3. CAMEROON AND CONGO ESTUARINE SYSTEMS

Cameroon's coastal zone and estuarine systems

Cameroon (8-16°E; 2-13°N) is situated on the extreme north-eastern end of the Gulf of Guinea with a surface area of 469,440 km². The main topographical regions are: the low coastal plain covered by equatorial rain forests in the south, the mountain forests peaking at the active Mount Cameroon (4,070 m) in the west, the transitional plateau rising to the Adamaoua Mountains in the centre, and rolling savannah slopes gradating down to the marshlands surrounding Lake Tchad to the north of the Adamaoua Mountain range. Cameroon is drained by four major drainage basins: Atlantic, Zaire/Congo, Niger and Tchad. A watershed exists along the southern Cameroon plateau separating the coastal from the Congo system, with freshwater input into the Atlantic drainage basin.

Cameroon's coastal zone (Figure 3.1), extends along 402 km (Sayer *et al*. 1992), from latitude 2.30°N at the Equatorial Guinea borders to 4.67°N at the Nigeria borders. The coastal zone area is estimated at 9,670 km² (Adam 1998) representing 22% of the Gulf of Guinea countries.

Figure 3.1. Cameroon and the Gulf of Guinea.

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

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

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

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

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

Salinity distribution within Cameroon's estuarine complexes is determined by huge inputs of freshwater from rivers, rainfall and groundwater. Salinity is generally low with values at the Douala Port of 9-12 psu. Lafond (1967) showed maximum values of 20 psu at 15 km from the port offshore during the dry season and less than 12 psu in the rainy season. These values decrease towards the port to average values of 0 psu for every 100 m (2.6 psu for each km) near Japoma on the Dibamba River, and maximum values as low as 6.5 psu at low tide. Values of between 12.0-17.5 psu have been recorded within the Mungo River, with increased values due to seawater intrusion during the dry season and mixture with freshwater. Salinity distributions are in line with regional surface values which show significant fresh water in the Gulf of Guinea and in particular, in the Bight of Biafra, with values lower than 29 psu (ICITA 1973; GATE 1980).

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

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

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

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

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

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

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

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

C.E. Gabche and S.V. Smith

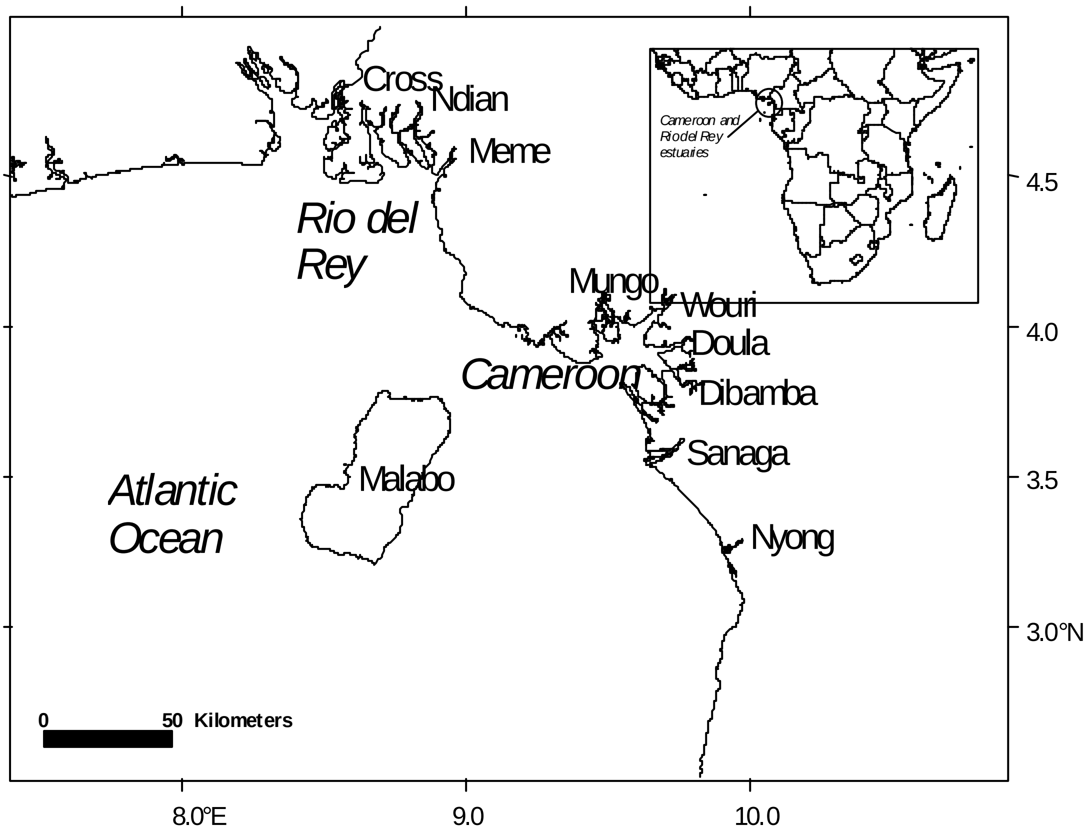

Figure 3.2. The Cameroon and Rio-del-Rey estuarine systems.

3.1 Cameroon estuary complex, Cameroon

C.E. Gabche and S.V. Smith

Water and salt balance

The Cameroon estuary complex has three main rivers (Mungo, Wouri and Dibamba) with input directly into the estuary. The volume of runoff (V_Q) calculated from mean discharge (Table 3.2) gives total volumes of $120x10^6$ m^3 d^{-1}; $20x10^6$ m^3 $d^{-1}$and $170x10^9$ m^3 d^{-1} for annual, dry and rainy seasons, respectively. River runoff, rainfall and evaporation with seasonal values (where available) are given in Table 3.2.

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

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

Total evaporation (V_E) for the dry season and rainy seasons is calculated with the assumption of mean monthly values of 100 mm for the 1,500 km^2 Cameroon estuary area. This gives a mean evaporation of $5x10^6$ m^3 d^{-1} for both the dry and rainy seasons. The precipitation (V_P) values for the dry and rainy seasons are obtained from rainfall for Douala. These gave mean monthly values of 40 mm and 390 mm for the dry and rainy seasons, respectively (Table 3.2). The mean precipitation values are $2x10^6$ m^3 d^{-1} and $20x10^6$ m^3 d^{-1} for the dry and rainy seasons, respectively. Salinity values with seasonal variations at different depths and various stations (fresh, estuarine and marine) of the Cameroon estuary complex are given in Table 3.3. Areas of high input of freshwater have low salinity with higher values at the Cameroon estuary due to salt water intrusion. V_G (groundwater inflows) and V_o (other inflows) like sewage are assumed to be zero. The water exchange time (t) was 315 and 48 days in the dry and rainy seasons, respectively.

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

Parameter	River		Estuary		Ocean	
	Dry	**Wet**	**Dry**	**Wet**	**Dry**	**Wet**
Temp (^oC)	29.9	21.7	25.0	21.1	30.4	27.5
Salinity (psu)	0	0	15.8	8.7	21.4	16.5
Si (μM)	26	27	24.5	24	20	18.1
NO_3 (μM)	2.6	2.4	3.8	3.6	2.5	2.5
PO_4 (μM)	2.1	2.0	1.2	1.1	0.6	0.5

Balance of nonconservative materials

DIP balance

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

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

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

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

Parameter	**Dry**	**Rainy**	**Annual**
$\mathbf{A_{syst}}$ (km2)	1,500	1,500	1,500
$\mathbf{V_{syst}}$ (10^9 m^3)	23	23	23
V_Q (10^6 m^3 d^{-1})	20	170	120
V_E (10^6 $m^3 d^{-1}$)	-5	-5	-5
V_P (10^6 $m^3 d^{-1}$)	2	20	14
V_R (10^6 $m^3 d^{-1}$)	-17	-185	-129
V_X(10^6 $m^3 d^{-1}$)	56	299	218
t (days)	315	48	137
$V_O DIP_O$(10^3 mol d^{-1})	15	15	15
$V_Q DIP_Q$(10^3 mol d^{-1})	42	340	241
$V_R DIP_R$(10^3 mol d^{-1})	-15	-148	-104
V_x $(DIP_{ocn}$-$DIP_{syst})$ (10^3 mol d^{-1})	-34	-179	-131
$DDIP$(10^3 mol d^{-1})	-8	-28	-21
$DDIP$(mmol m^{-2} d^{-1})	-0.01	-0.02	-0.02
$V_O DIN_O$(10^3 mol d^{-1})	104	104	104
$V_Q DIN_Q$(10^3 mol d^{-1})	52	408	289
$V_R DIN_R$(10^3 mol d^{-1})	-54	-564	-394
$V_X(DIN_{ocn}–DIN_{syst})$($10^3$ mol d^{-1})	-73	-329	-244
$DDIN$(10^3 mol d^{-1})	-29	+381	+244
$DDIN$(mmol m^{-2} d^{-1})	-0.02	+0.3	+0.2
$(p\text{-}r)_{plankton}$(mmol m^{-2} d^{-1})	+1	+2	+2
$(p\text{-}r)_{mangroves}$(mmol m^{-2} d^{-1})	+10	+20	+20
$(nfix\text{-}denit)_{plankton}$(mmol m^{-2} d^{-1})	+0.1	+0.6	+0.4

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

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

3.2 Rio-del-Rey estuary complex, Cameroon

C.E. Gabche and S.V. Smith

<u>Water and salt balance</u>

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

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

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

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

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

Parameter	**River**		**Estuary**		**Ocean**	
	Dry	**Wet**	**Dry**	**Wet**	**Dry**	**Wet**
Temp (^oC)	29.2	28.4	28	27	30	29
Salinity (psu)	0	0	17.8	11.3	19.2	15.3
Si(μM)	32	30	26	25	24	23
NO_3(μM)	1.9	1.8	3.2	3.1	0.4	0.3
PO_4 (μM)	2.0	1.6	0.9	0.8	0.5	0.4

The total average discharge (V_Q) as $30x10^6$ m^3 d^{-1} and $130x10^6$ m^3 d^{-1} for the dry and rainy seasons, respectively. The total evaporation (V_E) for the dry and rainy seasons was calculated for the mangrove area of 1,350 km^2. The monthly mean evaporation is 120 mm (Table 3.5). This gave V_E values of water evaporated from the estuary area of $5x10^6$ m^3 d^{-1} for the dry and rainy seasons. The total precipitation values were obtained from rainfall data for Calabar, which has a monthly mean of 90 mm for the dry and 330 mm for the rainy season (Table 3.5). These values gave volumes of $4x10^6$ m^3 d^{-1} for the dry season and 15 x $10^6 m^3$ d^{-1} for the rainy season. The groundwater inflows (V_G) and others (V_o) such as sewage are considered to be zero. The water exchange time (τ) was 48 days and 33 days for the dry and rainy seasons, respectively.

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

DIP balance

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

$2x10^3$ mol d^{-1}. DIP fluxes are summarized in Table 3.7. Nonconservative DIP, *DDIP* of the system shows that the system is a net source of DIP for both seasons.

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

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

Parameter	Dry	Rainy	Annual
$\mathbf{A_{syst}}$ (km2)	1,350	1,350	1,350
$\mathbf{V_{syst}}$ (10^9 m^3)	20	20	20
V_Q (10^6 m^3 d^{-1})	30	130	97
V_E (10^6 $m^3 d^{-1}$)	-5	-5	-5
V_P (10^6 $m^3 d^{-1}$)	4	15	11
V_R (10^6 $m^3 d^{-1}$)	-29	-140	103
V_X(10^6 $m^3 d^{-1}$)	384	466	439
t (days)	48	33	38
$V_O DIP_O$(10^3 mol d^{-1})	2	2	2
$V_Q DIP_Q$(10^3 mol d^{-1})	60	208	159
$V_R DIP_R$(10^3 mol d^{-1})	-20	-84	-63
V_x $(DIP_{ocn}-DIP_{syst})$ (10^3 mol d^{-1})	-154	-186	-175
DDIP(10^3 mol d^{-1})	+112	+60	77
DDIP(mmol m^{-2} d^{-1})	+0.08	+0.04	+0.05
$V_O DIN_O$(10^3 mol d^{-1})	11	11	11
$V_Q DIN_Q$(10^3 mol d^{-1})	57	239	178
$V_R DIN_R$(10^3 mol d^{-1})	-52	-238	-176
$V_X(DIN_{ocn}-DIN_{syst})$($10^3$ mol d^{-1})	-1,075	-1,304	-1,228
DDIN(10^3 mol d^{-1})	+1,059	+1,297	+1,218
DDIN(mmol m^{-2} d^{-1})	+0.8	+1	+0.9
$(p\text{-}r)_{plankton}$(mmol m^{-2} d^{-1})	-8	-4	-5
$(p\text{-}r)_{mangroves}$(mmol m^{-2} d^{-1})	-80	-40	-50
$(nfix\text{-}denit)_{plankton}$(mmol m^{-2} d^{-1})	-0.5	+0.4	+0.1

Stoichiometric calculation of aspects of net system metabolism

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

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

Congo River

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

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

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<u>Study site description</u>

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

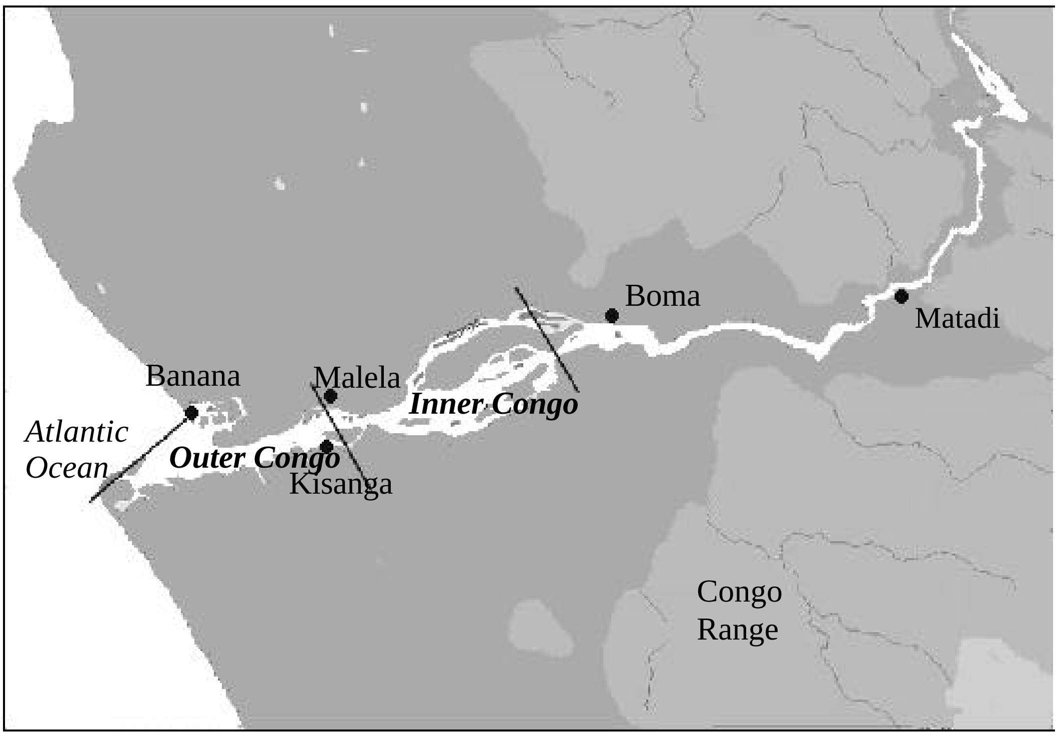

Figure 3.3. Map and location of the Congo River estuary. Solid lines indicate boundaries of the inner and outer estuarine zones, the budgeted areas.

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

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

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

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

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

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

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

Parameter	**Outer estuary (surface)**	**Outer estuary (deep-canyon)**	**Inner estuary**
Surface area (km^2)	146	46	95
Volume (m^3)	$1.2x10^9$	$12x10^9$	$0.47x0^9$
Average depth (m)	8	260	5

Water and salt balance

Water and salt budgets (Figure 3.4) are calculated from average annual data. The estimated annual river discharge of water was 1,450x10^9 m^3 yr^{-1} or 4x10^9 m^3 d^{-1}. Average annual precipitation and potential evaporation values were measured at Matadi, Democratic Republic of the Congo, approximately 100 km upstream (5º 47' S, 13º 26' E) as precipitation = 1,011 mm yr^{-1} and evaporation = 1,703 mm yr^{-1}. Hamon's equation used with monthly temperature measured at Matadi, provides an estimate of evaporation ~ 1,350 mm yr^{-1}. These values are generally consistent with regional values as they appear on global maps (e.g. see http://data.ecology.su.se/mnode/Methods/precevap.htm). The estimated net atmospheric flux, precipitation-evaporation, of -240 to -600 mm yr^{-1} over the area of the estuary is insignificant in relation to river inflow.

Budgets of nonconservative materials

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

Stoichiometric calculations of aspects of net system metabolism

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

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

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

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

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

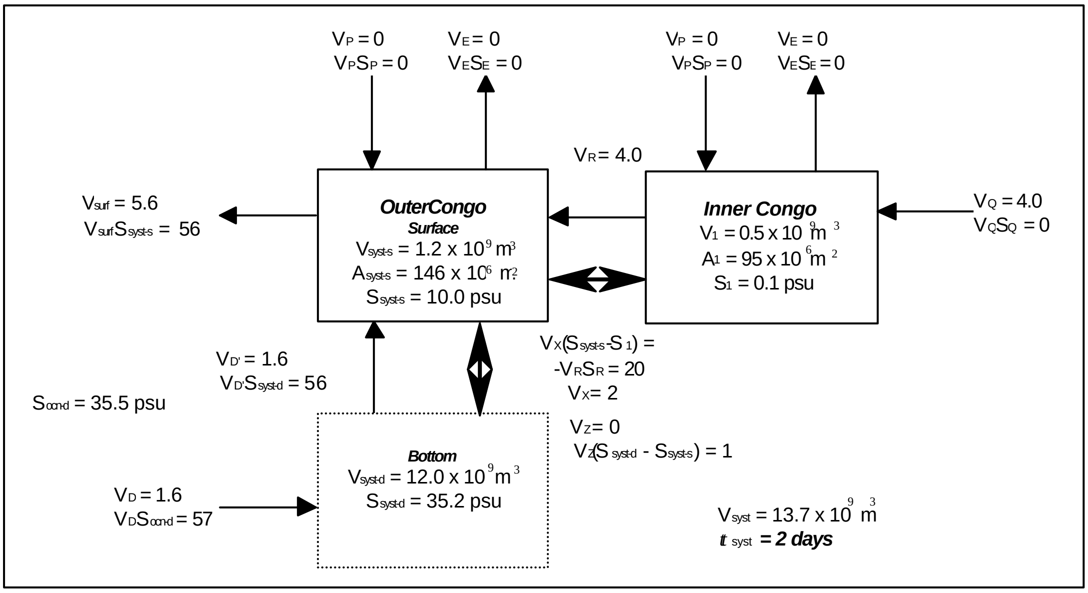

Figure 3.4. Water and salt fluxes of the Congo River estuary. (Units of volume and salinity flux are 10^9 m^3 d^{-1}, 10^9 psu-m^3 d^{-1})

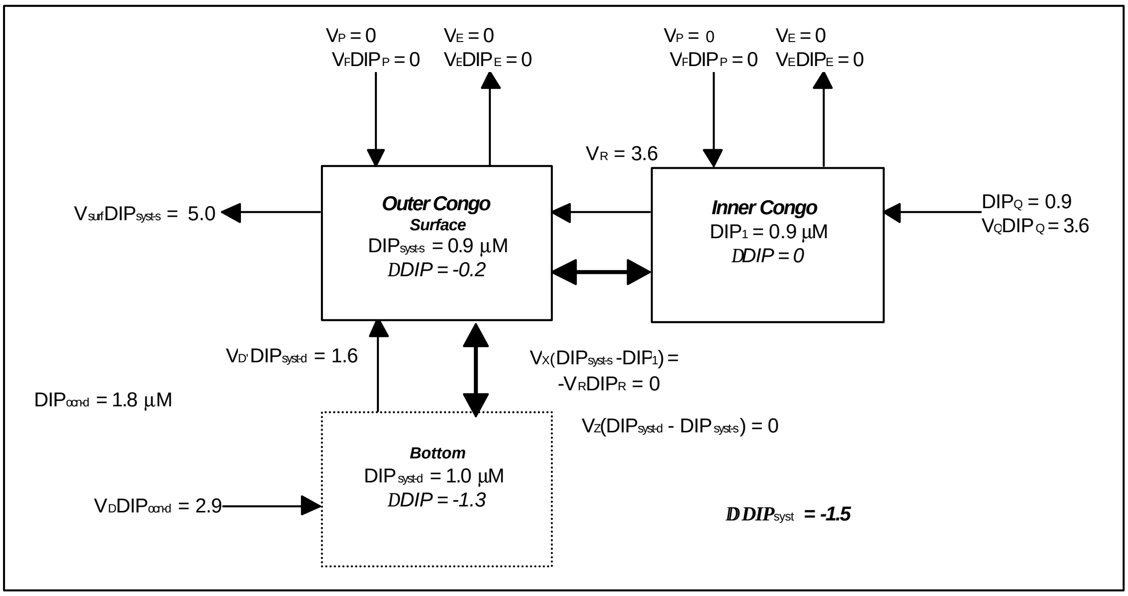

Figure 3.5. DIP flux for the Congo River estuary. Units of flux are 10^6 mol d^{-1}.

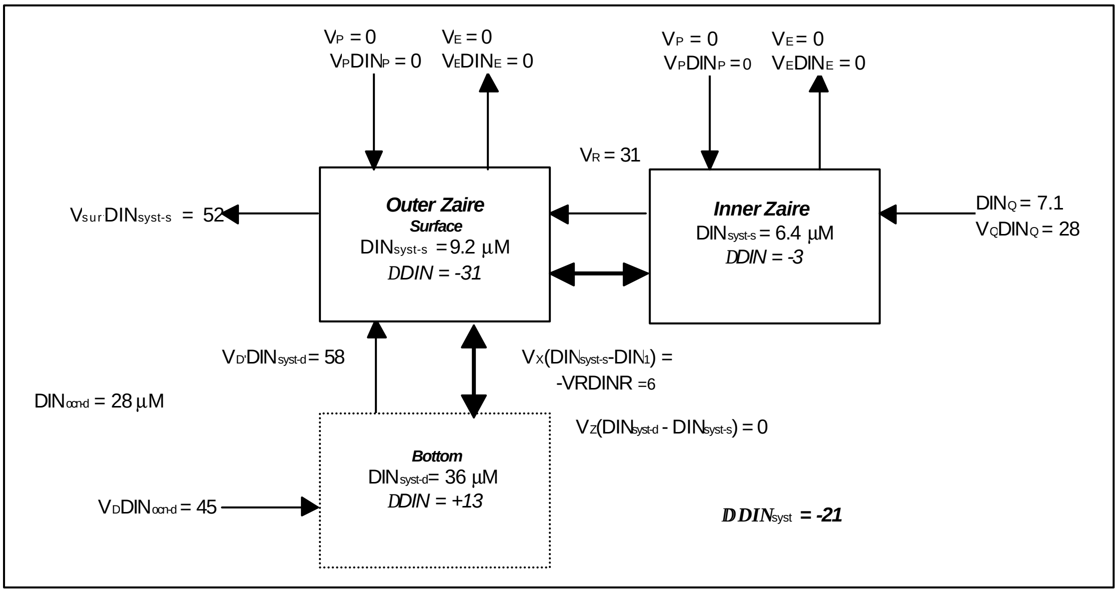

Figure 3.6. DIN flux for the Congo River estuary. Units of flux are 10^6 mol d^{-1}.