Water, Salt and Nutrients Budgets of Two Estuaries in the Coastal Zone of Cameroon

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Abstract

A biogeochemical model of water, salt and nutrients budgets for two estuarine systems within Cameroon's coastal zone (Latitudes 2°-13°N, Longitudes 2°-16°E) of sub-Sahara Africa is presented. Data requirements for the budgets include a detailed description of the estuarine systems (Cameroon estuary; Longitudes 9.25° – 10.00° E+, Latitudes 3.83° – 4.1° N+, considered as a pollution 'hot spot' and the Rio-del-Rey estuary (Longitude 8.3° E+, Latitude 4.8° N+), considered as a relatively similar but less polluted area). Others include the salinity of the systems and adjacent ocean, volume of fresh water input and output, concentration of nutrients for systems, adjacent ocean, fresh water and other sinks and sources. Hydrological data used include river discharge, rainfall and evaporation obtained from Cameroon's meteorological service, government sources and research. Modeling methodology was according to the Land Oceans Interaction in the Coastal Zone (LOICZ) biogeochemical budgeting guidelines and Computer Assisted Budget Analysis, Research, Education and Training (CABARET) note. For two seasons, one layered and one box models were developed for the estuarine systems considered to be completely mixed. Other budget estimates are given on the Dissolved Inorganic Phosphate (DIP) and Dissolved Inorganic Nitrogen (DIN), non-conservative materials and stoichiometric calculations of aspects of net metabolism. These results are compared to those of other estuarine systems of sub-Sahara Africa and similar regions of the world. The results gave indications of the level of eutrophication of coastal and ocean ecosystems and the degree of impacts on aquatic living resources (e.g. fish species and their food within the ecosystems). Mitigation strategies and measures are proposed for the future.

Introduction

The state of biogeochemical (nutrient cycling between living and dead organisms, along ecological food webs and the earth's inorganic materials) processes of estuarine and associated ecosystems (coastal lagoons, mangroves and deltas) is based on land–based, offshore influences and physical processes. For regions bordering the Gulf of Guinea Large Marine Ecosystem, over 60% of industries are concentrated along coastal estuarine systems (UNDP, 1993). Of the approximately 14 estuarine and associated systems of the Gulf, six are highly polluted in parts, with eutrophication being a problem. These ecosystems lie along an approximate 25,000 km along west and central African zone of sub-Sahara Africa (Shumway, 1999). They are constantly facing threats of degradation from multiple based human impacts such as over fishing; use of chemicals (e.g. gamma line) in fishing; sewage discharge; pollution from pesticides, fertilizers and industrial wastes; conversion of land for agriculture, fuel wood, oil and mineral extraction, land for reclamation, deforestation, dam construction and freshwater diversion. These threats are exacerbated by the rapid expansion of the coastal human population, growing at twice the mean annual rate of 2.9% in the region, with related increase in their needs and dependence on the resources for sustainability.

Within these ecosystems, the impacts of high and variable nutrients inputs can result in destabilization of plankton communities, resulting in high accumulation of phytoplankton biomass. Such instabilities may cause shifts in the flow of energy and nutrients from metazoan food webs, which support high fish production, to microbial food webs, which lead to greater decomposition and oxygen consumption. It can also lead to changes in floristic composition by altering the relative availability of essential nutrients. This is seen in a strong littoral transport system which carries oil pollution, toxic and solid waste from point sources upstream to other coastal countries (Shumway, 1999). Mangrove deforestation causes serious erosion and flooding, destroying fishing villages along the muddy coasts of the Niger Delta. More stress comes from decrease in freshwater input from rivers impounded upstream (e.g. Sanaga in Cameroon) resulting in low supply of nutrients, substrate instability and other significant down-stream effects (Collins & Evans, 1986; Gabche *et al.*, 2000). These stresses on estuarine and related systems will result in the deforestation of 70% of mangroves by the year 2025 if no action is taken (Gabche *et al.*, 2000).

Early studies on land-based sources of pollution in Cameroon were based on quantitative analysis of land–based pollutants from industries and the population of coastal towns to the estuarine and related complexes (UNEP/UNIDO, 1982; Angwe & Gabche, 1997). An indication on the percentage increase of such pollutants is given in Tables 1 and 2. Dominant land-based pollutants sources are made up of agricultural concerns, other chemical industries, communities, cities and non point sources. Within the urban centres are 60% of the country's manufacturing industries with 2.4 million (20% of national count) inhabitants (1987 census) in the coastal zone and annual national population growth rate of 3.2%. Agricultural activities (30% gross domestic product (GDP), 70% export revenue and employs three quarters of labour force) are dominant with agro-chemical imports of between 115,000 tons/year and application rate of 16 kg/ha. Projections for the year 2000 of agro-chemical usage stood at 346,000 tons/year of which 80,000 were urea-based. The animal industry has main slaughter houses

TABLE I

Nutrients loads (tons/year) dynamics from population and industries of Cameroon's coastal zone in 1982 (UNEP, 1982) and 1996 (Angwe & Gabche, 1997)

Types of Nutrients	*Source Contribution*	*Nutrient loads (tons/year)*	
		1982	*1996*
BOD_5	Population	13,221	16,500
	Industries	2,187	159,032
SS	Populatiбn	18,802	38,400
	Industries	4,800	156,285
Oil/Greece	Population	-	-
	Industries	258,860	1,041,000
N	Population	ND	7,920
	Industries	ND	26,580
P	Population	ND	63,780
	Industries	ND	-
COD	Population	4,572	63,780
	Industries	4,572	-

(BOD_5 - Biochemical oxygen demand; SS = Suspended solids; N = Total nitrogen as N, NO_3; P = Total phosphorus; COD = Carbon oxygen demand and ND = Values not determined)

TABLE 2

Water pollution loads (tons/year) – BOD, SS, Oil, N and P from various industries of Cameroon's coastal zone (Angwe & Gabche, 1997)

Type of industry	*Pollution loads*				
	BOD_5	*SS*	*Oil/Greese*	*N*	*P*
Agriculture and Livestock production	55.8	666	-	22	6.25
Food processing	62.350	92.420	13	3	0.42
Beverage production	6.497	2.646	-	-	-
Chemicals, glass and other products	18.060	5.504	26	516	344
Metal products	5.684	27.935	-	53	-
Petroleum products	66.000	17.000	104×10^3	26×10^3	-
Textiles	375	114	-	-	-
*Sanitary/Domestic services	16.500	38400	-	7.920	960
**Total	175.532	194.685	10×10^3	345×10^3	1.311

* Population of coastal zone = 2,400,000 inhabitants
** Excluding population figure

in the estuary-based town of Douala. An average of 180 heads of cattle is slaughtered each day for 22 days of each month. Each head produces about 7 *l* of blood and 30 kg of stomach contents with 95% pumped into the tributary of river Wouri that enters the sea west of Douala.

Fisheries and other industrial activities have deleterious effects on the estuarine, related aquatic ecosystems and their living organisms. Other studies on solid wastes to the coastal and marine environment of Cameroon that can indicate sources of increased nutrient loads and poor water quality include those of Folack & Ngassa (1994) and Gabche *et al.* (1998). Some of these gave the negative impact on tourism, threats to fish biological diversity, aesthetic degradation on beaches, exposure of humans to chemical packaging and possible spread of contagious diseases. The processes involved in nutrients distribution within Cameroon's coastal systems have been discussed (Keita *et al.*, 1991; Gabche & Folack, 1997). The interest in water quality and nutrients monitoring and modeling along Cameroon's coastal and marine environment increased from the recent eruption in 1999 (18th eruption since 1815 (Epale, 1987)) of the active Cameroon Mountain (4070 m high). It lies to the northern portion of the coastline (402 km long), which is low and swampy, with the peak of the mountain forming an exception to this characteristic, and separating the Cameroon and Rio-del-Rey estuaries.

Quantitative assessments of nutrients in aquatic ecosystems alone are not enough to determine spatial-temporal variations and predictions of future changes and impacts. This can be improved by the use of models. Models used in biological oceanography (Platt *et al.*, 1981) range in scope from process models (e.g. physiological, behavioral or demographic) to ecosystem models (from organism to ecosystem dynamics effects). These have provided a lead way to recent developments of models that determine the interaction of natural and human activities within estuarine systems.

Further to this, complex mathematical models describing physical and biogeochemical processes in the aquatic environment are becoming popular tools for studying the present ecological situation as well as forecasting future changes.

Several examples of such modeling practices exists, covering seas and coastal areas (Baretta *et al.,* 1995; Malgrem-Hansen, 1996), rivers and ground water (Szczepanski, 1996), urban water infrastructure systems (Maksimovic *et al.*, 1996), coastal lagoons and estuaries (Smith *et al.*, 1997), and in integrated modeling of coastal zones. These model applications serve as useful tools in establishing the most efficient strategy of reducing nutrient loads. The calibration process of modeling alters values of selected parameters in the equation to obtain the best possible correspondence between the measured and calculated values. Experience, intuition and understanding of the natural processes and the structure with the model are essential. This will lead to a model with levels of parameters studied.

The objective of this study is to develop biogeochemical models of water, salt and nutrients budgets for two estuarine systems (Cameroon estuary; Longitudes 9.25°–10.00° E+; Latitudes 3.83°-4.1° N+, considered as a pollution "hot spot" and the Rio-del-Rey estuary; Longitude 8.3° E+, Latitude 4.8°N+, considered as a relatively similar but less polluted area) within Cameroon's coastal zone (Longitudes 2°-16° E Latitude 2°-13° N) of sub-Sahara Africa. It is hoped that such models will provide the opportunity to characterize terrigeneous inputs from natural and anthropogenic influences and outputs, with net determination of the role of the estuarine zone as a source or sink for nutrients within the coastal zone, estuaries and adjacent ocean.

Materials and methods

Description of the study area

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 Savanna slopes gradually down to the marsh lands surrounding Lake Tchad to the North of the Adamaoua range. Cameroon is drained by four major drainage basins: Atlantic, Zaire/Congo, Niger and Tchad. A watershed exists along the southern Cameroon plateau separating coastal and Congo system with fresh water input into the Atlantic drainage basin. Cameroon's coastal zone (Fig. 1) extends along 402 km long (Sayer *et al.*, 1992) from Latitude 2.30° N at the Equatorial Guinea borders to Latitude 4.67° N at the Nigeria borders. The coastal zone area is estimated at 9,670 km² (Adam, 1998) representing 22% of the countries of the Gulf of Guinea.

Cameroon's coastal climate is of an equatorial type and 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. Two distinct seasons; a long rainy season of more than 8 months (March-October) and

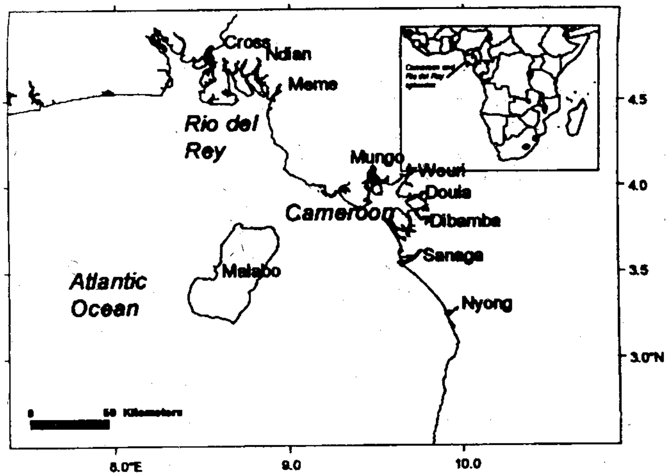


Fig. 1 Map of Cameroon's coastal zone.

a dry season of 4 months (November-February) exist. Air temperatures are high throughout the year. South–westerly monsoon winds modified by land sea breezes predominate, causing humidity values to almost saturation point. Wind speeds attain exceptional 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 dry season is hot with north-easterly harmattan when inter tropical convergence zone deviates from its normally southern position at 5°-7° N.

Cameroon's coastline tropical rain forest is interrupted at the active Cameroon Mountain and within the mangroves 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 matured ones are reached at 2 m. Mangrove estuarine complexes occupy approximately 30% (3,500 km^2) of Cameroon's coastal zone. There exists about 38 species of mangroves dominated by *Rhizophora (R. racemosa* and *R. harrisanii*) species. (Gabche, 1997). The Atlantic forest dominated by families of Caesalpinacea, Guttiferae and Euphorbiaceae follows the order; swamp forest dominated by *Rapphia* spp., *Matritia quadricorius* and *Clenolephon englerianus*, and seasonal inundated forests of *Guitbortia demeussei* and *Oxysttigma menil.* Phytoplankton species (Folack, 1991) were dominated by diatoms such as *Chaetoceros testissimus*, *Nitzchia closterium*, *Diatomavulgare*, *Trachyneis* and *Coscinodiscus*.

Dense river networks which are classified into three estuarine systems, characterize the coast. The West/Rio-del-Rey system has several rivers (Cross-river, Ndian and Meme) that discharge at the Rio-del-Rey point (4.8° N, 8.3° E). The Cameroon estuarine system with several rivers (Mungo, Wouri, Dibamba, etc.) discharges at the Douala point (3.8° – 4.1° N and 9.25°–10° E). This extends towards the west at the Bimbia and the south to the Sanaga river estuary. Some physical characteristics of the Cameroon and Rio-del-Rey estuarine complexes are given in Table 3. 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 coastline and land ward extension of 30 km. The Cameroon estuary extends along a coastline of 60 km from the Sanaga to the Bimbia estuary, and 30 km into the hinterlands giving an area of

1,800 km². Other estuarine mangrove swamps supplied are those of the southern river systems at the Ntem.

The main hydrological characteristics (seasonal runoff) are indicated in Table 4, and these include the rainfall and evaporation with seasonal values. The supplies from the dense river network, groundwater and rainfall make major sources of freshwater into the continental shelf (area = 15,400 km²) (Gabche & Folack, 1997). The gradual descends (10 m, 30 m, 50 m and 100 m depth) of the continental shelf result in generally weak circulation with subsequent high sedimentation rates.

Hydrodynamic processes within the estuarine complexes indicate that tidal wave (semi-diurnal) action in the rivers can be felt

TABLE 3

Physical characteristics of some Cameroon's coastal zone estuarine systems

Estuarine system	Long. (°E+)	Lat. (°N+)	River	Catchment's area(km²)	Estuarine area(km²) Mangrove	Water	Mean depth(m)
Cameroon	9.25-10.00	3.83-4.10	Mungo	4,200			15
			Wouri	8,250			15
			Dibamba	2,400			15
Total/Mean				14,850	1,800	1,500	15
Rio-del-Rey	8.28	4.83	Cross river	800			14
			Ndian	2500			13
			Meme	500			14
Total/Mean				3800	1,500	1,350	14

TABLE 4

River runoff, rainfall and evaporation of some Cameroon's coastal estuarine systems

Estuarine system/ Rivers	River runoff ($m^3 s^{-1}$)			River runoff ($10^6 m^3 d^{-1}$)			Rainfall Douala (mm month⁻¹)			Evaporation (mm month⁻¹)
	Annual	Dry	Rainy	Annual	Dry	Rainy	Annual	Dry	Rainy	Annual
Cameroon							273	44	388	100
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				
Rio-del-Rey							246	86	326	117
Cross river	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				

a long distance from the sea (40 km in the Wouri; 35km 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, which is enormous (Olivry, 1986; Morin & Kuete, 1989). Tidal currents are sometimes violent: 1-1.5 m sec^{-1} for flux and up to 2.6 m sec^{-1} for reflux. Chaubert & Garrand (1977) noted that sea swells are from south to southwest and distant in origin. This peculiarity results from the double obstacle constituted by the Bioko Island and the widening of the continental shelf at the Rio-del-Rey (80 km as compared to 40 km at the Kribi coast). The swells of stronger magnitude (226 m long) are common between June and September with lesser ones between November and April.

Cameroon estuarine complexes and mangroves serve as habitats for *meiofauno taxa* such as nematodes, copepods, amphipods and protozoans, which contribute 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., etc.) and sponges (*Holothurids*, etc). They also serve as breeding grounds and nurseries for shell fish (crabs, e.g. Grapsidae, Ocypodidae and Portunidae; Shrimps, e.g. Peneidae and Palaenonidae) and fin fish species (mud skippers (*Periopthalnus* sp.), Oysters (*Crassostrea gasar*), Cichlidae, Scianidae, Polynemidae, Clupeidae, Drepanidae, etc.

Data sources

The physical characteristics of Cameroon's estuarine systems were obtained and modified from literature (Gabche & Folack, 1997; Angwe & Gabche, 1997; UNEP, 1984; ICITA, 1973; Gate 1980; Van den Bosche & Bernacsell, 1990; Sayer *et al.*, 1992; Mahé, 1987; Gabche & Hockey, 1995; Folack *et al.*, 1999). Hydrological and climate data (Tables 4 and 5) such as river discharge, rainfall and evaporation, etc., came from Cameroon's Annual Hydrological Handbook (1997), Fraser *et al.* (1998) and Cameroon's Meteorological Services in Douala, with

TABLE 5

Mean temperature, salinity and nutrient levels of Cameroon's coastal zone estuarine systems.

Estuarine system	*Parameter*	*River*		*Estuary*		*Ocean*	
		Dry	*Wet*	*Dry*	*Wet*	*Dry*	*Wet*
Cameroon estuary	Temp. (°C)	29.9	21.7	25.0	21.1	30.4	27.5
	Salinity (psu)	0	0	15.8	8.7	21.4	16.5
	Si (µg/ml)	26	27	24.5	24	20	18.1
	NO_3 (µg/ml)	2.6	2.4	3.8	3.6	5.2	2.5
	PO_4 (µg/ml)	2.1	2.0	1.2	1.1	0.6	0.5
Rio-del-Rey estuary	Temp. (°C)	29.2	28.4	28	27	30	29
	Salinity (psu)	0	0	17.8	11.3	19.2	15.3
	Si (µg/ml)	32	30	26	25	24	23
	NO_3 (µg/ml)	1.9	1.8	3.2	3.1	0.4	0.3
	PO_4 (µg/ml)	2.0	1.6	0.9	0.8	0.5	0.4

some modifications. Data on nutrient levels (Table 5) came from routine monitoring by the Ministry of Environment and Forestry in Douala and the Research Station for Fisheries and Oceanography in Limbe, Cameroon. These consisted of monthly *in situ* measurements of surface water quality parameters such as temperature in degree Celsius (°C), salinity in parts salinity units (psu), silicate (Si) in μg/ml, nitrates (NO_3) in μg/ml and phosphates (PO_4) in μg/ml. For ease of comparison, nutrients values were later converted to standard values of moles. Sampling locations were located within the river, estuary and ocean of the respective ecosystems. Further to this, *in situ* concentrations were validated by collecting 20 random samples of water per sampling station (river, estuary and ocean) and preservation in 5 ml concentrated sulphuric acid, and further analysis using phenol disulphuric acid method (APHA, 1981).

Models for budgetary estimates

The budget estimates describe the rate of material delivery to the estuarine system ("inputs"), the rate of material removal from the system ("outputs") and the rate of change of material mass within the system ("storage"). Some materials may undergo internal transformations of state, which leads to appearance or disappearance. Such changes are sometimes referred to as "internal sources of sinks". (David *et al.*, 2000). The Lands Oceans Interactions in the Coastal Zone (LOICZ) Biogeochemical Modelling Guidelines (Gordon *et al.*, 1996), tutorials presented in the LOICZ Modelling web page (http://data.ecology.su.se/MNODE) Smith *et al.* (1997), the tutorials by David *et al.* (2000) and the Computer Assisted Budget Analysis Research Education and Training (CABARET) note were used as guidelines for the budgetary procedure. Budgetary estimations for the Cameroon and Rio-del-Rey estuary systems were separated into 4 months (November–February) for dry season of 120 days and 8 months rainy season (March–October) of 245 days. Hence two seasons, one layered and one box models are developed for the estuarine systems considered to be completely mixed. A small freshwater input compared to volumes of systems and thorough mixing of water column was assumed. The persistent strong monsoon winds, energetic wave action or huge tides induce the fresh water input and thorough mixing.

Water budget

For each of the estuarine systems, a budget of freshwater inflows (such as runoff, precipitation, groundwater, sewage) and evaporative outflow (Fig. 2) is established. These are itemized as follows:
Rate of river discharge (V_Q), Precipitation (V_p), Evaporation (V_E), Groundwater discharge (V_G), if important, and Sewage discharge (V_O). If fluxes are expressed in m^3/d, then:

$$V_R \text{ (residual flux)} = V_{out} - V_{in} \quad (1)$$

or

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

Salt budget

Salt is conserved in the system (Fig. 3). Therefore, salt flux not accounted for by the salinity used to describe the freshwater flow in the water budget must be balanced by mixing.

Let the salinity of system be (S_{sys}) and salinity of the adjacent ocean be (S_{ocn}). If concentration is expressed in parts salinity

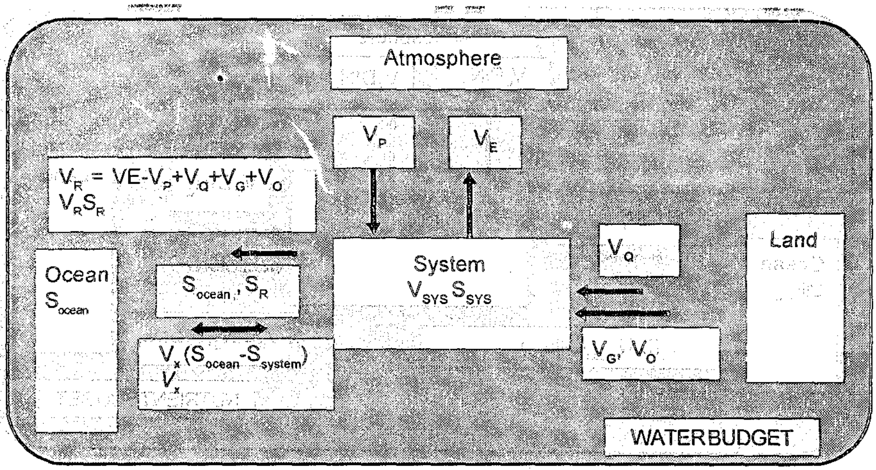


Fig. 2. Typical water budjet of freshwater inflows (such as runoff, precipitation, groundwater, sewage) and evaporative outflow with compensation for outflow (or inflow) to balance the water volume in the system. Symbols used: Rate of river discharge (V_Q), Precipitation (V_P), Evaporation (V_E), Groundwater discharge (V_G) if important, Sewage discharge (V_O).

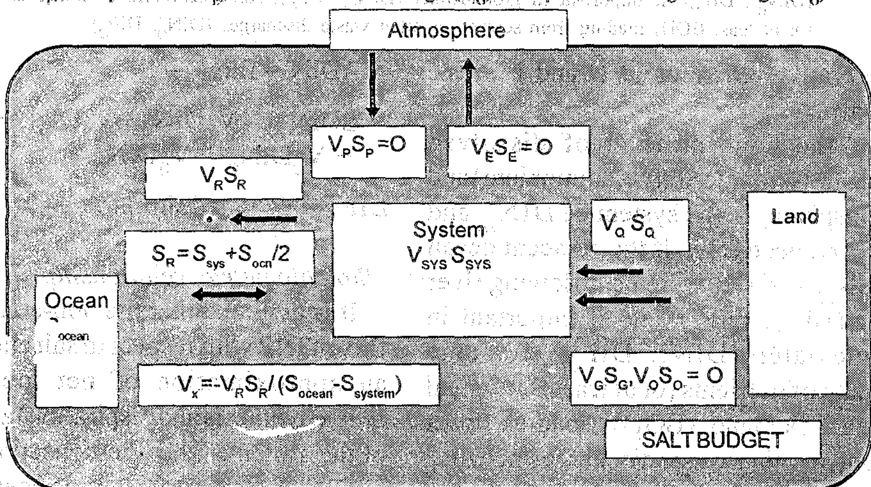


Fig. 3. Typical salt budget of estuarine system. Symbol used: Salinity of system (S_{SYS}), Salinity of the adjacent ocean (S_{OCN}).

units (psu), then:

S_R (average salinity at the boundary) = $(S_{ocn} + S_{sys})/2$ (3)

Note that V_RS_R is the salt flux carried by the residual flow. Salt must be conserved so the residual salt flux is brought back to the system through the mixing salt flux across the boundary (V_xS_x) via the tides, wind, and general circulation pattern. Hence

$$V_RS_R = - V_XS_X \quad (4)$$

$$S_X = (S_{ocn} - S_{sys}) \quad (5)$$

$$V_X \text{ (mixing flux)} = - V_RS_R/S_X \quad (6)$$

N and P budgets

All dissolved N and P will exchange (Fig. 4) between the system of interest and adjacent ocean according to the criteria established in the water and salt budgets. Deviations are attributed to net non-

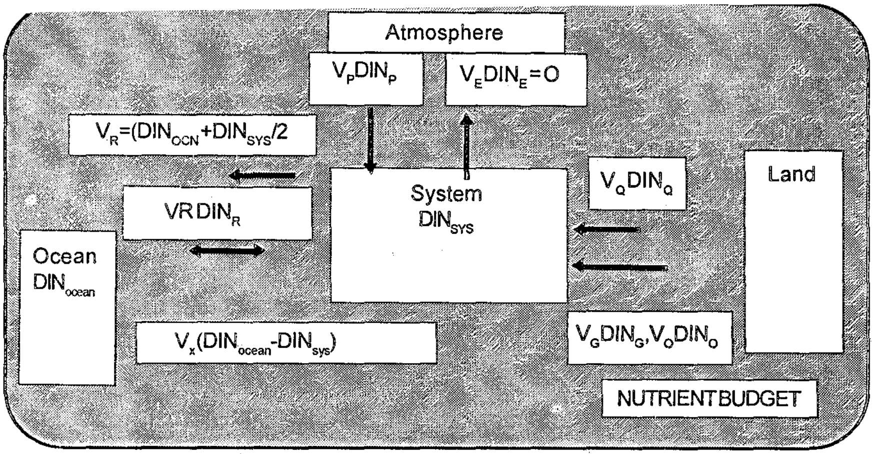


Fig. 4. Typical N and P budgets for an estuarine system. Symbols used: Concentration of dissolved inorganic N (nitrate, nitrite, ammonium) and P (phosphate) in the system (DIN_{SYS}, DIP_{SYS}), in the adjacent ocean (DIN_{OCN}, DIP_{OCN}), in the inflowing river water (DIN_Q), DIP_Q), if important in groundwater (DIN_G, DIP_G); some estimates of nutrients (or at least BOD) loading from sewage or other waste discharges (DIN_O, DIP_O).

conservative reactions of N and P in the system.

Let the concentration of dissolved inorganic N (nitrate, nitrite, ammonium) and P (phosphate) in the system be DIN_{sys} and DIP_{sys}, respectively, if the adjacent ocean be DIN_{ocn} and DIP_{ocn} in the inflowing river water (DIN_Q, DIP_Q), and if important in groundwater (DIN_G, DIP_G); if some estimate of nutrients (or at least Biological Oxygen Demand (BOD)) loading from sewage or other waste discharges be DIN_O and DIP_O with concentrations expressed in µmol/l, then:

$$\text{DIN flux (river)} = V_Q\, DIN_Q \quad (7)$$

$$\text{DIN flux (ground water)} = V_G\, DIN_G \quad (8)$$

$$\text{DIN flux (sewage)} = V_O\, DIN_O \quad (9)$$

$$\text{DIN flux (residual)} = V_R\, DIN_R \quad (10)$$

where $DIN_R = (DIN_{ocn} + DIN_{sys})/2$ (11)

$$\text{DIN flux (mixing)} = V_X DIN_X \quad (12)$$

where $DIN_X = (DIN_{ocn} - DIN_{sys})$ (13)

$$\Delta DIN = flux_{out} - flux_{in} \quad (14)$$

$$\Delta DIN = -(V_X DIN_X + V_R DIN_R + V_G DIN_G + V_O DIN_O + V_Q DIN_Q) \quad (15)$$

DIP is calculated similarly.

Stoichiometric relationships

It is assumed that the non-conservative flux of DIP with respect to salt and water is an approximation of net metabolism (photosynthesis and respiration) at the scale of the system. The non-conservative flux of DIN approximates net nitrogen fixation minus denitrification. The calculation is derived from (p – r) which is the photosynthesis (p) minus respiration (r).

$$(p - r) = -\Delta DIP\ (C{:}P)_{part} \quad (16)$$

(nfix – denit) is N fixation minus denitrification

$$(nfix - denit) = \Delta DIN - \Delta DIP\ (N{:}P)_{part} \quad (17)$$

where $(C{:}P)_{part}$ and $(N{:}P)_{part}$ are the ratios of organic matter reacting in the system.

Results and discussion

Illustrations of budgets

Quantitative estimates of water and salt budgets for the Cameroon estuary for the dry (Fig. 5a) and rainy (Fig. 5b) seasons and DIP and DIN budgets for the dry (Fig. 6a) and rainy (Fig. 6b) seasons are illustrated. This estuary is considered as a hot spot when compared to the Rio-del-Rey estuary. Here, there are low anthropogenic activities with quantitative estimates of the water and salt budgets for the dry (Fig. 7a) and rainy (Fig. 7b) seasons and DIP and DIN budgets for the dry (Fig. 8a) and rainy (Fig. 8b) seasons being illustrated.

Cameroon estuarine system

Water and salt balance.

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

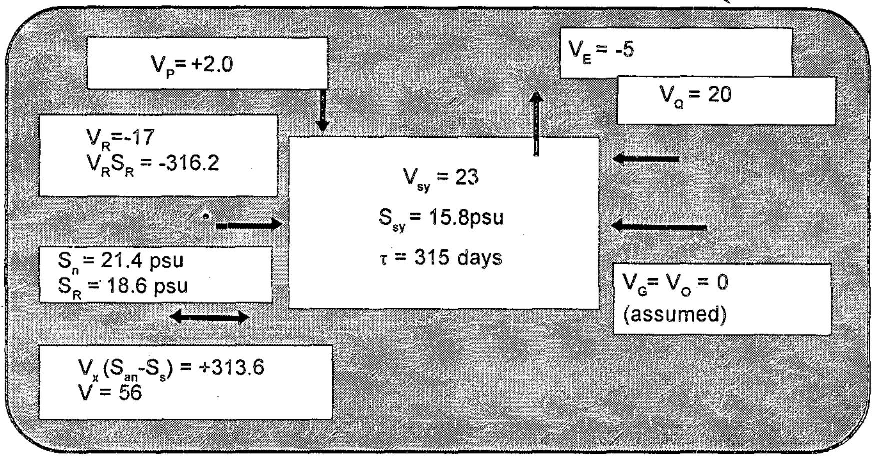


Fig. 5a. Water and salt budgets for the Cameroon estuary (A=1500 km^2; V=23 × 10^9 m^3) during the dry season. System volume is in units of 10^9 m^3. Water fluxes in 10^9 m^3 year^{-1}. Salt fluxes in 10^3 psu m^3 day^{-1}.

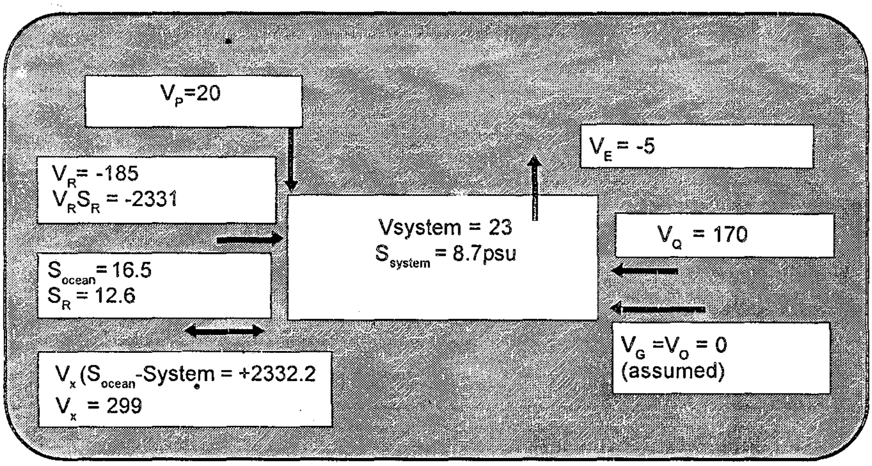


Fig. 5b. Water and salt budgets for the Cameroon estuary (A=1500 km^2; V=23 × 10^9 m^3 during the rainy season. System volume is in units of 10^3 m^3. Water fluxes in 10^9 m^3 year^{-1}. Salt fluxes in 10^3 psu m^3 day^{-1}.

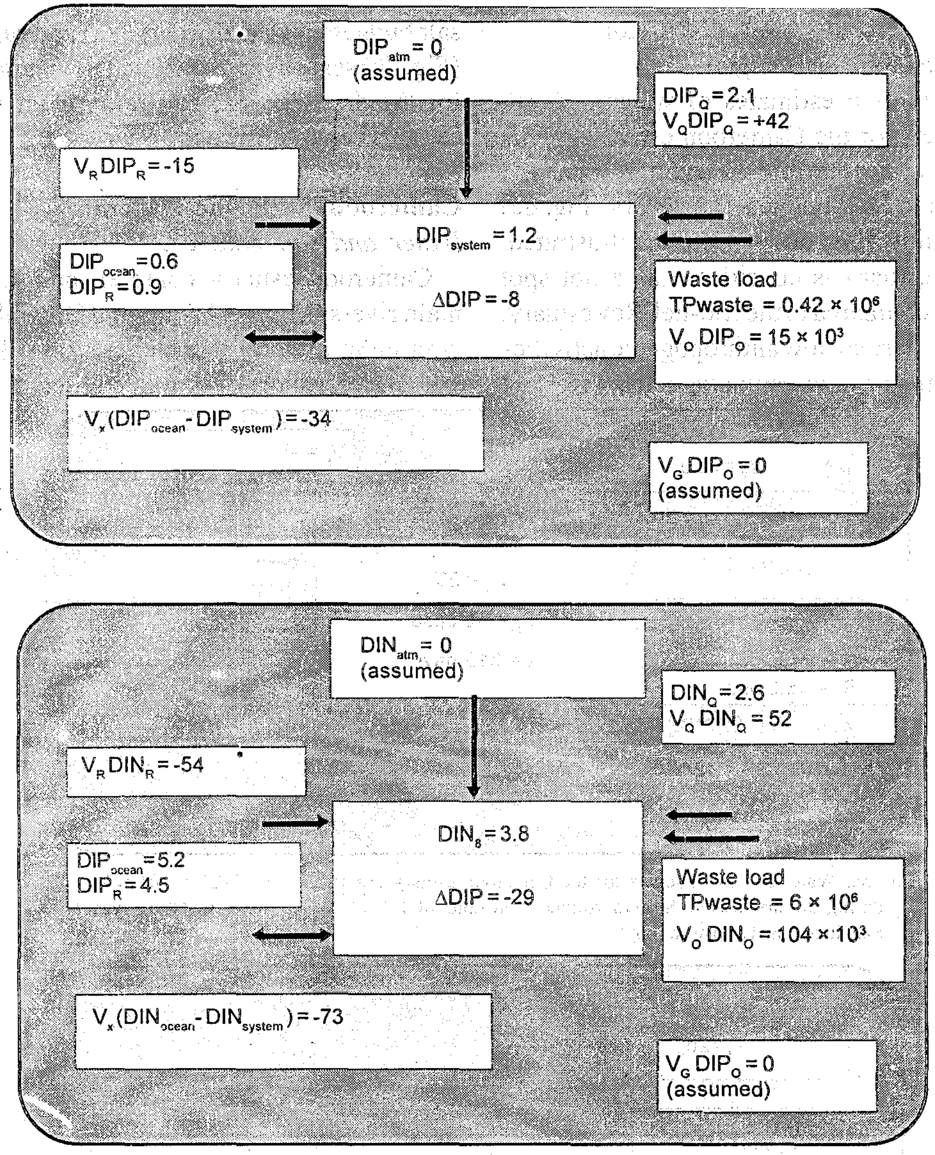
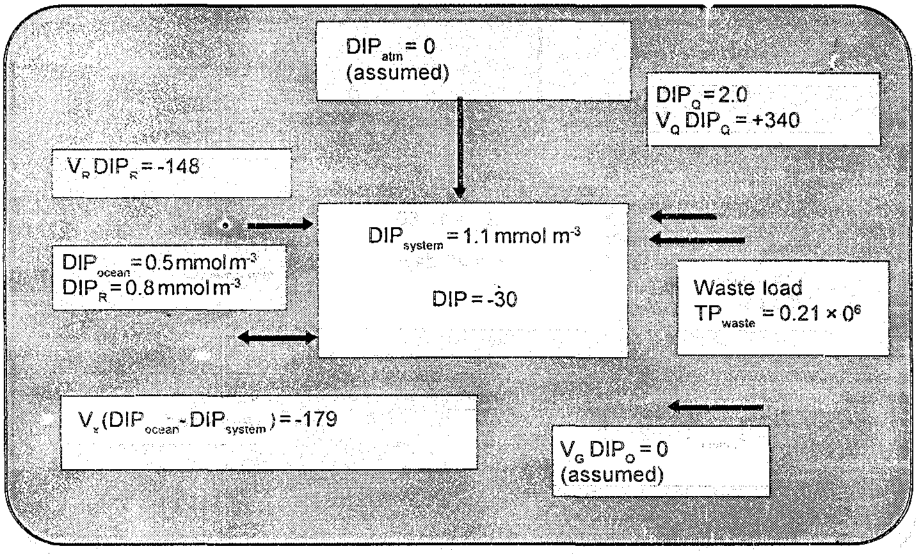


Fig. 6a. DIP and DIN (mmol m^{-3}) budgets for the Cameroon estuary in the dry season. Fluxes in ($\times 10^9$ mmol day^{-1} with waste loads in mol day^{-1}.

mean discharge (Table 4) gives total volumes of $120 \times 10^6 m^3 d^{-1}$; $20 \times 10^6 m^3 d^{-1}$ and $170 \times 10^9 m^3 d^{-1}$ for annual, dry and rainy seasons, respectively.

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 $5 \times 10^6 m^3 d^{-1}$ 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



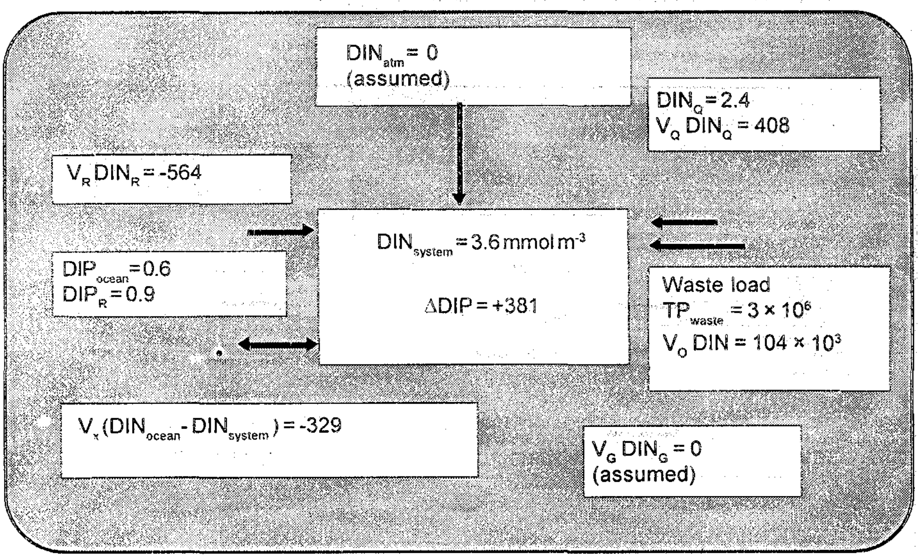


Fig. 6b. DIP and DIN (mmol m^{-3}) budgets for Cameroon estuary in the rainy season. Fluxes (× 10^9 mmol day^{-1}).

rainy seasons, respectively (Table 5). The mean precipitation values are 2 × 10^6 m^3 d^{-} and 20 × 10^6 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 estuarine complex are given in Table 4. Areas of high input of freshwater have low salinity with higher values at the Cameroon estuary due to salt water. V_G (groundwater inflows) and V_O (other inflows) like sewage are assumed to be zero. The water exchange time (τ) was 315 and 48 days in the dry and rainy seasons, respectively.

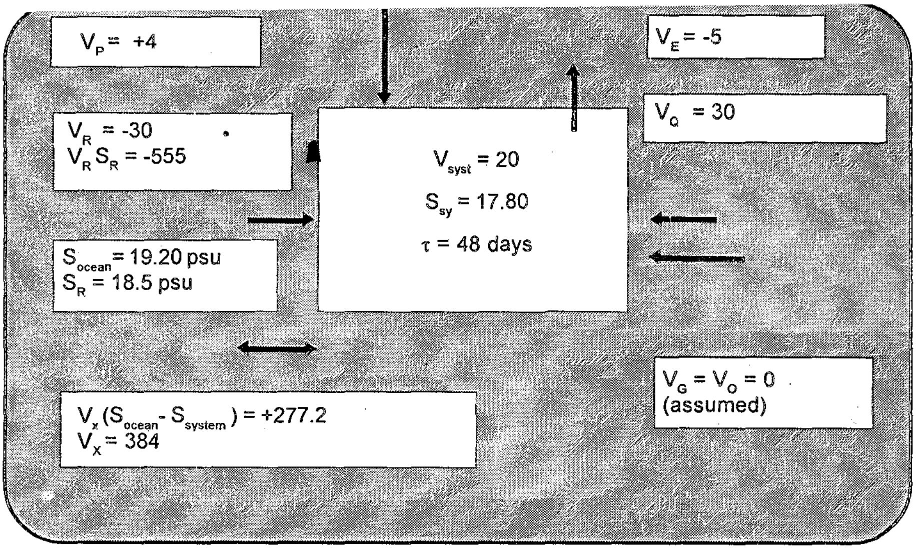


Fig. 7a. Water and salt budgets for Rio-del-Rey estuary (V_{system}=20 × 10^9 m^3; A_{system}=1350 km^2) during the dry season. System volume is in units of 10^3 m^3. Water fluxes in 10^9 m^3 $year^{-1}$. Salt fluxes in 10^3 psu m^3 day^{-1}.

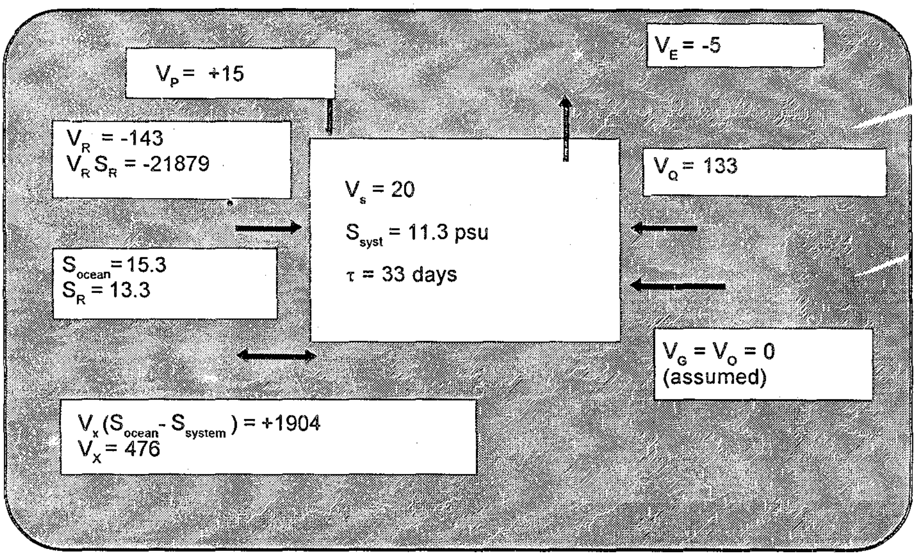


Fig. 7b. Water and salt budgets for Rio-del-Rey estuary (V_{system}=20 × 10^9 m^3; A_{system}=1350 km^2) during the dry season. System volume is in units of 10^3 m^3. Water fluxes in 10^9 m^3 $year^{-1}$. Salt fluxes in 10^3 psu m^3 day^{-1}.

Balance of nonconservative materials

DIP balance. The population of Douala city within the estuary is estimated at 1.4 million inhabitants. The human waste is discharged directly into the system hence waste water loading is considered an important contributor to nutrient loading to the estuary. DIP equivalent of the domestic sewage from the population was estimated based on this population. Non-conservative

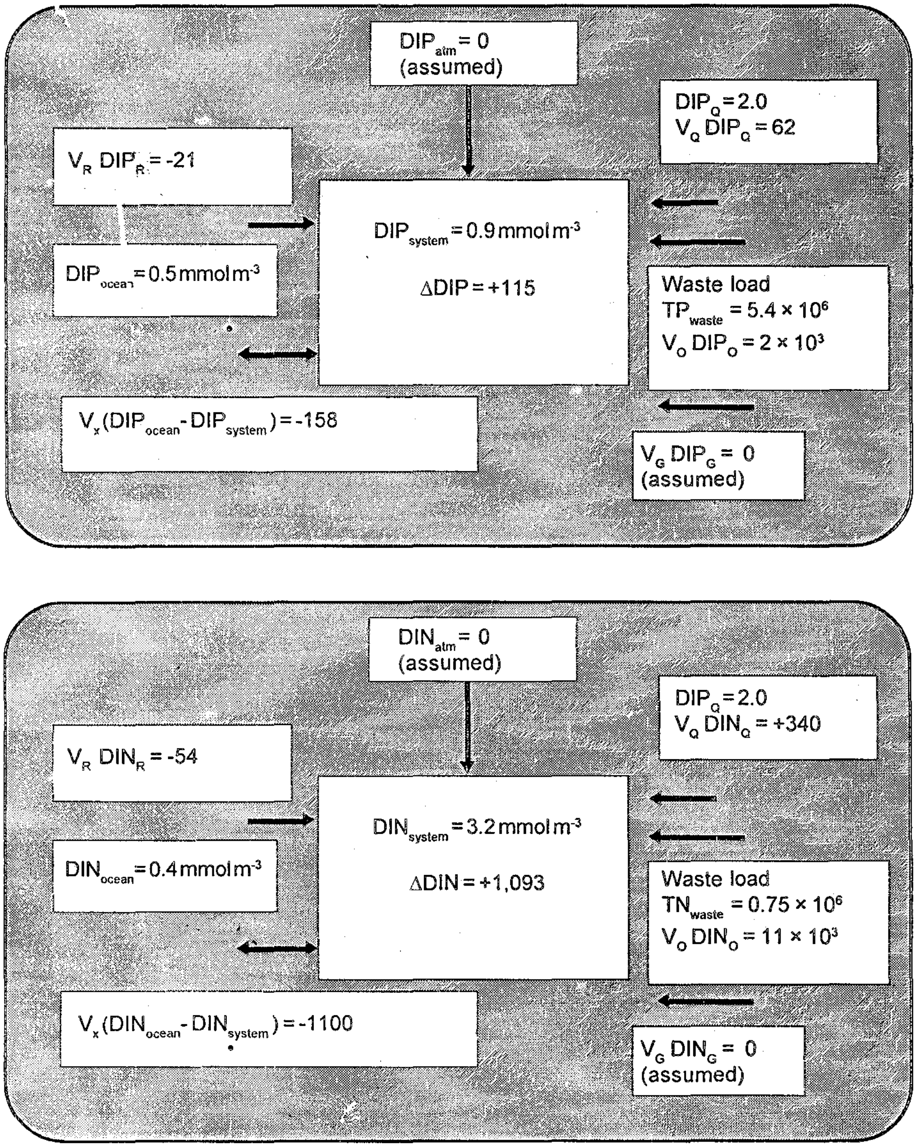


Fig. 8a. DIP and DIN (× 10^9 mmol^{-3}) budgets for the Rio-del-Rey estuary in the dry season. Fluxes (× 10^3 mmol day^{-1}).

flux of DIP (ΔDIP) was calculated for the Cameroon estuary. DIP fluxes are presented in Table 6. The system is a net sink of DIP both in the dry and rainy seasons.

DIN balance. The waste load for DIN from the human population was considered based on the 1.4 million inhabitants or respective population of the estuarine systems. DIN fluxes are summarized in Table 6. The system is a net sink in the dry season and a net source in the rainy season for DIN.

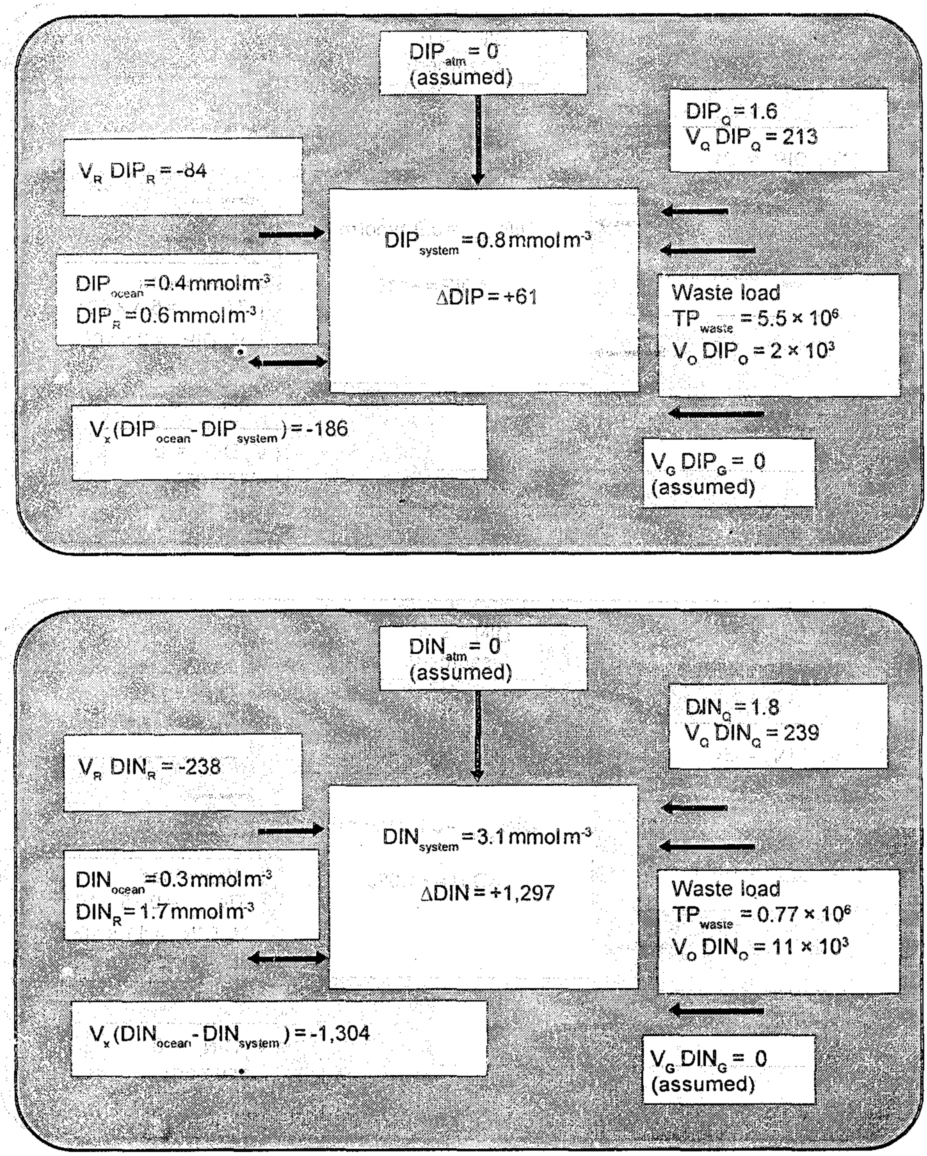


Fig. 8b. DIP and DIN ($\times 10^9$ mmol m^{-3}) budgets for the Rio-del-Rey estuary in the rainy season. Fluxes ($\times$ 10^3 mmol day^{-1}).

Stoichiometric calculation of aspects of net system metabolism

The net ecosystem metabolism (NEM = p-r) can be estimated as negative of the ΔDIP 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. This gives a (p - r) of +7 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 ΔDIN. Expected ΔDIN is ΔDIP 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.

Rio-del-Rey estuarine system

Water and salt balance

The Rio-del-Rey estuary of the west coast of Cameroon has relatively low anthropogenic influence. It is dominated by fishing activities, mainly shrimps, as well as offshore petroleum drilling and some industrial agricultural palm plantations of the Cameroon Development Cooperation (CDC). Water, salt and nutrient budgets for this estuary were considered for the three main rivers (Cross, Ndian and Meme) which discharge into the Atlantic Ocean at the point mentioned earlier.

The total average discharge V_Q is 31 × 10^6 m^3 d^{-1} and 133 × 10^6 m^3 d^{-1} for the dry and rainy seasons, respectively. The total

TABLE 6

Water, salt and nutrient budgets for the Cameroon and Rio-del-Rey estuaries

Parameter	Cameroon estuary			Rio-del-Rey estuary		
	Dry	Rainy	Annual	Dry	Rainy	Annual
A_{syst} (km^2)	1,500	1,500	1,500	1,350	1,350	1,350
V_{syst} (10^9 m^3)	23	23	23	20	20	20
V_Q (m^3 d^{-1})	20	170	120	30	130	97
V_E (m^3d^{-1})	-10	-5	-15	-15	-5	-20
V_P (m^3d^{-1})	2	20	14	4	15	11
V_R (m^3d^{-1})	-17	-185	-129	-29	-140	103
V_X(m^3d^{-1})	56	299	218	384	466	439
τ (days)	315	48	137	48	33	38
V_ODIP_O(10^3 mol d^{-1})	15	15	15	2	2	2
V_QDIP_Q(10^3 mol d^{-1})	42	340	241	60	208	159
V_RDIP_R (10^3 mol d^{-1})	-15	-148	-104	-20	-84	-63
V_x (DIP_{ocn}-DIP_{syst}) (10^3 mol d^{-1})	-34	-179	-131	-154	-186	-175
DDIP (10^3 mol d^{-1})	-8	-28	-21	+112	+60	77
DDIP (10^3 mol d^{-1})	-0.01	-0.02	-0.02	0.08	+0.04	+0.05
V_ODIN_O(10^3 mol d^{-1})	104	104	104	11	11	11
V_QDIN_Q(10^3 mol d^{-1})	52	408	289	57	239	178
V_RDIN_R(10^3 mol d^{-1})	-54	-564	-394	-52	-238	-176
V_X(DIN_{ocn}–DIN_{syst})(10^3 mol d^{-1})	-73	-329	-244	-1,1075	-1,304	-1,228
DDIN(10^3 mol d^{-1})	-29	+381	+244	+1,059	+1,297	+1,218
DDIN (mmol d^{-1}	-0.02	-0.02	-0.02	+0.8	+1	+0.9
$(p\text{-}r)_{plankton}$(mmol m^{-2} d^{-1})	+1	+2	+2	-8	-4	-5
$(p\text{-}r)_{mangroves}$(mmol m^{-2} d^{-1})	+7	+20	+16	-80	-40	-50
$(nfix\text{-}denit)_{plankton}$(mmol m^{-2} d^{-1})	+0.1	+0.6	+0.4	-0.5	+0.4	+0.1

evaporation V_E for the dry and rainy seasons was calculated for the mangrove area of 1,350 km². The monthly mean evaporation is 117 mm (Table 6). This gave V_E values of water evaporated from the estuary area of 5×10^6 m³ 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 86 mm for the dry and 326 mm for the rainy season (Table 6). These values gave volumes of 4×10^6 m^3 d^{-1} for the dry season and 15×10^6 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 47 days and 32 days for the dry and rainy seasons, respectively.

Water and salt budgets for this estuary are presented in Fig. 2b.

Balance of non-conservative materials

DIP balance. The Rio-del-Rey estuary has a population dominated by fishermen estimated at 150,000 discharging directly into the system. Computed $V_O DIP_O$ from this population is 2×10^3 mol d^{-1}. DIP fluxes are summarized in Table 6. Non-conservative DIP, ΔDIP (10^3 mol d^{-1}) of the system shows that the system is a net source of DIP for both seasons.

DIN balance. DIN fluxes are presented in Table 6 and Fig. 5a and b. DIN flux from the population was considered. The system seems a source for DIN in both seasons.

Stoichiometric calculation of aspects of net system metabolism

The net ecosystem metabolism for the estuarine area (NEM = [$p - r$]) is estimated as –9 mmol m^{-2} d^{-1} in the dry season and –9 mmol m^{-2} d^{-1} using plankton C:P ratio of 106:1 (Table 6) and Fig. 3a and b. If the system is dominated by mangrove, ($p - r$) is estimated as –85 mmol m^{-2} d^{-1} in the dry season and –45 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 ΔDIP × 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 –0.6 mmol m^{-2} d^{-1} in the dry season and +0.3 in the rainy season. The system seems to behave as net denitrifying in the dry season and nitrogen fixing in the rainy season.

Conclusion

Both physical characteristics and anthropogenic influences have an impact on the dynamics of nutrients and water quality. The main sources of high nutrient loads and poor water quality along Cameroon's coastal zone include input from industries (60% in coastal zone), domestic liquid wastes discharged directly into streams or open drains and estuaries, use of fertilizers (nitrogen and phosphorus) as well as organochlorine pesticides (DDT, lindane, herbicides and deldrine) which drain from agricultural farm lands into rivers, petroleum refinery discharges and oil spills from tankers at the refinery and on transit, aesthetic degradation of beaches from fisheries and municipal activities with the reduction of their use of recreation and tourism. All these have resulted in pollution of the coastal waters and poor health of the population.

Apart from the above-mentioned, and in the absence of significant upwelling in

Cameroon's coastal waters, certain advantages still come up from the nutrient input. The dense network facilitates nutrient input (Gabche & Folack, 1995). This results in a large primary production of organic matter, which is consumed by zooplankton at successively higher trophic levels. This is associated with rich fishery resources. Crosmier (1964) indicated a significant level of fish diversity along Cameroon's coastal zone with *Palaemon hastatus* representing 16%, pelagics (63%), demersals (19%) and Penaeus shrimps (2%) of species exploited. Schneider (1992) noted that the total marine catch from the Gulf of Guinea (Côte d'Ivoire to Gabon) reported to FAO in 1988 totaled 630,315 mt, of which only 177 mt were taken by foreign fleets. The shares in 1988 of the countries bordering the Gulf of Guinea were as follows: Ghana, 302,935 mt; Nigeria, 15,709 mt; Cameroon, 62,529 mt; Côte d'Ivoire, 60,764 mt; Gabon, 10,000 mt; Togo, 14,755 mt; Benin, 9,693 mt and Equatorial Guinea, 36,000 mt. The high production values in some countries (Ghana, Côte d'Ivoire and Benin) are associated to upwelling while those for others (Cameroon and Nigeria) are associated to nutrient input from the coastal waters.

Some measures can be taken to reduce nutrients loads to the estuarine and related ecosystems based on concrete facts. For example, since pollution from land-based sources, organic matter and nutrients is of much impact to the fisheries, tourism and human health of Cameroon's coastal and marine environment, there is the need to monitor nutrients and water quality on a continuous basis. Expertise on water quality and nutrients monitoring analysis should be intensified through training and education. Equipment needed for both *in situ* and laboratory analysis of water quality parameters and nutrients should be made available to ensure precision in results obtained. An inter-calibration exercise on the nutrients is necessary to standardize methodologies for analysis. A manual should be developed with standardized methodologies for water quality and nutrients analysis within the Gulf of Guinea Large Marine Ecosystem, in consultation with others such as Valderrame (1995) and WHO (1989). Finally, the establishment of Internet access between main laboratories within the sub-Sahara Africa region is important for exchange of data and experience between scientists on land-based sources of pollution water quality and nutrients levels, purification processes and production trends in estuaries and marine environment.

Acknowledgement

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