4. ESTUARIES OF SOUTH AFRICA

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

A wide variety of estuarine types can be found in South Africa, reflecting substantially different physical environments. The eastern seaboard has the steeply tilted coastal plains subject to heavy summer rainfall, whereas the arid west coast is less tilted, and estuaries become functional only during events of exceptional precipitation. Although numerous, South African estuaries are generally small and cover only some 600 km^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).

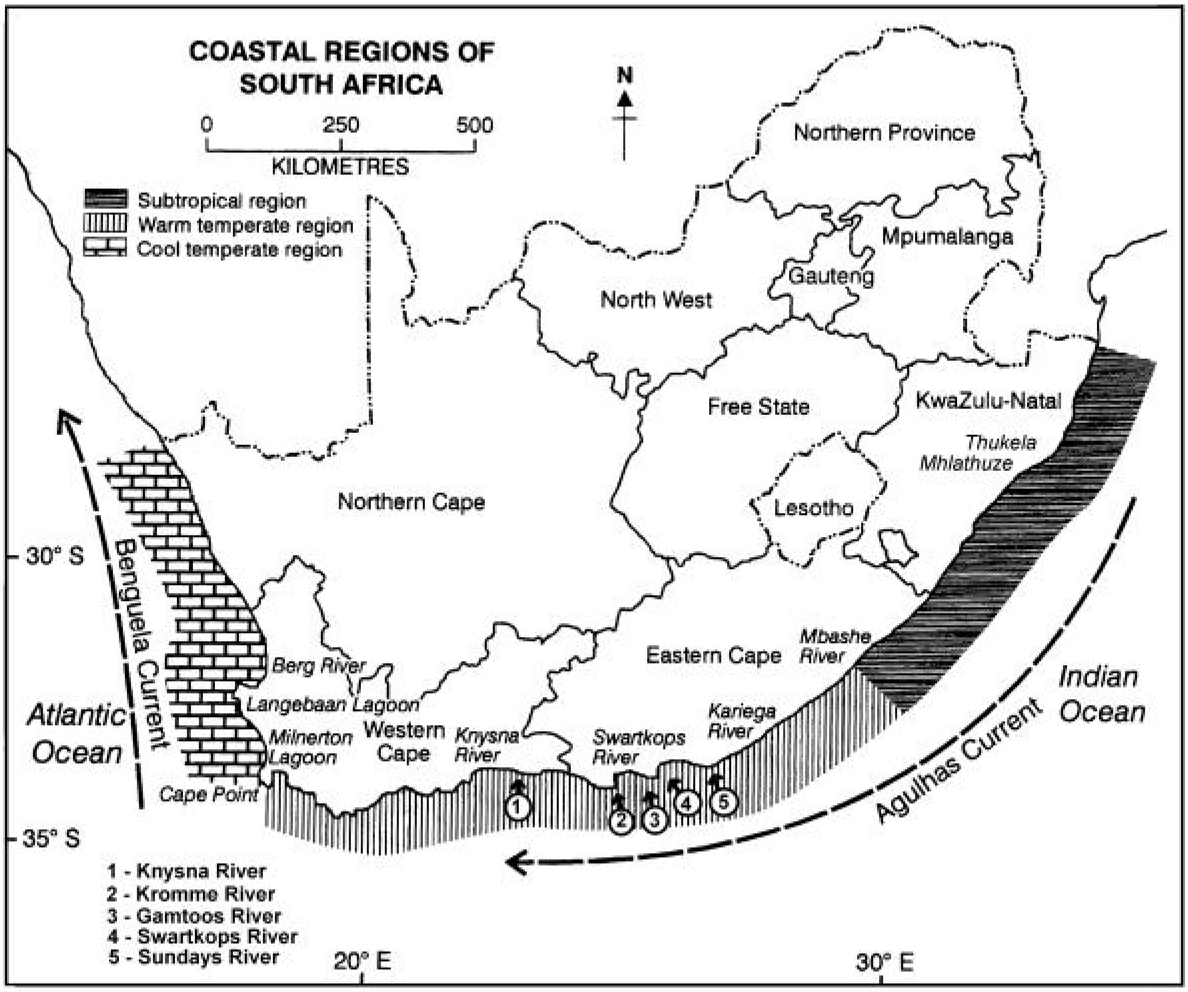

Figure 4.1. Climatological/biogeographical regions and ocean currents along the South African coast.

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

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

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

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

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

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

Since much of southern Africa is semi-arid and prone to extremes of drought and floods, and with a growing population, South Africa is faced with the task of providing water to all users. The abstraction of water from rivers for human needs resulted in gross interference with the hydraulic structure of estuaries, and in some instances lead to the destruction of the ecosystem. As well as the influence of activities in the catchments of estuaries, there is also direct pressures on them. Because of the rugged coastline, the limited number of truly sheltered embayments, the high energy wave regime and strong winds throughout the year, development pressure has focused on estuaries. Most of South Africa’s major industries are located in the interior, so that this pressure is mainly in the form of residential and recreational developments (Morant and Quinn 1999). They have not, in general, attracted large settlements of people with the exception of important estuarine settlements including urban and industrial developments at Richards Bay (near Lake St. Lucia) and Durban in KwaZulu-Natal, the Buffalo and Swartkops rivers in the Eastern Cape Province, Knysna and Saldanha in the Western Cape (Allanson *et al.* 1999). The condition of South African estuaries varies from “excellent” (i.e. in a nearly pristine condition) to “poor” (i.e. where major ecological degradation occurs due to a combination of anthropogenic influences). About 30% of estuaries are considered to be in an “excellent” condition, 31% in a “good” condition, 24% are considered to be “fair” and 15% “poor”. Management of South African estuaries has in the past mainly been undertaken on a piecemeal basis, dependent on and driven by sectoral interests such as fishermen, property developers and owners, and local interest groups. More recently the management and research of estuaries have been incorporated into legislation and policy, such as the Marine Living Resources Act (No. 18 of 1998), the National Water Act (No. 36 of 1998), and the White Paper for Sustainable Coastal Development in South Africa. An authoritative and comprehensive review of the status of estuarine research and management in South Africa is given by Allanson and Baird (1999).

Dan Baird

4.1 Knysna Lagoon, Western Cape

Todd Switzer and Howard Waldron

Study area description

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

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

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

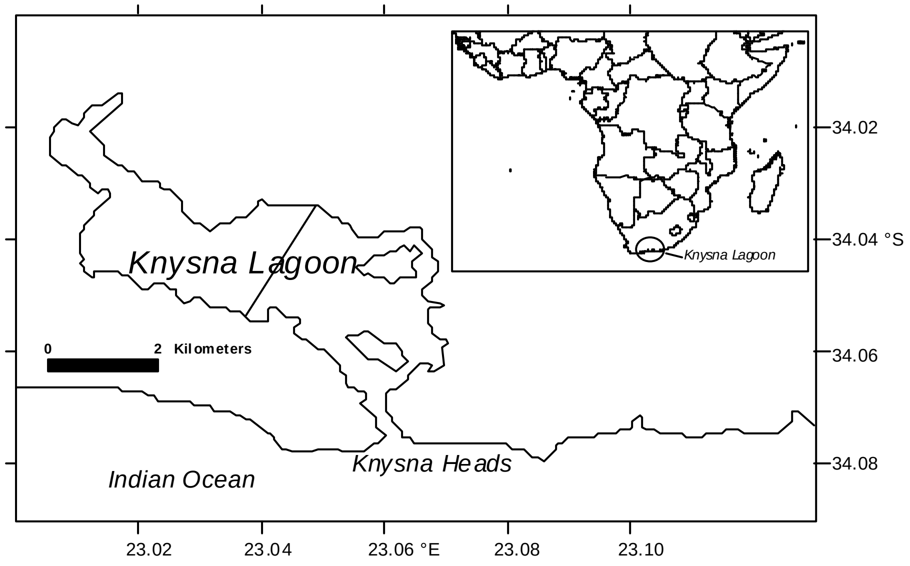

Figure 4.2. Location and map of Knysna Lagoon.

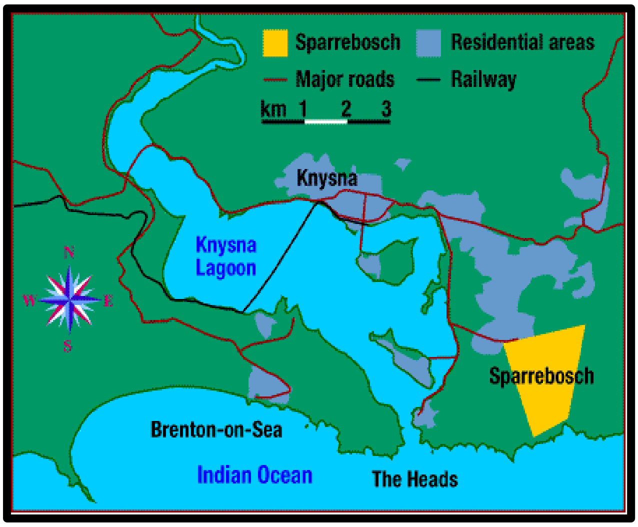

Figure 4.3. Detailed map of Knysna Lagoon.

Figure 4.4. Aerial view of Knysna Heads.

Water and salt balance

Based on data relating to riverine input, precipitation, evaporation and salinity, there was a residual flux of water (V_R) of -37x10^3 m^3 d^{-1} between estuary and the bay and -43x10^3 m^3d^{-1} between bay and the ocean. The negative value of these numbers denotes residual flow of water from the estuary to the bay, and from the bay to ocean waters.

The salt flux carried by this residual flow (V_RS_R) was -1,227x10^3 psu-m^3 d^{-1} between estuary and bay and -1,487x10^3 psu-m^3 d^{-1} between bay and ocean.

Following the underlying physical principles of the LOICZ budgeting method salt must be conserved. The residual salt flux, denoting a loss of salt from the estuary is brought back to balance in the system through the mixing flux of salt across intra- and inter- system boundaries. This can be seen in the figures given in the model for $V_X(S_{ocn}-S_{syst})$ between estuary and bay and between the bay and the ocean. Minimal salt fluxes from the rivers ($V_{Q2}S_{Q2} + V_{Q3}S_{Q3}$) were considered in Box 2 (Figure 4.5). The mixing fluxes (V_X) between estuary and bay and between bay and ocean were 722×10^3 m^3 d^{-1} and $1{,}193 \times 10^3$ m^3 d^{-1}, respectively.

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

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

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

Budgets of nonconservative materials

The criteria established in the water and salt budgets also apply to exchanges of dissolved N and P with the caveat that deviations result from net non-conservative reactions of N and P in the system. Concentrations of NO_3, NO_2, NH_4 (DIN) and PO_4 (DIP) were available from samples taken at stations spaced at intervals of approximately 800 meters along the navigable channel of the bay and estuary. These 14 stations were sampled quasi-synoptically.

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

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

DIP balance

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

DDIP values of -90 mol d^{-1} and +891 mol d^{-1} were obtained for the estuary and bay (see Figure 4.6). This indicates that the estuary is experiencing a net loss of DIP while the bay realises a net gain at the annual time scale. Given the system's total surface area of 48 km^2 this translates to a system average uptake of 0.02 mmol m^{-2} d^{-1}. These values are unrealistically low due to the fact that one dry season is being extrapolated to a full year.

DIN balance
The residual DIN fluxes (V_RDIN_R) between estuary and bay and bay and the ocean were -133 mol d^{-1} and -97 mol d^{-1}, respectively.

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

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

$(nfix - denit) = DDIN_{obs} - DDIN_{exp}$

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

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

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

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

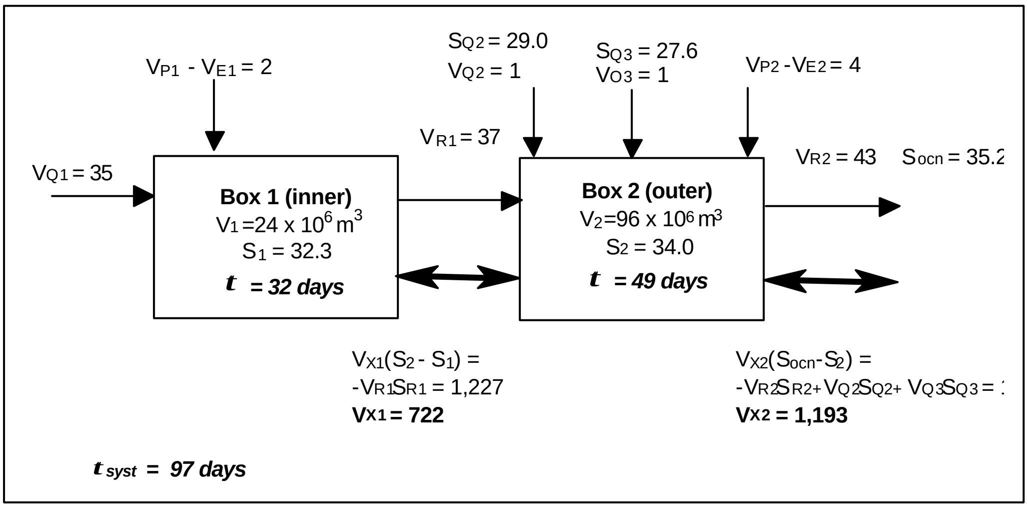

Figure 4.5. Water and salt budgets for Knysna Lagoon in the winter. Water and salt fluxes in 10^3 m^3 d^{-1} and 10^3 psu-m^3 d^{-1}, respectively.

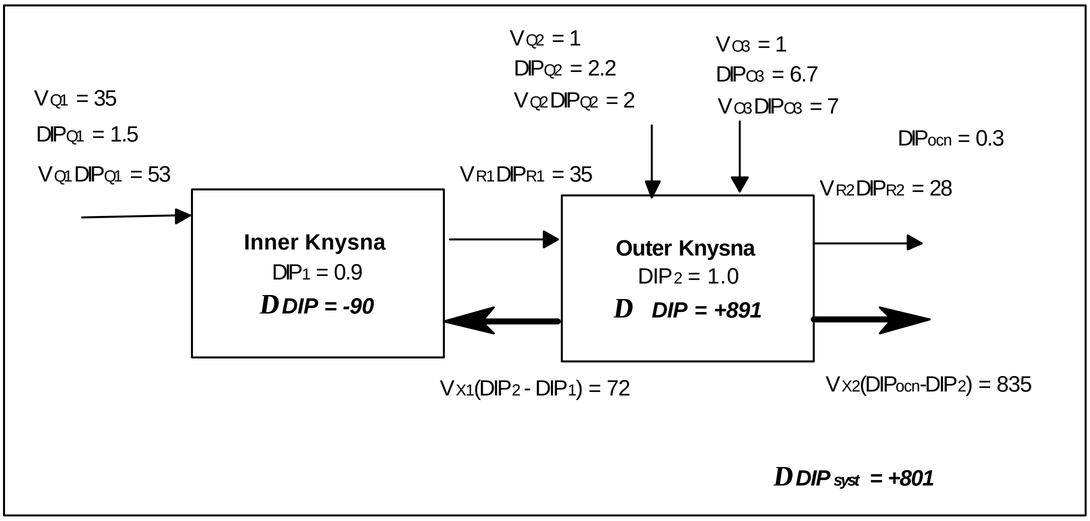

Figure 4.6. DIP budget for Knysna Lagoon in the winter. DIP flux in mol d^{-1}.

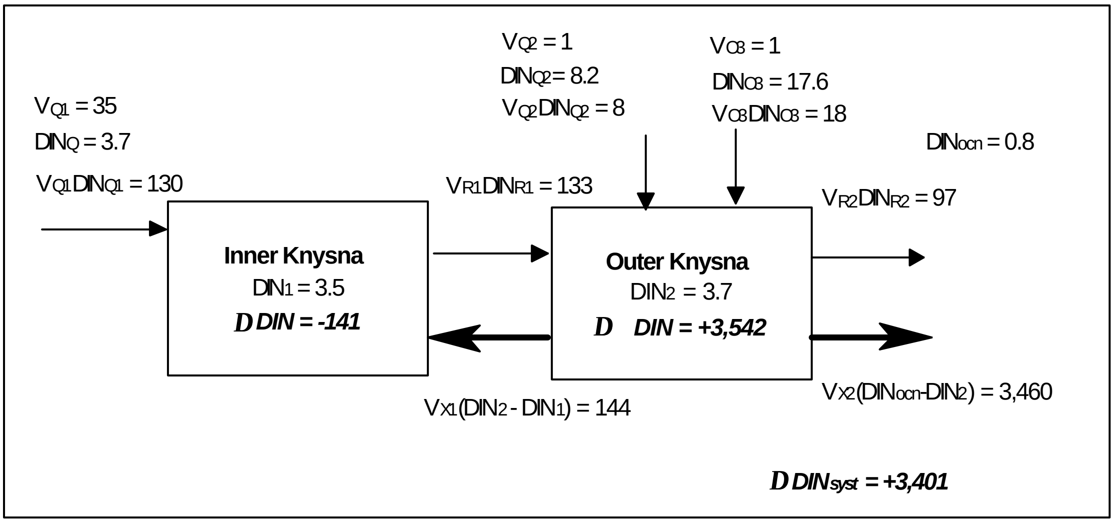

Figure 4.7. DIN budget for Knysna Lagoon in the winter. DIN flux in mol d^{-1}.

4.2 Kromme River Estuary, St Francis Bay, Eastern Cape

Dan Baird

Study area description

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

The 95 km long Kromme River originates in a coastal mountain range (the Tsitsikamma Mountains) and drains a catchment of about 936 km^2 (Reddering and Esterhuysen 1983), which is partly vegetated by fynbos vegetation and natural forest. Limited areas in the catchment are utilized for stock raising and grain cultivation. No industrial activities occur in the catchment or in the estuarine floodplain (Baird, Marais and Bate 1992), so that this estuary is considered to be one of the few relatively pristine systems in the country. Rainfall occurs throughout the year, with lowest precipitation during summer (December to February) (Bickerton and Pierce 1988) and peaks during the austral spring and autumn. Annual rainfall varies between 700 mm and 1,200 mm with a mean annual runoff (MAR) of about 106x10^6 m^3 (Reddering and Esterhuysen 1983). The high MAR is a consequence of the geomorphological characteristics of the catchment, i.e. high relief, rocky slopes and sparsely vegetated areas. Alterations to the river flow in the Kromme River as a result of two dams have severely reduced freshwater input into the estuary. The dams have the combined capacity of storing ca 133% of the MAR of the Kromme River catchment. The runoff into the estuary prior to the construction of the second dam in 1982 was about 117x10^6 m^3 yr^{-1} was subsequently drastically reduced to 1x10^6 m^3 yr^{-1}. Freshwater inflow into the Kromme estuary is low and irregular with a mean annual flow rate of about 11x10^3 m^3 d^{-1}. The flow rate during the rainy months increases to about 13x10^3 m^3 d^{-1} and decreases to about 6x10^3 m^3 d^{-1} during the dry months. The system is effectively freshwater-starved, with relatively low concentrations of DIN and DIP reaching the estuary from the catchment (Scharler *et al.* 1998), despite the fact that, in addition to the natural freshwater runoff, about 2x10^6 m^3 yr^{-1} are released from the upstream impoundments to compensate for evaporation in the estuary (Jezewski and Roberts 1986) (EMATEK (CSIR) 1994).

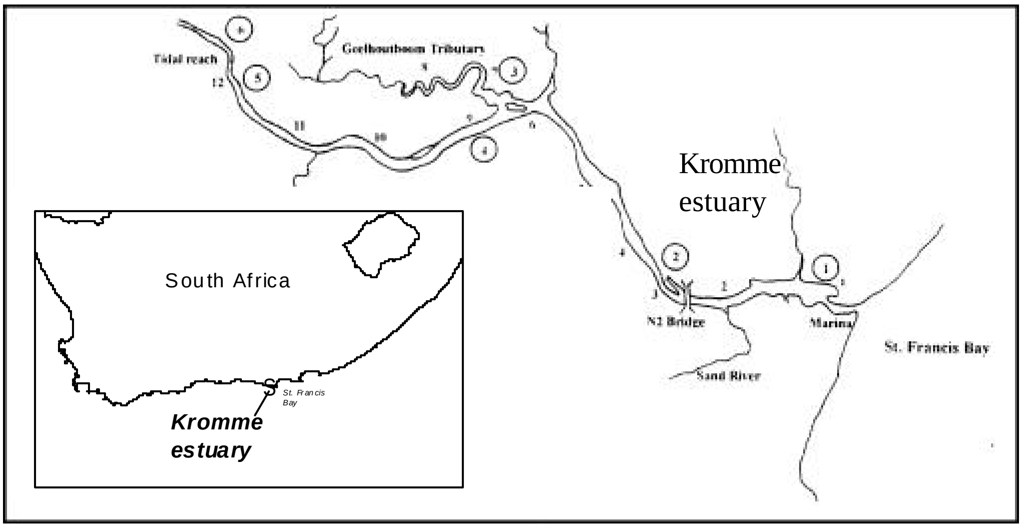

Figure 4.8. Map and location of the Kromme River estuary.

The estuary is about 14 km long, with a surface area of about 3 km^2 (Bickerton and Pierce 1988). The estuary is shallow (average depth at low water spring 3 m), with tidal amplitude of 2 m at the mouth. The tidal prism during spring tides is on average 2x10^6 m^3 and during neap tides about 1x10^6 m^3 in volume. The average flushing time at spring tide is about 27 h. The water temperature fluctuates between 12°C in winter and 27°C in summer (Baird and Pereyra-Lago 1992). The salinity has rarely dropped below 30 psu since the completion of the dams in 1984. Salinity in the Kromme estuary ranges from 32.8 psu in the lower reaches to 31.1 psu in the upper reaches. Salinity stratification may occur in the upper and middle reaches of the estuary during low to moderate freshwater inflow (Scharler *et al.* 1998). The data on the salinity structures of the estuary, and on the concentrations of dissolved inorganic nutrients in both the freshwater reaches and the estuary considered in this study, were obtained from various theses and published information. Most of this information was collected during the years 1996-1999 (*cf.* Baird and Pereyra-Lago 1992, Scharler *et al.* 1998, Allanson and Baird 1999, Scharler 2000, Scharler and Baird 2000). The physical characteristics of the Kromme estuary are given in Table 4.2.

Table 4.2. Physical characteristics of the Kromme River estuary.

Characteristic	*Value*
Catchment (km^2)	936
Length of estuary (km)	14
Surface area (km^2)	3
Average depth (m)	3
Average system volume (10^6 m^3)	9

Water and salt balance

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

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

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

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

Season	**Freshwater input** (10^3 m^{3}d^{-1})			**Residual flow** (10^{3}m^{3}d^{-1})	**River salinity** (psu)	**Ocean salinity** (psu)	**Lagoon salinity** (psu)	**Exchange volume** (10^{3}m^{3}d^{-1})	**ô** (day)
	V_Q	V_P	V_E						
Dry	6	5	6	5	0.6	35.3	32.7	64	130
Wet	13	9	6	16	0.6	35.3	31.0	121	66
Annual Mean	11	8	6	12	0.6	35.3	31.6	102	87

Budgets of nonconservative materials

DIP balance

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

DIN balance

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

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

Time	***DDIP*** (mol d^{-1})	***DDIN*** (mol d^{-1})	**(*p-r*)** (mol d^{-1})	**(*nfix-denit*)** (mol d^{-1})	**(*p-r*)** (mmol m^{-2} d^{-1})	**(*nfix-denit*)** (mmol m^{-2} d^{-1})
Dry	+35	+817	-3,710	+257	-1	+0.1
Wet	+67	+1,552	-7,102	+480	-2	+0.2
Annual mean	+56	+1,307	-5,971	+406	-2	+0.2

Stoichiometric calculations of aspects of net system metabolism

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

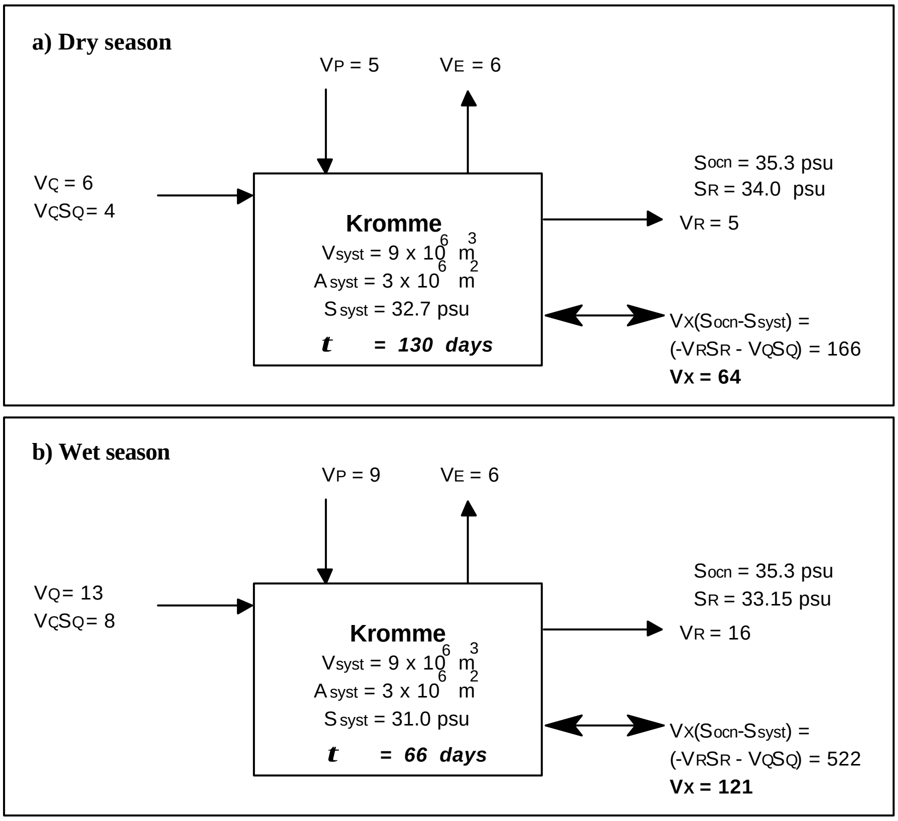

Figure 4.9. Water and salt budgets for Kromme River estuary in the dry (a) and wet (b) seasons. Water flux in 10^3 m^3 d^{-1} and salt flux in 10^3 psu-m^3 d^{-1}.

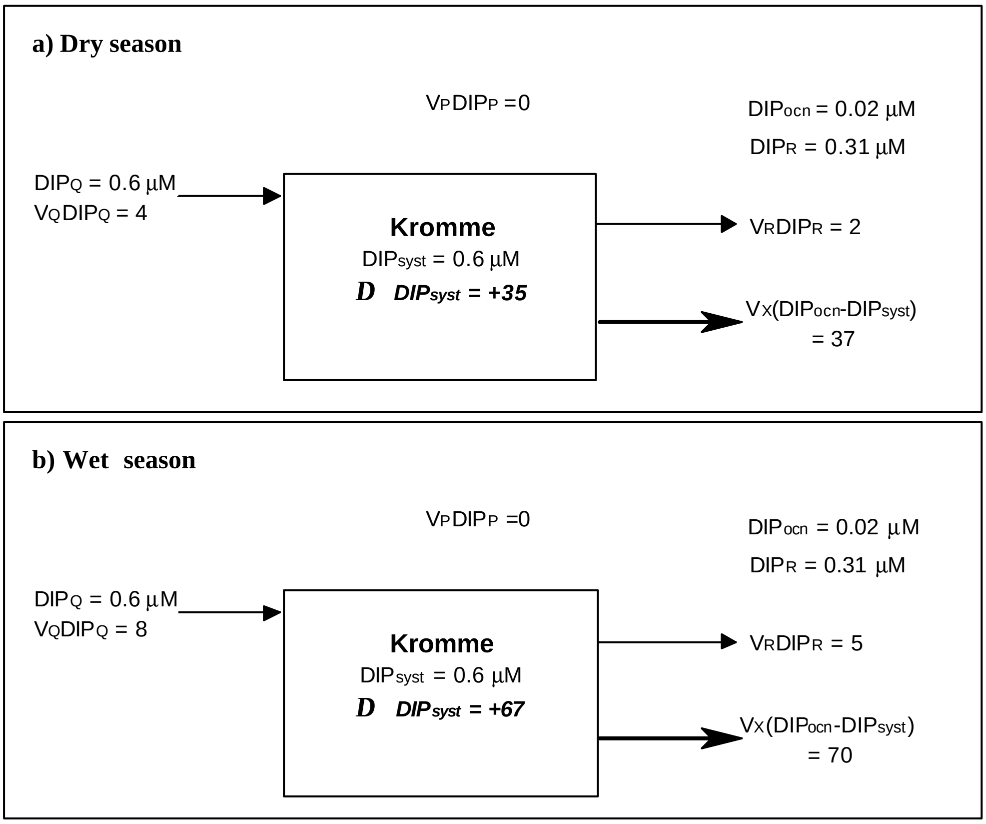

Figure 4.10. DIP budget for Kromme River estuary in the dry (a) and wet (b) seasons. Flux in mol d^{-1}.

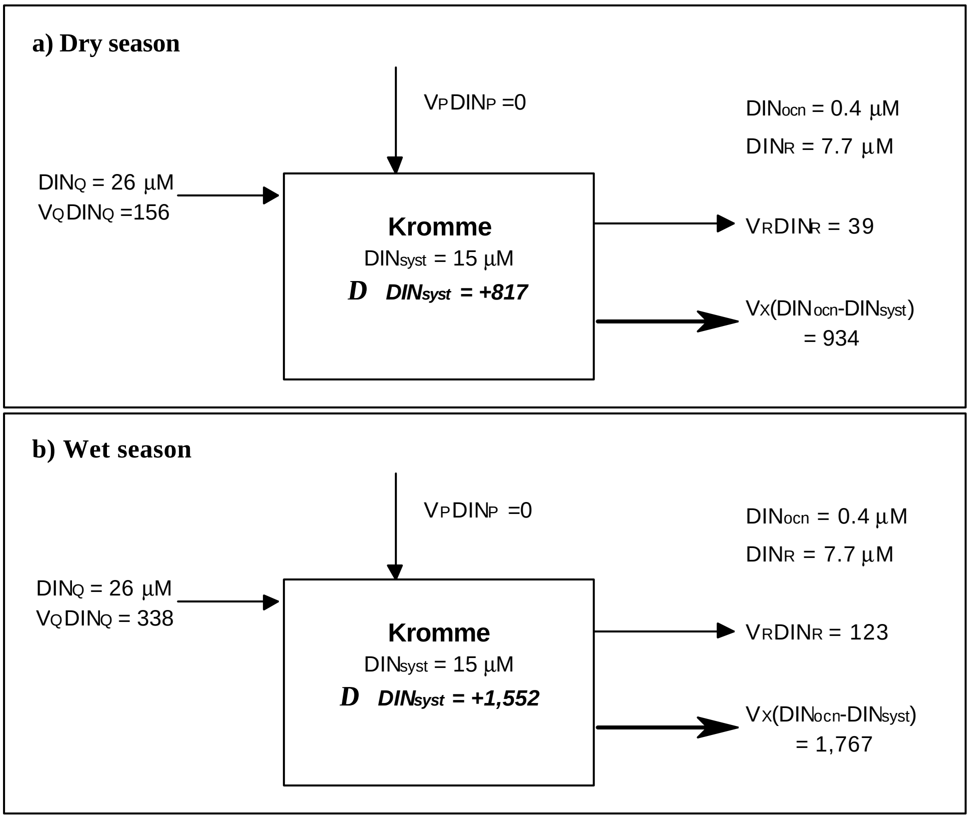

Figure 4.11. DIN budget for Kromme River estuary in the dry (a) and wet (b) seasons. Flux in mol d^{-1}.

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

Dan Baird

Study area description

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

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

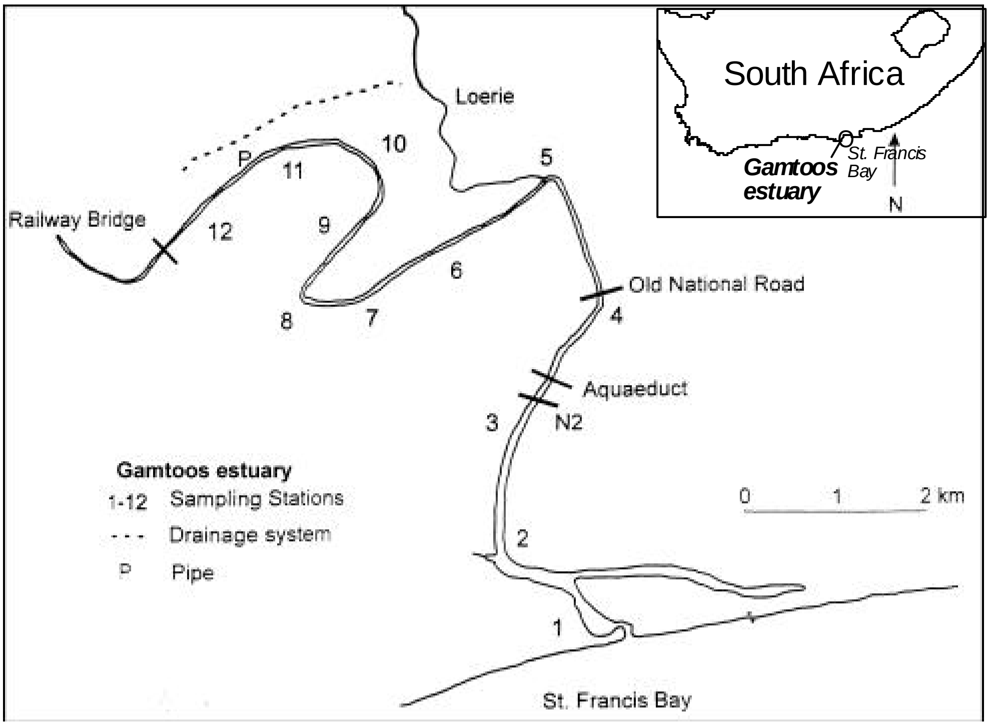

Figure 4.12. Map and location of the Gamtoos River estuary.

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

Table 4.5. Physical characteristics of the Gamtoos River estuary.

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

Water and salt balance

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

Budgets of non-conservative materials

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

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

Season	**Freshwater input** (10^3 m^3 d^{-1})				**Residual flow** (10^3 m^3 d^{-1})	**River salinity** (psu)	**Ocean salinity** (psu)	**Lagoon salinity** (psu)	**Exchange volume** (10^3 m^3 d^{-1})	**t** (days)
	V_Q	V_O	V_P	V_E						
Dry	35	0.3	2	-5	32	0.6	35.3	18.5	50	49
Wet	138	0.3	3	-5	136	0.6	35.3	14.6	160	14
Annual mean	**104**	**0.3**	**3**	**-5**	**101**	**0.6**	**35.3**	**15.9**	**123**	**26**

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

Stoichiometric calculations of aspects of net system metabolism

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

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

Time	*DDIP*		*DDIN*		**(*p-r*)**	**(*nfix-denit*)**
	(mol d^{-1})	(mmol m^{-2}d^{-1})	(mol d^{-1})	(mmol m^{-2} d^{-1})	(mmol m^{-2} d^{-1})	(mmol m^{-2} d^{-1})
Dry	-20	-0.01	+627	+0.3	+1	+0.5
Wet	-38	-0.02	+1,318	+0.7	+2	+1
Annual	**-32**	**-0.02**	**+1,088**	**+0.5**	**+2**	**+1**

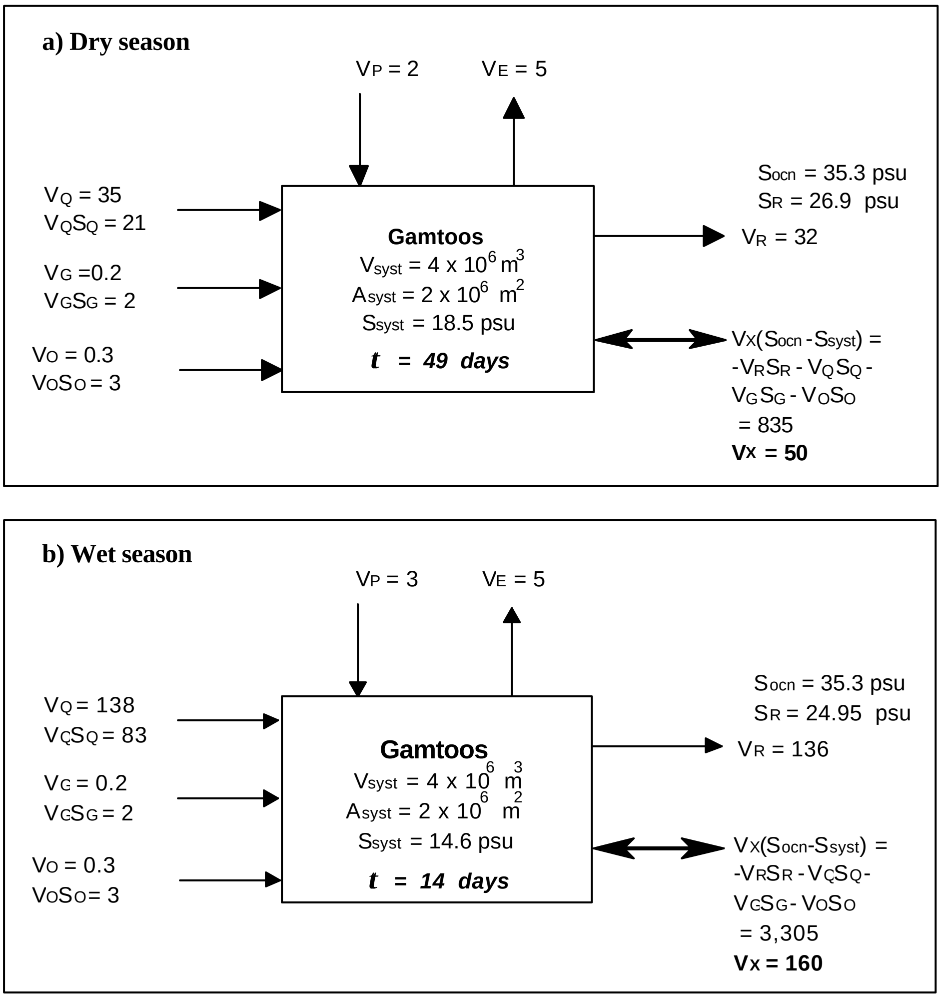

Figure 4.13. Water and salt budgets for Gamtoos River estuary in the dry (a) and wet (b) seasons. Water flux in 10^3 m^3 d^{-1} and salt flux in 10^3 psu-m^3 d^{-1}.

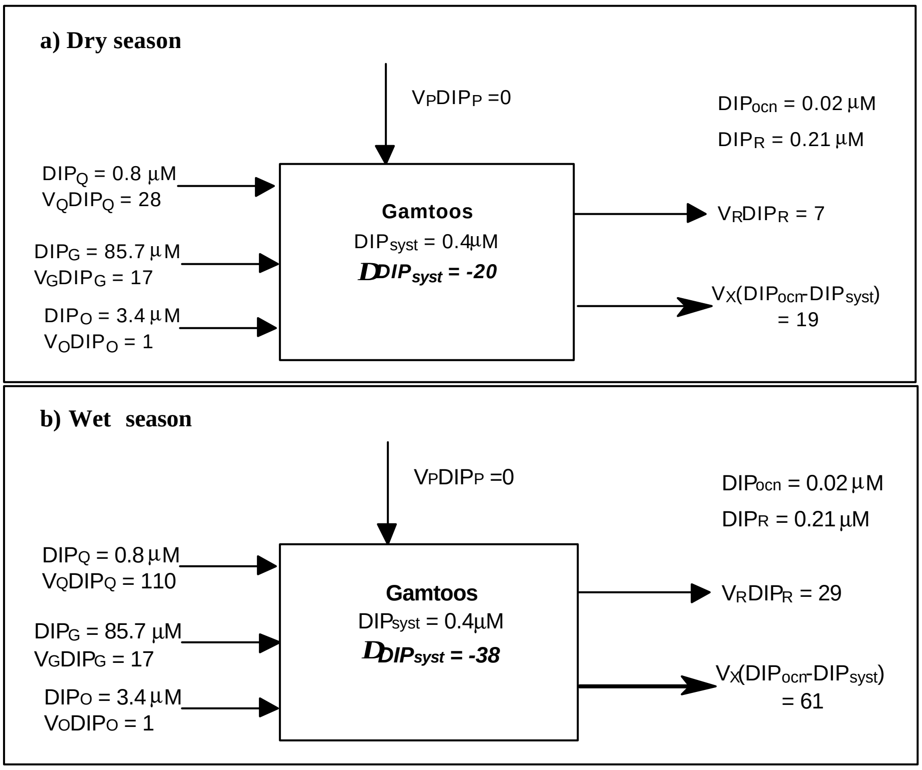

Figure 4.14. DIP budget for the Gamtoos River estuary in the dry (a) and wet (b) seasons. Flux in mol d^{-1}.

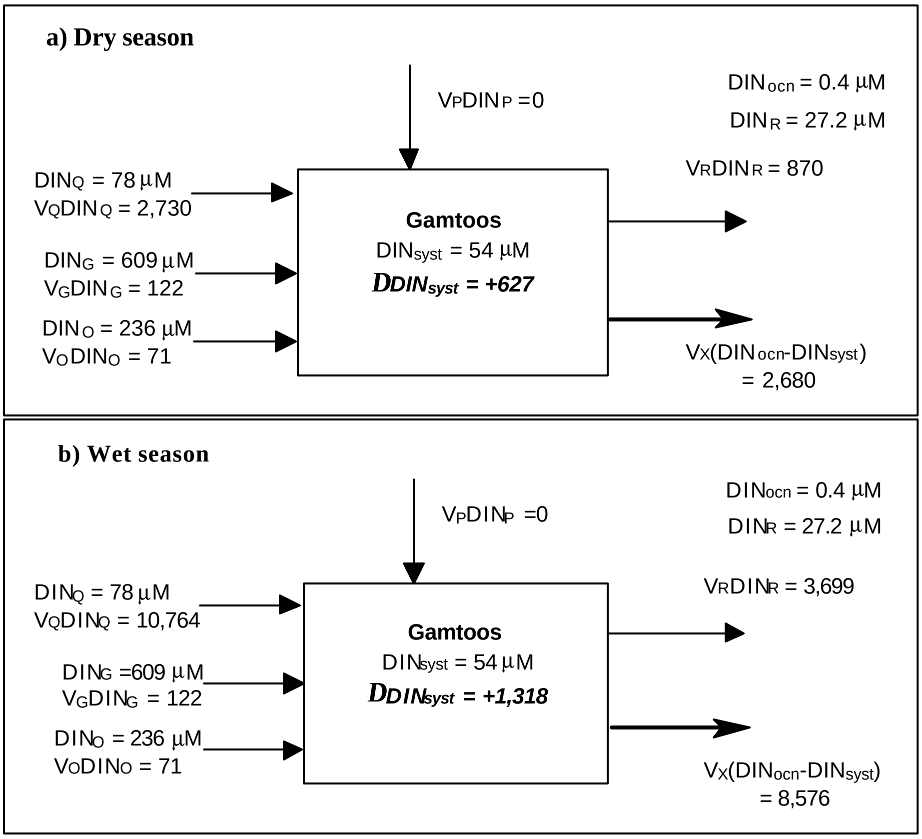

Figure 4.15 DIN budget for the Gamtoos River estuary in the dry (a) and wet (b) seasons. Flux in mol d^{-1}.

4.4 Swartkops River Estuary, Algoa Bay, Eastern Cape

Dan Baird

<u>*Study area description*</u>

The Swartkops River estuary (32.87°S, 25.63°E; Figure 4.16) is located in Eastern Cape province on the south-east coast of South Africa and opens into Algoa Bay, in the Indian Ocean, about 15 km from the harbour of the city of Port Elizabeth (Baird *et al.* 1986). The Swartkops River and its main tributary (the Elands River) originate in the Great Winterhoek Mountains and meander for about 155 km to the estuary. The total catchment of both rivers is about 1,400 km^2. The mean annual rainfall (MAR) is about 636 mm (range 500 mm–1,000 mm), or about $84x10^6$ m^3; about 17% of the MAR is retained by impoundments in the catchment (Reddering and Esterhuysen 1981). Freshwater inflow into the estuary at spring tides was measured at $130x10^3$ m^3 d^{-1} (Scharler *et al.* 1998).

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

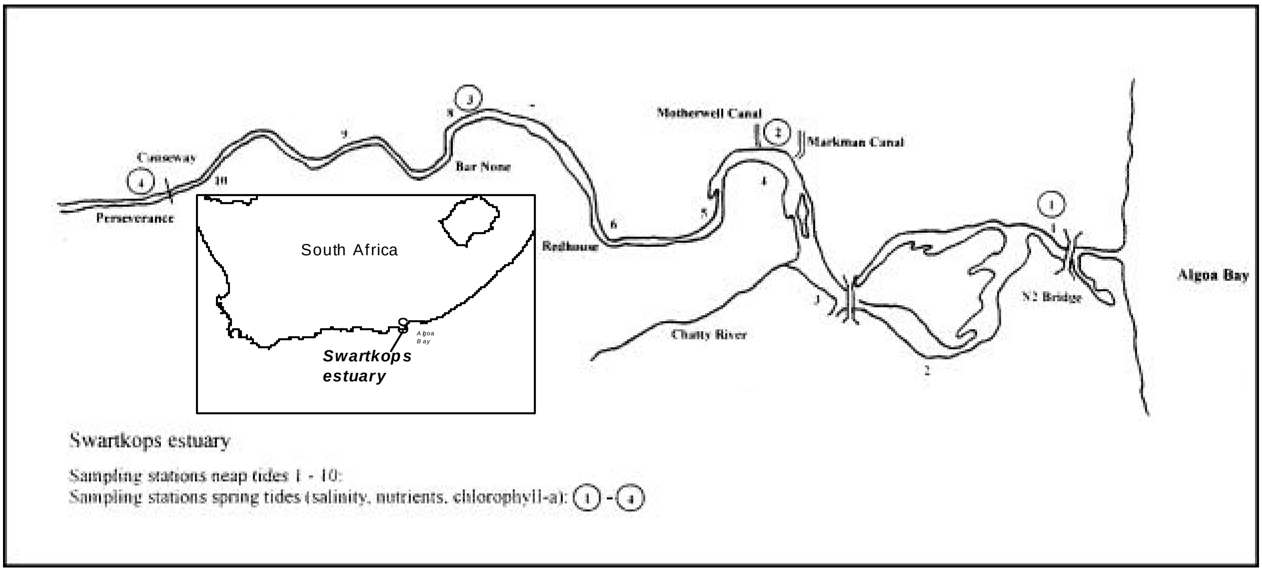

Figure 4.16. Map and location of the Swartkops River estuary.

The estuary is about 15 km long and has a total surface area of 4 km^2. The tidal prism during spring tides is on average $3x10^6$ m^3 and the average flushing time during spring tides about 22 h. The estuary is shallow, turbid and well-mixed during periods of low river flow (Winter and Baird 1991). During floods, the estuary may exhibit highly stratified waters (Scharler *et al.* 1998). It attracts thousands of migrating Palearctic birds (Martin and Baird 1987) and is a popular recreational area for boating, angling and swimming (Lord and Thompson 1987). The estuary exhibits a salinity gradient along its longitudinal axis throughout the year, but this gradient may be reversed at times due to its high evaporative water requirement (Jezewski and Roberts 1986). The salinity ranges from 35 psu at the mouth to 10 psu at the head, while the temperature fluctuates between 28°C in summer to 13.5°C in winter (Baird and Ulanowicz 1993).

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

Table 4.8. Physical characteristics of the Swartkops River estuary.

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

Water and salt budgets

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

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

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

Budgets of nonconservative materials

DIP balance

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

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

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

DIN balance

The DIN budget (Table 4.10 and Figure 4.19) shows the Swartkops River estuary is a net sink for DIN, as for DIP. The principal load of DIN is by means of the wastewater flux (V_ODIN_O).

Stoichiometric calculations of aspects of net system metabolism

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

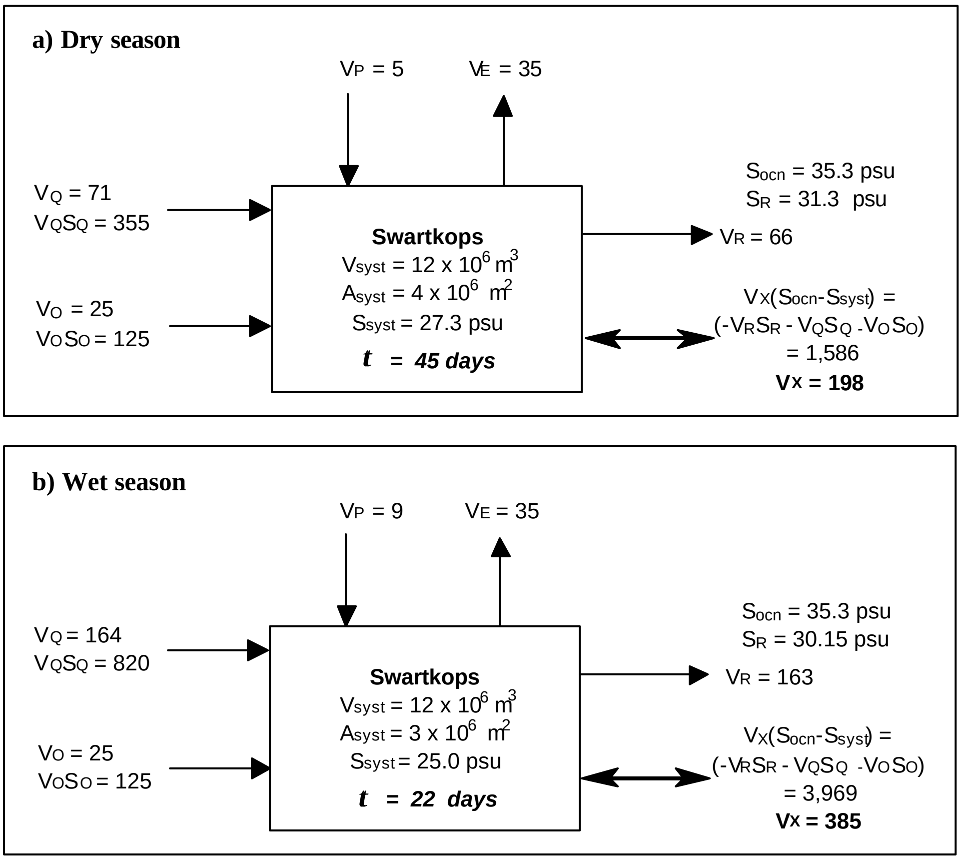

Figure 4.17. Water and salt budgets for the Swartkops River estuary in the dry (a) and wet (b) seasons. Water flux in 10^3 m^3 d^{-1} and salt flux in 10^3 psu-m^3 d^{-1}.

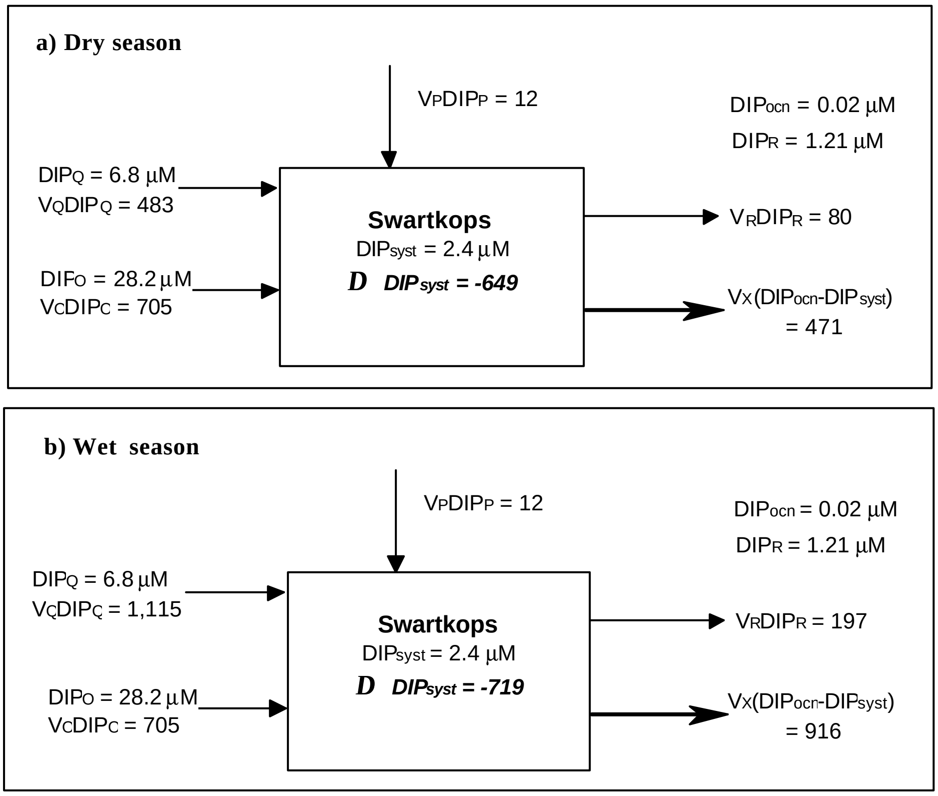

Figure 4.18. DIP budget for Swartkops estuary in the dry (a) and wet (b) seasons. Flux in mol d^{-1}.

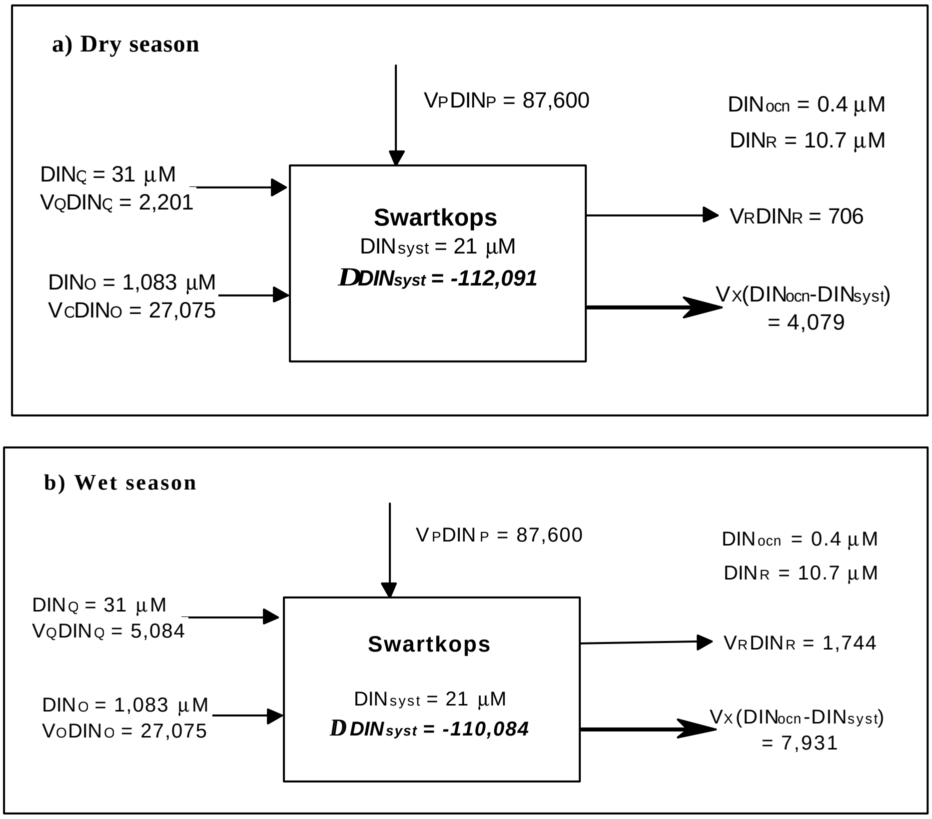

Figure 4.19. DIN budget for the Swartkops River estuary in the dry (a) and wet (b) seasons. Flux in mol d^{-1}.

4.5 Sundays River Estuary, Algoa Bay, Eastern Cape

Dan Baird

Study area description

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

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

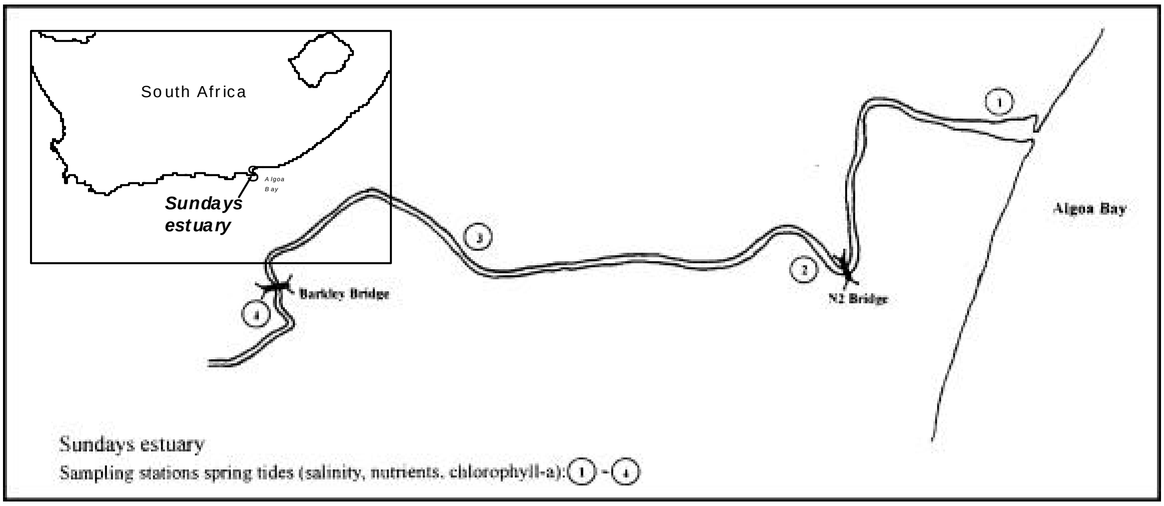

Figure 4.20. Map of Sundays River estuary, Algoa Bay.

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

Table 4.11. Physical characteristics of the Sundays River estuary.

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

Water and salt balance

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

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

Season	**Freshwater input** (10^3 m^3d^{-1})			**Residual flow** ($10^3m^3d^{-1}$)	**River salinity** (psu)	**Ocean salinity** (psu)	*System* **salinity** (psu)	**Mixing volume** ($10^3m^3d^{-1}$)	**ô** (day)
	V_Q	V_P	V_E						
Dry	86	2	8	80	0.5	35.3	17.6	117	61
Wet	237	2	8	231	0.5	35.3	15.1	282	23
Annual mean	**162**	**2**	**8**	**156**	**0.5**	**35.3**	**16.4**	**200**	**42**

Budgets of nonconservative materials

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

Stoichiometric calculations of aspects of net system metabolism

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

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

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

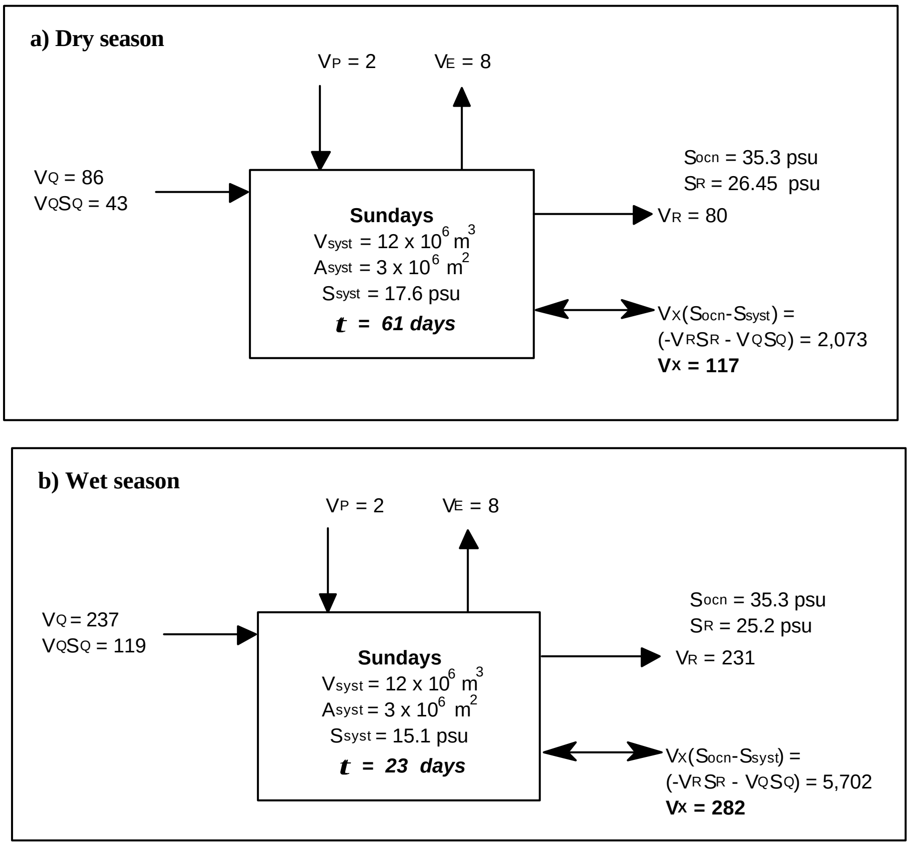

Figure 4.21. Water and salt budgets for Sundays River estuary in the dry (a) and wet (b) seasons. Water flux in 10^3 m^3 d^{-1} and salt flux in 10^3 psu-m^3 d^{-1}.

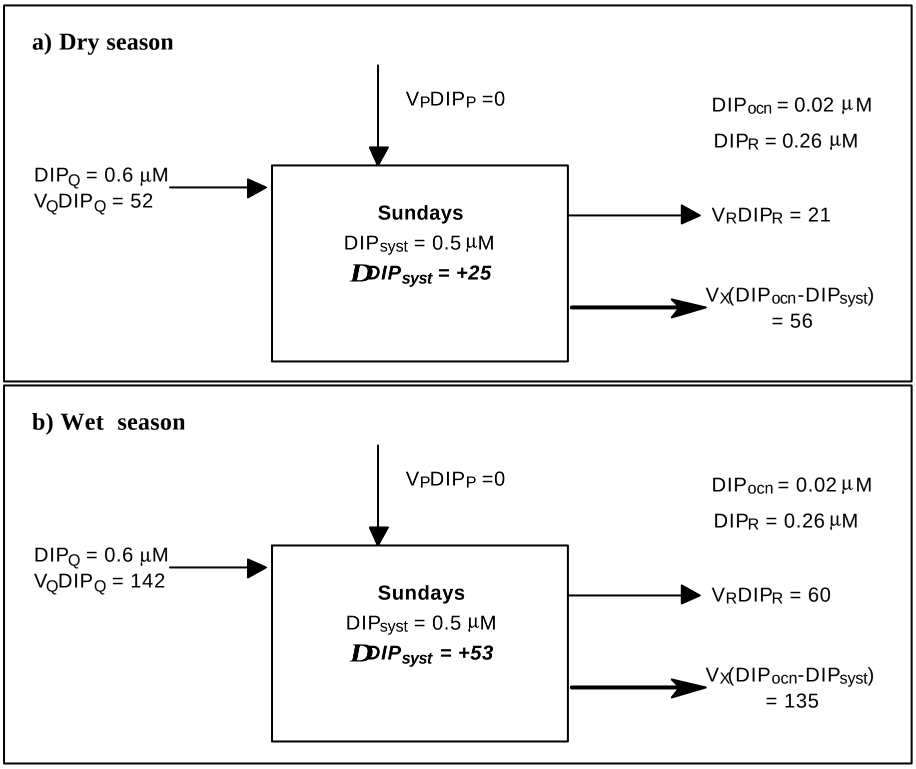

Figure 4.22. DIP budget for Sundays River estuary in the dry (a) and wet (b) seasons. Flux in mol d^{-1}.

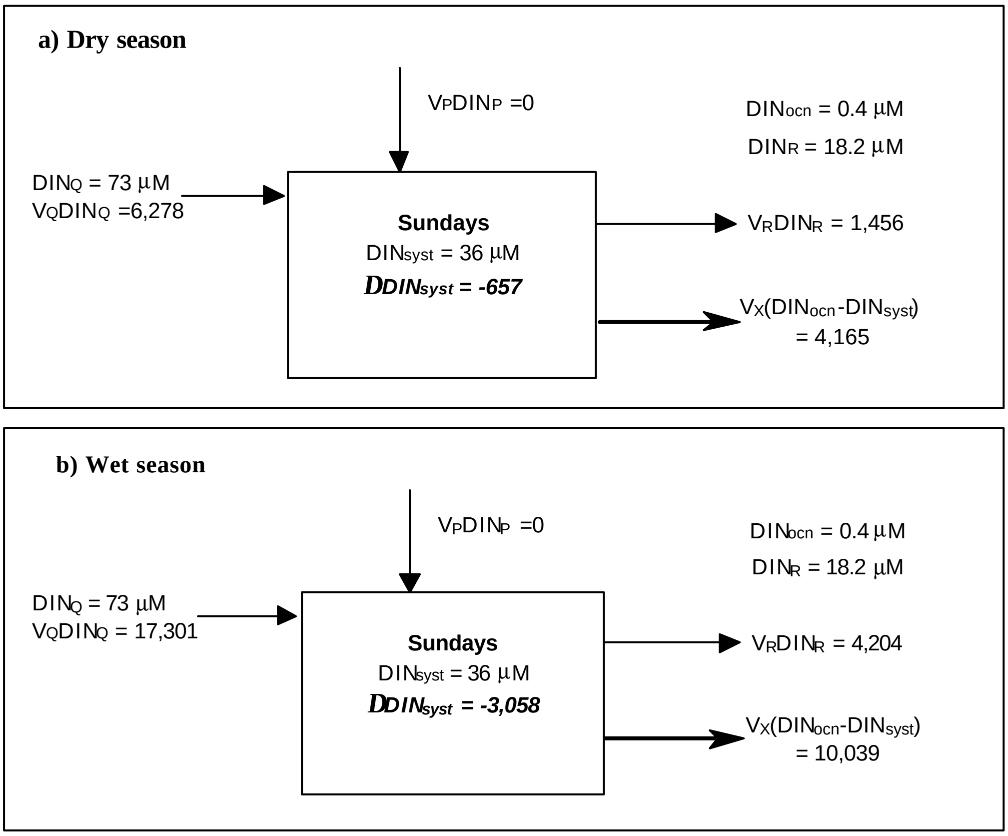

Figure 4.23. DIN budget for Sundays River estuary in the dry (a) and wet (b) seasons. Flux in mol d^{-1}.

4.6 Mhlathuze River Estuary, KwaZulu-Natal

V. Wepener

Study area description

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

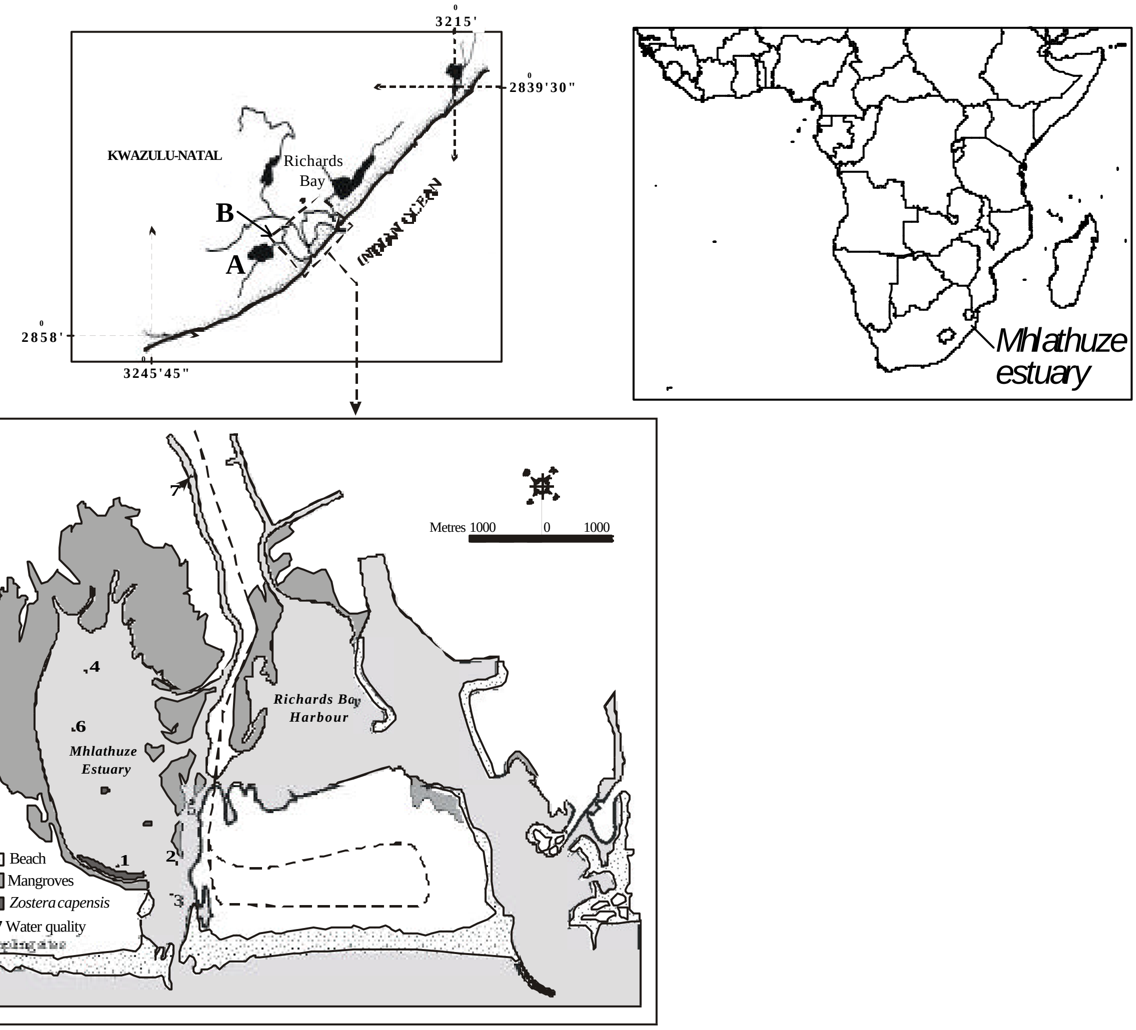

Figure 4.24. Map and location of Mhlathuze River estuary. In the upper map, A indicates the position of Lake Chubu and B the Mtantatweni River. In the lower diagram, the dotted lines indicate the margins of the estuary.

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

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

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

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

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

Water and salt balance

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

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

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

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

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

$V_X = D_h\ (A/F)$ where: (2)

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

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

$D_h = (200^{0.85}\ (0.1*86{,}400)^2)/\ 2180$
$D_h = 3{,}100\ 10^3\ m^2\ d^{-1}$

$V_X = D_h\ (A/F)$
$V_X = 3{,}100 \times 10^3\ m^2\ d^{-1}(5{,}000\ m^2/3{,}000\ m)$
$V_X = 5{,}200 \times 10^3\ m^3\ d^{-1}$

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

Budgets of nonconservative materials

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

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

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

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

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

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

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

DIP balance

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

DIN balance

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

Stoichiometric calculations of aspects of net system metabolism

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

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

$(p-r) = -DDIP$ ´$(C:P)_{ratio}$

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

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

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

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

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

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

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

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

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

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

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

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

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

Comments

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

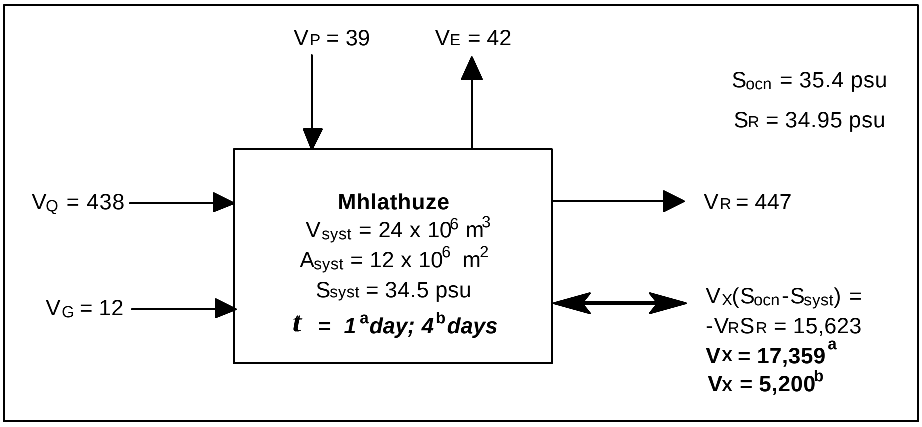

Figure 4.25. Water and salt budgets for Mhlathuze River estuary. Water flux in 10^3 m^3 d^{-1} and salt flux in psu-m^3 d^{-1}.

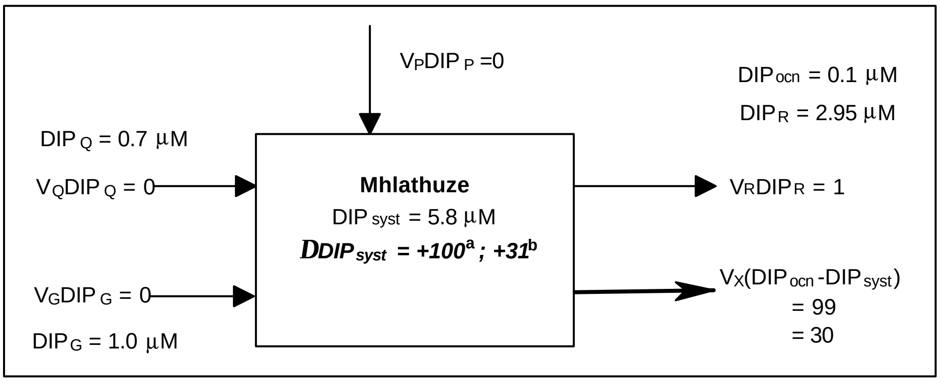

Figure 4.26. DIP budget for Mhlathuze River estuary. Flux in 10^3 mol m^3 d^{-1}.

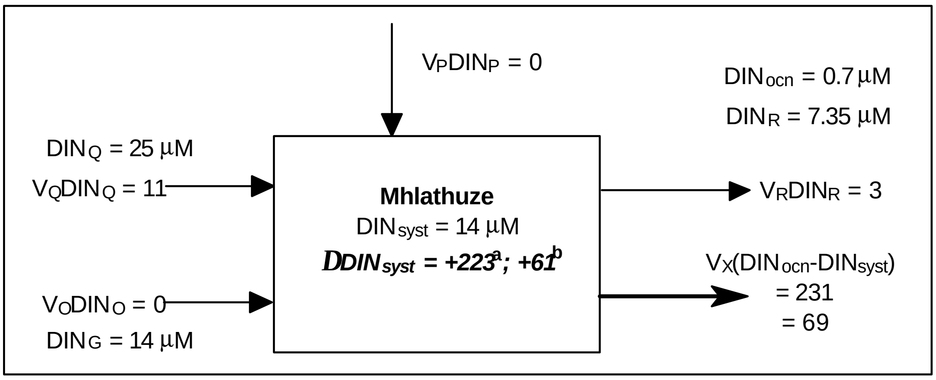

Figure 4.27. DIN budget for Mhlathuze River estuary. Flux in 10^3 mol m^3 d^{-1}.

4.7 Thukela River Estuary, KwaZulu-Natal

V. Wepener

Study area description

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

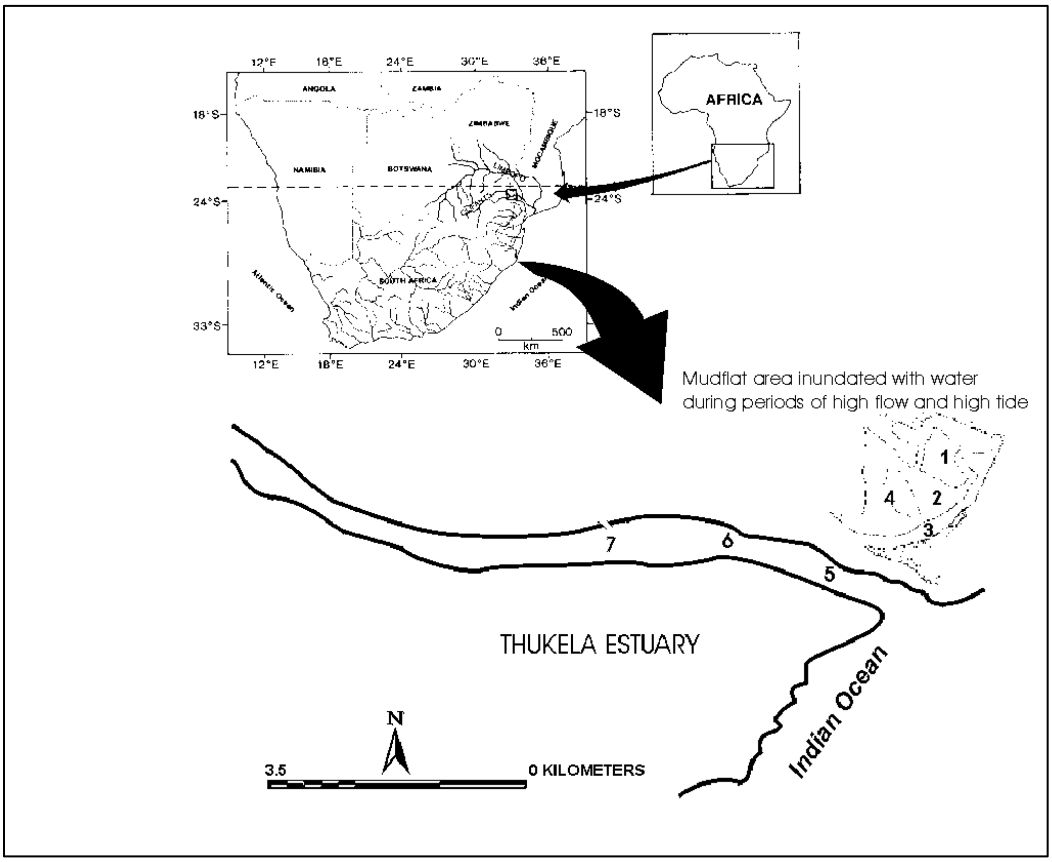

Figure 4.28. Map and location of the Thukela River estuary.

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

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

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

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

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

Water and salt balance

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

Figure 4.29 illustrates the water and salt balance for the Thukela estuary with annual averages using the LOICZ methodology. Residual water flux (V_R in the notation of Gordon *et al.* 1996) from this system, to balance freshwater inflow, is approximately $3x10^6$ m^3 d^{-1}, while exchange flux (V_X) is $2x10^6$ m^3 d^{-1}. The system volume ($0.9x10^6$ m^3) divided by the sum of these water fluxes gives an estimate of water exchange time of less than a day. These results indicate an extremely rapid seawater exchange within the estuary, which is caused by the significant freshwater outflow. It is this abundant freshwater supply from the Thukela River, which has led to the large inter-basin water transfer schemes currently in place and planned for the future.

Budgets of nonconservative materials

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

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

It should be borne in mind that nitrate in runoff is likely to be important since there are large sugar-cane fields on the banks of the lower reaches of the river and the estuary. However, no quantifiable data are available and consequently, nitrate concentrations were estimated from the mean NO_3 to NH_4 data described in the introduction. DIP and DIN concentrations of the various systems are shown in Table 4.15. The nonconservative fluxes of DIP and DIN (*DDIP*, *DDIN*) calculated for this one-box model is positive, indicating that the estuary is a net source of nutrients (Figures 4.30 and 4.31). The flux of nonconservative DIP, *DDIP*, is $+15x10^3$ mol d^{-1} or 25 mmol m^{-2} d^{-1}; and nonconservative DIN, *DDIN*, is $+399x10^3$ mol d^{-1} or 665 mmol m^{-2} d^{-1}.

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

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

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

Stoichiometric calculations of aspects of net system metabolism

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

Comments

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

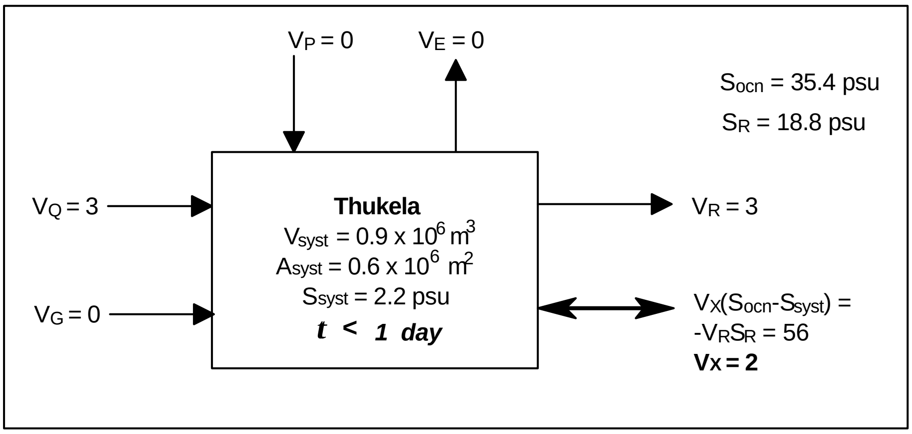

Figure 4.29. Water and salt budgets for Thukela River estuary. Water flux in 10^6 m^3 d^{-1} and salt flux in 10^6 psu-m^3 d^{-1}.

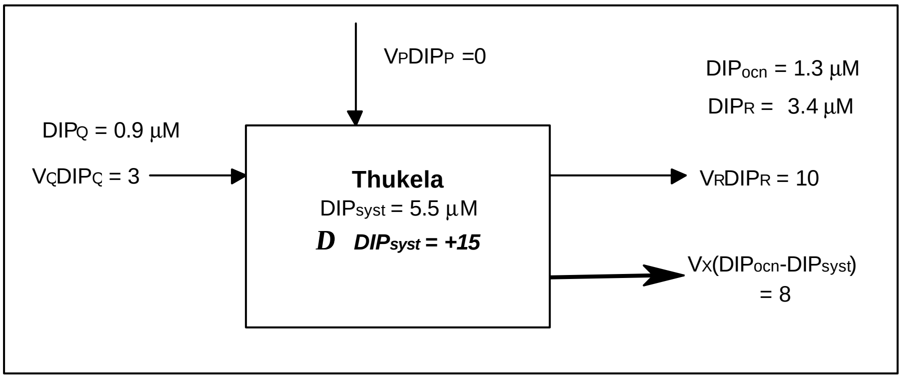

Figure 4.30. DIP budget for the Thukela River estuary. Flux in 10^3 mol m^3 d^{-1}.

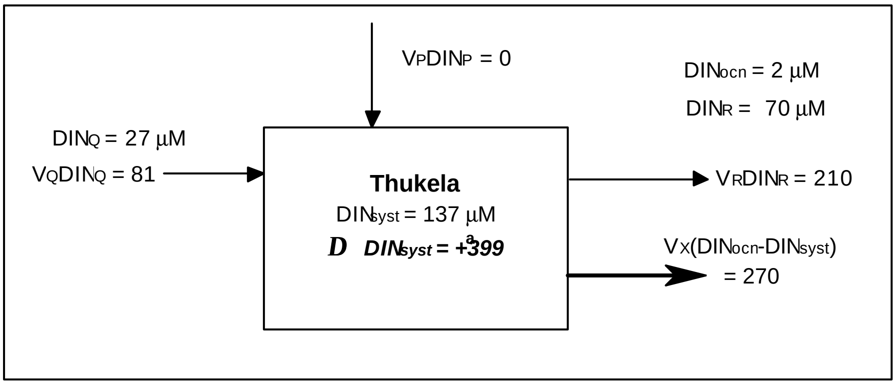

Figure 4.31. DIN budget for the Thukela River estuary. Flux in 10^3 mol m^3 d^{-1}.