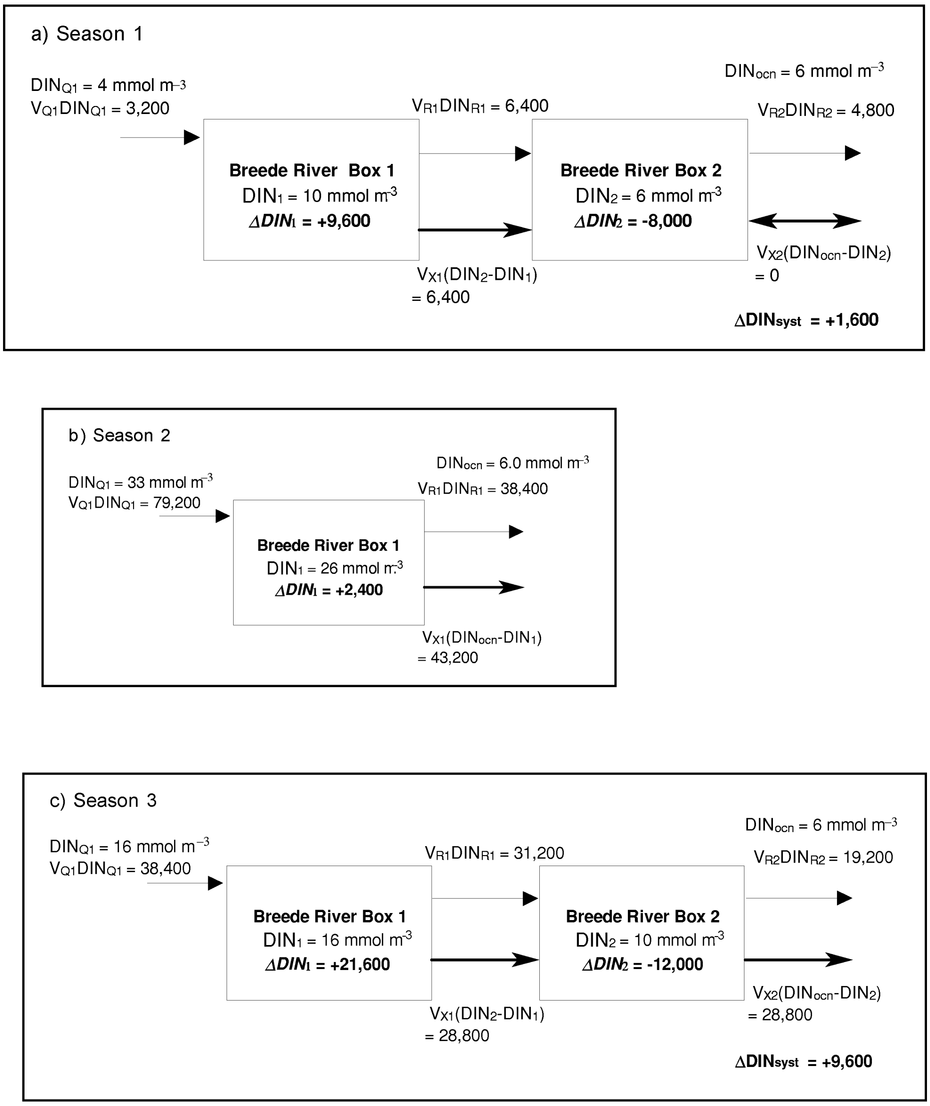


Figure 2.12. DIN budgets for the Breede River system in Season 1 (a), season 2 (b) and Season 3 (c). Flux in mol day^{-1}.

2.4 Knysna Lagoon, Eastern Cape

Todd Switzer and Howard Waldron

Note: This budget, for a year, replaces an earlier budget (Switzer and Waldron 2001) which only covered the winter season.

Study area description

Knysna Lagoon (34.10°S, 23.0°E) is located on the southern Cape coast of South Africa (Figure 2.113). 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 and salt water exchange occurs at the abrupt and perennially open interface between the estuary and the sea, called Knysna Heads (Figure 2.14). The tide in the estuary is semi-diurnal with a range of approximately 0.5m-2.0m. The tidal influence extends 19 km inland from Knysna Heads (Largier *et al.* 2000) and is prevented from further incursion by a weir.

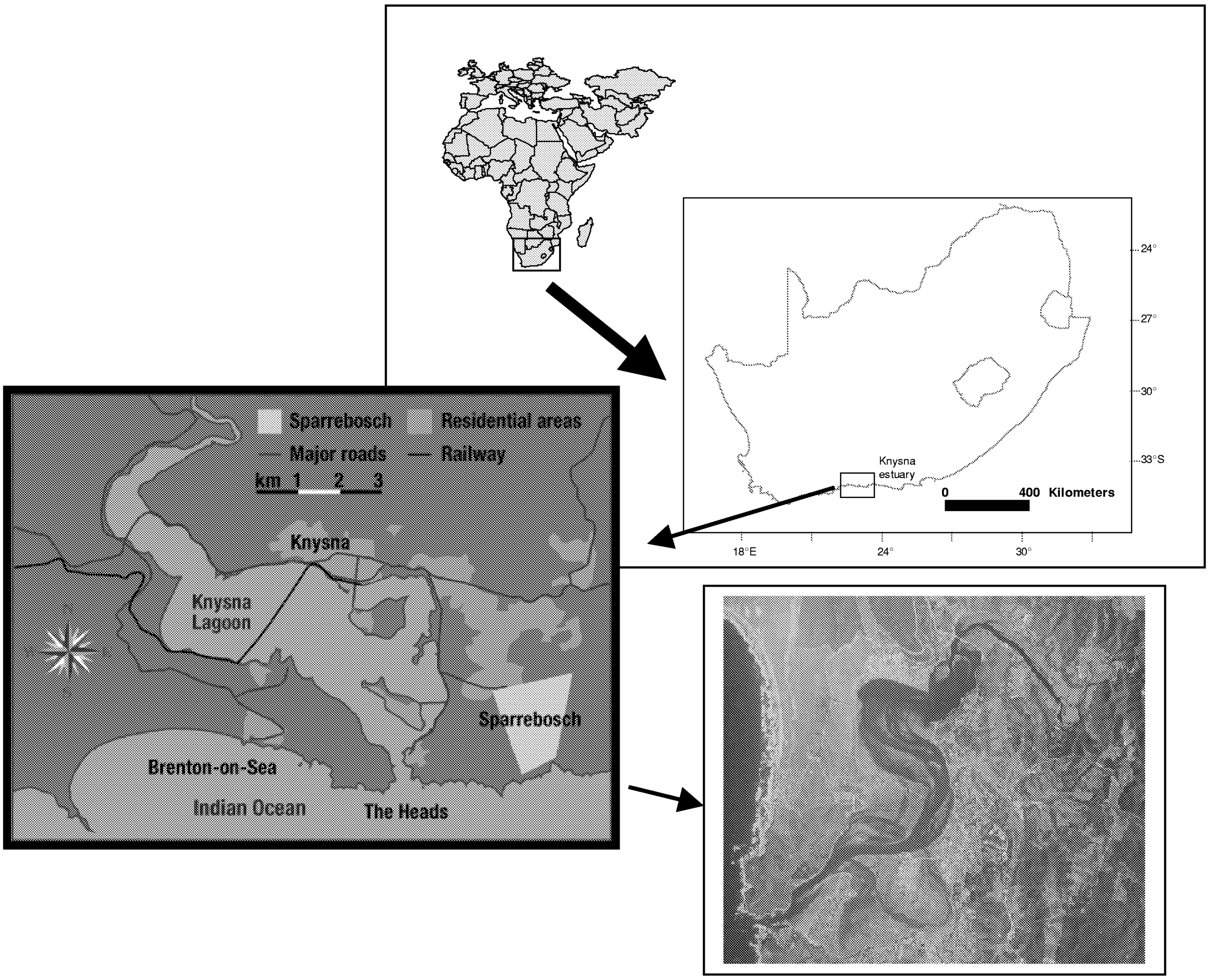


Figure 2.13. Location of Knysna River and Lagoon and aerial photograph of the system.

The climate at Knysna is transitional between the summer rainfall-dominated eastern region of 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 and minimum monthly average 16.6°C in July). The average annual precipitation for the 12-month period used in this budgeting exercise was 490 mm. The minimum monthly average of 5 mm occurred in August 2000 and the maximum of 100 mm in

November 2000. The rainfall data were collected at the South African National Parks offices on Thesen Jetty, Knysna Table 2.16). However, as annual average temperatures were not available in Knysna, the temperature data mentioned above is from the George airport, 50 km to the west (Table 2.17). The rainfall recorded for this 12-month period reflect a winter rainfall near an 80-year low for this area, while the summer values are near normal.

Table 2.16. Precipitation from SANP on Thesen Jetty, Knysna.

Year	Month	mm month^{-1}
2000	May	13
2000	June	9
2000	July	20
2000	August	5
2000	September	45
2000	October	62
2000	November	99
2000	December	81
2001	January	84
2001	February	18
2001	March	45
2001	April	43
2001	May	11

Table 2.17. Meteorological data for Knysna estuary (data were recorded at George Airport).

	Air Temperature (° C)	**Precipitation** (mm month^{-1})	**Air Pressure** (hPa)
January	24.4	134	992
February	24.6	113	992
March	23.9	120	993
April	21.7	73	994
May	19.1	59	995
June	16.8	28	997
July	16.6	39	998
August	17.7	62	998
September	19.3	73	996
October	20.4	98	996
November	21.8	108	994
December	23.4	102	992
Annual	20.8 (mean)	1,009 mm year^{-1}(total)	995 (mean)

The Knysna estuary lies immediately adjacent to the medium-sized town of Knysna, population 40,800 (February 2001 voter census information). It is subjected to a suite of pressures exerted by an urban and industrialised population, the majority of the effluent of these activities affecting the system through drainages into Ashmead Channel. The catchment area of the estuary has extensive forestry and agricultural activities. In what is becoming a typical juxtaposition, Knysna and its surrounding area is a hugely popular tourist destination. All these activities are likely to increase in the future, placing the estuarine environment under increasing anthropogenic pressure.

Figure 2.14. Knysna Heads.

The system was divided into a two-box model on the basis of salinity gradients down the navigable channel from river source (Knysna River) to the ocean (Knysna Heads). The estuary (Box 1) extended from the head of the estuarine system at the river input to the south-east end of the Bay of Biscay, where the morphology of the lagoon constricted the seaward flow. From salinity sections a haline front of 2 psu was evident at this position at low water. The bay (Box 2) extended from this position to the mouth of the system (the 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.

It should be noted that flux of groundwater has not been included in the model since the geology of the area was not thought to be conducive to groundwater transport (Grindley 1985). However, recent canals cut into Thesen Island (August 2001) have exposed a shallow water table of freshwater that is currently influencing the Ashmead Channel. This and the perennial freshwater spring which flows near Carter Jetty in the bay region of the estuary indicate that a shallow water table may have to date unmeasured influence on the Knysna estuary.

Water and salt balance

Data on river flow, precipitation and salinity were collected during a 12-month period from May 2000 through May 2001. Evaporation was calculated via Hamon's equation for potential evaporation. In the winter period, there was a mixing volume of water (V_X) of $106\text{x}10^3$ m^3 day^{-1}, and $2{,}866\text{x}10^3$ m^3 day^{-1} between the estuary (Box 1) and the bay (Box 2), and between the bay and the ocean, respectively. In the summer period, there was a mixing volume (V_X) of $51\text{x}10^3$ m^3 day^{-1} between the estuary and the bay, and $958\text{x}10^3$ m^3 day^{-1} between the bay and the ocean. Taking into consideration the dramatic change in the freshwater inputs of the estuary and the bay from winter to summer during this period, the increases in residual flux (V_R) over this time period are reasonable.

Following the underlying physical principles of the LOICZ budgeting method, salt must be conserved. The mixing salt flux $V_X(S_{ocn}\text{-}S_{syst})$, denoting the salt that is brought back to the estuary from the bay to balance in the system across intra- and inter- system boundaries. This can be seen in the figures given in the model for $V_X(S_{ocn}\text{-}S_{sys})$ of $394\text{x}10^3$ psu-m^3day^{-1} between the estuary and the bay, and $1{,}433\text{x}10^3$ psu-m^3day^{-1} between the bay and the ocean for the winter season. For the summer season these values increase to $729\text{x}10^3$ psu m^3day^{-1} and $1{,}915\text{x}10^3$ psu-m^3day^{-1}, respectively.

The water exchange time during winter in the estuary was given as 119 days and in the bay as 34 days. In the summer, the water exchange time 177 days for the estuary and 95 days for the bay. For the whole Knysna system, the water exchange time was 40 days in the winter and 114 days in the summer. This water exchange time was primarily determined by the mixing volume which was calculated based on residual salt flux and salinity gradients between compartments. Given this, the increase in water exchange time for the estuary and the bay from winter to summer results from the increasing residual flux. Table 2.18 and Figure 2.15 summarise the water flux, salinity and water exchange time for the system.

Table 2.18. Water flux, salinity and water exchange time for Knysna Lagoon in winter and summer.

	Water Flux (10^3 m^3 day^{-1})						**Salinity** (psu)		**Water exchange time** (days)
	V_Q	V_G	V_P	V_E	$\boldsymbol{V_R}$	$\boldsymbol{V_X}$	S_{syst}	S_{ocn}	τ
Winter									
Box 1	7	0	7	2	12	106	31.0	34.7	119
Box 2	0.2	4	33	8	41	2,866	34.7	35.2	34
Whole system	7.2	4	40	10	41	2,866	34.7	35.2	40
Summer									
Box 1	23	0	7	2	28	51	18.9	33.2	177
Box 2	0	4	33	9	56	958	33.2	35.2	96
Whole system	23	4	40	11	56	958	33.2	35.2	114

Budgets of nonconservative materials

DIP and DIN balance

The criteria established in the water and salt budgets also apply to exchanges of dissolved inorganic phosphorus and nitrogen with the caveat that deviations result from net nonconservative reactions of the nutrients in the system. Concentrations of PO_4 (DIP), and NO_3, NO_2 and NH_4 (DIN) were available from samples taken at stations spaced at intervals of approximately 400m along the navigable channel of the estuary and the bay. These 14 stations were sampled quasi-synoptically, 16 times (8 during HWST and 8 during LWST) during the period of study.

In order to obtain a single representative value for the estuary and bay in this model, the full suite of nutrient concentrations from each station was averaged with respect to the given season. This gave a single mean value for DIP and DIN for the estuary and bay for each of winter and summer.

The nutrient concentrations were also determined for river inputs, point-sources (including sewage) and the adjacent ocean for each season. The value of DIP and DIN for the ocean was assumed constant at 5.3 and 1.1 mmol m^{-3}, respectively (Prof. Dan Baird, personal communication).

The average nutrient concentrations of point source water, weighted for their respective flow volumes, were calculated and this value used in the model as representative of all point source input for each season. The values obtained in testing these point sources for DIP and DIN were remarkably consistent between winter and summer.

Water samples from both the Knysna River and the Salt River were taken several times in both summer and winter conditions. The nutrients and flow rates represented in this report (Table 2.19) demonstrate conditions of flow situations that were typical for each season. It should be noted that the concentrations of nutrients in these rivers varied substantially depending upon flow rates, rainfall (duration and magnitude) during the summer, while they remained consistent during this dry winter period.

Table 2.19. Nutrient concentrations for Knysna Lagoon and the adjacent ocean in the winter and summer.

	DIP (mmol m^{-3})		DIN (mmol m^{-3})	
	DIP_{syst}	DIP_{ocn}	DIN_{syst}	DIN_{ocn}
Winter				
Box 1	0.6	1.5	3.3	5.3
Box 2	1.5	1.1	5.3	5.4
Summer				
Box 1	0.6	1.5	5.1	4.2
Box 2	1.5	1.1	4.2	5.4

The mixing fluxes of DIP ($Vx(DIP_{ocn} - DIP_{syst})$) in the winter between the estuary and the bay, and between the bay and the ocean were +95 mol day^{-1} (flux to the estuary) and -1,146 mol day^{-1}(flux from the bay), respectively. For the summer these values were +46 mol day^{-1} for the estuary and -383 mol day^{-1} for the bay.

Nonconservative DIP fluxes (ΔDIP) in the winter for the estuary were -83 mol day^{-1} and +990 mol day^{-1} for the bay. For the summer these values were -22 mol day^{-1} for the estuary and +208 mol day^{-1} for the bay. Calculated for the unit area these values become -0.03 mmol m^{-2} day^{-1} and +0.06 mmol m^{-2} day^{-1} for the estuary and bay in the winter, and -0.007 mmol m^{-2} day^{-1} and +0.01 mmol m^{-2} day^{-1} for the estuary and bay in the summer, respectively (see Figure 2.16).

This indicates that the estuary is experiencing a net loss of DIP while the bay realises a net gain at the annual time scale. These figures support the contention that the estuary and bay regions defined for this budget are operating as separate systems. Given the system total surface area of 18.5 km^2 (3 km^2 for the estuary, 15.5 km^2 for the bay) this translates to a system average DIP production normalised with respect to area of 0.03 mmol m^{-2} day^{-1}.

The DIN fluxes ($V_X(DIN_{ocn} - DIN_{sys})$) between estuary and bay and bay and the ocean were +212 mol day^{-1} and +287 mol day^{-1} for the winter, and -46 mol day^{-1} and +1,150 mol day^{-1} for the summer, respectively.

Nonconservative DIN flux (ΔDIN) for the estuary was -167 mol day^{-1} and -409 mol day^{-1} for the bay in the winter. For the summer these values were +112 mol day^{-1} for the estuary and -3,077 mol day^{-1} for the bay. Calculated these values for the unit area they become -0.06 mmol m^{-2} day^{-1} and -0.03 mmol m^{-2} day^{-1} for the estuary and bay in the winter, and +0.04 mmol m^{-2} day^{-1} and -0.2 mmol m^{-2} day^{-1} for the estuary and bay in the summer, respectively (Figure 2.17).

This indicates that both the estuary and bay were experiencing a net loss of DIN during the winter months. During the summer period the estuary is experiencing a net gain of DIN while the bay realises a net loss of DIN.

Calculating the nonconservative DIN fluxes (ΔDIN) by unit area gives values of -0.06 mmol m^{-2} day^{-1} and -0.03 mmol m^{-2} day^{-1} in the winter and +0.04 mmol m^{-2} day^{-1} and -0.2 mmol m^{-2} day^{-1} during the summer for the estuary and the bay, respectively.

Nonconservative fluxes are summarised in Table 2.20.

Table 2.20. Nonconservative fluxes of DIP and DIN for the Knysna Lagoon in winter and summer.

	ΔDIP		ΔDIN	
	(mol day^{-1})	(mmol m^{-2} day^{-1})	(mol day^{-1})	(mmol m^{-2} day^{-1})
Winter				
Box 1	-83	-0.03	-167	-0.06
Box 2	+990	+0.06	-409	-0.03
Whole system	+907	+0.05	-576	-0.03
Summer				
Box 1	-22	-0.007	+112	+0.04
Box 2	+208	+0.01	-3,077	-0.20
Whole system	+186	+0.01	-2,965	-0.16

Stoichiometric calculations of aspects of net system metabolism

Assuming that all the nonconservative behaviour is of biological origin, and the Redfield ratio applies to the system as a whole, then the observed ΔDIP values in the Knysna system can be used to estimate the net production of organic matter. The nonconservative flux can be calculated using the formula:

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

The expected ΔDIN (ΔDIN_{exp}) can be determined using the Redfield ratio of 16:1 for N:P, and the observed value for ΔDIP (ΔDIP_{obs}). This allows ΔDIN_{exp} to be expressed as $16(\Delta DIP_{obs})$.

Yielding values of +0.4 mmol N m^{-2} day^{-1} and -1.0 mmol N m^{-2} day^{-1} for the estuary and bay during the winter, respectively. For the summer these values are +0.2 mmol N m^{-2} day^{-1} for the estuary and -0.4 mmol N m^{-2} day^{-1}for the bay.

This would indicate that the estuary is fixing nitrogen while the bay is denitrifying during both winter and summer. Given the increase of mudflat areas in the bay region as compared with the estuary, it is conceivable that the loss of nitrogen as calculated by this method is due to sediment-driven denitrification. These results indicate that, on balance, the system is a net denitrifying environment by 0.6 mmol N m^{-2} day^{-1}.

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

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

Values of +3 mmol C m^{-2} day^{-1} and -6 mmol C m^{-2} day^{-1} were obtained for the estuary and the bay during winter, respectively. For the summer period these values were +0.7 mmol C m^{-2} day^{-1} and -1 mmol C m^{-2} day^{-1}. The estuary can be viewed as a net producer of organic matter, while the bay is a net consumer of organic matter. The whole Knysna system is net heterotrophic by 3 mmol C m^{-2} day^{-1} (Table 2.21).

Table 2.21. Apparent net system metabolism for Knysna Lagoon in the winter and summer.

	(p-r)	*(nfix-denit)*
	(mmol C m^{-2} day^{-1})	(mmol N m^{-2} day^{-1})
Winter		
Box 1	+3	+0.4
Box 2	-6	-1.0
Whole system	-5	-0.8
Summer		
Box 1	+0.7	+0.2
Box 2	-1	-0.4
Whole system	-1	-0.3

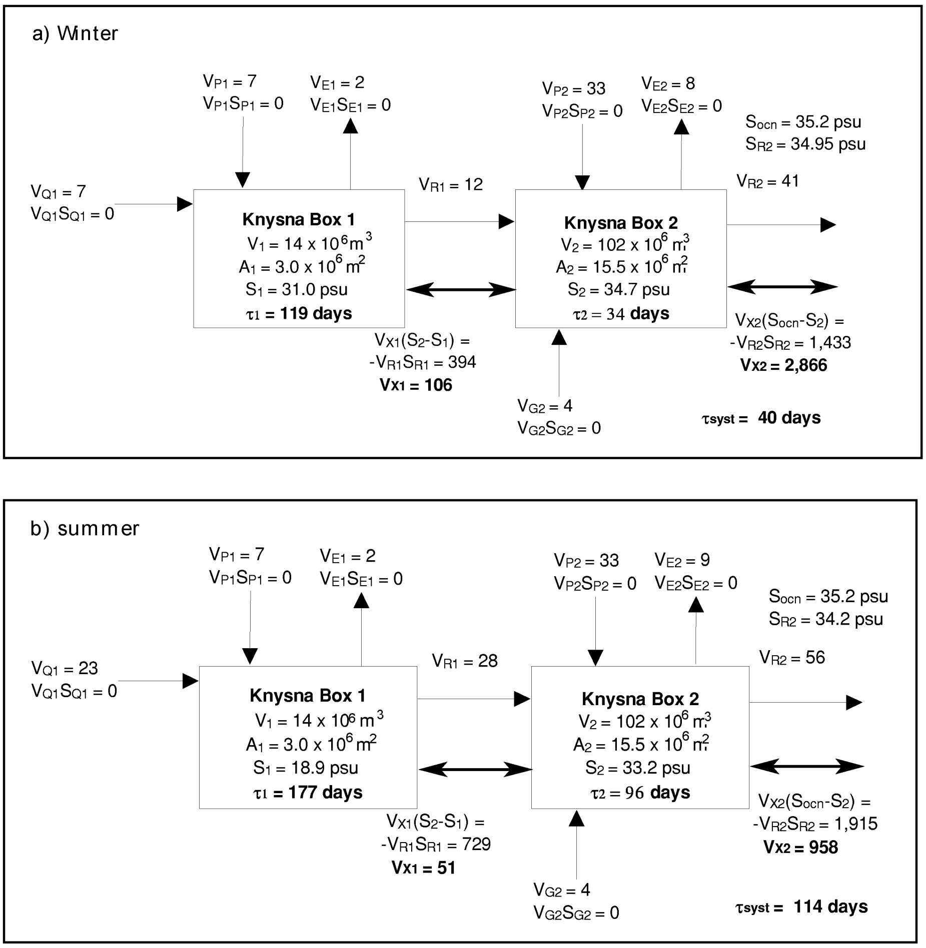


Figure 2.15. Water and salt budgets for Knysna Lagoon in the winter (a) and summer (b). Water flux in 10^3 m^3 day^{-1} and salt flux in 10^3 psu-m^3 day^{-1}.

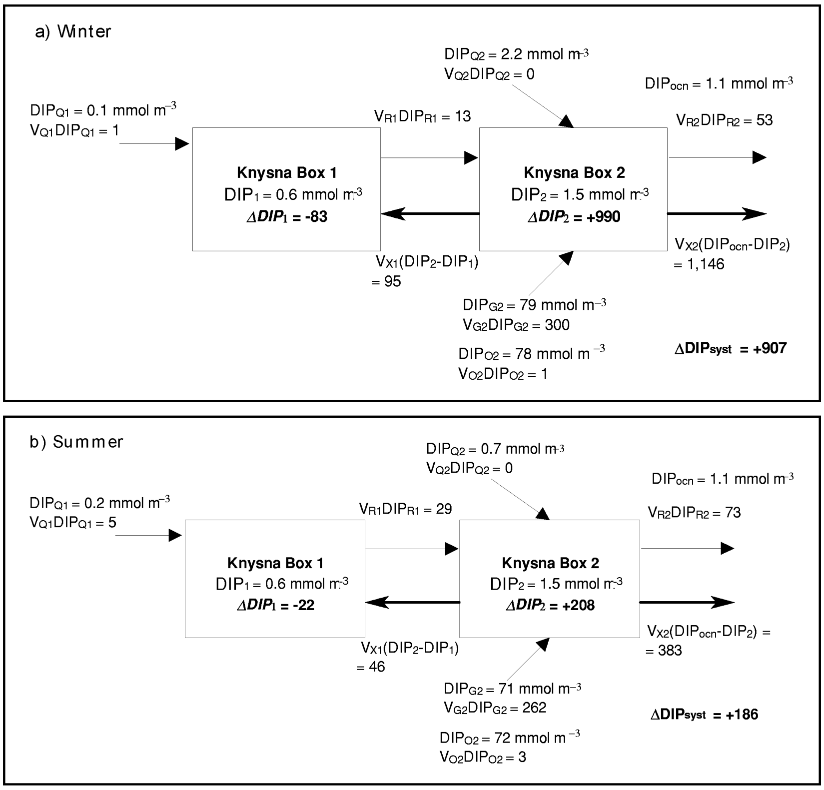


Figure 2.16. DIP budget for Knysna lagoon in the winter (a) and summer (b). Flux in mol day^{-1}.

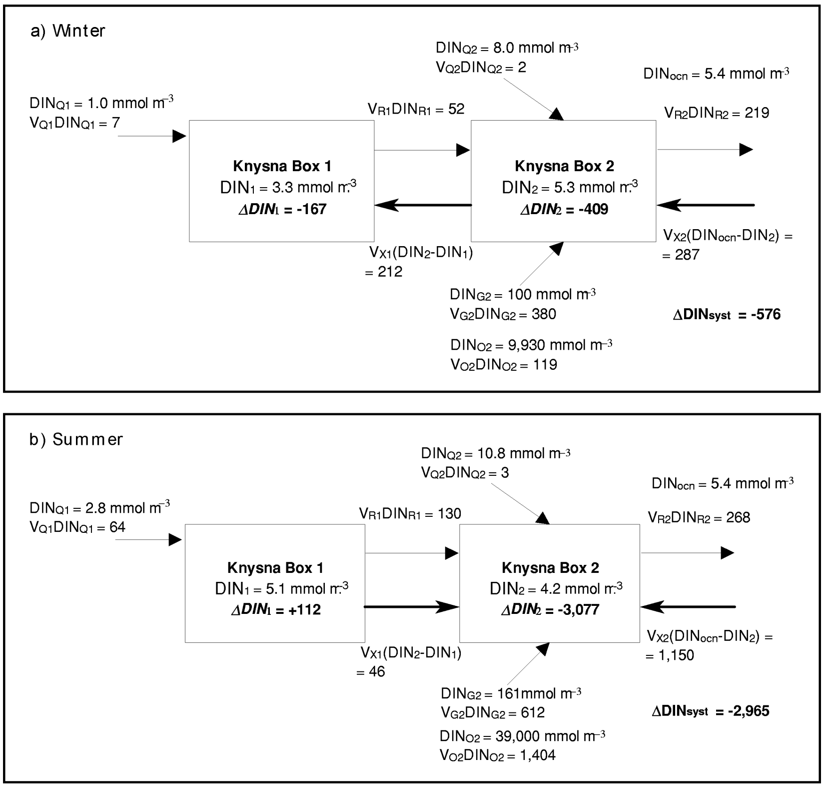


Figure 2.17. DIN budget for Knysna Lagoon in the winter (a) and summer (b). Flux in mol day^{-1}.

2.5 Kariega River estuary, Eastern Cape

Brian Allanson and Nadia Smith

<u>Study area description</u>

The Kariega River estuary (33.68°S, 26.70°E; Figure 2.18) is a relatively small system with a surface area of 1.6 km^2 and a length of about 17 km. The average depth of the estuary is 2.4 m. It has a small catchment of about 690 km^2. Dams have regulated the main stream and the tributaries and in view of the semi-arid nature of the catchment, streams often have to fill the dams first before water is spilled downstream. As a result of low freshwater inflow, the Kariega River estuary is a homogeneous marine-dominated system (Grange and Allanson 1995). The estuary rarely shows thermohaline stratification and during extended droughts the system behaves as a negative estuary. This system, as with many other Eastern Cape estuaries, has a small tidal prism (of the order of 10^6 m^3). Changes in the water level occur in response to the semi-diurnal and spring-neap cycles (MacKay and Schumann 1990).

Recent studies by Taylor (1992), Taylor and Allanson (1993, 1995) have emphasized the role of intertidal wetlands in the Kariega River estuary, while Grange and Allanson (1995) underlined the major influence of freshwater inflow upon the nature, distribution and amount of seston in the estuaries of the Eastern Cape. The system is described as oligotrophic, with extremely low phytoplankton standing stocks (indicated by chlorophyll *a*) throughout the year.

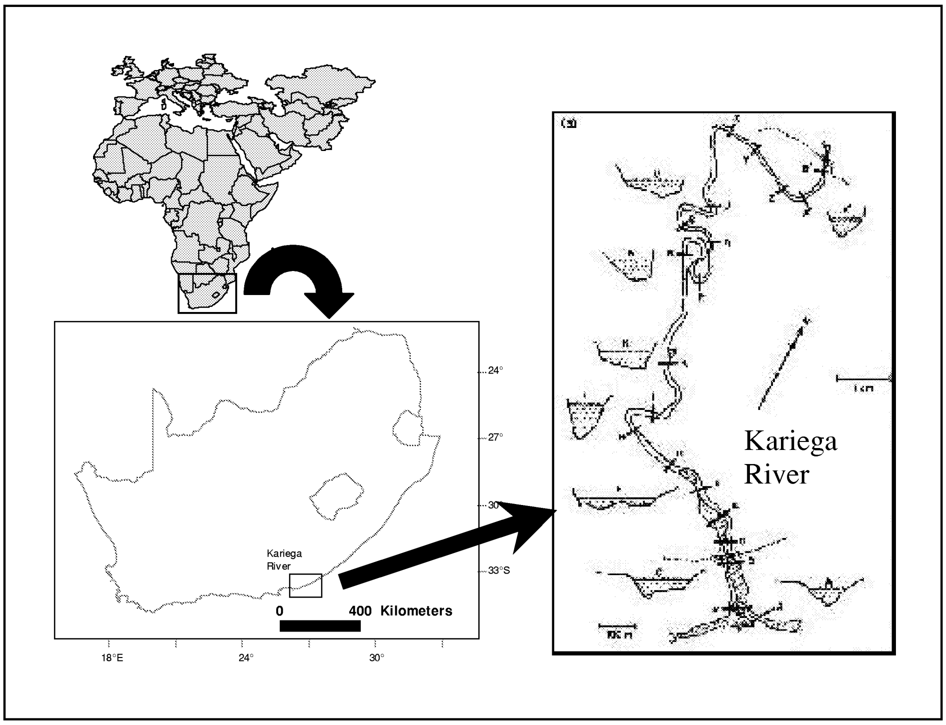


Figure 2.18. Location and morphometry of the Kariega River.

<u>Water and salt balance</u>

The estuary was divided halfway along its length into two boxes (Box 1 and Box 2) to accommodate the significant salinity gradient. Within each box a budget was calculated for dry (September–October) and wet (November–December) periods in 1984. The estuary occurs in the warm temperate climatological region (de Villiers and Hodgson 1999), the transition zone between summer rainfall (eastern) and winter rainfall (Western Cape) regions. Thus, wet and dry periods relate to stochastic episodes of minimum and maximum flow, rather than seasonal flow regimes.

Precipitation and evaporation data for these periods were obtained from the South African weather service, CLIP section. Precipitation rates were measured at Grahamstown municipality and evaporation at Somerset East.

Figure 2.19 illustrates the water and salt budgets for Kariega River estuary in the dry (a) and wet (b) periods. Results are summarized in Table 2.22. In the dry period where river runoff is zero, water exchange time for the whole estuary with the adjacent ocean is about 10 days. In the wet period, water exchange time is about one day.

Table 2.22. Water flux, salinity and water exchange time for Kariega River estuary in the dry and wet periods.

	Water Flux (10^3 m^3 day^{-1})					**Salinity** (psu)		**Water exchange time** (days)
	V_Q	V_P	V_E	$\mathbf{V_R}$	$\mathbf{V_X}$	S_{syst}	$\underline{S_{ocn}}$	τ
Dry								
Box 1	0	0	-4	+4	38	40.0	36.0	42
Box 2	0	0	-4	+8	356	36.0	35.2	5
Whole system	0	0	-8	+8	356	36.0	35.2	10
Wet								
Box 1	250	205	-4	-451	324	4.5	25.0	2
Box 2	0	205	-4	-652	1,956	25.0	35.0	<1
Whole system	250	410	-8	-652	1,956	25.0	35.0	1

Budgets of nonconservative materials

The Kariega River estuary is not subjected to significant point sources of nutrient input, although agricultural runoff during high rainfall may contribute additional dissolved inorganic phosphorus and nitrogen (DIN and DIP) to the system. The DIN load delivered via the river in the wet season, though minimal, was the only nutrient input in the budgets.

Hourly measurements of DIN and DIP throughout a spring tide cycle were taken in 1984 during an extended drought and following a short period of rain which allowed the river to flow. The results are likely to be close to the mean of the values (expressed per day) if the samples had been obtained over much longer periods in view of the extended nature of the dry periods within the Kariega catchment. Similarly, the river flow data would be typical of characteristically short periods of heavy rain.

Nutrient concentrations for the estuary and adjacent ocean are presented in Table 2.23 Mean DIP concentrations in the estuary compartments are slightly higher than DIP in the adjacent ocean in both the dry and wet periods. On the other hand, the mean DIN concentrations in the adjacent ocean were about twice as high as the mean DIN concentrations in the system.

Table 2.23 Nutrient concentrations for Kariega River estuary and the adjacent ocean in the dry and wet periods.

	DIP (mmol m^{-3})		DIN (mmol m^{-3})	
	DIP$_{syst}$	DIP$_{ocn}$	DIN$_{syst}$	DIN$_{ocn}$
Dry				
Box 1	1.1±0.1	0.6	2.3±0.8	1.6
Box 2	0.6±0.2	0.4	1.6±1.2	3.2
Wet				
Box 1	0.6±0.2	0.5	0.2±0.1	1.9
Box 2	0.5±0.04	0.4	1.9±1.7	3.2

DIN and DIP balance

Nonconservative DIP flux (ΔDIP) is positive for both upper (Box 1) and lower (Box 2) estuary in the dry and wet periods (Figure 2.20; Table 2.24). This indicates that the system behaves as a net source for DIP. This is consistent with Taylor's (1992) investigation of the release of DIP from system salt marshes and the well-established pattern of DIP mobilization between estuarine compartments where new DIP sources (e.g., via river inflow) are limited.

For nonconservative DIN flux (ΔDIN), the whole system with the exception of the upper estuary (Box 1) is negative in the dry period (Figure 2.21; Table 2.24). This is due partly to the effects of tidal inundation of salt marshes. Taylor (1992) showed that inundation during non-upwelling conditions released nitrate and ammonium into the estuary and that these were consequently transferred during ebb to the sea.

Table 2.24. Nonconservative fluxes of DIP and DIN for the Kariega River estuary in the dry and wet periods.

	ΔDIP		ΔDIN	
	(mol day^{-1})	(mmol m^{-2} day^{-1})	(mol day^{-1})	(mmol m^{-2} day^{-1})
Dry				
Box 1	+16	+0.02	+19	+0.02
Box 2	+51	+0.06	-608	-0.8
Whole system	+67	+0.04	-589	-0.4
Wet				
Box 1	+280	+0.4	-98	-0.1
Box 2	+209	+0.3	-802	-1.0
Whole system	+459	+0.3	-900	-0.6

Stoichiometric calculations of aspects of net system metabolism

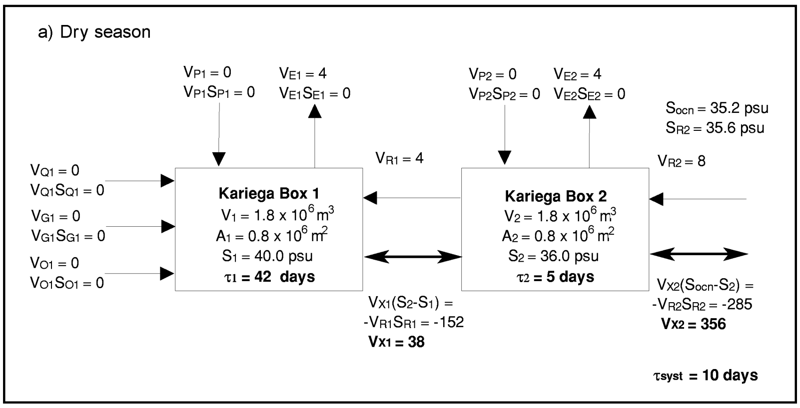
In the dry period, respiration in the estuary exceeds primary production, rendering the system net heterotrophic. Apparent system net nitrogen metabolism indicates that the estuary exhibits denitrification.

Due to very rapid water exchange in the wet period, calculation of net system metabolism may not be reliable and was not further interpreted in this paper. Allanson and Winter (1999) have reported a conservative pattern for DIN during high river flow while DIP shows marked positive departure from theoretical dilution line (TDL) implying a gain within the estuary.

Both (*p-r*) and (*nfix-denit*) are negative for the whole estuary in both dry and wet seasons (Table 2.25). This raises the question: Is this a feature of freshwater starved estuaries?

Table 2.25. Apparent net ecosystem metabolism for Kariega River estuary in the dry and wet periods.

	(p-r)	***(nfix-denit)***
	(mmol C m^{-2} day^{-1})	(mmol N m^{-2} day^{-1})
Dry		
Box 1	-2	-0.3
Box 2	-6	-1.8
Whole system	-4	-1.0
Wet		
Box 1	-42	-7
Box 2	-32	-6
Whole system	-32	-5



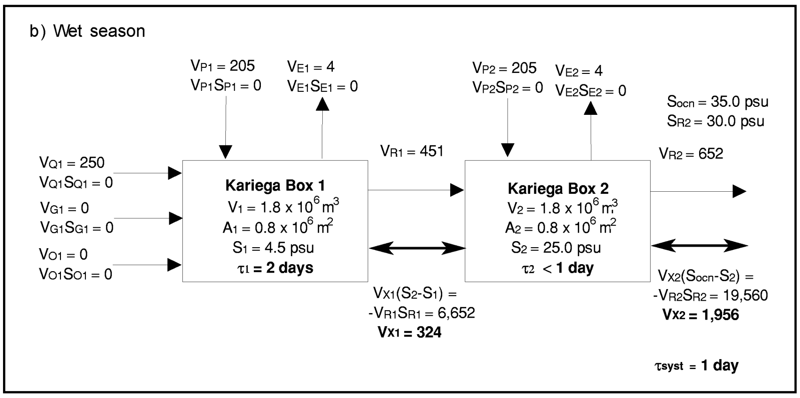


Figure 2 19. Water and salt budgets for Kariega River estuary in the dry (a) and wet (b) periods. Water flux in 10^3 m^3 day^{-1} and salt flux in 10^3 psu-m^3 day^{-1}.

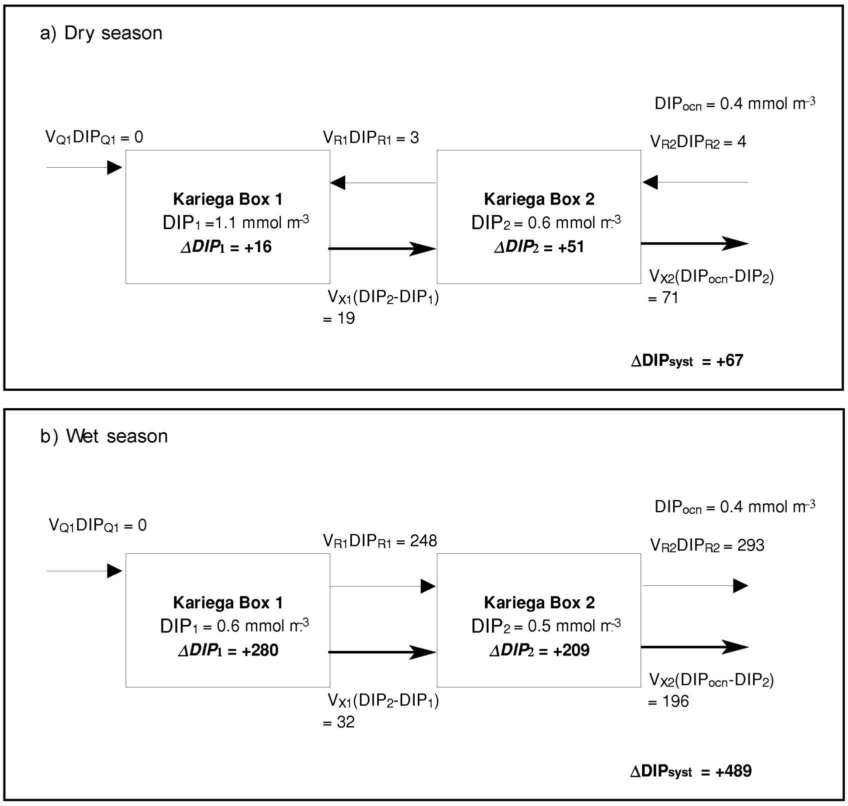


Figure 2.20. DIP budget for Kariega River estuary in the dry (a) and wet (b) periods. Flux in mol day^{-1}.

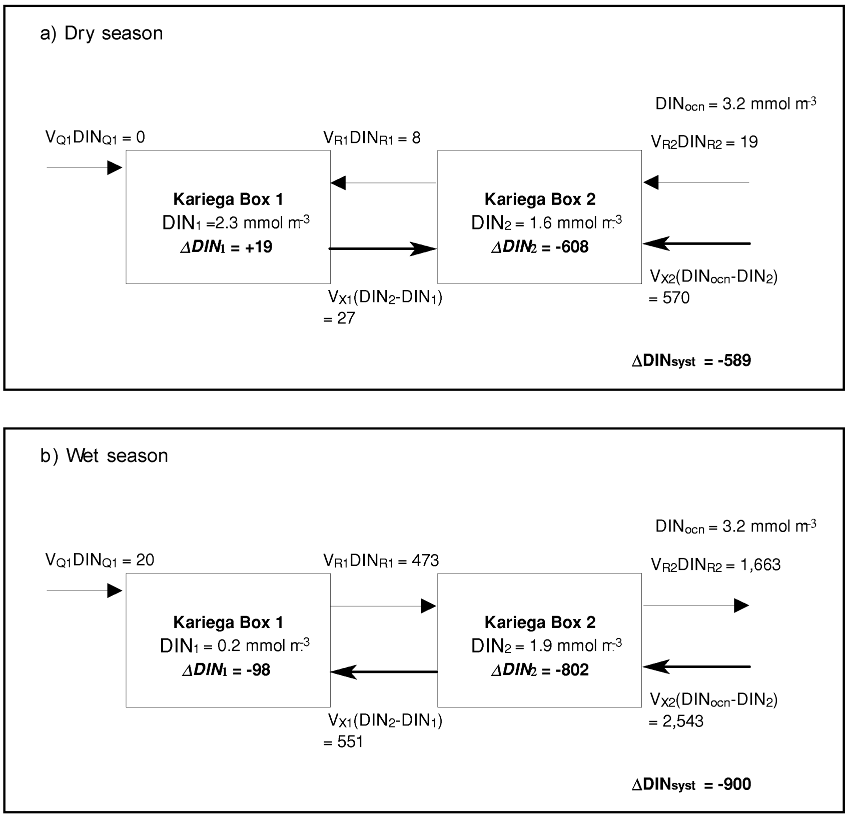


Figure 2.21. DIN budget for Kariega River estuary in the dry (a) and wet (b) periods. Flux in mol day^{-1}.

2.6 Great Fish River estuary, Eastern Cape

Nadia Smith and Brian R. Allanson

Study area description

The Great Fish River estuary (33.50°S, 27.13°E; Figure 2.22) is one of the few estuaries in the Eastern Cape region that maintains an outlet in spite of low subtidal and intertidal volume. The system's predominant fluvial influence was resulted from the development of the Orange River Interbasin Transport system via the Gariep dam on the Orange River. This transport involves flows as high as 360×10^6 m^3 $year^{-1}$ from the Gariep dam via a system of tunnels into the upper Fish River and its main tributary (the Little Fish) and onwards to the adjacent river catchment of the Sundays River. The large quantities of freshwater received from the Orange River in the north renders the Great Fish River estuary an excellent example of a 'renewed' estuarine system. The estuary had previously experienced long periods of low to zero inflow.

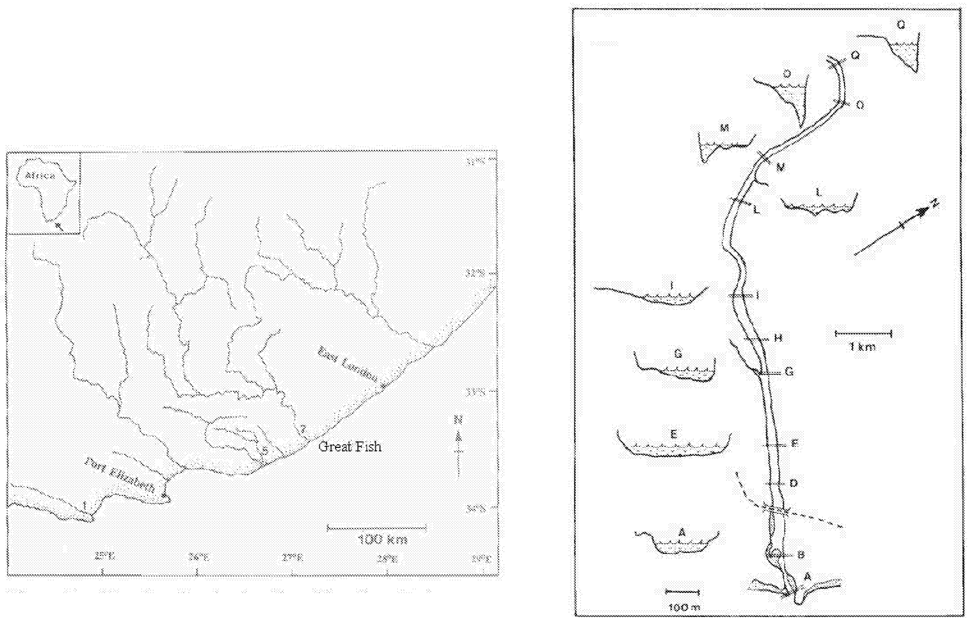


Figure 2.22. Map and location of the Great Fish River estuary.

The estuary is 10 km in length with an average depth of 2.2 m and a surface area of 1 km^2. Its river catchment is 29,940 km^2 and has a tidal prism of 1.6×10^6 m^3. The Great Fish estuary is always stratified; under normal flows it is partially stratified and during floods a typical fjord-like stratification can exist for the period of maximum river flow. However, the estuary was considered as a single-layer in this paper because of its shallow depth.

Water and salt balance

The estuary was divided into upper (Box 1) and lower (Box 2) estuary to accommodate the significant gradient in salinity. Within each box budgets were developed for the dry and wet periods. It should be understood that these periods are for tidal periods over one or two days. The results obtained are likely to be close to the means, expressed per day, obtained over much longer periods in view of the persistent inflow of the Great Fish River.

The results of the water and salt budgets are illustrated in Figure 2.23. Evaporation exceeds precipitation during both the dry and wet periods but the net contribution to the water budget is insignificant compared to the high river runoff (Table 2.26). Water exchange time for the whole system in the dry period is 2 days and less than a day in the wet period.

Table 2.26. Water flux, salinity and water exchange time for Great Fish River estuary in the dry and wet periods.

	Water Flux (10^3 m^3 day^{-1})					**Salinity** (psu)		**Water exchange time** (day)
	V_Q	V_P	V_E	$\boldsymbol{V_R}$	$\boldsymbol{V_X}$	S_{syst}	S_{ocn}	τ
Dry								
Box 1	280	0.2	-3	-280	391	13.0	27.5	2
Box 2	0	0.2	-3	-280	1,140	27.5	35.2	<1
Whole system	280	0.4	-6	-280	1,140	27.5	35.2	2
Wet								
Box 1	5,000	0.5	-2	-5,000	6,565	10.0	22.3	<1
Box 2	0	0.5	-2	-5,000	11,143	22.3	35.2	<1
Whole system	5,000	1	-4	-5,000	11,143	22.3	35.2	<1

Budgets of nonconservative materials

The nutrient datasets available were in themselves quite detailed, as both dissolved inorganic phosphorus (DIP) and nitrogen (DIP) were measured at hourly intervals during the tidal cycle on days when typical low and high river inflow in the respective rivers occurred. Nutrient concentration means and standard deviations are presented in Table 2.27.

The system is not subject to significant point sources of nutrient input, although agricultural runoff during high rainfall must contribute to an elevation of DIP and DIN levels.

Table 2.27. Nutrient concentrations for Great Fish River estuary and the adjacent ocean in the dry and wet periods.

	DIP (mmol m^{-3})		**DIN** (mmol m^{-3})	
	$\mathbf{DIP_{syst}}$	$\mathbf{DIP_{ocn}}$	$\mathbf{DIN_{syst}}$	$\mathbf{DIN_{ocn}}$
Dry				
Box 1	0.9±0.3	1.0	0.5±1.0	3.0
Box 2	1.0±0.1	0.4	3.0±3.3	3.2
Wet				
Box 1	2.7	0.4	8.3±4.0	1.9
Box 2	0.4±0.4	0.4	1.9±0.5	3.2

DIP and DIN balance

The DIP and DIN budgets are illustrated in Figures 2.24 and 2.25. In the dry period, the net nonconservative fluxes (*ΔDIP* and *ΔDIP*) for the estuary are -0.01 mmol m^{-2} day^{-1} and +0.2 mmol m^{-2} day^{-1} (Table 2.28). In the wet period, nonconservative fluxes are very high, with *ΔDIP* -11 mmol m^{-2} day^{-1} and *ΔDIN* -49 mmol m^{-2} day^{-1}.

Table 2.28. Nonconservative fluxes of DIP and DIN for the Great Fish River estuary in the dry and wet periods.

	ΔDIP		*ΔDIN*	
	(mol day^{-1})	(mmol m^{-2} day^{-1})	(mol day^{-1})	(mmol m^{-2} day^{-1})
Dry				
Box 1	-644	-1.3	-881	-1.8
Box 2	+653	+1.3	+1,128	+2.3
Whole system	-9	-0.01	+247	+0.24
Wet				
Box 1	+10,350	+21	+20,016	+40
Box 2	-20,850	-42	-69,252	-139
Whole system	-10,500	-11	-49,236	-49

Stoichiometric calculations of aspects of net system metabolism

The above results of nonconservative fluxes must be interpreted cautiously when use to derive net system metabolism since the water exchange time is very short (<1 to 2 days). This is particularly true of the wet period data. Table 2.29 presents the derived net metabolism. Stoichiometrically-derived net system metabolism calculated from the nonconservative fluxes of a system with very rapid water exchange times are almost certainly not reliable (see discussion in Mvoti estuary paper in this report).

Table 2.29. Apparent net ecosystem metabolism for Great Fish River estuary in the dry and wet periods.

	(p-r)	***(nfix-denit)***
	(mmol C m^{-2} day^{-1})	(mmol N m^{-2} day^{-1})
Dry		
Box 1	+138	+19
Box 2	-138	-19
Whole system	+1	+0.4
Wet		
Box 1	-2,226	-296
Box 2	+4,452	+533
Whole system	+1,166	+127

The earlier work of Lucas (1986) established that the estuary, and particularly the upper estuary, exhibits sustained high levels of chlorophyll *a* (60 – 70 μg/l) and, therefore, primary production during periods of low river flow. The onset of summer flooding destabilized stratification patterns which were only reestablished later in the summer. The consequent appearance of high levels of chlorophyll *a* (>106 μg/l) due to an array of transient pycnoclines at which nutrients accumulate (Grange and Allanson 1995) is supported by the marked sink of DIP shown in Table 2.26. The comparable events for DIN reflect the high phytoplankton activity within the estuary as a consequence of this sustained yet variable river inflow.

A substantial net production ([*p-r*] = 1 mmol C m^{-2} day^{-1} and 1,200 mmol C m^{-2} day^{-1}) in the dry and wet periods respectively matches earlier observations that chlorophyll *a* levels were high in the estuary, which explains the DIP sink, although this should be adjusted by the influence of high algal biomass upon net production.

It has been repeatedly shown in phytoplankton assemblages that production is reduced when a large algal mass is present. Much of this is due to self-shading etc. We argue for this study that no clear-cut relationship between chlorophyll (as a measure of biomass) and production is possible with our present dataset, other than to expect production to be reduced where chlorophyll levels are high. This being so then certainly 1,200 mmol C m^{3} day^{-1} is too high.

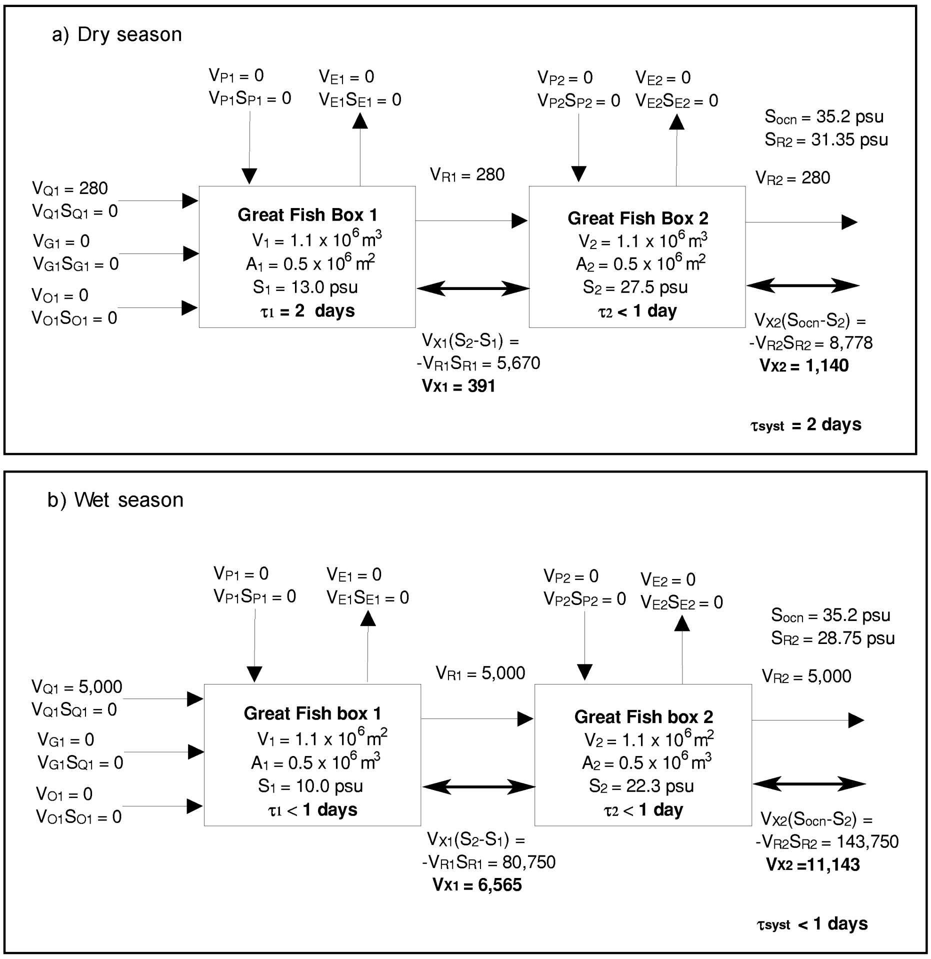


Figure 2.23. Water and salt budgets for Great Fish River estuary in the dry (a) and wet (b) periods. Water flux in 10^{3} m^{3} day^{-1} and salt flux in 10^{3} psu-m^{3} day^{-1}.

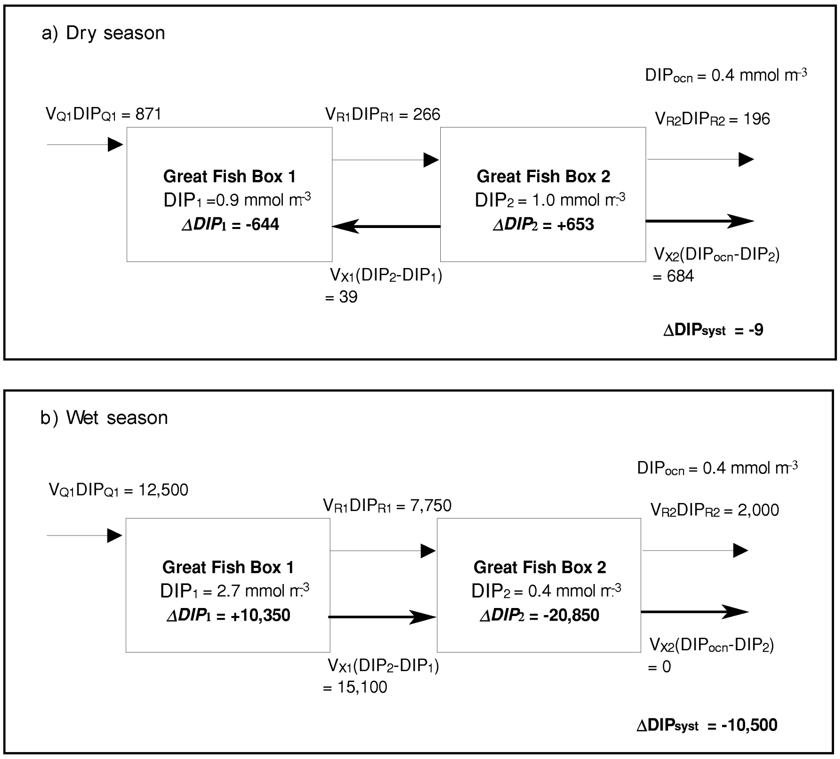


Figure 2.24. DIP budget for Great Fish River estuary in the dry (a) and wet (b) periods. Flux in mol day^{-1}.

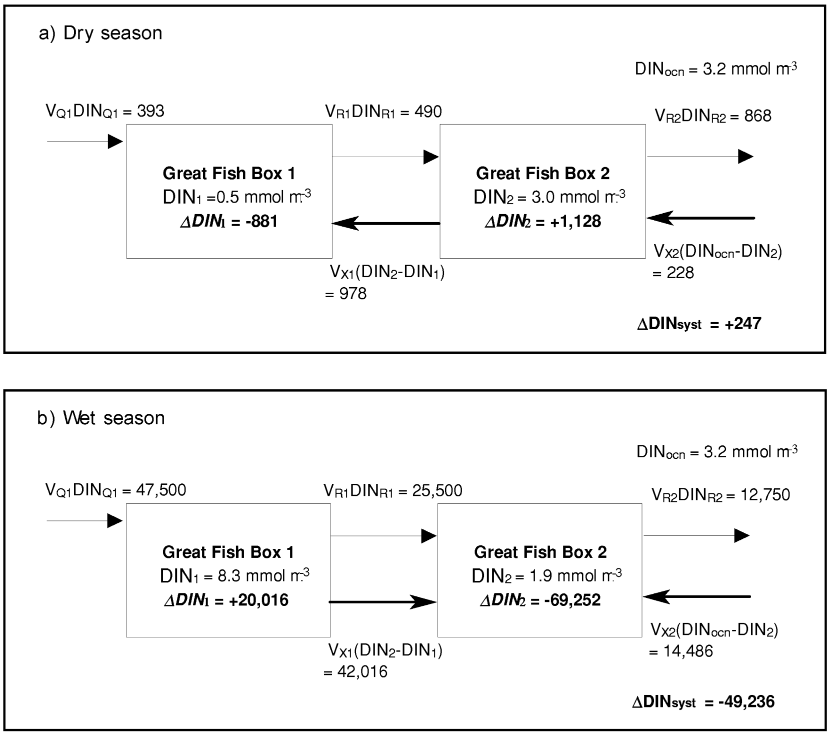


Figure 2.25. DIN budget for Great Fish River estuary in the dry (a) and wet (b) periods. Flux in mol day^{-1}.

2.7 Mvoti Estuary, KwaZulu-Natal

V. Wepener and C.F. MacKay

Study area description

The abiotic and biotic characteristics of the Mvoti Estuary (29.40°S, 31.35°E; Figure 2.26) are not comparable with any other estuary in KwaZulu-Natal (Begg 1984). The system is best regarded as a river mouth with an extremely shallow mean depth (<0.5 m; Mackay *et al.* 2000). The Mvoti catchment area is 2,730 km^2 (Chunnet *et al.* 1990) and the 2 km estuary occupies 0.2 km^2 of this space. The river length is 180 km to 215 km (Begg 1978), with flow to the estuary ranging from 7 m^3 sec^{-1} to 15 m^3 sec^{-1}. Depth at high tide varies from 0 to 0.4 m (Porter 1990).

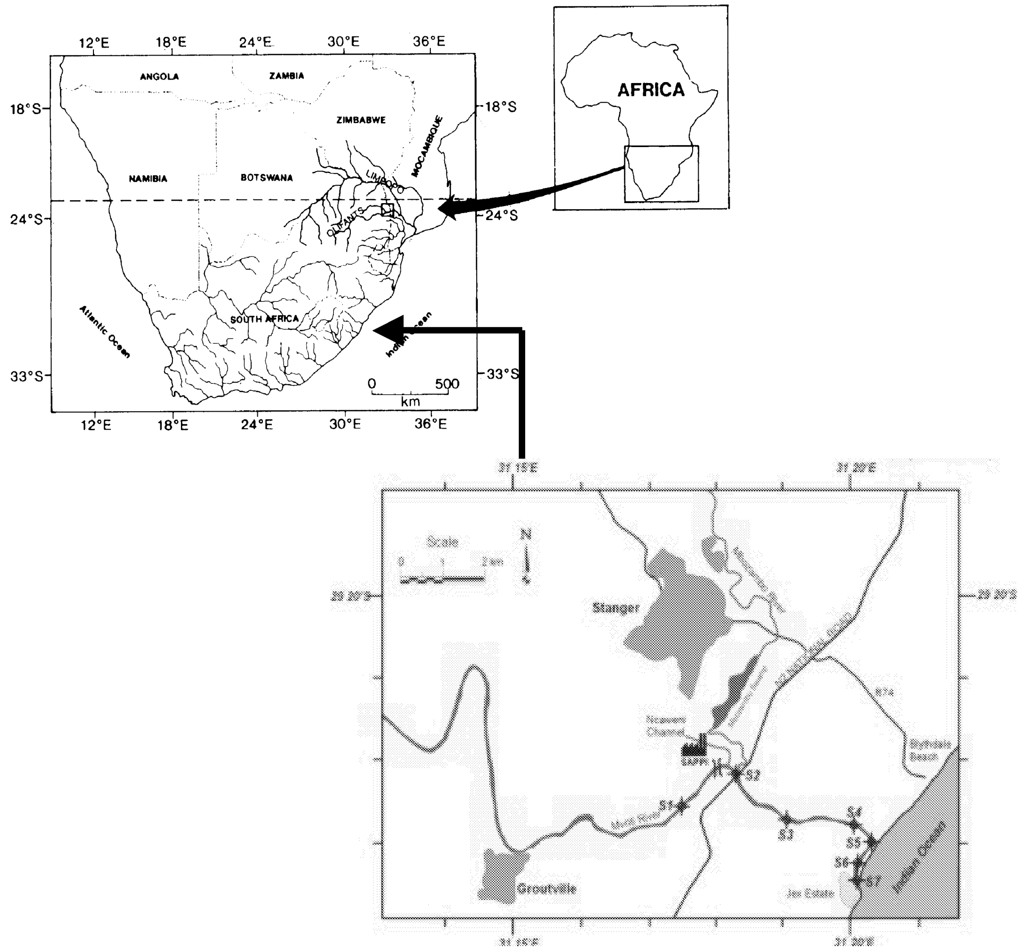


Figure 2.26. Map and location of the Mvoti estuary.

A 1 km long sandbar separating the estuarine area from the marine environment occupies approximately 20% of the total estuary area. Consequently, the river deflects 90° at the coast and opens to the south. The current opening is over a rocky ledge of Ecca shale to the south (Begg 1978). The mouth has remained stable since the mid 1990's and over the last decade has seldom closed, but if necessary has been breached by bulldozer to drain flooded sugarcane fields. Before then, records show that the mouth was usually closed with an overflow channel only on the south side (Badenhorst 1990). Under flood conditions the river takes a straighter course to the ocean and breaks through the spit in a more northerly position.

Badenhorst (1990) calculated that due to a sedimented bed, the mouth area was -0.3 m mean sea level (MSL). However, 250 m in from the mouth the bed level was measured at 3.6 m (MSL) and increased to 13.1 m (MSL) in the mid reaches of the system. If it is assumed that tidal exchange through an open mouth is only possible to a bed level of +1 m (MSL) then the Mvoti has limited potential for meaningful tidal exchange. The furthest penetration of seawater was 500 m upstream (Begg 1978). From a sedimentological point of view, the estuary is severely degraded. This condition deteriorates with time due to high sediment loads during floods (Badenhorst 1990).

The physico-chemical characteristics of the Mvoti have from as early as 1964 been described as 'grossly polluted' (Begg 1978). This pollution was almost entirely due to effluent input of treated sewage from Stanger via the Mbozambo Swamp, and sugar and paper mill effluents from Gledhow Sugar Mill and Sappi Stanger. The lower Mvoti River is still used for treated effluent disposal, agricultural irrigation and various domestic uses by informal settlements. Abstraction from the river upstream of the estuary takes place for the sugar and paper mill operations. Although it has been long recognised that there has been broad-scale organic enrichment of the river and estuarine system from industrial and agricultural uses, dissolved oxygen levels have been described as favourable. However, in the most recent study, dissolved oxygen concentrations did not comply with Department of Water Affairs and Forestry (DWAF) standards set for the aquatic environment at 80% - 120% saturation or 6-12 mg/l (DWAF 1996). A slight gradient of increasing concentration existed from headwaters to the mouth. Generally, the poor water quality that was measured in the last 4 km of river was reflected along the length of the estuary with no improvement of conditions.

Data used for the budgeting purposes were obtained from a weekly sampling programme that was undertaken for six consecutive weeks during August 2000 in the Mvoti River and estuary. Sampling sites are indicated in Figure 2.26. All discharge and nutrient recordings representing the Mvoti River were sampled at Site 3, whereas all estuarine data were collected at sites 4 to 7. Note that the discharges from the paper mill and sewage treatment works at Site 2 would have been taken into account with the riverine samples being taken at Site 3. The results only allow a budget to be calculated for the low-flow dry season.

From a biological point of view, there are backwaters in the deeper areas that provide important refuge areas for fish. These backwaters occupy approximately 30% of the estuary (Porter 1990). Fringing the backwaters are reed beds and perennial weed species. The lower section on the Mvoti River is considered to have the poorest habitat integrity, both instream and along the riparian zone (Mackay *et al.* 2000). According to Tharme (1996) *'the riverine system has been modified completely, with an almost total loss of natural habitat and biota and the destruction of many basic ecosystem functions'*. The Mvoti estuary also reflects the various impacts to which the river is subjected. Besides the combination of unacceptable levels of water quality variables and poor habitats, low volumes of outflow have a negative effect on this small estuary. The Mvoti estuary is a degraded system functioning very differently from the way it did in its pristine state (Mackay *et al.* 2000).

From a conservation perspective, it has been stated that the Mvoti estuary has some value in that it provides a nursery for fish (seven species of obligate estuarine users: Porter 1990). It is the only estuary that has retained this function on 80 km of coastline and the bird life associated with the estuary includes Red Data species and a large variety of migrant species. The most important bird species present is the Redwinged Pratincole. This estuary hosts one of the few nesting sites of the bird in the country and has the only South African record of the Redthroated Pipit.

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 Mvoti estuary has a permanently open mouth and levels therefore fluctuate markedly due to a combination of riverine inflow and to a lesser extent 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 thus necessary to average the water balance equation over the entire study period (six weeks during August/September 2000), over which time the water level remains essentially constant.

Figure 2.27 illustrates the water and salt balance for the Mvoti estuary with six-weekly 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 236x10^3 m^3 day^{-1}, while exchange flux (V_X) is 121x10^3 m^3 day^{-1}. The system volume (125x10^3 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 through the mouth. The rapid water exchange is characteristic of the permanently open estuaries along the eastern seaboard of South Africa. The morphologies of most of these estuaries are relatively narrow riverine channels with little or no backwater areas that could contribute towards longer retention times.

Budgets of nonconservative materials

DIP and DIN balance

Due to extremely high flushing rate of this estuary, nutrient budgets probably cannot be considered reliable. However assuming a steady state for both dissolved inorganic nitrogen (DIN) and dissolved inorganic phosphorus (DIP) over the sampling period, 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:

$$\Delta Y= -V_R Y_R - V_Q Y_Q - V_x (Y_{ocean} - Y_{out})$$

The DIP and DIN concentrations used for calculating nutrient fluxes are shown in Table 2.30. The nonconservative flux of DIP, ΔDIP is +634 mol d^{-1} or +3.4 mmol m^{-2} d^{-1} probably indicative of removal of DIP from the system. Nonconservative DIN flux (ΔDIN) was positive (-1,544 mol d^{-1} or +8.4 mmol m^{-2} d^{-1}) indicating that the estuary is acting as sink for nonconservative DIN (Figures 2.28 and 2.29). The source function of the estuary for both DIP and DIN from the system was expected since the input of primary treated sewage discharge into the Mvoti River is not reflected as concomitant increased DIP and DIN in the ocean adjacent to the estuarine mouth.

Estuarine systems with very short water exchange time often appear to behave as high sinks or sources of DIP and DIN e.g., Camboriu estuary (Filho and Schettini 2000). This apparent behavior reflects the dominance of hydrographic processes, along with uncertainty (even small uncertainty) in the nutrient loads or concentrations. In fact, these systems more properly should be considered to flush out all the nutrients as in the case of Mamberamo (Muchtar and Ilahude 2000), Kuala Terrengganu (Law 2000) and Thukela (Wepener 2001) estuaries. This conclusion does not, in any sense, suggest that there is no nonconservative flux of nutrients in such systems; rather, the nonconservative flux is small relative to the conservative flux and cannot be resolved.

Stoichiometric calculations of aspects of net system metabolism

As 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. Therefore, no stoichiometric calculations were made.

Comments

Very little water quality data exists for most of the smaller estuaries in South Africa. This issue will need to be addressed on a national level. A single-box LOICZ budget was set up for the Mvoti estuary due to the nature of the available estuarine data. The data from this study period (August 2000) is representative of dry seasonal flow patterns. An ongoing monitoring programme has been initiated for the estuary, which should later make possible the construction of models for wet seasons.

Table 2.30. Water fluxes, salinity and nutrient concentrations, and data sources for the Mvoti River estuary.

Quantity	Value	Data source
V_Q (10^3 m^{3}day^{-1})	236	Runoff measured at gauging weir in the Mvoti River at Site 3 (Figure 1) during August 2000 (Mackay *et al.* 2000)
V_P (10^3 m^{3}day^{-1})	0.5	Mean annual precipitation in Mvoti catchment (Chunnet et al. 1990; Mvoti IFR Starter Document 1996)
V_E (10^3 m^{3}d^{-1})	-0.8	Mean annual evaporation in Mvoti catchment (Mvoti IFR Starter Document 1996)
V_G (10^3 m^{3}d^{-1})	0.05	Ground water recharge for the Mvoti estuary subcatcment calculated as 30% of MAR in estuarine catchment. (Prof. B. Kelbe *pers. comm.*, Department of Hydrology, University of Zululand)
S_{ocn} (psu)	35.4	CSIR off-shore sampling – KwaZulu-Natal coast
S_{syst} (psu)	0.5	The average salinity of four sites measured in the Mvoti estuary during August 2000 (Mackay *et al.* 2000).
DIP_Q, DIN_Q (mmol m^{-3})	4.5, 44	Six-week average of nutrients measured at Site 3 in the Mvoti river during August 2000 (Mackay *et al.* 2000).
DIP_{syst}, DIN_{syst} (mmol m^{-3})	7.1, 37	Six-week average of nutrients measured at Sites 4-7 in the Mvoti estuary during August 2000 (Mackay *et al.* 2000).
DIP_{ocn}, DIN_{ocn} (mmol m^{-3})	0.3, 0.8	Since the mouth of the estuary was never completely flushed with fresh seawater it was necessary to use average nutrient data for the east coast of South Africa as contained in the Levitus 94 dataset of the Lanman-Doherty Environmental Observatory.

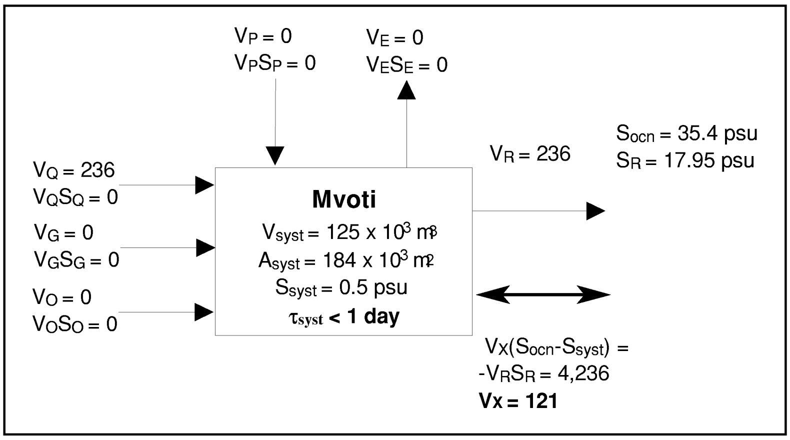


Figure 2.27. Water and salt budgets for the Mvoti estuary. Water flux in 10^3 m^3 day^{-1} and salt flux in 10^3 psu-m^3 day^{-1}.

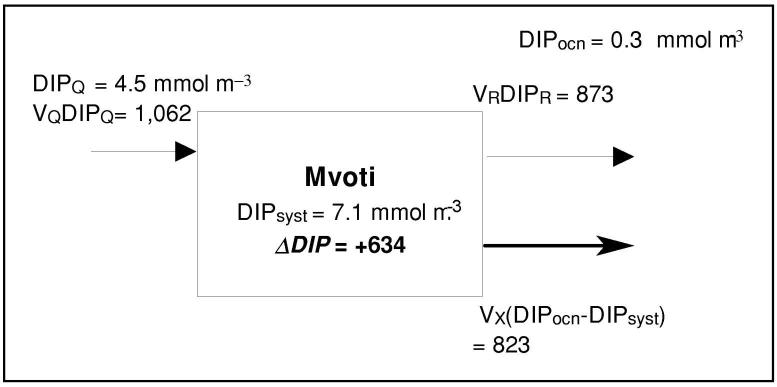


Figure 2.28. DIP budget for the Mvoti estuary. Flux in mol day^{-1}.

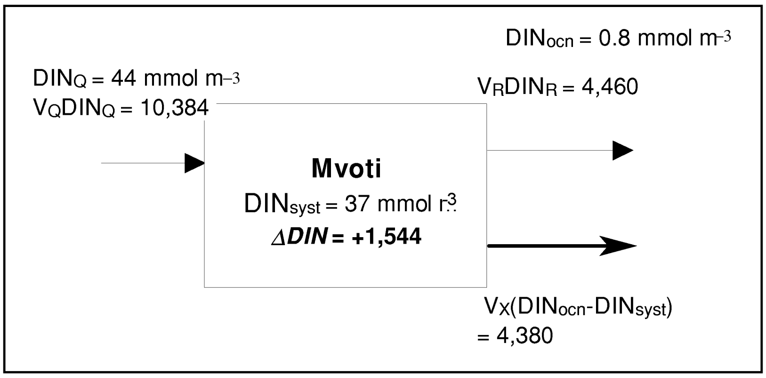


Figure 2.29. DIN budget for the Mvoti estuary. Flux in mol day^{-1}.

2.8 Nhlabane Estuary, KwaZulu-Natal

V Wepener

Study area description

Based on the classification by Whitfield (1992), the Nhlabane estuary (28.65°S; 32.25°E), situated in the subtropical coastal zone on the east coast of South Africa, is a temporarily open/closed estuary. The estuary is small, 3 km in length with a maximum width of 55 m in the lower reaches (Figure 2.30). It has a relatively pronounced basin with steep banks and associated riparian vegetation, but it does meander through a small floodplain (Vivier *et al.* 1998). The marginal, and at times emergent, vegetation, is dominated almost exclusively by *Phragmites australis*.

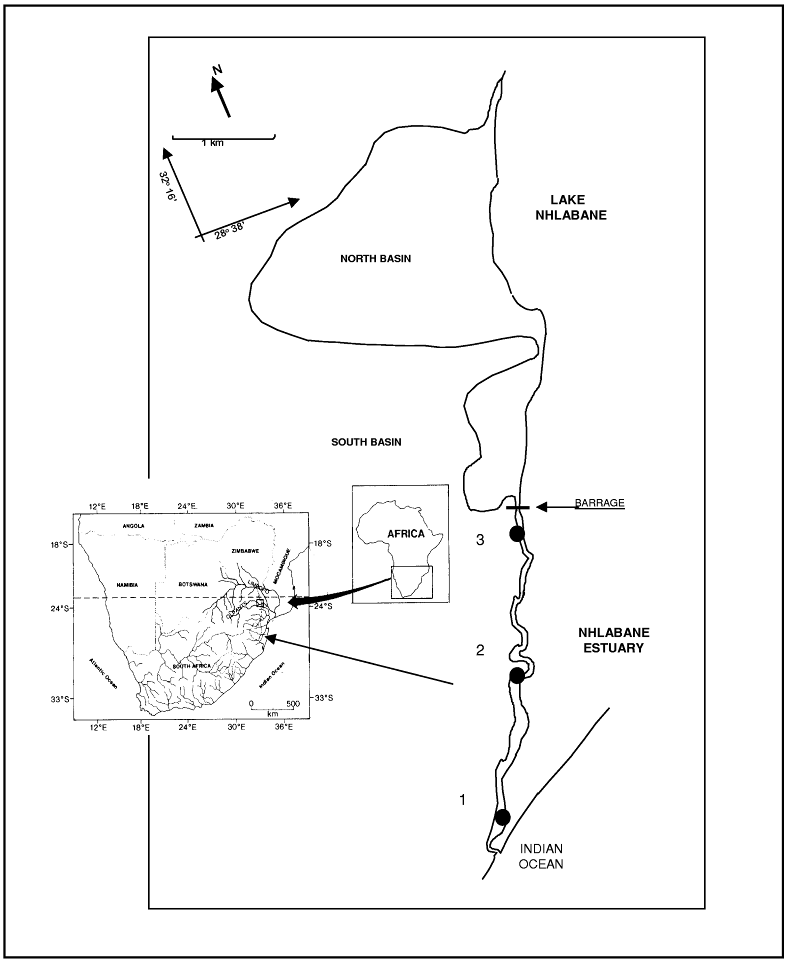


Figure 2.30. Map and location of the Nhlabane River estuary.

River hydrology does not play a role in natural variation within the estuary. The catchment of the estuary is very small (107 km^2) and is dominated by an impoundment, Lake Nhlabane. The lake has very small tributaries. The surface water runoff and groundwater recharge are responsible for water supply to the lake. The barrage effectively cut off all freshwater outflow into the estuary during the drought period from mid-1991 to November 1995, and this resulted in the closure of the estuary mouth for four years. The mouth was artificially breached in August 1995. The reasons for breaching are discussed in detail by Vivier *et al.* (1998). In the intervening period, salt water entered the estuary through occasional overtopping during spring high tides. Hypersaline conditions did not develop during the mouth closure period, because of groundwater recharge of the estuary due to seepage from the lake, the surrounding catchment and mine ponds in the adjacent dunes. Since the end of 1995 the mouth of the estuary has opened and closed frequently. This has resulted in the development of a salinity gradient in the estuary.

The mouth of the Nhlabane estuary is at an open coastline and directly exposed to wave action, without any protection (e.g. natural headland). The beaches at the mouth are very steep, which is typical for this area and this is caused by the interaction of the local wave climate and the coarse sand particles on these beaches. The breaker zone therefore normally consists of one offshore breaker line about 100 m from the beach and a second breaker line on the beach itself. The action of breaking waves at the beach places large quantities of sediments in suspension, which are flushed into the mouth during the incoming tide and thereby provide the main closing force at the mouth.

Due to the infrequent breaching of the mouth and the substantial freshwater inflow into the estuary there is limited salinity stratification. Under natural conditions (prior to the construction of the barrage in 1976) the mouth was normally open one to three times a year for periods of one to three weeks at a time (Huizenga and Van Niekerk 1999). It is estimated that a total cumulative inflow of $10x10^6$ m^3 was required before a natural breaching would take place. Based on experience from other estuaries, the maximum flow rate after a breaching could well exceed 100-200 m^3 sec^{-1} for several hours. The outflow of freshwater would probably have lasted for a few days, after which the intrusion of saline marine water would then have occurred at high tides until mouth closure (Huizenga and Van Niekerk 1999). Overtopping of the berm by high waves at high tides would later have caused additional inflow of marine water, especially in the period shortly after closure when the berm was still low. The influx of marine water under tidal flows would have resulted in some saline water reaching the southern basin of Lake Nhlabane as has been observed in the past (Begg 1978).

At present the mouth normally closes within a few tidal cycles after a natural or artificial breaching (Huizenga and Van Niekerk 1999). This is considerably shorter than the estimated open-mouth periods of one to three weeks which probably normally occurred under natural conditions. Under present conditions the flushing effects at mouth breachings are strongly reduced because of the much smaller storage volume of the estuary now compared to that of the complete system under natural conditions. However, flushing of sediments during major floods will still take place (Quinn 1999). In the instances when artificial breaching was carried out, salinities of up to 10 psu were recorded at the barrage. This clearly indicates that the artificial breachings were not only effective in keeping the water level in the estuary low, but also resulted in a meaningful influx of salt water into the estuary.

There is very little information available on the water quality of the Nhlabane estuary. The only documented historical data for the estuary was recorded between February 1976 and January 1977 prior to the construction of the barrage (Begg 1978). Physico-chemical water quality data have been collected by the Coastal Research Unit of Zululand (CRUZ) since 1992 as part of a quarterly monitoring programme to study the effects of a dredger crossing on the fauna of the estuary. Due to a number of circumstances the programme is still ongoing with input by both CRUZ and the CSIR (Fowles *et al.* 1997; Vivier *et al.* 1998). During this period samples were collected and analyzed for selected chemical variables by the Environment Health and Safety department of Richards Bay Minerals (RBM). Data is presented through kind permission of RBM. Catchment-derived nutrient data was based on limited nutrient surveys undertaken by RBM at eight sites in the northern and southern basins of Lake Nhlabane for the period 1993-1996. There was however no overtopping over the barrage for most of the study period and very limited (no quantitative) data towards the beginning of 1996.

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. Nhlabane estuary undergoes marked water level changes due to the opening and closing of the bar. Thus the assumption of a steady water level is not valid for this system over short 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. Water fluxes, salinity and nutrient concentrations, and data sources for Nhlabane estuary used in this budgetary assessment are presented in Table 2.31.

Table 2.31. Water fluxes, salinity and nutrient concentrations, and data sources for Nhlabane estuary.

Quantity	Value	Data source
V_Q ($10^3\ m^3 day^{-1}$)	192	Average annual runoff in Nhlabane catchment (Quinn 1999) but was not used in the budget calculation due to no water entering the estuary from the lake during the study period.
V_P ($10^3\ m^3 day^{-1}$)	0.5	Average yearly rainfall in the Nhlabane catchment – Source R. Hattingh (Environmental Scientist, RBM).
V_E ($10^3\ m^3 day^{-1}$)	-0.4	Average yearly evaporation rates from the South African Weather Bureau as supplied by the Computing Center for Water Research (CCWR) for the Richards Bay coastal plain area.
V_G ($10^3\ m^3 day^{-1}$)	21	Ground water recharge calculated for the Nhlabane system (Quinn 1999).
S_{ocn} (psu)	35.4	CSIR off-shore sampling
S_{syst} (psu)	8.8	This represents the average salinity of the outflowing surface layer measured at three sites between 1993 and 1996 (Vivier *et al.* 1998).
DIP_G, DIN_G (mmol m^{-3})	2.1, 28	Nutrient concentrations measured in borehole samples from Lake Nhlabane catchment – Source R. Hattingh (Environmental Scientist, RBM).
DIP_{syst}, DIN_{syst} (mmol m^{-3})	4.5, 84	Average of three sites in Nhlabane estuary monitored during 1993-1996 (Kemper 1999).
DIP_{ocn}, DIN_{ocn} (mmol m^{-3})	0.7, 2	Readings at Site 1 when completely flushed with fresh seawater.

Figure 2.31 illustrates the water and salt balance for the Nhlabane 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 $21x10^3$ m^3 day^{-1}, while exchange flux (V_X) is $17x10^3$ m^3 day^{-1}. The system volume ($200x10^3$ m^3) divided by the sum of these water fluxes gives an estimate of water exchange time of approximately 5 days. During the study period the opening of the mouth was primarily driven by groundwater recharge from the surrounding dunes since no (or very little) freshwater input from the lake took place. Based on personal observations the estuary would drain very rapidly during low tide once the sandbar is breached. Normal tidal exchange would take place in the estuary for five to seven days before wave action closes the mouth of the estuary again. Continuous groundwater recharge then fills the estuary over a period of approximately seven days resulting in the breaching of the sandbar again.

The data presented were recorded during an extreme drought period; in the less dry years additional freshwater input from the lake can be expected. However, there is no gauging facility on the barrage structure so no quantitative assessment of surface water input is available. Therefore this budget represents only the conditions experienced during low-flow periods in the Nhlabane estuary.

Budgets of nonconservative materials

DIP and DIN balance

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

$$\Delta Y = -V_R Y_R - V_G Y_G - V_X (Y_{ocn} - Y_{syst}) \qquad (1)$$

DIP and DIN concentrations of the various systems are shown in Table 2.31. The nonconservative fluxes of DIP and DIN (ΔDIP, ΔDIN) calculated for this one-box model are positive, indicating that the estuary is a net source of nutrients (Figures 2.32 and 2.33). The calculated flux of nonconservative DIP (ΔDIP) is +76 mol day^{-1} or +0.8 mmol m^{-2} day^{-1} and that for nonconservative DIN (ΔDIN) is +1,709 mol day^{-1} or +17 mmol m^{-2} day^{-1}.

The system is a net source of DIP and DIN and can be interpreted to indicate that heterotrophic processes prevail. It is possible that the groundwater input of DIN and DIP are an overestimation of input via this route, since the data used were obtained from boreholes along the banks of Lake Nhlabane and not in the dunes surrounding the estuary.

Stoichiometric calculations of aspects of net system metabolism
The net ecosystem metabolism [NEM = primary production-respiration = (p-r)] is calculated as the negative of ΔDIP multiplied by the C:P ratio of the reacting organic matter. Thus:

$(p\text{-}r) = -\Delta DIP\ (C{:}P)_{part}$

It is not certain which reactive organic matter dominate: the extensive reed beds (*P. australis*) that filled the estuary during the drought period or phytoplankton, so two N:P ratios were estimated.

Assuming the bulk of the reacting organic matter is phytoplankton, the C:P ratio is 106:1, then for the Nhlabane estuary, net ecosystem metabolism (p-r) = -84 mmol m^{-2} d^{-1} and assuming the bulk of the reacting organic matter is reed beds, the C:P ratio is 300:1 (Smith *pers. comm.*) and for the Nhlabane, the net ecosystem metabolism (p-r) = -240 mmol m^{-2} d^{-1}

The negative net ecosystem metabolism (p-r) values indicate that the system is net heterotrophic with a net loss of organic matter from the Nhlabane estuary.

If the ΔDIP values in Nhlabane estuary are a measure of the net production of organic matter in the system, the expected ΔDIN (ΔDIN_{exp}) would be ΔDIP multiplied by the N:P ratio of the reacting organic matter. Large differences between ΔDIN_{obs} and ΔDIN_{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.

If phytoplankton is the principal form of organic matter in the Nhlabane estuary then, based on the Redfield ratio $\Delta DIN_{exp} = 16\ \Delta DIP$: $(nfix\text{-}denit)_{\text{phytoplankton}}$= +4 mmol m^{-2} d^{-1}. If the *Phragmites* reedbeds are the principal form of organic matter then, based on a realistic ratio for these macrophytes of C:N:P 300:20:1, $\Delta DIN_{exp} = 20\ \Delta DIP$, so that:

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

The positive values obtained indicate apparent slight net nitrogen fixation in the estuary.

Comments

A single box LOICZ budget was set up for the Nhlabane estuary due to the nature of the available estuarine data. During the study period, (1993-1996) the estuary was subjected to extreme drought conditions and water input was limited to ground water recharge through the dune cordon. The data presented were recorded during an extreme drought period and it is probable that in the subsequent years additional freshwater input from the lake can be expected. However, there is no gauging facility on the barrage structure so no quantitative assessment of surface water input could be expected. Therefore this budget represents only the conditions experienced during low-flow periods in the Nhlabane estuary.

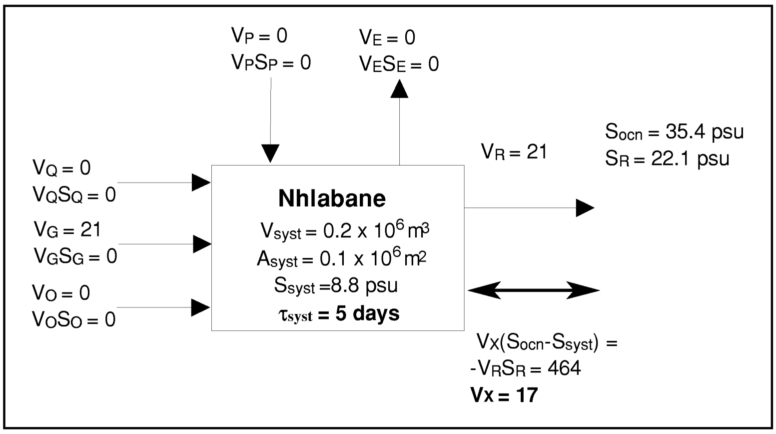


Figure 2.31. Water and salt budgets for the Nhlabane estuary. Water flux in 10^3 m^3 day^{-1} and salt flux in 10^3 psu-m^3 day^{-1}.

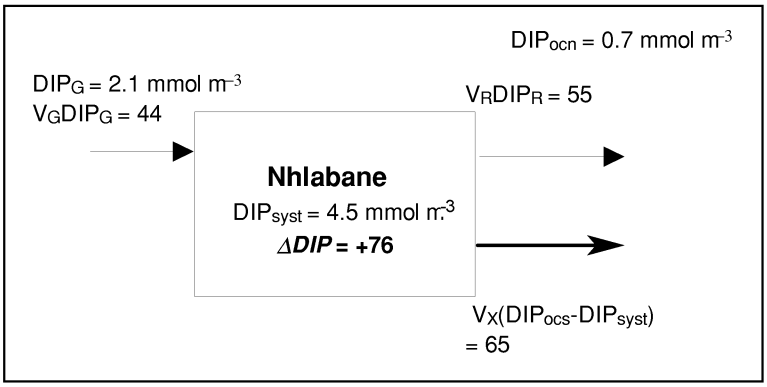


Figure 2.32. DIP budget for the Nhlabane estuary. Flux in mol day^{-1}.

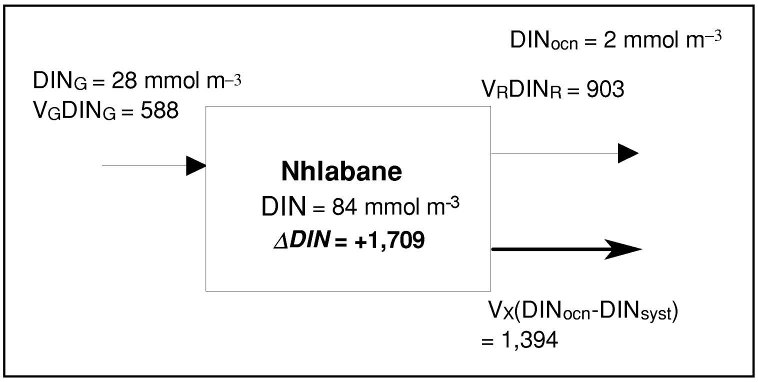


Figure 2.33. DIN budget for the Nhlabane estuary. Flux in mol day^{-1}.

3. ESTUARINE SYSTEMS OF KENYA

A brief description of Kenyan coastal systems was given in Dupra *et al.* (2001).

3.1 Gazi Bay mangrove creek

Johnson U. Kitheka and Benjamin M. Mwashote

Study area description

Gazi Bay (4.92°S, 39.50°E; Figure 3.1) is a shallow tropical coastal water system located on the southern coast of Kenya, approximately 50 km south of Mombasa. The total surface area of the bay including that covered by the mangrove forest is 15 km^2. The mangrove forest covers a surface area of about 7 km^2 (Kitheka 1996, 1997). Seagrass meadows and mangrove forest cover a surface area of about 12 km^2. The bay is open to the Indian Ocean through a relatively wide (3,500 m) entrance, and is mostly shallow with mean depth at the entrance about 5 m. There are several narrow shallow cuts through the reef, which is mostly submerged except during spring tide. The bay is drained by two main rivers, the Kidogoweni River on the north-west part of the bay and the Mkurumuji River on the south-west side of the bay.

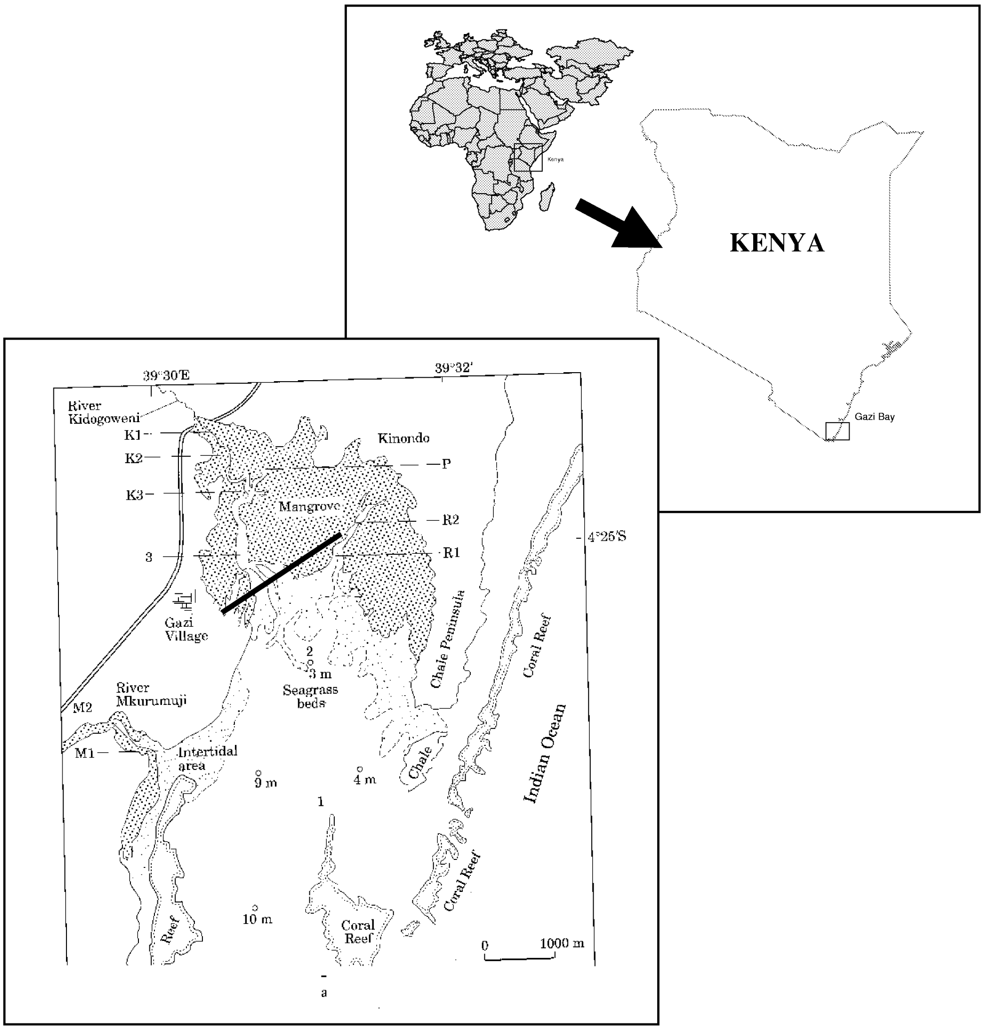


Figure 3.1. The location of Gazi Bay with Kidogoweni and Mkurumuji rivers.

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

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

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

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

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

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

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

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

Water and salt balance

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

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

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

Following the underlying physical principles of the LOICZ budgeting method, salt must be conserved. The residual salt flux, denoting a loss of salt from the system, is brought back to balance in the system through the mixing flux of salt across intra- and inter- system boundaries. This can be seen in Figure 2 given in the model for $V_X(S_{ocn}-S_{syst})$ between mangrove-fringed tidal creek and the bay. During the wet season, the volume mixing (V_X) in the mangrove-fringed tidal creek compartment is 324x10^3 m^3 day^{-1} (Figure 3.2a). On the other hand, during the dry season the mixing volume (V_X) between the mangrove-fringed tidal creek compartment and the bay is 5,875x10^3 m^3 day^{-1} (Figure 3.2b).

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

Budgets of nonconservative materials

Nutrient concentrations have been determined for the nitrate-nitrogen, nitrite-nitrogen, ammonium, silicate and phosphate (Kitheka, *et al*. 1996; Ohowa *et al*. 1997). In general, nutrient concentrations are usually higher in the wet season than in the dry season, because nutrients are supplied into the creek not only directly from the Kidogoweni River, but also indirectly from the Mkurumuji River through the bay. The wet and dry season inputs of ammonium-nitrogen, nitrate-nitrogen, nitrite-nitrogen and ortho-phosphate from the Kidogoweni River are shown in Table 3.1. The fluxes shown in Table 3.1 were calculated using the mean river discharges during wet and dry seasons.

Table 3.1. River nutrient inputs from the Kidogoweni River in the wet and dry seasons.

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

The characteristic nutrient concentrations within the mangrove-fringed tidal creeks in both wet and dry seasons are shown in Table 3.2. There was a tendency for much higher nutrient concentrations during ebb tide than during flood tide, indicating that oceanic water inflow was low in nutrients in the wet season. In the dry season when there is no river discharge, there is no significant difference in nutrient concentrations in flood or ebb tide. The influence of the river is usually very low in dry seasons.

Table 3.2. Nutrient concentrations for the mangrove creek zone in wet and dry seasons.

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

The mean nutrient concentrations in the mangrove-fringed tidal creeks, bay (seagrass meadows) and the coral reef zone are shown in Table 3.3. The mean concentrations of NH_3 and NO_3+NO_2 with their respective standard deviations in the coral reef zone, bay and mangrove-fringed tidal creeks for the wet season are also presented in Table 3.3.

Table 3.3. Mean nutrient concentrations for the different zones in wet and dry seasons.

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

DIP and DIN balance

The criteria established in the water and salt budgets also apply to exchange of dissolved inorganic phosphorus and nitrogen within the mangrove creek compartment. Deviations result from net nonconservative reactions of P and N in the system (Table 3.4). Concentrations of NO_3 + NO_2 + NH_4 (DIN) and PO_4 (DIP) were available from samples taken at stations established in the mangrove-fringed tidal creek and the bay (seagrass zone) stations designated in Figure 3.1 as stations 3 and 2, respectively (Kitheka *et al.* 1996 and Ohowa *et al.* 1997). These stations were sampled quasi-synoptically. In order to obtain a single representative value for the bay and mangrove-fringed tidal creek, nutrient concentrations from each station sampled at both high and low water conditions were averaged (Table 3.3). This gave a single mean value for DIN and DIP in the mangrove-fringed tidal creek and bay sectors, respectively. The nutrient concentrations were also determined for river inputs (Table 3.1). Those for point sources such as sewage from Gazi Village were not determined, but it is suspected that the sewage load is very small considering that population in the village is also small. This term was therefore neglected in the calculations.

Table 3.4. Nonconservative fluxes of DIP and DIN for Gazi Bay mangrove creek in the wet and dry seasons.

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

The residual fluxes of DIP ($V_R DIP_R$) in the wet season between the mangrove-fringed tidal creek compartment and the bay was -197 mol day^{-1} representing a transport of DIP from the mangrove creek to the bay. During the dry season, the residual flux of DIP ($V_R DIP_R$) in the mangrove-fringed tidal creek compartment was +12 mol day^{-1} representing a transport gain of DIP from the bay into the mangrove-fringed tidal creek. DIP nonconservative flux (ΔDIP) in the wet season was -28 mol day^{-1} for the mangrove-fringed tidal creek-bay compartment (Figure 3.3a). The wet season ΔDIP value per unit area is -0.004 mmol m^{-2} day^{-1}. During dry season, ΔDIP for the mangrove creek compartment was -42 mol.day^{-1} or -0.006 mmol m^{-2} day^{-1} (Figure 3.3b). This indicates that the mangrove-fringed tidal creek compartment acts as a slightly net sink of DIP in both wet and dry seasons.

During the wet season, the residual DIN flux ($V_R DIN_R$) in the mangrove-fringed tidal creek compartment was -372 mol day^{-1} (Figure 3.4a), and ΔDIN was -773 mol day^{-1} or -0.1 mmol m^{-2} day^{-1} for the mangrove-bay system. This indicates that the mangrove creek system is experiencing a net sink of DIN during the wet season. During the dry season, the residual DIN flux ($V_R DIN_R$) for the mangrove creek compartment was +19 mol day^{-1}, and ΔDIN was +1,116 mol day^{-1} or +0.2 mmol m^{-2} day^{-1} (Figure 3.4b). This indicates that the mangrove creek compartment experiences a net release of DIN during the dry season.

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

Stoichiometric estimates of aspects of net system metabolism

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

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

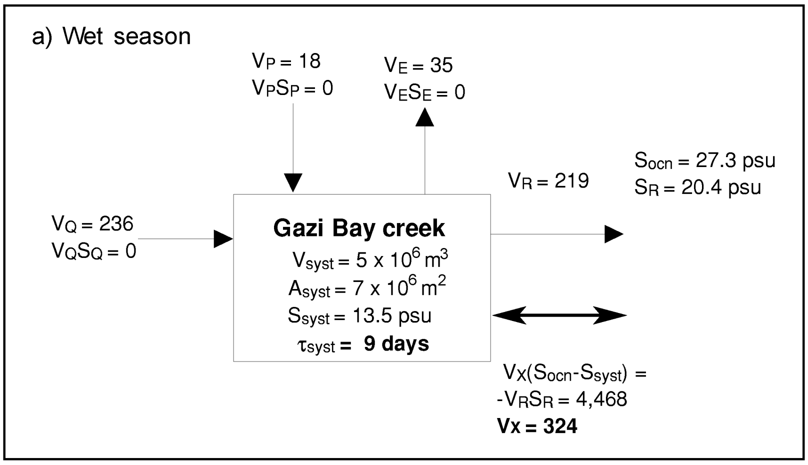
During the wet season, the positive (p-r) of +0.4 mmol m^{-2} day^{-1} for the mangrove-fringed tidal creek compartment shows that the mangrove creek system is slightly net autotrophic in the wet season. If the higher C:N ratio of mangrove detritus were used, then the estimated autotrophy would be larger.

Net nitrogen metabolism can be calculated using the formula:

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

The expected ΔDIN (ΔDIN_{exp}) can be determined using the Redfield ratio of 16:1 for N:P, and the observed value for $\Delta DIP(\Delta DIP_{obs})$. This allows ΔDIN_{exp} to be expressed as $16(\Delta DIP_{obs})$. During wet season, using the Redfield ratio of 106:16:1, ($nfix$-$denit$) = -0.04 mmol m^{-2} day^{-1} and using the typical mangrove C: N: P ratio of 1000:11:1, (*nfix-denit*) = -0.06 mmol m^{-2} day^{-1} for the mangrove creek. The negative (*nfix-denit*) values indicate that the mangrove-fringed tidal creek compartment is net denitrifying during wet season.

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



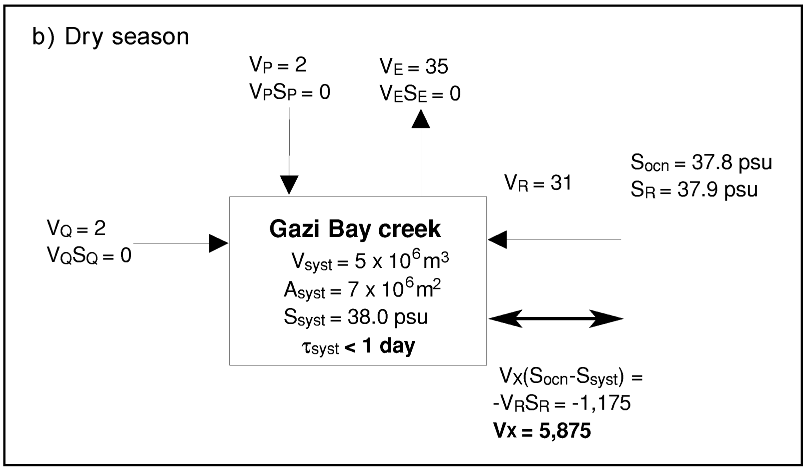


Figure 3.2. Salt and water budgets for Gazi mangrove creek in wet (a) and dry (b) seasons. Water flux in 10^3 m^3 day^{-1} and salt flux psu-m^3 day^{-1}.

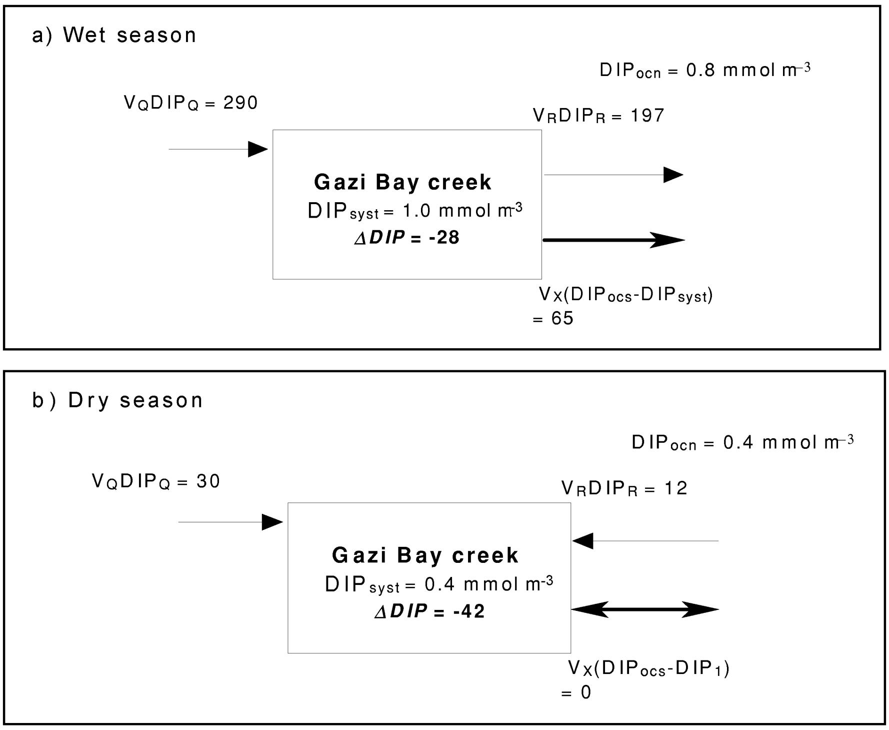


Figure 3.3. DIP budgets for Gazi mangrove creek in wet (a) and dry (b) seasons. Flux in mol day^{-1}.

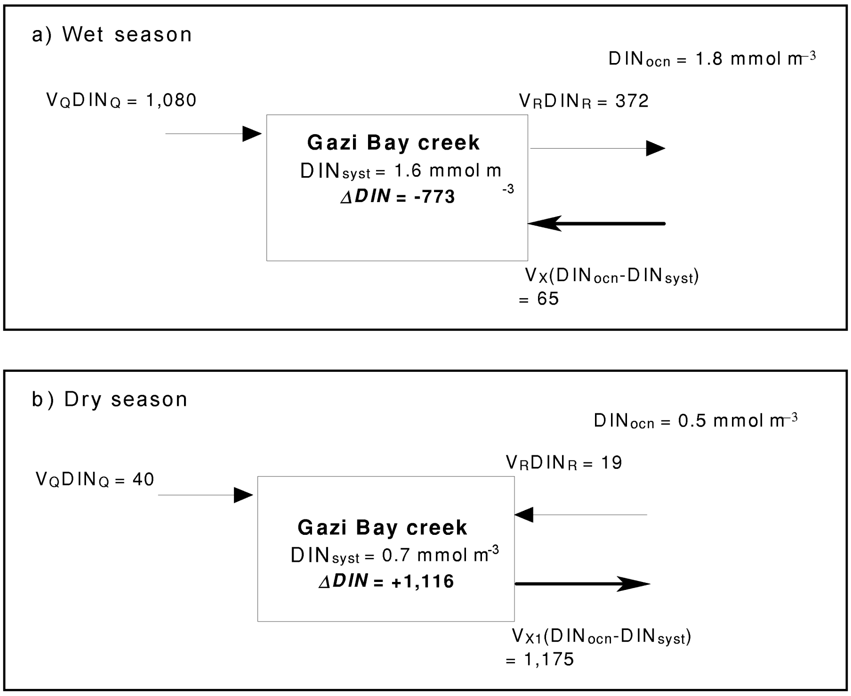


Figure 3.4. DIN budgets for Gazi mangrove creek in wet (a) and dry (b) seasons. Flux in mol day^{-1}.

4. COASTAL SYSTEMS OF EGYPT

4.1 Nile River delta: Rosetta branch and Lake Edku

Hassan Awad and Nabiha A. Youssef

Study area description

The Nile delta is situated almost in the middle of the Egyptian Mediterranean coastline (Figure 4.1), which extends about 1,000 km (16% of the total Mediterranean coast). It connects to the Mediterranean Sea through its two branches surrounding the delta, the Damietta in the east and the Rosetta in the west. Since 1964, when the High dam was built on the Egyptian Nile upstream in Aswan (~1200 km south of Alexandria), Nile water discharge through the Damietta Nile branch has almost stopped, but the Rosetta Nile branch (east of Alexandria) is still discharging into the Mediterranean Sea through four coastal lakes: Manzala, Burullus, Mariut and Edku. These lakes could be considered as transitional sinks for the majority of anthropogenic wastes of Egypt. The budget of the pollutant cocktail in these lakes is expected to be exposed to significant alteration in quantity and quality before reaching the sea.

The River Nile has a large discharge area of about $3x10^6$ km^2 with a high flow rate (up to 500 m^3 sec^{-1}). The flowing Nile water reaches the Mediterranean Sea directly or indirectly through the terminals of the drainage network effluents. These effluents are continuously pumped to the sea carrying a complex of various wastes. The quantity and quality of these wastes reflect the variation of human activities starting with those situated in the eight Upper Nile basin countries bordering its catchment.

The dramatic deterioration observed in the resources of the Egyptian coastal lakes and lagoons indicates that the impact of pollutant discharges in the upper Nile, as well as those in the Egyptian part, are being delivered to Mediterranean coastal waters through these lagoons.

The type, properties and persistence of discharged pollutants in Nile waters are determinant factors for their dispersal, residence, remobilization and impacts in their receiving aquatic environments (fresh, brackish or saline).

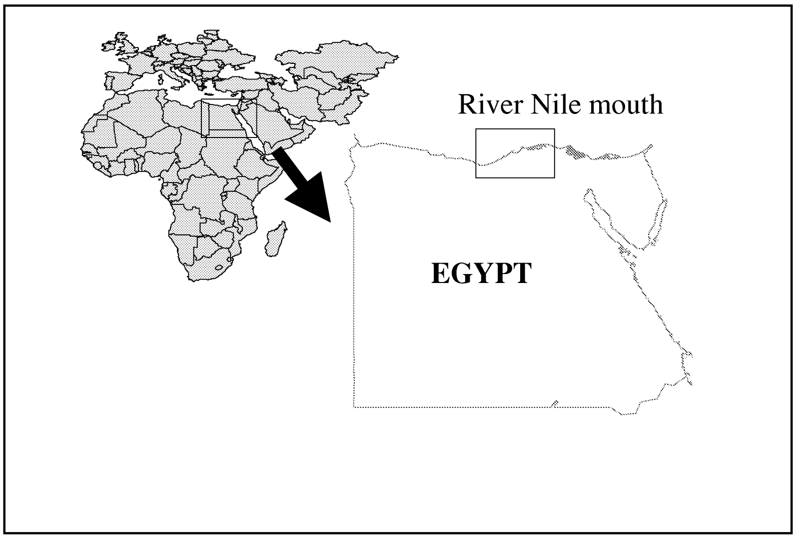


Figure 4.1. Location of the Nile River delta and mouth.

Deterioration of the nearby marine environment in some areas, especially off the region of Alexandria metropolis, is a result of direct discharge of industrial pollutants and untreated domestic wastes into the coastal waters. The zone of Mediterranean coastal waters off Alexandria is considered as one of the "hot spots" of the region (UNEP/MAP 1997).

The present work utilised information on the inputs and dispersal of dissolved inorganic phosphorus (DIP) and dissolved inorganic nitrogen (DIN) in a coastal embayment (Abu Qir Bay) subjected to the influence of terrigenous water discharge; freshwater from the Rosetta Nile distributary and brackish water from a coastal lagoons (Lake Edku) (Figure 4.2).

Abu Qir Bay

This shallow bay lies between 31.27-31.47°N and 30.07-30.33°E, with an average depth of less than 10 m and water volume of 4.3×10^9 m³. The area of the bay is about 430 km^2. It receives a substantial load of pollution from the various land-based activities surrounding it and through River Nile drainage and Lake Edku. The pollution inputs in the bay from these two main sources are as follows:

a) **El Tabia Pumping Station (TPS)**, in the south-east part of the bay with about 2×10^6 m³ day^{-1} discharging capacity. It was estimated that about 730×10^6 m^3 of waste waters are discharged annually through this point source, in a channel (El Amia) of 200 m length. These wastes are mainly industrial, with some agricultural and domestic contribution.
b) **Lake Edku** (31.27°N, 30.15°E). This coastal lagoon is almost an agricultural drain. It covers an area of 126 km² with a mean depth of 1 m. Through its connection with the bay (El Boghaz) about 389×10^6 m^3 of agricultural wastewater is discharged annually into Abu Qir Bay.

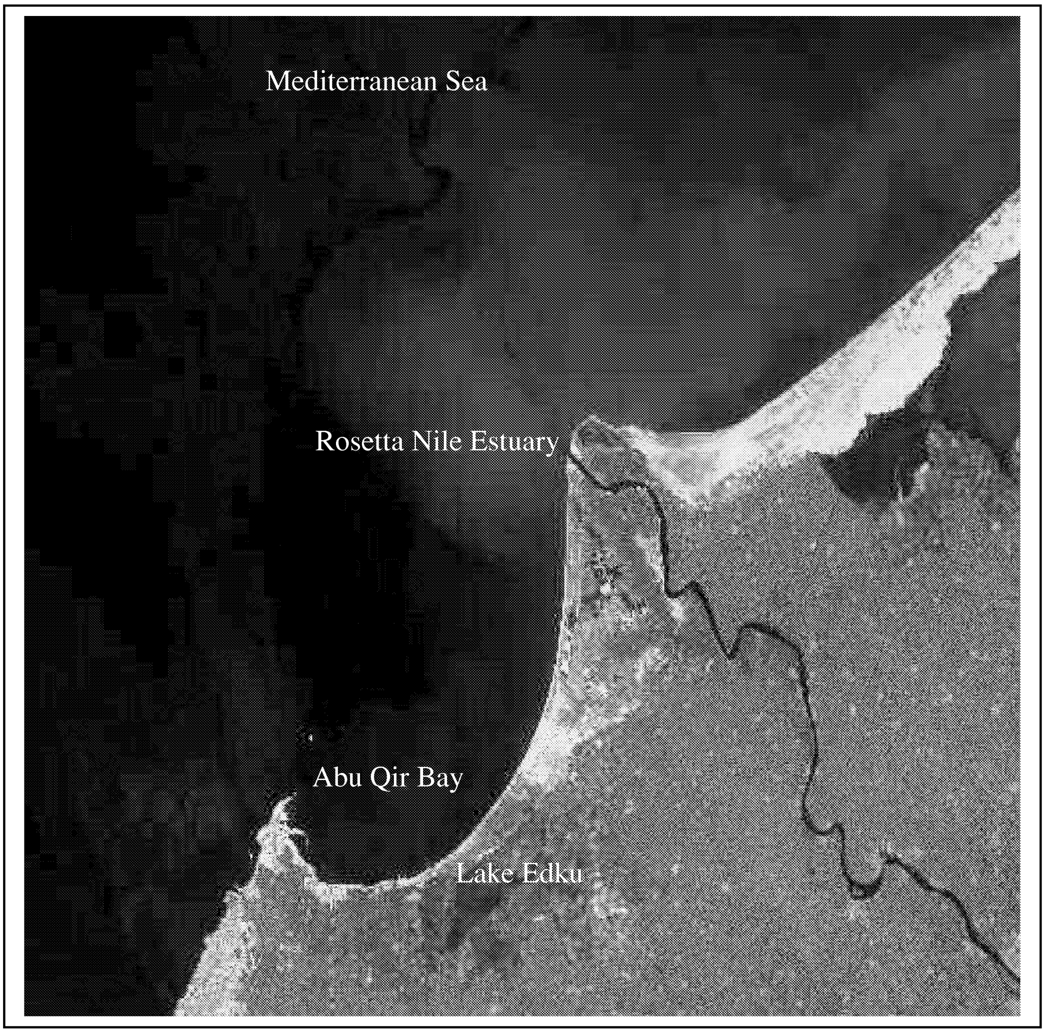


Figure 4.2. Satellite photograph of the Rosetta branch estuary, Lake Edku and Abu Qir Bay.

Historical data on the hydrography of Abu Qir Bay shows that the dispersal pattern of the land-based materials is governed by its water stratification and circulation regimes, which in turn depend on the seasonal variation in discharged fresh waters coming either from Lake Edku or through the Rosetta Nile branch.

While the bay environment receives almost the same amounts of freshwater from Lake Edku all around the year (about 400×10^6 m³), the contribution through Rosetta branch is enormously variable depending on the prevailing current direction. During summer, when the current is mainly eastwards, a relatively small amount from the Rosetta branch reaches the bay (about 80×10^6 m³ month^{-1}). This amount increases drastically to about $2{,}000 \times 10^6$ m³ month^{-1} when the prevailing current alters towards the west.

The Rosetta Nile estuary

The Rosetta branch (31.50°N, 30.35°E; Figure 4.2) of the River Nile is about 220 km in length with an average width of 180 m (area of about 40 km^2) and depth varying between 2 and 4 m (Abed el-Sattar an Elewa 2001). The estuary is delimited by a barrage for controlling water discharge at Edfina City, 30 km before its connection with the sea. It was estimated that the aquatic environment of this branch receives daily more than 0.5×10^6 m^3 of untreated or partially treated domestic and industrial wastes and huge amount of agricultural drain waters.

From a biogeochemical viewpoint of the terrigenous substances in the marine environment, it is preferable to estimate the nutrient budgets for the Rosetta Nile estuary and Lake Edku separately.

The data used in the present estimation is "secondary," covering a wide timeframe and obtained mainly from historical references.

Table 4.1. Physical characteristics of the Rosetta Nile estuary and Lake Edku.

Rosetta Nile estuary	
Depth	2-4 m
Area	40 km^2
Volume	45×10^6 m^3
Lake Edku	
Depth	1 m
Area	126 km^2
Volume	126×10^6 m^3

Rosetta Nile estuary

<u>*Water and salt balance*</u>

The results indicate a normal state where the V_R values are usually negative (Figure 3a). The short water exchange time both in the winter and summer is significant. This is in spite of the significance seasonal difference in the runoff rate (67×10^6 m day^{-1} in winter against 5×10^6 m day^{-1} in summer). The water exchange time (τ) is less than a day in the winter and about 3 days in the summer (Table 2).

Table 4.2. Runoff, precipitation and evaporation for the Rosetta Nile estuary.

Season	**Runoff**	**Precipitation**	**Evaporation**
		(10^6 m^3 day^{-1})	
Winter	67	0.002	0.02
Summer	5	0	0.04

Budgets of nonconservative materials

DIP and DIN balance
Calculated *ΔDIP* in the winter (-271×10^3) and summer (-13×10^3) mol m^{-3} day^{-1} (Figure 4.3a), indicated that the estuary seems to be a sink for DIP. During the wet season (winter), the rate of phosphorus supply via the river reaches twenty times more than that during summer. The same remark is noted for *ΔDIN,* as shown in the corresponding budget (Figure 4.4a).

Net system metabolism was not estimated from the nonconservative nutrient fluxes because of the very short water exchange time in the system in both seasons.

Lake Edku

Water and salt balance

The obtained values parallel the variation in the rate of water draining into the lagoon as shown in Figure 4.2b. However, the water exchange time (τ) during winter (42 days) is more than twice that during summer (16 days) which corresponds to the change in runoff during the two seasons, from 2×10^6 m^3 day^{-1} and 4×10^6 m^3 day^{-1}, respectively (Table 4.3).

Table 4.3. Runoff, precipitation and evaporation for Lake Edku.

Season	Runoff	Precipitation	Evaporation
	(10^6 m^3 day^{-1})		
Winter	2	0.05	0.002
Summer	4	0	0

Budgets of nonconservative materials

DIP and DIN balance
The result for these two parameters indicate that, while the lagoon represents a sink for DIP during winter (*ΔDIP* = -2×10^3 mol day^{-1}), it releases the DIP during summer (*ΔDIP* = $+3\times10^3$ mol day^{-1}). Conversely, the lagoon supplies the marine environment with nitrogen during winter (*ΔDIN* = $+47\times10^3$ mol day^{-1}) and takes up DIN (*ΔDIN* =-99×10^3 mol day^{-1} during summer.

Stoichiometric calculations of aspects of net ecosystem metabolism
The lagoon changes from autotrophic ([*p-r*] = +2 mmol m^{-2} day^{-1}) in the winter to heterotrophic conditions ([*p-r*] = -3 mmol m^{-2} day^{-1}) in the summer.

The results indicate that this lagoon seems to be net nitrogen fixing in the winter, (*nfix-denit*) = +0.7 mmol m^{-2} day^{-1}, and net denitrifying, (*nfix-denit*) = -1.1 mmol m^{-2} day^{-1}, in the summer.

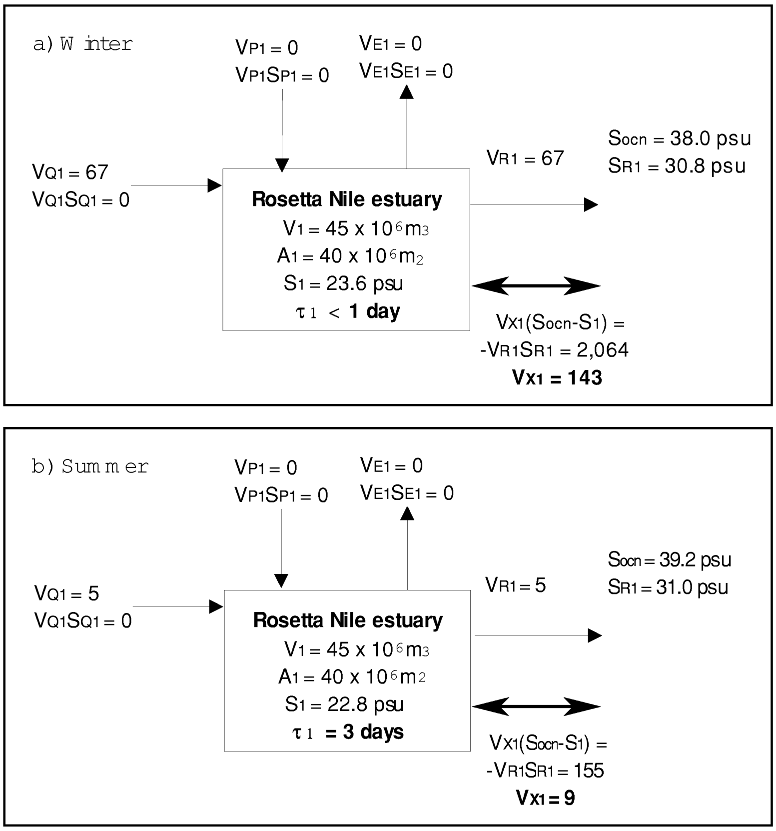


Figure 4.2a. Water and salt budgets for Rosetta estuary in the winter (a) and summer (b). Water flux in 10^6 m^3 day^{-1} and salt flux in 10^6 psu-m^3 day^{-1}.

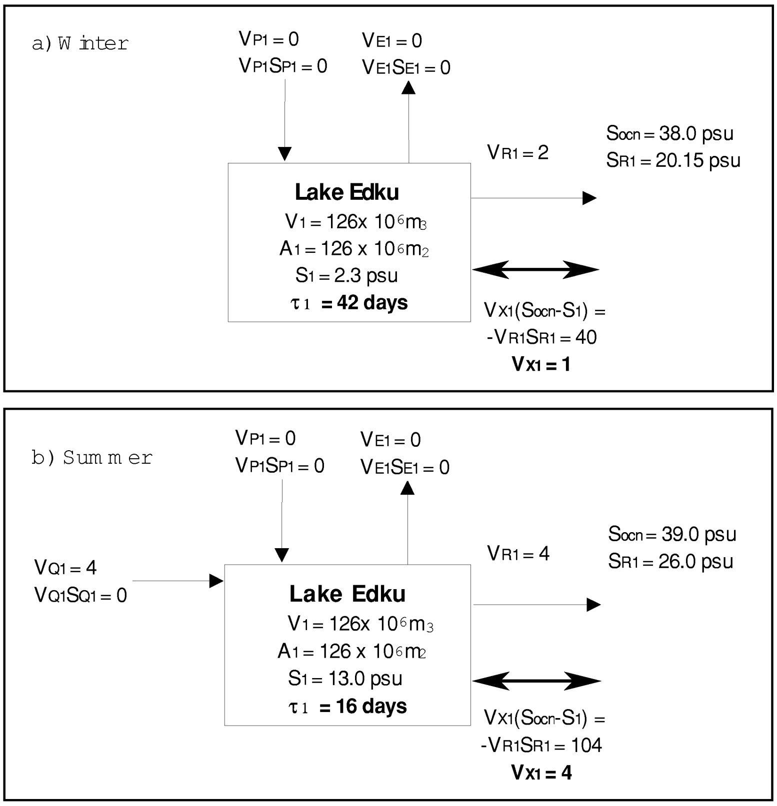


Figure 4.2b. Water and salt budgets for Lake Edku in the winter (a) and summer (b). Water flux in 10^6 m^3 day^{-1} and salt flux in 10^6 psu-m^3 day^{-1}.

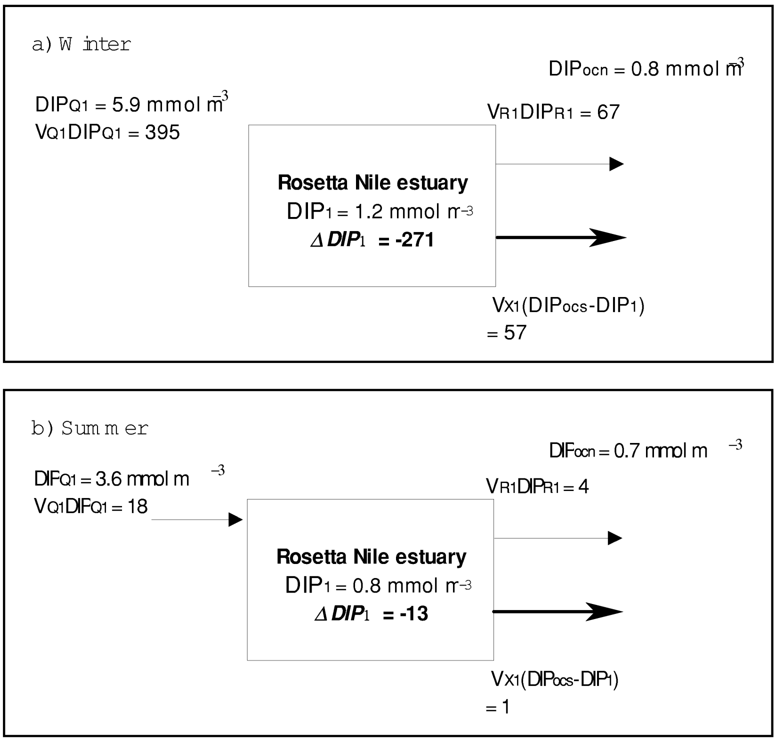


Figure 4.3a. DIP budget for the Rosetta estuary in the winter (a) and summer (b). Flux in 10^3 mol day^{-1}.

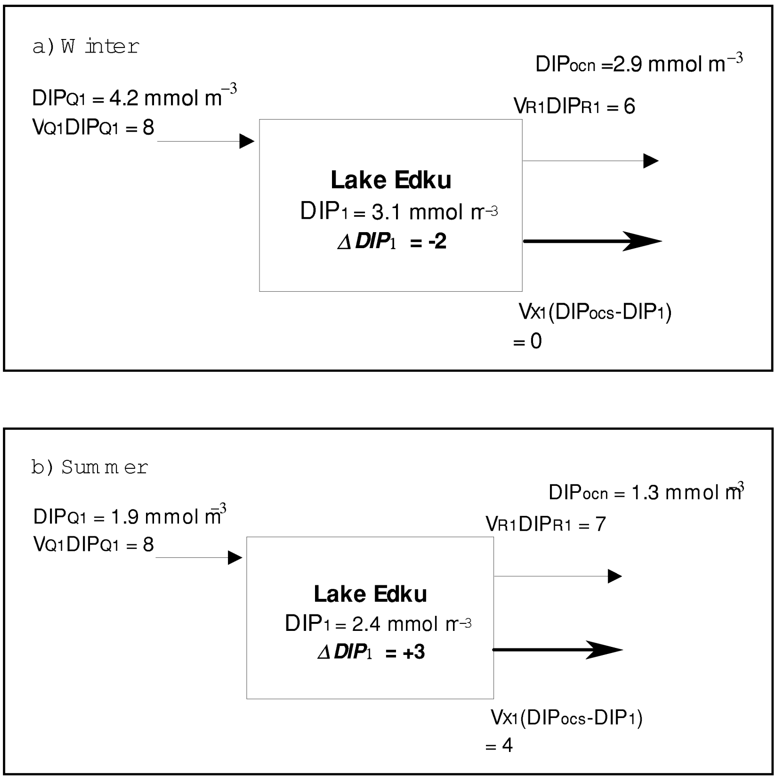


Figure 4.3b. DIP budget for Lake Edku in the winter (a) and summer (b). Flux in 10^3 mol day^{-1}.

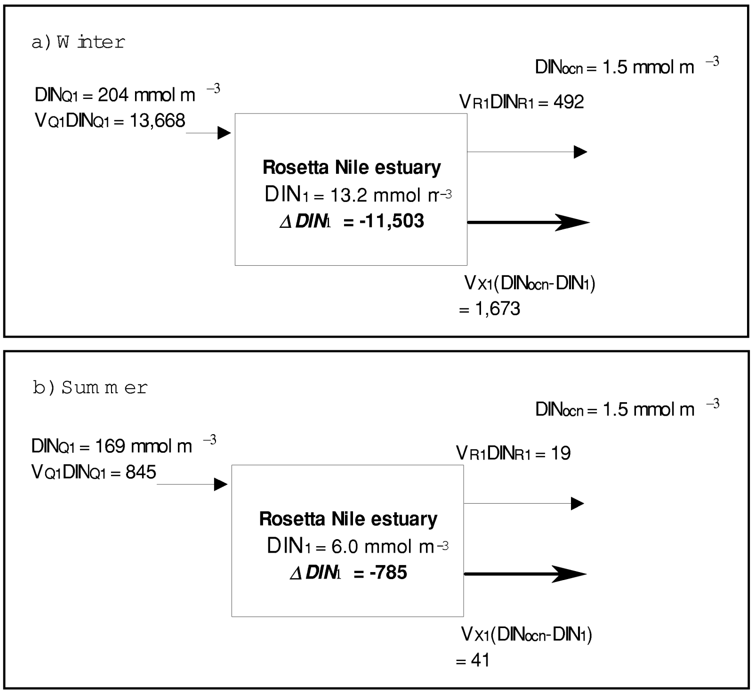


Figure 4.4a. DIN budget for the Rosetta estuary in the winter (a) and summer (b). Flux in 10^3 mol day^{-1}.

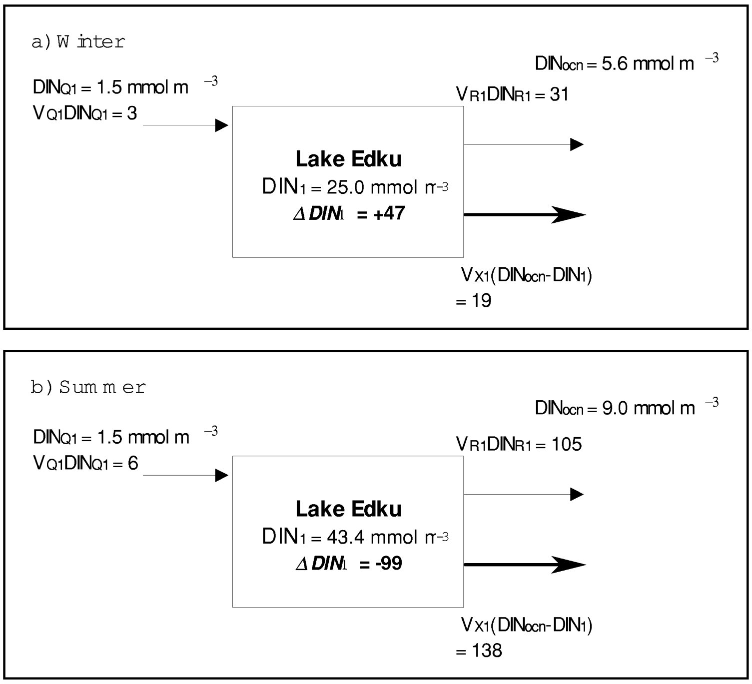


Figure 4.4b. DIN budget for Lake Edku in the winter (a) and summer (b). Flux in 10^3 mol day^{-1}.

5. GHANA

The West African coastline is noted for the existence of a great number of lagoons and estuaries, which contribute to the nutrient budgets of the adjacent coastal waters. In Ghana alone, over 90 such lagoons exist. Some are perpetually open to the sea while others are closed and only open to the sea once in a year or in some cases once every two or three years (Armah 1993). In West Africa, the fluxes of water, salt and nutrients such as phosphate and nitrate between the coastal water bodies and the adjacent shelf water have not been studied much. In recent times some analyses have been made based on data from Nigeria, Ghana and Cote d'Ivoire (Hall *et al.* 1996). This study is an attempt to provide fluxes of water, salt, phosphates and nitrates in a deltaic lagoon in a mangrove area in Ghana, West Africa.

5.1 Angaw Lagoon, in the Volta Deltaic estuary of Ghana

A.K. Armah, G.A. Darpaah and G.Wiafe

Study area description

Angaw Lagoon is located to the east of the main estuary of the Volta River in Ghana (5.60°N, 0.45°E; Figure 5.1). A dam was constructed on the Volta River in 1965 and this has curtailed annual flooding of the delta. Since the impoundment, saline water penetration has dropped from about 30 km to a mere 10 km from the sea (Pople and Rogoyska 1967). The area falls under two seasons; a dry season from November to March and a wet season from April to July followed by a short break in August. Although linked to the main Volta River at its mouth, Angaw Lagoon has no major streams running into it. The main known source of freshwater inflow is direct precipitation and surface water runoff from rainfall, which occurs during the main wet season from April to July and the minor wet season in September and October. The lagoon responds to tidal inflow with an average tidal range of 1 m. The watershed area is 120 km^2. The area of the lagoon is 8 km^2. Depth and volume measurements of the lagoon are given in Table 5.1.

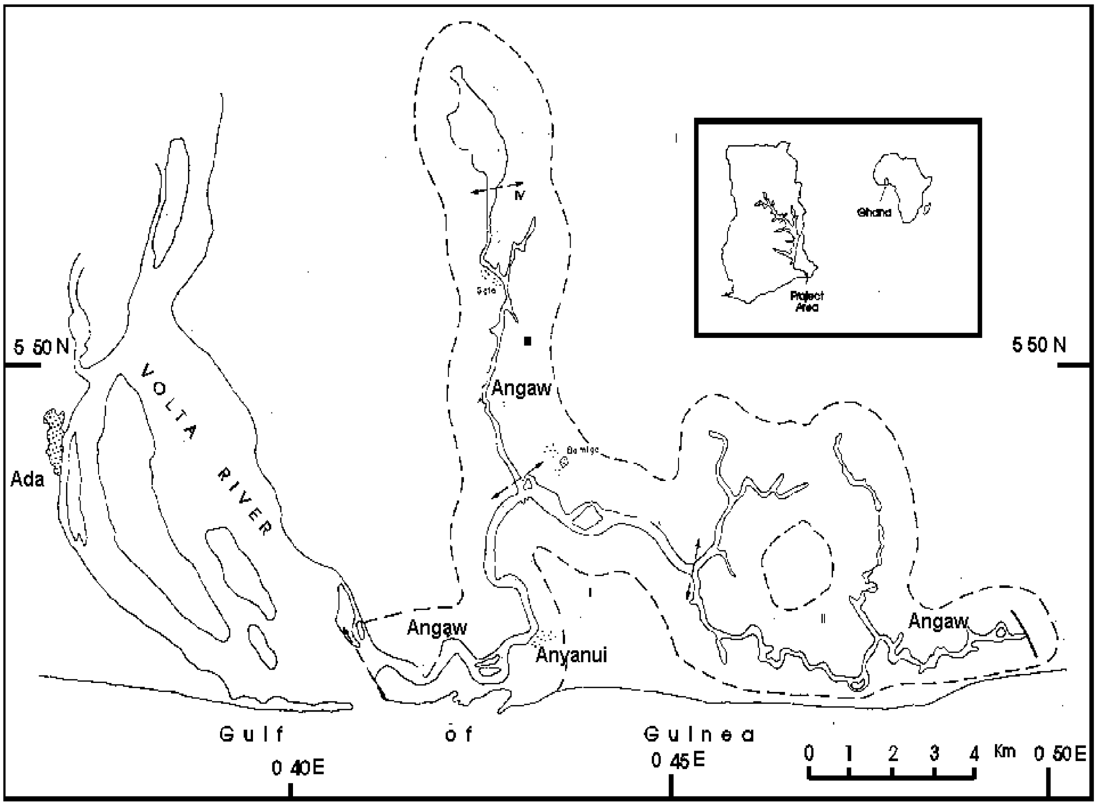


Figure 5.1. Locality and map of Angaw Lagoon, Ghana.

The depth of the system varies from less than 0.25 m in the mangroves to between 1.0 m and 8.0 m in the main channel. Fish diversity is high, with 38 species of finfish and 14 species of shellfish. The dominant families are Mugilidae, Bagridae, Cichlidae, Gerridae, Osteoglossidae and Claridae. The most common shellfish is the gastropod, *Tympanotonus* spp. which are found in very high numbers with densities reaching 320 individuals m^{-2} (Gordon 1997). The vegetation of the area is dominated by the mangrove, *Rhizophora racemosa*. Other important plant species in the area are *Acrostichum aureum, Cyperus articulatus, Paspalum vaginatum* and the ground creepers *Philoxerus vermicularis and Sesuvium portulacastrum*. The bulrush, *Typha domingens*is occur in patches between the mangroves and the waterway. A recent study by Tsikata *et. al.* (1997) indicated that about 43% of the inhabitants in the area are involved in mangrove-related activities. The population of the area is estimated to be about 1,000.

The lagoon was divided into four sections (I, II, III and IV) and salinity, nitrate and phosphate were measured along various points on the lagoon (Figure 5.1). Salinity was measured with a refractometer and the nutrients (nitrate and phosphate) with a HACH 2000 spectrophotometer. The determinations were made at both low and high tide periods in September 1997 and in October 1998. The values obtained did not vary much and their means were used for estimating the salt and nutrient fluxes. All the calculations were based on the methods outlined in Gordon *et al.* (1996).

Table 5.1. Average depth and volume for the Angaw Lagoon system.

Section	**Depth** (m)	**Volume** (10^6 m^3)
I	6.2	12.8
II	3.0	1.4
III	3.0	1.6
IV	1.0	0.5
Whole system	2	16

Water and salt balance

Figure 5.2 illustrates the water and salt budgets for a tropical coastal lagoon in Ghana, West Africa in September 1997 and in October 1998. The budget is based on the principle of conservation of mass. Runoff (V_Q) plus precipitation (V_P) greatly exceeds evaporation (V_E), and groundwater input is assumed to be zero. Surface water runoff was 264x10^3 m^3 day^{-1}. Evaporation from the system was estimated to be 2x10^3 m^3 day^{-1} and precipitation to be 19x10^3 m^3 day^{-1}. The residual flow (V_R) indicates movement of water out of the system at a rate of 281x10^3 m^{3}day $^{-1}$. Mean lagoon and ocean salinities measured were 13 and 34 psu, respectively. The mixing volume (V_X) between the system and the adjacent ocean is 314x10^3 m^{3}day $^{-1}$.The results indicate a water exchange time for the system of 27 days.

Budgets of nonconservative materials

The results of the chemical determinations indicate a slight difference in the concentrations of dissolved inorganic phosphorus (DIP) in the system and the open sea (Figure 5.2). A significant difference in dissolved inorganic nitrogen (DIN) was however obtained between the system and the ocean (Figures 5.3 and 5.4, Table 5.2).

Nutrient concentrations for the surface water runoff drained into the lagoon because of the absence of measurements were assumed similar to the nutrient concentrations in the Volta River (Table 5.2).

DIP balance

The nonconservative flux (ΔDIP) for the Angaw system is +316 mol day^{-1} or +0.04 mmol m^{-2} day^{-1}. It appears that substantial DIP leaves the system with both the residual flow (V_RDIP_R = -407 mol day^{-1})

and exchange flow {$V_x(DIP_{ocn}$ - $DIP_{syst})$ = -94 mol day^{-1}}. The system thus seems to be a net source for DIP. This is with the assumptions that groundwater source is zero and that the surface water runoff has the same DIP concentration as in the Volta River.

Table 5.2. Chemical composition of water samples from the Angaw lagoon, adjacent ocean and Volta River.

	Salinity (psu)	**DIP** (mmol m^{-3})	**DIN** (mmol m^{-3})
Lagoon	13	1.6	57.2
Ocean	34	1.3	28.6
Volta River	2	0.7	42.9

DIN balance

The nonconservative flux (ΔDIN) for the Angaw system is +9,709 mol day^{-1} or +1.2 mmol m^{-2} day^{-1}. The flux pattern for nitrogen (Figure 5.3) is similar to that for phosphorus in that substantial DIN leaves the system with both the residual flow ($V_R DIN_R$ = -12,055 mol day^{-1}) and exchange flow {$V_X(DIN_{ocn}$ - $DIN_{syst})$ = -8,980 mol day^{-1}}. The system thus seems to be a significant net source for DIN. Thus, as with the case of DIP, the initial assumption of groundwater sources for DIN as zero and that DIN concentration of the surface runoff is similar as in the Volta River may be questionable.

Stoichiometric calculations of aspects of net system metabolism

The ΔDIP and ΔDIN values of the Angaw system are positive, indicating a net production of the nutrients within the system. This production could come from either the benthic sediments of the system and/or organic matter decomposition as well as from groundwater seepage which was assumed to zero as there were no data available.

It is reasonable to assume organic matter decomposition in the system is high and comes mainly from mangrove litter and felling because of heavy utilization of mangroves for fuel wood in the area. Mangrove harvesting involves 43% of the population of the people in the area (Tsikata *et al.* 1997). The stoichiometric relationship between carbon, nitrogen and phosphorus based on plankton, the Redfield ratio, is in the molar ratio of 106:16:1. Mangrove litter has, however, been estimated to have a C:N:P: molar ratio of about 1,300: 11:1 (Gordon *et. al.* 1995). It is reasonable to assume a modified Redfield ratio based on mangroves rather than plankton since the system is dominated by mangroves. Using this modified Redfield N:P molar ratio, the expected nonconservative DIN value (ΔDIN_{exp}) should be 11x(ΔDIP).

Thus for Angaw Lagoon:

$$\Delta DIN_{exp} = 3{,}476 \text{ mol day}^{-1}$$
$$\Delta DIN_{obs} - \Delta DIN_{exp} = +6{,}233 \text{ mol day}^{-1} \text{ or } +0.8 \text{ mmol m}^{-2} \text{ day}^{-1}.$$

Since contribution of dissolved organic nitrogen (DON) to the system is assumed to be very small, the difference between ΔDIN_{obs} and ΔDIN_{exp} would represent the difference between nitrogen fixation and denitrification (*nfix-denit*). The positive value of (*nfix-denit*) suggests that Angaw Lagoon is a system where nitrogen fixation exceeds denitrification.

The net metabolism [NEM or (*p-r*), production minus respiration] of the system can be estimated as the negative of ΔDIP multiplied C:P ratio (Gordon *et. al.* 1995). Using the modified Redfield C:P ratio of 1300:1 for a mangrove-dominated system, primarily net organic metabolism and not inorganic sorption or precipitation. This result suggests that the Angaw system is a net heterotrophic system if the DIP release represents net respiration product; (*p-r*) is -52 mmol m^{-2} day^{-1}.

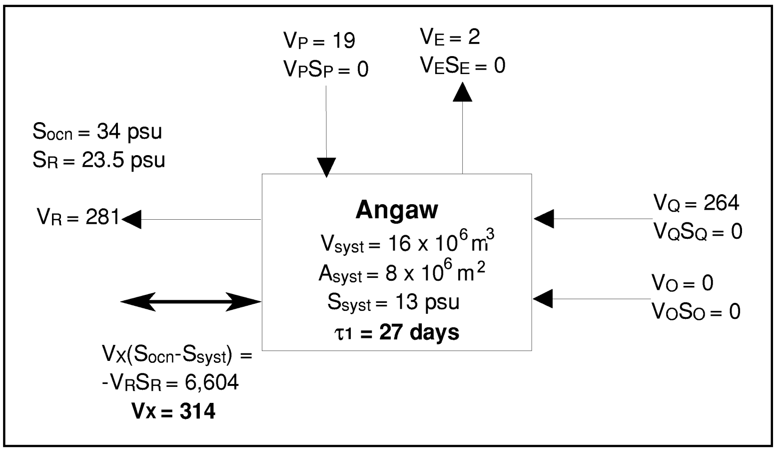


Figure 2. Water and salt budgets for Angaw Lagoon. Water flux in 10^3 m^{3}day^{-1} and salt flux in 10^3 psu-m^3 day^{-1}.

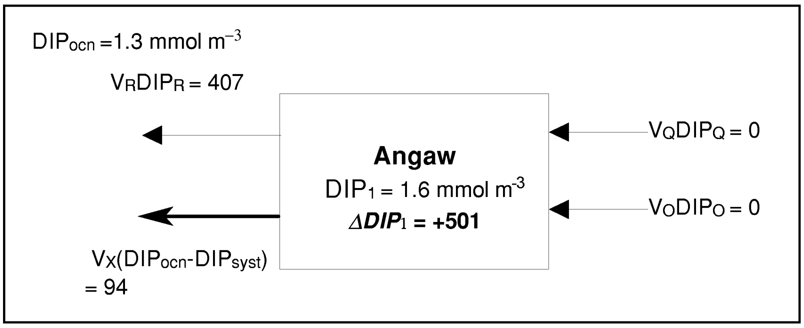


Figure 3. DIP budget for Angaw Lagoon. Flux in mol day^{-1}.

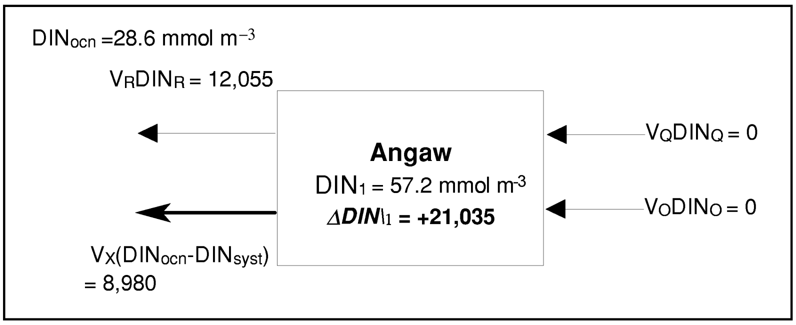


Figure 4. DIN budget for Angaw Lagoon. Flux in mol day^{-1}.

6. REFERENCES

Abdel-Satar, A.M. and Elewa, A.A. 2001 Water quality and environmental assessments of the River Nile at Rosetta Branch. *Proceeding of the 2nd International Conference and Exhibition for Life and Environment, 3-5 April, 2001, Alexandria, Egypt*. pp. 136-164.

Al-Kholy, A.A. and El-Wakeel, S.K. 1975 Fisheries of the south-eastern Mediterranean Sea along the Egyptian coast. Soviet-Egyptian Expedition 1970-1971. *Bull. Nat. Inst. Oceanogr. and Fisheries (NIOF), A.R.E.* Vol. **5**

Allanson, B.R and Winter, D. 1999 Chemistry: The primary chemical structure. Pages 53-70 in B. R. Allanson and D. Baird (eds): *Estuaries of South Africa*. Cambridge University Press, Cambridge. England.

Allanson, B.R., Baird, D. and Heydorn, A.E.F. 1999 Perspectives. Pages 321-327 in Allanson, B.R. and Baird, D. (eds): *Estuaries of South Africa*. Cambridge University Press, Cambridge. England.

Allanson, B.R., Maree, B. and Milne, R. (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.*

Allersma, E. and W.M.K. Tilmans 1993 Coastal conditions in West Africa - a review. *Ocean and Coastal Management* **19**:199-240.

Armah, A.K. 1993 Coastal wetlands of Ghana. *Coastal Zone* **93**: 313-322.

Badenhorst P. 1990 *Mouth dynamics and siltation of the Mvoti Estuary*. Document prepared for a workshop to determine the ecological requirements of the Mvoti Estuary, 25-26 April 1990.

Begg, G.W. 1978 The Estuaries of Natal. *Natal Town and Regional Planning Report* Vol. **41**, Pietermaritzburg.

Begg, G.W. 1984 The Estuaries of Natal part II. *Natal Town and Regional Planning Report* Vol. **55**, Pietermaritzburg.

Carter, R.A. 1983 Estuaries of the Cape. Part II: synopses of available information on individual systems. Report No 21: Breede (CSW 22). *CSIR Research Report 420*, Stellenbosch.

Christie N.D. 1981 Primary production in Langebaan Lagoon. Chapter 7, pages 101-115 in Day, J.H. (ed.): *Estuarine Ecology, with particular reference to southern Africa*. Balkema, Cape Town.

Chunett, Fourie and Partners 1990 Ecological water requirements of the Umvoti River Estuary. Umvoti River Water Resources Development Study. *RSA/KwaZulu Permanent Water Commission Report* No. **P.U400/07/0791**.

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. England.

David, L.T., San Diego-McGlone, Crossland, C.J. and Smith, S.V. (eds) 2000 *LOICZ Biogeochemical Budgeting Procedure: A Tutorial Pamphlet*. LOICZ-IPO, Texel, The Netherlands, 29 pages.

de Villiers, C. and Hodgson, A. 1999 Studies on estuarine macroinvertebrates. Pages 167-191 in Allanson, B.R. and Baird, D. (eds): *Estuaries of South Africa*. Cambridge University Press, Cambridge, England.

Department of Water Affairs and Forestry of South Africa (DWAF) 1993 *Western Cape system analysis. Report on the Berg River Estuary Work Session. Volume* **1**: *Main Report.*

Department of Water Affairs and Forestry (DWAF) 1996 *South African water quality guidelines. Volume* **7**: *Aquatic ecosystems.*

Department of Water Affairs and Forestry of South Africa (DWAF) (provided data on precipitation, evaporation and nutrient inputs at Laaiplek, Langebaanweg and Jantjiesfontein, respectively.

Dupra, V., Smith, S.V., Marshall Crossland, J.I. and Crossland, C.J. 2001 Estuarine systems of sub-Saharan Africa: carbon, nitrogen and phophorus fluxes. *LOICZ Reports and Studies* **18**, LOICZ, Texel, the Netherlands, i+83 pages.

El-Gindy, A.A.H., Shereet, S. and El-Shiekh, S. 1991 Circulation and water masses and their implication on pollutant transport during summer in Abu Qir Bay (Egypt). *Qatar University Science Journal* **11**:379-390.

El-Hehyawi, M.L.E. 1976 Study on the surface water inorganic phosphate in the southeast Mediterranean. *Bull. Nat. Inst. Oceanogr. and Fish. (NIOF), A.R.E.* **6**: 126-155.

El-Rayis, O.A., El-Sabrouti, M.A., Moussa, A. and Khalil, M. 1994 Change in phosphorus storage in Lake Edku and its role in eutrophication of Abu-Qir Bay. *The Proceedings of the 1st Arab Conference on Marine Environment Protection, 5-7 February 1994, Alexandria Egypt*, pp. 191-204.

El-Shenawy, M.A. 1994 *Azolla filiculoides*, a new effective dinitrogen fixer in Lake Edku, Egypt. *Bull Nat. Inst. Oceanogr. and Fish. (NIOF), A.R.E.* 20(1): 83-97.

Filho, J.P. and Schettini, C.A. 2000 Camboriu River estuary, Santa Catarina State. Pages 33-36 in Dupra, V., Smith, S.V., Marshall Crossland, J.I. and Crossland, C.J. (eds): Estuarine systems of the South American region: carbon, nitrogen and phosphorus fluxes. *LOICZ Reports and Studies* **15**, LOICZ, Texel, The Netherlands, 87 pages.

Fowles, B.K., Thorpe, H.E. and Blair, A.G. 1997 Study of the recovery of the benthic fauna and meiofauna following the fine sediment intrusion in the Nhlabane Estuary. *CSIR Report No. ECP-97-010.* CSIR, Durban.

Gharib, S.M. and Solinan, A.M. 1998 Some water characteristics and phyto-zooplankton relationship in Lake Edku (Egypt) and adjacent sea. *Bull. Fac. Sci. Alex. Univ.* **38 (1,2)**: 25-44.

Gordon, C. 1997 Summary of research results of the Lower Volta Mangrove Project. *Lower Volta Mangrove Project Technical Report* No. **11**, Gordon, C. (Series Editor), DFID/Ghana Wildlife Department/Ghana Environmental Protection Agency, 83 pages.

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 & Studies* No **5**, vi+96 pages.

Grange, N. and Allanson, B.R. 1995 The influence of freshwater inflow on the nature, amount and distribution of seston in estuaries of the Eastern Cape, South Africa. *Estuarine, Coastal and Shelf Science* **40**: 403-420.

Grindley, J.R. 1985 *Estuaries of the Cape. Part II Synopses of available information on individual systems. Report No. **30**. Knysna* CMS **13**.

Hall, J., Smith, S.V. and Boudreau, P.R. (eds.) 1996 Report on the International Workshop on Continental Shelf Fluxes of Carbon, Nitrogen and Phosphorus. *LOICZ R&S* **9**, ii+50 pages, LOICZ, Texel, The Netherlands.

Hamed, A.A. 1979 Atmospheric circulation features over the southeasterly part of the Mediterranean sea in relation with weather conditions and wind waves at Alexandria. *M.Sc. Thesis, Faculty of Science, Alexandria University, Egypt.*

Huizenga, P. and van Niekerk, L. 1999 Nhlabane estuary: Physical aspects. In Quinn, N. (ed.): Nhlabane estuarine flow requirements: an initial assessment. *Mhlathuze Ecological Reserve Study*, IWR Environmental.

Kemper, N. 1999 Nhlabane lake water level requirements: an initial assessment. *Mhlathuze Ecological Reserve Study*, IWR Environmental.

Khadr, A.M., El-Sabrouti, M.A. and El-Khatib, E.A. 1992 Texture and chemistry of Lake Edku Sediments, Egypt. *Proceeding of the 2nd International conference on Environmental Protection Is A Must, 24-27 February 1992, Alexandria, Egypt*, pp. 247-263.

Kitheka, J.U. 1996 Water circulation and coastal trapping of brackish water in a tropical mangrove-dominated bay in Kenya. *Journal of Oceanography and Limnology* **41(1)**: 169-176.

Kitheka, J.U. 1997 Coastal tidally driven circulation and the role of water exchange in the linkage between tropical coastal ecosystems**.** *Estuarine, Coastal and Shelf Science* **45**:177-187.

Kitheka, J.U., Ohowa, B.O., Mwashote, B.M., Shimbira, W.S., Mwaluma, J.M. and Kazungu, J.M. 1996 Water-circulation dynamics, water column nutrients and plankton productivity in a well-flushed tropical bay in Kenya. *Journal of Sea Research* **35 (4)**: 257-268.

Largier, J.L., Attwood, C. and Harcourt-Baldwin, J-L. 2000 The hydrographic character of Knysna Estuary. *Transactions of the Royal Society of South Africa* **55(2)**: 107-122.

Law, A.T. 2000 Kuala Terengganu River estuary. Pages 19-21 in Dupra, V., Smith, S.V., Marshall Crossland, J.I. and Crossland, C.J. (eds): Estuarine systems of the South China Sea region: carbon, nitrogen and phosphorus fluxes. *LOICZ Reports and Studies* **14**, LOICZ, Texel, The Netherlands, 156 pages.

Lucas, A.B. 1986 The distribution of chlorophyll pigments in relation to cyclic, sporadic and episodic events in the Great Fish River Estuary. *Unpublished MSc thesis, Rhodes University, Grahamtown.*

MacKay, C.F., Weerts, S.P. and Cyrus, D.P. 2000 High and low flow survey of the Lower Mvoti River and estuary: Preliminary results of high flow survey. *CRUZ Investigational Report* No. **88**: 1-21.

Mackay, H.M. and Schumann, E.H. 1990 Mixing and circulation in the Sundays River estuary, South Africa. *Estuarine, Coastal and Shelf Science* **31**: 203-216.

Mohamed, L.A. and El-Maradny, A. 2001 Studies on the water quality of Abu Qir Bay during December 1999 to November 2000. *Proceeding of the 2nd International conference and Exhibition for Life and Environment, 3-5 April, 2001, Alexandria, Egypt*, pp. 361-383.

Muchtar, M. and Ilahude, A.G. 2000 Mamberamo estuary, Irian Jaya. Pages 16-18 in Dupra, V., Smith, S.V., Marshall Crossland, J.I. and Crossland, C.J. (eds): Estuarine systems of the South China Sea region: carbon, nitrogen and phosphorus fluxes. *LOICZ Reports and Studies* **14**, LOICZ, Texel, The Netherlands, 156 pages.

Mvoti IFR Starter Document 1996 *Unpublished Report for Instream Flow Requirements Workshop of the Mvoti River*, Department of Water Affairs and Forestry, Pretoria, South Africa.

Ohowa, B.O. 1996 Seasonal variations of the nutrient fluxes into Indian Ocean from the Sabaki River. *Discovery and Innovations* **8(3)**: 265-274.

Ohowa, B.O., Mwashote, B.M. and Shimbira, W.S. 1997 Dissolved inorganic nutrient fluxes from two seasonal rivers into Gazi Bay, Kenya. *Estuarine, Coastal and Shelf Science* **45**: 189-195.

Pernetta, J.C. and Milliman, J.D. (eds) 1995 Land-Ocean Interactions in the Coastal Zone: Implementation plan. *IGBP Global Change Report* No. **33**, International Geosphere Biosphere Program, Stockholm, 215 pages.

Pople, W. and Rogoyska, M. 1967 The effect of the Volta River Hydroelectric Project on the salinity of the Lower Volta River. *Ghana Journal of Science* **9(1)**: 9-20.

Porter, I. 1990 *Desired future status of the Mvoti Estuary from a nature conservation perspective.* Document prepared for a workshop to determine the ecological requirements of the Mvoti Estuary, 25-26 April 1990.

Quinn, N. 1999 Nhlabane estuarine flow requirements: an initial assessment. *Mhlathuze Ecological Reserve Study*, IWR Environmental.

Saad, M.A.H., Mahmoud, T.H. and Hassan, E.M. 2000 Environmental conditions of Mediterranean water affected by Nile estuary. *Proceeding of the Regional workshop on the Exclusive Economic Zone, 3-5 April, 2000*, pp. 67-77.

Slinger, J.H. and Taljaard, S. 1994 Preliminary investigation of seasonality in the Great Berg Estuary. *Water SA* **20**(4):279-288.

Slinger, J.H. and Taljaard, S. 1996 Water quality modelling of estuaries. Field data collection for calibrating the Mike 11 water quality module on the Great Berg Estuary. *CSIR Report* **EMAS-D 96002.**, Stellenbosch.

Slinger, J.H, Taljaard, S and Visser, E. 1996 Water quality modelling of estuaries. Field data collection for calibrating the Mike 11 water quality module on the Great Berg Estuary. *CSIR Report* **EMAS-D 96004**, Stellenbosch.

Soltan, M.E. and Awadallah, R.M. 1994 Chemical survey on the River Nile water from Aswan into the outlet. *Proceeding of the National Conference on The River Nile, 10-14 December, 1994, Assiut, Egypt*, pp. 157-196.

Switzer, T. and Waldron, H. 2001 Knysna Lagoon, Western Cape. Pages 39-43 in Dupra, V., Smith, S.V., Marshall Crossland, J.I. and Crossland, C.J. (eds): Estuarine systems of sub-Saharan Africa: carbon, nitrogen and phosphorus fluxes. *LOICZ Reports and Studies* **18**, LOICZ Texel, The Netherlands, i+ 83 pages.

Taljaard, S. and Slinger, J.H. 1992 Assessment of hydrodynamic and water quality aspects of the Berg river Estuary 1989/90. *CSIR Report* **EMAS-D 92006**, Stellenbosch.

Taljaard, S., Van Niekerk, L. and Huizinga, P. (in prep.) Appendix C: Specialist report on physical dynamics and water quality. In Intermediate determination of resource-directed measures for the Breede River estuary. *CSIR Report*, CSIR, Environmentek, Stellenbosch.

Taylor, D.I. 1992 The influence of upwelling and short term changes in concentration of nutrients in the water column on fluxes across the surface of a salt marsh. *Estuaries* **15**: 68-74.

Taylor, D.I. and Allanson, B.R. 1993 Impacts of dense crab populations on carbon exchanges across the surface of a salt marsh. *Marine Ecology Progress Series* **101**: 119-129.

Taylor, D.I. and Allanson, B.R. 1995. Organic carbon fluxes between high marsh and estuary, and the applicability of the Outwelling Hypothesis. *Marine Ecology Progress Series* **120**: 263-270.

Tharme, R. 1996 Rivers of southern Africa: Mvoti River. *African Wildlife* **50(5)**: 31.

Tsikata, I.E., Senah, K. and Awumbila, M. 1997 Mangrove resource utilization and community-based management in the Lower Volta: a socio-anthropological study. *Lower Volta Mangrove Project Technical Report* No. **4**, Gordon, C. (Series Editor), DFID/Ghana Wildlife Department/Ghana Environmental Protection Agency, 83 pages.

UNEP/MAP 1997 Identification of priority pollution hot spots and sensitive areas in the Mediterranean. *Draft report*.

Vivier, L., Cyrus, D.P., Jerling, H.L. and Cilliers, G.J. 1998 Effect of the dredger crossing on the Nhlabane Estuary - Final Report. *CRUZ Investigational Report No.* **57**: 1-69.

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. 2001 Thukela River estuary, KwaZulu-Natal. Pages 66-69 in Dupra, V., Smith, S.V., Marshall Crossland, J.I. and Crossland, C.J. (eds): Estuarine systems of sub-Saharan Africa: carbon, nitrogen and phosphorus fluxes. *LOICZ Reports and Studies* **18**, LOICZ, Texel, The Netherlands, i+83 pages.

Whitfield, A.K. 1992 A characterisation of southern African estuarine systems. *South African Journal of Aquatic Sciences* **18(1/2)**: 89-103.

Zahran, M.A, Serag, M.S. and Persson, S. 1994 On the ecology of canal bank vegetation of the Nile delta, Egypt. *Proceeding of national conference on the River Nile, 10-14 December, 1994, Assiut University (AUCES)* **3**:27-45.

Appendix I List of Participants and Contributing Authors

Resource Persons

Prof. Stephen Smith
Department of Oceanography
University of Hawaii
1000 Pope Rd
Honolulu, Hawaii 96822
USA
Phone: +1 808 956 8693
Fax: +1 808 956 7112
Email: svsmith@soest.hawaii.edu

Dr. Laura David
Marine Science Institute
College of Science
University of the Philippines
Roces Ave., Diliman, Quezon City
PHILIPPINES
Phone: +63-2 922 3959 or +63-2 922-3944
Fax: +63-2 924 7678
Email: ldavid@upmsi.ph
or ltdavid@eudoramail.com

Dr 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

Todd Switzer
Dept of Oceanography,
University of Cape Town, Rondebosch, 7700,
South Africa.
Tel +27 21 650 3284
Fax +27 21 650 3979
Email: todd@cyberperk.co.za

Regional Participants

Prof. 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

Dr Victor Wepener
Dept Dierkunde,
RAU
POBox 524
Auckland Park, 2006
South Africa
Phone: +27 11 489 3373
Fax: +27 11 489 2286
Email: vw@na.rau.ac.za

Prof. Brian Allanson
16 Steenbok Crescent
Leisure Isle
Knysna 6570
South Africa
Phone/Fax: +27 44 384 0658
Email: ba11@pixie.co.za

Dr Susan Taljaard
CSIR
POBox 320
Stellenbosch 7599
South Africa
Phone: +27 21 888 2400
Fax: +27 21 888 2693
Email: staljaar@csir.co.za

Carl Wainman
Institute for Maritime Technology
F46 East Dockyard Rd
Somon's Town
Cape
South Africa
Phone: +27 21 786 1092
Fax: +27 21 786 3634
Email: ckw@inet.imt.za

Nadia Smith
Zoology Department
University of Port Elizabeth
PO Box 1600
Port Elizabeth
South Africa
Phone: +27 41-5042341
Fax: +27 41-5042317
E-mail: zlchns@zoo.upe.ac.za

Bomba Bazika
Instituto de Investigacao Pesqueira
Ilha de Luanda
C. Postal 2601
Luanda, Angola
Phone:
Fax:
Email: vbarros@netangola.com

Dr Johnson Kitheka
Ecology and Environmental Research Programme
Kenya Marine Fisheries Institute
PO Box 81651
Mombasa, Kenya
Phone: +254-11-475153/4
Fax: +254-011 475157
Email: jkitheka@recoscix.org

Prof. Hassan Awad
National Institute of Oceanography & Fisheries
Qayet Bay
Alexandria
Eqypt
Phone: +203 429 3126
Fax: +203 429 3126
Email: awads_alex@yahoo.fr

Contributing authors

Nabiha A. Youssef
National Institute of Oceanography and Fisheries
Qayet Bey, Alexandria, Egypt
Phone: 002033590143
e-mail: Sc_alex2@cns.sisnet.net

Benjamin M. Mwashote
Ecology and Environmental Research Programme
Kenya Marine Fisheries Institute
POBox 81651
Mombasa, Kenya
Phone: +254-11-475153/4
Fax: +254-11 475157
Email: bmwashote@recoscix.org

Craig Attwood
Dept of Oceanography, UCT,
Rondebosch 7700, RSA
Tel: +21 650 3277
Fax: +21 650 3979
Cell: 0833687515
Email: attwood@iafrica.com

C.F. (Fiona) MacKay
Coastal Research Unit of Zululand
University of Zululand
Private Bag X1001
KwaDlangezwa 3886
KwaZulu-Natal
Tel: +27 35 902 6161
Fax: +27 35 902 6750
Email: fmackay@pan.uzulu.ac.za

Appendix II Workshop Report

Welcome

Participants (Appendix I) were welcomed to South Africa by Dr Howard Waldron, on behalf of the University of Capetown, and meeting organisation and arrangements were reviewed. The terms of reference for the workshop (Appendix III) were reviewed and various working documents, electronic information and tutorial materials were distributed.

Introduction and Background

A round-table introduction of participants was made. LOICZ goals and approaches were presented by Prof. Steven Smith and emphasis was given to the central questions of evaluating material fluxes and, the influence of human dimensions on global changes in processes within the coastal zone. The purpose of the workshop was outlined 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, Dr Laura David 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.

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:

South Africa
Berg River estuary, Western Cape
Breede River estuary, Western Cape
Knysna Lagoon, Western Cape
Great Fish River estuary, Eastern Cape
Kariega River estuary, Eastern Cape
Mvoti River estuary, Kwa-Zulu, Natal
Nhlabane River estuary, Kwa-Zulu, Natal

Kenya
Gazi Bay mangrove creek

Egypt
Nile River delta, Rosetta Branch and Lake Edku

Angola
Quanza River 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 budget model 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.

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 participate in a mutual review process for budget descriptions.

The participants joined with LOICZ in expressing thanks to Dr Howard Waldron and staff from the University of Capetown for support and hosting of a fruitful training and information workshop. The financial support of the Global Environment Facility was gratefully acknowledged.

Appendix III Terms of Reference

LOICZ-UNEP WORKSHOP ON ESTUARINE SYSTEMS OF THE SOUTHERN AFRICAN REGION

Oatlands Holiday Village and Conference Centre
Simonstown
Republic of South Africa
3-6 September 2001

Primary Goals:

To work with researchers dealing with estuarine and coastal systems of the southern African region, in order to extract C, N, P budgetary information from as many systems as feasible using existing data. The African systems include one of the major coastal regions of the world oceans and are little described in system model terms. An earlier Sub-Saharan regional workshop helped establish a number of biogeochemical models for sites, but there is both opportunity to extend this geographical coverage and a need to do so within the LOICZ context. 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 Mexico (Central and South Americas: 1997, 1999, 2001), Australia (Australasia: 1998), Manila (South-East Asia: 1999), Argentina (South America: 1999), Goa (South Asia: 2000), Hong Kong (East Asia: 2000), Zanzibar (Sub-Saharan Africa: 2000) and Athens (Mediterranean and Black Seas: 2001), by the analysis of additional data from an important coastal 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 may additional systems can be budgeted over an additional 2 months.
3. Prepare a LOICZ technical report and a CD-ROM summarizing this information.

Participation:

- The number of participants will be limited to fewer than 15 persons, to allow the active involvement of all participants.

Workplan:

Participants are expected to come prepared to participate in discussions on coastal budgets. Preparation should include reading the LOICZ Biogeochemical Modelling Guidelines (Gordon *et al.* 1996), an earlier workshop report (see Dupra *et al.* on LOICZ web site), 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 write-ups 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 write-ups 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 a 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

September 2: Arrival of non-Cape Town residents
September 3: Arrival of Cape Town residents
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 4: Continue breakouts; afternoon plenary to evaluate progress.
September 5: Continue breakouts; afternoon plenary to evaluate progress.
September 6: Breakouts/plenary as required to develop synthesis.
September 7: Departure.

Background Documents:

1. 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.
2. 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.
3. 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-ROM with the web page. Please do not request the CD-ROM 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 IV Glossary of Abbreviations

NH_4	Ammonium
NO_3	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_4	Silicate
nfix	Nitrogen fixation
denit	Denitrification
p	Primary production
r	Respiration
TDN	Total dissolved nitrogen
TDP	Total dissolved phosphorus
CTD	Conductivity Temperature Depth